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ECONOMIC GEOLOGY

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PREFACE TO SEVENTH EDITION

In preparing a new edition the plan of the book remains the same, but a number of changes have been made in the subject matter and references, in an effort to keep the work up to date, a task by no means easy with a rapidly expanding subject like Economic Geology. That nothing has been overlooked is perhaps too much to hope for. The chapter on Oil and Gas has been completely revised and many other parts have been rewritten. Less space has been devoted to statistics, and there has been a reduction in size of the work as a whole.

All statistics are taken either from the reports of the U. S. Bureau of Mines, or those of the Dominion Statistics Bureau of Canada.

The writer wishes to acknowledge the assistance given him by Prof. W. A. ver Wiebe of the University of Wichita, and by Dr. Ralph Tuck of the Alaskan Railroad. Many state geologists have also kindly checked over the material relating to their states.

CORNELL UNIVERSITY, ITHACA, N. Y.
June, 1937.

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PART I

NONMETALLICS

CHAPTER I

COAL

Definitions and Kinds.—Coal may be defined as a stratified rock formed from the accumulation and decay under water of vegetable matter, and its subsequent consolidation.

By a series of slow changes (pp. 4, 14) the plant remains lose water and gases, the carbon becomes concentrated, and the material assumes the appearance of coal.

Coal is a complex substance, since it not only contains many different kinds of plant tissue, but these, together with their decomposition products, represent various chemical compounds. Several well-marked changes in the process of coalification are recognized and described below.

Peat (171–186).—This, which represents the first stage in coal formation, is formed by the growth and decay of grasses, sphagnum, and other plants in moist places. A section in a peat bog from the top downward may show: (1) a layer of living plants; (2) a layer of dead plant fibers, whose structure is clearly recognizable and which grades into (3) a layer of fully formed peat, a dense, brownish black mass, of more or less jellylike character, in which the vegetable structure is often indistinct.

The following analyses show the difference in composition of the different layers. They also show that, while during this change the hydrogen and oxygen diminish, the carbon increases in proportion.

ANALYSES OF DIFFERENT LAYERS OF A PEAT BOG

<table>
<tr><th>MATERIAL</th><th>CARBON</th><th>HYDROGEN</th><th>OXYGEN</th><th>NITROGEN</th></tr>
<tr><td>Sphagnum . . . .</td><td>49.88</td><td>6.54</td><td>42.42</td><td>1.16</td></tr>
<tr><td>Porous, light brown sphagnum peat</td><td>50.86</td><td>5.8</td><td>42.57</td><td>.77</td></tr>
<tr><td>Porous, red-brown peat . . . . . .</td><td>53.51</td><td>5.9</td><td colspan="2">40.59</td></tr>
<tr><td>Heavy brown peat . . . .</td><td>56.43</td><td>5.32</td><td colspan="2">38.25</td></tr>
<tr><td>Heavy black peat . . . .</td><td>59.7</td><td>5.7</td><td>33.04</td><td>1.56</td></tr>
</table>

Lignite.—This substance, also called *brown coal,* representing the second stage in coal formation, is usually brown or sometimes yellowish in color, woody in texture, and yellow-brown streak. It burns readily, but with a long smoky flame, and with lower heating power than the higher grades of coal. Because of the large amount of moisture it often dries out on exposure to the air, and rapidly disintegrates to a powdery mass.

Lignite is distantly jointed, and as mined is as a rule irregularly slabby.

The lignites are usually restricted to the younger formations. They are found in the various stages of the Cretaceous and Tertiary of the United States and Canada. Exceptionally they occur in beds as old as the Carboniferous, as in Russia (11).

Jet is a coal-black variety of lignite, with resinous luster and sufficient density to permit its being carved into small ornaments. It is obtained on the Yorkshire coast of England, where a single seam produced 5180 pounds, valued at $1250. According to Phillips, jet is simply a coniferous wood, still showing the characteristic structure under the microscope. ("Geology of England and Wales," p. 278.)

Subbituminous Coal or Black Lignite.—A grade intermediate between lignite and bituminous, and sometimes difficultly distinguishable from these. It is usually glossy black, and relatively free from joints. The moisture content is commonly over 10 per cent and the calorific value on an ash-free basis is 7000–11,000 B.t.u. Campbell (19) has pointed out that it checks irregularly on drying and when weathered splits parallel with the bedding, while bituminous coal shows a columnar cleavage (Plate I).

Bituminous Coal.—This represents the fourth stage in coal formation. It is denser than the lignites, deep black, comparatively brittle, and breaks with cubical or sometimes conchoidal fracture. On superficial inspection it shows imperfect traces of vegetable remains (Plate III); but in thin sections examined under the microscope, traces of woody fiber, lycopod spores, etc., are commonly seen (Plate II). Bituminous coal burns readily, with a smoky flame of yellow color, but with greater heating power than lignite. It does not disintegrate on exposure to air as readily as lignite does. Most bituminous coal is of earlier age than lignite; but where the two occur in the same formation, as in parts of the West, the lignite is commonly in horizontal strata, while the bituminous coal occurs in areas of at least slight disturbance.

PLATE 1

FIG 1 —Subbituminous coal showing the irregular checking developed in drying (*After Campbell, Econ Geol, III*)

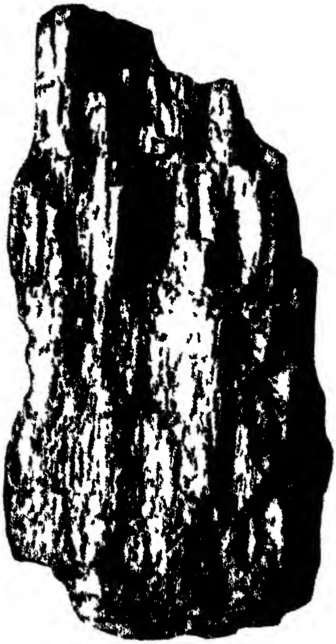

FIG. 2.—Bituminous coal, showing prismatic structure (*After Campbell*)

When freed of their volatile hydrocarbons and other gaseous constituents by heating to redness in a coke oven, many bituminous coals cake to a hard mass called *coke*. Since not all bituminous coals possess this characteristic, it is customary to divide these coals into *coking* and *non-coking* coals.

The formation of coke by natural processes is referred to on p. 6.

Semibituminous Coal.—A rank next higher than bituminous, which is nearly smokeless. Campbell gives the fuel ratio (p. 8) as 2.5–5. The fixed carbon (p. 8) figured on a mineral-matter-free basis is 28–86 per cent, and the volatile matter (p. 8) dry between 22 and 14 per cent. It is non-agglomerating.

Semianthracite.—The next higher rank is designated as a smokeless fuel whose fixed carbon figured on the same basis as the preceding is 92–98 per cent and volatile matter 8–14 per cent.

Anthracite Coal.—This coal is black, hard, and brittle, with high luster and conchoidal fracture. It represents the last stage in the formation of coal, and like bituminous coal, may show jet-like bands, representing flattened stems or trunks. Anthracite has a lower percentage of volatile hydrocarbons and higher percentage of fixed carbons than any of the other varieties. On this account, it ignites much less easily and burns with a short flame, but gives great heat.

The geological distribution of anthracite is more restricted than that of biuminous coal, and in fact its occurrence is often more or less intimately connected with dynamic disturbances.

Cannel Coal.—This is a massive non-coking black coal, of compact grain, dull luster, and conchoidal fracture. It has a low fuel ratio, high hydrogen content, ignites easily, and burns with a long yellow flame. It is composed chiefly of pollen and spore material (2, 6, 17).

Ashley makes the following classification of cannel coals: 1. Subcannel coal. (*a*) Brown subcannel of brown coal and lignite rank; (*b*) black subcannel of subbituminous rank. 2. Cannel of bituminous rank. (*a*) Boghead cannel (fuel ratio .5); (*b*) typical cannel (fuel ratio under 1); (*c*) lean cannels or semicannels (fuel ratio over 1). 3. Canneloid of semibituminous, semianthracite, or anthracite rank.

Carbonite or Natural Coke.—This term is applied to natural coke, which is formed by igneous rocks cutting across bituminous coal seams. As illustrative may be mentioned an occurrence in central Utah,[1] where "dikes of igneous rocks ten feet in width have cut vertically across the coal bed, nine to sixteen feet thick, metamorphosing the coal

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[1] Taff, Science, N. S., XXIII: 696, 1906.

into a coke-like substance to a distance of three feet on either side. The coal thus fused is distinctly columnar, the columns standing perpendicular to the face of the dike; it has a graphitic luster, but is not vesicular like artificial coke." Natural coke is also found in New Mexico, Virginia, and Illinois (5).

The higher quantity of volatile matter in carbonite than artificial coke may be due to its having formed at some depth below the surface, thus preventing the escape of the volatile matter, short heating, or enrichment by gases from the neighboring coal.

ANALYSES OF NATURAL COKE

	I	II	III
Moisture	1.116	.32	4.55
Volatile hydrocarbons	11.977	20.38	4.43
Fixed carbon	75.081	65.90	84.67
Ash	11.826	13.10	6.35

I. Richmond, Va., coal basin.—Watson, Min. Res. of Va., p. 343, 1907. II. Book Cliffs coal field, Utah.—Taff, Science, N.S. XXIII: 696, 1906. III. Cerrillos Hills district, N.M.—Johnson, Sch. of M. Quarts., XXIV: 492, 1903.

Rank and Grade. — The term rank refers to the position of the coal in the series, anthracite being the highest. Grade is a term applied to the purity of the coal.

Specific Gravity. — The specific gravity as given by different writers is as follows (37):

Lignite (Moore)	.5 –1.3
Bituminous (Moore)	1.15–1.5
Bituminous, pure (Porter)	1.26–1.32
Cannel (Moore)	1.2 –1.3
Cannel (Ashley)	1.14–1.51

The specific gravity increases with the amount of ash.

Proximate Analysis of Coal.—An elementary analysis of coal (see p. 17) is of comparatively little practical value. Therefore proximate analyses are commonly employed, in which the probable method of combination of the elements is given. By the proximate method the elements in the coal are grouped as moisture, volatile matter, fixed carbon, ash, and sulphur.[1]

Moisture is usually highest in peat and lignite.

Volatile matter, which is driven off at a red heat, varies in its character.[2] In the western coals of the younger geological formations there is a large proportion of carbon dioxide, carbon monoxide, and water, with a correspondingly small proportion of hydrocarbons and tarry vapors, while in the Appalachian coals the reverse is true. The value of coal for fuel purposes is determined mainly by the relative amounts of its fuel constituents which named in the order of their calorific value are, hydrogen, volatile hydrocarbons, and fixed carbons. Some bituminous coals have a higher heating value than anthracite, due probably to the presence of free hydrogen. Volatile matter in coal promotes free burning and easier ignition.

The *fuel ratio* is the ratio of fixed carbon to volatile matter.

Sulphur is commonly present as an ingredient of pyrite and may vary in amount in any rank of coal. The latter is also true of ash which represents noncombustible mineral matter.

The ash consequently bears no direct relation to the rank of the coal; and the same is true of sulphur, which is usually present as an ingredient of pyrite or less often gypsum. The clinkering of coal is commonly due to a high percentage of fusible impurities in the ash, and for metallurgical work the composition of the ash often has to be considered.

The following analyses will also serve to illustrate the composition of the ash:

ASH ANALYSES

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	MnO_2	SO_3	Na_2O K_2O	Cl	P_2O_5
Peat, average of several . . .	25.50	5.78	18.70	24.00	3.20	....	7.50	1.72	.60	2.56
Lignite	30.14	13.48	11.70	23.59	.88	3.32	14.22			
Bituminous coal	34.32	14.62	22.94	14.85	1.42	1.16	10.97			

Sulphur is an objectionable impurity in steaming coals on account of its corrosive action on the boiler tubes. It is also undesirable in coals to be used for metallurgical purposes and gas manufacture.

Origin of Coal (1–17).—It has been shown that there are gradations between unquestioned plant beds and mineral coal, and that coal, besides containing the same elements as plant tissues, although in different proportions, often shows the presence of plant fibers, leaves,

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[1] The proximate analysis, though apparently a simple operation, needs to be carefully carried out to prevent variable results. See in this connection U. S. Geol. Surv., Prof. Pap. 48, I, and Bur. Mines, Tech. Pap. 8, 1913.

[2] Bur. Mines, Bull. 1, 1910.

FIG 1 —Enlarged section of bituminous coal from Ohio Crenulated bands are modified lignitic material Dark bands canneloid White bodies, flattened spores (*E C Jeffrey, photo*)

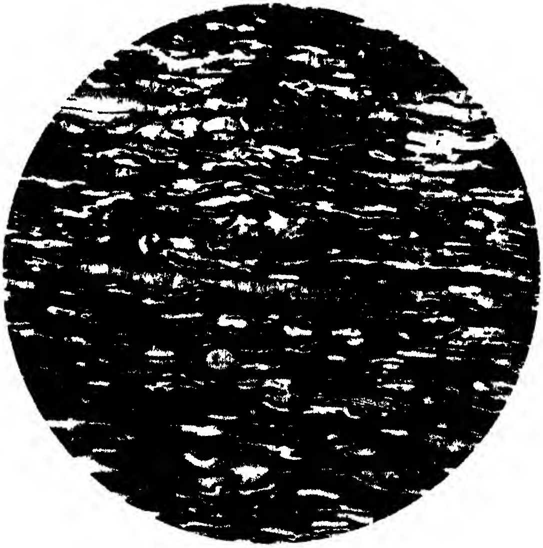

FIG 2 —Enlarged section of cannel coal from Kentucky Light undulating bands, wood White bodies, flattened spores (*E C. Jeffrey, photo.*)

stems, seeds, etc., in addition to their occurrence in the associated rocks. Moreover, stumps of trunks of trees are sometimes found standing upright in the coal, with their roots penetrating the underlying bed of clay (8, 9), just as trunks of trees at present stand in bogs. While these facts point unmistakably to a vegetable origin of coal, it is less easy to understand the exact manner in which the great accumulations of vegetable matter have been made, and the changes from plant tissue to mineral coal. The several points requiring explanation therefore are: (*a*) conditions of accumulation, (*b*) character of organisms forming coal, (*c*) conditions of initial process of organic decomposition, and (*d*) nature of forces bringing about subsequent alteration of organic residues.

Conditions of Vegetable Accumulation (6, 9, 12, 15).—While it is generally agreed that coal originated by the accumulation and slow decay of vegetable matter under water, a difference of opinion may exist as to whether the vegetable matter accumulated by growth in place (*autochthonous origin*) or by the accumulation of transported vegetable matter (*allochthonous origin*).

As favoring the former theory we have the perfect preservation of many plant remains, a condition unlikely to exist if the material had been transported by streams, and the upright trunks in coal, with roots extending into the under clay, the latter supposedly representing the old soils or bottom muds of the swamps in which the coal-forming plants grew.

It is true, however, that allochthonous coals may exist, because some formations have local coal deposits occurring as thin wedges or lenses, derived from drifting plant material, with no roots penetrating the under clay. Indeed, some writers, among them Jeffrey in the United States (6, 34), have argued most strongly in favor of this view, because of the high spore content of many coals, which could be due only to accumulation in open water. The process is a slow one, but its analogue is to be seen in modern lakes.

Possibly also some deposits represent vegetable accumulations in delta deposits, or in lacustrine beds, as in the case of the Commentry fresh-water basin of France[1] or the Tertiary coals of the Frazer delta in British Columbia.

A difficulty to be overcome is the fact that while peat bogs are known covering several square miles of area, they are not comparable in size to the extensive coal deposits found in many parts of the world.

Perhaps the most perfect resemblance to coal-forming conditions is

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[1] Stevenson, Ann., N. Y. Acad. Sci., XIX: 161, 1910.

PLATE III

FIG. 1.—Subbituminous coal from Marshall, Colo.

a. Jet-black Lenses represent Stems Flattened by Pressure.
b. Dull layers, composed of Decayed Wood, Cuticles, Leaf Laminæ, etc.

FIG. 2.—"Mineral charcoal." (*After White and Thiessen, Bur. Mines, Bull.* 38.)

that now found in the Dismal Swamp of Virginia and North Carolina, or the Great Sumatra Swamp.[1]

In the former the area is very level, though with slight depressions in which there is either standing water or swamp conditions. Indeed, there is such a general interference with free drainage that the swamp areas are extensive, and vegetable accumulations are taking place, a thickness of 8–12 feet of peat having formed. There is, moreover, a general absence of sediment.

In the latter swamp, which covers more than 80,000 hectares (308.8 square miles), there is being deposited a high-grade peat reaching a depth of 9 meters, and having only 6.39 per cent ash in the dry fuel.

If either of these areas were submerged beneath the sea, the vegetable remains would be buried and a further step made toward the formation of a coal bed. Re-elevation, making a coastal plain, would permit the accumulation of another coal bed above the first, and this process might be continued again and again.

The evidence now at hand indicates that the vast deposits of peat which represent the first stage in coal formations were probably accumulated near tide level for the following reasons: (1) Marine beds are often intercalated in the coal measures, and are sometimes found overlying the coal; (2) brackish-water molluscs are found in some of the rocks of the coal basins; (3) the coal strata show a marked parallelism and a frequency of salt-water invasion.

The coal-forming plants were of fresh-water character, and the ingress of the sea was probably prevented either by the presence of barrier ridges which kept out the salt water, or in other cases a thick plant growth around the borders of the swamps may have prevented any serious inflow of salt water.

The presumption is, then, that in many cases the coal-forming plants grew in coastal or lacustrine swamps developed in regions of slight submergence of a very mature and broadly extended peneplain.[2]

Some peat swamps were probably located in vast deltas, but it is doubtful if such large vegetable accumulations took place in salt water, for although peat is known to be in process of formation in salt marshes, White (17) says, "it does not seem clear that coal with so large a percentage of mother of coal, jet-like wood, etc., and with such pure carbonaceous matter, that is, containing such a moderate per-

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[1] Potonié, Entstehung der Steinkohle, 5th Ed.: 154, 1910.

[2] Schuchert points to the persistent high sulphur content of the Mississippi Valley coals as significant, for he states that this element is always present in marine marshes and almost wanting in fresh-water ones.

centage of ash, as the coal in the Carboniferous of Illinois or Indiana, or that interbedded with marine or brackish water beds in Wyoming, was laid down in estuaries flooded by sea water."

A distinction is, however, sometimes made between: (1) *limnetic* coals, or those derived from plant remains accumulated in fresh water; and (2) *paralic* coals, or those derived from plant remains which collected in marshes near the sea border.

Character of Organisms Forming Coal (6, 12, 22, 34, 44).—Microscopic study of different coals shows that they may be made up of the following constituents (41, 42, 43).

Anthraxylon, or bright coal, consisting of black lustrous or jet-like lenses, representing woody material (Plate III, Fig. 1) in which the tissue may still be recognized under the microscope. It is the same as *vitrain.*

Durain, a dull-band granular coal, which has no counterpart in American coals.

Attritus, which includes the finely divided solid residues of plant decay, being made up chiefly of the more resistant plant products, such as cuticle, spore and pollen matter, resinous matter, and mineral matter; practically the same as clarain.

Dull coal is usually composed largely if not wholly of attritus, of varying sizes, but it may have some small strips of anthraxylon.

Clarain, a term used by English writers, is usually applied to a mixture of vitrified woody plant material, not distinguishable from vitrain, which is embedded as bands, lenses or irregular strips, in dull detrital matter. It may grade into durain.

Mineral charcoal, mother of coal, or fusain is carbonized wood (Plate III, Fig. 2) relatively unmodified as to structure, and resembling wood charcoal. It may form layers in coal of any rank.

Cannel coal is formed almost entirely of spore eximes, the resins and cuticles forming only a small proportion of the mass. These spores were formerly mistaken by some for algæ, and it is now recognized that neither the latter nor any homogeneous fundamental jelly-like substance of this nature is present in bog-head, cannel, or any other coal.

Types of Coal (44).—According to the nature of the plant remains present in coals they may be divided into: (1) *banded,* those composed of both anthraxylon and attritus, and (2) *nonbanded,* or those composed almost entirely of attritus.

The banded coals are further divided into several subtypes depending on the proportions and character of the anthraxylon and attritus.

These subtypes are: (1) bright coal, (2) semisplint coal, which breaks into fairly regular parallelopiped blocks and is known in trade as block coal, and (3) splint coal, which shows an irregular fracture.

Theoretically the several types mentioned above should be found in coal deposits of all ages, but splint coals are found most abundantly from the middle Pottsville to middle Kittanning. The differences between the subtypes mentioned above become less clear with a rise in the rank of the coal.

The microstructure of coal is to be seen clearly in thin sections up to semibituminous. Anthracite is difficult to section, and the microstructure is best studied on a polished and etched surface (46).

Conditions of Decomposition.—Two stages may be recognized in the coalification process, viz., (*a*) the putrefaction stage, which is a biochemical process, and (*b*) the alteration or metamorphic stage, involving dynamo-chemical action.

When dead vegetable matter accumulates under water, it does not remain unchanged, but undergoes a deoxygenation and dehydrogenation process, which is accomplished by fermentation or maceration in which minute plants (*bacteria*) and also animals take part. As a result of this the plant tissues break down to a greater or less degree, depending on the stage of decay. The change may advance no further than to convert the mass into woody or fibrous peat, or it may go far enough to obliterate most of the plant structures, giving a somewhat jelly-like black peat, which changes into the so-called amorphous coal. It is highly probable that the process of decay had not advanced to the same stage in all peats prior to their burial under sediment.

The decomposition of the original cellulose ($C_6H_{10}O_5$) of the plant tissue liberates substances such as CH_4, as well as CO_2, CO, H_2O, etc. It seems probable that the jellification process leads no further than peat, and that for the development of the later stages dynamo-chemical changes are necessary.

While in peat beds the lower layers are under gentle pressure, so that a bed 1 foot thick, when buried under 15 or 20 feet of other peat layers, may be reduced to about 1 inch in thickness, the real consolidation does not begin until it is buried under a greater weight of sediment.

Indeed, heat and pressure seem necessary for the change from lignite to bituminous coal, and long periods of time are apparently required for the slow changes that take place.

The process of change from lignite on is to be regarded as a dynamo-chemical one, which may in fact overlap the biochemical changes.

The first stage in the densification of peat under load is of this nature. Occluded gases are expelled, liquid putrefaction products forming the cementing paste or binder of the coal are partly hardened, and a reduction of the mass takes place.

As the change continues, there is a progressive devolatilization due to geodynamic processes, and while the exact changes and compounds evolved are not known, we do know that there is a reduction of the volatile combustible matter.

It has been commonly assumed that to produce the higher grades such as anthracite, strong folding was necessary, in order to develop sufficient heat and pressure for this degree of metamorphism. M. R. Campbell (3) has, however, argued with apparent reason that while the chemical changes involved are induced by heat (of ordinary temperature), still these changes are retarded or prevented unless the structural conditions (presence of joints, etc.) are favorable for the escape of the gaseous products of this change.

Thus, for example, the Pennsylvania anthracites are formed not so much because of heat and pressure, but because of the cracking of the rocks which allowed thorough oxidation. The same amount of folding in the Pocono rocks of Maryland has not produced any anthracite, as the structural conditions were not favorable for the free escape of the gases.

Cases are known, where the heat causing the changes is intense and local, as in the Cerrillos coal field of New Mexico (106), or the Crested Butte district of Colorado (73), where bituminous coal has been locally changed to anthracite by a near-by igneous intrusion.

Some geologists, notably J. J. Stevenson, have argued that the anthracite coal has not been developed from bituminous coal by metamorphism, but that the volatile constituents were partly removed by longer exposure of the vegetable matter to oxidation before burial. Among paleobotanists there is also a difference of opinion as to whether the succession, peat, lignite, etc., is a strictly lineal one.

David White (17) has called attention to the thrust-pressure hypothesis, which postulates that the devolatilization of coal is the result of thrust pressure.

He points out that as a result of regional thrust pressure, essentially horizontal in direction, the coal has become dense, lithified, jointed, further reduced in volume, schistose and even crushed, or possibly cemented, while gradually becoming progressively dehydrated, devolatilized, and concentrated both as to volume and as to its combustible matter.

This pressure, acting on and transmitted with diminishing (progressively compensated) force through the buried and loaded coal-bearing strata, has converted lignite successively into subbituminous, semibituminous, semianthracite, anthracite, and even into graphitic coal.

The degree of devolatilization depends, other things being equal, on the intensity and the duration of the pressure movement, a long moderate pressure being as effective as a short intense one.

In considering the evidence bearing on this hypothesis White points out that we must remember that: (1) The devolatilization of coal is still going on in many parts of the world, the rate being almost insensible in some districts, but clearly perceptible in others, where active gas production is observed in certain mines. (2) There is no sharp line of separation between the different kinds of coal, the intergradation being complete between peat, lignite, and semigraphitic coal. (3) The physical evidences of thrust pressure, such as jointing, cleavage, folding, faulting, crushing, etc., become in general more highly developed and conspicuous, not only in the coal, but also the enclosing rocks, as the alteration of the coal proceeds, and hence regions of greater change in the coal show the physical effects of greater pressure.

In regions of initially equal stress the metamorphism will, other things being equal, be greater in districts where no buckling or overthrusting of beds has permitted escape from the intensity of the thrust.

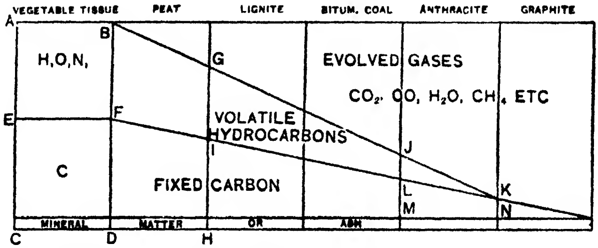

FIG 1.—Diagram showing changes occurring in passage of vegetable tissue to graphite. (*After Newberry.*)

To bring out this lineal succession in the ranks of the coal series as well as to show the changes by a graphical method we may use the diagram (Fig. 1) prepared by the late Professor Newberry.

In this diagram the rectangle *ABCD* represents a given volume of fresh vegetable matter, which contains a small percentage of mineral matter, the rest being organic substances consisting roughly of 50 per cent carbon (*EFCD*) and 50 per cent hydrogen, oxygen, and nitrogen (*ABEF*). In the change from fresh vegetable tissue to peat, part of these four elements pass off as gaseous compounds, so that the remaining volume of peat is less (*BGDH*) than the original volume of vegetable matter (*ABCD*). Since, however, H, O, and N have passed off in larger amounts than the carbon, the percentage of the latter in the peat will be higher than it was in the fresh plant tissue. (Compare *BFGI* and *FIDH* with *ABEF* and *EFCD*.) The actual weight of mineral matter will be the same, but its percentage will be larger. This change, continued, will result finally in anthracite, the last of the coal series, in which the percentage of carbon (*LKMN*) is high and that of the other organic elements low (*JKL*). The amount of compression that occurs in such changes as those illustrated in the diagram may be understood when it is stated that it is estimated that from 16 to 30 feet of peat are required to make one foot of true coal.

The following elementary analyses of peat, lignite, and various grades of coal clearly illustrate this gradual concentration of carbon by losses of volatile elements.

ELEMENTARY ANALYSES OF COALS

KIND	C	H	O	N	S	ASH	MOISTURE
Peat	59.47	6.52	31.51	2.51	—	—	22
Lignite	52.66	5.22	27.15	.71	2.02	12.24	—
Subbituminous	58.41	5.06	28.99	1.09	.63	4.79	—
Bituminous	82.70	4.77	9.39	1.62	.45	1.07	—
Semibituminous	83.14	4.58	4.65	1.02	.75	5.86	—
Anthracite	90.45	2.43	2.45	—	—	4.67	—

Classification of Coals.—The development of a generally acceptable classification of coals has long been the aim of the geologist and technologist. Many classifications have been suggested (18-30), but none have been widely accepted. The primary basis of classification has in all cases been the physical and chemical properties, but these are influenced by the origin, composition, and constitution of the coal.

The most recent classification of coals, and one adopted as a tentative standard by the American Society for Testing Materials, includes coals from lignite to anthracite. The higher rank coals are classified according to fixed carbon on the dry basis, while the lower rank coals are classified according to British thermal units on the moist basis (containing its natural bed moisture). Agglomerating and weathering indices are used as a means of differentiation between certain adjacent groups.

The classification follows (25).

CLASSIFICATION OF COALS BY RANK [1]

(Legend: F.C. = fixed carbon; V.M. = volatile matter; B.t.u. = British thermal units)

CLASS	GROUP	LIMITS OF FIXED CARBON OR B.T.U., MINERAL-MATTER —FREE BASIS	REQUISITE PHYSICAL PROPERTIES
I. Anthracite	1. Meta-anthracite	Dry F.C., 98 per cent or more (dry V.M., 2 per cent or less)	Nonagglomerating
	2. Anthracite . . .	Dry F.C., 92 per cent or more and less than 98 per cent (dry V.M., 8 per cent or less and more than 2 per cent)	
	3. Semianthracite .	Dry F.C., 86 per cent or more and less than 92 per cent (dry V.M., 14 per cent or less and more than 8 per cent)	
II. Bituminous[2]	1. Low-volatile bituminous coal . .	Dry F.C., 78 per cent or more and less than 86 per cent (dry V.M., 22 per cent of less and more than 14 per cent)	
	2. Medium-volatile bituminous coal	Dry F.C., 69 per cent or more and less than 78 per cent (dry V.M., 31 per cent or less and more than 22 per cent)	
	3. High-volatile A bituminous coal	Dry F.C., less than 69 per cent (dry V.M., more than 31 per cent); and moist[3] B.t.u. 14,000 or more[4]	
	4. High-volatile B bituminous coal	Moist[3] B.t.u., 13,000 or more and less than 14,000[4]	
	5. High-volatile C bituminous coal	Moist B.t.u., 11,000 or more and less than 13,000[4]	Either agglomerating or nonweathering[5]
III. Subbituminous . . .	1. Subbituminous A coal	Moist B.t.u., 11,000 or more and less than 13,000[4]	Both weathering and nonagglomerating
	2. Subbituminous B coal	Moist B.t.u., 9500 or more and less than 11,000[4]	
	3. Subbituminous C coal	Moist B.t.u., 8300 or more and less than 9500[4]	
IV. Lignite . .	1. Lignite	Moist B.t.u., less than 8300	Consolidated
	2. Brown coal . . .	Moist B.t.u., less than 8300	Unconsolidated

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[1] If agglomerating, classify in low-volatile group of the bituminous class.

[2] Pending the report of the Subcommittee on Origin and Composition and Methods of Analysis, it is recognized that there may be noncaking varieties in each group of the bituminous class.

[3] Moist B.t.u. refers to coal containing its natural bed moisture but not including visible water on the surface of the coal.

[4] Coals having 69 per cent or more fixed carbon on the dry, mineral-matter-free basis shall be classified according to fixed carbon, regardless of B.t.u.

[5] There are three varieties of coal in the high-volatile C bituminous-coal group, namely, variety 1, agglomerating and nonweathering; variety 2, agglomerating and weathering; variety 3, nonagglomerating and nonweathering.

Agglomerating Index.—Coals which in the volatile matter determination produce either an agglomerate button that will support a 500-gram weight without pulverizing, or a button showing swelling or cell structure, shall be considered agglomerating from the standpoint of classification. (Rep. Spec. Comm. Classn. Coals, A.S.A. Project M. 20)

Structural Features of Coal Beds.—*Outcrops* (18).—The outcrop of a coal bed is usually easily recognizable on account of its color and coaly character; but unless the exposure is a rather fresh one, the material is disintegrated and mellowed, the wash from it mingling with the soil, and if the outcropping bed is on a hillside, often extending some feet down the slope. This weathered outcrop has been termed the "smut" or "blossom" by coal miners. In areas where the beds have been tilted and the slopes are steep, the outcrops of coal can usually be easily traced; but in regions where the dip is low and the surface level, the search for coal is often attended with difficulty, which is increased if the country is covered with glacial drift. In such cases boring or pitting is commonly resorted to.

The number of coal beds found in any given region varies, and may at times be large. Thus in the Pennsylvania section, as many as 20 beds are known; in Alabama, at least, 55 have been counted, but not all are workable; while in Indiana there are 25, of which 9 are minable over large areas. The beds are rarely parallel, and, moreover, thin out if followed any distance.

Associated Rocks.—Most coal beds are interbedded with shales, clays, or sandstones, though conglomerates or limestones are at times also found in close proximity, the latter sometimes, even when of marine character, resting directly on them. Coal beds are often underlain by a bed of clay, which in some regions is of refractory character (Fig. 2); but the widespread belief that all these under clays are fire-clays is unwarranted.

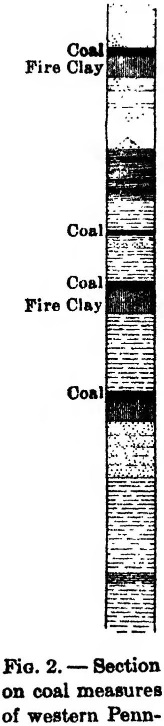

Fig. 2. — Section on coal measures of western Pennsylvania, showing fire clay under coal beds (*After Hopkins.*)

Variations in Thickness.—Coal beds or "seams" are rarely of uniform thickness over large areas; indeed, a bed which is of sufficient thickness to work in one mine may be so thin in a neighboring one as to be scarcely noticeable. This irregularity is in some cases due to variations in thickness of vegetable accumulations, in other cases to local squeezing of the coal bed subsequent to its formation. These thinnings and thickenings are commonly called "pinchings" and "swellings" (Fig. 3). In regions of pronounced folding, the beds are usually found in separate synclinal basins, the intervening anticlinal folds having been worn away.

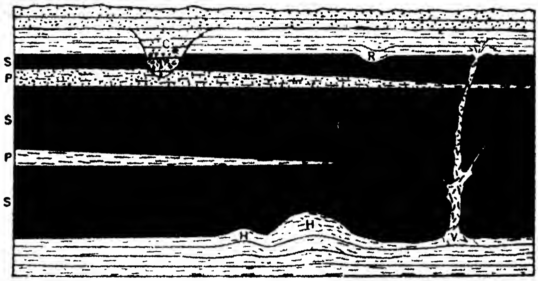

FIG. 3.—Diagram illustrating: *C*, cut-out; *H*, horseback; *P*, parting; *R*, roll; *S*, split; *V*, clay vein. (*After Moore*, Coal.)

While coal beds may vary in thickness from a mere film, to even more than 100 feet in extreme cases, they are rarely over 8 or 10 feet thick.

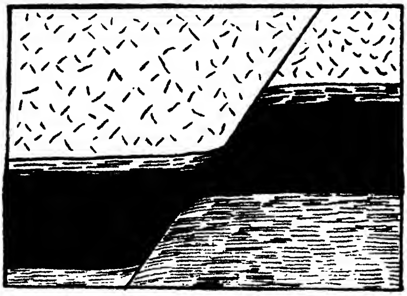

FIG 4.—Section of faulted coal seam. (*After Keyes, Ia. Geol. Surv., II.*)

The Mammoth seam of the Pennsylvania anthracite region is 50 to 60 feet thick. The Commentry basin of central France contains a single bed of Permian coal that locally exceeds 80 feet in thickness. But on one side of the basin the coal splits up into six beds separated by sand and shales. This indicates that coal accumulation went on continuously on one side of the basin, but was interrupted six times by sand deposits on the other side.

Other Irregularities.—Splitting (Fig. 3) is a common feature of many coal seams. The Mammoth bed, so prominent in most of the anthracite basins of Pennsylvania, splits into three separate beds in the Wilkesbarre basin. This splitting is caused by the appearance of beds of shale (called "slate" by coal miners), which often become so thick as to split up the coal seam into two or more beds. When narrow, such a bed of slate is called a parting. The Pittsburgh seam of western Pennsylvania shows a fire-clay parting or "horseback" from 6 to 10 inches over many square miles.

An interesting case of parting is found in the 13-foot seam at Inverness, Nova Scotia At the outcrop this showed three shale partings, of 1 foot, 9 inches and 11 inches respectively. At 2500 feet down the dip, these partings had increased to 19, 3, and 22 feet respectively. A 7-foot seam, lying 284 feet below the 13-foot one, maintained its thickness, however, for this same distance on the dip.

In addition to these "slate" partings, which run parallel with the bedding, others are often encountered which cut across the beds from top to bottom. These in some cases represent erosion channels formed in the coal during or subsequent to its formation, and later filled by the deposition of sand or clay. In other cases they are due to the filling of fissures formed during the folding of the strata.

Coal beds may pass into shale, the latter representing possibly islands of mud or ridges which arose above the level of the marsh in which the coal plants accumulated.

Faulting (Fig. 4) is not an uncommon feature of coal beds, and the coal is sometimes badly crushed on either side of the line of fracture. The amount of throw and the number and kinds of faults may vary, so that one might expect normal, reverse, overthrust, and even step faults.

Coal Fields of the United States.[1] (Pl. IV.)—Coal in commercial quantities occurs in thirty-three states, as well as in Alaska. These occurrences can be grouped into the following fields:

	Area, sq. mi.
(1) *Appalachian*, including parts of Pennsylvania, Ohio, Maryland, Virginia, West Virginia, Eastern Kentucky, Tennessee, Georgia, and Alabama	69,755
(2) *Atlantic Coast Triassic*, including parts of Virginia and North Carolina	210
(3) *Eastern Interior*, including parts of Indiana, Illinois, and Western Kentucky	47,000
(4) *Northern Interior*, including a part of Michigan	11,000
(5) *Western Interior*, including parts of Iowa, Missouri, Nebraska, Kansas, Oklahoma, Arkansas, and Texas	74,900
(6) *Gulf Coast Lignite Field*, including portions of Arkansas and Texas	2,100
(7) *Rocky Mountain field*, including parts of Colorado, Arizona, New Mexico, Utah, Wyoming, Idaho, Montana, North Dakota, South Dakota	126,022
(8) *Pacific Coast Field*, including parts of Washington, Oregon, and California	1,900
	332,887
(9) *Alaska*	1,210

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[1] The Rhode Island area of graphitic anthracite, formerly included in this list, is referred to under Graphite.

GEOLOGIC AND GEOGRAPHIC DISTRIBUTION OF COAL IN UNITED STATES AND ALASKA *

Field	State	Carboniferous						Triassic	Jurassic	Cretaceous			Tertiary		
		Mississippian	Pennsylvanian				Permian			Colorado	Montana	Lance	Eocene	Miocene	Pliocene
			Pottsville	Allegheny	Conemaugh	Monongahela									
Appalachian	Pennsylvania	......	+ ×	+ ×	+ ×	+ ×	+ ×								
	Ohio, Md.	....	+ ×	+ ×	+ ×	+ ×	+ ×								
	Virginia	⊙ O ×	O ×												
	West Virginia	......	×	×	×	×	×								
	Kentucky	......	×	×	×										
	Ga., Ala., Tenn.	......	×												
Triassic	Virginia							⊙ ×							
	North Carolina							⊙ ×							
N. Int.	Michigan	......	×	×											
E. Int.	Ill., Ind., Ky	......	×	×	×?	×?									
W. Int.	Iowa	......	×	×	×										
	Kansas	......	×	×	× ⊙	×									
	Mo., Ark., Okla., Tex.	......	×	×		×									
S. W.	Texas	......	....	....	....	....	....	....	...	......	×	......	⊕		
Gulf Prov.	Ala., Miss., La.	......	....	....	....	....	....	....	....	......	....	......	⊕	⊕	
	Arkansas	......	....	....	....	....	....	....	....	......	......	......	⊕		
Rocky Mt.	Colorado	......	....	....	....	....	....	....	...	×	+ × □	+ O ×	□		
	Wyoming	......	....	....	....	....	....	....	....	O ×	O × □	□ ⊕ × □ ⊕	⊕		
	Montana	......	....	....	....	....	....	..	× □	□ ⊕	× □	⊙ O ×	□ ⊕	....	□ ⊕
	North Dakota	......	....	....	....	....	....	....	....	......	....	□ ⊕ ⊕	⊕		
	Idaho	......	....	....	....	....	....	....	....	......	×	□	□ ⊕		
	Nevada	......	....	....	....	....	....	....	....	......	....	....	......	×?	
	Arizona	......	....	....	....	....	....	....	....	□	□	×			
	New Mexico	......	×	....	....	....	....	....	....	×	+ × □	× ⊕			
	Utah	......	....	×	....	....	....	....	....	+ O × ⊙	×	....	× □		
Pac. Coast	California	......	....	....	....	....	....	....	....	...	....	......	⊕	□ ⊕	
	Oregon	......	....	....	....	....	....	....	....	......	....	......	× □ ⊕		
	Washington	......	....	....	....	....	....	....	....	......	....	......	+ × ⊙ ⊕		
	Alaska	×	....	....	□....		....	....		⊕ ×	□	......	× □ ⊙ ⊕	....	....

* Prepared by J. D. Thompson, Jr. +, anthracite; ⊙, semianthracite; O, semibituminous; ×, bituminous; □, subbituminous; ⊕, lignite.

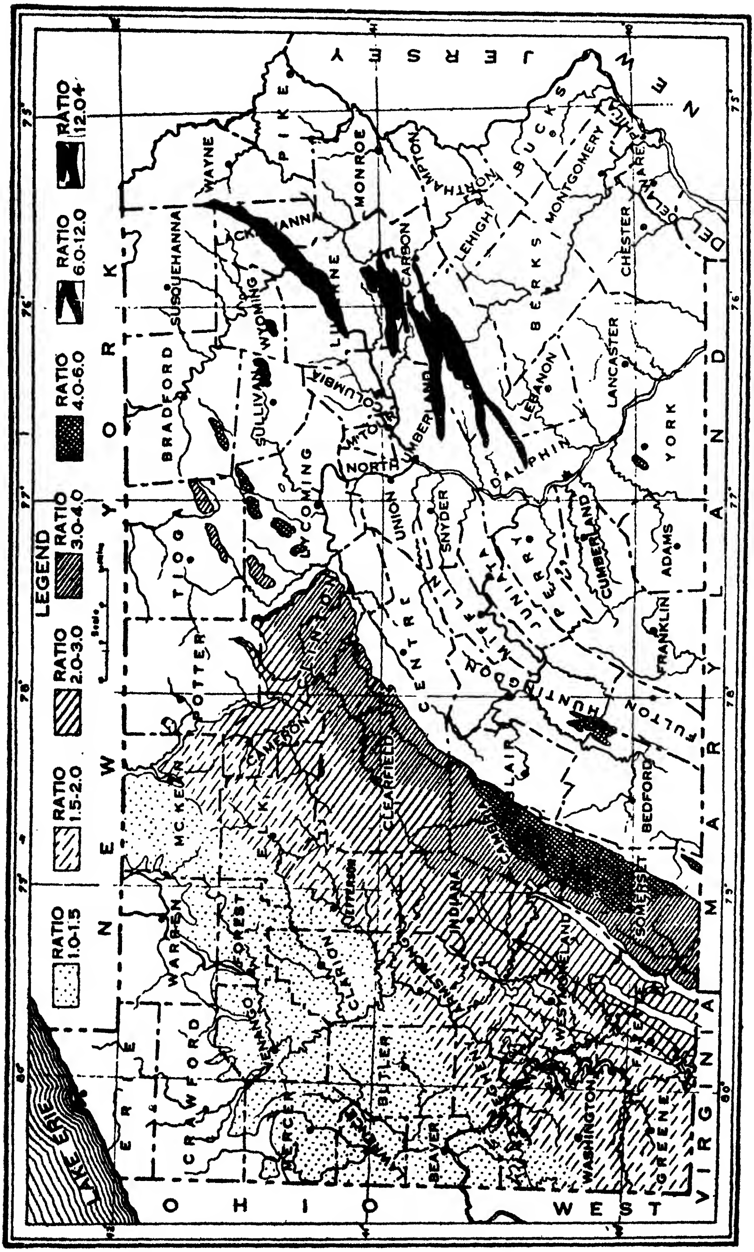

PLATE V.—Map of Pennsylvania, showing distribution of coals by fuel ratios. (*Pa. Geol. and Top. Com Rept.*, 1906–1908.)

The estimates of areas given above are from calculations made by the United States Geological Survey, and are to be regarded as fairly accurate, but some of these fields may be extended in the future by the development of areas now classed as unproductive. This applies especially to those in which the coal lies too deep to be profitably mined at present. It is a noteworthy fact that the production of the fields is by no means proportional to their areas. Proximity to markets, value of the coal for fuel, and relative quantity of coal per square mile of productive area are factors of importance in determining the output of a field.

Geologic Distribution of Coals in the United States.—The table given on p. 22, which shows both the geologic and geographic distribution of coals in the United States, indicates that the Carboniferous coals are found chiefly in the eastern half of the country, and the younger coals in the western half. The separation of the Carboniferous coals into well-defined areas is probably the result of folding and erosion,[1] and to a certain extent, the same is true of the Rocky Mountain coal fields. The latter have often been seriously disturbed by post-Cretaceous uplifts.

Appalachian Field (49, 52, 55, 117, 124).—This, the most important coal field in the United States, extends 850 miles, from northeastern Pennsylvania to Alabama. It shows a maximum width of 180 miles at the northern end, is less than 30 miles in Tennessee, and expands again to 85 miles in Alabama. About 75 per cent of its area contains workable coal. At the southern end the Coal Measures pass beneath the coastal plain deposits, and they may connect with the Arkansas Coal Measures beneath the Mississippi embayment.

Being closely associated with the Appalachian Mountain uplift, the Coal Measures of this region partake of the structural features of the Appalachian belt. The eastern margin of the field borders on a belt of steeply folded strata, forming the Appalachian Valley, and hence the coal-bearing formations are much folded here (Fig. 5, 9), while at the southern end of the field they are faulted in addition (Fig. 5). Extensive erosion following the folding of the Coal Measures has resulted in the development of a number of basins.

The Coal Measures of the Appalachian field consist of a great thickness of overlapping lenses of conglomerate, sandstone, limestone, shale, fire clay, and coal. The formations in general show a thinning from the eastern margin of the field, westward, as well as showing a decrease in the number and thickness of the beds. Owing to the len-

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[1] Ashley, Econ. Geol., II: 650, 1907.

ticular character of the deposits, and the local thickenings, it is difficult to trace individual beds of coal over wide areas, or correlate sections at widely separated points.

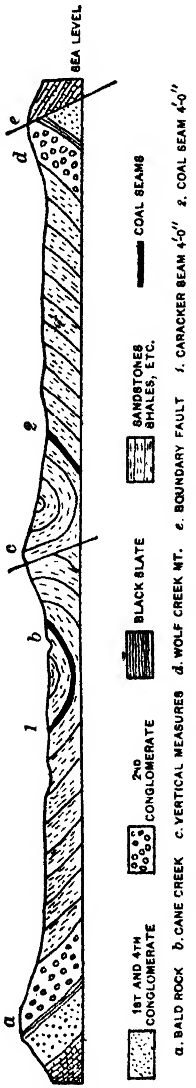

FIG. 5.—Section across Coosa coal field, Alabama, showing folding and faulting characteristics of southern end of Appalachian coal field. (*After Gibson, Ala. Geol. Surv.*, 1895.)

The Middle Carboniferous or Pennsylvanian includes most of the coal beds of the Appalachian field, but there are some also in the upper Carboniferous and in the Pocono of the lower Carboniferous or Mississipian (See table p. 22).

The Appalachian field is divisible into two parts of very unequal size, viz. (1) the anthracite field of northeastern Pennsylvania; and (2) the bituminous area, which occupies the balance of the field.[1]

Pennsylvania Anthracite Field (55, 127).—This field (Fig. 6) lies in the northeastern part of the state and has four main subdivisions, known respectively as the northern, eastern middle, southern, and western middle, with a total area of 484 square miles. Intense folding (Fig. 7) has placed some of the coal in synclinal troughs, where it has been preserved from erosion which has removed the coal from the intervening anticlines. Therefore the anthracite is found in a number of more or less separated narrow basins. It is estimated that the original quantity of coal was about 20,000,000,000 tons, of which 4,400,000,000 have been removed to date, with about 9,000,000,000 of the remainder recoverable.

The Coal Measures of the anthracite district consist of beds of sandstone, shale, and clay, with coal beds at intervals varying from a few feet to several hundred feet, though rarely exceeding 200 feet. The coal beds, which vary in thickness from a few inches to 50 or 60 feet, occur throughout the entire section of the Coal Measures, but are most important in the lower 300 to 500 feet. Among these the Mammoth is of importance, but splits in some areas.

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[1] This includes some small areas of semianthracite.

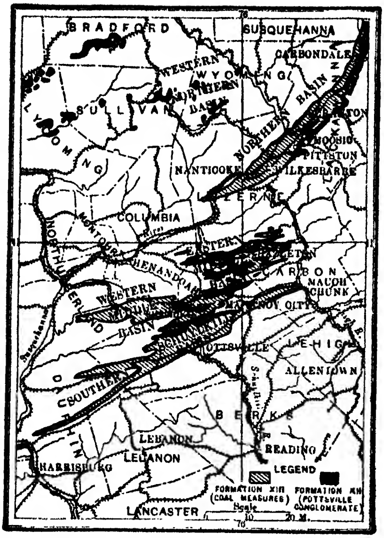

Fig 6.—Map of Pennsylvania anthracite field. (*After Stoek, U. S. Geol. Surv., 22nd Ann. Rept., III.*)

The position of the coal beds and physical characteristics of the coal have necessitated the use of special methods of mining and of treatment after mining (127). Sharpness of folding and steep dips prevail, these introducing many mining problems not found in bituminous regions. When brought to the surface, the anthracite consists of lumps varying in size and mixed with more or less shaly coal called *bone,* so that before shipment to market it is necessary to break, size, and sort it. This is done in a *coal breaker* (Fig. 8), in which the coal is crushed in rolls and sized by screens while the slate is separated by automatic pickers or other machines. These breakers are a prominent feature of the anthracite region, and much money has been spent in increasing their efficiency. As a result of years of mining, the refuse from the breakers, consisting of a fine coal, dust and bone, termed "culm," has accumulated in enormous piles. Much of it is now being washed to save the finer particles of clean coal; and some is also washed into the mines to support the roof, so that the pillars of coal, originally left for that purpose, can be extracted.

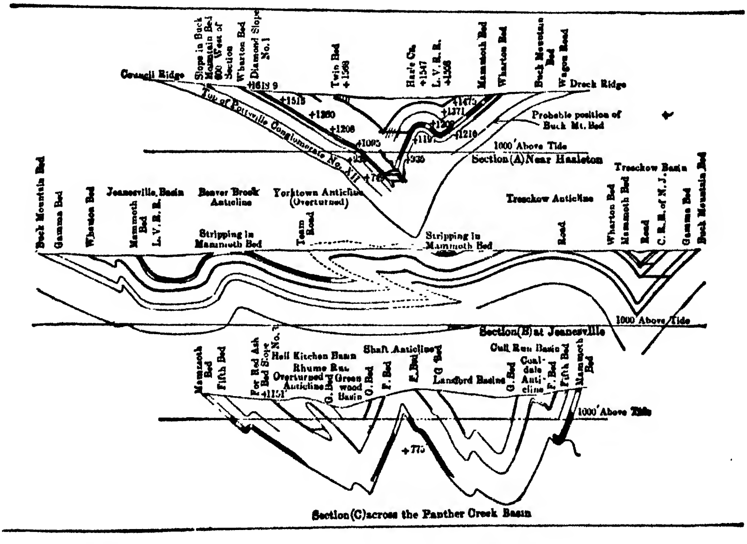

Fig. 7—Sections in Pennsylvania anthracite field. (*After Stoek, U. S. Geol. Surv., 22nd Ann. Rept., III.*)

On account of its cleanliness and high fuel ratio, anthracite coal is much prized for domestic purposes. Most of that mined is marketed in the eastern and middle states, although small quantities are shipped to the western states, especially those that can be reached by way of the Great Lakes.

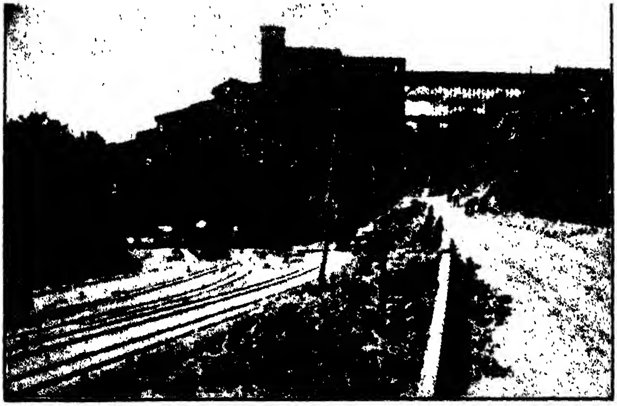

Fig. 8.—Coal breaker in Pennsylvania anthracite region.

Appalachian Bituminous Area (52, 124).—The northern part of the area includes portions of the states of Pennsylvania, Ohio, Maryland, Virginia, and West Virginia (Pl. V).

In Pennsylvania the bituminous area covers about 12,000 square miles lying mostly in the western part of the state (Pl. V). In the northwestern part, where folding is slight, the coal measures form outliers capping the high hills and ridges, but eastward, the more marked synclinal ridges result in a series of basins, of which the most northeastern ones are quite isolated and include among others the Bernice (semianthracite). Nearly half of the bituminous coal mined comes from the Alleghany series.

In Ohio (114–119) there are at least 16 coal beds, among which the famous Pittsburgh seam, also known in Pennsylvania, is found.

In Maryland (98) the coals lie in three broad northeast-southwest synclinal folds. The eastern or Potomac basin is the most important. The Pittsburgh coal is also present. The coals are good steaming fuels and will coke (98).

The West Virginia Coal Measures (143–145) occupy an irregular rectangle extending from the Alleghany Mountain region northwestward to the Ohio River. The coal formations are found as low in the stratigraphic series as the Pocono, but the coals in this are unimportant. The Monongahela series of the Pennsylvanian carries 6 distinct beds, one of them the Pittsburgh.

The Virginia coals are of two ranks (139). Those of the Mountain Province which are of Mississippian or Pennsylvanian age are semibituminous or semi-anthracite. Of much more importance are the Pennsylvanian coals in the Cumberland Plateau region of southwest Virginia (Fig. 9). In the Pocohontas field there are at least six workable beds, yielding coal of excellent steaming and coking quality.

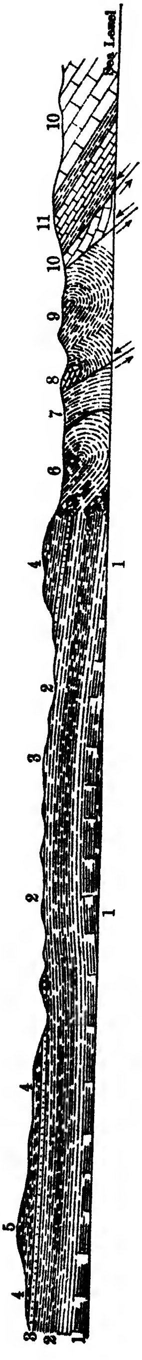

FIG. 9.—Structure section in Tazewell County, east of Richlands, southwest Virginia coal field. 1–8, Carboniferous; 9, Devonian; 10, Cambro-Silurian; 11, Cambrian. (*From Min. Res. Va.*, 1907.)

Southern Appalachian Field.—Here the rocks are mainly of Pottsville age, and though worked in eastern Kentucky, Tennessee (130–132), and northwest Georgia (74), the most important area is in Alabama (58–63). While folding is present, there is in addition much faulting. There are three main districts, known as the Jellico, Chattanooga, and Birmingham, the last containing four fields. Some of the coals are coking.

The Triassic Field (109, 158).—This coal field, which is more important historically than economically, having been worked as early as 1700, includes several small steep-sided basins (Fig. 10), lying in the Piedmont region of Virginia and North Carolina. It is probable that the coal-bearing beds of the several areas, originally horizontal, were formerly continuous, having been separated by folding, faulting, and denudation. In addition to this, the coal is cut by dikes and sheets of igneous rock, which have locally altered it to natural coke or *carbonite*.

Eastern Interior Field (50, 75–79, 88–96).—This field is an oval, elongated basin (Fig. 11), extending northeast and southwest, with the marginal beds dipping gently toward the lowest portion, which lies in Illinois, where the beds are nearly horizontal. It covers most of Illinois, southwestern Indiana, and a small part of western Kentucky, with some small outliers in Missouri (101, 102) near St. Louis and St. Charles, and two in Illinois.

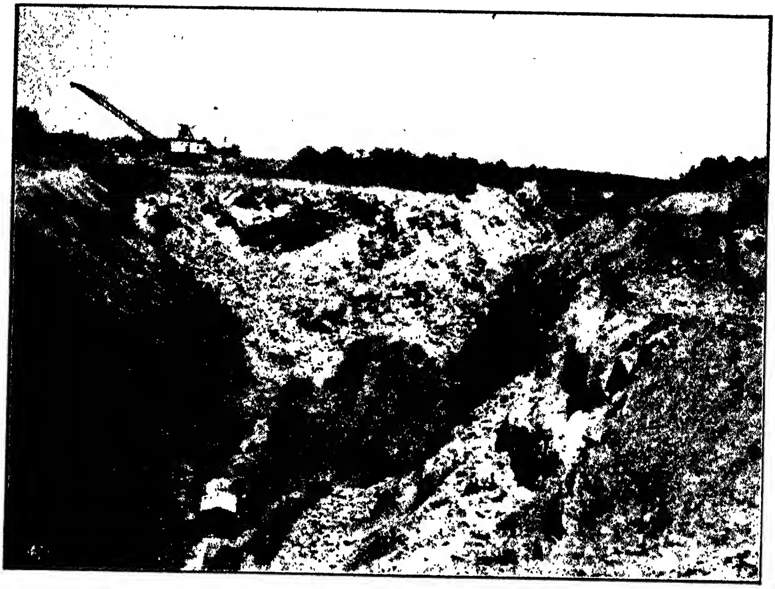

FIG. 1.—Pit working (strippings) in the Pennsylvania anthracite district. (*H. Ries, photo.*)

FIG. 2.—View in Arkansas coal field. (*H. Ries, photo.*)

The coal seams occur in the lower portion of the section, and hence outcrop around the margin, the mining operations being therefore confined to a narrow belt, because near the center of the basin the coal beds underlie too great a thickness of unproductive strata to permit of profitable working under present conditions.

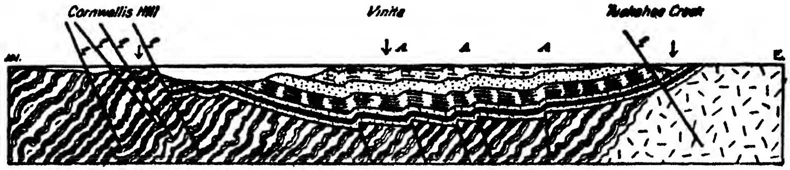

FIG. 10.—General structure section of the Richmond Basin in the vicinity of James River. *A, A, A,* minor flexures, with beds downthrown to the west; *f, f, f,* faults. The heavy black band represents the supposed position of the coal beds. North and south of this section the beds appear to be deeply faulted down against the western margin, and the apparent synclinal structure disappears. The superficial portion of this section is based on observation and reliable information; the deeper portion is hypothetical. (*After Shaler and Woodworth, U. S. Geol. Surv., 19th Ann. Rept., Pt. II.*)

The coals of the Eastern Interior field are all bituminous. On account of their higher percentage of ash and sulphur, they are little used for coking, but they are widely used for steaming and domestic purposes. The only commercially important cannel coal in this field comes from Cannelsburg, Kentucky.

The Indiana section shows at least 25 distinct coal beds (80), nearly all of them 2 feet or more thick in some places, and nine of them continuing of minable thickness over large areas. Some are coking and occur in broad sheets.

Northern Interior Field (99).—This field forms a large basin in which the coal dips irregularly from the margin toward the center (Fig. 13), but on account of the heavy mantle of glacial drift it has been difficult to determine its exact boundaries, and prospecting is necessarily done by means of drilling. The coal beds which are of Pottsville age are irregular in thickness and horizontal extent. They are all bituminous, and used chiefly for fuel. Coal is found near the center of the basin at depths of 400 feet or more, though the beds that are mined are mostly at depths of 100 to 250 feet.

Western Interior Field and Southwestern Fields (51).—These two fields form a practically continuous belt of coal-bearing formations, extending from northern Iowa southwestward for a distance of 880 miles into central Texas. Throughout most of this area the beds lie horizontal, or have a gentle westward dip averaging 10 to 20 feet per mile, but a notable exception is found in the beds of eastern Oklahoma and Arkansas, which are rather strongly folded, reminding one of the Pennsylvanian anthracite area.

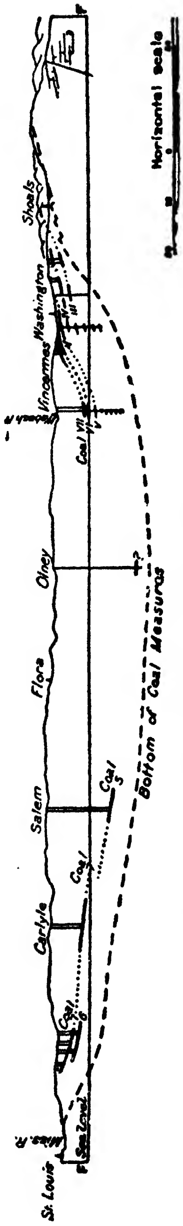

Fig. 11.—Section across Eastern Interior coal field. (*After Ashley, U. S. Geol. Surv., 22d Ann. Rept., III.*)

Western Interior Field (51, 83, 84–87, 101).—The Coal Measures in a general way have a prevailing dip westward. The coal mined in this field comes from the Pennsylvanian. All of the coals are essentially bituminous and used for heating or steaming purposes. In eastern Oklahoma and western Arkansas (68) the Coal Measures are more strongly folded and the coals have been metamorphosed to semi-bituminous and semianthracite.

Fig. 12.—Shaft house and tipple, bituminous coal mine, Spring Valley, Ill.

While the reserves of this field are large and the beds in many cases can be easily worked, the area suffers because of competition with oil and natural gas fuels.

Southwestern Field (56).—This area, lying in northern Texas, is separable into a northern and southern portion by an arm of Cretaceous strata, extending across it. The coals, which are all Pennsylvanian, rest unconformably on the Mississippian and are overlain by the Permian on the north. There are five divisions, which carry three workable coal beds, and while all are of bituminous character, none of them are coking.

Rocky Mountain Fields (54).—These cover a broad area extending from the Canadian boundary southward into New Mexico, a distance of about 1000 miles, and including a large number of fields of varying size and irregular shape. Most of these beds lie within the mountainous region, but at the northern end of the area, in Wyoming and the Dakotas, the coal fields extend eastward under the Great Plains for some distance. The age of the coal ranges from Lower Cretaceous to Eocene (Tertiary), though most of it belongs to the former.

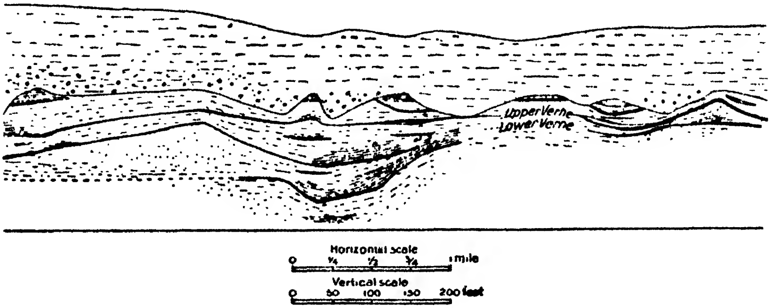

FIG. 13.—Generalized section of Northern Interior coal field. (*After Lane, U. S. Geol. Surv., 22nd Ann. Rept., III.*)

While portions of this enormous area of coal-bearing strata are only slightly disturbed, mountain-building forces and igneous intrusions have affected a large proportion of the region, often materially changing the character of the coal. Thus, while in undisturbed portions of the field the beds may be lignitic (Pl. VIII, Fig. 2), in the disturbed parts they have been altered to bituminous (Fig 14). Igneous intrusions may have changed the latter locally to anthracite, as in the Crested Butte (73) area of Colorado or the Cerillos field of New Mexico (106). Some of the bituminous coals produce an excellent quality of coke.

The Raton (108) field of southeastern Colorado yields coking coals, while the subbituminous coals of the South Platte field and the bituminous ones of Canyon City are also important. Although a large percentage of Wyoming (146, 147) is underlain by coal-bearing rocks, most of these lie in the Great Plains region, where the coals, chiefly Cretaceous in age, are subbituminous. The Book Cliffs coal field of Utah (137) produces Upper Cretaceous bituminous coals of coking character.

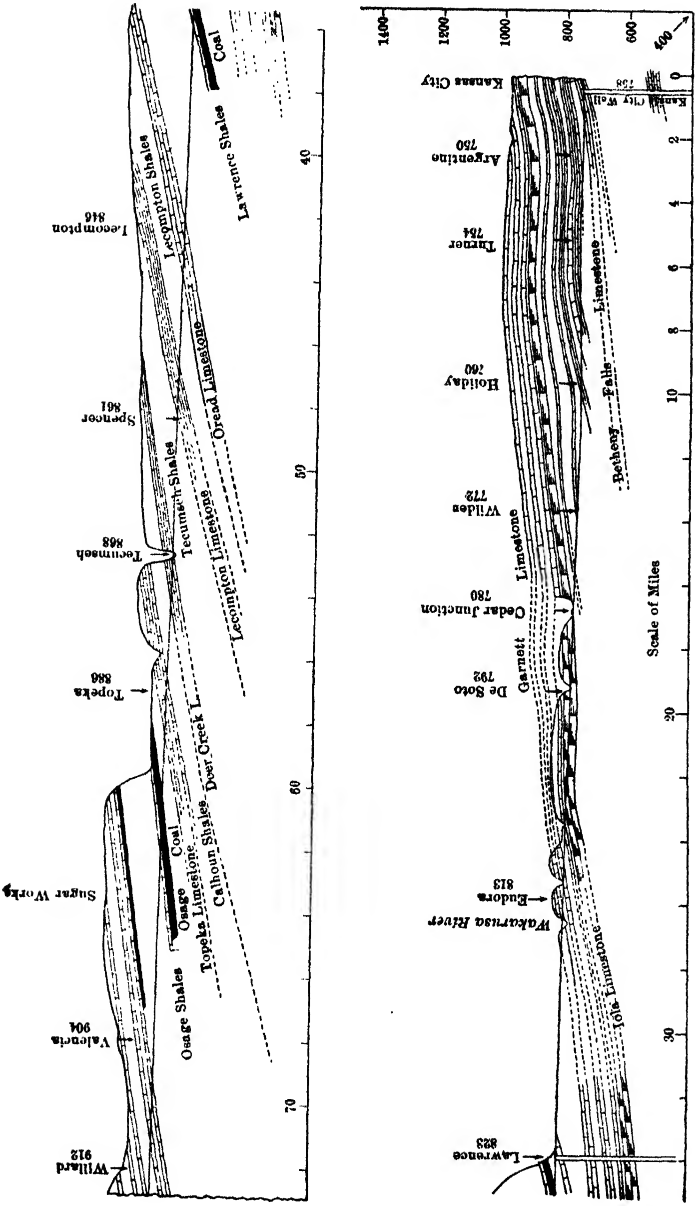

PLATE VII.—Geologic Section from Kansas City to Topeka, Kans. (*Kans. Geol. Surv., III.*)

North Dakota (112–113), South Dakota (129), and Montana (103) contain great areas of Eocene lignite, but there is a limited demand for it.

PLATE VIII

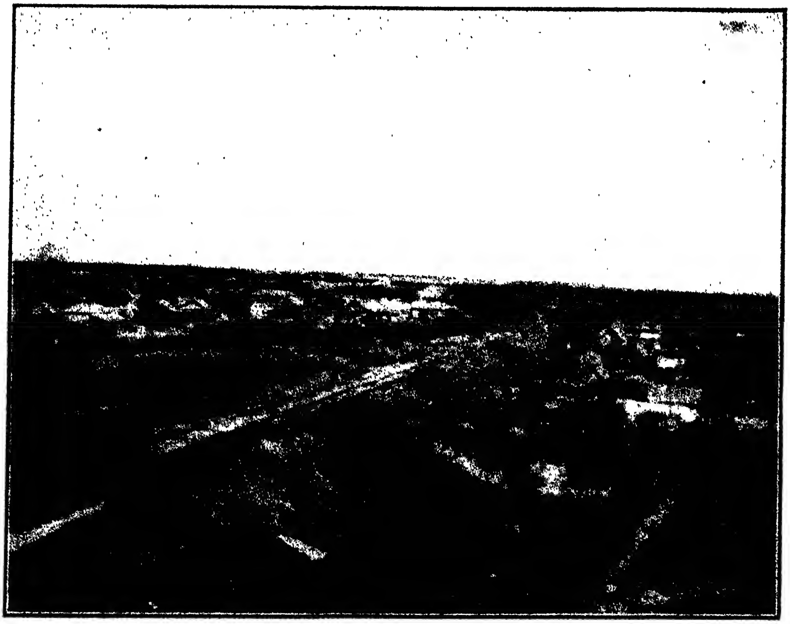

FIG. 1.—View in subbituminous coal area, between Minera and Cannel, Texas. (*H. Ries, photo.*)

FIG. 2.—Lignite seam, Williston, N. Dak. (*After F. Wilder, photo.*)

Gulf Province Lignites (100, 133).—These are of Eocene (Tertiary) age and are all low grade, with the exception of those along the Rio Grande, northwest of Laredo, which may be regarded as subbituminous. Those found near Eagle Pass are of still better quality, but occur in the Cretaceous.

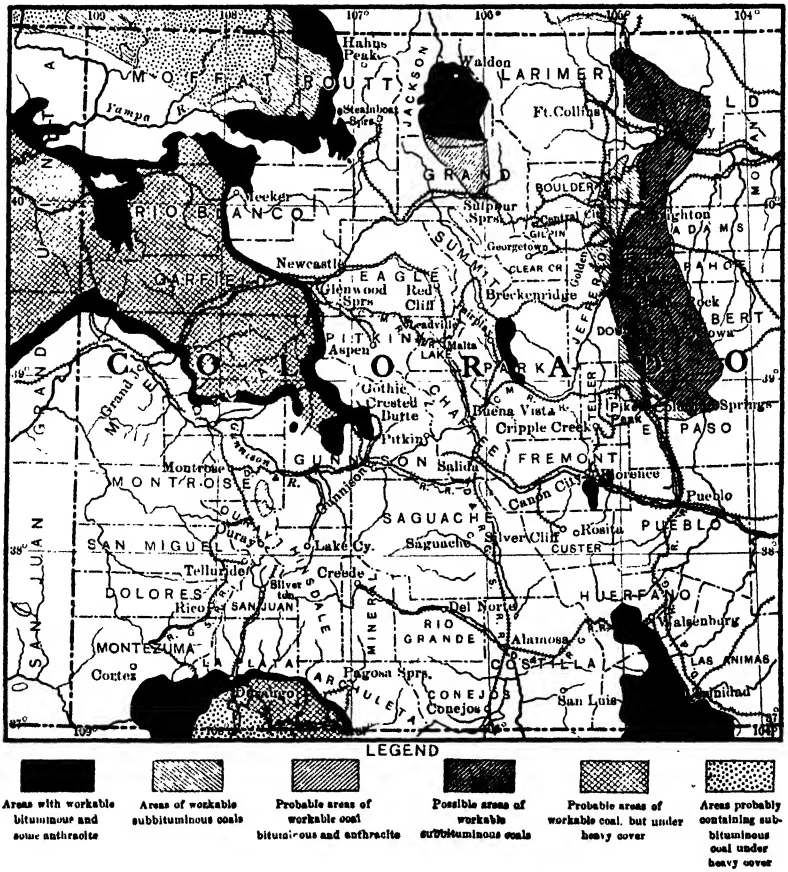

FIG. 14.—Map showing distribution of different kinds of coal in Colorado. (*After Parker, U. S. Geol. Surv.*)

Pacific Coast Fields (53).—Tertiary coals, partly bituminous, though mainly lignitic, occur scattered over a wide area in the states of California (69–71), Washington (141), and Oregon (122, etc.). The separate fields are limited in extent, and widely separated. Their output is small as compared with some other states, but still it is becoming of growing importance.

Of the scattered fields in Washington, the most important lie directly east of Seattle and Tacoma. The rank of the coal varies with the extent of the dynamic disturbance, and hence there may be variation even in a single field. Some of the coal is coking. The industry suffers, however, from competition with oil fuel.

Both California and Oregon are small producers. In the former, coals of subbituminous character have been mined near Tesla, Alameda County, and recently coal of good bituminous grade has been worked in Stone Canyon, Monterey County. Indeed this is of sufficiently high quality to compete with foreign coals brought into San Francisco.

In Oregon, the Coos Bay field has been a small but fairly steady producer.

Oil may be said to dominate the fuel situation along the Pacific coast, and as long as this continues, the demand for coal will be limited.

Alaska (64, 65).—Coal deposits have been discovered at a number of localities. All of that now produced comes from the Healy or Nenana (subbituminous), and Matanuska (bituminous) fields, the latter having produced since 1915. The Bering River area is unde-

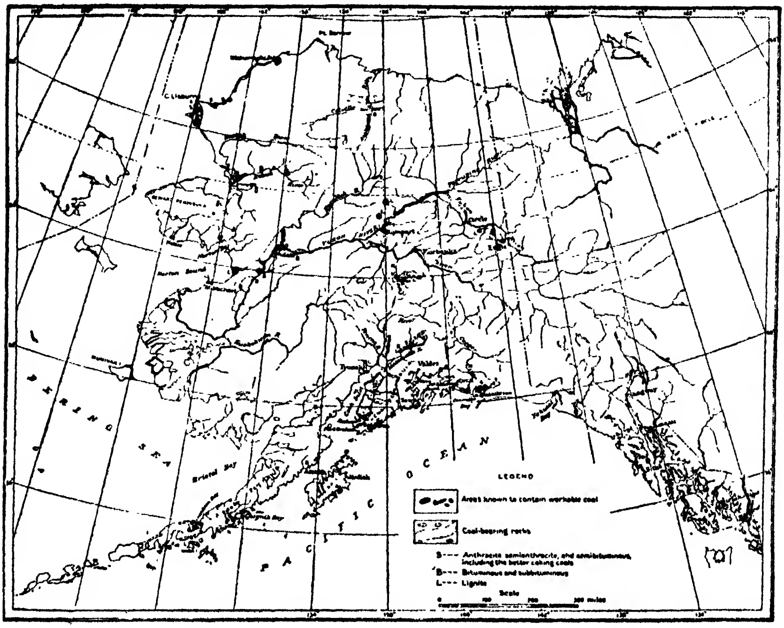

FIG. 15.—Map of Alaska, showing distribution of coal and coal-bearing rocks, so far as known. (*After Martin, U. S. Geol. Surv., Bull.* 314.)

veloped. Large deposits of lignite are known at various localities, particularly Cook Inlet and Susitna Valley. Subbituminous and bituminous are also known in the Cape Lisburne area.

The production for 1935 was about 90,000 short tons.

Canada (148–170).—The coal regions of Canada include: (1) the Maritime Provinces; (2) Western Provinces; (3) Vancouver and other Pacific Coast islands.

Maritime Provinces (158, 159, 160, 168).—Leaving out the coals of New Brunswick, which are of little importance, we have several areas of active production in Nova Scotia. There the coal-bearing rocks range from Lower Carboniferous to possibly Permian, but the only important beds are those occurring in the Coal Measures proper, lying above the Millstone Grit. The four areas are (1) the Cumberland (including Joggins and Spring Hill), (2) Pictou, (3) Inverness, and (4) Sydney. In all of these the coal is bituminous, and in (2) and (4) of coking character. The beds show more or less folding, and in one area at least (Pictou) some strong faulting. It is interesting to note that, in the Pictou area, the upper and lower series of seams are separated by oil shales.

Western Provinces.—Coal-bearing rocks of Cretaceous, and to a lesser extent Tertiary, age are widely distributed throughout the western provinces.

Within the Great Plains regions the beds lie fairly flat, and the coals are either lignite or subbituminous, but along the foothills and in the mountains themselves the coal measures are folded and faulted, the sediments usually more consolidated, and the coals of a higher grade, ranging from bituminous to semianthracite.

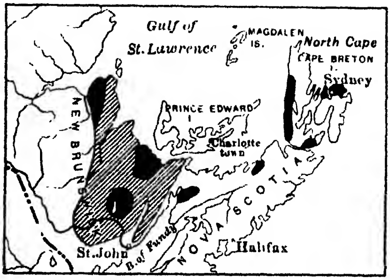

Fig. 16.—Map showing coal areas of Nova Scotia. (*After Dowling, Can. Geol. Surv., Mem.* 59.)

Some of the areas are actively worked at several points, but there still remain undeveloped districts, awaiting a market and transportation facilities.

Saskatchewan (154).—Lignite-bearing Tertiary rocks cover a wide extent of territory in the southern part of the province, and a number of beds are known, which are worked chiefly in the Souris field. (Fig. 17.) The Cretaceous coals of the Belly River series are as yet unimportant.

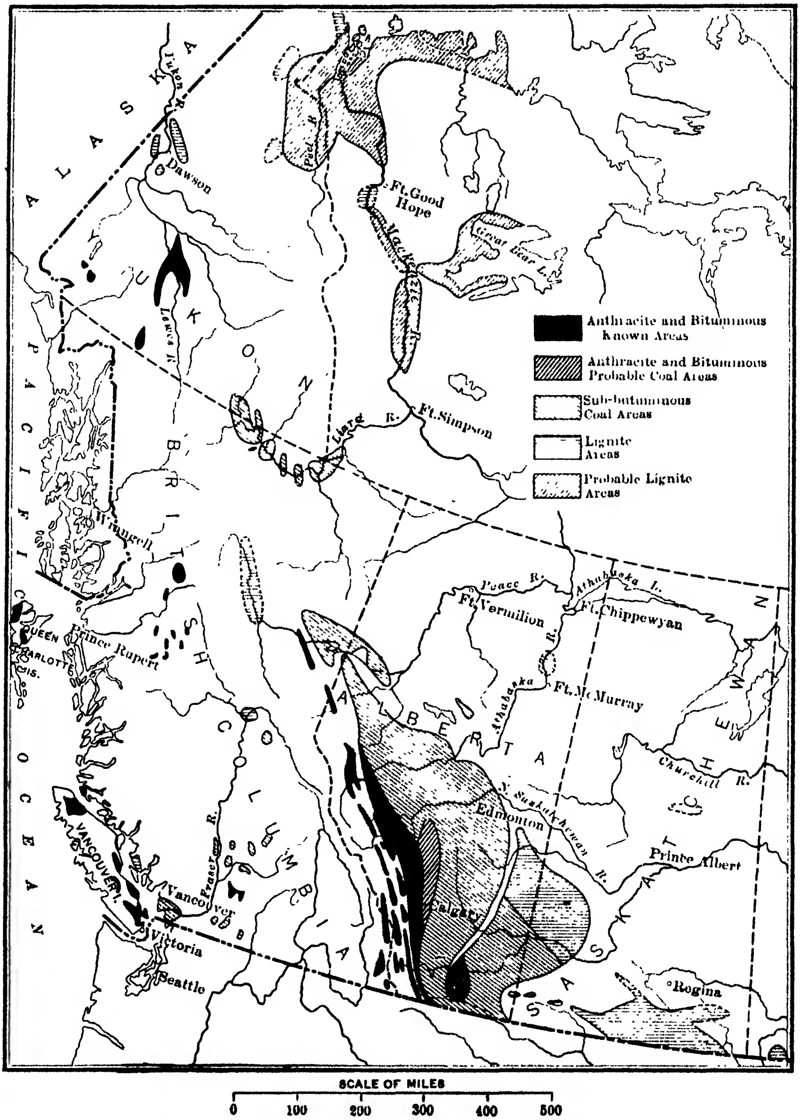

FIG. 17.—Map showing coal areas of Western Canada. (*After Dowling, Can. Geol. Surv. Mem.* 59.)

Alberta (148, 169).—Coal is found at three horizons of the Cretaceous, viz., Edmonton, Belly River, and Kootenay. The Edmonton coals lie in a great syncline, with the Paskapoo sandstone forming the upper beds in the center. The beds of the eastern limb have a

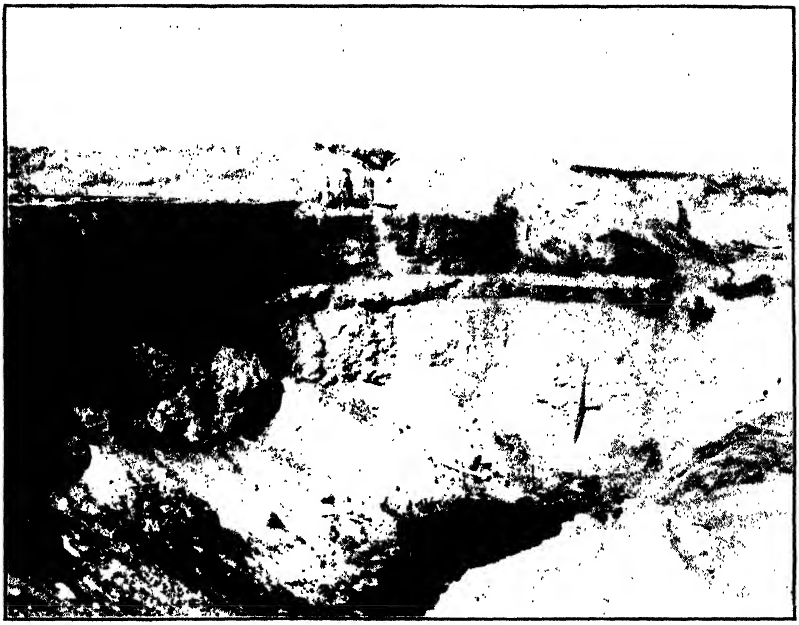

FIG. 1.—Beds of subbituminous coal near Estevan, Sask. (*H. Ries, photo.*)

FIG. 2.—Coke ovens and tipple at Coleman, Alberta; Crows Nest Pass field. (*H. Ries, photo.*)

lower dip than those of the western one towards the mountains, so that the coals change from lignites in the northeastern part to coking coals in the foothills. Drumheller is an important mining center.

The Belly River coal series, which covers about 16,000 square miles in central and southern Alberta, carries coals ranging from lignites near Medicine Hat to subbituminous coals around Lethbridge, but the series traced to the foothills also carries bituminous coking coals.

The coal of the Kootenay formation lies deeply buried under the Plains, but in the Rocky Mountains it is exposed at a number of points in uplifted fault blocks, and along the crests of anticlines. Some is also found in synclinal troughs. The Alberta areas are known both in the outer ranges and in the foothills from near the international boundary to beyond the Athabasca River. The coals are generally bituminous, sometimes of coking character, but semianthracite beds are also known. The bituminous type is worked in the Crows Nest Pass district at Coleman, Hillcrest, and Blairmore, while semianthracite has been mined in the vicinity of Canmore.

British Columbia.—On the mainland, the coal areas, which are more or less isolated, are chiefly of Lower Cretaceous age, and of bituminous character, although sometimes locally altered to anthracite. An important basin is situated in the western part of the Crows Nest Pass, where the section, sometimes showing 3700 feet of measures, may carry over 20 beds, exceeding 1 foot in thickness. Scattered deposits of Tertiary coal are also known, and worked specially around Princeton, Coalmont, and Nicola. These have been partly covered by igneous flows, and locally altered to bituminous coal.

Vancouver Island.—The coals, so far as known, are of Upper Cretaceous age, associated with the thick Nanaimo series of plastic sediments. A variable degree of folding and faulting occurs, and the seams lack persistence. Some of the bituminous coals are coking. Nanaimo and Comox are mining localities.

Yukon.—Lignites of Tertiary, and lignites to anthracites of Jura-Cretaceous age are known.

Other Foreign Fields.—Europe contains extensive deposits of coal, the bituminous and anthracite varieties being chiefly of Upper Carboniferous age, although important Lower Carboniferous deposits are known in Central Russia and Scotland. Of the Upper Carboniferous or Coal Measures proper, there are important deposits in western Germany, Belgium, Northern France, and Great Britain. They are mostly bituminous, and may show strong folding and faulting. Anthracite is mined in Wales and Russia.

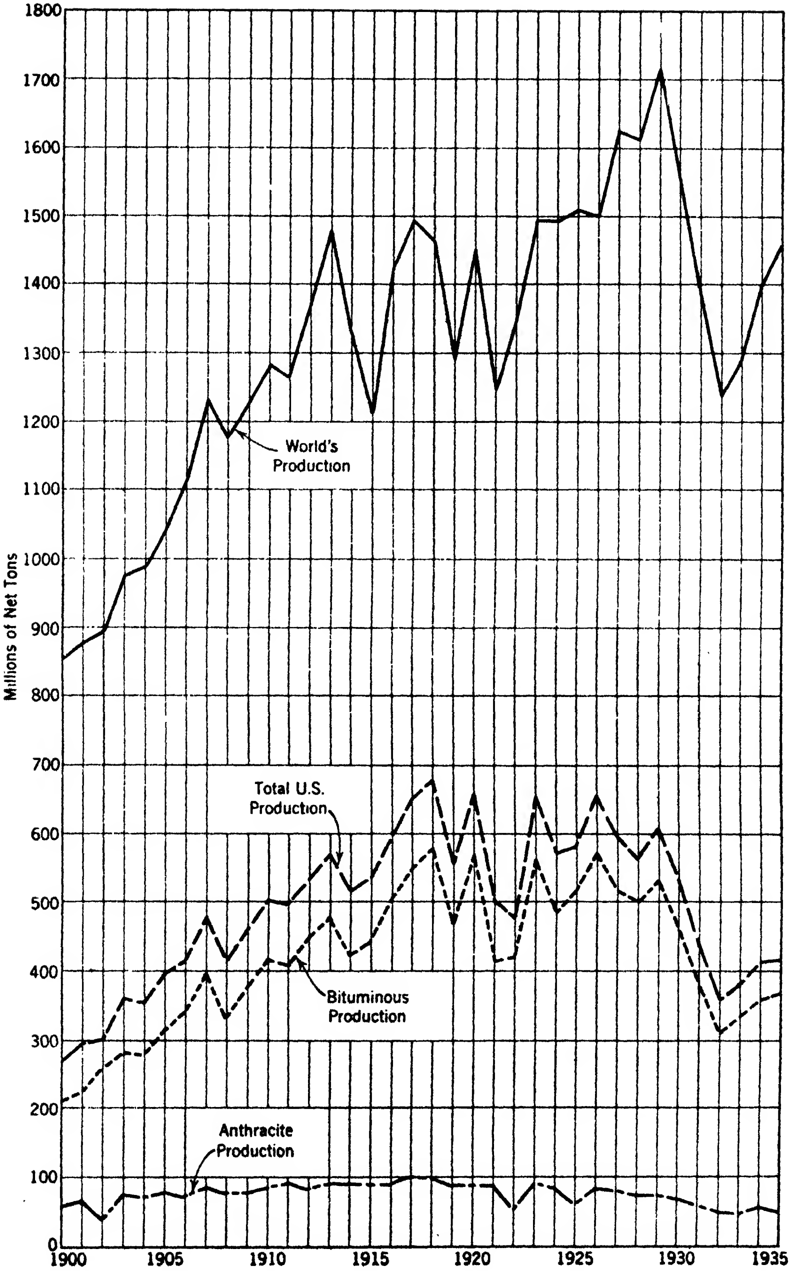

FIG. 18.—Diagram showing production of coal in the United States from 1900 to 1935

The lower grades of coal, chiefly of Tertiary age, are an important source of supply in southern Russia, as well as in Austria, Germany, and to a lesser extent France.

Asia contains extensive areas of Permo-Carboniferous coals in China (anthracite to lignite), as well as India, while Tertiary coals are an important source of supply in Japan (bituminous) and northeast Siberia.

Australia contains both Carboniferous and Tertiary coals, the former being especially important in New South Wales. In South America the best grades of coal appear to be those along the Pacific and Gulf of Mexico in formations of Tertiary age, while in Africa, the important deposits—of Carboniferous to Jurassic age—are confined to the southern part of the continent.

In Mexico the most important fields are Cretaceous ones of bituminous character, near the Texas border, on the Rio Grande and its tributaries.

The Philippine coals are of Tertiary age, and range from lignite to bituminous, but the area known to be underlain by minable coal does not cover more than 7 square miles.

Estimated Coal Reserves of the World.—In 1913 the International Geological Congress published a report on the world's coal reserves.[1] These were estimated at 7,397,548 millions of tons. About 68 per cent of this was credited to the United States and Canada, and about 17 per cent to Asia.

Production of Coal.—The first mention of coal in the United States is probably in the journal of Father Hennepin, who in 1679 recorded the site of a "cole mine" on the Illinois River near the present city of Ottawa, Illinois, but the first actual mining appears to have occurred in the Richmond basin, Virginia, about seventy years later. The first records of production are in 1822. Ohio probably ranks second in priority of production, as coal was discovered there in 1755, but the records of mining date only to 1838. The mining of Pennsylvania anthracite began in 1790, and in 1807, 55 tons were shipped to Columbus, Ohio. The regular production dates from 1814.[2]

The growth of the coal mining industry over a period of years is shown by the diagram (Fig. 18).

The average price per ton for anthracite at the mines was $4.27 in 1940, which is a decrease of nearly a dollar since 1931, while the average price for bituminous for the same year is given as $1.90, an increase over 1931.

The three leading states and their productions in 1940 were: Pennsylvania, anthracite, 51,484,640 net tons, bituminous, 112,907,000 net tons; West Virginia, 126,302,000 net tons; Illinois, 49,495,000 net tons.

The exports of anthracite in 1940 were 2,667,632 net tons, and of bituminous, 16,465,928 net tons. Canada is the chief market.

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[1] The Coal Resources of the World. Vols. I, II, III and Atlas. Morang & Co., Ltd., Toronto, 1913.

[2] Parker, E. W., U. S. Geol. Surv., Min. Res., 1908.

The imports in 1940 were: anthracite, 135,436 net tons, and bituminous, 371,571 net tons. The imports of anthracite originate mainly in Russia and Great Britain. Canada is the chief source of supply of the imported bituminous coal.

The production of coal in Canada in 1940 totaled 17,566,884 tons, valued at $54,676,993. About 80 per cent of the tonnage was bituminous, about 20 per cent lignite, and subbituminous. Nova Scotia was first with bituminous coal, Alberta second with bituminous and lignite in about equal amounts, and British Columbia with bituminous third. Manitoba and Saskatchewan produced only lignite.

The imports of coal into Canada in 1939 were 13,884,816 tons. Approximately 23 per cent of this was anthracite obtained chiefly from the United States and Great Britain. The rest was mostly bituminous, and came chiefly from the United States.

Canada, in the same year, exported 376,203 tons, mostly bituminous.

The world's production of coal amounted in 1938 to 1,469,000,000 metric tons. The United States ranked first (27 per cent), Germany second (26 per cent), and Great Britain third (15 per cent).

Coke Production.—The quantity of coke produced in the United States in 1940 was as follows: by-product, 54,014,309 net tons; beehive, 3,057,825 net tons; total, 57,072,134 net tons. The amount of coal used to produce the above amount of coke was 81,385,776 net tons.

The by-products produced in coke manufacture included ammonium sulphate, ammonia liquor, gas, light oils and derivatives, naphthalene, tar derivatives, phenol, sodium phenolate, etc., and the total value of these produced in 1940 amounted to $159,866,903.

It may be noted that when coke is made in beehive ovens all these by-products are lost.

Competition with Other Fuels.—In recent years coal as a fuel has had to compete with oil, natural gas, and water power, but it still remains the largest source of energy, having in 1940 contributed about 50 per cent of the supply.

PEAT

Origin. — So much attention has been attracted to this material in the last few years that it seems desirable to treat it as a separate topic, and partly so because it can be used for other purposes than fuel.

Peat (172) may be defined as "vegetable matter in a partly decomposed and more or less disintegrated condition," and represents much of the "dark-colored or nearly black soil found in bogs and swamps."[1] The dry peat may be very fibrous and light colored, or compact, structureless, and dark brown or black. If wet, it contains as much as 80 to 91 per cent or even more water. As previously mentioned (p. 1) it is produced by the slow decay, under water, of accumulated plant remains.

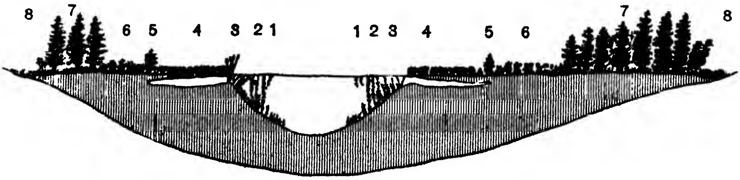

FIG. 19.—Diagram showing how plants fill depressions from the sides and top, to form a peat deposit.—1. Zone of Chara and floating aquatics. 2. Zone of Potamogetons. 2. Zone of water lilies. 4. Floting sedge mat. 5. Advance plants of conifers and shrubs. 6. Shrub and Sphagnum Zone. 7. Zone of Tamarack and Spruce. 8. Marginal Fosse. (*After Davis, Mich. Geol. Surv., Ann. Rept. for 1906.*)

The two essential conditions for peat formation are (1) restricted access to air to impede growth of decay-producing organisms, and (2) abundance of water to permit profuse plant growth.

This decay is accomplished mainly through the agency of fungi and air-requiring bacteria which break down the tissues, the decay involving decrease in bulk, darkening in color, and liberation of gaseous constituents. Both moisture and air are essentials to this process.

Since an abundance of water is essential to peat formation, and as it is formed by accumulation of plants in the spot where they grew, it requires plants of a water-loving nature. But peat may form in lakes or ponds, or in moist depressions or flat areas, and hence, plants adapted to these different sets of conditions being different, it follows that the product may come from more than one kind.

Peat may be formed in lakes or similar depressions by aquatic plants, including minute algæ, building up a deposit from the bottom and around the sides, in water shallower than 15 feet. The extension of this deposit into deeper water and building up of the bottom permits growth of aquatic seed plants, resulting in establishment of characteristic zones. These are characterized (175) by (1) the pond weeds,

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[1] If this material contains too much mineral matter to burn freely, it is technically known as muck.

Potamogeton, next to the deepest water; (2) shoreward of this the pond lilies; (3) the lake bulrush, *Scirpus;* and (4) the amphibious sedges, especially the turf-forming slender sedge. In some localities some of the zones may be absent. The sedges may also extend outward from the shore, forming a floating mat, which may cover the entire surface of the pond, and become covered by a growth of shrubs and even large trees, although the mat may not be more than 4 or 5 feet thick.

Peat may also form on moist, flat, or sloping surfaces, in depressions from which standing water is naturally absent, provided the plant remains are kept saturated with water, which they hold there partly by capillarity. In such situation plants of the rush, grass, sedge type, or *sphagnum* are important. This type of peat accumulation flourishes best in regions of heavy rainfall and moist atmosphere, and the deposit shows an irregularly stratified structure, but more uniform character than the filled-basin type first described, whose structure is more uniform below the original water level, but whose upper 3–5 feet is nearly always of different structure and composition from that below. Some bogs may be of composite origin.

The present surface vegetation of the bog does not necessarily indicate the kind of plant from which the peat was formed.

An interesting type of peat is that found in salt marshes, of which there are thousands of acres along the Atlantic coast, these marshes being poorly drained plains subject to frequent overflow by the sea-water. Studies by Davis of the Maine marshes (172) indicate that the peat is either of "fresh-water origin below a relatively thin stratum of salt-water peat, or else made up entirely of plants similar to those growing on the marshes to-day at about high tide level." The suggested explanation is that the fresh-water peat has been formed in fresh-water bogs situated on a slowly sinking coast, while the upper or salt-water peat formed when the land was low enough to permit an influx of salt water, thus permitting the growth of only such plants as could stand it.

The fresh-water peat may be of fuel value, but that formed wholly by the growth of salt-marsh plants is too full of fine silt and mud tidal deposits to be of marketable character.

Uses of Peat (180, 175).—The main use of peat is for fuel, but it has never been extensively used in America for this purpose. A number of experimental plants have been built in Canada, but most of them have not been successful nor have any been so in the United States. The failure may have been due to lack of capital, improper machinery, or competition with true coal. Since a detailed discussion of peat-fuel technology is beyond the limits of this work, those wishing to follow it up are referred to Nos. 180, 175, and 172 of the bibliography.

For fuel purposes the peat may be used in air-dried form as it comes from the bog, pressed into blocks (machine peat), in briquettes with or without binder, or in gas producers. Peat powder has been successfully used in special burners. Peat fuel has been used in European glass factories. It is not likely to be used where better grades of fuel are available.

Of importance is the use of the more fibrous kinds of peat as a material for bedding for stock and for packing, as well as for deodorizing and disinfecting. Those varieties of powdered peat which are rich in nitrogen are dried and sold for filler in certain kinds of artificial fertilizer. At the present time the chief domestic use of peat is for soil improvement, and this accounted for about 98 per cent of the sales in 1935. Poultry litter accounted for most of the remainder.

Those peats having a strong fiber can be used in the manufacture of cloth and paper. Peat can also be utilized for making ethyl alcohol, and for pressing into a structural material resembling wood.

Distribution in the United States.—Those regions possessing peat beds of sufficient size and depth to be of commercial value lie mostly outside of the coal-producing territory.

Davis states that workable beds are found in many states lying north of the Ohio and east of the Missouri rivers, in the coastal portions of the Middle and South Atlantic and Gulf States, and in the narrow strip along the Pacific coast from southern California northward to the Canadian boundary.

Production of Peat.—The production of peat and peat humus in the United States in 1940 amounted to 70,097 short tons, valued at $516,865. The imports in 1940 were 21,689, with a value of $454,632.

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CHAPTER II

PETROLEUM, NATURAL GAS, AND OTHER HYDROCARBONS

Introductory. — Under this head are included the following well-known substances, viz., natural gas, petroleum, mineral tar or maltha, asphaltum, and paraffin, all essentially compounds of carbon and hydrogen — hydrocarbons — or mixtures of such compounds. In addition they may contain many impurities, such as sulphur compounds, oxidized and nitrogenous substances, etc., whose exact nature may be doubtful.

The hydrocarbons are divisible primarily into a number of regular series, each of which has a generalized formula as indicated below.

1. C_nH_{2n+2}
2. C_nH_{2n}
3. C_nH_{2n-2}
4. C_nH_{2n-4}
5. C_nH_{2n-6}
6. C_nH_{2n-8}
7. C_nH_{2n-10}
8. C_nH_{2n-12}

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18. C_nH_{2n-32}

Of the above formulas, the first represents the paraffin hydrocarbons, beginning with marsh gas or methane, CH_4, and ranging at least as high as the compound $C_{35}H_{72}$. Methane is gaseous, the middle members of the series are liquids, while the higher members are solids, like ordinary paraffin. Members of the second series are also important in petroleums, especially the olefine subseries. The third or acetylene series is represented in some petroleums by its higher members. The fifth or benzine series occurs in nearly all petroleums, but not in large amounts.

Properties of Petroleum (6). — Crude petroleum is a liquid of complex composition and variable color and density. It consists of a mixture of hydrocarbons, mainly liquid, with some gaseous and solid ones, the last two being in solution.[1]

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[1] For a résumé of the different hydrocarbons discovered in American and Canadian oils, see F. W. Clarke, U. S. Geol. Surv., Bull. 770, and Day, Handbook of Petroleum Industry, 1922.

Oils which contain chiefly paraffin hydrocarbons, and which usually yield paraffin scales when the heavier distillates are subjected to a freezing temperature, may be said to have a *paraffin base*. Those containing asphaltic bodies, and yielding on evaporation a residue consisting essentially of asphalt, are said to have an *asphaltic base*. A third group may have a mixed base, while a fourth group is sometimes referred to as having a naphthene base, which contains a high percentage of the heavier hydrocarbon called naphthene (C_nH_{2n}).

Sulphur may be present as a constituent of hydrogen sulphide, as free sulphur, or as organic sulphur compounds. The first two, which occur for example in the Mexican, and in the Gulf Coast oils of Texas and Louisiana, are not difficult to remove. Organic sulphur, such as occurs in the Lima, Ohio, and the Ontario limestone oils, is more difficult to eliminate, even though in small amounts.

Most petroleum contains some nitrogen, but it rarely exceeds 2 per cent, except in some California oils, where it may reach 10 or 20 per cent.[1]

The following are analyses of several petroleums from American and foreign localities:

ELEMENTARY ANALYSES OF PETROLEUM

	Per Cent			Specific Gravity $H_2O = 1$
	C	H	O	
Heavy oil, W. Va.	83.5	13.3	3.2	.873
Light oil, W. Va.	84.3	14.1	1.6	.8412
Heavy oil, Pa.	84.9	13.7	1.04	.886
Light oil, Pa.	82.0	14.8	3.2	.816
Parma, Italy	84.0	13.4	1.8	.786
Hannover, Germany	80.4	12.7	6.9	.892
Galicia, Austria	82.2	12.1	5.7	.870
Light oil, Baku, Rus.	86.3	13.6	0.1	.884
Heavy oil, Baku, Rus.	86.6	12.3	1.1	.938
Java	87.1	12.0	0.9	.923
Beaumont, Texas	86.8	13.2	—	.920

Most crude oils are opaque by transmitted light, except in thin layers. Some of the thinner grades of Pennsylvania oils, and some Alberta ones, may show pale straw, yellow, red, and brown colors.

Crude oils usually have a green cast by reflected light, but otherwise vary in color from yellow to black.

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[1] Jour. Soc. Chem. Ind., XIX: 505, 1900.

Petroleums vary in specific gravity between .9 and 1.0, the following being some of the approximate limits shown by American oils:

SPECIFIC GRAVITY OF SOME AMERICAN PETROLEUMS

STATE	SPECIFIC GRAVITY	GRAVITY BEAUMÉ[1]
California (Placerita Cañon)	.77+	50+
Pennsylvania	.801–.817	46.2–42.6
Ohio	.816–.860	42.8–32.5
Kansas	.835–1.000	38.8–10.0
West Virginia	.841–.873	37.6–30.0
Beaumont, Texas	.904–.925	24.8–31.1
Wyoming	.912–.945	23.3–11.9
California	.920–.983	21.9–12.3

The viscosity of the oil increases with the specific gravity.

The temperature at which crude petroleum solidifies ranges from 82° F. in some Burma oils to several degrees below zero in certain Italian oils. The flashing point, or the lowest temperature at which inflammable vapors are given off, may be as low as zero degrees in the Italian oils to as high as 370° F. in an oil found on the Gold Coast of Africa, but these are extreme limits. There is also a great range in the boiling point, which is 180° F. in some Pennsylvania oils and 338° F. in oils found at Hannover, Germany.

The various liquid hydrocarbons making up crude petroleum vary in their specific gravity and boiling point. The more important oils which can be separated from crude petroleum by distillation are gasoline, benzine, heavy naphthas, and residuum. Those with a paraffin base are generally lighter and more valuable on account of the higher quantity and quality of the naphthas, illuminating oils, and lubricating oils which they produce. Those with an asphalt base are of inferior quality and chiefly valuable for fuel.

The percentage of the different distillates varies.

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[1] A specific gravity of 1, compared with water, is 10° on the Beaumé scale. Conversion from one scale to the other may be made by the following formula:

$$\text{Beaumé} = \frac{140}{\text{Sp. gr.}} - 130;\ \text{or Sp. gr.} = \frac{140}{130 + \text{Beaumé}}.$$

The A. P. I. scale now much used may be converted from other scales by the following formula:

$$\text{A. P. I. gravity} = 1.01071 \times {}^{\circ}\text{Be} - 0{,}107142 \text{ or } \frac{141.5}{\text{Sp. gr. at } 60^{\circ}\text{ F.}} - 131{,}5$$

The following table shows how the percentages of distillates may vary in different fields (Garfias):

FIELD	APPALACHIAN	LIMA, IND.	MID-CONT.	GULF COAST	MEXICO
Gasoline	35	35	22	——	2
Kerosene	27	15	15	——	4
Gas oil	10	12	12	7	14
Lubricating oil. .	15	——	9	75	12
Fuel oil	——	25	29	——	——
Asphalt	——	——	——	12.5	66

Properties of Natural Gas. — This consists chiefly of marsh gas — fire damp — CH_4. It is colorless, odorless, burns often with a luminous flame, and when mixed with air it is highly explosive.

"Casing head gas," or that coming from oil wells, often contains considerable amounts of ethane (C_2H_6), propane (C_3H_8), and butane (C_4H_{10}). This is also called "wet gas," and the last two hydrocarbons form part of the gasoline extracted from such gases chiefly by the adsorption method. Natural gas free or nearly so from gasoline constituents is known as "dry gas." Natural gas may also be classed as *sweet* or *sour*, depending on whether or not it contains sulphur. Some sweet gas wells become sour after being heavily drawn on. Sulphur is an undesirable constituent.

Natural gas may also contain varying though usually small amounts of other gases such as carbon monoxide, carbon dioxide, and hydrogen sulphide, the last being especially undesirable. Nitrogen is variable, and oxygen if present in quantity may be due to the contamination of the sample with air. Some wells supply carbon dioxide almost exclusively, and may be used as a source of supply for that gas (p. 55).

The analyses given on p. 55 represent a number of American occurrences. It will be seen that methane is the predominating constituent in nearly all of them.

The gas from Dexter, Kansas (No. 4 of the table on p. 55), is interesting because of its high content of nitrogen. Of 47 samples of gas examined[1] by Cady and McFarland, all except one showed helium, in amounts averaging .10 per cent. One Kansas sample contained

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[1] Jour. Amer. Chem. Soc., XXIX: 1524.

1.84 per cent more than the others, and this same one carried the high nitrogen contents referred to above. Helium (p. 56) rarely occurs in commercial amounts. The rare element neon was also discovered.

Natural gas from different localities will vary in calorific value depending on the hydrocarbons present. Thus the calorific value of methane is 966, ethane 1728, and propane 2477, B.t.u. per cu. ft.

Analyses of Natural Gas *

No.	Methane, (CH$_4$)	Ethane (C$_2$H$_6$)	Olefine (C$_2$H$_4$)	Carbon Dioxide (CO$_2$)	Carbon Monoxide (CO)	Oxygen	Nitrogen	Hydrogen	Helium	Hydrogen Sulphide
1	94.40	—	—	—	—	.23	5.08	—	.183	—
2	96.20	.78	—	—	.11	tr.	2.46	.18	.27	—
3	82.25	—	.12	.61	—	tr.	16.40	—	.616	—
4	14.85	.41	—	—	—	.20	82.70	tr.	1.84	—
5	62.93	—	—	.50	tr.	.70	24.36	11.51	undet.	—
6	13.97	—	—	.10	.05	.05	85.83	—	undet.	—
7	92.61	—	.30	.26	.50	.34	3.61	2.18	undet.	.20
8	80.94	14.60	—	—	.40	.20	3.46	tr.	undet.	—
9	86.48	7.65	—	—	.50	.30	4.87	—	undet.	—
10	98.40	—	—	—	.95	tr.	.40	tr.	undet.	tr.
11	94.20	—	.39	1.06	1.13	.92	3.31	—	tr.	—
12	92.20	—	—	1.40	.21	tr.	5.59	.40	—	.20

1. Iola, Kas., p. 270; 2. Buffalo, Kas., p. 270; 3. Fredonia, Kas., p. 270; 4. Dexter, Kas., p. 270; 5. Stockton, Cal., p. 252; 6. Princeton, Ill., p. 251; 7. Trenton limestone, Findlay, O., p. 248; 8. Big Injun sand, Shinnston, W. Va., p. 242; 9. Fifty-foot sand, same locality, p. 242; 10. Trenton limestone, Baldwinsville; N. Y., p. 241; 11. Gas from coal mine, Scranton, Pa., 1–11, quoted by Kas. Geol. Surv., IX on page given after each; 12. Kent County, Ont.

* For additional analyses of gas used in different cities, see Burrell, G. A., and Oberfell, G. G., Bur. Mines, Tech. Pap. 109, 1915.

The following table (p. 56) brings out the essential differences between natural gas and other fuel or illuminating gases.

Carbon Dioxide (8).—While carbon dioxide in small amounts is found in the natural gas at many localities, wells are occasionally brought in which contain this gas in sufficient quantity to make its utilization worth while.

Such wells are confined chiefly to a few western states and the Panuco district of Mexico.

ANALYSES OF NATURAL AND MANUFACTURED GASES

	Aver. Pa. & W. Va.	Aver. O. & Ind.	Aver. Kas.	Aver. Coal Gas	Aver. Water Gas	Aver. Producer Gas Bit. Coal
Marsh gas, CH_4	80.85	93.60	93.65	40.00	2.00	2.05
Other hydrocarbons	14.00	.30	.25	4.00	.00	.04
N	4.60	3.60	4.80	2.05	2.00	56.26
CO_2	.05	.20	.30	.45	4.00	2.60
CO	.40	.50	1.00	6.00	45.00	27.00
H	.10	1.50	.00	46.00	45.00	12.00
H_2S	.00	.15	.00	.00	.00	.00
O	tr.	.15	.00	1.50	1.50	.05
Lbs. in 1000 cu. ft.	47.50	48.50	49.00	33.00	45.60	75.00
Sp. gr.	.624	.637	.645	.453	.600	.985
B.t.u. per 1000 cu. ft.	1,145,000	1,095,000	1,100,000	755,000	350,000	155,000

The following table gives a list of a number of occurrences:

WELLS SUPPLYING CARBON DIOXIDE GAS *

Locality	Formation	Depth	Per Cent CO_2
Kevin–Sunburst field, Mont.	Cambrian	4600	56.74
	Devonian	3058	80–95
Walden field, Colo.	Up. Cretaceous	4875	92.00
Garmesa anticline, Colo.	Jura–Cretaceous	2857–2769	20–61.05
Colfax Co., N. Mex.	Triassic	1509	67.20
Mora Co., N. Mex.	Triassic	1420	90
Carbon Co., Utah	Permian	3013	98.80
Panuco, Mex.	Cretaceous	——	50–98

* Miller, A. I. M. M. E., Tech. Pub. 736, 1936.

Various theories have been advanced to account for the origin of the carbon dioxide, such as metamorphism of the basement rocks, oxidation of hydrocarbons through contact with mineralized waters, and the action of hot magmas on limestone.

Unfortunately many of the occurrences are remotely located, but some of them are being utilized.

Considerable carbon dioxide is obtained from the mineral waters at Saratoga Springs, New York.

Helium (93–96). — As already mentioned, helium occurs in many natural gases in very small amounts, but the only known gas fields in the world yielding gas with enough helium to warrant its extraction are located in the United States.

Helium was first discovered in a high-nitrogen gas from Dexter, Kas., the content being 1.84 per cent, but not all gases of this type contain it. Another Kansas gas was reported with 3.5 per cent helium and one from Colorado with 7 to 8 per cent. The resources of gas in these districts, however, are not great. The gas from the Petrolia field in Texas contains 1.94 per cent helium, while that from the Amarillo field in the same state has 1.5 per cent.

In order to be commercially extractable the gas should contain not less than 0.5 per cent helium.

The first government plant was started at Fort Worth, Texas, and up to December 1921 had produced 2,300,000 cubic feet of 92–95 per cent purity. This was closed in 1929 because the supply was exhausted.

The next one was established at Amarillo, Texas, where the gas is obtained from depths of 1400 to 2900 feet.

It is interesting to note that in 1918 the cost of helium production was $2500 per cubic foot, but by 1935 it had been reduced to about $11.00 per 1000 cubic feet. At 60° F. helium has 92.64 per cent the lifting power of hydrogen.

Origin of Oil and Gas. — That the solid, liquid, and gaseous hydrocarbons are more or less closely related is evident from the fact that the gases given off by petroleum are similar to those predominating in natural gas, while the exposure of many petroleums to the air results in a change to a viscous mass and finally to a solid asphalt or paraffin-like substance. It is a well-known fact that petroleum is rarely free from natural gas, although this gas may sometimes form alone, as in coal mines, or from decaying vegetation in stagnant pools. The origin of the hydrocarbon compounds has been the subject of much speculation among both chemists and geologists, the former for a time arguing for an inorganic or mineral origin, the latter for an organic derivation, the same evidence curiously enough being sometimes used by persons holding opposite views.

It cannot be said that the matter has yet been settled to the satisfaction of all, although the majority of observers admit the organic origin of petroleum. One cause of uncertainty is that oils, unlike coals, do not usually contain visible traces of their original constituents.

Inorganic Theories (2). — Several thories have been advanced to account for an inorganic origin of oil. Humboldt was the first to propose it, in 1804, although it was later more definitely stated by Berthelot,[1] and still later elaborated by Mendeljeff,[2] under whose name it is frequently referred to. The general substance of these and several others' hypotheses is that surface water has percolated downward through the earth's crust, where on reaching the heated interior it becomes converted into steam, which, attacking the carbide of iron, forms hydrocarbons, such as are found in oil and gas.

Hydrocarbons have been produced experimentally by this method, but it does not accord with geologic facts. If petroleum were formed in this manner, we should expect to find it widely distributed through the oldest rocks of the earth's crust.

On the contrary, hydrocarbon compounds like oil, gas, and asphalt are rarely found in crystalline rocks. In Ontario, a hard compressed asphalt is found in them, but it is significant that that material (Anthraxolite) which was probably originally petroleum, occurs in rocks which may be metamorphosed sediments. Another case is found in California,[3] where oil occurs in a much-folded crystalline schist, but its associations are such that it may have been derived from neighboring sediments.

A volcanic origin for oil and gas was strongly advocated by E. Coste (7), but the theory has few adherents.

Organic Theory (6, 13, 17). — Most geologists now believe that oil and gas are of organic origin, and derived chiefly from plant remains, a view that has been held for a long time.[4] Some have suggested its derivation from decaying animal matter.

As pointed out by David White (28), the oil has probably been derived mostly from plants of low orders which on decay yield waxy, fatty, gelatinous or resinous products, mixed with which there may be more or less animal matter.

This organic material is deposited in muds or slimes in quiet water, usually of marine character.

The biochemical changes which are supposed to accompany the burial of organic matter consist in the transformation of highly hydrogenous, or fatty, substances, into fatty acids, from which oil and other hydrocarbons may be formed.

The plant remains which have been recognized by different observers under the microscope are chiefly algal filaments, pollen cover-

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[1] Comptes Rendus, LXII: 949, 1866.

[2] Ber. Deutsch. Chem. Gesell., X: 229, 1877, and Jour. Chem. Soc., XXXII: 283.

[3] Eldridge and Arnold, U. S. Geol. Surv., Bull. 309, 1907.

[4] Höfer, Proc. Manchester. Lit. Phil. Soc., Vol. III, p. 136, and Das Erdöl, p. 118. Newberry, Geol. Surv. Ohio, 1878, Pt. I, pp. 125 and 174.

ing, spore cases, fragments of woody cell walls, wax, resin fragments, etc. (1, 3, p. 25).

After aerobic bacteria had ceased to act on the organic debris, it was probably subjected to slow deoxidation by anærobic ones, the effect of which would be to change carbohydrates to hydrocarbons.

It is known that anærobic bacteria can generate methane, but there is no definite proof of their forming liquid hydrocarbons.

Cannel coals, oil shales, etc., which yield oil on distillation are known to be full of plant remains.

The sulphur found in some oils may, it is thought, have been yielded by the decomposition of marine animal organisms, and have been gathered in the organic muds through the agency of sulphur bacteria, but in some cases it may have come from outside sources.

There exists a difference of opinion, however, whether the plant remains were changed to oil or gas before burial, the globules of petroleum becoming entrapped by clay particles and carried to the bottom, or whether the organic matter only underwent partial decay before burial (13).

If the latter view is correct we must assume not only that the hydrocarbons (oil and gas) were changed to oil or gas after burial, but also that the process was assisted by pressure and probably some heat. Indeed these two agents might continue to act after the vegetable matter was buried.

There is little direct evidence of oil forming at the present day, although cases have been noted where seaweeds became covered with an oily coating while decomposing.[1]

Diatom cases found in some rocks are known to contain small globules of oil, which in some regions have been regarded as sources of petroleum. However, 2000 samples of marine sediments rich in organic matter were not found to contain any liquid hydrocarbons,[2] and a detailed study of certain recent diatom deposits[3] indicates that, while these organisms may contain oil globules as reserve food, they do not have the power of synthesizing the hydrocarbons found in oil.

This might therefore lead to the belief that the origin and progressive devolatilization of oil is a dynamo-chemical process.

Whether bacteria are capable of acting after organic matter is buried in sediments is open to dispute. No active organisms have been found at greater depths than 18 feet in a peat bog, but on the other

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[1] Redwood, Petroleum and Its Products, 2d ed., I, pp. 126, 142.

[2] Trask and Wu, Amer. Assoc. Pet. Geol., XIV, p. 1451, 1930.

[3] Tolman and Becking, Proj. 5, Amer. Petrol. Inst., pt. 3, p. 12, 1932.

hand active bacteria have been reported from depths of 3000 feet in Carboniferous oil field brines.[1]

Source beds. — Sediment, usually of a clayey but sometimes of calcareous nature, in which the vegetable matter accumulates and changes to oil or gas, is known as the source bed.

It is generally considered that such beds are dark gray, blue, or black shales, although not all shales of this color are to be regarded as source beds. In some cases limestones or sandstones may function similarly.

Trask (Ref. 13, p. 27) states that the diagnostic characteristics of source beds are not known, but that the mother rock of oil is apparently of marine origin. From his studies he concludes that the organic constituents of recent sediments are chiefly nitrogenous and lignin-humus compounds, with pigments, waxes, and carbohydrates in small amount, and with oils and fats in insignificant quantities. The apparent absence of liquid hydrocarbons in fresh deposits, he believes, indicates that petroleum probably does not form in sediments at the time they were deposited.

A means of recognizing source beds is of considerable importance, and work towards this end is being actively prosecuted.[2] The ratio of the nitrogen content to the reducing power of the sediment (the nitrogen-reducing ratio) is regarded as probably the most promising means of recognizing a source sediment, for the nitrogen content is a rough index of the organic contents, and the nitrogen-reduction ratio a crude index of the degree of oxidation of the sediments.

Source beds are closely associated stratigraphically with those in which the oil and gas are now found.

Migration of Oil and Gas. — The oil and gas as now found are not in the source beds, but in the reservoir rock (p. 61).

This means, then, that they have migrated from one to the other, but there is no unanimity of opinion as to the cause of this movement or its extent, although some geologists believe the hydrocarbons may have traveled a considerable distance (18, p. 13).

Among the motivating causes mentioned are: 1. Gravity, which assumes that if gas, oil, and water are in a porous rock they tend to range themselves according to their specific gravities, and move upwards in porous beds. 2. Replacement (18, p. 259). This assumes

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[1] Bastin, Amer. Assoc. Petrol. Geol., X, p. 1270, 1926.

[2] Trask, P. D., and Patnode, H. W., Drilling and Petroleum Practice, 1936, Amer. Petrol. Inst., 1937.

that connate or mixed water enters the source rock and drives the oil into the reservoir rock, this being due to the fact that the adhesive tension between water and source rock is greater than between the latter and the oil, and also because the surface tension of the water is greater than that of the oil. 3. Moving water, suggested by Munn and later by Rich.[1] According to them, waters circulating through the rocks carry oil or gas with them, which may become trapped in favorable structures. 4. Gas pressure, which, since it is the force that sometimes drives oil from wells, is regarded by some as being capable of causing its migration through the rocks. 5. Differential compaction, which operates as the clays or calcareous oozes, in which oil may have accumulated, are compressed by the weight of overlying sediments, thus driving the oil and water out of them into less compactable beds. 6. Diastrophic pressure has been appealed to, but since oil will migrate from a fine-grained to coarse-grained rock without pressure, this factor does not appear to have much weight, although it might exert some influence on the migration in the rock in which the oil finally accumulates.

Reservoir Rocks. — Sandstones and sands are the commonest reservoir rocks, but limestone or dolomite are important in some regions particularly where they are porous, owing to dolomitization or weathering.

In exceptional cases serpentine and volcanic rocks have been found to contain oil or gas, although it is not indigenous to them.

According to Powers [2] the porosity of reservoir rocks ranges from 7 to 40 per cent. The capacity of a sand with an average porosity of 20 per cent would be 8700 cubic feet, or 1550 barrels per acre foot. If such a sand has a thickness of 50 feet it could hold 77,500 barrels per acre. However the average amount of oil recovered is only 15–20 per cent.[2]

In the Bradford, Pa., field the sand is locally as much as 90 feet thick, but not all of it is oil bearing. The porosity may be from 15 to 20 per cent, but only a relatively small percentage of the oil in this pore space is obtained. An additional 20 per cent or more has been secured by flooding the sands and by other means.

In the unconsolidated fine sands of California and the Gulf Coast the porosity range is from 25 to 40 per cent, while 10-30 per cent of oil is recovered. A large amount of gas may be present in solution

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[1] Amer. Assoc. Petrol. Geol., VIII, p. 213, 1923.

[2] A. I. M. M. E., Tech. Pub., 377, 1931.

in light oils. Thus the average content in Oklahoma is 2000 cubic feet per barrel of oil.[1]

Both porous and well-cemented sands of low porosity may supply dry gas.

Carbon-Ratio Theory. — White has called attention to the fact that, in regions where the progressive devolatilization of organic deposits in any formation has passed 65–70 per cent fixed carbon in the associated or overlying coals, commercial oil pools are not present in that formation, or any other normally overlying it, although gas may occur. The lowest ranks of oils of each type are found in regions and formations in which the carbonaceous deposits have been least altered, and vice versa (21).

While the theory of the carbon ratio as advanced by White has been substantiated in a general way, it should be regarded, according to Thom (13, p. 69), as a qualitative rather than a quantitative index.

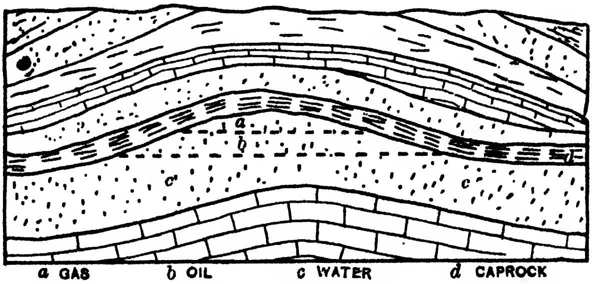

FIG. 20.—Section of anticlinal fold showing accumulation of gas, oil, and water. (*After Hayes, U. S. Geol. Surv., Bull.* 212.)

In regions of semianthracite and semibituminous coals, the chances of finding commercially valuable oil pools are relatively slight.

Mode of Occurrence (6, 10, 22). — The accumulation of oil and gas is governed either by structural features which tend to trap the hydrocarbons, or by sedimentary structures in which porous rocks are more or less enveloped by others of low porosity and permeability.

Several classifications of these features have been proposed (6), but it is probably sufficient here to call attention to the more important structural features which have served to trap the hydrocarbons.

Anticlines and Synclines. — As early as 1861, the Canadian geologist, T. Sterry Hunt, and A. Höfer, the Austrian geologist, called attention to the fact that oil and gas occurrences appeared to be

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[1] Powers, *Loc. cit.*

associated with anticlinal folds, but the *anticlinal theory*, as it came to be called, was most fully developed by I. C. White (22). This assumed that in folded areas the gas collects at the summit of the fold, with oil immediately below, on either side, followed by the water (Fig. 20).

Oil and gas are associated with this type of structure in many parts of the world. Where water is also present the oil and gas collect at the crest of the anticline (Appalachian field), but should the sands be dry the oil may accumulate in the synclines.

The flanks of large anticlines or synclines may have subordinate anticlines which serve to trap oil and gas.

Terrace, Nose and Dome.—A terrace represents a local flattening of a uniform dip. If the sands are sealed up dip, it forms a closure to prevent the escape of oil or gas (Fig. 22).

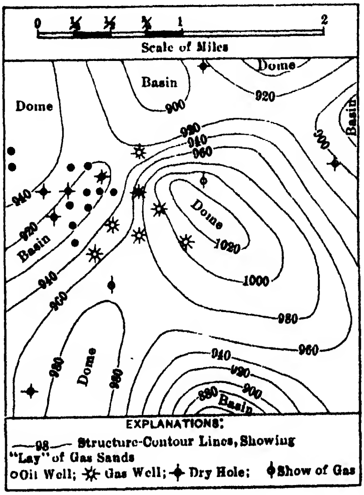

FIG 21.—Contour map of "sand," showing occurrence of gas on a structural dome in Oklahoma. (*Clapp, Econ. Geol. VIII.*)

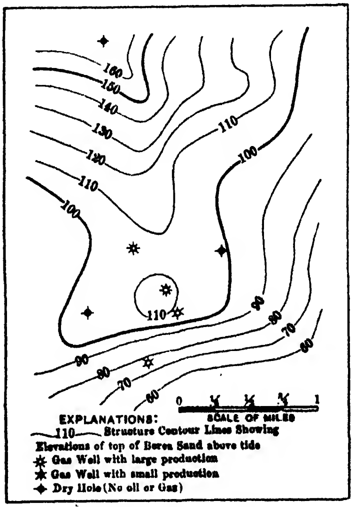

FIG. 22.—Gas pool coincident with a structural terrace. (*Clapp, Econ. Geol. V.*)

A nose represents a partially developed elongated dome or an anticline, of which one end is left open without closure. It forms a rather important structure for oil and gas accumulation, when the underlying beds thicken in the opposite direction from which the nose points.

A dome is an uplift or upfold in which the beds dip in all directions from a crestal point. In many cases domes serve for the accumulation of oil or gas (Fig. 21).

Homocline (Including Monocline).—These structures may have subordinate folds or terraces that act as reservoirs. In the case of terraces these may be sealed on the up dip side, which accounts for their holding the oil or gas.

In some cases the oil or gas may be held because the porous beds are sealed up dip owing to: 1. The sands lensing out upward, and lying between less permeable beds. This condition is not an uncommon one. 2. Porous sands grading up dip into less porous ones, which the oil in its migration cannot penetrate. 3. Sands which up dip are sealed by asphaltic material resulting from change of oil to asphalt. 4. Sands which are sealed by faults, owing to the fault fracture being filled with finely crushed rock.

Unconformities.—If folded beds are eroded, and a second series laid down on the eroded edges, or if a series of monoclinal beds are covered by tight ones, the upper series may act as a seal to shut in oil or gas accumulated in porous beds of the lower series.

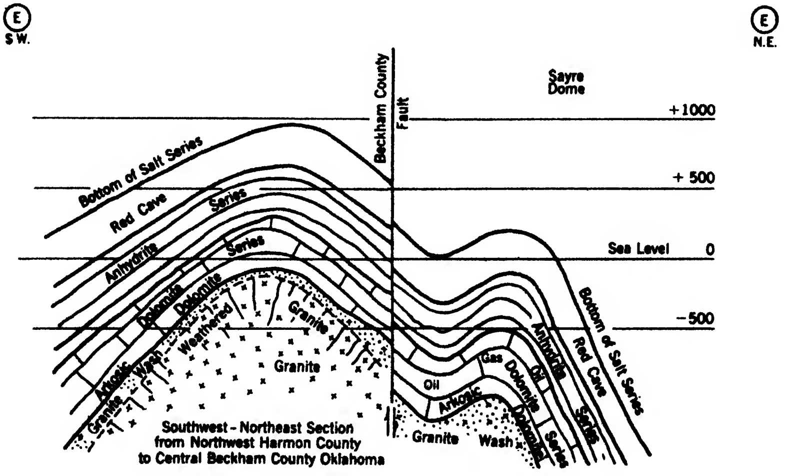

FIG. 23.—Cross section of an anticline in Texas Panhandle showing arching of oil-bearing rocks over granite dome and faulting on one side of dome. (*After Cotner and Crum, A. A. P. G., Bull. XVII:* 877.)

Limestones are now regarded as an important reservoir rock, yielding oil in many fields. In many cases the oil or gas is found within a relatively short distance of an underlying unconformity and the porosity is regarded as being largely the result of weathering.

Buried Hills.—In some regions where oil and gas are associated with arch-like folds it is found that these may be caused by the deposition of clay and sand sediment above and around a submerged ridge (Fig. 23). Owing to the shrinkage and compaction of the clay, as well as the fact that deposition was heavier on the flanks of the ridge than the crest, compaction leads to the development of an anticlinal structure.

First encountered along the Nemaha buried granite ridge of Kansas, buried hills have been discovered in other states, and have served as important sources of supply.

In addition to being formed by ridges of granite, buried hills may in some instances represent uplifted fault blocks, or anticlinal arches along which further uplift has occurred.

Shoestring Sands.[1] — These represent a unique type of occurrence, and consist of relatively long, narrow, sometimes thick bodies of sand, surrounded by much less pervious material. In some cases they represent filled river channels, but in most cases they seem to be beach deposits, bars or even spits. The first group might show dendritic patterns, while the second would have accumulated usually (except some spits) parallel to the ancient shore lines. Subsequent to their formation they may have partaken of the folding in the region where they occur, so that gas would accumulate in the anticlines and oil lower down. Good examples of this type are found in eastern Kansas.

Salt Domes (13). — These are of great importance in the Gulf Coast area of Louisiana and Texas but are also known in foreign countries as Persia, Rumania, and Germany, although in the last two they may be in the form of elongated domes.

The salt may be covered by a cap rock consisting of anhydrite, gypsum, and limestone, although all three are not necessarily present. In the uplift or rise of the salt, the overlying beds have been domed up so that they arch up over the dome (Fig. 24). In other cases the dome has pushed up the beds, and broken through them, the oil or gas having accumulated in these upturned strata which surround the dome. Some domes instead of having vertical sides may show an overhang of salt at the top, with oil-bearing beds beneath it.

Oil and gas may also occur in porous beds of the cap rock, or those overlying them. Not all domes have oil and gas associated with them.

Igneous Rocks (12).—Ordinarily one would not expect to find oil or gas in, or closely associated with, igneous rocks. It is conceivable, however, that a porous mass of igneous rock might serve as a reservoir into which the hydrocarbons had migrated. Thus at Lytton

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[1] Rich, J. L. A. A. P. G., VII, p. 103, 1923.

Springs, Texas, the upper part of a mass of porous igneous rock termed serpentine has supplied a considerable amount of oil.

In some cases a dike of igneous rock may by its intrusion have so shattered the adjoining rock as to make a reservoir for oil or gas to migrate into. If the igneous rock itself is crushed it may also serve as a collecting ground.

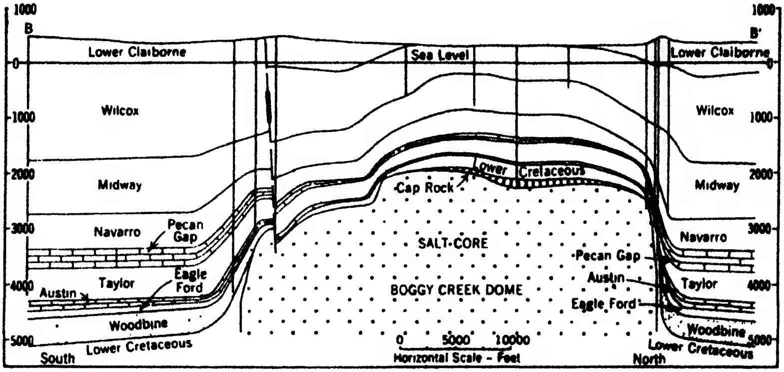

FIG. 24.—Section across Boggy Creek salt dome, Anderson County, Texas, showing tilting of rocks on sides of dome and arching of rocks over top of same. (*After McLellan, Wendlant*, and *Murchison, A. A. P. G., Bull. XVI:* 584.)

Faults.—These may operate in several ways to encourage oil and gas accumulation, viz.: (1) by sealing off a porous bed up dip, or (2) by developing folds due to drag, which serve as traps for oil or gas.

Joint Fissures.—Just as joint planes are capable of holding subsurface water, so it is that they sometimes carry appreciable supplies of oil or gas. They are particularly important in rocks like shales, which have a very low permeability. The Florence, Colo., oil field was one of the first in which this type of supply was recognized. Similar conditions are found in some other fields of the Rocky Mountain region, California, Ohio, etc.

Number and Thickness of Sands.—The number and thickness of sands vary in different fields or even in different parts of the same field (Fig. 25), thereby making correlation difficult.

The Appalachian region is said to contain as many as 56 sands, while in others only 3 or 4 are known.

The thickness of the producing rock ("pay sand") varies in the different fields. White, referring to West Virginia, regards 5 feet of sand as sufficient for good productive territory, but thicker ones are found in the Appalachian field. The Illinois sands range from 2 to over 30 feet in thickness, while that estimated for Spindle Top in Texas averages 75 feet. The Kern River field of California is said to have pay sands as much as 100 feet thick.

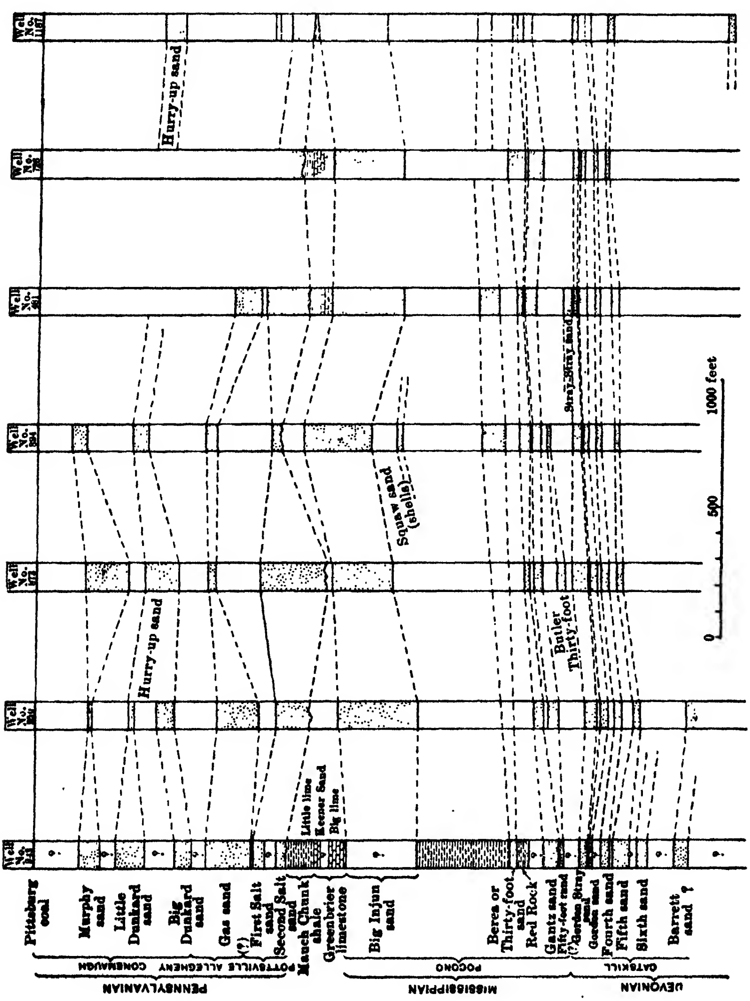

FIG. 25.—Sections of deep wells in the Clayville, Pa., quadrangle, showing irregularity in thickness and number of the oil and gas sands. (*After Griswold and Munn.*)

Pressure of Oil and Gas Wells.—Since both oil and gas usually occur in the rocks under pressure, any break in the porous rock or reservoir which contains them permits their escape, sometimes giving rise to surface indications, and the force with which the oil and gas oftentimes issue from a well indicates the pressure under which they are confined. It has been known to be sufficient to blow out the drilling tools as well as to cause the oil to spout many feet into the air. Considerable effort is sometimes required to close in these *gushers.*

A famous case was that of the Lucas well at Beaumont, Texas, which in 1901 for nine days gushed a 6-inch stream to a height of 200 feet, at the rate of 75,000 barrels per day. Even larger ones are known.

The depth of producing wells drilled has varied from 69½ feet for the first Drake well in Pennsylvania to over 10,569 feet for a well in the Ventura, Calif., pool.

The maximum pressure which a well develops when closed has been called *rock pressure,* and it is generally ascribed to two possible causes, viz.: 1. Hydrostatic pressure, or that exerted by a column of water whose height is equal to the depth of the reservoir below the surface of the ground. In such a case the pressure would increase at the rate of about 43.4 pounds per 100 feet depth. 2. Gas, associated with the oil or by itself, may because of its expansive force be a source of pressure. In some fields both gas and hydrostatic pressure may be operative.

In general, reservoirs in which the rock is porous may have moderate initial production, gradual decline, and long life, while those in which the rock is cavernous commonly have high initial production and decline rapidly.

Either the drilling of additional wells or a drain by excessive use from wells already bored commonly causes a decrease in pressure in an oil or gas field.

Distribution of Petroleum and Natural Gas in the United States (Pl. X). — The United States is at the present time the leading country in the production of oil and natural gas. It is also unique in that practically every known type of occurrence of these materials is recognized, and furthermore their stratigraphic distribution is greater than in any other country.

The distribution of oil and gas can be made on a geographic or on a structural basis, the latter having been particularly developed by Ver Wiebe (18).

In the following table the two are combined, the larger areas being designated as *regions,* and their subdivisions as *provinces.* Within these there may be districts or pools. The term sand is rather loosely used to designate any reservoir rock, although in most cases it is a sand or sandstone. Any district may contain one or more sands at different depths.

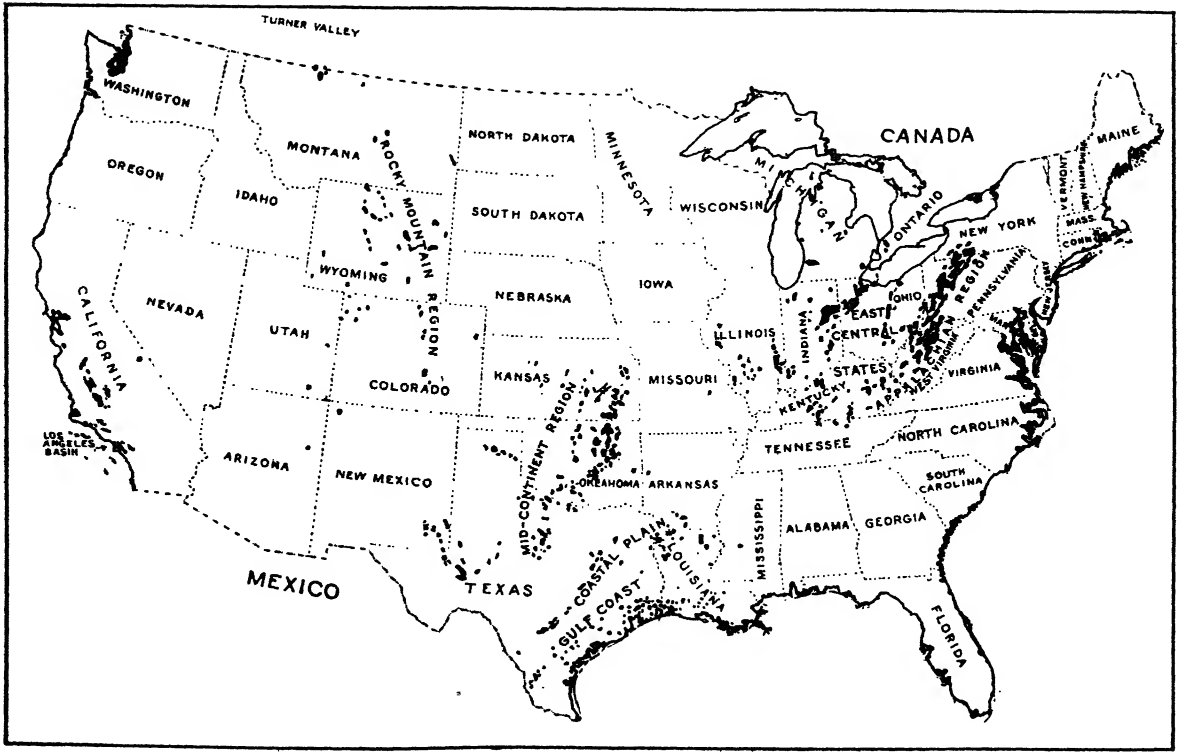

Plate X.—Map showing oil and gas fields of United States. (*After Powers, A. I. M. M. E., Tech. Pub.* 377, 1931.)

Oil and Gas Regions	Tectonic Provinces	States
East Central States	Applachian geosyncline	N. Y., Pa., W. Va., e. Ohio, e. Ky.
	Cincinnati arch	W. Ohio, e. Ind., s. cent. Ky., Tenn., Ala., Miss.
	Eastern Interior Basin	N. w. Ky., Ill., Ind.
	Michigan Basin	Mich.
Mid-Continent Region	Western Interior Basin	Kas., n. Okla.
	Ouachita–Amarillo	S. Okla., n. cent. Tex., Tex. panhandle
	Bend arch	N. cent. Tex.
	West Texas Basin	W. Tex., s. e. N. Mex.
Gulf Embayment Region	Balcones	E. Tex.
	Reynosa	S. e. Tex.
	Sabine and Ouachita uplifts	N. La., n. e. Tex., Ark.
	Salt domes	S. Tex. and La.
Rocky Mountain	Rocky Mountain geosyncline	
California	Pacific geosyncline	California districts

East Central States Region

Appalachian Geosyncline (18, 23, 50–51, 47, 56, 46).—This extends from New York southwestward to Tennessee and includes portion of New York, Pennsylvania, Ohio, West Virginia, and Kentucky.

It represents the largest single region in the United States, having been a producer of oil for many years, and also of considerable quantities of gas.

The oil and gas-bearing formations, which range from Cambrian to Permian, are chiefly sandstones, interstratified with and underlain by a great thickness of shale, below which are more limestone beds.

The pre-Pennsylvanian rocks outcrop in rather narrow bands on the eastern edge of the syncline, but form broader areas on the western side, where they are exposed by erosion in the center of gentle folds. The deepest part of the trough is in northwestern West Virginia. Within this geosynclinal trough there are subordinate structures (Fig. 26).

At the northern end of the trough in Pennsylvania the producing sands are chiefly Catskill, Chemung, and Portage, while at the southern end Mississippian, Pottsville and some higher beds yield supplies.

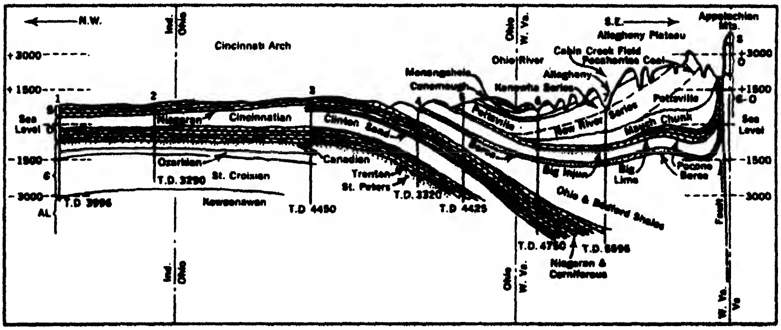

FIG. 26.—Generalized section from Cincinnati anticline to Appalachian Mountains, showing geologic structure. (*After Theron and Wasson, A. A. P. G., Bull. XI*; 705, 1927.)

The Upper Cambrian or Lower Ordovician has yielded gas in central New York, and the Trenton limestone has also produced gas in the same state.

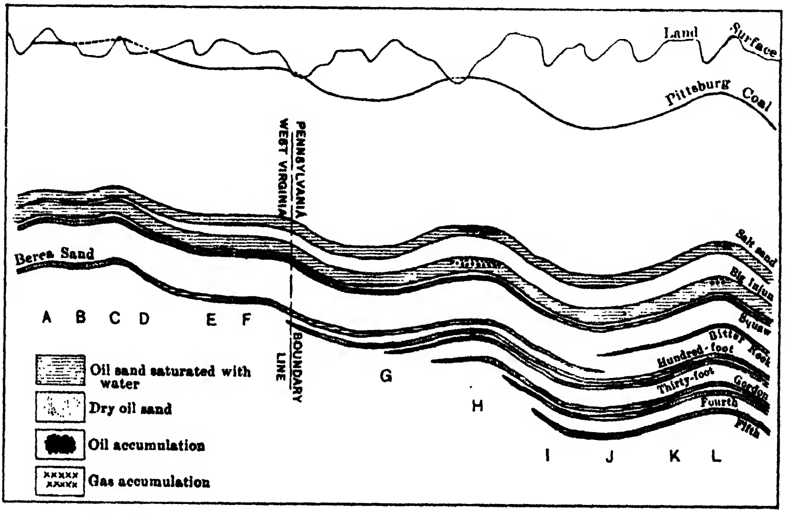

FIG. 27.—Diagrammatic section of sands in the central Appalachian region. (*After Griswold and Munn, U. S. Geol. Surv., Bull.* 318.)

The Oriskany has produced large quantities of natural gas in Pennsylvania, New York and West Virginia, and is being actively prospected in other areas.

This field is said to contain more oil and gas horizons than any other in the world, there being 56, although only two, the Big Injun and Berea, are productive over most of the area.

The Clinton and Oriskany may be found to be similarly extensive.

The Devonian sands disappear to the westward, but in central Ohio the Clinton sand which lies very deep in the center of the trough is within drilling distance and has been an important producer of gas and much oil (Fig. 26).

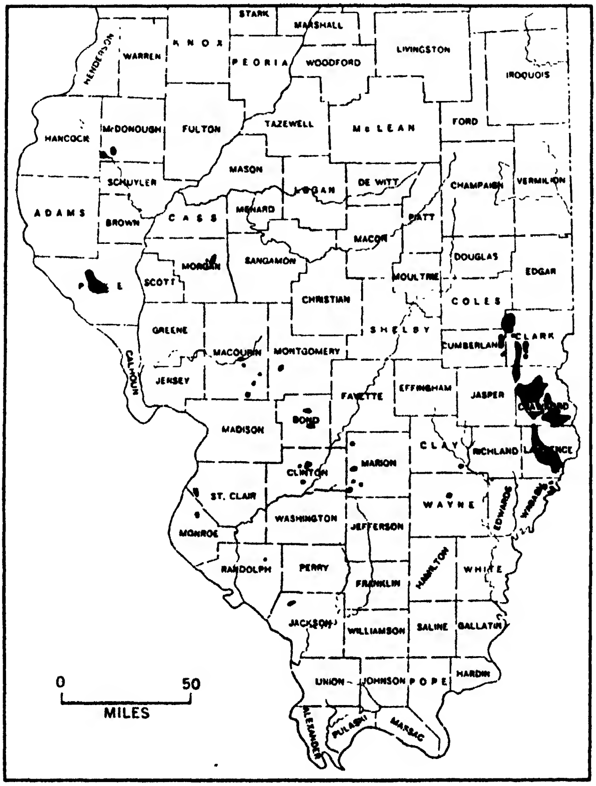

FIG. 28.—**Map of Illinois showing distribution of oil and gas fields.** (*From Ill. Geol. Survey.*)

Most of the oil and gas comes from sandstones which average less than 25 feet in thickness, but some limestones are also productive. The oil varies from 38 to 47 Bé. with a paraffin base. The sands vary in depth from 1000 to 4500 feet.

While the theory of the relation of oil and gas to anticlines was originally worked out in this field, it does not hold true in all parts of the area.

The Appalachian province is of interest historically because the Drake well at Titusville, Pa., drilled in 1859, was the first successful one drilled in this country.

This province was formerly the leading oil-producing area of the United States, but reached its peak between 1891 and 1900, and is now of secondary importance in point of production, but still ranks as the best high-grade oil field of the world.

Cincinnati Arch Province (18, 23).—This structural feature extends from Alabama to northern Ohio and into Ontario. At its northern end is the Lima-Indiana field, while smaller ones occur in southern Kentucky and northwestern Alabama.

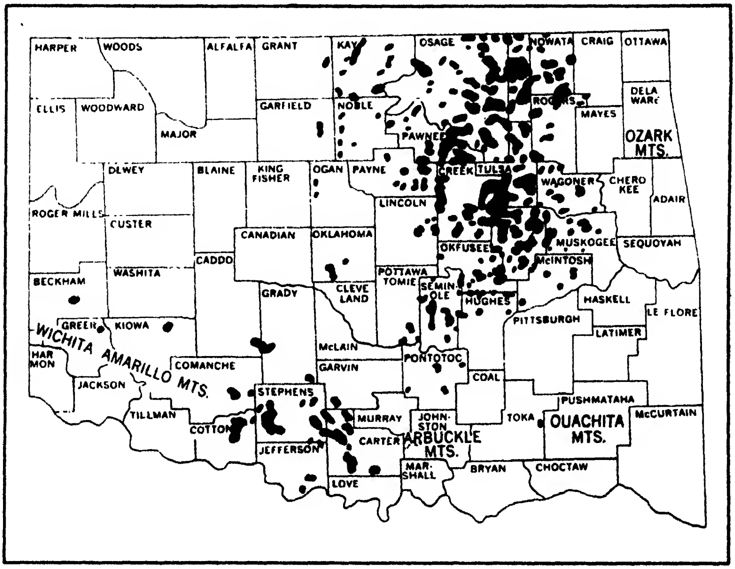

FIG. 29.—Map of oil fields of Oklahoma. (*From Okla. Geol. Survey.*)

The important oil and gas horizons are found in the Devonian, Silurian, and Ordovician.

In the Lima-Indiana field, which was developed in 1884, oil and gas were found in limestone for the first time. It is still an oil producer, but the gas output is of little importance. Very little oil has been produced in Tennessee, but in Alabama some has been yielded by the Pottsville.

Gas has been developed in Kentucky, Tennessee, Mississippi, and

Alabama, coming chiefly from porous and fissured limestones which range from Ordovician to Mississippian in age.

Eastern Interior Basin Province (18, 23, 37, 38, 40).—This includes northwestern Kentucky, Illinois, and a part of Indiana, the general outline corresponding somewhat with the coal basin of the same name. The three important sub-areas are southeastern llinois (Fig. 28), southwestern Indiana, and northwestern Kentucky.

Several structural elements in this basin, such as the LaSalle anticline, the Cincinnati anticline, and the Rough Creek fault zone, are supposed to have exerted an influence on the migration and accumulation of the oil. Most of the oil has come from the Mississippian and Pennsylvanian strata, the former being the more important. The wells are from 350 to 2900 feet deep, and the oil which ranges from 29° to 34° Bé. has a paraffin base. Northwestern Kentucky has yielded small amounts of oil and gas from the Mississippian. There is no production from the Trenton, which is such a prolific producer in eastern Indiana and Ohio.

Twenty years ago this province yielded 20 per cent of the United States production of oil, but now it supplies but 1 per cent.

Gas occurs in formations ranging from Ordovician to Pennsylvanian. Its production in the past has been incidental to oil, with which it is associated. In recent years, however, there has been considerable exploitation of gas alone, particularly in western Kentucky and southwestern Indiana.

Michigan Basin Province (18, 23, 42, 43).—All the oil fields are located within a great basin which occupies the center of the southern peninsula of Michigan. The formations range from Cambrian to Pennsylvanian, and while coal occurs in the latter formation, the oil is obtained from the Devonian, and also from the Mississippian (Berea), being associated with subordinate anticlines, which are on the slopes of the basin. At Saginaw the Berea sand is encountered at a depth of 1800 feet, and the Dundee at 2900. The latter is more important in the Mount Pleasant field of central Michigan where it produces nearly all the oil.

Commercial quantities of gas were not developed until 1927. It comes chiefly from the Mississippian sandstone and Devonian dolomite. A not inconsiderable quantity of gas has been found at the contact of bed rock and the heavy covering of glacial drift.

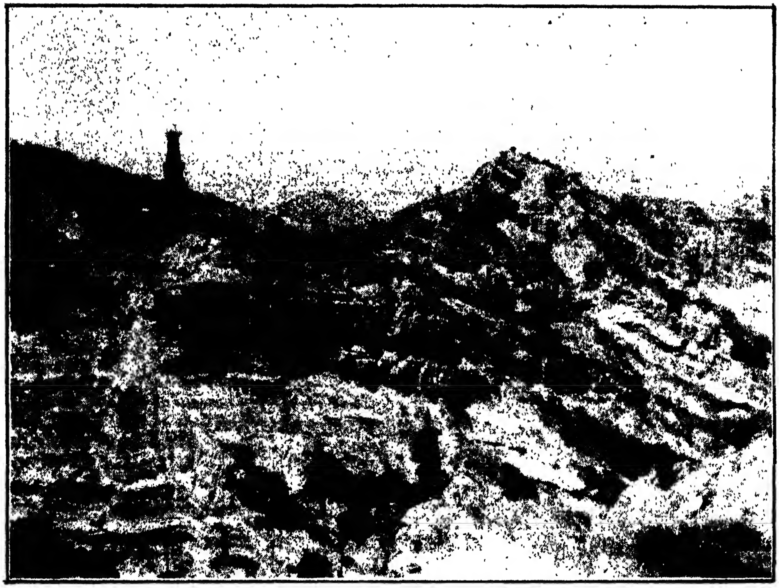

FIG 1.—View in South Mountain oil field, California, showing oil derricks on anticline. (*H. Ries, photo.*)

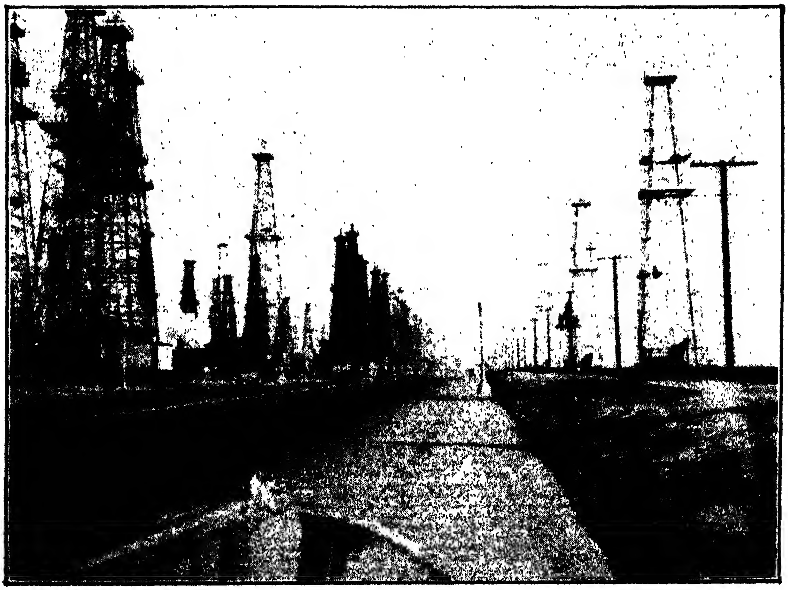

FIG. 2.—View in Huntington Beach, Calif., oil field. (*H. Ries, photo.*)

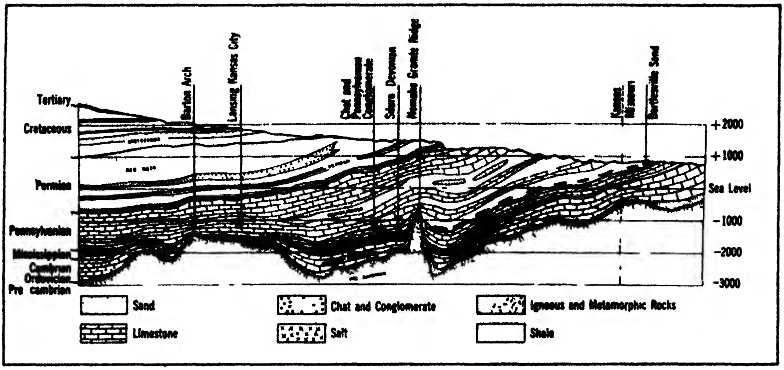

FIG. 30.—Geologic cross section from western Missouri to western Kansas. (*After Kellet, Kas. Geol. Soc.*, 1932.)

MID-CONTINENT REGION

Western Interior Basin (18, 23, 39, 48).—This province which lies along the eastern edge of the Rocky Mountain geosyncline is productive in Kansas and Northern Oklahoma (Fig. 29).

The oil horizons range from the Cambrian to the Permian, the first of these and the Pennsylvanian being the more important. Kansas has 30 sands which yield oil or gas locally while Oklahoma has 36.

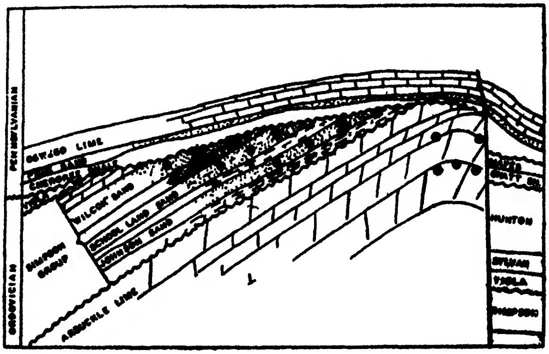

FIG. 31.—Section across Oklahoma City, Oklahoma field. (*After Levorsen, in Problems of Petroleum Geology.*)

Structurally the field is underlain by Paleozoic sediments which have a regional dip westward (Fig. 30), but under these are buried hills of pre-Cambrian rocks of which the Nemaha ridge is prominent.

East of this there are a number of shoestring sands which run northeast-southwest, with some at right angles to this direction. These sands are regarded as shore-line deposits, such as bars and spits.

In northern Oklahoma the oil is in sand lenses and anticlines. The Oklahoma City field is rather typical of many (Fig. 31). In western Kansas there are 14 producing gas fields, as well as some in the southwestern part of the state. The gas has a stratigraphic distribution similar to that of the oil. The shoestring sands of eastern Kansas also yield gas.

In eastern Oklahoma gas is yielded by the Pennsylvanian sands.

Ouachita-Amarillo Province (18, 23).—This includes a group of oil fields in southern Oklahoma, north central Texas, and the Texas Panhandle. The field lies between the Ouachita mountains in the east and the buried Amarillo mountains in the west.

Production is associated with structural features, and occurs either over buried hills or where the older rocks have been greatly disturbed resulting in the formation of anticlines. The rock formations are quite lenticular, but there is a close relation of production to structure, and the structural elements which are long and narrow trend northwest-southeast.

There are a number of sands, but the production comes from the Ordovician, Pennsylvanian, and Permian, with the second the most important, the Big Lime division yielding much oil and gas in the Panhandle area.

This province is important as an oil producer, and many of the oil pools also yield gas. There are enormous gas reserves in the Amarillo district, which ranks first in the United States in the production of natural gas and carbon black.

Pipe lines have been constructed from this field to Denver, Fort Worth, Indianapolis, and Chicago.

Bend Arch Province (18, 23).—This includes the fields of central Texas which are separated from the preceding one by a deep syncline. The occurrence of oil is associated with the Bend Arch which has no surface expression, and the oil comes from a cavitous limestone of the Bend series (Pennsylvanian). The anticlinal structures are, in some cases, the result of deformation, and in others due to a difference in the thickness of the sand. Wells range from 1800 to 4200 feet in depth, and many of them show a rapid decline.

Gas was also produced for some years, but until the construction of pipe lines much of it was allowed to go to waste. It is obtained

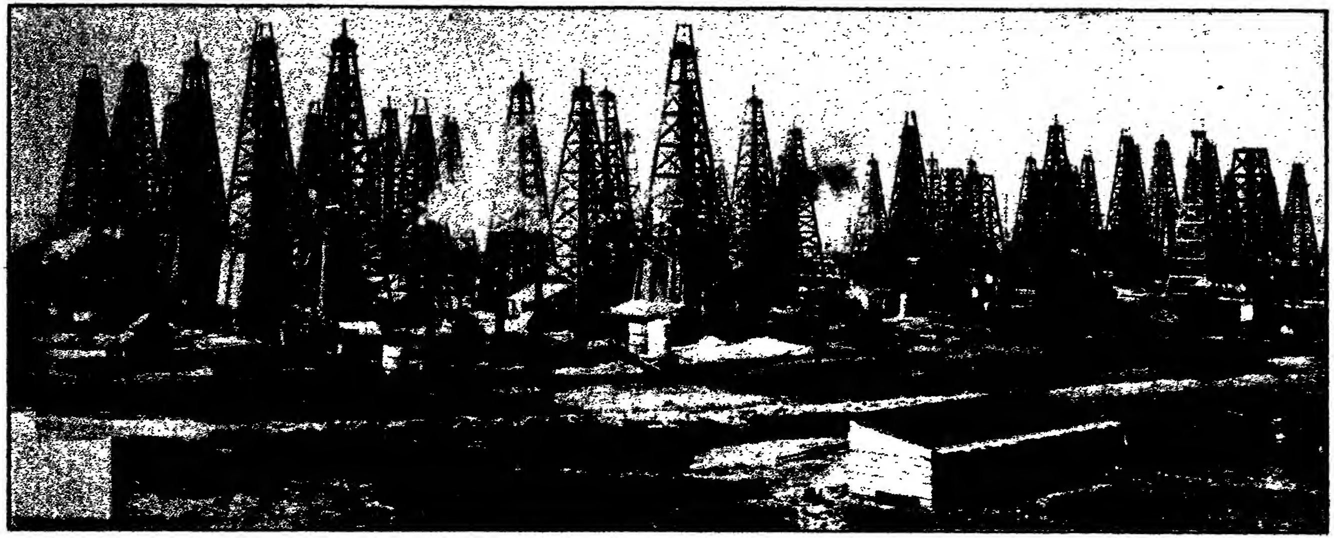

Plate XII.—General view of Spindle Top oil field, Beaumont, Texas. (*Photo. by Troost.*)

chiefly from the upper and lower Pennsylvanian, and the wells are from 1600 to 4500 feet deep.

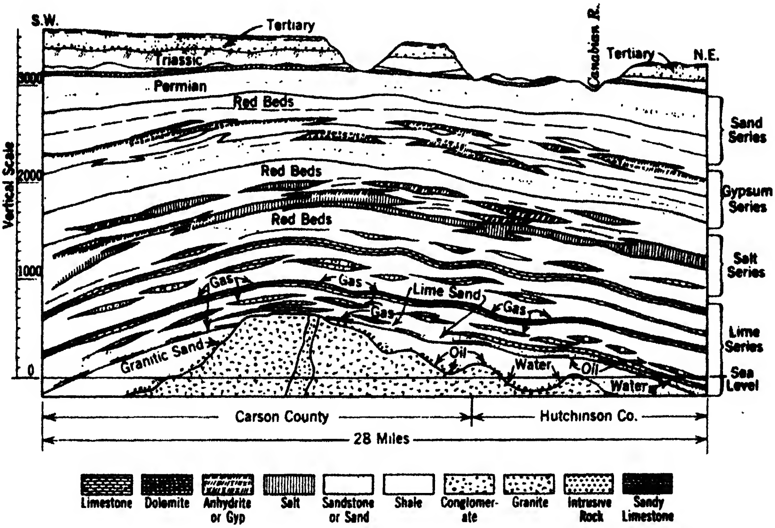

FIG. 32.—Cross section in Texas Panhandle anticline showing buried hill, sand lenses, and oil-bearing granite wash, over granite. (*After Bauer, A. A. P. G. Bul'. X*: 733.)

West Texas Province (18, 23).—In this province which includes part of west Texas and southeastern New Mexico there is a large north-south Permian syncline, on which there are minor anticlines. Surface structures are of no value in locating oil pools because the Permian is unconformably overlain by the Comanchean. The chief production is obtained from the Big Lime. The field also has large gas reserves.

Gulf Embayment Region.—According to Ver Wiebe (18) this has four subdivisions, viz.: (1) Balcones fault zone of east central Texas; (2) Reynosa escarpment of southern Texas; (3) Sabine and Ouachita uplifts of northeastern Texas, northwestern Louisiana, and southwestern Arkansas; and (4) Salt Dome province. They are all regarded as being related tectonically, and the area as a whole is traversed by some prominent lines of faulting, as well as in some cases folding which has influenced oil and gas accumulation.

Balcones Fault Zone.—This area which includes the Powell and Mexia pools obtains its oil supply chiefly from the Woodbine (Cretaceous) sandstone and Edwards (Comanchean) limestone, adjoining the Balcones and Mexia faults. In the Thrall and Lytton Springs pools the oil occurs in volcanic rock.

Reynosa Escarpment District (18).—Here the oil is found in Eocene formations in stratigraphic traps along ancient shore lines wedging out to the northwest. In a few pools faulting has occurred and may have aided in trapping the oil.

Sabine and Ouachita Uplifts (18).—This area contains a number of scattered pools, the most important being the famous East Texas pool, the largest in the world. Engineers and geologists estimate that its total ultimate production will exceed two billion barrels, or the equivalent of two years' needs of the United States. Both oil and gas accumulation are related to structure, having been trapped by faults or folds. The production comes from the Comanchean, Cretaceous, and Tertiary. Some of the wells are 6000 feet deep.

This field also includes the Monroe gas field of Louisiana which ranks third in area and initial reserves of the fields known in the United States. The gas comes from the Upper Cretaceous.

Salt Dome District (18, 23).—Here we have a number of oil and gas pools which individually cover a small area, but whose yield has been very large.

The production has in all cases come from the vicinity of salt domes, mostly from the upturned beds surrounding them, but in some cases from the caprock overlying the salt.

These domes consist of three groups. The first parallels the Texas-Louisiana Gulf coast and is within 150 miles of it. A second is in northwestern Louisiana, and a third in northeastern Texas. Most of the oil and gas have come from the first.

The first of these occurrences was discovered at Spindletop south of Beaumont, Texas, where oil under tremendous pressure was encountered at a depth of 1134 feet. This threw a 6-inch stream 200 feet high and was uncontrolled for some days.

Since then a number of wells have been located in the salt dome belt. The oil in most cases comes from Miocene beds at various depths. A relatively small amount of gas is yielded in proportion to the oil, in fact only 3 of the 68 producing salt dome pools yield gas in sufficient quantities for commercial use.

The salt may be encountered at as shallow a depth as 50 feet, but in the Goose Creek field it had not been reached at 5000 feet, the deepest oil sand which supposedly overlies a dome being about 4200 ft.

ROCKY MOUNTAIN REGION

The Rocky Mountain geosyncline (18, 23) represents the largest petroliferous province on the North American continent, and includes oil and gas pools in New Mexico, Colorado, Utah, Wyoming, and Montana, all of which are controlled by structural conditions. The production is obtained chiefly from the Cretaceous, except at the north end where the Mississippian limestone is productive.

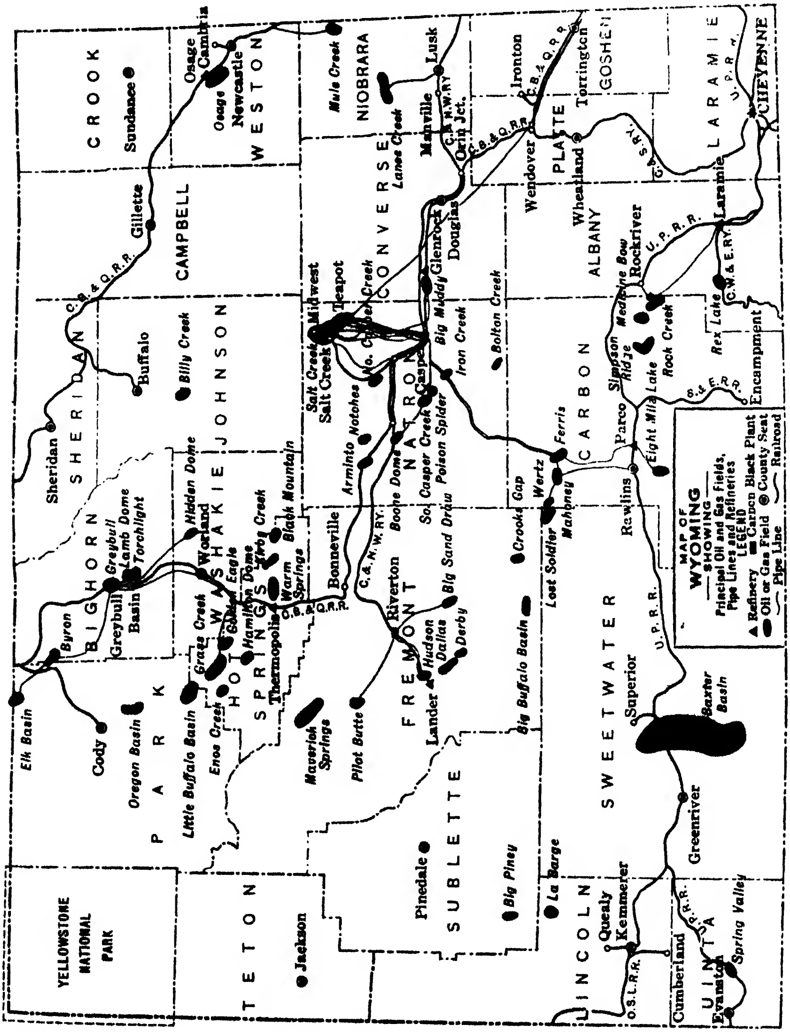

FIG. 33.—Map of Wyoming, showing approximately the areas underlain by oil and gas. (*Rocky Mountain Oil Producers Assn.*)

While both oil and gas occur, the production of the latter comes chiefly from western Colorado and eastern Utah. Wyoming (Fig. 33) has been the most important oil-producer, with Montana next. In the former state the Salt Creek, Grass Creek, and Big Muddy have led in yield, while the famous Teapot Dome has also been important.

The Cedar Creek field of Montana is the most important gas-producer.

The gas wells at several localities yield carbon dioxide chiefly.

CALIFORNIA REGION

This includes the Pacific Geosyncline province (18, 23, 28-35), which has been noted for a number of important fields, some of them with a large production. Certain general features are noteworthy. The oil sands are mostly poorly cemented, and often of great thickness, and while 10 feet would be the average some are as much as 1500 feet.

There has been strong deformation of the beds, and many of the earlier pools were located by seepages, of which the La Brea with its asphalt pools and entombed vertebrate remains is particularly interesting.

The oil is all obtained from Tertiary strata, mostly Pliocene, the Miocene and Oligocene yielding a small but increasing percentage of the total. Little has been found in the Eocene or Cretaceous.

The oil fields of California (Fig. 34) are divisible into three areas, viz.: San Joaquin Valley, Los Angeles basins, and Coastal belt.

San Joaquin Valley.—These are located at the southern end of the valley on the west and east sides respectively. Those on the west side include the Coalinga field on an anticline and an adjoining syncline, with mostly shallow wells. The Kettleman Hills field is located on 3 domes, the oil coming mostly from the northern one (Fig. 35). One drilled on the middle dome encountered oil in Eocene at 10,000 feet. A third is the McKittrick, and a fourth the Sunset-Midway which represents the largest field in California. On the east side of the valley the oil is located in a monocline overlying granite, but whether the oil is trapped by faults or sand lenses is open to dispute.

Los Angeles Basin.—The fields lie in a lowland in the southern Coast Ranges. This lowland is underlain by a trough formed in Miocene times, and filled with a great thickness of Pliocene and Pleistocene sediments. Although the bulk of the oil comes from the Pliocene some is also found in the Miocene.

Along the northern edge of the basin the fields are associated with faults or sharp folds along faults, and are mostly small producers.

A second group of fields lying along the Coyote Hills and Newport-Inglewood uplifts is associated with anticlines. This zone also includes the Long Beach (Fig. 36) (Signal Hill) and Santa Fé fields, which supply oil chiefly from the Pliocene with some from the Miocene. In some of these areas oil has been obtained from successively deeper zones. The Huntington Beach field is a good example of close drilling.

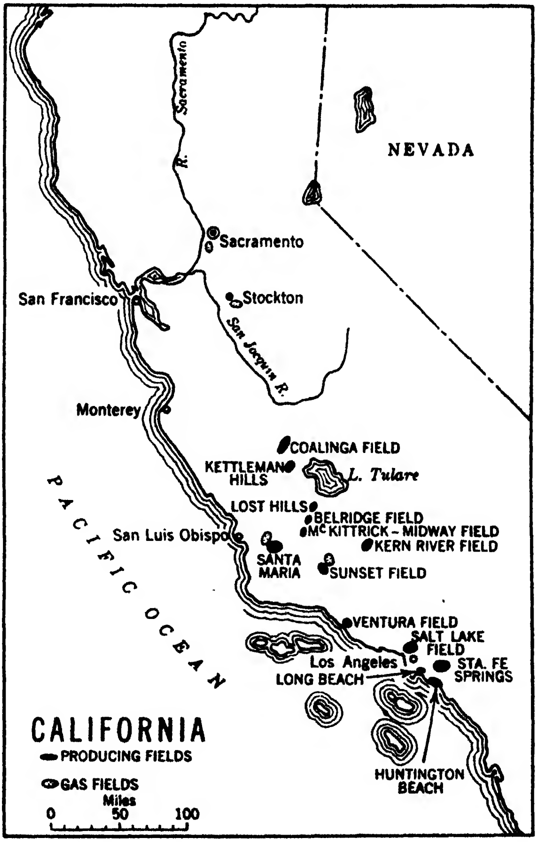

FIG. 34.—Map of California showing location of oil fields. (*Modified from Garfias.*)

Coastal Fields.—These lie at the southern end of the southern coast ranges. This area includes the well-known Santa Barbara, Ventura, and Santa Maria fields, in which the oil is associated with anticlines, and obtained from Pliocene beds. The Ventura field has obtained oil from a depth of more than 10,500 feet, and also contains much gas.

While the California fields yield a large amount of gas, more than

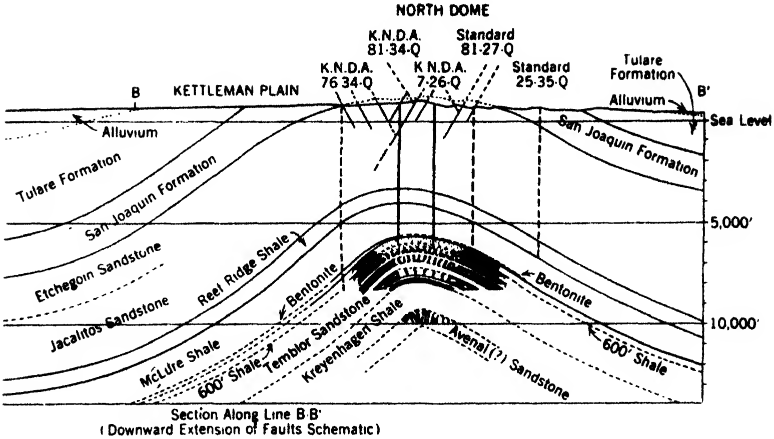

Fig. 35.—Cross section of North Dome, Kettleman Hills, Calif. (*After Woodring, Petrol. Invest. Hear., H. R.* 441, 1934.)

95 per cent of it is said to be wet gas associated with the oil. Kettleman Hills has the largest estimated oil reserves, but others are Dominguez, Santa Fé Springs, Elk Hills, Elwood, and Ventura.

Alaska (25).—Oil has been found in Alaska in promising amounts at four localities. Wells have been driven at three, and disclosed the

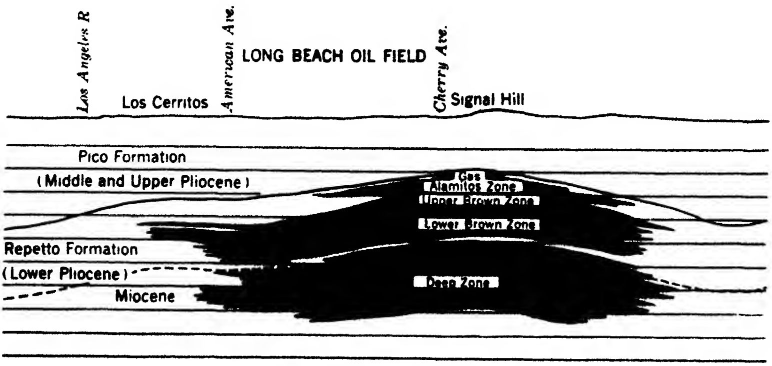

Fig. 36.—Section across Long Beach, Calif., Long Beach oil field. (*Sixteenth Internat. Geol. Congr.*, 1933).

presence of oil similar to that of Pennsylvania. All the fields lie in the Pacific Coast region, but none have been extensively developed, as the low price of imported oil and high cost of drilling in Alaska have discouraged attempts towards development.

In the Katalla field, located near the mouth of the Copper River, the oil is found in complexly folded and faulted Tertiary shales and sandstones. At Cook Inlet, folded and faulted Jurassic shales and sandstones form the petroliferous horizon. At Cold Bay the structural conditions and age of the oil-bearing strata are similar to those at Cook Inlet. Seepages are found in Tertiary rocks near Cape Yakataga, but no wells have been drilled.

Canada (58–60).—Oil and gas are obtained in Ontario, New Brunswick, and Alberta.

In Ontario oil has been obtained in a number of small fields in the southwestern part of the province, Oil Springs and Petrolia being the largest producers. Most of the production has come from the Onondaga, but other subdivisions of the Silurian have also yielded some oil. The oil is associated with local folds. Gas is also obtained from the various members of the Silurian, and while in some cases it is obtained in the same areas as oil, the most extensive one is southeast of St. Catherines.

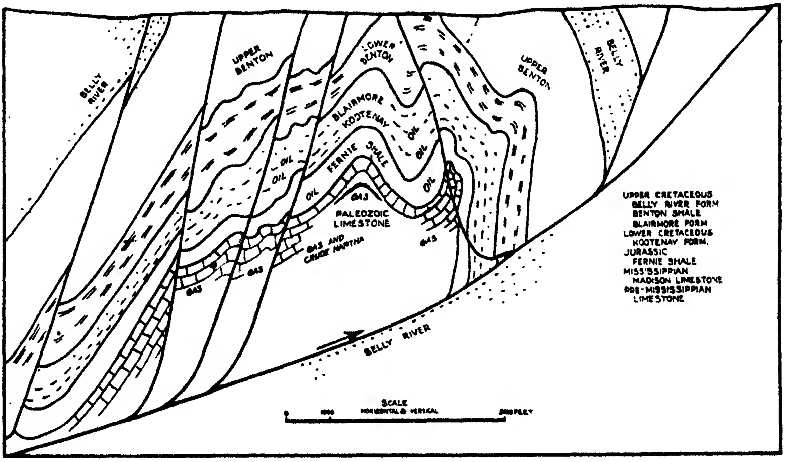

FIG. 37.—Section of Turner Valley, Alberta, oil field. (*From Powers, A. I. M. M. E., Tech. Pub.* 377, 1931.)

In New Brunswick the Stony Creek oil and gas field near Moncton is the only producer east of Ontario. Both the oil and gas come from sandstone members of the Albert formation which consists predominantly of shales.

Alberta is the most important oil and gas-producing province of Canada and has several oil and gas fields. The Turner Valley field

(Fig. 37) located along the eastern edge of the Rocky Mountains is of outstanding importance. The oil is obtained from a Paleozoic dolomite below its unconformity with the overlying Mesozoics.

The latter were the first source of oil and gas, but now the main production comes from the Mississippian. The product is crude naphtha, light oil, and gas (59).

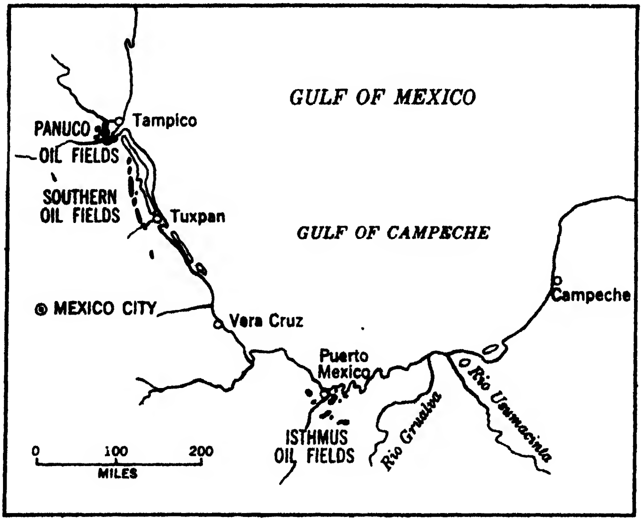

Fig. 38.—Map showing location of Mexican oil fields. (*After Powers, A. I. M. M. E. Tech. Pub.* 377, 1931.)

In the Sweet Grass Arch region the gas is found in sand lenses of the Cretaceous. The only structure is a low angle regional dip (59).

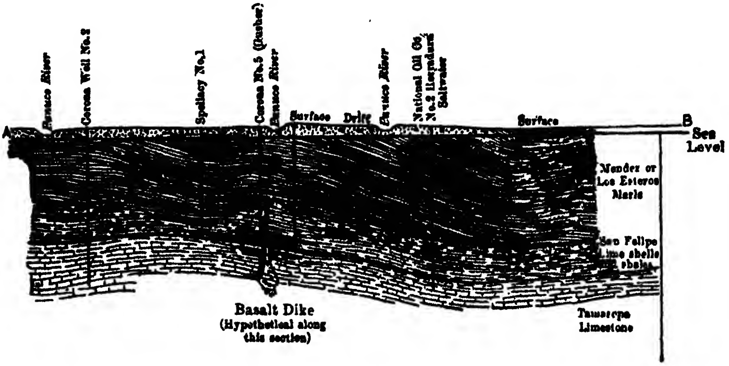

Fig. 39.—Hypothetical Section through the Panuco Field, Mexico, showing anticlinal terrace and fracture. (*After Huntley, Amer. Inst. Min. Engrs., Bull.* 105, 1915.)

Mexico.[1]—Mexico has three oil-producing areas. One is on the Isthmus of Tehuantepec where the oil is found associated with salt domes, and the production not large. A second, along the Gulf coast, extends for a distance of about 50 miles, from Dos Bocas on the north, southward past the Tuxpan River. The structure is that of a buried hill of Cretaceous limestone, which is oil bearing, and a covering of Tertiary sediments. This field which was brought in with a gusher in 1908 showed a steady increase in yield to 1919, when salt water appeared in many wells. The production peak was in 1923. The field is interesting because it yielded two of the largest wells in the world. One of these, Potrero No. 4, yielded 100 million barrels in 9 years. The third area known as the Panuco is located on the plunging prolongation of a geanticline. The production comes from the faulted and fractured flanks of subsidiary folds in Lower Cretaceous.

Other Important Foreign Fields.—Among the world's producers, Russia ranks second at present. The Baku [2] region of the eastern Caucasus yields most of the country's output. The rocks involved are Pliocene, Miocene, and Oligocene sediments, with some volcanic ash, and the whole series has been strongly folded and faulted, mud volcanoes and seepages being distributed along the main line of uplift.

The oils are all of high grade, mostly light in color and density, rich in distillates, and very free from sulphur.

Iran, which ranked fourth among the world's producers in 1940, may develop into one of the important oil-producing countries of the world. The oil occurs in porous Tertiary limestones. The Dutch East Indies ranking fifth, also yields Tertiary oil. In Rumania, which is sixth, and whose petroleum industry was set back by the destructive work of the Germans during the war, the oil occurs in Tertiary beds, the largest pools being near salt deposits, although according to some writers, neither originated in the rocks where found. In Venezuela, which ranked third in 1940, the bulk of the proven production comes from the Miocene and to a less extent from the Eocene. Active prospecting for new fields is going on in many parts of the world.[3]

Uses of Petroleum.—Three important uses of petroleum are for light, heat, and lubrication, although the first, for which the product kerosene is used, is not as important as formerly. Gasoline is a most important refinery product, with fuel oil another. Recent changes in refining methods as a result of the introduction of the "cracking" process, through which large molecules of fuel oils can be broken up into small molecules of gasoline, has permitted a larger production of the latter from a given oil than was possible by the old fractional distillation process. The paraffin residue is placed on the market

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[1] Powers, A. I. M. M. E., Tech. Pub. 377, 1931; Geology Tampico Region, Mexico, 1936, A. A. P. G.

[2] Adiassevich, A. I. M. E., XLVIII: 613, 1915; Dalton, Econ. Geol., IV: 89, 1909; Thompson, A. I. M. and M. E., special volume on oil papers, 1924.

[3] See *Ibid.*, volumes for 1923 and 1924, and later years.

under the name of vaseline, etc. Fuel oil has become an important competitor of coal.

Uses of Natural Gas.—Natural gas is widely employed as a fuel in factories, metallurgical establishments, glass works, cement plants, etc. For domestic purposes, such as heating, cooking, and lighting, it is also widely used. Its cheapness, cleanliness, and good calorific power, and the ease with which it can be used, have been important factors in insuring its widespread selection for the above purposes. Much is used in the manufacture of carbon black.

The trade term *carbon black* refers to lamp black made upon the surfaces of metal or stone, by direct impact of flame, while *lamp black* is a soot deposited by the smudge process and made from oil, resin, or some other solid or liquid raw material. Over 568 million pounds of carbon black were produced in the United States in 1940.

A profitable industry now is the separation of the more volatile grades of gasoline from natural gas issuing from oil wells.

Uses of Carbon Dioxide.[1]—Carbon dioxide is used for the manufacture of liquid carbon dioxide, refrigerants (dry ice), fire extinguishers, fumigating agents, and baking soda.

In the solid form it represents a refrigerant of minimum weight and volume per pound. The chief source at present is from coke ovens, limekilns, and fermentation plants.

Some manufacturers claim that the carbon dioxide obtained from wells has impurities which are difficult to remove, such as sulphur and the lighter hydrocarbons.

SOLID AND SEMI-SOLID BITUMENS

Under this heading are included (1) bitumens of a more or less solid character which are found filling fissures in the rocks, or sometimes occupying basin-shaped depressions on the surface, and (2) bitumens of viscous character, or *maltha*, which is found oozing from fissures or pores of the rocks and sometimes collecting in pools on the surface.

Both of these are usually of rather high purity, and those belonging to the first-named group may have a rather wide geologic and geographic (Fig. 40) range.

Those of the first group were termed *asphaltites* by Eldridge, but since they are not all true asphalts, it seems best perhaps to avoid

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[1] Miller, C. J., A.I.M.M.E., Tech. Pub. 736, 1936.

this term. They are most commonly found filling fissures, usually in sedimentary rocks,[1] and might perhaps be termed *vein bitumens.*

Vein Bitumens.—There are several varieties of these, all black or dark brown in color, commonly with a pitchy odor, burning readily with a smoky flame, and insoluble in water, but soluble to a varying degree in ether, oil of turpentine, and naphtha. Their specific gravity ranges from 1 to 1.1. They are closely related chemically and in their mode of occurrence, but differ somewhat in their behavior toward solvents, as well as in their fusibility, so that their identification is often somewhat uncertain. The most important varieties are described below.

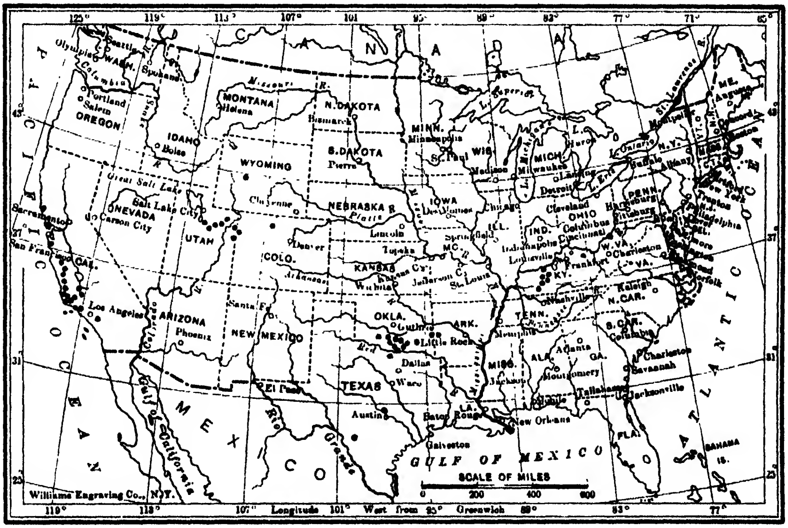

FIG. 40.—Map of asphalt and bituminous rock deposits of the United States. (*After Eldridge, U. S. Geol. Surv., 22d Ann. Rept., IX.*)

Albertite (76). A black bitumen with a brilliant luster and conchoidal fracture, a hardness of 1 to 2, and specific gravity 1.097. It is barely soluble in alcohol, and dissolves to the extent of 4 per cent in ether and 30 per cent in oil of turpentine.

Some American occurrences of vein bitumens are thought to belong here, but the most important occurrence is at Albert Mines, New Brunswick (76), where a vein of albertite is found in the Subcarboniferous shales. The vein had a length of about half a mile and was followed down its steep dip to a depth of 1500 feet. Its thickness varied from 15 feet to zero, and branch veinlets ran off into the wall rock. It was worked for 30 years and proved to be one of the most profitable mineral industries of New Brunswick.

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[1] The anthraxolite of Ontario occurs in slate, and an asphalt vein in quartz porphyry has been described from near Heidelberg, Germany. (Geol. Zentralbl. XIII: 547, 1909.)

Anthraxolite (87) is a coaly, lustrous, black mineral, with a hardness of 3 to 4, and a specific gravity of 1.965. It is found at Sudbury, Ontario, forming veins in a black fissile slate, but has also been described from other localities.

Ozokerite (92), also termed *mineral wax* or *native paraffin,* is a wax-like hydrocarbon, yellow brown to green, translucent when pure, and of greasy feel. Its specific gravity ranges from 0.845 to 0.97. It is easily soluble in petroleum, benzine, benzole, turpentine, and carbon disulphide, but more difficultly so in ether and ethyl alcohol.

It is known to occur in Utah (89), where the material is found filling fissures in zones of crushed Tertiary shales, sandstones, and limestones, near Midway, Soldiers Summit, and Coulters station on the Rio Grande and Western Railway. The conditions are not regarded as very favorable for working. The most important deposit of Ozokerite is in Galicia. There it is found forming veins from a few millimeters up to several feet in thickness, in much-disturbed Miocene shales and sandstones.

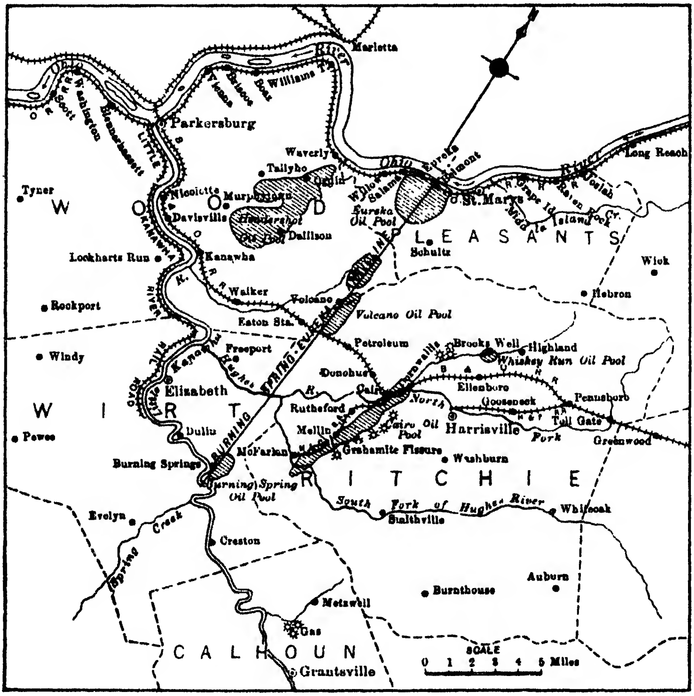

FIG. 41.—Map showing relation of grahamite fissure to anticlinal fold, in Ritchie County, W. Va. (*After White, Bull, Geol. Soc. Amer., X.*)

Grahamite (79, 91).—This has a hardness of 2, and a specific gravity of 1.145. It is pitch-black, slightly soluble in alcohol, partly so in ether, petroleum, and benzole, but almost completely in turpentine. Carbon disulphide and chloroform dissolve it completely.

PROXIMATE ANALYSES OF OKLAHOMA AND ARKANSAS BITUMENS

	I	II	III
Moisture	.25	.09	2.51
Volatile bitumen	43.33	23.06	17.78
Fixed carbon	55.97	75.90	79.15
Ash	1.45	.95	.56
Sulphur	1.47	1.69	1.38

I. Impson Valley grahamite. II. Black Fork Mountain vein bitumen. III. Fourche Mountain vein bitumen. Nos. II and III occur in the more highly folded rocks, and show effects of metamorphism.

Grahamite was originally found in the Carboniferous sandstones of Ritchie County, W. Va. There it occurred in a deep vertical fissure 1 to 5 feet wide at the surface, and nearly a mile in length, which was opened up at right angles to the direction of an anticlinal fold (Fig. 41). Through this the oil escaped upwards from an oil pool, known to occur below, and was oxidized to grahamite. The vein has long since been worked out

Deposits of grahamite are also known in southeastern Oklahoma, where the material occurs in steeply pitching veins, in sandstones, and shales. The wall rocks, which are of Ordovician to Carboniferous age, vary from flat to highly folded, and the grahamite shows corresponding fluctuations in composition which are due no doubt to differences in the degree of metamorphism which the rocks have undergone. The veins are uncertain in extent, and with two exceptions have not warranted extensive development.

Other deposits are located in western Arkansas and eastern Oklahoma, but the material is badly crushed and more highly metamorphosed (88).

Wurtzilite (79) is a bitumen related possibly to gilsonite, but distinguished from it by its behavior towards solvents and by its elastic and sectile properties. It has a hardness of 2–3, and specific gravity of 1.03; is black, with pitchy luster, and petroleum-like odor. *Tabbyite* is regarded by some as similar. Wurtzilite is found filling fissures in Tertiary calcareous shales and limestones in the western part of the Uinta Basin, Utah. It has been but little mined.

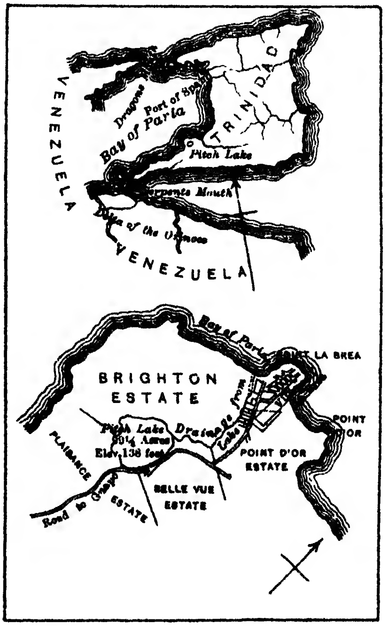

FIG. 42.—Plan of Trinidad pitch lake. (*After Peckham.*)

Lake Asphalt (13) is not found in the United States, but occurs in the famous pitch lake on the island of Trinidad, off the coast of Venezuela.

The deposit, Pl. XIII, Fig. 1, appears to occupy a basin-shaped depression of about 100 acres and nearly circular outline (Fig. 42) lying 138 feet above the sea level. The material evidently has arisen from some oil pool below. Two forms of the asphalt are recognized, viz., the lake pitch and the land pitch, the latter being asphalt which has overflowed from the lake at a low point on its rim, and run down to the sea. Up to the present time over 3 million short tons of asphalt have been exported from the island.

Manjak (83) is the name applied to a bitumen resembling Uintaite, found on the island of Barbados. It is a hydrocarbon of high purity, black color, brilliant luster, and conchoidal fracture.

The Manjak is found in veins cutting obliquely across the upper strata of the oil series (Oligocene) and disseminated through the clays. The largest vein is over 27 feet thick and often shows unusually rich pockets. More recently manjak has been found on the island of Trinidad and the deposits are said to be larger than those in Barbados.

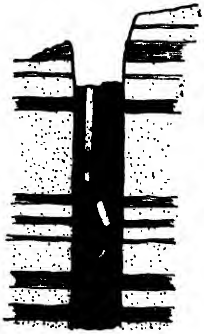

FIG. 43.—Section of Gilsonite vein, Utah. (*After Eldridge, U. S. Geol. Surv., 17th Ann. Rept., I*).

Uintaite, or *Gilsonite* (79), is a black, brilliant bitumen, with conchoidal fracture, hardness 2 to 2.5, and specific gravity of 1.065 to 1.07. It is partly soluble in alcohol (45.4 per cent), more so in ether, and completely in chloroform and warm oil of turpentine. It is found filling a series of fissures (Figs. 43 and 44), termed veins, in the Bridger beds of the Tertiary of Uintah and Wasatch counties, northeastern Utah, and, to a less extent, in western Colorado. The veins strike usually northeast-southwest, and vary greatly in width, extremes of 18 feet being reported. They are traceable for long distances, but their vertical depth appears to be unknown.

Maltha.—This is usually found issuing from crevices or pores of the rocks. It can also be extracted from bituminous rock and asphaltic oils.

Maltha is not known to occur in large deposits in the United States, although it is somewhat widely distributed in some of the California oil fields, where the petroleum exudes from the rocks, and on exposure to the air becomes converted into maltha by the loss of its more volatile constituents. In the Santa Barbara (13) and Kern County oil fields it is found in fissures of limited extent. Its occurrence has also been noted in Oklahoma.

FIG. 44.—Gilsonite mine at Dragon, Utah. The cut represents position of vein. (*Rept. of Coal Mine Inspector, Utah,* 1905-1906.)

FIG. 1.—View of portion of Trinidad asphalt lake, showing digging operations. (*Photo loaned by Barber Asphalt Company.*)

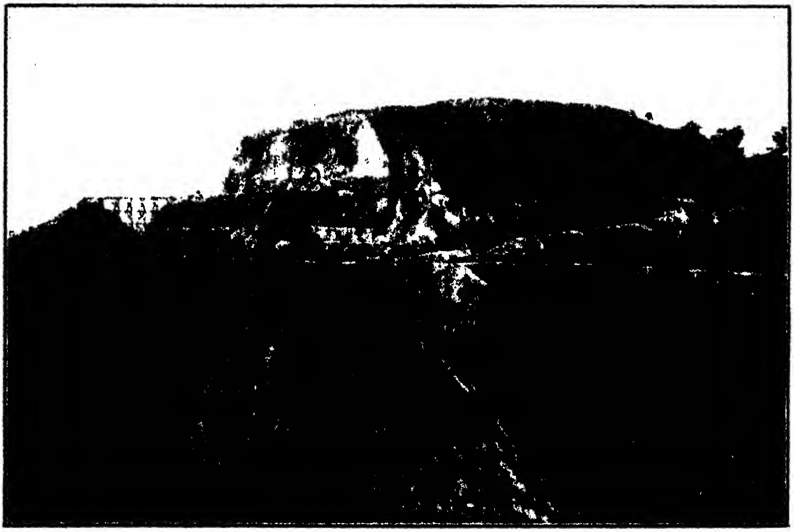

FIG. 2.—Quarry of bituminous sandstone, Santa Cruz, Cal. (*After Eldridge, U. S. Geol. Surv., 22d Ann. Rept., I.*).

Elementary Analyses of Bitumens and Maltha

	1	2	3	4	5	6	7	8	9	10	11
	Ozokerite, Utah	Maltha, Carpinteria, Cal.	Impsonite, Okla.	Grahamite, W. Va.	Grahamite, W. Va	Albertite, Nova Scotia	Albertite, Nova Scotia	Gilsonite, Utah	Gilsonite, Utah	Wurtzilite, Utah	Lake Pitch, Trinidad
C	85.25	85.72	86.57	76.45	59.20	86.04	85.53	88.30	89.28	80.00	83.68
H	15.09	11.83	7.26	7.83	5.77	8.96	13.20	9.96	8.66	12.23	10.84
N	—	1.21	1.48	tr.	1.01	2.93	.42	.32	.79	1.78	.45
O	—	—	2.00	13.46	14.68	1.97	—				
S	—	1.32	1.38	tr.	—	tr.	1.20	1.32	1.79	5.83	5.10
Ash	—	—	1.31	.10	19.34	.10	—	.10	—	—	—
Moisture . . .	—	—	—	—	—	—	—	—	—	—	—

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BITUMINOUS ROCKS

Under this heading are included consolidated and unconsolidated rocks, whose pores are more or less completely filled with bituminous matter, often of asphaltic character (79).

They are commonly classified according to the character of the containing rock as bituminous sands or sandstones, bituminous limestones, shales, or schists.

Bituminous rocks vary not only in their richness, but also in their value for paving purposes, for while in some the bituminous matter is purely asphalt proper, in others it may consist wholly or in part of maltha or some liquid bitumen, which may interfere with its use for paving purposes.

Deposits of bituminous rock are more widely distributed than the

Analyses of Bituminous Rocks

Locality	Moisture	Soluble in CS_2	$CaCO_3$	$MgCO_3$	Sand or Clay
California	2.50	20.20	3.00	—	74.00
Kentucky	—	5.76	—	—	94.22
Seyssel, France	—	8.15	91.70	—	—
Limmer, Germany	—	18.26	56.50	27.01	4.98

vein bitumens, being found in several geological horizons, and have been worked in Kentucky (85), Oklahoma (86), California (78), and Texas.

In California deposits of asphaltic shale and sandstone are not of rare occurrence in the oil regions from Santa Cruz southward.

The Kentucky rock asphalt is found principally along the southern and eastern outcrop of the western Kentucky coalfield, where it occurs in the Chester sandstone, and the lower sandstones of the Coal Measures. The deposits are lenticular, 3 to 30 feet thick, with a bituminous content ranging from 5 to 21 per cent, but 7 per cent is claimed to be sufficient for commercial purposes.

In Oklahoma deposits have been found in a belt extending from the Arkansas boundary westward to the Wichita Mountains. The material includes bituminous sandstone of Permian and also Pennsylvanian age, and Ordovician limestones (80). Bituminous limestones have been worked in Texas.

Alberta has a remarkable deposit of bituminous sands, which are located 300 miles north of Edmonton, and underlie about 750 square miles. These belong to the upper Cretaceous, and carry from 1 to 20 per cent of bituminous matter. Their chief use is for road construction (77).

Bituminous limestones have been worked in the Jurassic of France, the Tertiary of Italy, and other European localities.[1]

OIL SHALES

Oil shales are those containing so-called "kerogen" or bituminous matter, which on destructive distillation yields oil and tarry matters. They may also yield ammonia.

They are found in the Carboniferous of New South Wales, Australia, New Zealand, and Scotland, and in the Cretaceous of Brazil. Those in New South Wales have been worked, and in Scotland the industry has thrived under careful management for a number of years (70). Esthonia is also a producer.

In Scotland the crude oil extracted by distillation from a ton of shale varies from 16 to 35 gallons, while the ammonium sulphate ranges from 30 to 75 pounds.

In the United States thick deposits of oil shale have been found in the Eocene of Colorado (62), Utah, Wyoming, and Nevada. They seem to represent a great fresh-water deposit and contain many

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[1] Dammer and Tietze, Die Nutzbaren Mineralien, 2*d* ed., II; 1917.

microscopic plant remains. Different lots tested have yielded from 11 to 65 gallons of oil per ton, the oil having a gravity ranging from 17 to 33° B. Fresh shale is richer in oil than the weathered rock. The deposits may be regarded as a large reserve source of supply.

In addition to the region noted above, oil shales have been found in different parts of the United States, although they are not all to be regarded as promising commercially (61, 74).

Many are optimistic over the future development of an oil shale industry in the United States, but there are various commercial considerations and technologic details to be considered before the production of oil from shale becomes a permanent industry.

In Albert and Westmoreland counties of New Brunswick, Canada, there is a considerable area underlain by black, brown, and gray shales of Subcarboniferous age, which contain a number of bands of oil shale. Tests of some of these have yielded 63 gallons of crude oil per ton, but they have not been developed (65).

The oil can be obtained by distillation in retorts; but in view of the large available supplies of petroleum, obtainable in many parts of the world, the material at present has but little commercial value.

Origin of Solid Bitumens and Bituminous Rocks.—A study of the deposits leads to the conclusion that these solid bituminous compounds have been derived from petroleum (79, 82), for the following reasons: In the vein deposits the solid bitumens are often associated with petroleum springs, or with fissures leading down to or toward petroleum-bearing strata. In some cases the material not only fills such a fissure, but impregnates the wall rock to a distance of a foot or more on either side of the vein, indicating that the material came up through the fissure in a liquid condition, filling it, and even penetrating the wall rock.

The bitumen in bituminous rocks may either have originated from organic remains within the rock itself or have seeped into it from some neighboring pool. In either case the material seems originally to have been liquid petroleum, some of which later solidified.

Uses of Asphalt.—Trinidad asphalt mixed with powdered rock and tar is much in use for pavements, and the bituminous rocks are employed for similar purposes. Ozokerite, known as Ceresin in its purified form, is used in the manufacture of candles, ointments, powders, as an adulterant of beeswax, and for bottles to hold hydrofluoric acid. Ichthyol is obtained from an Austrian bituminous rock filled with fossil fish.

Uintaite and Manjak are used for making low-grade and dipping varnishes, for iron work and baking Japans. Other uses of Uintaite are for preventing electrolytic action on iron plates on ship bottoms, coating masonry, acid-proof lining for chemical tanks, roofing pitch, insulating electric wires, as a substitute for rubber in common garden hose, and as a binder pitch in making coal briquettes.

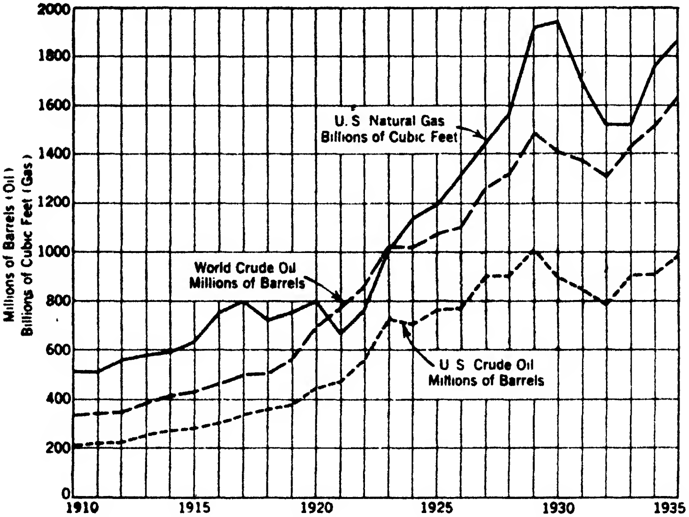

FIG. 45.—Production of oil and natural gas from 1910-1935.

Production of Petroleum and Natural Gas.—Petroleum has long been known in many parts of the world because of its presence in bituminous springs or as a floating scum on the surface of pools. It was used at an early date on the walls of Babylon and Nineveh, and was obtained by the Romans from Sicily for use in their lamps.

In the United States petroleum was mentioned by French missionaries even in 1635, and the early Pennsylvania settlers obtained small quantities by scooping out the oil from dug wells. Its discovery at a greater depth on the western slope of the Alleghanies was made during the drilling of brine wells; but its early use was chiefly a medicinal one until 1863, when attempts were made to purify it for use as a lubricant and illuminant. The beginning of the oil industry is usually considered to date from the sinking of a successful well by Colonel Drake on Oil Creek, Pennsylvania, in 1859. Oils fields have since been developed in many states, until now petroleum production and refining rank among the leading industries.

Natural gas was discovered and first employed for economic purposes at Fredonia, N. Y., in 1821. In 1841 it was used in the Great Kanawha Valley as a fuel in salt furnaces, but its first extensive use began in 1872 at Fairview, Pa. It was used in 1885 for iron smelting at Etna Borough near Pittsburgh, and in 1886 was piped 19 miles from Murraysville to Pittsburgh. Now natural gas is piped long distances to cities, being used as a fuel in many industries, as well as for domestic heating and lighting.

The production of petroleum in the United States has reached almost staggering figures, the amount in 1940 having amounted to 1,351,847,000 barrels valued at $1,352,000,000. The production for a period of years is shown in Fig. 45.

In 1940 the three leading states in order of rank were Texas (36.4 per cent), California (16.5 per cent), and Oklahoma (11.5 per cent).

The imports of crude petroleum in 1940 were 42.7 millions of barrels, and the exports 51.6 millions of barrels.

The average price per barrel dropped from $1.68 in 1925 to $1.00 in 1940.

The world's production in 1940 of the leading countries was:

	Barrels	Per Cent
United States	1,351,847,000	62.8
Russia	212,909,000	9.9
Venezuela	184,761,000	8.6
Iran	78,592,000	3.6
Netherlands Indies	60,830,000	2.7
Total world	2,149,378,000	

The production of natural gas in the United States in 1940 was 2,672,000 million cubic feet, valued at $28,256,000 at the wells. The five leading states with their percentage of total production were Texas (39.6 per cent), California (14.1 per cent), Oklahoma (10.1 per cent), Louisiana (11.9 per cent), and West Virginia (6.4 per cent).

The production of petroleum in Canada in 1940 amounted to 8,590,978 barrels, valued at $11,190,213. Of this quantity Alberta produced 97 per cent, and Ontario most of the balance.

The total value of petroleum crude and refined as well as some asphalt imported in 1939 was $56,875,714, while the exports of similar products were valued at $1,039,360.

The production of natural gas in Canada in 1939 amounted to 35,185,146 thousand cubic feet, valued at $12,507,307, of which Alberta supplied a little under two-thirds and Ontario about one-third, with small amounts from New Brunswick, Saskatchewan, and Manitoba in the order named.

The bituminous sands of Alberta produced some oil.

Production of Asphalt and Bituminous Rock.—The production of native asphalt and bitumens in the United States in 1940 amounted to 490,665 short tons, while the petroleum asphalt production in 1940 from domestic petroleum was 5,346,700 short tons, and from foreign petroleum, 126,281 short tons.

The sales of bituminous rock in 1940 were 458,665 short tons valued at $1,949,166, of gilsonite, 31,930 short tons, valued at $770,711; and of wurtzilite, 70 short tons, valued at $5,460.

The imports of 1940 included Trinidad asphalt, 7,959 short tons, value $81,428, and Cuban grahamite, 3,147 tons, value $55,732.

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CHAPTER III

BUILDING STONES

Under this term are included all stones for ordinary masonry construction, as well as for ornamentation, roofing, and flagging. The number of different kinds used is very great, and includes practically all varieties of igneous, sedimentary, and metamorphic rocks, but a few stand out prominently on account of their widespread occurrence and durability.

The cost of a building stone naturally exerts decided influence on its use. Since the ease of splitting and dressing a stone influences its cost, the texture is also of importance. Color is another factor in determining the value of a building stone, and this, together with other considerations, sometimes gets a fashion leading to the widespread use of certain stones. This has been well illustrated in the eastern cities of the United States, where, for many years, Connecticut brownstone was in such great demand for use in building private dwellings that much inferior stone was put on the market. More recently Indiana limestone and Ohio sandstone have met the popular fancy, and these two are now used in vast quantities.

Properties of Building Stones[1] (1–8).—The following properties have an important bearing on the value of a building stone:

Color.—The color of rocks varies greatly, and those shown by common building stones include white, black, brown, red, yellow, and buff, while some are green, blue, or mottled. The color may vary in the same quarry.

In igneous rocks the color may be that of the prevailing mineral, as in pink granite, where there is an excess of pink feldspar; or it may be a composite due to the blending of the colors of several minerals, as in the case of ordinary gray granite, where the color results from the mixture of black mica and whitish quartz and feldspar. Sedimentary rocks commonly owe their color to ferruginous cements, or to carbonaceous matter. The former give brown, yellow, red, or green colors depending on the condition of oxidation and form of combination of the iron, while the latter produces gray, black, and bluish tints depending on the amount present. Sandstone and limestone free from either of these coloring agents are nearly if not quite white.

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[1] Only the more important ones are here considered. Excellent detailed discussions will be found in Refs. 2, 51, 71, 75, 85.

Some stones change color on exposure to the air. For example, limestones or sandstones containing carbonaceous matter may bleach; some black marbles fade to a white or gray; and some red and green roofing slates, as well as a few red granites, change color. Oxidation of evenly distributed pyrite may change gray or bluish-gray sandstones to buff color. If the minerals responsible for such change in color are not uniformly distributed, the stone assumes a blotchy appearance, but such changes are not necessarily an indication of deterioration.

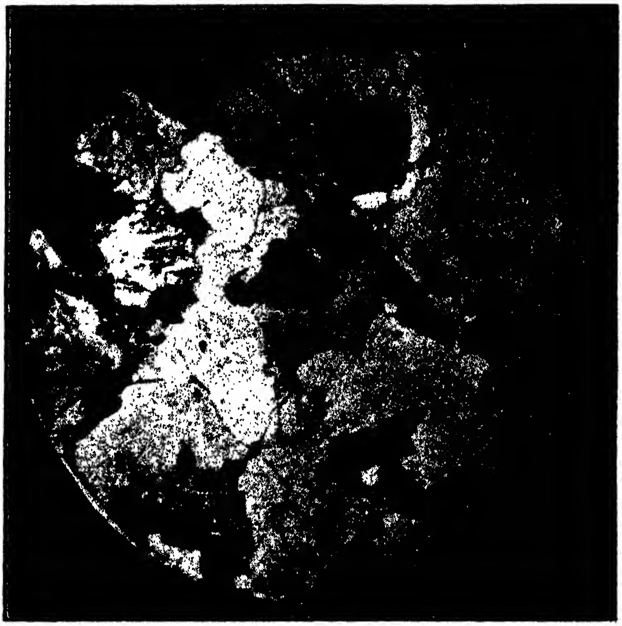

FIG. 46.—Photomicrograph of a section of Granite. (*Photo. loaned by A. B. Cushman.*)

Texture.—Building stones vary in their texture from coarse-grained granites and conglomerates to fine-grained sandstones, limestones, and porphyries.

Texture is an important property, for it influences both the durability and the cost of stone. Other things being equal, a fine-grained rock is not only more durable, but splits better and dresses more evenly, than a coarse-grained rock. Uneven texture, whether due to mineral grains or cement, is undesirable, since it often causes uneven weathering.

Density.—On the whole, dense stones resist weather better than porous ones, but there is great difference in the density of building stones.

In general, though with some exceptions, igneous and metamorphic rocks have high density because of the close interlocking of the crystalline grains.

Sedimentary rocks of clastic origin, on the other hand, have less closely fitting grains, and unless the latter are very small, or the pores well filled with cement, they are apt to be porous.

The specific gravity of a stone indicates its density; and from the specific gravity the weight per cubic foot may often be approximately estimated by muliplying it by 62.5, the weight of an equal volume of water. While sufficiently accurate for very dense stones, this method is liable to lead to incorrect results when applied to very porous rocks. Following are some average specific gravities of common building stones, as given by Hirschwald (1): granite, 2.65; syenite, 2.80; diabase, 2.80; gabbro, 2.95; serpentine, 2.60; gneiss, 2.65; limestone, 2.60; dolomite, 2.80; sandstone, 2.10; slate, 2.70.

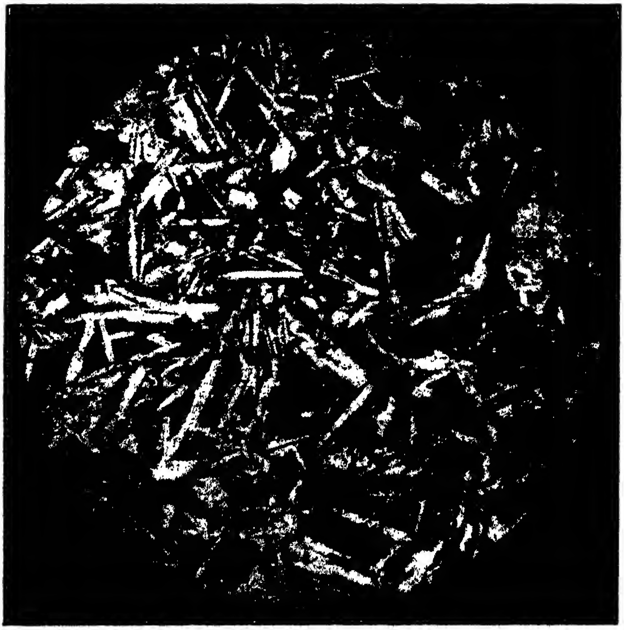

Fig. 47.—Photomicrograph of a section of Diabase. (*Photo. loaned by A. B. Cushman.*)

Hardness.—The hardness of a building stone is not necessarily dependent on the hardness of its component minerals, but is largely influenced by their state of aggregation, and to some extent their hardness.

For example, a sandstone composed of quartz grains, but with little cementing material, may be so soft as to crumble easily in the fingers while a limestone, whose grains of soft carbonate of lime fit closely and are firmly cemented, may be difficult to break with a hammer. The nature of the cement in sedimentary rocks, that is, whether it is lime, silica, or iron, will also affect the hardness of the stone. Crystalline rocks owe their great hardness to the firm interlocking of the mineral grains. The abrasive resistance (8) of a stone will depend in part on the state of aggregation of the mineral particles, and in part on the hardness of the grains themselves. Some stones wear very unevenly because of their irregularity of hardness, and such may be less desirable than one which is uniformly soft.

No standard form of abrasion test exists, and yet one should be applied to those stones which are used for paving, steps, or flooring, as well as to those placed in situations where they may be subjected to the attacks of wind-blown sand, or the rubbing action of running water.

Strength.—Two kinds of strength, compressive and transverse, are to be considered in building stones.

The compressive or crushing strength, which is expressed in pounds per square inch, is the resistance which the rock offers to a crushing force, and is dependent chiefly on the size of the grains, state of aggregation, and mineral composition. Because of the close interlocking of the grains of igneous rocks they are stronger than those of sedimentary origin, in which the strength is due chiefly to the cement which binds the grains together. Sedimentary rocks show greatest strength when dry, or when pressure is applied at right angles to the bedding.

Few building stones when in use are subjected to pressures even approximately equal to their crushing strength. No domestic building stone at present used in the eastern market has a crushing strength of less than 6000 pounds, yet the pressure even in the tallest buildings does not require a stone with a crushing strength exceeding 314.6 pounds, and this includes the factor of safety of twenty usually allowed by architects. Computations show that a stone at the base of the Washington monument sustains a maximum pressure of 6292 pounds per square inch, which includes the usual factor of safety of 20; the crushing strength of the stone used in the base of the monument is, however, not less than 10,000 to 12,000 pounds per square inch.

The crushing strength of some soft limestones or sandstones may be but little above 3000 pounds per square inch, while that of diabase often exceeds 30,000 pounds per square inch. The accompanying table gives the crushing strength of a number of stones. (Many others are given in the state reports.)

CRUSHING STRENGTH OF BUILDING STONES

Granite, Vinal Haven, Me.	13,381
Granite, East Saint Cloud, Minn.	28,000
Granite, Port Deposit, Md.	19,750
Dolomite marble, Tuckahoe, N. Y.	13,076
Limestone, Caen, France	3,550
Sandstone, Portland, Conn.	13,310
Sandstone, E. Longmeadow, Mass.	8,812

Transverse Strength.—The transverse strength is the load which a bar of stone, supported at both ends, is able to withstand without breaking. It is measured in terms of the *modulus of rupture,* which represents the force necessary to break a bar of one square inch cross section, resting on supports one inch apart, the load being applied in the middle. Although stones in buildings are rarely, if ever, crushed, they are frequently broken transversely, and therefore a knowledge of the transverse strength is of more importance than the crushing strength. A high crushing strength does not necessarily mean a high transverse strength. Unfortunately few stones have been tested in this manner.

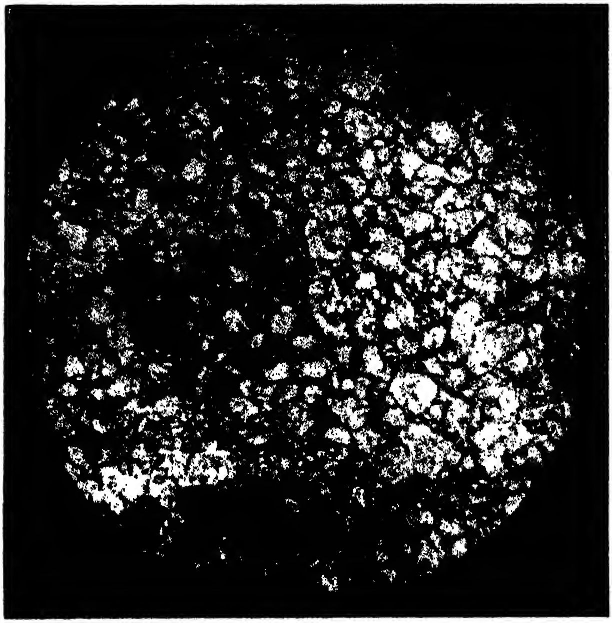

Fig. 48.—Photomicrograph of a section of quartzitic sandstone. (*Photo. loaned by A. B. Cushman.*)

Porosity and Permeability.—The porosity and permeability of building stones vary widely. Most igneous rocks have little pore space and hence absorb little water; but sedimentary rocks, especially sandstones, are often very porous and permeable.

Porosity and permeability are important properties, the latter particularly because it permits water to enter the stone and thus facilitates weathering processes. In marbles permeability also exerts an important influence in that it may permit discoloring solutions to enter the stone (15).

Many rocks, especially those of the sedimentary class, contain water in their pores when first quarried. This is known to quarrymen as *quarry water,* and it is present in some porous sandstones in sufficient quantities to interfere with quarrying during freezing weather. Mineral matter in solution in the quarry water is deposited between the grains when the water evaporates, often in sufficient quantities to perceptibly harden the stone.

Water is also present in the joint planes, and by its passage along these planes causes oxidation and rusting of the iron of the rock-forming minerals. This discolors the stone along and on either side of the joint planes, giving rise to a yellow color known as *sap*.

Resistance to Frost.—Building stones show a varying degree of resistance to frost.

Dense rocks, like granites, quartzites, and many limestones, and even some very porous rocks, are little affected; but many porous and laminated rocks, like open sandstones and schists, disintegrate under frost action. This is due to the fact that moisture absorbed in the warmer weather, on freezing in the pores, expands, and either forces off small pieces or disrupts the stones. Since clay readily absorbs water, clayey rocks are sometimes similarly affected.

Resistance to Heat.—All rocks expand when heated, and contract when cooled, but do not shrink down to their original dimensions. This permanent increase in size is termed *permanent swelling*, and though small when figured for one linear foot, is appreciable in long pieces.

The following figures give the average of a number of tests of permanent swelling in stone bars 20 inches long, heated from 32° F. to 212° F., and then cooled to the original temperature: granite, 0.009 inch; marble, 0.009 inch; limestone and dolomites, 0.007 inch; sandstone, 0.0047.

The most severe test of a stone's resistance to rapid changes of temperature is to heat it to about 800° C. and then immerse it in cold water. Quartzites and hard sandstones withstand such treatment best; some granites crack and crumble, and the carbonate rocks change to lime.

Chemical Composition.—Many chemical analyses of building stones have been made, but most of them are of little value, largely because they tell us nothing regarding the physical properties of the stone. They are perhaps of most value in the case of sedimentary rocks. The chemical analysis of a limestone will indicate whether it is dolomitic or not, also whether it is clayey in its character. So too the analysis of a sandstone will indicate whether it is siliceous or clayey.

Life of a Building Stone.—This may be considered as the period of time a stone will stand exposure to the weather without showing signs of decay. Even for the same stone, it may vary with location and climate. Julien makes the following deductions from observations made on stones in use:

Coarse brownstone	5–15 years
Fine-laminated brownstone	20–50 years
Coarse fossiliferous limestone	20–40 years
Coarse dolomite marble	40 years
Fine-grained marble	50–100 years
Granite	75–200 years
Quartzite	75–200 years

Structural Features affecting Quarrying.—All rocks are traversed by planes of separation of one sort or another. In sedimentary rocks these consist of bedding and joint planes; in igneous rocks, the latter alone are present; and in metamorphic rocks, joint planes, a banding of minerals and, very often, cleavage planes.

Bedding planes.—(Pl. XV, and Pl. XX, Fig. 1.) These may be either an advantage or a disadvantage to the quarryman. They are desirable because they facilitate the extraction of the stone; but if numerous and closely spaced, the layers may be too thin for any purpose except flagging. They often serve as a means of entrance for the agents of weathering, and the stone may be disintegrated along the bedding planes while elsewhere fresh.

Incipient planes of weakness, due either to the arrangement of minerals or to microscopic fractures in them, often give rise to planes of easy splitting which are of great value in quarrying, notably of granite. The most prominent plane is called *rift;* and a less prominent vertical plane, approximately at right angles to the rift, is called the *grain.* Granites often show a sheeted (Pl. XIV, Fig. 1) structure, due to the presence of horizontal joints. These are slightly curved, and hence tend to separate the granite mass into a series of lenses.

The position of the beds exerts an important influence on the cost of quarrying. When horizontal and of different quality, it may often be necessary to strip off worthless rock in order to reach the beds of good quality. In such cases, there is often less stripping to do in quarries opened on gently sloping ground. In regions of steep dip, it is sometimes possible to work the quarry as a cut, extracting the desired beds and leaving useless ones standing.

GRANITES

Characteristics of Granites (75) —As commonly used by quarrymen, the term *granite* includes all igneous rocks and gneiss; but in this book it is used in the geological sense, which is more restricted. From the geological standpoint a granite is a holocrystalline, plutonic igneous rock consisting of quartz, orthoclase feldspar, and either mica or hornblende, or both. There are also varying but usually small quantities of other feldspars, and there may be subordinate accessory minerals, such as pyrite, garnet, tourmaline, and epidote.

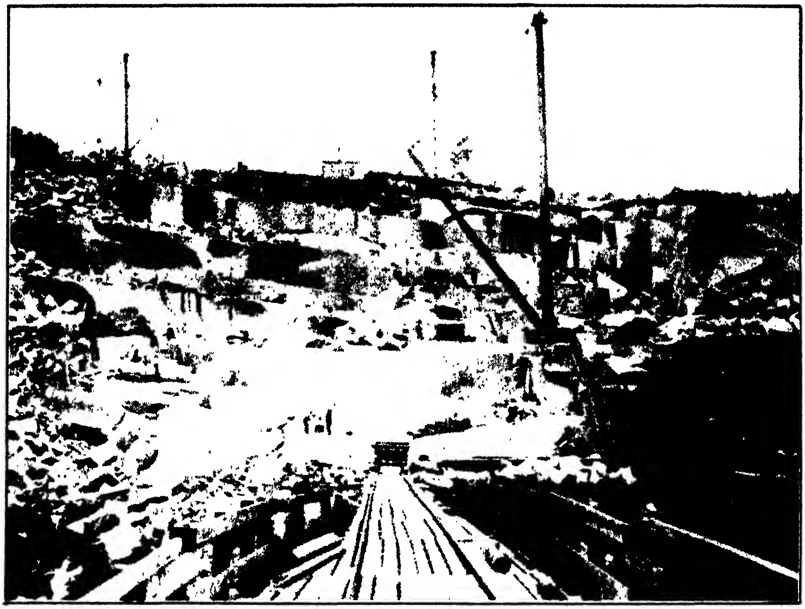

FIG. 1.—Granite quarry, Hardwick, Vt. (*Photo. by G. H. Perkins.*)

FIG. 2.—Quarry in volcanic tuff, north of Phoenix, Ariz.

Granites vary in texture from fine to coarse grained, and in some cases are porphyritic. They pass into gneisses by such insensible gradations that no sharp line can be drawn between the two. In color they vary, being, most commonly, gray, mottled gray, red, pink, white, or green, according to the color or abundance of the component minerals. Most granites are permanent in their color, but some of bright red color bleach on continuous exposure to sunlight.

The average specific gravity of granites is 2.65, which corresponds to a weight of 165.6 pounds per cubic foot. They commonly contain less than 1 per cent of water, and often absorb two or three tenths more. Their crushing strength varies, but is apt to lie between 15,000 and 30,000 pounds per square inch.

Granites are among the most durable of building stones, but there is some variation in the durability of the different kinds. Other things being equal, fine-grained granites are more durable than coarse-grained, being less easily affected by changes of temperature. One of the most beautiful granites known, the Rapikivi granite of Finland, lacks in durability on this account. Pyrite and marcasite are injurious minerals, since they rust rapidly and may discolor the stone in an unsightly manner. Very few granites now in use show signs of decay; but in those that do, the darker silicates are rusted, the luster of the feldspar is dulled, and, in some cases, the stone has begun to disintegrate.

Distribution of Granites in the United States (2).—Granite usually occurs in batholithic masses sometimes forming the cores of mountain chains. Removal of the overlying strata by denudation has revealed the granite, which, owing to its greater durability, is often left standing as peaks or domes by the farther removal of the surrounding, weaker strata. Granites show a wide geologic range, but most known occurrences are associated with the older formations.

Granite forms an important source of durable building stone widely distributed in the United States (Fig. 49); but nearly 70 per cent of that quarried comes from the Atlantic states. There are several areas which will be briefly considered.

Eastern Crystalline Belt (2, 22, 33, 44, 54, 76, 77).—From northeastern Maine southwestward to eastern Alabama there is an important belt of granites and gneisses, mostly of pre-Cambrian age. Those at the northeastern end of the belt, as far south as New York, are most extensively quarried, largely because of their peculiarly favorable location. In this belt those of Quincy, Mass. (46), Barre, Vt. (76), and Westerly, R. I. (71), are of value for monumental work. Many large quarries have also been opened up in Maine (43), but their output is employed mainly for structural work. A gneissic granite quarried at Port Deposit, Md. (44), a white granite from

Mt. Airy, N. C. (62), gray granite worked at Stone Mountain Ga. (34), and a dark blue monumental granite from Elberton, Ga., are also important. Much granite has been quarried near Richmond, Va. (81).

Minnesota-Wisconsin Area (85).—There are several detached areas in these two states, some of which supply granites of value for ornamental work. That from Montello, Wis., bears a high reputation, and those from Wausau, Wis., and Ortonville, Minn., are favorably known.

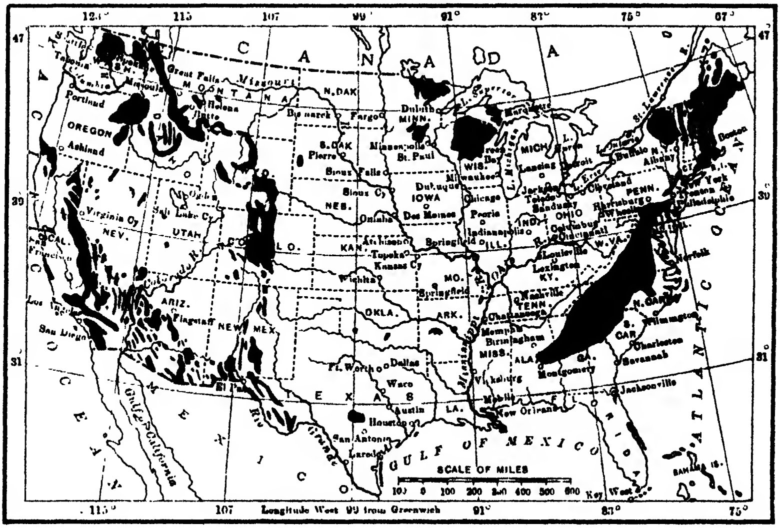

FIG. 49.—Map showing distribution of crystalline rocks (mainly granites) in United States. (*After Merrill, Stones for Building and Decoration.*)

Southwestern Area.—This includes portions of Missouri, Arkansas, Oklahoma, and Texas.

These four states contain small areas, worked mainly to supply a local demand. Those of southeastern Missouri vary from light gray to red in color and fine grained to porphyritic in texture. Some of the rock is rhyolite. The Graniteville red granite is important (51). Important granite deposits are known in the Arbuckle and Wichita Mountains of Oklahoma (65), but their development thus far has been slight. Arkansas contains quarries of syenite west of Little Rock (2), and for purposes of convenience it is mentioned under granite. In Texas quarries have been opened in Llano County, and yield both pink and gray granite (2, 75).

Western States.—There are many areas of true granite, and closely allied rocks such as grano-diorite and rhyolite, in the western states. The central portion of the Black Hills of South Dakota is a great granite mass, but little of it is quarried. Granites are known in Colorado (2), and quarried to some extent, and the rhyolites of Castle Rock are of considerable importance. In California the grano-diorite mass forming the central portion of the Sierra Nevada Mountains yields an inexhaustible supply, which is quarried at several points. Montana, Washington (82), and Oregon also contain granites which are quarried for local use. On the whole, however, the Cordilleran granite industry is somewhat restricted because of lack of demand.

Uses of Granite.—On account of its massive character and durability, granite is much employed for massive masonry construction, while some of the granites that take and preserve a high polish, and are susceptible of being carved, are in great demand for ornamental and monumental work. Because of its greater durability, granite has in recent years largely replaced marble for monumental purposes.

The refuse of the quarries is sometimes cut for paving blocks or crushed for roads and railroad ballast. The size of the blocks which can be extracted from a granite quarry depends in part on the spacing of the joint planes, in part on the perfection of development of the rift, some of the monoliths that have been quarried being of immense size: for example, one from Stony Creek, Conn., measured 41 ft. × 6 ft. × 6 ft.; one from Vinal Haven, Me., 60 ft. × 5½ ft.; one from Barre, Vt., 60 ft. × 7 ft. × 6 ft.

Miscellaneous Igneous Rocks.—But little space need be given to these, for they are of minor importance as compared with the granites. In the eastern states the diabase or trap rock is quarried at several points in Connecticut, New York, New Jersey, and Pennsylvania. Owing to its great hardness it is only occasionally used for dimension blocks, its chief value being for paving blocks and road metal. The basaltic rocks of the western states, especially those of Washington and California, are often employed for similar purposes. Anorthosites and gabbros, some of the former being of highly ornamental character when polished, occur in the Adirondack Mountains, New York; they are, however, but little utilized. Gabbros have been quarried for local use in Maryland and Minnesota, and diorites have been quarried to a small extent at scattered localities. Some of the porphyries and rhyolites of the Atlantic states possess considerable beauty when polished. A handsome porphyry is quarried in Wisconsin (85), and in the Cordilleran region both rhyolite and porphyry occur in numerous localities. Andesite tuffs are quarried in Colorado, and consolidated volcanic tuffs have also been used to some extent for building in Arizona.

LIMESTONES AND MARBLES

General Characteristics (1, 15).—A great series of sedimentary and metamorphic rocks, composed chiefly of carbonate of lime, or, in the case of dolomite, of carbonate of lime and magnesia, is included under the term *limestone and marble.* These rocks also contain varying, but usually small, amounts of iron oxide, iron carbonate, silica, clay, and carbonaceous matter. When of metamorphic character various silicates, such as mica, hornblende, and pyroxene, etc., may be present.

These calcareous rocks vary in texture from fine-grained, earthy, to coarse-textured, fossiliferous rocks, and from finely crystalline to coarsely crystalline varieties. There is, also, great range in color, the most common being blue, gray, white, and black, but beautiful shades of yellow, red, pink, and green, usually due to iron oxides, are also found. Their crushing strength commonly ranges from 10,000 to 15,000 pounds per square inch, while their absorption is generally low.

The mineral composition of limestone exerts a strong influence on its durability. Those limestones which are composed chiefly or wholly of carbonate of lime are liable to solution in waters containing carbon dioxide; but dolomite limestones, especially coarse-grained ones, disintegrate rather than decompose. Streaks of mineral impurities cause the stone to weather unevenly. Pyrite is an especially injurious constituent, not only on account of its rusting, but also because the sulphuric acid set free by its decomposition attacks the stone. Tremolite, which is found in some dolomitic marbles, is also liable to cause trouble by its decay. Black or gray limestones will sometimes bleach on exposure.

Varieties of Limestones.—In the geological sense limestones are of sedimentary origin, while marbles are of metamorphic character, but in the trade the term *marble* is applied to any calcareous rock capable of taking a polish. In addition to the different varieties of marble and the ordinary limestones, there are certain kinds of calcareous rock to which special names are given, as follows:

Chalk is a fine, white, earthy limestone, composed chiefly of foraminiferal remains.

Coquina is a loosely cemented shell aggregate, like that found near St. Augustine, Fla.

Dolomite, or *dolomitic limestone,* composed of carbonate of lime and magnesia, and to the eye alone often is indistinguishable from limestone.

Fossiliferous limestones is a general term applied to those limestones which contain many fossil remains. Under this heading are included crinoidal limestone and coral-shell marble.

Hydraulic limestone, an argillaceous limestone containing over 10 per cent of clayey impurities. Used mainly for cement manufacture (Chap. V).

Lithographic limestone is an exceedingly fine-grained, crystalline limestone, of gray or yellowish hue. It is used for lithographic and not structural work.

Oölitic limestone, composed of small, rounded grains of concretionary character.

Stalactitic and *stalagmitic deposits,* formed on the roofs and floors of caves, respectively, are often of crystalline texture and beautifully colored, and, when of sufficient solidity, are known as onyx marble.

Travertine, or *calcareous tufa,* a limestone deposited from springs. The Roman deposits supply much stone for flooring, stairtreads and decorative use, and some quarried in Montana has been used for similar purposes.

Distribution of Limestones in the United States.—Limestones are found in many states, and in all geological formations from Cambrian to Tertiary, but those of the Paleozoic, which are much used in the eastern and central states, are more extensive and more massive than those of later formations. Although many large quarries have been opened to supply a local demand, the product is shipped to a distance from only a few localities. At present the Subcarboniferous Bedford (37) oölitic limestone of Indiana (Pl. XV) is, perhaps, the most widely used limestone in the United States. It occurs in massive beds, and underlies a north south belt about 100 miles in length. Although soft and easily dressed, it has good strength, and has been used in many important cities of the United States. The same rock is quarried at Bowling Green, Ky. (41).

In the eastern and central states the Paleozoic limestones are worked at many points, mainly to supply a local demand (3).

Cretaceous limestones are worked in Kansas, Nebraska, and Iowa, although the most important sources are in the Paleozoic formations.

Distribution of Marbles in the United States (2).—While some variegated marbles are produced in the United States, still most of those quarried are white, the greater part of the variegated stones being imported. The main supply comes chiefly from regions of metamorphic rock, the eastern crystalline belt being the principal producer (Fig. 50). Vermont (76, 77) leads all the states in marble production, supplying a large percentage of all the marbles used for ornamental work in the country. The most important and largest quarries are those at Proctor and West Rutland (Pl. XVI). At the

Plate XV.—Quarry in limestone, Bedford, Ind. (*Photo, Bedford Quarries Co.*) A horizontally bedded limestone, showing some weathering along the vertical joint planes.

latter locality the marble bed has a thickness of 150 feet at the top of the quarry, narrowing to 75 feet at the bottom, and is divisible into a series of well-marked layers of varying thickness, quality, and color (77).

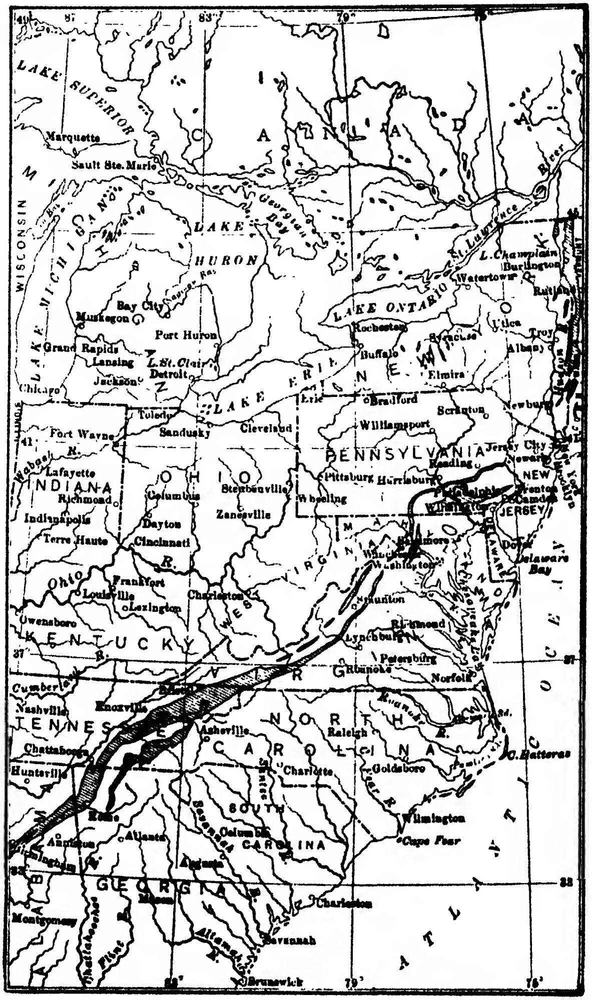

Fig. 50.—Map showing marble areas of eastern United States. (*After Merrill, Stones for Building and Decoration.*)

The Vermont marbles usually show a bluish-gray or whitish ground, the latter often showing a pinkish or creamy shade, and traversed by bands or markings of a green or brown color.

A beautifully colored series of variegated marbles[1] is quarried at Swanton, Vt. (77), and much used throughout the United States for flooring and wainscoting. Owing to their highly siliceous character they show excellent wearing qualities. White marbles for structural work have been quarried at Lee, Mass. (2), and at South Dover and Gouverneur, N. Y. (2), but gray ones are also obtained from the last-named locality. In Maryland quarries have been worked at Cockeysville (44), while white and also gray marble are quarried in Pickens and Tate Counties, Ga. (33) (Pl. XVII, Fig. 1).

The Trenton limestone in eastern Tennessee (15) supplies marble of gray and of pinkish chocolate color with white variegation. It is used chiefly for interior decoration. The Napoleon gray from Phenix, Mo., is very similar to the Knoxville, Tenn., gray.

White marble is said to occur at Marble, Colo., and that quarried in Inyo County, Calif., has attracted considerable attention (29). Wisconsin is also a producer. Marble has been obtained for some years from southeastern Alaska, and the product used in many Pacific Coast buildings (23).

Most of the variegated marble used for interior decoration in this country is imported, especially from Italy, Greece, France, and Belgium. Many of these imported stones are of rare beauty, but are usually unfitted for exterior use in severe climates, a fact often ignored by architects. Although ornamental stones of this class occur in the United States, up to the present time few attempts have been made to place them on the market. This may be due to the fact that most quarrymen do not care to assume the temporary expense which their introduction might involve.

Onyx Marbles.—Under this term are included two types of calcareous rock, one a hot-spring deposit, or travertine, formed at the surface, the other a cold-water deposit formed in limestone caves in the same manner as stalagmites and stalactites. Cave onyx is more coarsely crystalline and less translucent than travertine onyx. The beautiful banding of onyx is due to the deposition of successive layers of carbonate of lime, while the colored cloudings and veinings are caused by the presence of metallic oxides, especially iron.

Neither variety of onyx occurs in extensive beds, though both are widely distributed. Onyx is found in Arizona, California, Colorado, and Montana, but it has not been developed in any of these states except on a small scale. Most of the onyx used in the United States is obtained from Mexico, though small quantities are obtained from Egypt and north Algeria.

Uses of Limestones and Marbles.—The limestones are used mainly for ordinary dimension blocks, though some, as the Bedford stone, lend themselves well for carved work. Limestone has, however, a

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[1] These should perhaps be more properly classed as calcareous sandstones.

number of other uses, these in the order of their value as given in the 1935 statistics being crushed stone, fluxing stone, agricultural lime, rip rap, sugar manufacture, glass making, paper making, rubble, curbing, flagging, and paving. Impure limestones, with 20 to 30 per cent CO_2, are used for making rock wool for insulating purposes. The rock is fused, and the molten material shredded in a blast.[1]

In some cases quarry waste may be sold for the above purposes, in others the entire quarry output may be so consumed.

The use of limestone for lime or cement is discussed in Chapter V.

Marbles are used in increasing quantities for ordinary structural work, although many of the lighter-colored ones soon become soiled by dust and smoke. The output of many quarries, especially the Vermont ones, is well adapted to monumental purposes, and these, together with those from Georgia, Tennessee, and California, are much used for wainscoting and paneling. That from Swanton is also well adapted to flooring. Electrical switchboards are now frequently made of marble. The demand for marble tops for tables, washbasins, and similar uses is decreasing. The refuse from marble quarries is sometimes utilized for the same purposes as limestone. Special tests are applied to marbles (78).

SERPENTINE

Pure serpentine is a hydrous silicate of magnesium; but beds of serpentine are rarely pure, usually containing varying quantities of such impurities as iron oxides, pyrite, hornblende, and carbonates of lime and magnesia. The purer varieties are green or greenish yellow, while the impure types are various shades of black, red, or brown. Spotted green and white varieties are called ophiolite or ophicalcite.

Serpentine is sometimes found in sufficiently massive form for use in structural or decorative work; but, owing to the frequent and irregular joints found in nearly all serpentine quarries, it is difficult to obtain other than small-sized slabs. Its softness and beautiful color have led to its extensive use for interior decoration; but since it weathers irregularly and loses luster, it is not adopted to exterior work.

Though serpentine is found in a number of states, most of the numerous attempts to quarry it have been unsuccessful. Considerable serpentine for ordinary structural work has been quarried in Chester County, Pa., and a variety known as verdolite has been worked near Easton, Pa. (55). Quarrying operations have also been carried on in the state of Washington (82), Maryland, and Georgia.

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[1] Thoenen, U. S. Bur. Mines, Inf. Circ. 6142, 1929; Lamar, Ill. Geol. Surv. Bull. 61, 1934.

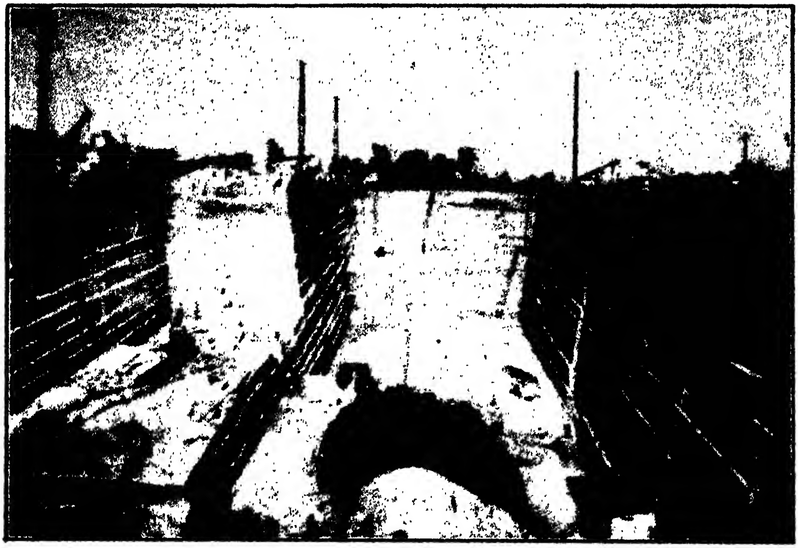

FIG. 1.—Sandstone quarry, S. Amherst, Ohio (*Cleveland Quarries Company.*)

FIG. 2.—Underground quarry, West Rutland, Vt. (*Vermont Marble Co.*)

SANDSTONES

General Properties (1, 12).—While most sandstones are composed chiefly of quartz grains, some varieties contain an abundance of other minerals, such as mica, or, more rarely, feldspar, which in rare cases may even form the predominating mineral. Pyrite is occasionally present, and varying amounts of clay frequently occur between the grains, at times in sufficient quantity to materially influence the hardness and dressing qualities of the stone. The hardness of sandstones, however, usually depends on the amount and character of the cement, varying from those having so small an amount of silica or iron oxide cement that the stone crumbles in the fingers to those quartzites whose grains are so firmly bound by silica that the rock resembles solid quartz. With these differences the chemical composition varies from nearly pure silica to sandstone with a large percentage of other compounds. (For analyses, see Kemp's "Handbook of Rocks.")

There are many colors among sandstones, but light gray, white, brown, buff, bluish gray, red, and yellow are most common. In density sandstones range from the nearly impervious quartzites to the porous sandrocks of recent geologic formations, and consequently they show a variable absorption. Most sandstones contain some quarry water, and those with appreciable amounts are softer and more easy to dress when first quarried; but they cannot be quarried in freezing weather. The average specific gravity of sandstone is 2.7, and accordingly a cubic foot weighs about 160 to 170 pounds.

On the whole, sandstones resist heat well and are usually of excellent durability, since they contain few minerals that decompose easily. When they disintegrate, it is commonly by frost action. The injurious minerals are pyrite, mica, and clay. Pyrite is likely to cause discoloration on weathering; the presence of much mica may cause the stone to scale off if set on edge; and clay may cause injury to the stone in freezing weather on account of its capacity for absorbing moisture. A slight quantity of clay, however, makes the stone easier to dress. The value of a sandstone is often lessened by careless quarrying, or by placing it on edge in the building, thus exposing the bedding planes to the entrance of water.

Varieties of Sandstone.—With an increase in the size of their grains, sandstones pass into conglomerates on the one hand and with an increase in clay into shales. By an increase in the percentage of carbonate of lime they may also grade into limestones.

FIG. 1.—Marble quarry, Pickens County, Ga. (*Photo. loaned by S. W. McCallie.*)

FIG. 2.—Slate quarry at Penrhyn, Pa. (*H. Ries, photo.*)

On account of these variations, as well as the difference in color and the character of the cement, a number of varieties of sandstone are recognized, of which the following are of economic value: *arkose*, a sandstone composed chiefly of feldspar grains; *bluestone*, a flagstone much quarried in New York; *brownstone*, a term formerly applied to sandstones of brown color, obtained from the eastern Triassic belt, and since stones of other colors are now found in the same formation, the term has come to have a geographic meaning and no longer refers to any specific physical character; *flagstone*, a thinly bedded, argillaceous sandstone used chiefly for paving purposes; *freestone*, a sandstone which splits freely and dresses easily.

Distribution of Sandstones in the United States.—Sandstones occur in all formations from pre-Cambrian to Tertiary. They are so widely distributed that for local supply there are numerous small quarries in many states, but there are several areas which have been operated on an extensive scale, some of them for many years. Of these, one of the best known is the Triassic Brownstone belt, which extends from the Connecticut Valley, in Massachusetts, southwestward into North Carolina.

This is a red, brown, or even bluish sandstone, of moderate hardness, and somewhat variable texture. That from the Connecticut Valley district was formerly used in enormous quantities.

Among the Paleozoic strata there are many sandstones, often massive, and usually dense and hard. Of these the Medina and Potsdam are specially important and much quarried in New York State (57). The same formations extend southward along the Appalachians and are available at several points. Devonian flagstones are extensively quarried at several localities in New York and Pennsylvania. The Lower Carboniferous Berea (Pl. XVI, Fig. 1) sandstone of Ohio (63) is in great demand because of its light color, even texture, and the ease with which it is worked. Moreover, it has the peculiar property of changing to a uniform buff on exposure to the air. There are numerous other Paleozoic sandstones in the central states, among them the Potsdam, which covers a wide area in Michigan and Wisconsin (85). Some of this stone is bright red in color.

The Mesozoic and Tertiary strata of the West contain an abundance of good sandstone, and quarries opened in many of them yield a durable quality of stone. Though usually less dense and hard than the Paleozoic sandstones, they serve admirably for buildings in the mild or dry climates of the West.

Uses of Sandstones.—The wide distribution of sandstones makes them an important source of local structural material. They are chiefly used for ordinary building work, and but little for massive masonry or monuments. The thin-bedded flagstones are much used for flagging, and some of the harder sandstones are split up for paving blocks. For other uses, see Abrasives.

SLATES

General Characteristics (13, 42).—Slates are metamorphic rocks derived from clay or shale or more rarely from igneous rocks (28). Their value depends upon the presence of a well-defined plane of splitting, called *cleavage* (Fig. 51), developed by metamorphism through the rearrangement and flattening of the original mineral grains and the development of micaceous minerals. The cleavage usually develops at a variable angle to the bedding planes which are often completely obliterated by the metamorphism. When not completely destroyed, the bedding planes are marked by parallel bands, called ribbons, cutting across the planes of cleavage, but so perfect is the cleavage in the best slates that the rock readily splits into thin sheets with a smooth surface.

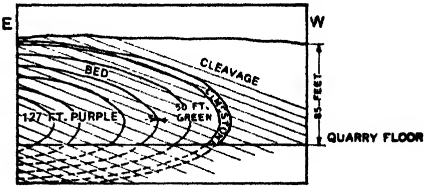

FIG. 51.—Section showing cleavage and bedding in slate. (*After Dale, U. S. Geol. Surv., 19th Ann. Rept., III.*)

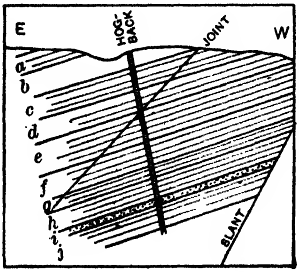

FIG. 52.—Section in slate quarry with cleavage parallel to bedding. *a*, purple slate; *b*, unworked; *c* and *d*, variegated; *e* and *f*, green; *g* and *h*, gray-green; *i*, quartzite; *j*, gray with black patches. (*After Dale.*)

Slates are commonly so fine grained that the mineral composition is not evident to the eye, but the microscope reveals the presence of many of the varied mineral grains found in shale, and in addition much chlorite, developed by metamorphism. Owing to the presence of carbonaceous particles, most slates are black or bluish black, but green, purple, and red slates are also known. The specific gravity of slate is about 2.7, and a cubic foot weighs between 170 and 175 pounds.

Most slates are fairly durable, though the presence of pyrite along the ribbons may lead to their decay. Lime carbonate if present in any quantity is injurious, and if the slate is to be used for switchboards, it should be as free from magnetite grains as possible. Some colored slates fade on exposure to the weather, but this change, which is due to the bleaching of certain mineral grains, does not necessarily result in loss of strength or disintegration.

In slate quarrying it is of importance to distinguish between bedding and cleavage. The following criteria may be used (*75*). Quartzite and limestone bands of some persistence indicate bedding, but care must be taken not to mistake vein quartz for quartzite. Fossil impressions are always on the bed surface. A microscopic section, transverse to cleavage, may be used, if other means fail, to indicate divergence between bedding and cleavage, although in some places the two may agree.

Special tests are necessary for determining the quality of slate. They include the determination of its sonoroüsness, cleavability, abrasive resistance, absorption, elasticity, and presence of injurious minerals. The chemical analysis is of limited value, but Merriman concludes that the strongest slate runs highest in silica and alumina but not necessarily lowest in lime and magnesium carbonates.

Dale divides slates into the following groups:

I. Aqueous sedimentary.
  A. Clay slates: cemented by clay, lime carbonate, or magnesium carbonate. Fissility, strength, and elasticity low.
  B. Mica slates: 1. Fading; with sufficient iron carbonate to discolor on exposure. 2. Unfading; without sufficient iron carbonate to produce any but very slight discoloration on prolonged exposure.
  Under each group we may have the following types: graphitic (gray-black); chloritic (greenish); hematitic and chloritic (purplish). The second group may also include hematitic (reddish).
II. Igneous.
  A. Ash slates.
  B. Dike slates.

Distribution of Slates in the United States (Fig. 53).—Since slates are of metamorphic origin, they are limited to those regions in which the rocks are metamorphosed, and at present the greater part of our supply comes from the Cambrian and Silurian strata of the eastern crystalline belt of the Atlantic states.

A series of quarries producing red, green, purple, and variegated slates are located in a belt of Cambrian and Hudson River strata along the border of New York (56) (Pl: XVIII) and Vermont (56, 77).

Black slates are obtained in Maine (3), New Jersey (55), Pennsylvania (3), (Pl. XVII, Fig. 2), Maryland (44), Georgia (3), and Virginia (81). Other producing states are Minnesota, California (28, 75), and Arkansas (26).

Uses of Slate.—Slate is best known as a roofing material, but it is also used for mantels, billiard-table tops, floor tiles, steps, flagging, slate pencils, acid towers, washtubs, etc. The process of marbleizing slates for mantels and fireplaces was formerly carried on at several localities.

In quarrying slate there is from 60 to 80 per cent waste, which is greater than in any other building stone; but the introduction of channeling machines in quarrying has done much to reduce this. The discovery of a use for this waste has been an important problem, which has thus far been only partially solved. It is sometimes ground for paint, and attempts have been made to utilize it in the manufacture of bricks and Portland cement.

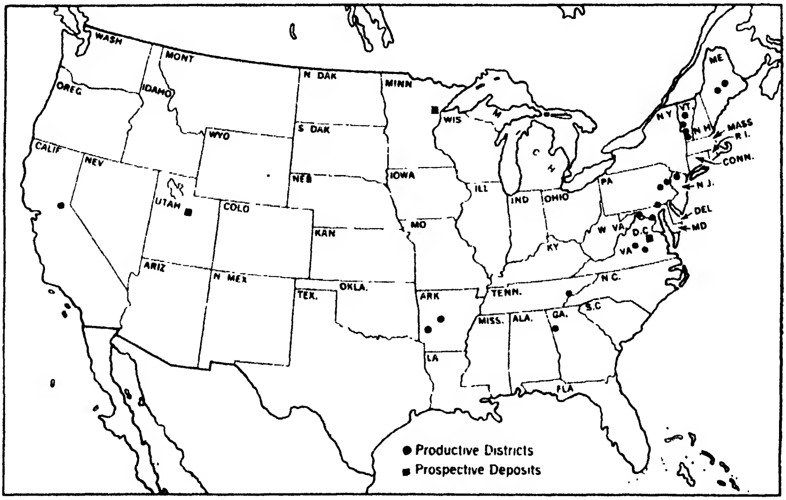

FIG. 53.—Map showing distribution of slate in the United States. (*After Dale, U. S. Geol. Surv., Bull.* 275.)

Building Stones in Canada (87).—The Canadian building stones are developed chiefly in the eastern provinces, including Ontario, and in the Far West, as along the Pacific Coast.

Igneous Rock (87).—Nova Scotia and New Brunswick contain a number of granite areas, yielding stone of varying texture and color, the red variety quarried near St. George, N. B., being well known. There is also considerable local development around Halifax. Nova Scotia has much fine-grained, dense volcanic rock, susceptible of decorative use. Some diorite and diabase for monumental work is also quarried in New Brunswick.

In Quebec granites and gneisses are worked at scattered points in the northern area, but the gray granite of the Stanstead district in the eastern townships is the best known, while so-called black granite (essexite) for monumental purposes has been quarried in the Monteregian Hills.

Ontario granites and gneisses though abundant are little developed.

Not a little granite is quarried along the Pacific Coast north of Vancouver, and the andesite from Vancouver Island is quite extensively used.

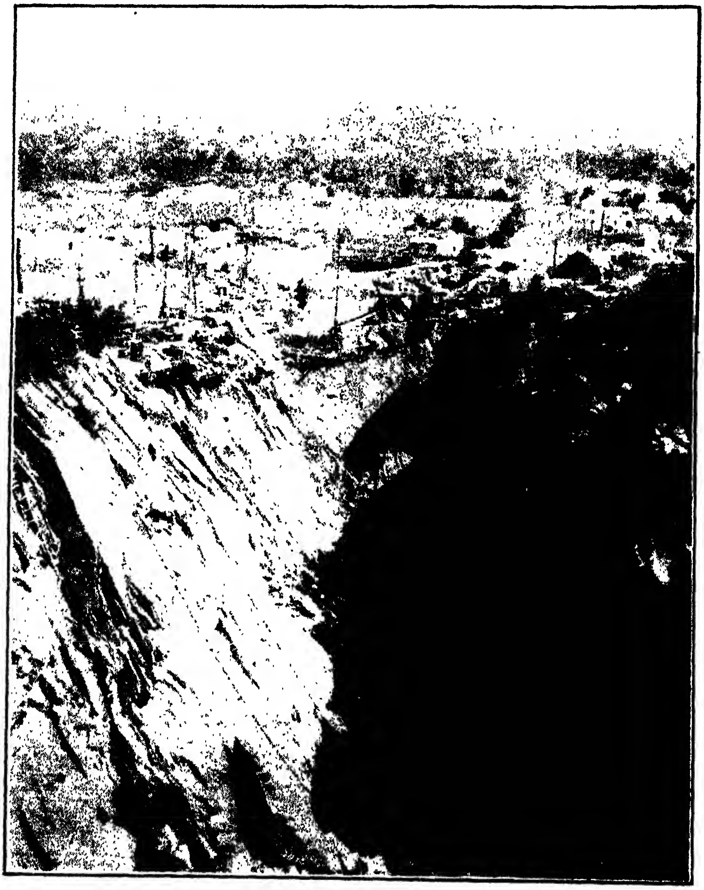

Plate XVIII.—View of green slate quarry, Pawlet, Vt. (*Photo. by H. Ries.*)

Limestones.—Limestones of Paleozoic age are extensively quarried in Quebec, notably around Montreal and Hull, and at many points in southern Ontario. West of Winnipeg a peculiar mottled limestone is quarried, and much used in Manitoba.

Sandstones.—The Carboniferous sandstones of New Brunswick and Nova Scotia, and the Ordovician and Silurian sandstones of Quebec and Ontario, have been developed at many points. Occasionally sandstone deposits are worked in the Cretaceous and Tertiary beds of the Western Provinces, and also on Vancouver Island.

Marble.—Highly decorative marbles of pre-Cambrian age are quarried at South Stukely, Quebec. Paleozoic ones of gray and green color, with veins and cloudings, are obtained near Phillipsburg in the same province. Crystalline limestones are abundant in Ontario, but the best known variegated marble is that quarried near Bancroft. A gray and white marble is obtained in the Kootenay district of British Columbia.

Slate.—Little good slate is obtained in the Dominion, this coming from the eastern townships of Quebec.

Other Foreign Building Stones.—Granites are quarried at a number of localities in Europe, but those exported to the United States, and used more or less for monumental purposes, come chiefly from Scotland and Sweden.

Of the many foreign sandstones quarried, the bright-red Scotch ones have been used in some quantity in the United States.

Volcanic tuffs are widely distributed and abundantly used in central Mexico, and these, together with lava rock, have been frequently quarried in Italy, the Auvergne region of France, and even other localities.

The roofing slates found in the Cambrian and Ordovician of North Wales are among the best known deposits of the world.

Many limestones are quarried, especially in the post-Carboniferous formations. Among these may be mentioned the Portland stone of the Jurassic on the Isle of Portland, near Weymouth, and the soft French limestones, of which the Caen stone, often used in America for interior work, is well known. Another soft, but dense limestone, capable of taking a polish, and frequently employed here, is that of Hauteville, France.

Marbles of great beauty are quarried in many foreign countries, and widely exported. Among the best known are: white statuary marble from Carrara, Italy; yellow, black-veined Sienna, and whitish, veined Pavonazzo, from the same country; Skyros breccia from Greece; Griotte or red from France; Parian white from Greece; banded Cippolino from Switzerland, and a host of others. Many of them are of highly decorative character, but of low weather-resisting qualities.

The same is true of the beautiful serpentine marbles, which may be obtained from Ireland, Italy, and Greece.

Production of Building Stones.—The value of dimension stones produced in 1940 was as follows: granite, $10,088,224, trap rock, $20,637; sandstone, $1,426,204; marble, $4,795,103; limestone, $4,259,965; slate, $3,436,368.

The total tonnage of dimension stone was about 2,000,000 short tons. In addition there was sold some 152,000,000 short tons of crushed and broken stone of all kinds. Furthermore, about 43,000,000 short tons of limestone were sold for making cement and lime.

In the case of slate roughly three-fifths the value is dimension slate, and the balance slate granules and flour. Vermont was the leading producer of granite and marble, New Jersey of traprock, Ohio of sandstone, Indiana of limestone, and Pennsylvania of slate.

The value of granite imported in 1940 was $29,760, and of marble $209,675. Exports of building stone were valued at $158,008, and of slate and granules, $196,694.

The production (sale) of stone in Canada in 1939 was as follows: granite, $943,064; limestone, $444,368; marble, $156,668; sandstone, $123,118; total, $1,667,218. The total value of imports of stone of all kinds: $963,560; exports, $215,860.

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CHAPTER IV

CLAY

Definition.—Clay may be defined as an earthy substance of fine texture containing a mixture of hydrous aluminum silicates, with fragments of other minerals, such as silicates, oxides, carbonates, etc., and colloidal material which may be of either organic or mineral character. The mass possesses plasticity (usually) when wet, and becomes rock-hard when fired to at least a temperature of redness.

Two important classes of clays are the residual and the transported ones.

Residual Clays (5).—Clays are derived primarily and principally from the decomposition of crystalline rocks, more especially feldspathic varieties. If the deposits are formed by weathering (Fig. 54), they will be found overlying the parent rock and often grading down into it. If formed by hydrothermal action, which is rare, their depth is unknown. Both these types are termed *residual clay.*

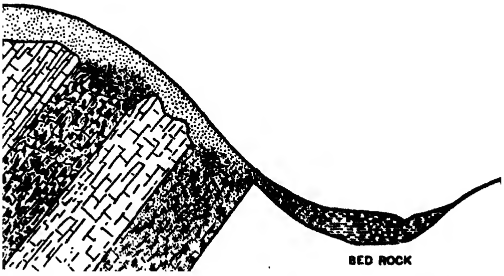

Fig. 54.—Section showing formation of residual clay. (*After Ries, U. S. Geol. Surv., Prof. Pap.* 11.)

All residual clays probably contain a variable amount of kaolinite (*6*) or clay substance. This mineral, which is white in color, results from the decomposition of feldspar, either by weathering, or, less often, by the action of volcanic vapors. The decay of a large mass of pure feldspar would therefore yield a mass of white clay, but, in most instances, the feldspar is associated with other minerals, such as quartz, mica, and hornblende, all of which, except the quartz, and muscovite, decay with greater or less rapidity, and some of these, such as the hornblende, may likewise yield a hydrous aluminum silicate. Any ferruginous minerals in the rock will, in decomposing, yield limonite, which stains the mass.

Large masses of pure feldspar are rare, but feldspathic rocks, such as granite or syenite, are more common, and these will also decompose to clay. Sedimentary rocks as well as crystalline ones may produce residual clay. That derived from limestone is the insoluble clayey impurities left after the carbonates are dissolved. Residual clays may rarely be formed by alterations due to underground waters, and the clay minerals deposited by replacement. Indianite formed by hydrous aluminum silicates replacing sandstone is an example (8).

The extent of a deposit of residual clay will depend on the extent of the parent rock and the topography of the land, which also influences its thickness. On steep slopes much of the clay may be washed away; and residual clays are also rare in glaciated regions, for the reason that they have been swept away by the ice erosion. They are consequently wanting in most of the Northern states, but abundant in many parts of the Southern states, where the older formations appear at the surface.

Transported Clays (5).—With the erosion of the land surface the particles of residual clay become swept away to lakes, seas, or the ocean, where they settle down in the quiet water as a fine aluminous sediment, forming a deposit of *sedimentary clay* (Fig. 55). Such beds are often of great thickness and vast extent. With the accumulation of many feet of other sediments on top of them, they become consolidated either by pressure or by the deposit of a cement around the grains. Consolidated clay is termed *shale,* and this upon being ground and mixed with water often becomes as plastic as an unconsolidated clay.

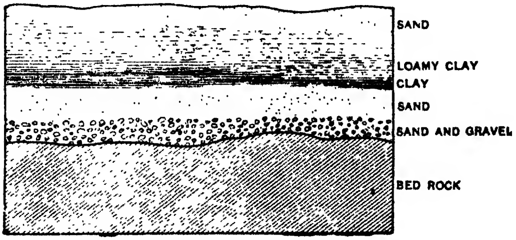

FIG. 55.—Section of a sedimentary clay deposit. (*After Ries, U. S. Geol. Surv., Prof. Pap.* 11.)

Residual materials may also have been transported by wind or glacial action, to form clayey deposits.

The following are important types of transported clays:

Marine Clays.—Formed by the deposition on the ocean floor of the finer particles derived from the waste of the land. Such ancient seabottom clays have been elevated to form dry land in all the continents, in many cases forming consolidated clay strata, but elsewhere, especially in coastal plains, in unconsolidated condition. Extensive clay deposits are also formed in protected estuaries and lagoons along the seacoast.

Flood-plain Clays.—Formed by the deposition of clayey sediment on the lowlands bordering a river during periods of flood. Layer upon layer, this deposit builds a flood plain often of great extent and depth. Such areas of flood-plain clays are most extensive along the greater rivers and in the deltas which they have built in the sea.

Lake Clays.—Clay is deposited on the bottom of many lakes and ponds in the same manner as on the ocean bottom. Where the streams bring only fine particles the filling of a lake may be entirely of clay. Many lakes have been either drained or completely filled and their clays therefore made available.

This is especially true of small, shallow lakes formed during the Glacial Period.

Glacial Clays, commonly known as till or bowlder clay, a rock flour ground in the glacial mill in which rock fragments were worn down to clay by being rubbed together or against the bed rock over which the ice moved. When the ice melted, this deposit was left in a sheet of varying thickness and characteristics over a large part of the area which the ice covered. It is not always, strictly speaking, a sedimentary deposit.

Æolian Clays.—Wind drifts dry clay about, and in favorable positions causes its accumulation in beds. This is true of the Chinese loess, a wind-blown deposit derived from residual soils and drifted about in the arid climate of interior China. Some at least of the loess clays of the Mississippi Valley seem to have a similar origin, the source of the clay being glacial deposits; in other cases loess seems to be a water deposit either in shallow lakes or else in broad, slowly moving streams.

Clay Minerals (10, 11, 12).—Kaolins commonly contain the mineral kaolinite ($Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O$) which is usually a product of weathering. Dickite, having the same composition, may be formed hydrothermally or possibly in some cases by meteoric waters, while nacrite with the same formula is only known to be of hydrothermal origin.

Halloysite, of similar composition to kaolinite, is a very finely crystalline form which may change to the latter by recrystallization, while allophane is regarded as a solid solution of silica, alumina and water ($Al_2O_3 \cdot 2SiO_2 \cdot H_2O$).

In impure clays the common clay mineral is often beidellite ($Al_2O_3 \cdot 3SiO_2 \cdot H_2O$), while in bentonite, formed by the alteration of volcanic ash, the product is montmorillonite ($(MgCa)O \cdot Al_2O_3 \cdot 5SiO_2 \cdot nH_2O$).

Properties of Clay.—These are of two kinds, physical and chemical, and since they exercise an important influence on the behavior of the clay, the most important ones may be described.

Physical Properties (5).—These include plasticity, transverse strength, air and fire shrinkage, fusibility, and specific gravity.

Plasticity may be defined as the property which clay possesses of forming a plastic mass when mixed with water, thus permitting it to be molded into any desired shape, which it retains when dry. This is an exceedingly important character of clay. Clays vary from exceedingly plastic, or "fat" ones, to those of low plasticity which are "lean" and sandy. Plasticity is probably due in part to fineness of grain, and in part to the presence of colloids (5).

Transverse strength is the resistance which a bar of dried clay offers to cross breaking strains, and indicates its probable bonding strength. It is expressed in terms of the modulus of rupture, which may range from a few pounds per square inch in weak clays, to as much as 1500 pounds in very strong ones.

Shrinkage is of two kinds: air shrinkage, which the molded clay undergoes while drying, and fire shrinkage, which the clay exhibits during firing. Both are variable and an excessive amount of either causes cracking and warping of the clay.

Fusibility. This takes place gradually, so that the clay softens slowly when subjected to a rising temperature. In fusing the clay passes through three stages, termed respectively incipient vitrification, complete vitrification (maximum fire shrinkage and density), and viscosity.

In the lower grades of clay, that is, those having a high percentage of fluxing impurities, incipient fusion may occur at about 1000° C., while in refractory clays, which are low in fluxing impurities, it may not occur until 1300° or 1400° C. is reached.

Specific gravity varies commonly from about 1.70 to 2.30.

Chemical Properties (5).—The number of common elements which have been found in clays is great, and even some of the rarer ones have been noted; but in a given clay the number of elements present is usually small, being commonly confined to those determined in the ordinary chemical analyses, which show their existence in the clay, but not always the state of the chemical combination. The common constituents of a clay are silica, alumina, ferric or ferrous oxide, lime, magnesia, alkalies, titanic acid, and combined water. Organic matter, and sulphur trioxide, though often present, are usually in small amounts. Carbon dioxide is always found in calcareous clays. The effect of these may be noted briefly.

Silica if present in the form of quartz or other crystalline grains, aids in lowering the plasticity and shrinkage at low temperatures. Silica in colloidal form probably increases the plasticity. *Alumina,* which is most abundant in white clays, is a refractory ingredient. *Iron oxide* acts as a coloring agent in both the raw and burned clay, small quantities usually coloring a burned clay buff, and larger amounts (4 to 7 per cent), if evenly distributed, turning it red. It also acts as a flux in burning. Whatever the iron compound present in the raw clay it changes to the oxide in burning. *Lime, magnesia,* and *alkalies* are also fluxing ingredients of the clay. The combined percentage of fluxing impurities is small in a refractory clay, and often high in a low-grade one. Lime, if present in considerable excess over the iron, will, in burning, exert a bleaching effect on the latter. For this reason, highly calcareous clays, such as those in the Great Lake region, burn cream or buff. When lime is present in large amounts, it also causes clay to soften more rapidly in firing than it otherwise would.

Chemically combined water passes off chiefly between 450° and 650° C., and carbonaceous matter mostly between 800° and 900° C. This loss leaves the clay temporarily porous until fire shrinkage sets in. *Titanic acid,* though rarely exceeding 1 per cent, acts as a flux at high temperatures at least. *Sulphur trioxide* is rarely present in sufficiently high amounts to interfere with the successful burning of the clay.

Carbon colors a raw clay gray or black, and several per cent may give much trouble in burning, unless driven out of the clay before it becomes dense.

Chemical Composition.—As might be expected from their diverse modes of origin, clays vary widely in their chemical composition. There is every gradation from those which, in composition, closely resemble the mineral kaolinite, to those, like ordinary brick clays, in which there is a high percentage of impurities. This variation is shown in the table on p. 136.

The absence of ferrous oxide, titanic oxide, sulphur trioxide, organic matter, and manganous oxide in many of the analyses quoted does not necessarily indicate their non-existence in these clays. Probably all contain at least small percentages of these substances, but they are rarely determined.

Classification of Clay.—It is possible to base a classification of clays either on origin, chemical and physical properties, or uses. But since the subdivisions which can be made are not sufficiently distinct, each of these gives rise to a more or less unsatisfactory grouping. The following classification is based partly on mode of origin and partly on physical characters (*8*):

A. Residual clays. (By decomposition of rocks *in situ.*)
  I. Kaolins, white in color, and usually white burning.
    (*a*) Veins, derived from pegmatite, rhyolite, etc.
    (*b*) Blanket deposits, from areas of igneous or metamorphic rocks.
    (*c*) Replacement deposits, as indianaite (34).
    (*d*) Bedded deposits from feldspathic sandstones.
  II. Red-burning residuals, derived from different kinds of rocks.
B. Colluvial clays, representing deposits formed by wash from the foregoing, and of either refractory or non-refractory character.
C. Transported clays.
  I. Deposited in water.
    (*a*) Marine clays or shales. Deposits often of great extent.
      White-burning clays. Ball clays and plastic kaolins.
      Fire clays or shales. Buff-burning.
      Impure clays or shales. $\left\{\begin{array}{l}\text{Calcareous.}\\ \text{Non-calcareous.}\end{array}\right.$
    (*b*) Lacustrine clays (deposited in lakes or swamps).
      Fire clays or shales.
      Impure clays or shales, red-burning.
      Calcareous clays, usually of surface character.
    (*c*) Flood-plain clays. Usually impure and sandy.
    (*d*) Estuarine clays (deposited in estuaries). Mostly impure and finely laminated.
  II. Glacial clays found in the drift, and often stony. May either be red- or cream-burning.
  III. Wind-formed deposits (some loess).
D. Chemical deposits (some flint clays?).

Kinds of Clay.—Clays are known by special names, indicating their use, or certain physical properties.

Analyses Showing Variation in Composition of Clays

	I	II	III	IV	V
Silica (SiO_2)	46.3	45.78	57.62	59.92	68.62
Alumina (Al_2O_3)	39.8	36.46	24.00	27.56	14.98
Ferric oxide (Fe_2O_3)	—	.28	1.9	1.03	4.16
Ferrous oxide (FeO)	—	1.08	1.2	—	—
Lime (CaO)	—	.50	.7	tr.	1.48
Magnesia (MgO)	—	.04	.3	tr.	1.09
Potash (K_2O)	—	.25	.5	.64	3.36
Soda (Na_2O)	—		.2		
Titanic oxide (TiO_2)	—	—	—	—	—
Water (H_2O)	13.9	13.40	10.5	9.70	3.55
Moisture	—	2.05	2.7	1.12	2.78
Carbon dioxide (CO_2)	—	—	—	—	—
Sulphur trioxide (SO_3)	—	—	.35	—	—
Organic matter	—	—	—	—	—
Manganous oxide (MnO)	—	—	—	—	.64
Total	100.00	99.84	99.97	99.97	100.66

	VI	VII	VIII	IX	X
Silica (SiO_2)	82.45	54.64	38.07	90.00	47.92
Alumina (Al_2O_3)	10.92	14.62	9.46	4.60	14.40
Ferric oxide (Fe_2O_3)	1.08	5.69	2.70	1.44	3.60
Ferrous oxide (FeO)	—	—	—	—	—
Lime (CaO)	.22	5.16	15.84	.10	12.30
Magnesia (MgO)	.96	2.90	8.50	.10	1.08
Potash (K_2O)	—	5.89	2.76	tr.	1.20
Soda (Na_2O)				tr.	1:50
Titanic oxide (TiO_2)	1.00	—	—	.70	1.22
Water (H_2O)	2.4	3.74	2.49	3.04	4.85
Moisture	—	.85		—	—
Carbon dioxide (CO_2)	—	4.80	20.46	—	9.50
Sulphur trioxide (SO_3)	—	—	—	—	1.44
Organic matter	—	—	—	—	1.34
Manganous oxide (MnO)	—	.76	—	—	—
Total	99.03	99.05	100.28	99.98	100.35

I. Kaolinite.
II. Washed kaolin, Webster, N. Ca.
III. Plastic fire clay, St. Louis, Mo.
IV. Flint fire clay, Salineville, O.
V. Loess clay, Guthrie Center, Ia.
VI. Pressed-brick clay, Rusk, Tex.
VII. Brick shale, Mason City, Ia.
VIII. Calcareous brick clay, Milwaukee, Wis.
IX. Sandy brick clay, Colmesneil, Tex.
X. Blue shale clay, Ferris, Tex.

Adobe. A sandy, often calcareous, clay used in the west and southwest for making sun-dried brick. *Ball clay.* A white-burning, plastic, sedimentary clay, employed by potters to give plasticity to their mixture. *Bentonite* (12). A clay formed by alteration of volcanic ash, and containing the clay mineral montmorillonite. *Brick clay.* Any common clay suitable for making ordinary brick. *China clay.* A term applied to kaolin (*q.v.*). *Earthenware clay.* Clay suitable for the manufacture of common earthenware, such as flower pots. *Fire clay.* A clay capable of resisting a high degree of heat. *Flint clay.* A peculiar flint-like fire clay, which when ground up and wet develops no plasticity. Chemically, it differs but little, if at all, from the plastic fire clays. Moreover, the two often occur in the same bed, either in separate layers or irregularly mixed. *Gumbo.* A very sticky, highly plastic clay, occurring in the central states, and used for making burned-clay ballast (5). *Kaolin.* A white-burning residual clay, employed chiefly in manufacture of white earthenware and porcelain. The term is also applied by some to the white-burning sedimentary clays of Georgia and South Carolina. *Loess.* A sandy, calcareous, fine-grained clay, covering thousands of square miles in the central states, and of wide use in brick making. *Paper clay.* Any fine-grained clay, of proper color, that can be employed in the manufacture of paper. *Pipe clay.* A loosely used term applied to any smooth plastic clay. Strictly speaking, it refers to a clay suited to the manufacture of sewer pipe. *Pot clay.* A dense-burning fire clay, used in the manufacture of glass pots. The domestic supply comes mainly from St. Louis, Mo., but much is imported. *Pottery clay.* Any clay suitable for the manufacture of pottery. *Retort clay.* A plastic fire clay, used in making gas retorts. The term is a local one used chiefly in New Jersey. *Sagger clay.* A loose term applied to clays employed in making saggers; they are of value for other purposes as well. *Sewer-pipe clay.* A term applicable to any clay that can be used for manufacture of sewer pipe. It is usually vitrifiable and red-burning. *Slip clay.* Under this term are included those clays which are easily fusible, and form a natural glaze, when applied to ware (such as stoneware) and burned at the proper temperature. The best-known variety comes from Albany, N. Y. *Stoneware clay.* A very plastic clay, which burns to a vitrified or stoneware body. It may be refractory. *Terra-cotta clay.* Clay suitable for the manufacture of terra-cotta. The term has no special significance, as a wide variety of clays are adapted to this purpose.

Geological Distribution.—Clays have a wider distribution than most other economic minerals or rocks, being found in all formations from the oldest to the youngest. The pre-Cambrian crystallines yield both white and colored residual clays, usually the result of weathering, though more rarely of solfataric action. In the Paleozoic rocks, deposits of shale, and sometimes of clay, are found in many localities; and, since they are usually marine sediments, the beds are often of great extent and thickness. The weathered outcrops of these may yield a residual clay. With the exception of certain Carboniferous deposits, the Paleozoic clays are mostly impure. The Mesozoic formations contain large supplies of clays and shale suitable for the manufacture of bricks, terra-cotta, stoneware, fire brick, etc.

FIG. 1.—Kaolin deposit, North Carolina, shows circular pits for mining, sunk in clay. (*Photo. loaned by Southern Railway Company.*)

FIG. 2.—Bank of sedimentary clay, Woodbridge, N. J. This section affords at least five kinds of clay. (*Photo. H. Ries.*)

The Pleistocene clays are all surface deposits, usually impure, and individually of limited extent, although they are thickly scattered all over the United States. Their chief value is for brick and tile making. They have been accumulated by glacial action, on flood plains, in deltas, or in estuaries and lakes.

Distribution of Clays by Kinds in the United States.—*Kaolins* (8).—Kaolins proper are derived only from crystalline or igneous rocks, hence their distribution is limited, and the only deposits worked are in the eastern states. Being commonly formed by the weathering of pegmatite veins, kaolin deposits have great length as compared with their width, which may be anywhere from 5 to 300 feet. Their depth ranges from 20 to 120 feet, depending on the depth to which the feldspar has been weathered.

	CRUDE KAOLIN	WASHED KAOLIN
SiO_2	62.40	45.78
Al_2O_3	26.51	36.46
Fe_2O_3	1.14	.28
FeO	——	1.08
CaO	.57	.50
MgO	.01	.04
Alkalies	.98	.25
H_2O	8.80	13.40
Moisture	.25	2.05
	100.66	99.84
Clay substance	66.14	93.24

Quartz and white mica are often present in kaolin, and it is then frequently necessary to put the clay through a washing process to remove these minerals. The difference between a washed and unwashed kaolin is well shown by the two preceding analyses, from which it is seen that the quartz content has been considerably lowered, and that the washed product approaches more closely to the composition of kaolinite.

North Carolina (60) is the most important residual kaolin-producing state, but deposits have been worked in Pennsylvania (72), Connecticut (22), Maryland (42), and Virginia (84). Kaolin is known to occur in Alabama (16). All these deposits except that in Connecticut are found south of the limit of the glacial drift. Kaolins occur in southeastern Missouri, but they have never become of great importance (8). Some are worked in Washington (86).

The Cretaceous of Georgia (25) and South Carolina (75, 81) contains important deposits of white-burning sedimentary clays, which might perhaps be termed plastic kaolins to distinguish them from the residual ones.

The output from the American kaolin deposits has been insufficient to supply the domestic clay working industry, and many tons have been imported annually from England, but the imports have shown a great decrease in the last ten years, owing to replacement of the foreign clay by domestic material. The average value of American kaolin is $8.48 per ton at the mines, and the production in 1940 was 833,450 tons, an increase of nearly 100 per cent over '30-'34.

Fire Clays.—Fire clays are found in the rocks of all systems, from the Carboniferous to the Tertiary, inclusive, with the exception of the Triassic.

The most extensive, and among the most important, beds of fire clay are those found in the Carboniferous strata of Pennsylvania (73), Ohio (65, 67), Kentucky (39), West Virginia (87), Maryland (42), Indiana (34), Missouri (50, 52), and Illinois (30, 31, 33). Those of the first two named states are on the average the most refractory. Here the fire clays are usually found underlying coal beds and often at well-marked horizons, especially in the Upper Productive Measures.

Those of Indiana and Illinois are so placed that one mine shaft may be used for extracting coal, fire clay, stoneware clay, and shale.

The beds of refractory clay, found in the Carboniferous strata near St. Louis (50, 52), are not only used in the manufacture of fire brick, but are, in some cases, found suitable, after washing, for mixture with imported German clays for the manufacture of glass pots.

In the Lower Cretaceous of New Jersey (55) there are many beds of refractory clay, variable in thickness and closely associated with beds of less refractory character. They not only support a thriving local fire-brick industry, but serve also as a source of supply for factories in other states. Maryland (42) and Alabama (12) have some refractory clay in the Cretaceous, but extensive deposits of this age are worked in Georgia (25) and South Carolina (75, 76).

The Tertiary formations of Texas (80) and Mississippi (8) hold abundant deposits of refractory material, but many are undeveloped. The Missouri Tertiary also supplies some fire clays (52).

Fire clays are found in the Black Hills of South Dakota (77), in the Laramie beds of Colorado (20, 21), and in California (19); but, excepting near Denver, where used for making fire brick and assayer's apparatus, and in parts of California these deposits are as yet slightly developed.

Pottery Clays.—Under this heading are included several grades of clay, the kaolins, already described, being the purest and best suited to the manufacture of high grades of pottery.

Another high-grade pottery clay of more plastic character, the ball clay, is of limited distribution in the United States. A small quantity is found in the Cretaceous (Pl. XIX) of New Jersey (55), and a much larger amount in the Tertiary of western Kentucky (39), and Tennessee (78), and southeastern Missouri (52), and Florida (24). The white sedimentary kaolins of Georgia are extensively used in white ware manufacture.

Stoneware clays form a third grade of pottery clays. They are usually of at least semirefractory character, but differ from fire clays proper in burning dense at a much lower temperature. Their distribution is essentially coextensive with that of fire clays; indeed, the two are often dug from the same pit or mine. Large quantities are obtained in the Carboniferous of western Pennsylvania (73) and eastern Ohio (63) and smaller amounts in the New Jersey Cretaceous formations (55).

Stoneware clays, usually in the same area as the fire clays, are also obtained in Illinois (29), Indiana (34), Kentucky (39), Tennessee (78), Alabama (16), and Texas (80); and they occur also in Missouri (52), Iowa (37), Colorado, and California (19).

Many of the Pleistocene surface clays in various states are sufficiently dense-burning to be used locally by small stoneware factories.

Brick and Tile Clays.—None of our states lack an abundant supply of good brick and tile clays, and in many areas there are extensive deposits near the large markets, and often near tide water. In such cases the clay beds are exploited to an enormous extent.

In the northeastern states the Pleistocene surface clays are found almost everywhere in great abundance, and are made use of in many places, especially near the large cities.

In the middle Atlantic states Columbian loams and clay marls are an important source of brick material.

In Ohio, Illinois, and Indiana Pleistocene clays, in part of glacial, and in part of flood-plain origin, are much used for brick and tile. Impure Paleozoic shales are also used in places, especially in the manufacture of vitrified paving brick, thousands of which are made annually in Ohio. Northern Illinois, Michigan, and Wisconsin draw their main supply of brick clays from the calcareous lake deposits.

Although glacial clays and flood-plain deposits are much used in the states west of the Mississippi, the loess which occurs over a wide area is probably even more important as a source of brick, while in the southwestern states loess and adobe are important. Residual clays river silts, glacial clays, and other forms of clay are employed in brick making along the Pacific coast.

Miscellaneous Clays of Importance.—Paper clays of good quality are much sought for by paper manufacturers. Much English kaolin is used for this purpose, but the domestic kaolins are also drawn upon, especially the sedimentary ones of Georgia and South Carolina. A small amount of *glasspot clay* (52) comes from western Pennsylvania, but much more from eastern Missouri. Refractory bond clays are dug in Mississippi. Terra-cotta clays are obtained from the same areas that supply fire clays, New Jersey being the principal producer.

Distribution of Clays in Canada.—*Kaolins.*—Deposits are hardly expected in the glaciated area, but one deposit formed from feldspathic quartzite has been worked near St. Remi, Quebec (94).

Fire Clays.—Extensive deposits occur in the Laramie of southern Saskatchewan (92, 98, 99, 100), and the Eocene delta deposits of the Frazer Valley, British Columbia. The same materials are utilized for pressed brick, terra-cotta, and certain beds for stoneware.

Red-burning Clays and Shales.—The Carboniferous shales of Nova Scotia and New Brunswick (97, 95), the Ordovician and Silurian shales of Ontario, and the Cretaceous and Tertiary shales of the Western Provinces (98) afford abundant material for making building and paving brick, drain tile, fireproofing, and, in some cases, sewer pipe.

Surface Clays.—These are widely distributed through the Dominion, and may be of the estuarine, lacustrine, flood-plain or glacial type according to their location and origin (91–100). Those found in the Great Plains region are not infrequently buff or cream burning, because of their calcareous nature.

Other Foreign Deposits.—The kaolin or china clay deposits of the Cornwall, England,[1] district are the most important of this type worked in the world, and supply a large export trade. Equally well known, but of less extent, are similar deposits in France, Denmark, Bohemia, and Germany.[2] Fire clays are worked at a number of localities for domestic use, but the glasspot clays of Belgium and Germany have not only been used at home, but also exported. So, too, have German clays employed in making graphite crucibles.

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[1] Searle, British Clays, Shales and Sands, London, 1911.

[2] Dammer und Tietze, Die Nutzbaren Mineralien, II: 379, 1914.

Uses of Clay.—So few people have even an approximate idea of the uses to which clays are put that it seems desirable to call attention to them briefly. In the following table an attempt has been made to do this:[1]

Domestic.—*Pottery of various grades; Polishing brick,* often known as *bath bricks; Fire kindlers; Majolica stoves.*

Structural.—*Brick; Tiles and Terra cotta; Chimney pots; Chimney flues; Door knobs; Fireproofing; Copings; Fence posts.*

Hygienic.—*Closet bowls; Sinks,* etc.; *Sewer pipes; Ventilating flues; Foundation blocks; Vitrified bricks.*

Decorative.—*Ornamental pottery; Terra cotta; Majolica; Garden furniture.*

Minor Uses.—*Food adulterants; Paint filler; Paper filling; Electrical insulations; Pumps; Fulling cloth; Scouring soap; Packing horses' hoofs; Chemical apparatus; Condensing worms; Ink bottles; Ultramarine manufacture; Emery wheels; Bonding clay, for synthetic foundry sands.*

Refractory Wares.—*Crucibles and other assaying apparatus; Refractory bricks* of various patterns; *Glass pots.*

Engineering Work.—*Puddle; Portland cement; Railroad ballast; Water conduits; Turbine wheels.*

Production of Clay.—The tonnage of clay used annually in the manufacture of clay products is enormous, but since most of it is produced and consumed by the manufacturer no record is kept of it. The statistics of clay production published represent only the material produced by clay miners and sold to consumers.

The value of domestic clays sold in 1940 was $19,633,568. About 58 per cent of the tonnage was fire clay, and about 17 per cent kaolin.

The imports of clay (chiefly kaolin and ball clay) in 1940 were valued at $1,159,790, mostly kaolin. The exports of clays in 1940 were valued at $2,071,336.

Canada in 1939 recorded shipments of 10,045 tons of fire clay, valued at $30,824. There was no production of kaolin.

The imports for 1939 were: fire clay, 1,060,786 cwt., value $162,925; kaolin, 877,425 cwt., value $376,750.

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[1] Table compiled by R. T. Hill and modified by the author.

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CHAPTER V

LIMES AND CALCAREOUS CEMENTS

Composition of Limestones (1, 43).—Limes and calcareous cements form an important class of economic products, obtained from limestones by heating them to a temperature ranging from that of decarbonation to clinkering. The term *limestone* is applied to one of the main divisions of the stratified rocks so widely distributed, both geologically and geographically, and formed under such different conditions, that its composition varies greatly, this range of variation becoming appreciable from an inspection of the following table, which contains a few selected types:

	I	II	III	IV	V	VI	VII	VIII
Silica (SiO_2)	.54	2.22	.48	4.9	14.30	15.05	16.99	12.13
Alumina (Al_2O_3) . . .	.42	.92	.20	6.5	.70	9.02	5.00	4.17
Ferric oxide (Fe_2O_3) .		.18			.80	1.27	1.79	3.28
Lime (CaO)	54.73	54.08	31.31	27.3	46.50	39.26	23.15	42.04
Magnesia (MgO) . . .	.19	.10	21.03	14.6	n.d.	1.90	16.60	.44
Sulphur trioxide (SO_3) .	—	—	—	—	—	—	—	n.d.
Carbon dioxide (CO_2) .	43.22	42.50	46.98	44.8	36.54	32.90	36.47	33.51
Water (H_2O)	—	—	—	—	—	—	—	—
	99.10	100.00	99.99	98.1	98.84	99.40	100.00	95.57

I. Pure limestone, Ilasco, Mo. II. Chalk, Marinas, Cuba. III. Dolomite, E. Canaan, Conn. IV. Magnesian limestone, Clinton, Hunterdon Co., N. J. V. Siliceous limestone for hydraulic lime, Teil, France. VI. Argillaceous (cement rock) limestone, Lehigh district, Pa. VII. Argillaceous magnesian limestone, Milwaukee, Wis. VIII. Clayey chalk.

From this table it will be seen that limestones vary from rocks composed almost entirely of carbonate of lime, or of carbonate of lime and carbonate of magnesia, to others which are high in clayey or siliceous impurities. The presence of such impurities in large quantity usually imparts an earthy appearance to the limestone, and sometimes even gives it a shaly structure.

Marked variations in composition may at times be found even in a single quarry (49), while in other cases a limestone formation may show remarkable uniformity of composition over a wide area.

Changes in Burning (1).—When limestones are calcined or "burned" to a temperature sufficiently high to drive off volatile constituents, such as carbon dioxide, water, and sulphur (in part), or, in other words, to the point of decarbonation, the rock is left in a more or less porous condition. If heated to a still higher temperature, the rock clinkers or fuses incipiently, provided clay impurities are present, but the temperature of clinkering depends on the amount of siliceous and clayey impurities in the rock.

Lime (1, 43).—Limestone free from or containing but a small percentage of argillaceous impurities is, by decarbonation, changed to quicklime, a substance which has a high affinity for water, and which, when mixed with water, "slakes," forming a hydrate of lime. This change is accompanied by the evolution of heat and by swelling, and this action becomes the more marked the higher the percentage of lime carbonate in the rock, for the slaking activity is retarded by the presence of magnesia and especially by argillaceous impurities. Limes may, therefore, be divided into "fat" limes and "meager" limes, depending on the rapidity with which they slake and the amount of heat they develop in doing so.

Hydraulic Cements.—With an increase in clayey and siliceous impurities, the burned rock shows a decrease in slaking qualities, and develops hydraulic properties, or sets when mixed with water, and even under the same. Products of this type are termed cements, and owe their hydraulic properties to the formation during burning of silicates and aluminates of lime. On mixing the burned ground rock with water, these take up the latter and crystallize, thereby producing the set of the cement.

Hydraulic cements can be divided into the following classes: Pozzuolan cements, hydraulic limes, natural cements, and Portland cements.

Pozzuolan Cement (1, 53).—This is produced from an uncalcined mixture of slaked lime and a silico-aluminous material, such as volcanic ash or blast-furnace slag.

This process was known to the ancients, and is named from its early use around Pozzuolano, Italy. The composition of an Italian Pozzuolano earth may vary between the following limits:[1] SiO_2, 52–60; Al_2O_3, 9–21; Fe_2O_3, 5–22; CaO, 2–10; MgO, up to 2; alkalies, 3–16; H_2O, up to 12.

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[1] Schoch, Die moderne Aufbereitung u. Wertung der Mörtel Materialien, Berlin, 1896.

No volcanic ash, for use in Pozzuolan cement, is worked in the United States, although deposits of the material are known to occur in the Rocky Mountain and Pacific Coast states. Little slag cement is now made in the United States (1).

High-alumina cement is a lime aluminate made by actually fusing a mixture of limestone and bauxite with coke in a furnace. The slag is ground and has an approximate composition of CaO, 50 per cent; Al_2O_3, 40 per cent; SiO_2, etc., 10 per cent. The cement is lower in lime than true Portland, its color is almost white, and it hardens so rapidly as to make a good heavy gun platform in 24 hours. Its resistance to sea water seems to exceed that of Portland.

Hydraulic limes (1) are formed by burning a siliceous limestone to a temperature not much above that of decarbonation. Owing to the high percentage of lime carbonate, considerable free lime appears in the finished product. Hydraulic limes generally have a yellow color, and a gravity of about 2.9. They slake and set slowly, and have little strength unless mixed with sand. This class is of little importance in the United States. They are, however, of great importance in Europe, and it may be of interest to give a few analyses of the raw material used abroad (1):

ANALYSES OF HYDRAULIC LIME ROCKS

	1	2	3	4
Silica (SiO_2)	14.30	11.03	7.60	17.00
Alumina (Al_2O_3)	.70	3.75	.75	1.00
Iron oxide (Fe_2O_3)	.80	5.07		——
Lime (CaO)	46.50	43.02	50.05	44.80
Magnesia (MgO)	undet.	1.34	.30	.71
Carbon dioxide (CO_2)	36.54	35.27	41.30	35.99
Water				

1. Teil, France. 2. Hausbergen, Germany. 3. Malain, France. 4. Senonches, France.

In the best types of hydraulic limestones, silica varies between 13 and 17 per cent, while alumina and iron oxide together rarely exceed 3 per cent.

Natural Rock Cements (1, 43).—These, known also as Roman cement, quick-setting cement, and Rosendale cement, are made by burning a silico-aluminous limestone (containing from 15 to 40 per cent clayey impurities) at a temperature between decarbonation and clinkering. The product shows little or no free lime. The following analyses will give some idea of the range in composition of natural cement rocks quarried in the United States:

ANALYSES OF NATURAL CEMENT ROCKS

	UTICA, ILL.	LOUISVILLE DISTRICT	FORT SCOTT, KAN.	HANCOCK, MD.	HANCOCK, MD.	MANKATO, MINN.
SiO_2	17.01	15.21	17.26	19.81	24.74	10.10
Al_2O_3	3.35	4.07	2.05	7.35	16.74	2.78
Fe_2O_3	2.39	1.44	5.45	2.41	6.30	1.34
CaO	32.85	33.99	34.45	35.76	23.41	25.96
MgO	8.45	7.57	5.28	2.18	4.09	14.91
Alk	n.d.	—	—	n.d.	6.18	3.50
SO_3	1.81	—	—	n.d.	2.22	.26
CO_2	34.12	35.03	32.87	31.74	22.90	41.29
H_2O					—	—

	LAWRENCEVILLE, N. Y.	LAWRENCEVILLE, N. Y.	HOWES CAVE, N. Y.	JAMESVILLE, N. Y.	AKRON-BUFFALO DISTRICT	MILWAUKEE WIS.
SiO_2	10.90	23.80	12.89	10.97	9.03	17.56
Al_2O_3	3.40	4.17	11.15	4.46	2.25	1.40
Fe_2O_3	2.28	4.71		1.54	.85	2.24
CaO	29.57	22.27	30.90	27.51	26.84	27.14
MgO	14.04	12.09	9.38	16.90	18.37	13.89
Alk	n.d.	n.d.	—	—	.85	—
SO_3	.61	.90	—	—	n.d.	—
CO_2	37.90	31.00	34.60	37.94	40.33	36.45
H_2O	n.d.	n.d.	—	—	.98	—

Natural cements differ from lime in possessing hydraulic properties and refusal to slake unless ground very fine. They differ from Portland cements in lighter weight, lower temperature of burning, quicker set, lower ultimate strength, and greater latitude of composition. Magnesia is not regarded as a detrimental impurity in natural cements as it is in Portland cement.

The following are some analyses of the burned material:

ANALYSES OF SOME NATURAL ROCK CEMENTS

	CaO	MgO	SiO_2	Al_2O_3	Fe_2O_3	Na_2O, K_2O	IGNITION
Natural rock cement, Rosendale, N. Y. . .	34.38	18	30.5	6.84	2.42	3.98	3.78
Natural rock cement, Akron, N. Y. . . .	40.68	22	22.62	7.44	1.40	2.23	3.63
Natural rock cement, Cumberland, Md. .	43.97	2.21	22.38	11.71	2.29	9.00	2.44
Roman cement, Rüdersdorf, Germany .	56.45	4.84	27.88	6.19	4.64	—	—

Portland Cement (1).—Portland cement is the product obtained by burning a finely ground artificial mixture consisting essentially of lime, silica, alumina, and some iron oxide, these substances being present in certain definite proportions. Portland cement was first made by Joseph Apsdin, of Leeds, England, who desired to make an artificial cement that would replace natural hydraulic cements. It received its name because it hardened under water to a mass resembling the Portland stone of England.

The following combinations of raw materials are at present used in the manufacture of true Portland cement in the United States: *bog lime and clay; limestone and clay, or shale; chalk and clay; pure limestone and argillaceous limestone; limestone and granite.*

In these combinations it is evident that the substances first named supply most of the lime and the second most of the silica, alumina, and iron. In the fourth the argillaceous limestone supplies some lime, as well as the silica and alumina. The nature of the raw materials chosen depends to a large degree on the location of the plant, whether in a limestone- or a bog-lime-producing region. Where both of these raw materials are available, as in parts of New York, questions of manipulation in the process of manufacture govern the selection of one or the other.

Bog limes, for examples, though easier to excavate and reduce than limestones, contain so much more organic matter and water than limestones that they are more expensive to handle and prepare. Bog lime beds are likewise apt to be of limited extent and irregular, while limestone beds are, so far as the needs of a manufacturing plant are concerned, practically limitless.

Comparing clay and shale,[1] the former is often easier to excavate, but, on account of the water it contains, has to be dried before it can be ground and

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[1] It is probable that the refuse of many slate quarries could also be used in place of shale.

mixed. The fossils in shales are sometimes an important source of calcium carbonate, and then careful grinding and mixing is necessary to bring about a uniform distribution of the lime through the mass.

Argillaceous limestone, mixed with a much smaller quantity of purer limestone, as in Pennsylvania and New Jersey, is superior to a limestone and clay mixture, because less thorough mixing and fine grinding are required. In such cements, even when grinding and mixing are incompletely done, the particles of argillaceous limestone so closely resemble the proper mixture in chemical composition as to affect the result but little.

The following table gives the analyses of some of the raw materials used in manufacture of Portland cement:

ANALYSES OF RAW MATERIALS USED FOR PORTLAND CEMENT

LOCALITY	MATERIAL	SiO_2	Al_2O_3	Fe_2O_3	$CaCO_3$	$MgCO_3$	H_2O + ORG. MATTER	MISCEL.
Lehigh Valley, Pa.	Calc. shale or cement rock	15.40	4.26	1.38	74.66	2.66	1.88	$CaSO_4$ .86
	Limestone	5.87	1.59		88.00	4.00		
	Mixture	13.97	5.07	1.88	74.1	2.04	1.82	
Glens Falls, N. Y.	Limestone	3.3	1.3		52.15	CaO 1.58	MgO	SO_3 .3
	Clay	55.27	28.15		CaO 5.84	MgO 2.25	8.37	SO_3 .12
Warners, N. Y.	Bog lime	.26	.10		94.39	.38	4.64	
	Clay	40.48	20.95		25.80	.99	8.50	
Sandusky, Ohio	Bog lime	Insol. 1.28	1.72		92.70	.50	1.13	$CaSO_4$ 2.06
	Clay	64.70	11.9	9.9	CaO .90	MgO .70	11.9	
White Cliffs, Ark.	Chalk	7.97	1.09		88.64	.73		
	Clay	53.3	23.29	9.52	CaO .36	MgO 1.49	5.16	

In the selection of the raw materials the aim of the manufacturers is to produce a raw mixture which runs approximately 75 per cent carbonate and the balance clay. In the burning of this mixture, which must be done at a high temperature, a fused mass termed clinker is formed. This consists largely of $3CaO \cdot SiO_2$, $2CaO \cdot SiO_2$, $3CaO \cdot Al_2O_3$, $5CaO \cdot 3Al_2O_3$, with a little free lime.[1] The finely ground clinker, which is the Portland cement, is blue to gray in color, and has a specific gravity of 3 to 3.25.

[1] Rankin and Wright, Amer. Jour. Sci., Jan., 1915.

In some localities argillaceous limestones are found which approach so closely to the proper composition, that but little additional material has to be added to make a mixture of the proper composition.

The raw materials must not only have the proper composition, but they also must show proper physical character, extent, and location, with respect to market and fuel supplies. As regards composition, 5 or 6 per cent magnesium carbonate is about the permissible limit. Chert, flint, or sand are also undesirable impurities, and alkalies and sulphates should not exceed 3 per cent. The clay used, if non-calcareous, should not contain less than 55 per cent silica nor more than 70 per cent, and the ratio of ($Al_2O_3 + Fe_2O_3$) to SiO_2 should be about 1 : 3. High alumina clays are undesirable because they raise the vitrification temperature and quicken the set of the cement.

The following are analyses of Portland cement mixtures before burning: [1]

ANALYSES OF PORTLAND CEMENT MIXTURES

SiO_2	12.85	12.92	14.53	14.94
Al_2O_3	4.92	4.83	6.56	2.66
Fe_2O_3.	1.21	1.77	——	1.10
$CaCO_3$	76.36	75.53	75.13	75.59
$MgCO_3$.	2.13	4.34	4.32	4.64
	97.47	99.39	99.53	98.93

The following analyses wil lserve to illustrate the composition of some American Portland cements:

ANALYSES OF CEMENTS

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3
Empire brand	22.04	6.45	3.41	60.92	3.53	2.73
Sandusky	23.08	6.16	2.90	62.38	1.21	1.66
Alpha	22.62	8.76	2.66	61.46	2.92	1.53

Distribution of Lime and Cement Materials in the United States. *Limestone for Lime.*—Limestones of suitable composition for making lime are so widely distributed that no particular regions or states require special mention.[2] In the New England states, crystalline

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[1] U. S. Geol. Surv., Min. Res., 1907.

[2] Analyses and detailed descriptions will be found in the areal reports, mentioned in the list of References.

limestones are the chief source of supply. In the Appalachian states, from New York to Alabama, there are many Paleozoic limestones of high purity, notably the Trenton, Lower Helderberg, and Carboniferous limestones (see state references). The same series of rocks are also of importance in the Mississippi Valley states from Tennessee (51) to Michigan (36). Lime of excellent quality is obtained from the Subcarboniferous in Iowa (24), Kansas (27), and Missouri (53), and from the Cretaceous in Texas (53). Limestones suitable for lime manufacture are also found in numerous localities in the Pacific coast states (53).

Hydraulic Limes (1).—Largely because of the great abundance of natural-rock cements, which are of superior value, these materials, though much used abroad, are of no importance in the United States.

It was stated that in 1906 and 1907[1] several natural cement plants had been making and marketing a true hydraulic lime, but little or none is made now.

Natural Rock Cements (1, 43, 53).—Calcareous rocks for making natural cement are found at a number of points, the more important ones being given in summarized form in the following table.

GEOLOGIC AGE OF NATURAL CEMENT ROCKS IN THE UNITED STATES

STATE	GEOLOGIC AGE	STATE	GEOLOGIC AGE
Georgia	Cambro-Ordivician	Ohio	Devonian
Illinois	Ordovician	Pennsylvania	Ordovician
Indiana-Kentucky	Devonian	Texas	Cretaceous
Kansas	Carboniferous	Virginia	Cambrian
Maryland	Silurian	West Virginia-Maryland	Cambrian
Minnesota	Ordovician	Wisconsin	Devonian
New York	Silurian		
North Dakota	Cretaceous		

In many districts the cement rocks occur in more than one bed, and may be interstratified with limestones or shales of no economic value for cement making.

Some of the important occurrences may be briefly referred to.

New York (43).—This state contains four localities in which natural cement rock is found, these in the order of their importance being: (1) Rosendale District in Ulster County; (2) Akron-Buffalo District in Erie County; (3) Fayetteville-Manlius District in Onondaga

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[1] U. S. Geol. Surv., Min. Res., 1907: 490, 1908.

County (mostly); (4) Howe's Cave, Schoharie County. The cement rock in all cases is obtained from the Silurian.

In Rosendale district (Fig. 51) two distinct beds are worked usually, which differ in chemical composition and geologic age. The lower or dark bed, according to Darton, averages about 21 feet, while the upper or light bed is about 11 feet, the two being separated by 14–15 feet of worthless limestone.

The lower bed rests directly on Clinton quartzite.

The folding and faulting are intense in the Rosendale district, but the beds show little disturbance in the others.

Other States.—Southward from New York natural cement rock is quarried at a number of points along the Appalachians, but owing to the folded character of the beds the extraction is often difficult. (Pl. XX, Fig. 1). The Lehigh district of Pennsylvania is an important producer of natural cement, but still more so of Portland cement.

Several beds are worked in the Cumberland-Hancock area of Maryland (32, 33), while in Virginia (54) limestones of suitable composition for natural cement manufacture occur at several horizons, but only the argillaceous magnesian limestones found in the lower part of the Shenandoah (Cambro-Ordovician) limestone will probably prove of economic value. Others are worked in Georgia (17, 53.)

Natural cement has been made at Utica, Ill. (53), from dolomitic limestone, for nearly fifty years.

Near Milwaukee, Wisconsin (53), the cement beds occur interstratified with Devonian limestone (Pl. XX, Fig. 2). Farther west near Fort Scott, Kansas, slightly magnesian Carboniferous argillaceous limestones, are worked.

Cement rock is also obtained in southeastern Ohio (44), and at Louisville, Kentucky (29).

Portland Cements.—Clay and limestone, in one form or another, are so widely distributed throughout the United States that it is possible to manufacture Portland cement at many localities, and the geologic age of the materials used ranges from Ordovician to Pleistocene (53), (Refs. under different states). Thirty-five states were making this cement in 1935, the factories being spread over the country from the Atlantic to the Pacific (Fig. 59).

Pennsylvania.—By far the most important district is the Lehigh Valley in Pennsylvania, which supplies about 18 per cent of the domestic product.

The cement belt lies in Northampton and Lehigh counties, Pennsylvania (Fig. 57), and the geologic section involved ranges from (49) Cambrian to Hudson River shale.

PLATE XX

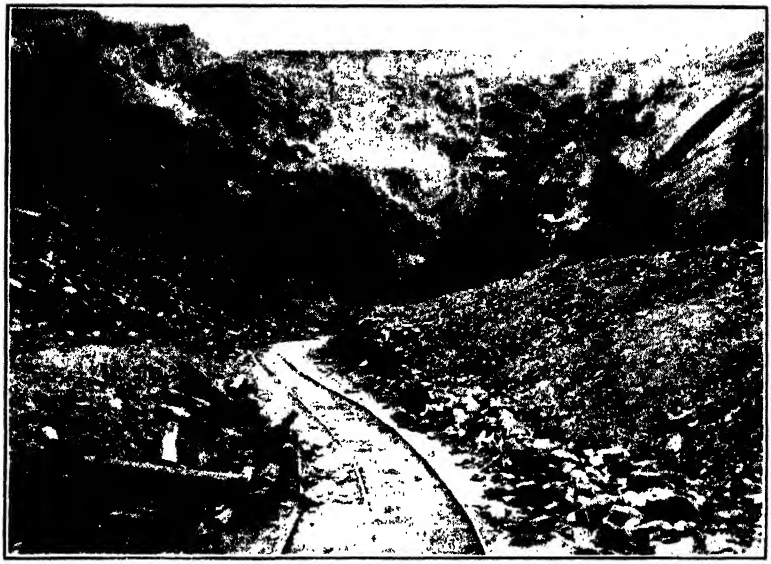

FIG. 1.—Quarry of natural cement rock, Cumberland, Md. (*H. Ries, photo.*)

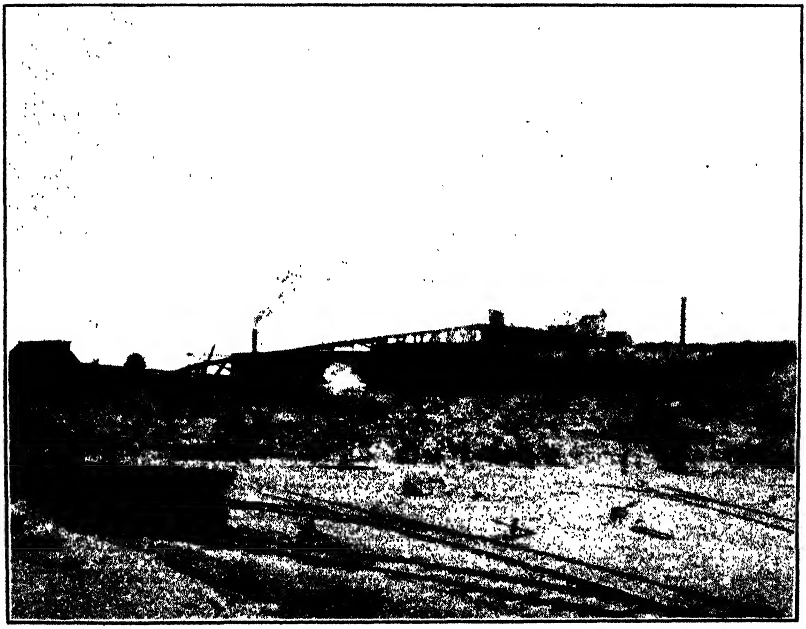

FIG. 2.—Natural cement rock quarry, Milwaukee, Wis. (*H. Ries, photo.*)

The lower member of the Trenton varies in its physical character, and furnishes material to raise the lime content of the cement rock for Portland cement manufacture. Its lime carbonate content varies from 80 to 97 per cent, but occasionally drops to 70 per cent, while the magnesian carbonate runs from 1.5 to 3 per cent. In a few it reaches 20 per cent, and these highly magnesian layers cause trouble in quarrying. The upper or slaty member of the Trenton grades into the lower one. The rocks of this region have, by post-Carboniferous

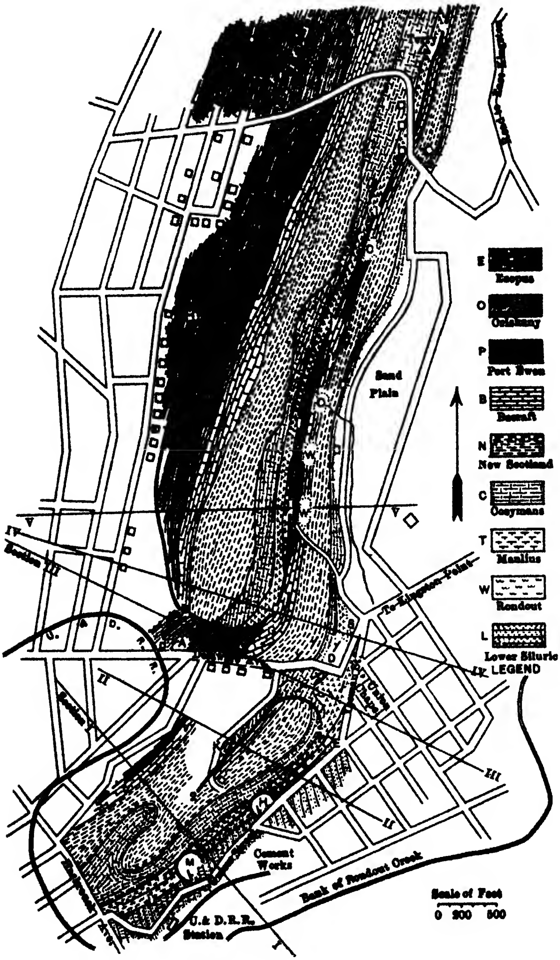

FIG. 56.—Geologic map through the Vlightberg at Rondout, N. Y. (*After van Ingen, N. Y. State Mus., Bull.* 69.)

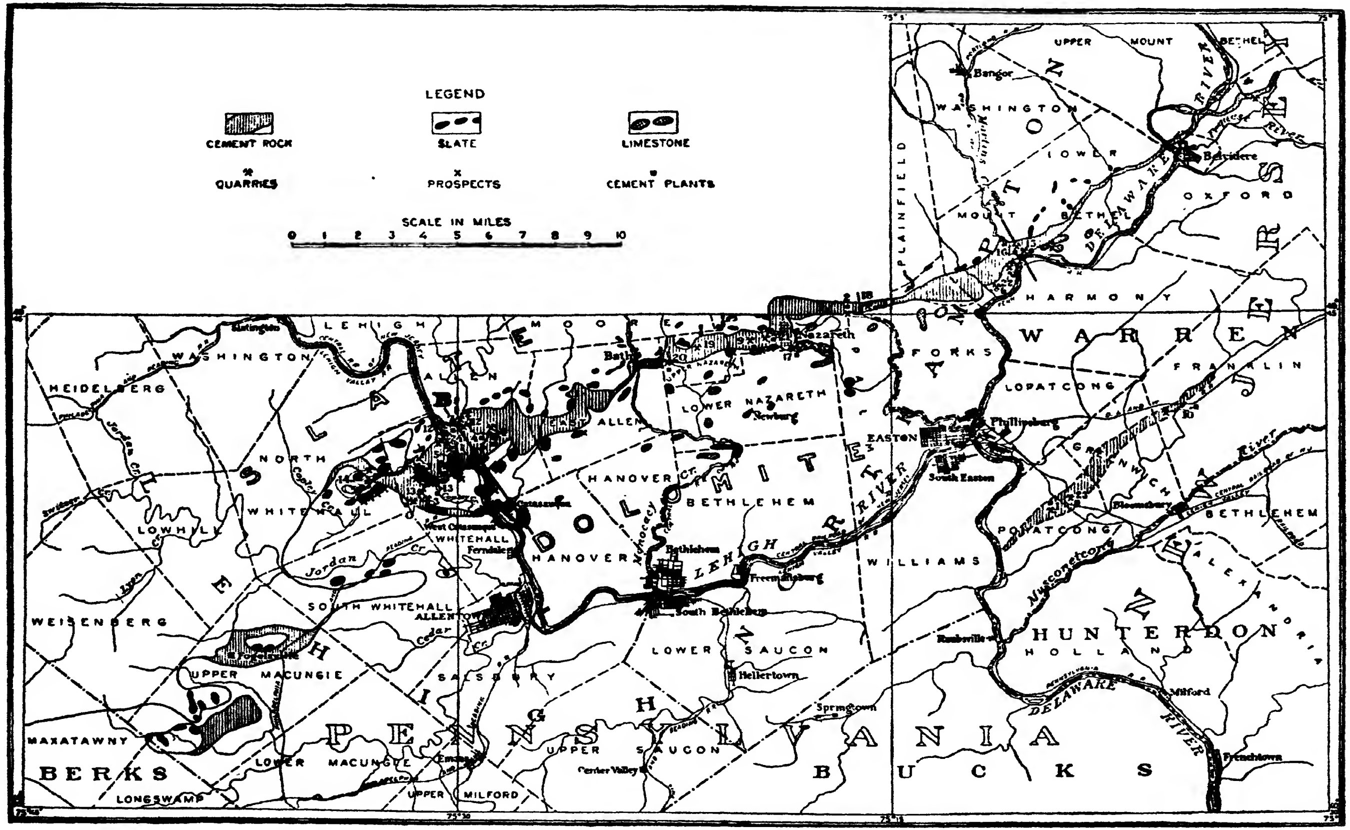

FIG. 57.—Map of cement belt of eastern Pennsylvania. (*After Peck, Econ. Geol.* III.)

folding, been bent into a complex series of folds (Fig. 58), whose axes trend northeast and southwest, and while the folds are in many cases overturned, there is comparatively little faulting.

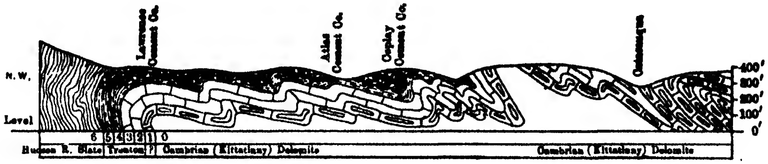

FIG. 58.—Diagrammatic section five miles long extending northwest from Catasauqua. 0 and 1 = Cambrian dolomite; 2 and 3 = Lower Trenton, rocks high in lime; 4 = cement rock, Upper Trenton, averaging 70 to 80 per cent $CaCO_3$; 5 = Upper Trenton cement rock with less than 70 per cent $CaCO_3$; 6 = Hudson River slate. (*After Peck, Econ. Geol.*, III.)

The cement rock extends as a continuous zone or belt of varying width southwest across Northampton County from the Delaware to the Lehigh River (Fig. 57), crosses in to Lehigh County, and ends abruptly at a point four and a half miles west of Coplay.

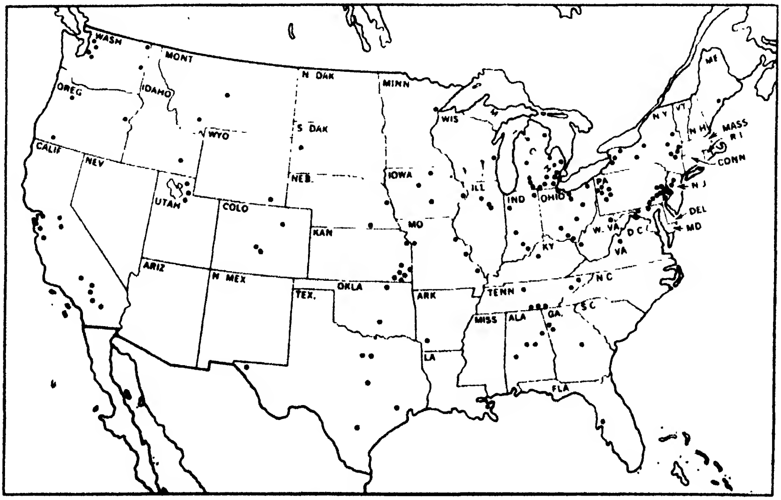

FIG. 59.—Map of United States, showing location of portland cement plants. (*Minerals Yearbook.*)

The same beds are found in the adjacent territory of New Jersey (41).

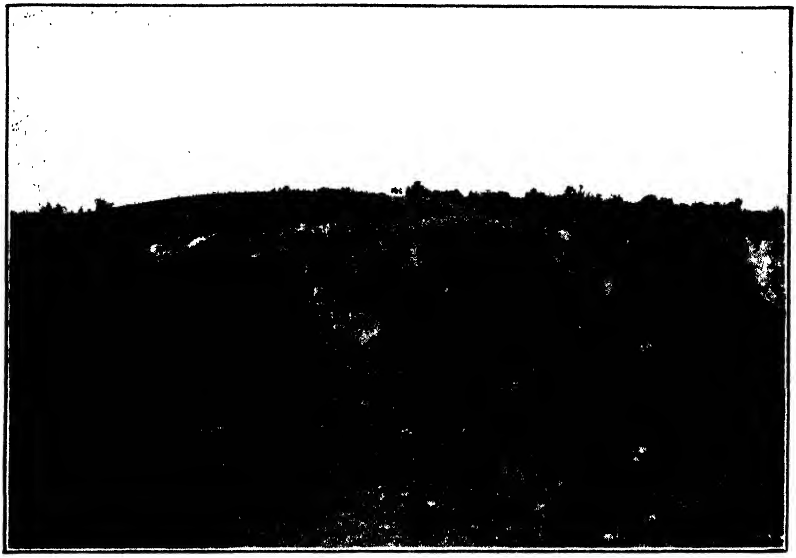

FIG. 1.—Limestone quarry in Lehigh cement district, Pennsylvania. (*H. Ries, photo.*)

FIG. 2.—Marl pit at Warners, N. Y. The dark streaks are peat, and the marl is underlain by clay. (*H. Ries, photo.*)

Other States.—In the eastern half of New York (43) the Ordovician and Silurian limestones form an inexhaustible supply of material to mix with Pleistocene surface clays. In the south central part of New York the Tully limestone and Hamilton shales are employed, while in the Hudson River Valley Silurian limestones and clay are used.

Ohio (44), Indiana (20–22), and Michigan (35–37) are important Portland-cement-producing states. Although bog lime was formerly extensively used in Indiana and Michigan in place of limestone, its use has been discontinued in the former state, and only three plants are employing it in Michigan.

In Kansas Carboniferous shales and limestones are used for making Portland cement (25, 28), and in Texas and Arkansas the Cretaceous shales and chalky limestones are employed (15, 17, 53); Alabama has a Cretaceous limestone of such composition that very little clay or shale has to be added to it (8–10). Portland cement is also manufactured in North Dakota (53), South Dakota (50), Utah (53), Colorado (53), and California (12, 53).

Cement Materials in Canada (60–69).—Portland cement plants are scattered over the Dominion from east to west. In Quebec and Ontario the Paleozoic limestones are used, and mixed with shales or surface clays, but a number of the Ontario plants are employing bog lime for the calcareous ingredient of the cement. As limestones are scarce on the Great Plains, there are few cement plants in this area, but between Calgary and the Pacific Coast, where Paleozoic and Mesozoic limestones are plentiful, some half-dozen plants have been established. There is also at least one in operation on Vancouver Island, which is using a mixture of Cretaceous limestone and a metamorphosed dacite or andesite.[1]

Uses of Lime (43, 2).—The most important single use of lime is for mixing with sand to form mortar, and many thousands of tons are used annually for this purpose. In addition to this use lime is employed for a great variety of purposes, of which the following are the most important: as a purifier in basic steel manufacture; ammonium sulphate, soap, bone ash, gas, potassium dichromate, paper, pottery glazes, and calcium carbide; as a disinfectant; as a fertilizer; as a polishing material; for dehydrating alcohol, preserving eggs, and in tanning.

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[1] C. H. Clapp, private communication.

Uses of Cement (1).—The use of hydraulic cement is constantly increasing in the United States, this being specially true of Portland cement, which is superseding natural cement to a great extent, and is finding an increasing use in building and engineering operations. For pavements, Portland cement is probably more extensively used in America than in any other country; and as an ingredient of concrete it is widely employed.

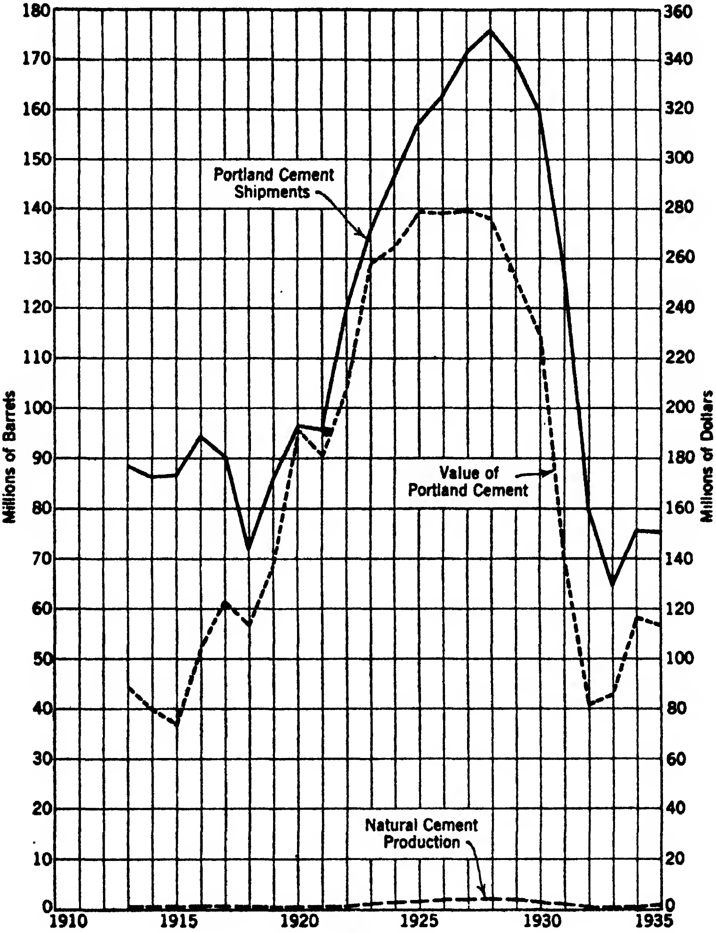

FIG. 60.—Chart showing production and value of Portland cement and natural cements from 1913 to 1935. (*Minerals Yearbook.*)

In recent years several special types of cement have been developed, such as high early strength cement, and one having a low heat of hydration. This latter is important in connection with the construction of such large concrete masses as Boulder Dam. Another type is one showing low heat of hydration and also resistance to active sulphate solutions such as sea water or alkali-salt solutions. This type has been used on the Norris and Fort Peck dams.

The Production of Cement.—The diagram (Fig. 60) shows the remarkable increase in the production of Portland cement up to 1928, and the small natural cement production, the latter being now of little importance in the cement industry.

The shipments of Portland cement in 1940 amounted to 130,349,786 barrels valued at about $190,078,068. The price in 1940 averaged $1.46. The production has increased 100 per cent in quantity since 1934, but is still below the peak of 1928. In 1940, the shipments of masonry cements was 2,514,597 barrels valued at $3,386,801. This represents an increase of about 50 per cent in quantity of production in the past five years.

Portland cement plants were in operation in 36 states in 1940 (Fig. 59), Pennsylvania being first, California second and Michigan third.

The imports of all cements in 1940 amounted to 535,619 barrels, valued at $497,838.

The sales of cement in Canada in 1939 amounted to 5,731,264 barrels, valued at $8,511,211. The imports for the same year of Portland cement and hydraulic lime were 16,620 barrels, valued at $58,316. The exports were 156,556 barrels, value $159,579.

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CHAPTER VI

SALINES AND ASSOCIATED SUBSTANCES

Under the heading of salines are included the substances, salt, borax, sodium sulphate, sodium carbonate, sodium nitrate, and potassium salts. They are all easily soluble substances, which are found dissolved in the waters of lakes, seas or oceans, or may be present at times in the rocks or soils. As a result of the leaching of the last-named by underground waters, they may be brought to the surface and deposited there as an incrustation often found in arid regions; or they may be carried into bodies of water, where they remain in solution until the waters by evaporation leave them behind as residues. Either mode of deposition would be characteristic of an arid climate.

The above outlines in general their manner of formation, although there may be exceptions, as will be seen in subsequent pages.

Bromine, calcium chloride, and iodine are also treated in this chapter, because of the association of the first two with sodium chloride, and of the third with sodium nitrate.

From what has been said above, it will be readily seen that bodies of saline water may vary not only in their degree of concentration, but also in the kind and relative amounts of the different saline substances which they contain in solution.

The analyses given on p. 166 will show this variation.

SALT

Types of Occurrence.—Common salt, the chloride of sodium (NaCl), is a widely distributed mineral, being found: (1) in solution in sea water or salt lakes; (2) as solid masses termed rock salt; (3) as natural brine in cavities or pores of the rocks, from which it may exude as salt springs or be tapped by wells; and (4) in marshes and soils.

Although all four of these types of occurrence may serve as commercial sources of salt, it is only the second that is of great economic importance.

ANALYSES OF LAKE AND SEA WATERS

	I	II	III	IV	V	VI	VII	VIII	IX
Cl	55.292	55.69	70.25	67.66	42.04	53.32	3.18	23.34	32.27
Br	.188	tr.	1.55	1.98	.05	.06	—	—	.04
SO_4	7.692	6.52	.21	.22	23.99	17.39	7.47	12.86	.13
CO_3	.207	—	tr.	tr.	.37	—	38.73	23.42	22.47
Na	30.593	32.92	6.33	10.20	24.70	11.51	10.10	37.93	38.10
K	1.106	1.70	1.70	1.62	.54	1.83	4.56	1 85	1.52
Ca	1.197	1.05	5.54	1 51	2.29	—	12.86	.04	.03
Mg	3.725	2.10	14.42	16.81	5.97	15.83	4.15	.10	.35
SiO_2	—	—	tr.	tr.	—	—	18.95	.14	.01
PO_4	—	—	—	—	—	—	—	—	.02
B_4O_7	—	—	—	—	—	—	—	.32	5.05
Salinity	3.301[1]	23.036[1]	20.709[1]	24.573[1]	1.294[1]	28.50[1]	.73[2]	51,170[2]	76,560[2]

[1] Salinity per cent.

[2] Salinity parts per million.

I. Mean of 77 analyses of sea water. II. Great Salt Lake, the same type as ocean water, but having no carbonates, higher sodium, and lower magnesium. III. Dead Sea water from depth of 20 meters. IV. The same, depth of 120 meters. This lake derives its chlorides and sulphates from leaching of surrounding deposits containing salt and gypsum, but carbonates and gypsum are deposited where the Jordan, its main feeder, enters the lake, hence the dissolved substances are largely chloride. V. Caspian Sea. VI. Karaboghaz Gulf. Note the quantity of Mg and SO_4. VII. Lake Tahoe, Calif. VIII. Mono Lake, Calif. This yields trona ($Na_2CO_3 \cdot HNaCO_3 \cdot 2H_2O$), on evaporation, and is typical of lakes occupying closed basins, in regions of great volcanic activity, the products of eruption having been leached, and the waters showing an abundance of sulphate and carbonates of sodium, as well as some chloride. Waters of this type may on evaporation also yield glauber's salt, borates and perhaps even nitrates. IX. Borax Lake, Calif. This is said to derive its boron from hot springs. Analyses I-IX from Clarke, United States Geological Survey, Bulletin 616, 1916.

Occurrences of Salt in Sea and Lake Waters.—Salt is present in all ocean water, and also in that of most inland lakes or seas having no outlet, as can be seen from the analyses in the preceding table.

Salt is sometimes obtained by artificial evaporation of the water of either the ocean or salt lakes; but in the United States this plan is profitable only under exceptional conditions, as around San Francisco Bay, California (11), or Great Salt Lake, Utah (1).

Natural Brines.—These, sometimes found in porous layers of the rocks, may result either from sea water imprisoned in the layers of sediment (20) or from the solution of rock salt by percolating waters.

Salt Marshes and Soils.—When away from the ocean, these owe their salinity to the infiltration of brine from neighboring saliferous formations. They sometimes represent the site of former salt lakes.

Rock Salt.—Rock salt, which is the most important source of commercial salt, occurs commonly in beds of variable thickness and purity interbedded with sedimentary rocks, such as shales or sandstones. Gypsum or anhydrite are common associates, and more rarely limestone, or easily soluble compounds of magnesia, potash, and lime. Less often, the rock salt is found in domelike masses in stratified rocks, but not conformable with them. Rock salt deposits vary in thickness from a few inches up to as much as 3600 feet (Sperenberg, Germany); and while found in all geological formations from the Cambrian to the Pleistocene, except the Cretaceous, the rock salt of the United States is not found in formations older than the Upper Silurian.

Origin of Rock Salt (1–9).—One of the interesting problems of geology has been to find a correct theory to account for the origin of salt deposits. Such a problem is not as simple as it may appear at first sight, for it must explain (1) the formation of salt deposits of extraordinary thickness, (2) the association of gypsum, either above or below the salt, and (3) the presence of other minerals, which may or may not be saline ones.

Evaporation Theory.—It is generally believed that most deposits of rock salt, or of rock salt and gypsum, have been formed by the evaporation of oceans and lakes, this process having gone on during a number of periods from the Silurian to the present.

If a body of salt water is evaporated until precipitation begins, the least soluble salts will generally separate out first, while the most soluble ones do not precipitate until the last.

Assuming then a basin filled with sea water, similar in composition to that of the present oceans, the order of precipitation would be: (1) iron hydroxide; (2) calcium carbonate; (3) calcium sulphate; (4) sodium chloride; and (5) easily soluble compounds, such as sulphates and chlorides of potash and magnesia, etc., these being often of quite complex composition.

This order of precipitation was demonstrated as early as 1849, by J. Usiglio,[1] who made an elaborate series of evaporation tests of Mediterranean water.

The four following analyses, reduced to ionic form and to percent-

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[1] Ann. chim. phys., 3d ser., XXVII: 92, 192, 1849.

ages of total solids, represent the composition of the sea water evaporated to different densities.[1]

ANALYSES OF MEDITERRANEAN WATER AND BITTERNS

CONSTITUENTS	A	B	C	D
Cl	54.39	56.18	49.99	49.13
Br	1.15	1.22	2.68	3.03
SO_4	7.72	5.78	14.64	17.36
Co_3	.18	——	——	——
Na	31.08	32.06	20.39	12.89
K	.71	.78	2.25	3.31
Ca	1.18	.26	——	——
Mg	3.59	3.72	10.05	14.28
Salinity	3.766	27.546	33.712	39.619

A. The water itself, density 1.0258. B. Bittern of density 1.21. C. Bittern of density 1.264. D. Bittern of density 1.32.

Clarke considers that the bromine determinations are excessive, and that the potash is too low. However, the analyses show: (1) the elimination of calcium as carbonate, and later as sulphate; (2) the subsequent deposition of sodium chloride, and (3) the still later accumulation of the more soluble substances in the mother liquors.

Simple as the phenomena of concentration of sea water would appear, they may yet be complex, and it is possible as well as probable that the order of precipitation is not always in the order of solubility, this being governed to some extent at least by other salts present, degree of concentration and temperature.

The Stassfurt Section.—There are few salt deposits in the world that show such a complete series of precipitates as Usiglio obtained in his experiments, and the most nearly perfect one is that found at Stassfurt, in Prussia, where more than thirty saline minerals are known to occur.

The section which occurs in strata of Upper Permian age is as follows:[2]

1. Lower Buntsandstein (capping rock)	
2. Red clay and concretions of anhydrite and salt cavities	20 m.
3. Anhydrite Layer (No. IV)	4 m.
4. Rock salt	40 m.

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[1] Quoted by F. W. Clarke, U. S. G. S., Bull. 616: 219.

[2] Grabau, Principles of Stratigraphy, p. 371, quoted from Walther.

5. Anhydrite No. III (Pegmatite anhydrite)	5 m.
6. Red clay	10 m.
7. Younger rock salt, with about 400 annual rings of polyhalite	80 m.
8. Main anhydrite, No. II	30–80 m.
9 Salt clay, averaging	5–10 m.
10. Carnallite ($KCl, MgCl_2 6H_2O$) zone	15–40 m.
11. Kieserite ($MgSO_4, H_2O$)	18 m.
12. Polyhalite ($K_2SO_4, MgSO_4, 2CaSO_4, 2H_2O$) zone	35 m.
13. Older rock salt with about 3000 annual rings averaging	245 m.

Nos. 11, 12, 13 have a combined thickness, ranging from 150 to perhaps 1000 meters. (Due perhaps to subsequent thickening.) The annual rings of anhydrite form layers averaging 7 mm. thick, separating the salt into sheets of 8 or 9 mm.

14. Older anhydrite (I) and gypsum, averaging	100 m.
15. Zechstein limestone or dolomite	
16. Copper slates	
17. Zechstein conglomerate	

The lower members, beginning with anhydrite I and ending with carnallite zone, form one depositional series. Above this, and separated from it by a clay member, is a second series, which lacks the more soluble salts.

Assuming then that the evaporation of a body of sea water may give a graded series as shown above, we must, in order to apply it, consider the following: (1) the most soluble salts are often wanting; (2) salt and gypsum may occur singly; and (3) many salt and gypsum deposits exhibit great thickness.

Mother liquor salts may never have been precipitated because the water did not become sufficiently concentrated, or if precipitated it is possible that they may have been redissolved.

Evaporation may have proceeded far enough only to precipitate gypsum, or an earlier compound like gypsum may have been more or less replaced by a later one, and hence appear to be absent (19), which if true might explain the absence of gypsum under salt.

Another hypothesis to account for abnormalities of succession would be to assume that the earlier oceans were of a different composition from existing ones.

The most difficult problem, however, is to explain the formation of very thick deposits of salt between stratified rocks, on the basis of simple evaporation of a body of water.

We can easily understand the formation of a thin bed of salt (or gypsum) in this way, but the insufficiency of this explanation appears, when we find that the formation of 15 feet of gypsum would require the evaporation of 35,000 feet of existing ocean water, and since salt is more soluble, a much greater depth would be required.

Bar Theory.—This theory, which seeks to explain the origin of salt deposits of great thickness, was first suggested by G. Bischof,[1] and later elaborated by Ochsenius (1, 7). It assumes a barrier partly shutting out the ocean water. Evaporation on the inclosed area of the sea exceeds the supply of water from inflowing rivers and from the open ocean. Therefore the water on the surface of the bay becomes more dense and settles to the bottom of the basin, being prevented from escape into the open ocean by the barriers at the entrance. As the surface of the bay is lowered by evaporation, ocean waters enter, furnishing a constant supply of salt. If the barrier is complete, forming a bar, sea water may enter at times of high tide or storm. Eventually evaporation will so concentrate the solution in the bay as to cause the precipitation of sodium chloride and other salts. So long as these conditions lasted, salt would be precipitated, but beds of clayey material would be deposited wherever fine-grained sediment was supplied from the land.

This theory has appealed to many, and the case of Karaboghaz Gulf on the eastern side of the Caspian Sea, is often quoted as illustrative of the deposition of salts according to the hypothesis mentioned above. The Gulf referred to is connected with the sea by a shallow channel through which it is continually supplied by water, the latter delivering a daily estimated load of 350,000 tons of dissolved salts.

Analyses V and VI, p. 166, show the composition of the waters of the Caspian Sea and the Karaboghaz Gulf respectively, and brings out the marked difference in salinity.

Karaboghaz water contains 285,000 parts per million of salts, while gypsum precipitates when the concentration is 202,000 parts per million. It is a sulphate chloride bittern, in which magnesium replaces lime. We find, then, that while some gypsum is deposited around the margins, the bottom is covered by magnesium sulphate, which in places is 7 feet thick, the total deposit being estimated at 1,000,000,000 tons. The salinity, although increasing, is not yet sufficient to precipitate salt, but the water is sufficiently saline to prevent marine life, so that any animals carried into the gulf die.

Of more interest are the Suez Bittern Lakes, which were formerly a continuation of the present Gulf of Suez, and the Red Sea.

When the gulf became silted up to such an extent that the supply of water from the Red Sea just balanced the evaporation from the

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[1] Allgemeine chemische u. physikalische Geologie, II: 48, 1864.

surrounding surface of the Gulf, and the salinity was of corresponding magnitude, salt began to deposit and continued until some time after the complete separation from the Gulf of Suez and transformation into the Bittern Lakes. When the Suez Canal was cut, a salt mass 13 km. long, 7 km. broad, and averaging 8 meters in thickness was found. It showed parallel layers separated by thin layers of earthy matter and gypsum.

The operation of the bar theory is probably restricted to arid regions, where there will be little inflow of fresh water into the bay, and where evaporation will be accelerated.

Grabau points out that: (1) the bay must be connected with a large sea; (2) that there should be a contemporaneous fossiliferous series in the sea; and (3) that the salt deposits themselves, as shown by Karaboghaz and Bittern Lakes, should be fossiliferous. If these criteria fail, he believes that the deposit could not have been formed by the evaporation of sea water.

More recently Branson (2) has suggested a modified bar theory, which postulates overflow basins connected with a main one, the precipitation of the salts taking place in the former.

Desert Theory.—According to the desert theory, as suggested by Walther, extensive salt deposits might be formed by the leaching of the salt from an older more or less saliferous formation. This salt might be contained in connate waters or in the rocks. If brought to the surface either by evaporation or erosion, it may perhaps first form a crust there, and be later removed by wind or rain. If in a drainless basin, it may accumulate in a body of water within the depression. As the water evaporates, and leaves any of the salt on the drainage slopes, it may still be washed down into the contracting sea or lake, whose salinity gradually increases to such an extent that the salt begins to deposit (9).

It is not clear why the salt would not be contaminated by soil washed down the slopes.

Grabau[1] thinks that the Siluric salt of North America has been derived from connate waters of the Niagara formation, of which a vast amount has been eroded, for he says, "The fact that all around the Salina area, the Upper Siluric strata rest on Niagaran except where the continental deposits of Salina time intervene, and the further fact that no undoubted marine equivalents of the Salinan are known in North America, greatly strengthen the argument for the wholly continental origin of these salt deposits."

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[1] Principles of Stratigraphy, p. 376.

Dome Theory.—In Louisiana and Texas, as well as in Mexico, Rumania, Germany, etc., there are found a number of curious salt domes or salt ridges, which sometimes appear to have been intruded for several thousand feet into the overlying formations. Those of Europe are undoubtedly due to the salt having been uplifted by folding or faulting (5), the plastic salt having been squeezed and folded into its present form. That the foreign domes are made up of salt of sedimentary origin is universally admitted, but much doubt has been expressed regarding those of the southern states. These latter are usually circular or subcircular in plan (Fig. 61), the salt core having an area of from one to six square miles, with flanks dipping from 60 to 90 degrees. The salt core in most of the domes is covered by a cap of anhydrite, gypsum and limestone. In some, native sulphur in veinlets or irregular masses is found at the contact of the limestone and gypsum anhydrite zones, being later in origin than the others.

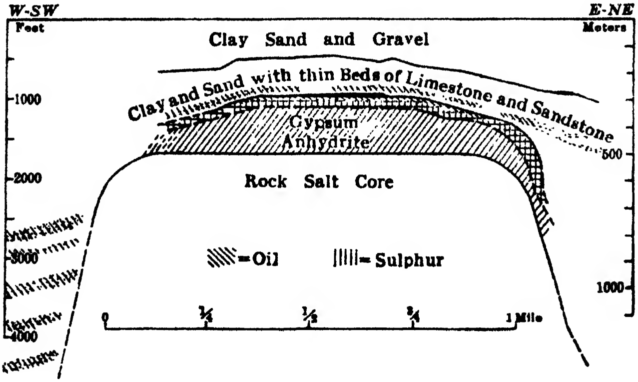

Fig. 61.—Generalized section of a salt dome. (After Barton.)

Various theories have been advanced to explain the origin of these domes (3), including deposition from rising saline waters, uplift by volcanic intrusions, etc., but the finding of fossil algæ in one, the occurrence of potash salts in some, and the demonstration that the anhydrite cap is probably in part at least sedimentary, all point to a tectonic origin for the structure.

Distribution of Salt in the United States.—Salt deposits are found in a number of states, as shown on the map, Fig. 62, but about 53 per cent of the production in 1935 came from two states, New York and Michigan. Most of the domestic production is obtained either in the form of artificial brine obtained by forcing water through wells to the

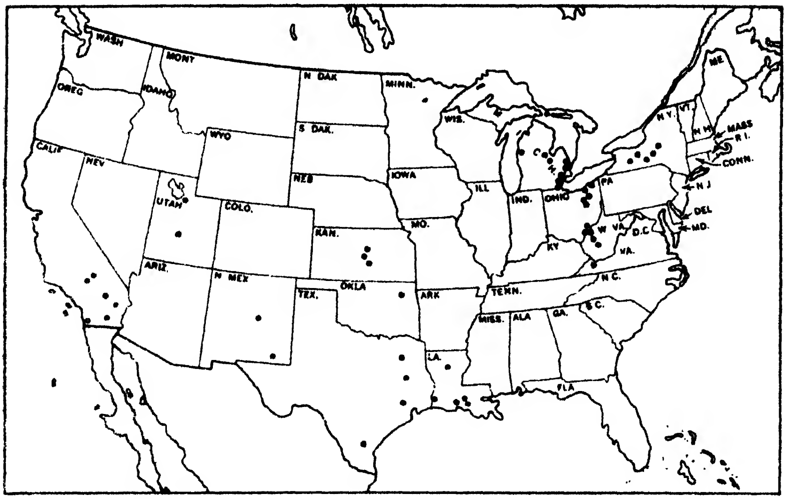

FIG. 62.—Map showing distribution of salt-producing areas in United States, compiled from *Minerals Yearbook.*

salt, which is then brought up in solution, or else as rock salt, raised through shafts from underground workings.

The range of geologic age of the United States deposits is shown in the following table:

TABLE SHOWING GEOLOGIC DISTRIBUTION OF SALT IN THE UNITED STATES

STATE	AGE	STATE	AGE
California	Present	Oklahoma	Permian (?)
Kansas	Permian	Pennsylvania	Carboniferous
Louisiana	Tertiary	Texas	Permian
Michigan	Silurian Mississippian	Utah	Recent
		Virginia	Mississippian
New York	Silurian	West Virginia	Middle Carboniferous (Pottsville)
Ohio	Silurian Mississippian		

New York (19).—Salt was manufactured from brine springs at Onondaga Lake as early as in 1788; but the presence of rock salt beds was not suspected until 1878, when a bed 70 feet thick was struck in drilling for petroleum in Wyoming County. Since then the development of the salt industry has been so rapid that for some years New York has been one of the two leading salt-producing states.

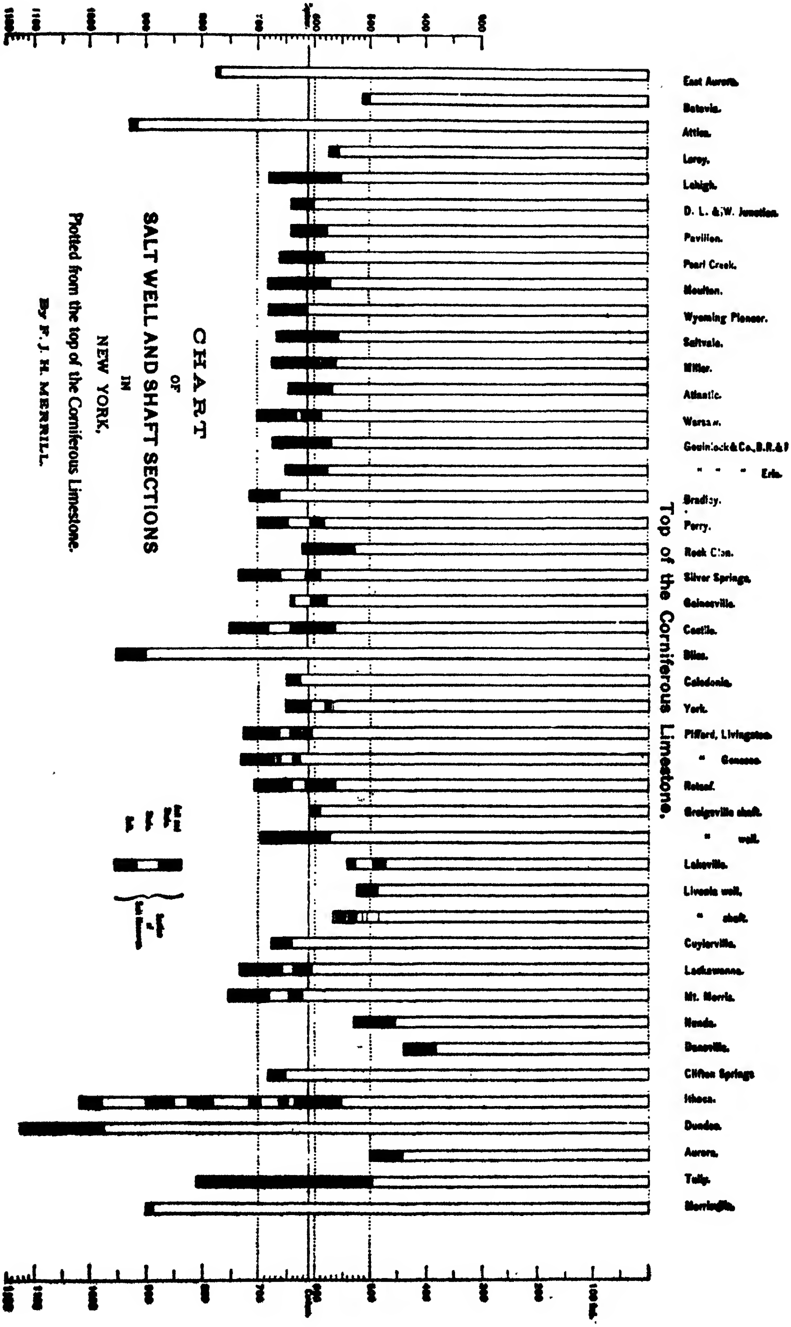

FIG. 63.—Section showing number and thickness of salt beds at different localities in New York State. (*After Merrill, N. Y. State Mus. Bull.* 11, 1893.)

PLATE XXII

FIG. 1.—Interior view of salt mine, Livonia, N. Y. Both roof and pillars are rock salt.

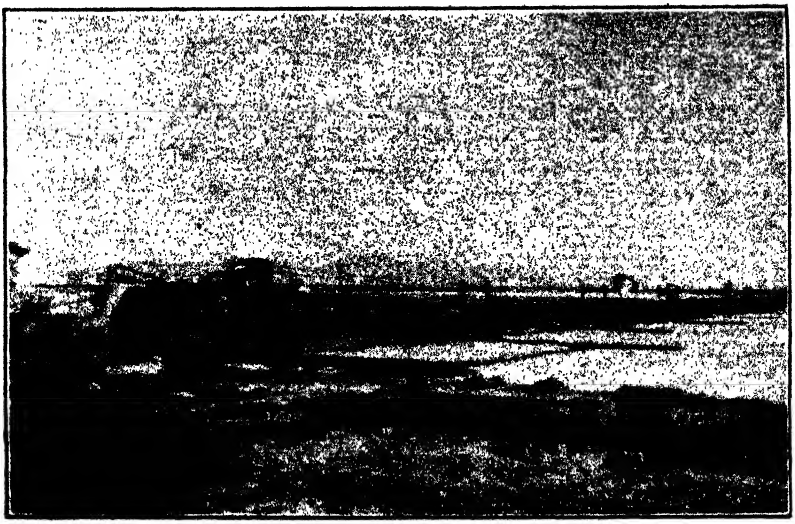

FIG. 2.—View of brine evaporating ponds, San Francisco Bay, Calif. (*H. Ries, photo.*)

The salt occurs in lenticular masses interbedded with soft shales of the Salina series (Fig. 63), which also carry gypsum deposits. The outcrop of the formation coincides approximately with the line of the New York Central Railroad, but owing to its soluble character, no salt is found along the outcrops. The beds dip southward from 25 to 40 feet per mile, so that the depth of the salt beneath the surface increases in this direction.

At Ithaca, salt is struck at 2244 feet, and there are seven beds. The thickness of the individual beds varies, but the greatest known thickness is in a well near Tully, where 325 feet of solid salt was bored through. Salt has also been struck by a deep boring in the oil field of southwestern New York at a depth of about 3000 feet. Though most of the New York product is obtained from artificial brines, a small quantity is mined by shafts.

Michigan (17).—Salt in Michigan is obtained both from natural brines and from brines obtained by dissolving rock salt, as in New York. The natural brines occur in the sandstones of the Mississippian, the most important locality being in the Saginaw Valley, where the brines are found in the Napoleon or Upper Marshall sandstone. They are remarkable for the large amount of bromine contained, more than half the bromine produced in the United States being obtained here. Rock salt which occurs in the Salina (Monroe formation) is being mined at Detroit. At other points of production it is dissolved by water forced down through wells, and the brine so obtained evaporated. In addition to being sold as salt, some of the product is employed for soda ash manufacture, by reaction with calcium carbonate.

Ohio.—Natural brines are obtained from the Big Injun sand (Mississippian) in the Pomeroy district, and used to supply salt, calcium chloride, and bromine. The salt beds of the Salina group supply wells in Cuyahoga, Summit and Wayne counties. These furnish salt, soda ash, and sodium chemicals. In Wayne and Cuyahoga counties the salt is encountered at depths of about 2000 to 2600 feet (20).

Natural brines are known at other horizons.

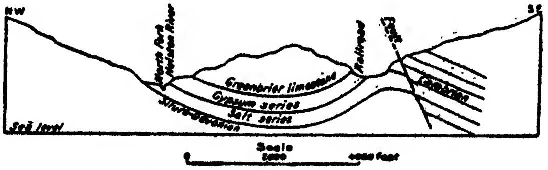

Fig. 64.—Section across Holston and Saltville valleys, midway between Saltville and Plasterco, Va. (*After Eckel, U. S. Geol. Surv., Bull.* 223.)

The two following analyses are of interest, partly on account of their completeness. The absence of sulphate in the first is noticeable.

ANALYSES OF OHIO BRINES

	GRAMS PER LITER	
	I	II
SiO_2	.012	.000
Fe_2O_3,Al_2O_3	.083	.000
$CaCl_2$	14.340	1.033
$MgCl_2$	5.59	.462
NaCl	84.3	310.977
KCl	.114	.713
$MgBr_2$	.155	.012
$BaCl_2$	.343	.000
NaI	.004	.000
$SrCl_2$	.000	.089
$CaSO_4$	.000	4.857
LiO_2	tr.	tr.
Sp. gr.	1.075	1.204

I. Natural brine, Pomeroy, O. II. Artificial brine, Cleveland, O.

Virginia (25).—Salt, associated with gypsum, is obtained by wells from the Mississippian shaly limestones in the Holston Valley near Plasterco, Washington County (Fig. 64) . The product is used entirely in the manufacture of alkali (25). The geology is referred to under Gypsum (Chap. VII).

West Virginia (27).—Brine is obtained from the Carboniferous (Pottsville) and Mississippian (Berea) in that portion of the state adjoining the Meigs County salt district of Ohio.

Pennsylvania supplies similar brines.

Kansas, Oklahoma (21), *Texas* (22, 23), *New Mexico* (13).—What is probably the largest known salt deposit in the world, with a north-south extent of fully 650 miles and an east-west dimension of 150 to 250 miles, is found in the Permian of these four states. The salt beds are found in a succession of red shales and sandstones, and have associated with them anhydrite, gypsum, limestone, and dolomite. The salt appears to occur in lenses, rather than continuous beds, and the irregular distribution of gypsum and anhydrite in relation to the salt is thought by Darton to indicate remarkable oscillations, while the presence of limestones would seem to indicate deeper submergence from time to time.

The thickness of the salt in places aggregates over 300 feet. It has been known and worked in central Kansas for some years, but in other areas has been determined by drilling, and has attracted attention because it may have associated potash in workable amounts.

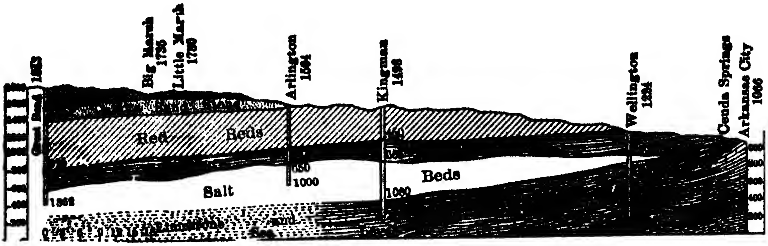

FIG. 65.—Geologic section from Arkansas City to Great Bend, Kas., showing occurrence of rock salt. (*Kas. Geol. Surv., Min. Res. Bull.*, 1898.)

Louisiana.—Brine occurs in springs and wells in the Cretaceous area of northern Louisiana, but the most important source of salt is that found in salt domes in the southern portion of the state. These underlie a series of low knolls, called the Five Islands (Fig. 66), and are covered by a series of clay, sand, and gravel beds. Salt is mined on Weeks, Jefferson, and Avery Islands, as well as at Winnfield. The age of the salt beds is pre-Pleistocene. Although the amount of rock salt present is evidently great, borings in one case revealing a thickness of nearly 3000 feet of solid salt, these deposits yield but a small percentage of the country's output.

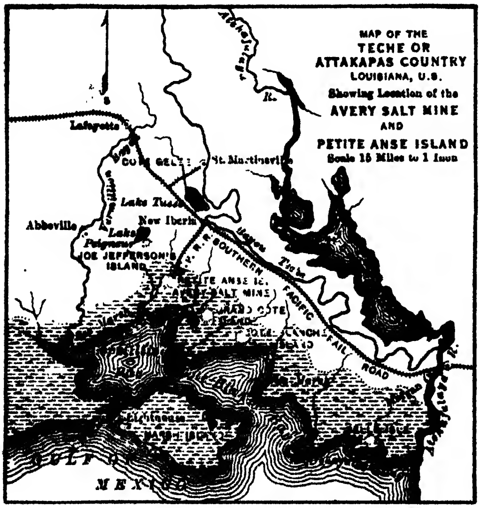

FIG. 66.—Map showing location of Petite Anse and other "salt islands," Louisiana. (*After Pomeroy.*)

Other Western States.—In California the main supply of salt is obtained by evaporating sea water (11), an elaborate system of ponds, covering thousands of acres, having been built on San Francisco Bay. These are filled at high tide, and the brine evaporated by solar heat, although artificial heat is used at some of the plants. A large deposit of salt was formerly worked at Salton Lake. This is a depression 27 miles long, 3½ to 9 miles wide, and at its lowest point 280 feet below sea level. The deposit was formed by evaporation of the lake waters, which were fed by saline springs from the surrounding foothills. The salt, which had accumulated to a depth of 6 inches, was gathered by scrapers. Salt is also found in marshes, springs, or wells in a number of other localities in California (11).

Rock salt is being obtained from salt domes at Palestine, Grand Saline, and Hockley, in Texas. It is mined through shafts.

In Utah, some salt is obtained by evaporating the waters of Great Salt Lake (24), and from rock salt near Redmond.

Brine is pumped from wells near West Tulsa, and used for salt, calcium chloride, and bromine. Some salt for local use is also obtained from playas (21).

Canada (31).—The main salt deposits now being exploited in Canada are those of southwest Ontario, where the material is obtained from the Salina formation. There appear to be a number of beds of varying thickness, interstratified with dolomite and shale. The average depth of the salt is over 1000 feet, and increases gradually to the south. Malagash, N. S., is the second largest producer, but does not supply more than about one-sixth the amount of Ontario. A small tonnage is also produced in Manitoba and Saskatchewan (32). In the other Canadian provinces salt springs are known to occur at many points. Rock salt has been found near McMurray, Alberta.

Other Foreign Deposits (14).—Rock salt deposits are widely distributed, but only the most important world's producers need be mentioned.

In England it is found in the Upper Triassic marls, the Cheshire district having two important deposits lying respectively from 120 to 210 feet, and 240 to 300 feet, below the surface. Many large deposits are also found in the Triassic as well as the Permian of Germany. Those of Stassfurt are specially well known. The German deposits may occur as lenses, beds or domes. France is another important producer, rock salt occurring as flattened lenses in saline clays of the Lorraine Triassic, and in rocks of the same age in the Pyrenees.

In Galicia the Miocene deposits of Wieliczka are among the most curious known. The upper part of the mass consists of irregular bodies of salt with blocks of sandstone, limestone and granite in saline clays, while below it is stratified salt associated with clay and anhydrite. Russia contains abundant supplies in the southeastern and southern part of the country. Of the Asiatic deposits the most important, perhaps, are those lying along the Salt Range of northwestern Punjab, where the beds, underlying gypsum, have been much disturbed by tilting and folding.

Extraction.—When salt forms underground deposits, it has to be extracted either by a process of solution or mining. In the former case water is forced down to the salt bed through a well, for the pur-

Analyses of Salt.—

ANALYSES OF ROCK SALT FROM VARIOUS LOCALITIES

LOCALITY	SODIUM CHLORIDE	CALCIUM CHLORIDE	MAGNESIUM CHLORIDE	CALCIUM SULPHATE	MAGNESIUM SULPHATE	ALUMINA, SILICA, IRON	WATER	AUTHORITY
Retsof, N. Y. . .	98.701	tr.	—	.446	—	.743	tr.	F. E. Englehardt
Pearl Creek, N. Y.	96.885	.157	.103	.437	—	1.21	1.21	F. E. Englehardt
Petite Anse, La. .	98.90	.146	.022	.838	—	.014	.08	P. Collier
Saltville, Va. . . .	99.084	tr.	—	.446	—	.47	—	C. B. Hayden

ANALYSES OF SOLID MATTER OF BRINES FROM VARIOUS LOCALITIES

LOCALITY	SODIUM CHLORIDE	CALCIUM CHLORIDE	MAGNESIUM CHLORIDE	CALCIUM SULPHATE	MAGNESIUM SULPHATE	ALUMINA, SILICA, IRON	PERCENTAGE SOLIDS IN BRINE	SPECIFIC GRAVITY OF BRINE	AUTHORITY
Warsaw, N. Y. .	96.60	.51	.20	1.68	——	——	26.34	1.204	F. E. Englehardt
Syracuse, N. Y. .	95.966	.90	.69	2.54	——	.004	18.50	1.142	G. H. Cook
Saginaw, Mich. .	82.14	12.39	5.01	.46	——	——	21.32	——	C. A. Goessman
Bay City, Mich. .	91.95	3.19	2.48	2.39	——	——	16.61	——	C. A. Goessman
Kanawha, W. Va.	79.45	16.48	4.07	——	——	——	9.20	1.073	G. H. Cook
Pittsburgh, Pa. .	81.27	13.93	4.80	——	——	——	2.80	1.019	G. H. Cook
Saltville, Va. . .	97.792	.033	——	2.17	——	Tr.	24.60	——	C. B. Hayden
Great Salt Lake .	98.10	.322	.000	.364	.021	.214	——	——	J. E. Talmadge

pose of dissolving the salt, the brine being brought to the surface and evaporated, sometimes by solar heat, but more commonly by artificial means. In the latter case a shaft is sunk to the salt bed, and the material mined like coal and brought to the surface in lumps, known as rock salt. Rock salt is simply crushed and screened without purification. Natural brines are pumped to the surface for evaporation. In the evaporation of brine care has to be taken to separate the gypsum and other soluble impurities present, which precipitate before the salt does.

Uses.—Salt is widely used in the meat-packing business and the manufacture of dairy products, as well as for domestic purposes. The per capita consumption of salt in connection with the food industry is about 75 pounds annually, but only 29 pounds is used in food and its preparation. Salt is also widely used as a source of chlorine, as a zeolite regenerator in water softening, and for curing hides. Salt ice made by freezing a eutectic brine in a special machine in the form of ribbons is used in the same manner as ordinary ice or dry ice. A relatively new and growing use of salt is in the making of stabilized roads, in which the salt not only binds the road constituents together but also retains moisture.[1] Large amounts of salt are also consumed in the manufacture of soda ash, sodium carbonate, caustic soda, and other sodium salts.

Production of Salt.—*United States.*—The production of salt in the United States in 1940 amounted to 10,003,448 short tons, valued at $26,118,107. Since 1930 the total annual production has slowly increased. The price per short ton in 1940 was $2.61. The form in which the salt is sold, together with its percentage of the 1940 production is: evaporated salt, 28 per cent; rock salt, 23 per cent; and in brine, 49 per cent. Much rock salt is now sold in pressed blocks, the amount in 1940 being 152,267 short tons.

The imports in 1940 amounted to 30,402 short tons, valued at $90,804. The countries which sent the largest supplies to the United States were Jamaica and other British possessions. The United States in 1940 exported 147,044 short tons valued at $699,340.

Canada.—The production of salt from all sources in 1940 amounted to 464,714 short tons, valued at $2,823,269, and came from Nova Scotia, Ontario, and Manitoba. This is the highest production in Canadian history.

The Canadian imports in 1939 were 117,629 short tons valued at 507,368, while the exports were 10,656 short tons, valued at $76,287.

World.—The world's production of salt in 1938 was about 26,000,000 metric tons. The United States is the largest world producer followed by Germany, China, and Great Britain.

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BROMINE

Sources.—Bromine occurs in nature combined with some metals, as in the minerals embolite, Ag (Cl, Br), bromyrite (Ag Br) and iodobromite (2 AgCl, 2 AgBr, AgI), which theoretically contain 25, 42.6, and 17.8 per cent respectively of bromine. None of these are commercial sources. Sea water averages 0.0064 per cent bromine, and the Dead Sea 0.4 per cent. The carnallite at Stassfurt, Germany, contains 0.2 per cent bromine.

In the United States bromine is extracted from natural brines found at several geological horizons, but not all rock brines contain it, some, as those of New York State, being very low in it.

At the present time Michigan, West Virginia, and Ohio brines are used. The first bromine was manufactured at Freeport, Pa., in 1846.

At Pomeroy and Syracuse district of Meigs County, Ohio, and at Hartford and Mason, Mason County, West Virginia, it is obtained as a by-product of the salt industry, the brine coming from the Big Injun sand (Mississippian). It is also separated from brines at Tulsa, Okla., and California. Bromine was extracted from sea water near Wilmington, N. C., for the first time in 1934.

That manufactured in Michigan comes from the Marshall sandstone of the Lower Carboniferous, the brine containing from 0.1 to 0.3 per cent bromine. The Dead Sea in Palestine contributes considerable, the product being extensively used in England.

Uses.—Bromine is used for making bromides of potash, soda, and ammonia, for medicinal purposes and photographic reagents. A large amount is used for the manufacture of ethylene dibromide, which in turn is used in making ethyl gasoline. A small amount is employed in the preparation of coal-tar colors known as eosine and Hoffman's blue. As a chemical reagent, it is utilized for precipitating manganese from acetic acid solutions, for the conversion of arsenious into arsenic acid, etc. It may also be used as a disinfectant when dissolved in water.

Production of Bromine.—The domestic production of bromine in 1940 was 29,633 short tons, valued at $11,772,515. It has almost doubled since 1938, and is accounted for by the production of bromine from sea water in North Carolina. The imports of ethylene dibromide in 1938 were 1,210,005 pounds, valued at $263,459.

No bromine is produced in Canada.

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CALCIUM CHLORIDE

A considerable quantity of calcium chloride is obtained from natural brines in connection with the salt and bromine industry of Michigan, Ohio, and West Virginia. An additional amount is obtained by the reaction of sodium chloride and calcium carbonate.

Uses.—The chief use of calcium chloride is as a dust layer. It is also used in refrigerating plants, as a dehydrant, and to prevent internal corrosion of oil pipe lines.

Production of Calcium Chloride.—The domestic production in 1940 was 94,238 short tons, valued at $1,485,784. The imports for 1939 were 996 short tons, valued at $12,314, while the exports in 1940 amounted to 8,907 short tons valued at $194,738.

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SODIUM SULPHATE

Occurrence and Distribution.—The hydrous sulphate, mirabilite or Glauber salt ($Na_2SO_4 + 10H_2O$), is a white saline material, which is collected on or near the surface of some alkaline marshes in desert regions. It may also be extensively deposited in some saline lakes, its precipitation preceding that of salt, and being affected more or less by the season of the year; for since it is much more soluble in warm than in cold water, the difference in temperature between summer and winter may cause its separation and re-solution (5). The phenomenon has been noticed in Great Salt Lake. Exposure to warm, dry air causes the mirabilite to lose its water and change to thenardite.

Sodium sulphate is produced from Searles Lake, Calif., and at several localities in Nevada, Texas, Oklahoma, and Washington. Glauber salt is obtained from Wyoming (7) and California. In northwest North Dakota a series of shallow lakes is said to contain 20 million tons of Glauber salts, but the deposits are not workable commercially under present conditions (5).

Natural sodium sulphate is said to occur in deposits of considerable size in Western Canada (3), the entire production for some years having come from Saskatchewan. The estimated tonnage made by the Mines branch for western Canada is 120 million tons.

Uses (7).—Sodium sulphate is used chiefly in the pulp and paper industry for making kraft paper by the sulphate process, also in the manufacture of glass, in the dye and soap industry, for medicinal purposes, etc. The Canadian product is used in the Orford process for separating nickel and copper.

Production of Sodium Sulphate.—The production of natural sodium sulphate in the United States in 1940 amounted to 187,233 short tons, valued at $1,528,633. The imports of crude, crystallized and anhydrous sodium sulphate in 1940 were 73,060 short tons, valued at $1,010,488, chiefly from Belgium, Canada and the United Kingdom.

The Canadian production in 1939 was 71,485 short tons, with a value of $628,151.

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SODIUM CARBONATE

Sodium carbonate, or natural soda, is obtained by the evaporation of the waters of alkali lakes, or is found as a deposit on or near the surface of alkaline marshes in arid regions. It is usually a mixture of sodium carbonate and bicarbonate in varying proportions, as well as impurities such as sodium chloride, sodium sulphate, borax, and sodium nitrate.

Most of the carbonate produced in the United States is obtained from Owens Lake, Inyo County, Calif., and from Searles Lake in San Bernadino County, Calif. The amount produced in 1935 was 93,230 short tons, valued at $1,173,003. Small deposits of no commercial value are scattered over the arid region of the west and southwest.

Sodium carbonate or soda ash has many industrial uses, being employed in the manufacture of glass, soap, etc. Most of it is artificially produced.

Production of Sodium Carbonate.—The 1940 domestic production was 130,034 short tons valued at $1,629,283. The estimated production of soda ash by chemical processes was 2,050,000 tons.

In Canada sodium carbonate has been obtained from deposits located in the Kamloops division of British Columbia, and the production in 1939 amounted to 300 tons valued at $2,400. The imports totaled 895 tons valued at $315,133.

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SODA NITER[1]

Soda niter, or Chile saltpeter ($NaNO_3$, with 63.5 per cent N_2O_5 when pure), is not found in commercial quantities in the United States, although small deposits are known. The main supply of this country continues to come from Chile, where extensive deposits are found in the desert region west of Iquique. There the niter (caliche) forms a bed 6 to 12 feet thick, under a cap of conglomerate (costra) 1 to 18 feet thick. The origin of this deposit is interesting, and has caused considerable discussion. One theory quite generally accepted

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[1] The term *niter*, when used alone, refers to potash niter.

is that the niter was formed primarily by the slow oxidation in air of guano or other nitrogenous organic matter in contact with alkali; a second theory refers its origin to the oxidation of organic materials and ammonia, by microscopic organisms known as nitrifying germs. Some have assigned a volcanic origin to it.

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BORATES

Various boron compounds are known in nature. When contained in complex borosilicates the material is of no commercial value as a source of borax. Boric acid has been found in the waters of hot springs, and certain ones of volcanic origin in Tuscany, Italy, have served as a source of supply for years.

Boron minerals have been found in many saline lakes and playas of Nevada, California, Oregon, Argentina, Bolivia, Chile, etc.

Borax minerals may also occur in solid beds.

The boron minerals of commercial value in the United States include: borax ($Na_2B_4O_7 \cdot 10H_2O$); ulexite ($NaCaB_5O_9 \cdot 8H_2O$); colemanite ($Ca_2B_6O_{11} \cdot 5H_2O$); and kernite ($Na_2B_4O_7 \cdot 5H_2O$). Others occur but they are of minor importance. Additional ones of commercial importance in other countries are: Turkey, priceite ($5CaO \cdot 6B_2O_3 \cdot 9H_2O$); Italy, sassolite ($B_2O_3 \cdot 3H_2O$); and Germany, boracite ($5MgO \cdot MgCl_2 \cdot 7B_2O_3$).

Distribution in the United States.—Deposits of borates (Fig. 67) have up to the present time been discovered only in California (1, 2, 5, 6, 8, 14), Nevada (9) and Oregon (15). Borax was originally obtained from Borax Lake (Pl. XXIII, Fig. 2), 80 miles north of San Francisco, being produced in commercial quantities in 1864.

Later, about 1872, this source was superseded by the discovery of large deposits of borax and ulexite in marshes of eastern California and western Nevada.

Still later, about 1887, came the development of colemanite deposits in southern California and southern Nevada.

Finally in 1926, the extraction of borax from the brines of Searles Lake, and borax and kernite in Kern County, California, initiated a new period of production, which has made the United States the leading borax-producing country of the world.

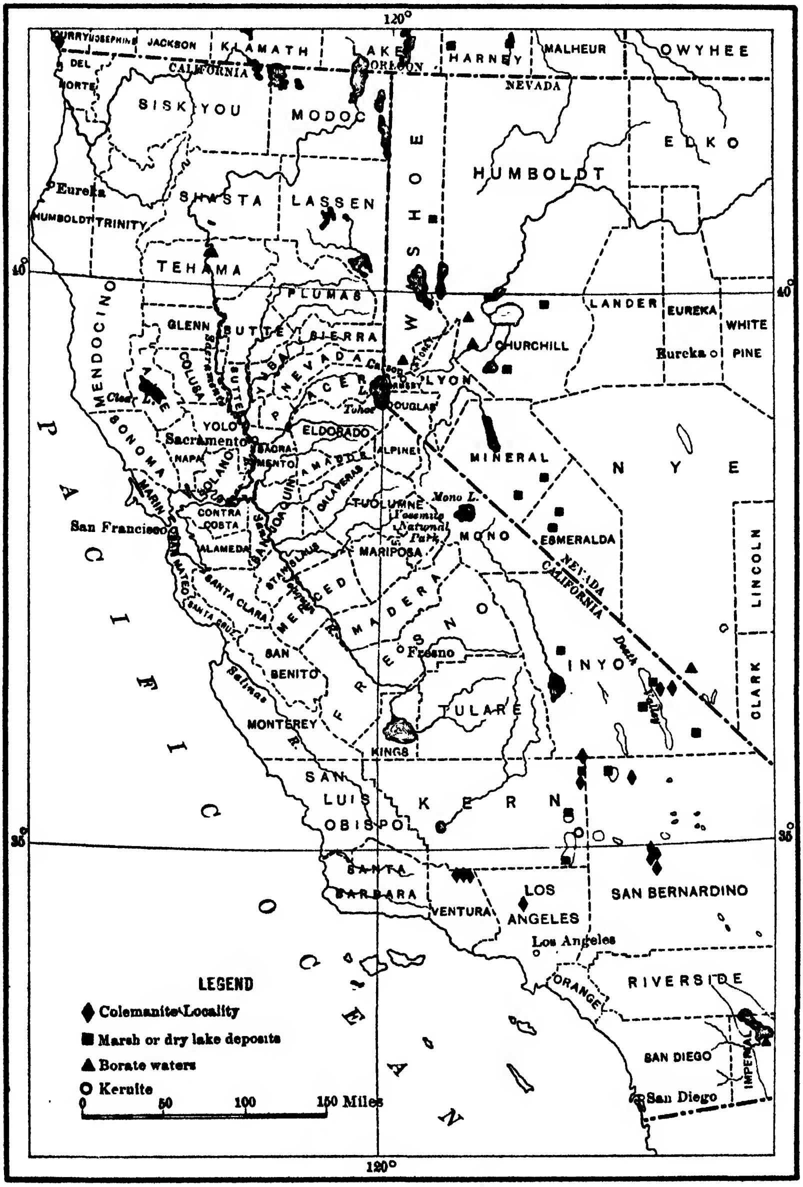

FIG. 67.—Map showing borate deposits in California and Nevada.

Playa Lakes and Marshes (5).—These occur at a number of localities in California and Nevada (Fig. 67). The borax and ulexite are formed from the repeated evaporation of playa lakes, and are associated with clays and volcanic ash. It is supposed that the lakes have been fed by saline springs containing boric acid of volcanic origin, associated with Tertiary eruptions of that region.

Of all these deposits Searles Lake in California (p. 194) alone is still of importance (Fig. 69). The total solids in the brine are about 36 per cent, of which 3 per cent is borax.

Colemanite Deposits (5, 8).—Colemanite was discovered in the Calico Mountains of California in 1882, and from 1887 to 1926 was the important domestic source of supply.

The Colemanite deposits, according to Foshag (5), occur interstratified with Tertiary lake beds, the latter being mostly volcanic ash laid down in shallow water in closed basins. The beds associated with the colemanite are thin bedded shales, but lavas of rhyolitic or basaltic composition are often present in the series. Limestones are also found. The borates are irregularly distributed through the shales, and the beds show a variable dip due to crustal movements.

Kernite Deposits (6, 13, 14).—Seven miles northwest of Kramer, Kern County, there have been developed some remarkable deposits of kernite and borax which are now one of the two important sources of domestic supply.

The borate minerals occur in clays and shales of Tertiary age, and associated with them are volcanic tuffs, limestone, and sandstone. Granitic and metamorphic rocks underlie the series. The beds dip steeply, being a part of a syncline, and the deposits of borates are from 350 to 900 feet below the surface. Although only borax and kernite are mined, ulexite and colemanite seem to underlie the entire area.

The deposits are not regarded by Schaller as being earlier playa accumulations, but represent concentration, evaporation, and in part later recrystallizations of sodium borate derived from the leaching of ulexite. When the deposits were later buried under other sediments and subjected to pressure and some heat, some of the borax was changed to kernite. At the present time some of the kernite is changing back to borax. It is interesting to note that realgar and stibnite are occasionally found in the kernite. The reserves of this area are said to be very large.

Uses.—Borax is widely used in many lines of industry. It is of importance as a cleansing agent, preservative, and disinfectant. A large amount is consumed by the glass industry, and it also forms a constituent of enamels for porcelain and metals. It is also used in industrial chemistry, in medicine, and as a laboratory reagent, in soldering brass and welding metals. Ferro-boron is a deoxidizer for steels, and boron-carbide is an abrasive. Manganese borate is sometimes employed as a drier in paints and oils.

Production of Borates.—Kramer and Searles Lake now supply about 95 per cent of the world's production of borax and other boron compounds. South America, at one time a large producer, has supplied little since 1929. Italy, however, still continues to produce boric acid.

The boron minerals sold or used by producers in the United States in 1940 amounted to 243,355 short tons, valued at $5,643,390. The production has risen steadily to 1937, but has dropped since then.

The exports of borax from the United States in 1940 amounted to 64,313 short tons, valued at $2,456,523.

The refined sodium borates imported during the same period were 752 pounds with a value of $185.

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IODINE

Sources.—This element is known to occur in sea water, in mineral springs, and in a few rare minerals, such as the iodides of silver, copper, and lead. In the Chilean nitrate deposits it exists as lautarite [$Ca(IO_3)_2$] and as a double salt of calcium iodate and chromate [$Ca(IO_3)_2$, $CaCrO_4$].

Production of Iodine.—Little naturally occurring iodine had been produced commercially in the United States prior to 1932, although during the war some was produced by kelp plants on the Pacific coast, but these are no longer active. More recently plants have been established, two in California and one in Michigan, for extracting iodine from oil well brines.[1]

The production in 1937 (last published) was 299,286 pounds, valued at $242,422, while the imports in 1940 were 1,244,166 pounds with a value of $1,296,181, and came chiefly from Chile.

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POTASH

Most of the world's supply of potash is at the present time obtained from deposits of salines, those of Germany and France yielding about 78 per cent. The element potassium is, however, a constituent of other minerals not to be classed as salines, but for purposes of convenience they will be discussed here.

Potash in Saline Deposits.—Saline deposits of potash are commonly associated with salt. Among the potash minerals which they may contain in appreciable amounts are: carnallite ($KCl \cdot MgCl_2 \cdot 6H_2O$); kainite ($MgSO_4 \cdot KCl \cdot 3H_2O$); polyhalite ($K_2SO_4 \cdot 2CaSO_4 \cdot MgSO_4 \cdot 2H_2O$); sylvite ($KCl$).

A section of the Stassfurt, Prussia, deposits has been given under *Salt*. The German deposits form a circle around the Harz Mountains, and extend under Hannover and into Thuringia. The French deposits occur in Alsace, near Mühlhaus (25). Other deposits are known to occur near Kaluz, Galicia, near Sauria, Spain[2] (24), in Russia, and in Poland.

The more important potash salts produced in Germany include carnallite, kainite, and sylvite; the French potash salts are almost entirely sylvite.

Wide search has been made in the United States to locate potash minerals with the rock salt deposits, with little success, except in New Mexico and Texas (28).

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[1] Robertson, G. R., Ind. and Eng. Chem., Apr., 1934.

[2] Inst. Geol. de España, Bol. 34: 173, 1914.

The potash deposits of southeastern New Mexico and western Texas (27, 28, 30) are part of a thick series of Permian marine deposits, which form a great north-trending geosyncline. The Permian salt basin extends from central Kansas in a southwesterly direction into southeastern New Mexico and southwestern Texas, but potash salts are found only at the southwest end of the area, and were discovered in connection with drilling for oil.

In the center of the basin the Permian beds are overlain by a considerable thickness of later formations, but on the edges only the Permian red beds cover the salt series. The depth to the top of the latter in different parts of the basin varies from 500 to 3000 feet. While the thickness of the salt series is about 1000 feet over many square miles, in one county it totals 3500 feet. Within the salt series there are beds of anhydrite and sodium chloride, and interbedded with these are thinner layers as well as lenses of the potash-bearing salts.

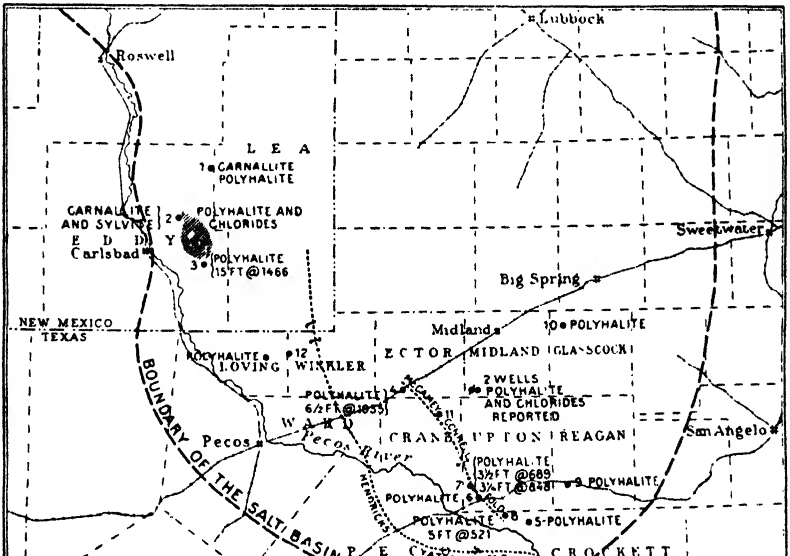

FIG. 68.—Map of potash area of New Mexico and Texas. (*After Mansfield, Jour. Chem. Ed. VII*, 1930.)

Why the potash salts are confined to this area in New Mexico and Texas is not clear, but it probably represents a portion of the Permian basin that was closed off by a barrier, and where evaporation went to an extreme.

There is a general succession of anhydrite, polyhalite and halite, while in some places more soluble salts have been deposited. The repetition of beds of clay, anhydrite, and halite indicates that the cycle of deposition may have been interrupted and renewed.

The fact that polyhalite replaces anhydrite and halite, and that the latter may be replaced by sylvite and carnallite, indicates that some of the minerals are secondary and that there has been widespread replacement.

Beds of polyhalite sufficiently thick to work have been found at several localities, and the material is now being mined near Carlsbad, N. Mex.

Some potash has also been found with the rock salt at Malagash, N. S. (26).

Brines and Bitterns (8).—A study of these shows that none of the artificial brines, natural brines, or rock-salt deposits of many examined contain sufficient potash salts to render them of commercial value for this purpose. The following table gives the composition of some.

COMPOSITION OF SOLID MATTER IN BRINES FROM SALT WELLS

Parts per Million

	1	2	3	4	5	6
K	11.8	3.0	9.4	5.8	4.2	2.7
Na	104.4	122.0	73.7	48.0	78.2	—
Ca	4.8	0.2	20.2	45.6	36.4	135.8
Mg	1.6	tr.	1.6	9.8	11.0	48.4
Cl.	179.1	189.4	135.0	187.0	202.2	355.2
SO_2	1.6	1.8	2.2	0.0	0.8	4.8
Br	1.1	tr.	—	0.4	3.3	11.0

1. Watkins, N. Y., artificial brine; 2. Wadsworth, O., artificial brine; 3. Rock Glen, N. Y., bittern, 6 weeks' evaporation in grainer, taken at time of run-off, 4. Fairport Harbor, O., natural brine; 5. Saginaw, Mich., bittern from grainer; 14 days' evaporation; 6. Mason, W. Va., bittern, before going to bromine still.

Saline Lake Beds (9–13).—It is well known that many of the depressions found in the Great Basin were formerly occupied by lakes, whose waters have entirely disappeared, and that during their existence they did not overflow. Some of these like the former Lake Bonneville and Lake Lahontan had considerable depth. Large quan-

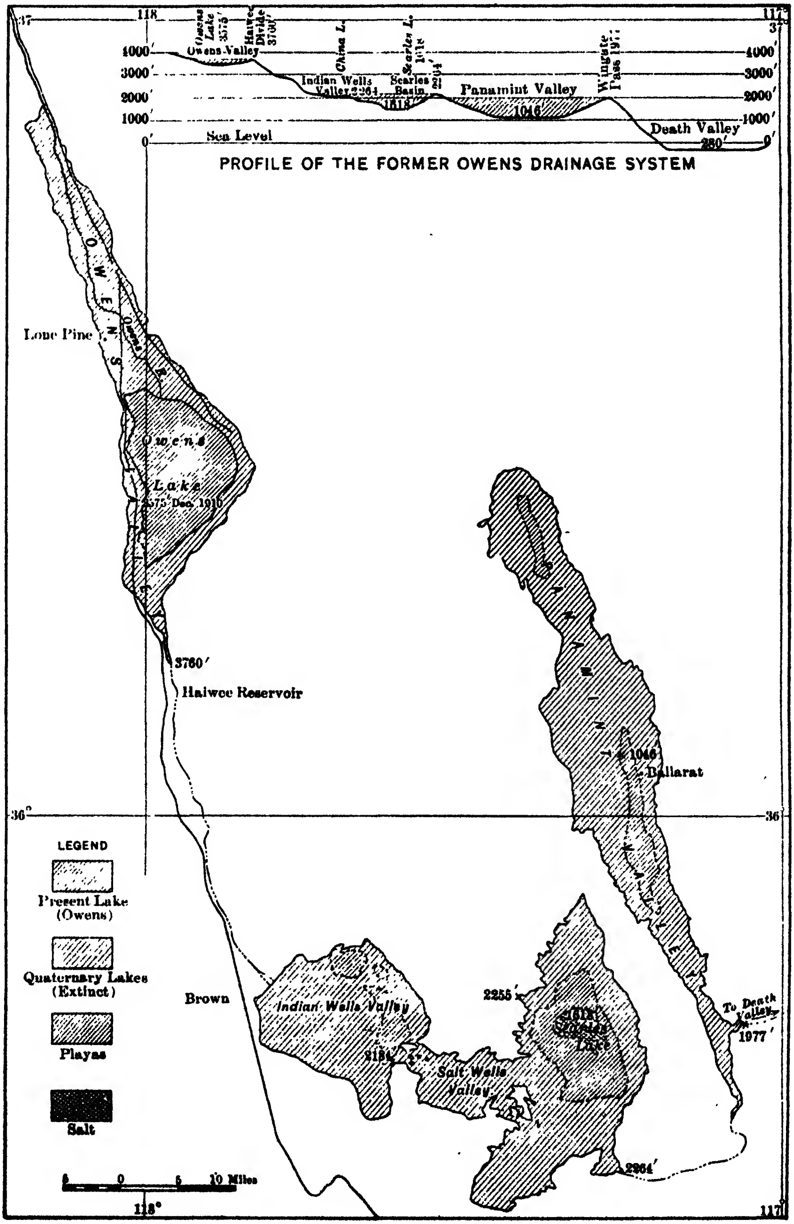

Fig. 69.—Map showing Owens and neighboring lakes of California. (*After Gale, U. S. Geol. Surv., Bull.* 530, 1915.)

tities of soluble saline and alkaline substances were carried into them by streams.

In addition to the two lakes mentioned, other important ones were Mono, Owens, Searles, and Panamint of Southern California; and Lake Le Conte in the Imperial Valley of the Colorado Desert, California.

If now such a large body of water evaporated, the assumption is that the salts would be left as a crust on the basin floor or be absorbed by the sands and clays underlying it. Another possibility is that residual brines may be found in the sands beneath the basin floor.

Attractive as this theory apparently is on first thought, a careful study of the subject tends to the belief that the outlook for finding potash or other salts under such conditions is not very promising, so that most of the saline crusts, dry-lake areas, salt flats, sinks or playas of the desert region offer little inducement as a source of potash. Two cases may, however, be mentioned.

Searles Lake, Calif. (9). In the evaporation of a natural saline solution, containing both soda and potash, the latter would normally remain in solution much longer, and hence become concentrated in the residual brine, after most of the sodium chloride had crystallized out, and theoretically we might expect to find these potash-enriched brines in the sediments underlying former lake basins.

The only important case of this sort thus far discovered is that of Searles Lake (Fig. 69). This lake, so-called, which is known also as Borax Flat, is a dry-lake basin of the ordinary type, occupying a depression which could be filled to a depth of 640 feet above the present salt flat before it would overflow into the Panamint Valley to the south and east. This it evidently did in the past, and, moreover, the water that contributed to this former high level was the overflow from Owens Lake.

At the present day we find the bottom of this desert basin covered by a great sheet of solid white salts, unique in the variety of its saline minerals. This forms a central area of firm, crusted salt, covering about 11 square miles, surrounded by a zone of salt-incrusted mud and sand, composed of salts and mixed alluvial material washed into the basin from the surrounding valley slopes.

The salt of the central area is said to vary from 60 to 100 feet in thickness, and it consists of "a consolidated mass crystallized from an evaporating mother-liquor brine in which the salts are still immersed, evaporation being about balanced by the influx of ground water from the hill slopes."

Analysis of the brine from six wells gave the following averages in the ignited residue: SiO_2, 0.02; As, 0.06; Mg, 0; Ca, 0; Na, 33.19; K, 6.22; CO_3, 7.11; SO_4, 12.76; Cl, 36.39; B_4O_7, 2.45. Several plants have been erected along the shore of Searles Lake for extracting the salts from the brine which occurs between the crystallized salts filling the valley bottom. One of these at least is now an important producer of potash and borax.

Potash-rich brines found in a number of alkali lakes of western Nebraska were worked during the war. The alkali is supposed to have been leached from the surrounding prairie soil (5).

The natural brines of the Dead Sea in Palestine are an important foreign source of potash.

Sources of Potash, not Saline Deposits

Alunite. — This mineral, which has the formula $K_2O \cdot 3Al_2O_3 \cdot 4SO_3 \cdot 6H_2O$, has been regarded as among future possibilities, provided a sufficient quantity exists and a proper method of extraction can be employed.

Several western localities have been recorded, as follows: 1. At Marysvale, Utah (3). 2. In San Cristobal quadrangle, Colo. (2), where there are several areas of alunitized granite, consisting of quartz, pyrite, and alunite, the last in some cases forming 29 per cent of the rock. 3. Near Patagonia, Ariz. (4); and 4, at Bovard, Nev. (4). The last two are probably not of commercial value.

Igneous Rocks (14, 15, 20a). — Potash is an abundant constituent of some igneous rocks, in such minerals as orthoclase and leucite, but the extraction of potash from these has not been worked out on a commercial scale in the United States. In Italy (20a) leucite in its ground form is used as a fertilizer.

The possibility of working feldspar dikes or veins for this purpose has also been suggested, but the total available quantity from this source would not be large.

Other Sources.—Some potash has been obtained from the flue dust of Portland cement kilns, and also from kelp (21, 22), along the Pacific coast. Other suggested sources are certain shales (17, 18), and the sericitized monzonite tailings from ore concentration mills (14).

Production of Potash. — It is of interest to devote a brief space to the history of potash production (27). About 1850 some 1.4 million dollars worth of potash was obtained in the United States from the leaching of wood ashes, but after this the industry declined steadily, and particularly after 1890, owing to the importation of cheap foreign potash. Germany at that time controlled the only known great deposits and was the world's source of supply.

In 1910 the German government passed a law invalidating all American contracts, and this caused a rise in price. It also stimulated search for potash in the United States. The start of the war also stopped importations, and led to the development of domestic sources of supply which could not operate successfully in normal times. Among these were certain saline lakes in western Nebraska. In 1915, 1000 tons of the equivalent of K_2O were produced by five plants in the United States, and in 1918, 54,803 tons of K_2O were put out by 128 plants. In 1914 the net price of 80 per cent muriate of potash was $33.00 per short ton, while during the war the price averaged from $245 to $415.

When the war ended a lowered price caused the shutdown of many domestic plants.

But while the French began to develop the Alsatian deposits, and low prices due to competition were hoped for, it was not long before the French and Germans combined and they with Polish and Spanish producers now have a Dutch selling agency. Indeed this cartel includes all foreign countries except Russia and Palestine.

However, the production of potash from Searles Lake, California, and particularly the development of the deposits in New Mexico, has developed a strong domestic output.

Thus we find that in 1935 consumption reached a peak of 420,000 short tons of pure potash (K_2O), of which about 48 per cent came from domestic mines and plants. Even since 1931 the domestic production of potash salts has almost tripled.

The sales of merchantable salts in 1940 was the equivalent of 393,058 short tons of potash valued at $12,562,050, with an average value of $18.52 per ton. This is really double the 1936 production in value. The 1940 supply was sufficient to supplement diminishing receipts from abroad, and over 99 per cent was from natural brines and bedded deposits.

Exports from the United States in the same year were half fertilizers, and were valued at $6,238,079.

Of the total world's production in 1935, Germany is credited with supplying 61.1 per cent; France, 15.3 per cent; United States, 7.7 per cent; Russia, 6.6 per cent; Spain, 5.3 per cent; and Poland, 3.1 per cent.

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CHAPTER VII

GYPSUM

Properties and Occurrence. — *Gypsum* (1, 2), the hydrous sulphate of lime ($CaSO_4$, $2H_2O$), occurs most frequently in sedimentary rocks, interbedded with shales, sandstones, and limestones, and sometimes more or less closely associated with rock salt. It is also found as surface deposits mixed with clay (*gypsite*) (13), or in the form of windblown sand (24 N. Mex.). The first two types are the most important commercially. It may form efflorescent deposits, periodic lake deposits, lumps and plates scattered through clays or shales, and veins. When occurring in bedded deposits it is often massive, of crystalline texture or earthy appearance, and of variable color, although most commonly white and gray.

Transparent, colorless forms, known as *selenite,* are found as veins or crystals in the massive gypsum, or as plates and crystals in many clays, shales, and limestones. This variety by itself never forms deposits of commercial importance, although selenite scales are sometimes plentifully scattered through the purer varieties. *Alabaster* is a pure white, fine-grained, massive variety, which is sometimes used for ornamental work.

Gypsum when pure contains 46.6 per cent sulphur trioxide, 32.5 per cent lime, and 20.9 per cent water. It has a specific gravity of 2.3, and a hardness of 1.5 to 2. It is therefore sufficiently soft to be easily scratched with a knife or even by the thumb nail.

Anhydrite differs from gypsum chemically in the absence of water, but changes to it on exposure to moisture. Its specific gravity is 2.8 to 2.9 and its hardness 3.0 to 3.5. When present it may occur as veinlets or masses in a gypsum deposit; indeed, its irregularity of occurrence is at times puzzling (Pl. XXIII, Fig. 1), and in many cases gypsum at the surface is found to change to anhydrite in depth. This may be a cause of some concern to gypsum miners, as the anhydrite is of little commercial importance.

Anhydrite has not usually been regarded as very abundant in the gypsum deposits of the United States. It is not uncommon in the Virginia mines, and Lane notes its occurrence in the deeper-lying

FIG. 1.—View in a Nova Scotia gypsum quarry, showing large mass of anhydrite. The anhydrite forms the buttress on right of quarry face, and is not removed. Good gypsum occurs on either side of it. (*H. Ries, photo.*)

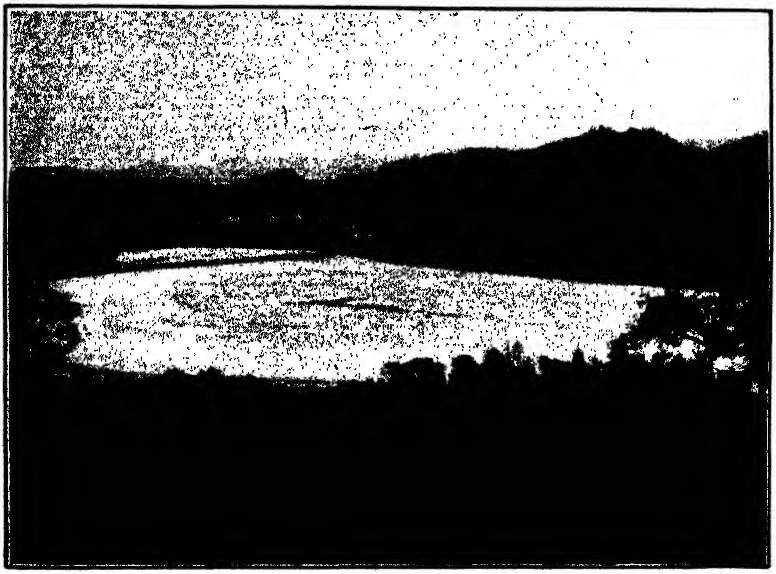

FIG. 2.—Borax Lake, Calif. (*H. Ries, photo.*)

parts of the Michigan gypsum series. It is also found with gypsum on top of the Texas and Louisiana salt deposits. Some extensive beds also occur in Oklahoma and a large mass has been found in Lyon County, Nevada. Scattered irregular masses and beds are abundant in some of the New Brunswick and Nova Scotia gypsum areas.

Anhydrite may be overlooked because of its resemblance to gypsum and limestone, but although closely similar to gypsum, the two can easily be distinguished by the following tests (5).

Anhydrite	Gypsum
Orthorhombic.	Monoclinic.
Cleavage, pseudo-cubic.	Cleavage, perfect in one direction.
Sp. gr., about 2.9.	Sp. gr., about 2.3.
Hardness, 3–3½.	Hardness, 1½ to 2½.
Fragments are square or rectangular, with parallel extinction.	Fragments are platy with oblique extinction.
Soluble with difficulty in dilute hydrochloric acid.	Easily soluble in dilute hydrochloric acid.
Little or no water in closed tube.	Abundant water (20.9%) in closed tube.
Double refraction rather strong.	Double refraction rather weak.

Impurities in Gypsum. — Clay is probably the commonest impurity, and occurs either uniformly distributed through the gypsum, giving it an earthy appearance and gray or brown color, or else it may be in layers. Lime carbonate is often present, though rarely in large amounts, although at times the gypsum is interbedded with layers of limestone. Magnesia, silica, and iron oxide may also be present, though not usually in large amounts.

Owing to its solubility, massive gypsum sometimes contains sink holes and underground solution channels, that not only permit surface dirt to wash into the deposit, but interfere at times with the mining. It may also cause irregularity in the top of the deposit (Pl. XXIII, Fig. 1).

Origin of Gypsum (1, 3, 7, 16, 37). — Gypsum is widely distributed both geographically and geologically, being found in various horizons from the Silurian to the Recent. Most beds of this substance have no doubt been formed by the evaporation of salt water either in inland seas or else in arms of the ocean, the process of precipitation having been discussed in the chapter on *Salt*. As gypsum is considerably less soluble in water than salt it is quite evident that the former could be deposited long before the water had become sufficiently evaporated to precipitate the latter. This may also explain why gypsum is more widely distributed than salt; and the fact that the percentage of gypsum in salt water is much less than that of salt probably accounts for its usual occurrence in the thinner deposits.

Thin beds of gypsum may be formed by water percolating through gypsum-bearing beds, and subsequently depositing the gypsum so dissolved, by evaporation on the surface; crusts may form by the drying up of the gypsiferous waters of playas. Replacement deposits are also recognized (26), those of Virginia being thought by some to have this origin.

Gypsum may also be formed by the decomposition of sulphides, such as pyrite, and the action of the sulphuric acid thus liberated on lime carbonate. Small quantities are formed in volcanic regions through the action of sulphuric vapors on the lime of volcanic tuffs or other rocks (1).

The conditions under which anhydrite forms do not appear to be thoroughly understood. According to Van't Hoff and Weigart, anhydrite forms from gypsum in sodium chloride solutions at 30° C., while in sea water the transformation takes place at 25° C. (quoted by Clarke, 1). Lane (14) believes that all calcium sulphate precipitated at a greater depth than 500 feet is really anhydrite rather than gypsum. Indeed, some believe that perhaps much of the gypsum now found was originally anhydrite.

Vater has pointed out that at ordinary temperatures calcium sulphate separates from a saturated salt solution as gypsum. The temperatures noted above are not likely to be found in sea water, although the Persian Gulf (3) has a mean temperature of 24° C. owing to its shallowness, and Grabau suggests that, if in such a warmed body of water the deeper layers had become a concentrated brine, the successive influxes of calcium sulphate, brought in by water during the rainy period would, on passing through these brine layers, be deposited directly as anhydrite, in alternating layers with the salts.

If the change of gypsum to anhydrite was brought about by penetrating surface waters, it might account for the irregularity of occurrence of the anhydrite in the gypsum. That such a transformation may extend to a considerable depth is shown by the deposits at Bex, Switzerland (1), where the alteration has reached a thickness of 60 to 100 feet.

But if the anhydrite represents the original mineral, then its change to gypsum must be accompanied by increase of volume in the mass, and one might expect to find a shattering or deformation of the surrounding beds, a condition actually found in some of the Paleozoic gypsum bearing-strata.[1]

Another suggestion is that originally precipitated gypsum (37) may change to anhydrite when buried to depths of 1500 feet or more. It seems probable that in many cases anhydrite was the original mineral, because the gypsum in numerous cases grades downward into it. Where the two are irregularly associated or mixed, the one may be derived from the other, but where they occur in separate beds with sharp and even lines of separation, both may be original.

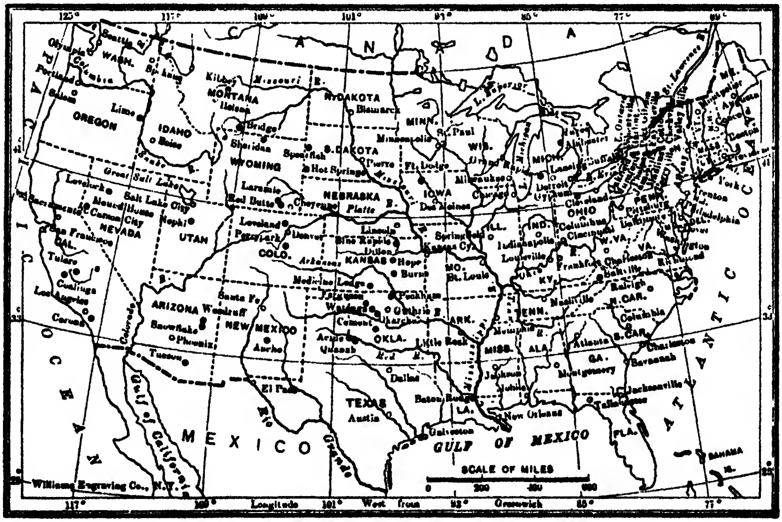

Fig. 70.—Map showing gypsum-producing localities of the United States. (*After Adams, U. S. Geol. Surv., Bull.* 223.)

Gypsite, or gypsum dirt, is an earthy or sandy variety of gypsum forming a surface deposit in Kansas (13), and other western states (24, 28), which in spite of its impure appearance may run high in calcium sulphate. It is believed to be a deposit either in the soil or in shallow lakes supplied by springs whose water has dissolved the calcium sulphate from gypsum beds or other rocks. During its precipitation by the second method, its impure character is caused by its becoming mixed with clay or sand washed in from the land.

Distribution in the United States (Fig. 70).—Nineteen states and territories are producers of gypsum, although three of these—New

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[1] Grabau and Sherzer, Mich. Geol. and Biol. Surv., Pub. 2.

York, Michigan, and Iowa—produce nearly 50 per cent of the total quantity mined.

The wide geologic range of gypsum deposits in the United States can be seen from the following table:

State or Territory	Age	State or Territory	Age
Alaska	Permian or Triassic	Nevada	Triassic
Arizona	Triassic and Tertiary (Pliocene)	New Mexico	Permian
Arkansas	Tertiary	New York	Silurian
California	Tertiary	Ohio	Silurian
Colorado	Permian	Oklahoma	Pleistocene Permian
Iowa	Permian	South Dakota	Permian
Kansas	Pleistocene Permian	Texas	Permian
Michigan	Lower Carboniferous	Utah	Jurassic
Montana	Lower Carboniferous	Virginia	Carboniferous
		Wyoming	Triassic

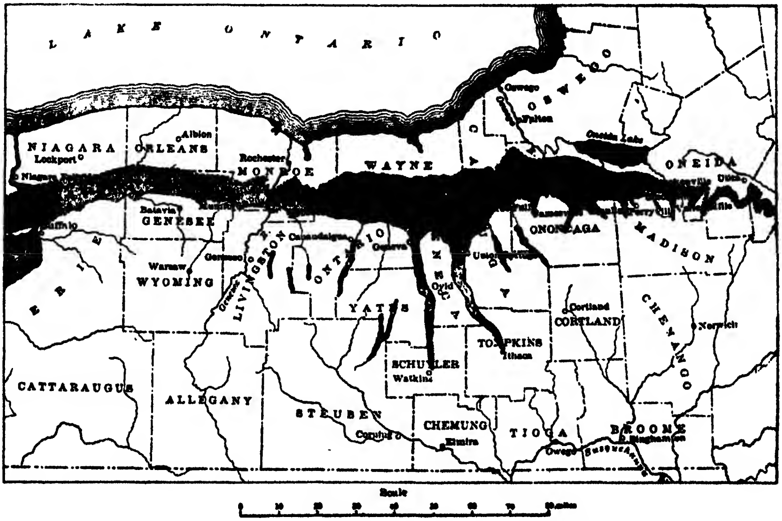

FIG. 71.—Map of New York showing outcrop of gypsum-bearing formations. (*U. S. Geol. Surv., Bull.* 223.)

New York (3, 18).—In this state, which is one of the three largest producers, the gypsum occurs as rock gypsum, interbedded with shales and shaly limestones of Salina (Silurian) age. The beds,

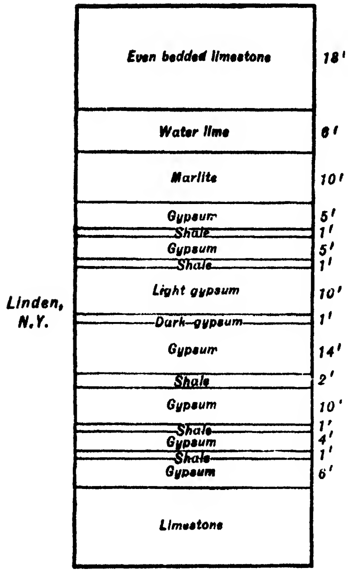

FIG. 72.—Section in gypsum deposit at Linden, N. Y. (*After Eckel, U. S. Geol. Surv., Bull. 223.*)

several of which may occur in the same section, are lenticular in shape, but of such horizontal extent that in any one quarry they appear of uniform thickness. In many quarries their thickness ranges from 4 to 10 feet, and their general dip is southward, but there are local irregularities. The main gypsum deposits occur in the upper part of the Salina, while the salt beds lie lower down in this formation. The area of outcrop of the Salina is shown in Fig. 71. The gypsum deposits, which occur mostly in the central part of the State, are usually impure, except in Genesee County. Fig. 72 shows a not uncommon mode of occurrence.

Michigan (14).—All the Michigan gypsum is rock gypsum and of high purity. There are two important areas, one being in the vicinity of Grand Rapids, and the other at Alabaster on Saginaw Bay (Pl. XXIV, Fig. 1), both in beds of Lower Carboniferous age. These beds, known as the Grand Rapids formation, surround the Michigan coal basin,[1] and carry the gypsum in their lower part. At Grand Rapids, the gypsum beds, which are interstratified with shale and limestone, are from 6 to 12 feet in thickness, and are worked either by quarrying or underground chambers. At Alabaster, Iosco County, the gypsum which immediately underlies the glacial drift, is 23 feet thick.

A third, possibly productive, area is near St. Ignace on the upper peninsula, but there the gypsum occurs in the Salina or Monroe group (Silurian).

Iowa (12).—Important deposits are found in this state in an area of about 25 square miles in Webster County, especially near Fort Dodge. The gypsum, which is presumably of Permian age, rests on the Coal Measures, or the St. Louis limestone (Lower Carboniferous), and is covered by glacial drift, but in places is overlain conformably

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[1] It is interesting to note that wells sunk in the central portion of the basin show that the gypsum passes into anhydrite, indicating that if the gypsum is of primary character it was deposited around the borders of the old interior sea.

PLATE XXIV

FIG. 1.—Gypsum quarry, Alabaster, Mich. Shows gypsum overlain by glacial drift. The dump in foreground is overburden removed from gypsum. (*Photo., A. C. Lane.*)

FIG. 2.—View in scythestone quarry, Pike Station, N. H. (*Photo. lent by Pike Mfg. Co.*)

by red shales. It varies from 3 to 30 feet in thickness, with an average of 16 feet, and much of it is sufficiently white for stucco.

Kansas. — Gypsum (13) is found occurring as rock gypsum, or as gypsite, the deposits forming a belt extending across the central part of the state in a northeast-southwest direction, and includes three important areas, viz., Northern, or Blue Rapids, in Marshall County, Central, or Gypsum City, in Dickinson and Saline counties, and Southern, or Medicine Lodge, in Barber and Comanche counties. The beds of rock gypsum are of Permian age, interbedded with red shales, those at the southern end of the belt being stratigraphically 1000 feet higher than those at the northern end.

The gypsite or gypsum dirt, which is of more recent age, is found in the central area, as well as at a number of other localities. The spring waters which have supplied it have leached the calcium sulphate either from the gypsum beds or the red shales. The gypsite is found especially in the central area, and the deposits were the first of their kind worked in the United States.

The product is used for fertilizer and cement plaster, and has also been used for making Keene's cement.[1] The rock, which is quarried especially in the northern and southern areas, is white in color, and may range from 8 to 16 feet in thickness.

Virginia. — Gypsum is also found in beds of Lower Carboniferous age in the Holston Valley of southwestern Virginia (27), the deposits occurring in shales, between Carboniferous (Greenbrier limestone) and Siluro-Devonian sandstones (Fig. 64). The section is faulted up against the Cambro-Silurian limestones, on the southeast, and both the gypsum and salt deposits seem to be limited to a narrow belt bordering on this fault.

The gypsum occurs in irregular masses in gray and red clays, and is interesting because of the abundant but irregular occurrence of anhydrite, which grades into the gypsum. The rock is mined partly by underground workings, and some of the beds are fully 30 feet thick. The product is used for land and wall plaster. Watson regarded it as a replacement deposit (27).

In Ohio gypsum has been obtained from the lower Helderberg beds of Ottawa County, 10 miles west of Sandusky. The material occurs at different horizons, the main ones having a thickness of about 12 feet (20, 24). It grades downward into anhydrite.

Other Occurrences.—Additional occurrences are known in Wyoming (28, 29), Utah (25), Nevada (16), California (10), Montana (24), Idaho (24), Colorado (24), South Dakota (22, 23), Oklahoma (21), Texas (24), and Arizona (3, 24). In the last, as well as in New Mexico, there are found important deposits of

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[1] A cement made by burning gypsum at high temperatures, and then treating it with alum or other chemicals.

gypsum sand, composed of gypsum grains obtained in part from rock gypsum and in part from playa deposits, and then gathered into hills or dunes by wind action. Some of these dunes are more than 100 feet high. The utilization of these sands in Otero County, New Mexico, was attempted some years ago.

Gypsum (8) of Permian or Triassic age is known to occur on Chichagof Island in southeastern Alaska. The beds, which are folded and steeply tilted, have been extensively developed during the last few years and shipped to Tacoma for preparation. It comes into competition with similar material from the western states.

Analyses of Gypsum.—The following analyses indicate the composition of gypsum from different localities in the United States and Canada. They cannot all be guaranteed as being of average character, and serve mainly to show variation in composition:

	Pure Gypsum	Dillon Kan.	Alabaster Mich.	Grand Rapids Mich.	Saltville Va.	Gypsite Marlow Okla.	Gypsite Burns Kan.	Gypsite Salina Kan.	Gypsite Dillon Kan.
$CaSO_4$ . . .	79.10	78.40	78.51	76.26	72.06	59.46	67.91	34.38	56.58
H_2O	20.90	19.96	20.96	20.84	21.30	16.59	17.72	8.50	15.16
SiO_2	—	.35	.05	tr.	1.68	10.67	2.31	34.35	17.10
Al_2O_3 and Fe_2O_3. . .	—	.12	.08	.54	1.95	.60	.37	4.11	2.04
$CaCO_3$ . . .	—	.56	—	n.d.	—	10.21	11.71	8.14	7.71
$MgCO_3$. . .	—	.57	.11	n.d.	—	1.10	.52	10.52	1.24
	100.00	99.96	99.71	97.64	96.99	98.63	100.53	100.00	99.83

	Onondaga, N. Y.	Fort Dodge, Ia.	Sandusky O.	Grand Etang Harbor, N. S.	Hillsborough, N. B.	Magdalen Islands	York, Ont.	Gypsumville, Man.	Salmon River B. C.
CaO	73.92	73.44	78.73	32.11	33.00	32.93	32.70	30.90	32.60
SO_3				45.88	46.80	44.93	46.88	42.52	46.67
H_2O		20.76	19.70	20.52	20.80	20.00	20.66	20.00	20.40
Insol. . . .	4.64	—	.91	.26	tr.	.60	.06	3.04	.04
Fe_2O_3. . . .		—	—	.42	—	24			
Al_2O_3 . . .		.65	.60						
MgO	—	—	.54	.23	—	tr.			
CO_2	21.44	—	—	—	—	.86			
CaO									

Distribution of Gypsum in Canada (30–37).—Canada ranks third in the world's production of gypsum, the United States and France being first and second respectively, but over 65 per cent of the crude gypsum is exported. The map, Fig. 73, shows a number of occur-

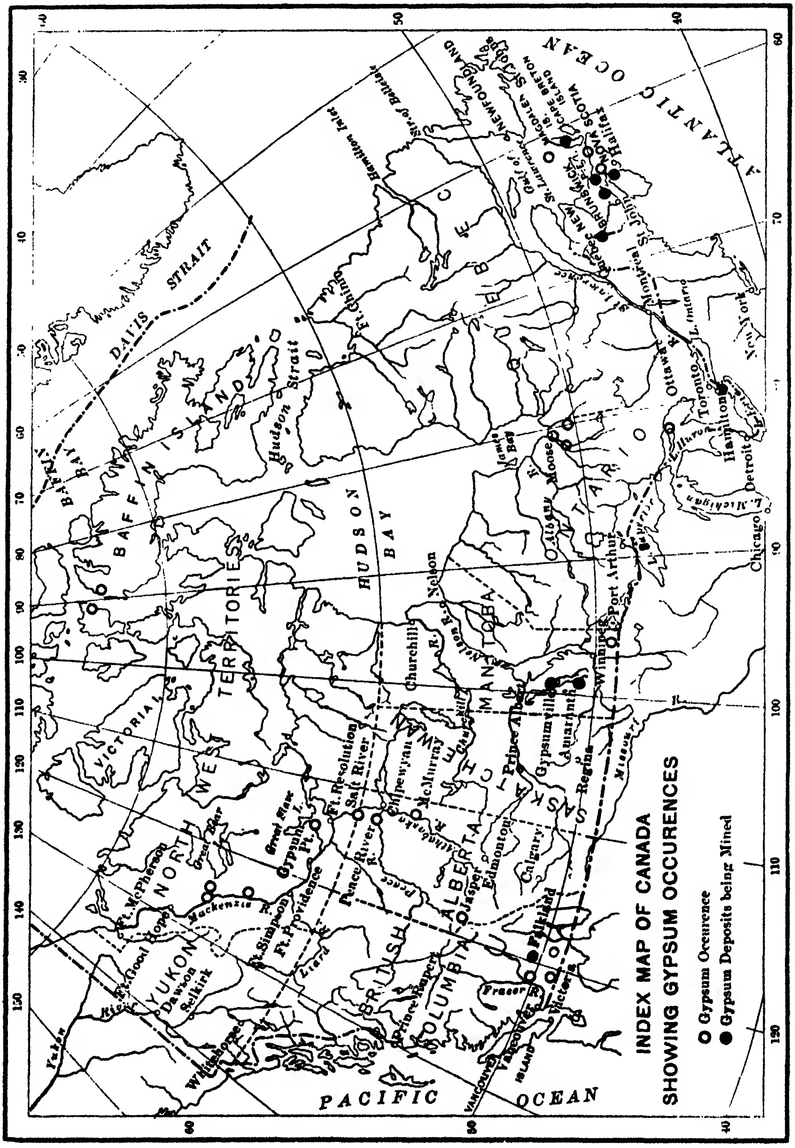

FIG. 73.—Map showing distribution of gypsum in Canada. (*After Cole and Allan.*)

rences, those of Nova Scotia and Ontario being the most important, followed by New Brunswick, Manitoba, and British Columbia. In

Nova Scotia there are many deposits, distributed over the northern half of the province from Windsor to Cape Breton; in New Brunswick the deposits are located chiefly in the southern part of the province, with Hillsborough and Plaster Rock as the two important localities.

The gypsum of these two provinces is of Lower Carboniferous age, and appears to form more or less lens shaped deposits, associated with shales and limestones. Anhydrite is a common accompanying rock (Pl. XXIII, Fig. 1), and while in many cases it is said to underlie the gypsum, it often occurs in it, in the form of irregular masses and veinlets. Considerable high-grade white gypsum is quarried near Hillsborough, N. B. Gypsum also of Lower Carboniferous age is known on the Magdalen Islands in the Gulf of St. Lawrence.

At York in southern Ontario, the Onondaga formation carries gypsum, interstratified with limestone, dolomite, and shale. The material is white, and forms lenticular masses averaging 4 feet in thickness, with some as much as 11 feet thick. The northern Ontario deposits are not worked.

Gypsum is actively worked in Manitoba at Gypsumville and Amaranth. Deposits are known in Alberta but are not worked.

British Columbia contains several localities. That near Spatsum on the Thompson River is interbedded with crystalline limestone, argillites, and volcanic rocks, while a second, east of Grand Prairie, shows one bed over 100 feet thick, and a second 30 feet thick, associated with gray schists and crystalline limestone.

Other Foreign Deposits.[1] — Of these France is the most important, the extensive Oligocene deposits of the Paris basin being a most important source of supply. The gypsum contains 10–20 per cent of calcium carbonate, and soluble silica, which is said to increase the hardness of the set plaster. England is the only other important European producer, the chief deposits being found in the Triassic of Cumberland, Nottinghamshire, and Staffordshire.

A number of other countries contribute to the world's supply, but they are far behind the countries mentioned.

Uses (2, 6). — Gypsum is sold either in the ground, uncalcined condition, or after calcining and screening.

Uncalcined gypsum is used in large quantities as a retarder for Portland cement, and in the past much was employed for fertilizing purposes under the name of *land plaster.* Other applications are for crayon manufacture, as an ingredient of steam pipe coverings, as a

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[1] For résumé see Dammer und Tietze, Nutzbaren Mineralien, 2d ed., II, 1917.

body for some paints, and as a food adulterant under the name of *terra alba*. The pure white rock gypsum, known as *alabaster,* has been used for statuary, basins, vases, and other objects for interior decoration.

Calcining Gypsum.—When heated to 250° F., gypsum loses a portion of its water of hydration, but if finely ground has the property of recombining with it. If heated to 300° to 400° F., it is said to lose this power and is called *dead-burned.* In addition to dehydration, burning also breaks up the crystals into minute particles. The *set* is due to the formation of a crystalline network of the rehydrated grains.

Since calcined gypsum sets in from 6 to 10 minutes, some retarding material, such as organic matter from slaughter-house refuse, is often added to it, and thus the setting process may be delayed from 2 to 6 hours. Those plasters which set slowly are termed *cement plasters.*

The following analyses show the composition of (1) uncalcined gypsum; (2) the calcined rock; and (3) the plaster after it has taken up water and set. From these it will be seen that the plaster takes up the amount of water lost in calcination.

SERIES OF ANALYSES SHOWING CHANGES IN GYPSUM DURING CALCINATION AND AFTER SETTING

	CRUDE	FINISHED	SET
SiO_2 and insol. res.	12.29	14.31	12.03
Fe_2O_3 and Al_2O_3	2.27	2.16	1.62
CaO	29.67	33.53	30.05
MgO	.78	.91	.61
SO_3	34.87	39.85	35.73
CO_2	3.52	4.11	3.55
H_2O	16.07	4.81	16.38

In its calcined form, gypsum comparatively free from impurities is known as *plaster of paris,* and has the following uses dependent on its property of hardening or setting when mixed with water: stucco, plastering for walls, whitewash, pottery molds, statuary, dental purposes, and as a bed for polishing plate glass. Hard finish plasters, such as Keene's cement, etc., and partition blocks consisting of plaster of paris with other substances are being used in increasing quantity.

Production of Gypsum. — Michigan, New York, and Iowa are the leading producers, but other states contribute considerable amounts.

The production of gypsum in the United States in 1940 was 3,699,015 short tons, and the value of the calcined and uncalcined sold was

$53,492,644. There has been considerable fluctuation in the output during the past twelve years, but the sales of gypsum products in 1940 compare favorably with the peak year of 1925.

The imports of crude gypsum and gypsum products in 1940 were valued at $1,427,966 and was mostly crude gypsum from Canada. The 1940 exports were valued at $264,128.

The sales of gypsum in Canada in 1939 were 1,421,934 short tons, valued at $1,935,127, of which Nova Scotia supplied probably over 80 per cent. The balance was produced by Ontario, New Brunswick, British Columbia, and Manitoba in the order named. The imports in 1939 were 698 tons, valued at $18,127, but the exports were 1,260,231 short tons, valued at $1,390,126. Proximity of many of the New Brunswick and Nova Scotia deposits to tidewater facilitates export.

Canadian anhydrite is exported to the United States chiefly as a fertilizer for peanut plants.

In England the use of anhydrite for the manufacture of sulphuric acid, ammonium sulphate, and special plasters is reported to be increasing.

France, the United States, the United Kingdom and Germany are the leading world's producers.

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CHAPTER VIII

FERTILIZERS

Under this term are included a number of mineral substances, limestone, marl, gypsum, phosphate of lime, greensand, guano, kainite (K_2SO_4, $MgSO_4$, $MgCl_2$, $6H_2O$), and niter, which are of value for adding to the soil to increase its supply of plant food and also in some cases correct its physical condition. Some of these have other uses as well, and have been discussed elsewhere.

Phosphate of Lime. — This occurs both as crystalline phosphate of lime, or apatite, associated with crystalline rocks, and rock phosphate usually associated with stratified rocks.

Apatite (12, 14). — This mineral when pure contains about 90 per cent tricalcic phosphate, and 10 per cent calcium fluoride, which may be replaced by calcium chloride. It is widely distributed in some igneous and metamorphic rocks, especially granites, gneisses, and some crystalline limestones, but rarely in sufficient quantity or in sufficiently concentrated masses to render its extraction profitable, at least while the supply of amorphous phosphate lasts. So, competition with rock phosphate has restricted mining to a few localities where it is associated with other valuable minerals.

In the United States apatite was formerly produced at Mineville, N. Y. (13), where it occurs disseminated in small grains through the magnetite, forming sometimes as much as 5 per cent of the ore. In the process of magnetic separation the apatite was removed as tailings, the first grade of these carrying about 60 per cent tricalcium phosphate, and the second about 30 per cent. Attempts were made to use this by-product for fertilizer manufacture, but they were discontinued.

A unique as well as extensive occurrence of phosphatic material is found at two localities in Nelson (figured under Titanium) and Roanoke counties, Virginia. The rock which Watson has named *Nelsonite* (16) consists of a hard granular aggregate of apatite, rutile, and ilmenite, and forms dike-like masses in metamorphic igneous rocks. The commercial value of this material as a source of phosphate remains to be proved.

Large quantities of crystalline apatite were formerly produced in Ontario and Quebec, where the material is found in pegmatites associated with much pyroxene, phlogopite, hornblende, etc. The output at present is very limited, as the material cannot compete with the cheaper and more easily ground rock phosphate. That produced is a by-product from mica mining.

Russia has recently been producing much apatite from the Kola Peninsula, where it occurs as veins in nepheline syemite. The apatite veins of Norway, which are of little importance as a producer of this mineral, are related to pegmatites.[1]

Some unique occurrences of apatite are those in the province of Estramadura, Spain, where the apatite associated with quartz and fluorite forms veins in granite, as well as in the neighboring slates and limestones. The solutions which deposited the apatite were evidently derived from the granite (9).

Rock Phosphates (9, 7, 14).—These, though composed chiefly of phosphate of lime, also carry variable quantities of other substances as will be explained below. They are sometimes called *phosphorites*, although this term should probably be restricted to the purer, denser, fine-grained forms.[2]

Rock phosphate varies greatly in its appearance. It may show a variety of colors, vary in its texture from coarse to fine and dense to porous. Some varieties are oölitic; others may show a greater or less abundance of fossils. It is not to be wondered at, therefore, that in the field rock phosphate has sometimes been mistaken for other kinds of material, such as limestone, coal, volcanic ash, etc.

A simple field test consists in putting a crystal of ammonium molybdate on the rock and adding a drop of nitric acid. If phosphoric acid is present, this should give a characteristic yellow precipitate.

Minerals in Phosphate Rock.—The chief minerals in phosphate rock are calcium phosphates. According to Rogers (8), phosphate rock appears to be a mixture of two minerals, amorphous collophanite, largely a solid solution of calcium carbonate in calcium phosphate, and crystalline dahllite, a calcium carbonophosphate with the formula $Ca_6(PO_4)_4CaCO_3\frac{1}{2}H_2O$, analogous to fluorapatite. The amorphous collophanite gradually changes to dahllite. Hydroapatite is sometimes present in mamillary masses resembling chancedony.

Phosphates of iron or aluminum may be present in small amounts, and calcium carbonate is not rare, though never present in large quan-

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[1] Vogt, Zeit. prak. Geol., 1895, 367, etc.

[2] See Dana, Syst. Min., p. 762; see also refs. 4, 9.

tity. Other substances may include quartz, clay and even small amounts of fluorine, titanium, manganese, etc.

Classification of Rock Phosphates.—Rock phosphates may be roughly classified as follows:

I. Bedded deposits, consisting of:

- (*a*) Beds of massive phosphate, of continuous or lense-shaped character, and varying purity.
- (*b*) Nodules in sedimentary rocks.
- (*c*) Bone beds mixed with more or less phosphatic material.

II. Replacement deposits, formed by the leaching of phosphate from guano or higher-lying phosphatic formations, and its deposition in lower-lying calcareous rocks.

III. Cavity fillings deposited from solution, and including:

- (*a*) Irregular cavities in limestones.
- (*b*) Fissures in limestones or other rocks.

These represent phosphates of high purity, and some replacement may accompany the filling.

IV. Residual deposits.

V. Mechanically formed deposits (placers), of marine or stream origin.

Objectionable Impurities.—These may be objectionable because they take the place of just so much phosphate, or because they interfere with the process of manufacturing acid phosphate. Iron and alumina are the most objectionable from the latter viewpoint, and hence phosphate is sold under a guarantee not to exceed 2 to 4 per cent of iron. Alumina if present as silicate is said to be more injurious than aluminum phosphate.

A small amount of calcium carbonate is beneficial, since its reaction with the acid added generates heat which promotes subsequent reactions among the other constituents, and the carbon dioxide gas given off facilitates drying. Fluorine if present in any quantity is objectionable because of the obnoxious gas generated, when the phosphate is treated with sulphuric acid. This trouble is met with more in using apatite than with rock phosphate.

Origin of Phosphate Deposits (2, 9, 14). — Considering the somewhat varied mode of occurrence of amorphous phosphate it is obvious that different deposits may have been formed in different ways.

We may perhaps regard the igneous and other crystalline rocks as the ultimate source of the element phosphorus. The phosphate minerals, of which apatite is the commonest, may on the weathering of the rock be attacked by the soil waters, different inorganic phosphates showing different degrees of solubility, and their solubility varying also with the conditions.

Thus the presence of decaying organic matter in water seems to increase the solubility of phosphate minerals, and carbonated water appears to exert a similar influence, as does also sodium chloride.[1] Surface waters gather carbon dioxide from the air, or from the soil, where they also collect organic acids. These then attack the phosphate compounds found in the rocks.

While a part of this dissolved phosphate of lime is no doubt taken up by plants or held in the soil, other portions may be carried to the sea. There a portion of it may be abstracted by marine animals in the construction of their shell covering or skeletons. The actual percentage of calcium phosphate in these hard parts is not high, but it is not to be overlooked.

It has been found in the case of certain swamp waters in South Carolina, that calcium phosphate was dissolved when organic matter was present to furnish organic acids. If these same solutions stood for a time over marl, the phosphate was precipitated. Phosphate may also be precipitated on the sea floor, either as grains or nodules, or sometimes apparently by replacement of calcium carbonate of shells by calcium phosphate.

A marine deposit might therefore contain phosphate formed by chemical precipitation, as well as that contained in bones and shells, and such a deposit might or might not be sufficiently rich to work. Individual beds in a section may vary in richness (Fig. 78).

These primary deposits, however, may become the source of richer ones of a secondary nature by: (1) leaching out of calcium carbonate from phosphatic limestones, leaving the phosphate behind; (2) removal of the phosphate by solution, and its redeposition by replacement at

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[1] Patten and Waggaman, Dept. Agric., Bur. Soils, Bull. 52.

a lower horizon; or (3) erosion of the phosphate formation, and mechanical concentration of nodules and bones, in streams.

We can, therefore, see that phosphate deposits may frequently exhibit considerable complexity of origin, involving in some cases several shifts of the phosphatic material.

ROCK PHOSPHATES OF THE UNITED STATES

Florida (19, 20).—This state is at present the most important phosphate producer, although the full extent and value of the deposits were unsuspected until the discovery of large beds along the Peace River in 1887. Three distinct types have been recognized, viz., hard rock, land pebble, and river pebble, but the last is no longer important, or even worked. Their mode of occurrence, origin and location is different.

The hard rock phosphate lies in a general north-south belt, about 100 miles long, roughly paralleling the Gulf Coast, while the land-pebble deposits are found farther south, chiefly in Polk and Hillsboro counties (Fig. 74).

The hard rock phosphate, rests on and replaces the porous and cavernous Ocala limestone (Lower Oligocene). It consists of boulders and lumps of phosphate rock, mixed with sands, clays, flint nodules, etc., the phosphate often forming more than 10 to 25 per cent of the entire mass.

Different opinions have been expressed regarding the origin of the hard-rock formation, but Sellards (20), especially, has shown that the Ocala limestone was formerly covered by the Chattahoochee limestone and Alum Bluff sands. These have disintegrated *in situ,* and the Alum Bluff formation, which is distinctly phosphatic, has by leaching supplied the phosphate which was carried downward and redeposited at a lower level, often by replacement of the limestone, the shells of which were in some cases completely phosphatized. There was also some precipitation of the phosphate in cavities, as shown by the botryoidal and stalactitic forms.

The thickness of the hard-rock phosphate formation is often from 30 to 50 feet, and in exceptional cases 100 feet (20), the high-grade material averaging 77 to 80 per cent tricalcic phosphate.

The land pebble phosphate (Fig. 74) is a conglomerate of pebbles, sands and clay, formed by the sea advancing, probably with minor oscillations in level, across the exposed surface of a great phosphatic marl, the Alum Bluff formation, while the overburden sands represent that part of the formation deposited following the accumulation of the pebble conglomerate. Within the phosphate bed, the rock has been improved by secondary enrichment by downward- and lateral-moving

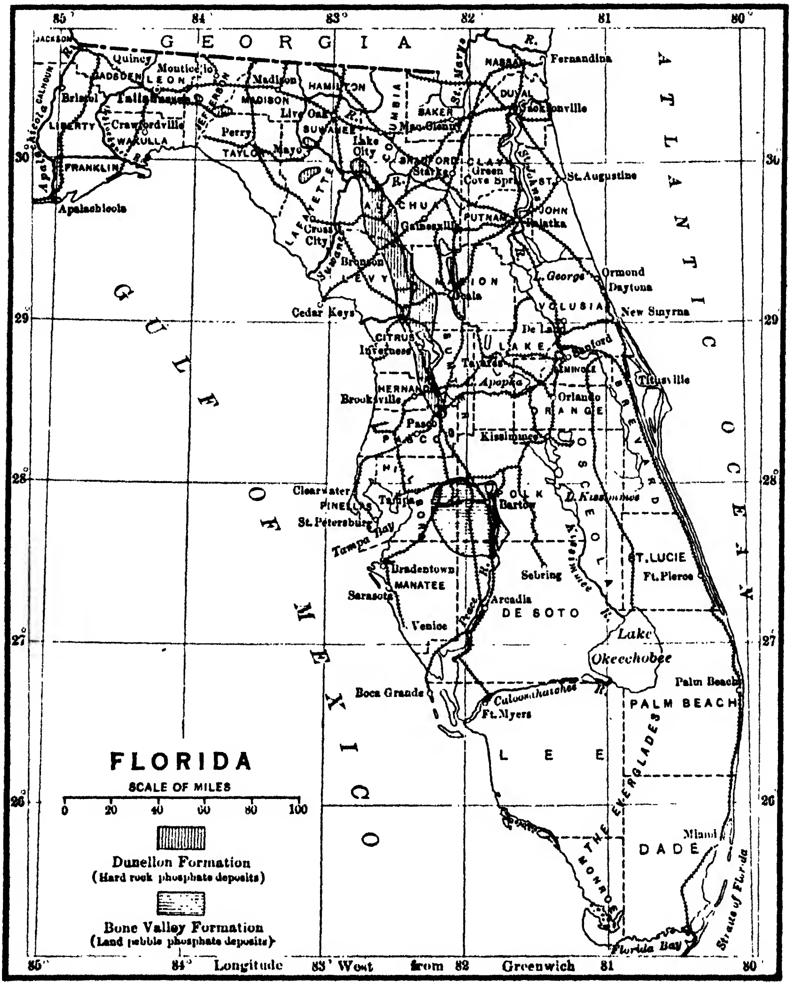

FIG. 74.—Map showing phosphate areas of Florida. (*After Sellards, Fla. Geol. Surv., 7th Ann. Rept.*)

waters, because the pebbles of the phosphate carry considerably more P_2O_5 than those of the parent rock.

The pebble phosphate appears to be 8 to 12 feet thick, with a maximum of 18 to 20 feet. In the workable deposits the phosphate

FIG. 1.—Rock phosphate mine near Ocala, Fla. (*Photo., A. W. Sheafer.*)

FIG. 2.—Mining land pebble phosphate, Mulberry, Fla. (*Fla. Geol. Surv.*)

makes up 10 to 25 per cent of the whole, while the marketed material runs from 60–74 per cent tricalcic phosphate.

Hard-rock phosphate, if in large lumps, is first crushed, after which, it, together with finer material, passes through a log washer to separate dirt and sand. Land pebble is put through a similar washing process, sometimes preceded by screening. After leaving the cleanser, hard rock is sorted on a picking table. Both kinds of phosphate must be dried before shipment. Not a little phosphoric acid is to be regarded as lost in the low-grade material which is thrown on the dump, and methods for saving this are needed.

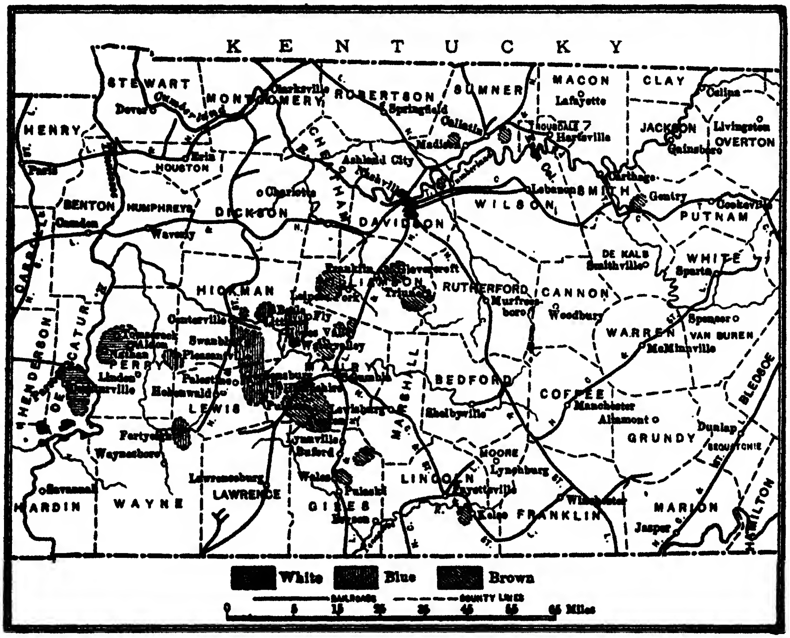

FIG. 75.—Map showing distribution of phosphates in Tennessee. (*Adapted from Ruhm, Eng. and Min. Jour. LXXXIII.*)

South Carolina.—Phosphate is found both on the land and in the river bottoms in a belt about 60 miles long lying inland from Charleston and Beaufort (25, 26). The phosphate, which rarely averages much over 1 foot in thickness, is commonly of nodular character, and often contains many bones and teeth. The presence of these animal remains, including both land and marine forms, has given rise to the belief that the deposits were caused by the accumulation of bones and excrements along a shore line, probably of Upper Miocene (Tertiary) age. Leaching of these remains may have permitted a later replacement of limestone or the formation of phosphatic concretions in swamp bottoms.

Two forms are recognized, viz., land rock (the type now mined) and river rock. The former ranges from 1 to 3 feet in thickness and is overlain by green-

FIG. 1.—View showing phosphate cutters, Mt. Pleasant, Tenn. (*J. S. Hook, photo.*)

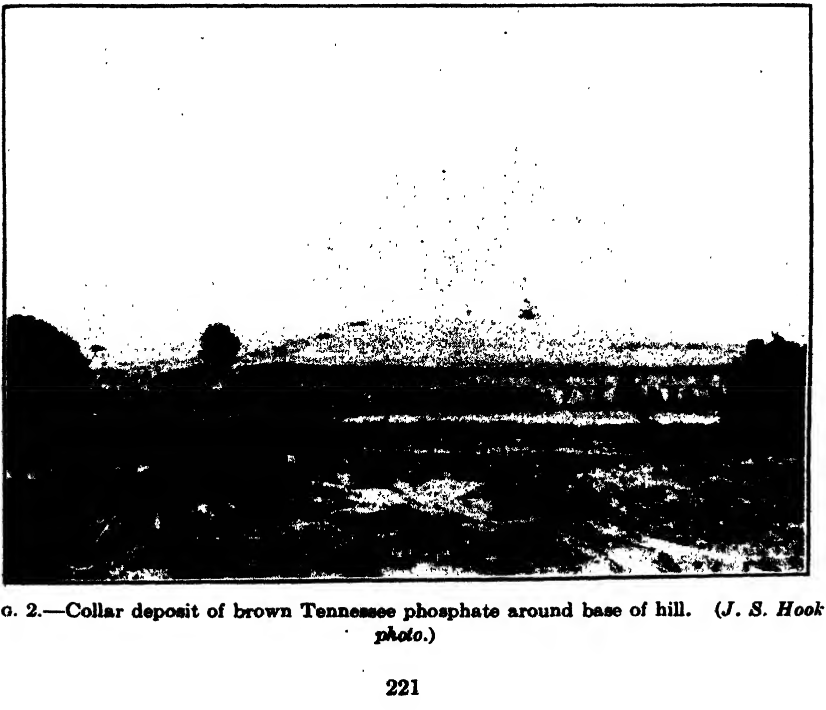

FIG. 2.—Collar deposit of brown Tennessee phosphate around base of hill. (*J. S. Hook, photo.*)

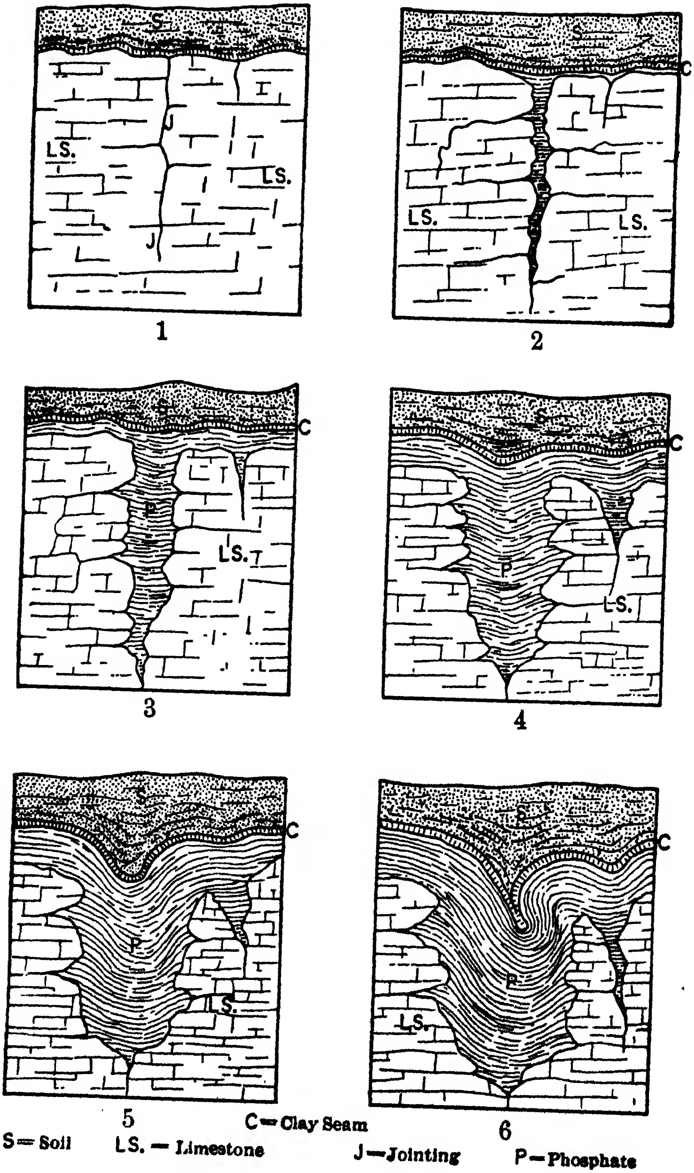

Fig. 76.—Sections, showing development of "cutters" of brown phosphate. (*After Hook, Min. Res. Tenn., IV, No. 2*, 1914.)

sand marl. The river rock is little more than water-worn fragments of the first type, and is mined from the river channels. The rock now shipped averages about 61 per cent bone phosphate.

The South Carolina phosphate rock was worked as early as 1867, and the production increased up to 1893, but since then it has fallen off almost steadily.

Tennessee (27–30). — Since the recognition, in 1893, of considerable quantities of high-grade phosphates in western middle Tennessee (Fig. 75), there have been important developments of the deposits.

Three types of phosphate deposits are recognized, viz.: brown, blue and white.

Brown Phosphate (28). This is more or less confined to the southwestern portions of the Central Basin of Tennessee, with Mount Pleasant as the most important producing district (Fig. 75).[1]

It occurs as a residuum filling solution cavities or pockets in phosphatic limestone (Fig. 76), which have been formed by the leaching action of surface waters, that removed the lime carbonate. Where the parent rock has not been exposed to weathering action no concentration has occurred.

Two types of deposit are recognized, viz.: (1) *rim* or *collar* deposits (Pl. XXVI, Fig. 2) in which a more or less connected group encircles a hill, and (2) *blanket* deposits formed where the limestone is exposed to weathering action over a considerable area. The two types grade into one another.

A dominant factor is the presence of major joints striking N. 60° W., and it is along these that the weathering proceeds (Fig. 76), resulting in long narrow trenches called *cutters* (Pl. XXVI, Fig. 1), filled with the commercially valuable phosphate. These average about 15 feet in depth, and 10 feet in width, with maxima of 45 feet and 20 feet respectively.

The commercial rock is either of a porous, platy, coherent structure, or of a loose, sandy nature.

The Bigby limestone (Ordovician) from which the phosphate is derived, is, when fresh, of dense, crystalline nature, usually banded with thin black layers, which are more phosphatic than the rest of the rock, and produce the best quality of platy phosphate.

After mining, the brown phosphate is put through a washer to eliminate clay, iron oxide, chert, limestone lumps, and other foreign matter. The washed product is sold under a guarantee of from 70 to 80 per

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[1] More recently described residual deposits in Cambrian are found in Johnson Co. (Jenkins, Res. of Tenn., VI: 51, 1916.)

cent bone phosphate, the maximum specified amounts of combined iron and alumina in each case being 6½ and 4 per cent.

Blue Rock (28).—In Hickman, Lewis, Maury, and Perry counties, especially, there occurs a phosphatic stratum, just below the Chattanooga shale in the Devonian, which varies from a few inches up to 2 or 3 feet in thickness. The more purely phosphatic portion, known as *blue rock*, grades into nonphosphatic sandstone or shale.

The blue rock appears to be a sediment, which has not been altered since its deposition, the phosphatic material having been supposedly derived from the subaerial decay of phosphatic Ordovician limestones, and mechanically concentrated by ocean currents into the lenticular deposits from which it is now mined.

White Phosphate (27, 29).—This is found in Perry and Decatur counties, and is directly associated with Silurian limestone and with breccias of Camden chert. It is of no commercial importance.

ANALYSES OF PHOSPHATE

	FLORIDA HARD ROCK PHOSPHATE				FLORIDA LAND PEBBLE	
	White Hard Rock, Nodular	White Hard Plate Rock	White, Soft, Earth-like	Washings from Phosphate	White Pebbles	Brown Pebbles
Bone phosphate	84.40	75.6	67.5	39.42	75.77	68.55
Fe_2O_3	.32	.8	11.68	2.25	.80	2.24
Al_2O_3	.82	.73	4.68	19.17	.60	.84
$CaCO_3$	——	——	——	——	——	——
FeS_2	——	——	——	——	——	——
SiO_2	1.32	——	.87	38.40	4.16	3.81
H_2O	——	——	——	——	——	——

	TENNESSEE				SOUTH CAROLINA			
	Brown Rock	Brown Rock	Blue	Blue Low Grade		Land Rock	River Rock	River Rock
Bone phosphate	77.77	63.5	73.90	26.16	$Ca_3(PO_4)_2$	58.25	54.88	59.51
Fe_2O_3	3.12	1.12	——	2.63	Insol.	11.89		
Al_2O_3	2.08	2.00	1.00					
$CaCO_3$	0.20	.88	10.90	7.79	$CaCO_3$	7.98	8.20	8.61
FeS_2	——	——	1.49	1.70				
SiO_2	——	——	3.19	54.48				
H_2O	——	——	3.11	1.90	H_2O	——	5.80	4.31
					Org.	6.58	——	——

Western States (32-34).—Large areas of phosphate rock have been discovered in the states of Montana, Idaho, Wyoming, and Utah.

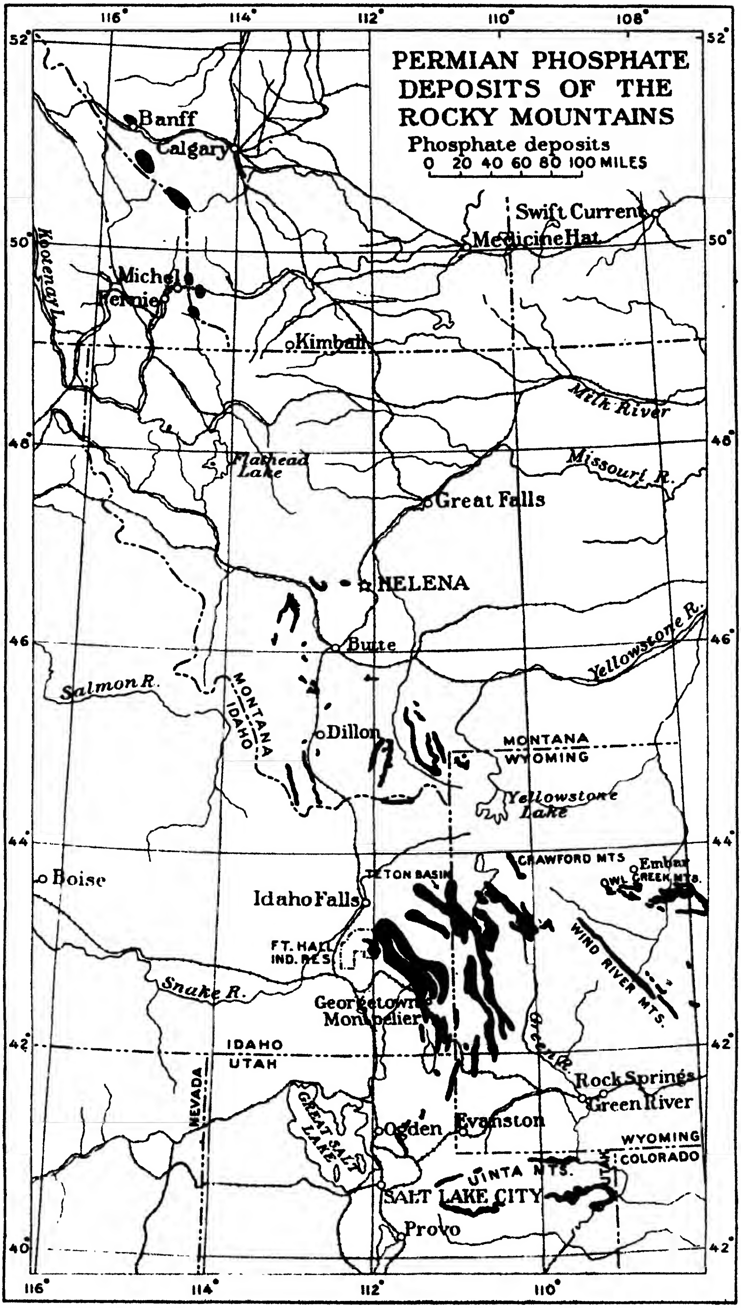

Fig. 77.—Map showing location of known phosphate-bearing areas of Permian age in the Rocky Mountains. (*After Mansfield, Ore Deposits of Western States.*)

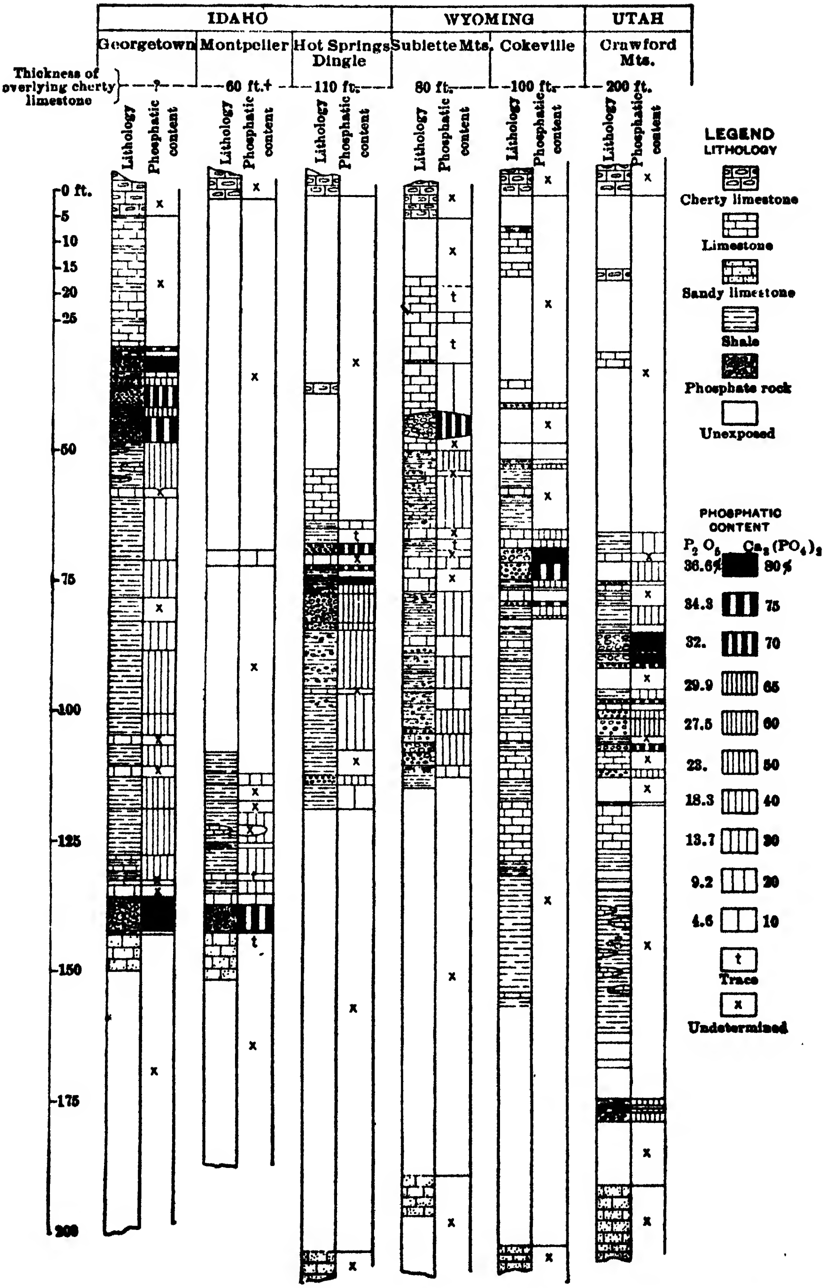

FIG. 78.—Columnar sections showing position and richness of phosphate beds in western states. (*U. S. Geol. Surv., Bull.* 430, 1910.)

To the north the phosphate is also formed in the vicinity of Banff, Alberta (Fig. 77). The deposits, which are said to be the most extensive thus far discovered in the world, will no doubt prove to be of great importance in the future, although at present their development has been retarded, partly by lack of transportation facilities and limited demand.

The beds of most commercial importance are found in southeastern Idaho, and adjacent parts of Wyoming and Utah.

The phosphate forms beds interstratified with limestones and shales, the series in all cases having been much disturbed by folding and faulting. Those of the Georgetown area have been involved in the great Bannock thrust fault.[1]

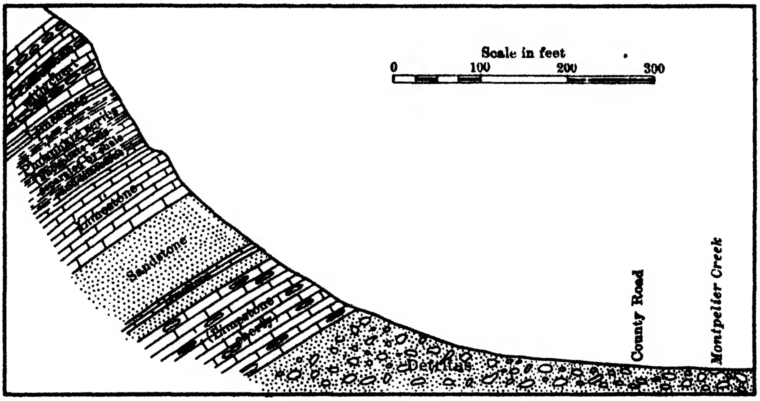

Fig. 79.—Section of Carboniferous strata on north side of Montpelier Creek, Idaho. (*After Weeks and Ferrier, U. S. Geol. Surv., Bull.* 315, 1906.)

The most extensive deposits are of Permian Age, but limited occurrences are found at the base of the Upper Mississippian in Idaho and Utah.

In hand specimens the phosphate is seen to be dense, with an oölitic texture. It is dark brown when fresh, but becomes bluish white on weathering. Under the microscope it shows an isotropic mineral, possibly collophanite, and a doubly refracting phosphate, possibly quercyite. The fresh phosphate has an oily odor.

The lime phosphate content of the workable beds varies from 65 to 80 per cent with an average of 70 per cent.

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[1] Richards and Mansfield, Jour. Geol. XX: 681, 1912.

The following analyses will serve to show its composition:

ANALYSES OF WESTERN PHOSPHATES

	1	2	3	4	5
CaO	45.34	50.97	46.80	48.91	51.15
P_2O_5	27.32	36.35	32.05	33.61	35.09
Al_2O_3	.89	.50	.90	.97	2.20
Fe_2O_3	.73	.26	.33	.40	.10
MgO	.28	.22	.26	.33	—
Na_2O	1.10	2.00	2.08	.97	—
K_2O	.48	.47	.58	.34	—
SO_3	1.59	2.98	2.34	2.16	—
Insol	10.00	1.82	9.40	2.62	4.49
SiO_2	0.00	.30	—	.46	—
CO_2	6.00	1.72	2.14	2.42	—
F	.60	.40	.66	.40	—
H_2O(110° C.)	1.04	.48	.61	1.02	—
H_2O	1.14	.57	.75	1.34	—

1. Main bed, Cokeville, Wyo.; 2. Crawford Mts., Utah; 3. Between Morgan and Devil's Slide, Utah; 4. Eight miles E. of Georgetown, Idaho; 5. Melrose, Mont.; Nos. 1–4, U. S. G.S., Bull. 430; No. 5, Bull. 470.

FIG. 80.—Oölitic phosphate, Cokeville, Wyo. ×30.

FIG. 81.—Bigbee limestone, Mt. Pleasant, Tenn. Oölitic bodies largely phosphate; light ground calcite with phosphate grains. ×30.

The Phosphoria formation which carries the phosphate is regarded by Mansfield as a marine deposit, "formed under conditions which slowed down, or even inhibited the accumulation of ordinary sediments, while at the same time they permitted the accumulation on the sea bottom of phosphatic solutions or colloids." No explanation is given of the condition which at one time permitted the precipitation of phosphate and at others of limestone.

Mansfield estimates the reserves at nearly 6,000,000 long tons. In 1931 the western phosphate field supplied 5 per cent of the country's production.

Arkansas (18).—Phosphate deposits have been developed on Lafferty Creek, on the western edge of Independence County, but the beds extend from about 10 miles northeast of Batesville, to St. Joe in Searcy County, a distance of about 80 miles. The phosphate which forms a bed 2 to 6 feet thick in the Cason shale of the Ordovician is light gray, homogeneous and conglomeratic with small pebbles. It carries from 25 to 73 per cent lime phosphate.

The field will be of doubtful importance until low and medium-grade rock is marketable.

Other Phosphate Occurrences.—Phosphate, in the form of nodules, white vesicular rock, and in limestone fragments, occurs along the contact of Oriskany (Devonian) sandstone and Lower Helderberg (Silurian) limestone in Juniata County, Pennsylvania. It contains 30 to 54 per cent bone phosphate. Nodular phosphate, although not worked for fertilizer, is known to occur in Cretaceous and Tertiary strata in Alabama (17), Georgia (21), North Carolina (24), and Virginia (31). Phosphate is now being obtained also from the Trenton of central Kentucky (22).

Canada (35). — The finding of phosphates at a definite geologic horizon in the western United States has encouraged the Canadian geologists to make a search for this material in the continuation of the phosphate-bearing formations to the north of the international boundary, resulting in the finding of phosphate rock in the Upper Carboniferous a short distance north of Banff, in the Rocky Mountains. The output from these deposits has been neither large nor steady.

Guano (14, 41, 43).—Under this name are included surface deposits of excrement, chiefly of birds. Most of the soluble guano of commerce was formerly obtained from Peru, where, it is said, the Incas, as well as the early Spaniards, valued it so highly that a death penalty was imposed for killing the birds which produced it. These deposits are now exhausted. No large deposits of bird guano are known in the United States. Leached guanos occur on islands in the southern Pacific and in the West Indies.

Bat guano has been found in the caves of Kentucky, Texas (42), and many other states, but few of the deposits have proved large enough to work.

Greensand.—This term is applied to beds of marine origin, made up in large part of the green sandy grains of glauconite, the hydrated silicate of iron and potash. It also contains small amounts of phosphoric acid. Greensand (37) is found at many localities in the Cretaceous and Tertiary formations of the Atlantic Coastal Plain, but only New Jersey (39) and Virginia have been important producers. The New Jersey greensand is spread on the soil in its raw condition, but that from Virginia is dried and ground for use in commercial fertilizers.

Uses. — Fertilizers are used either in their raw condition or after undergoing preparation. Lime carbonate may be calcined first, or ground raw, and then spread on the soil. Gypsum is first pulverized before being sold as land plaster.

Some phosphate rock may be ground crude and spread on the soil, but most of it is converted into *acid phosphate* or *super phosphate* by treatment with sulphuric acid, and the manufacture of this product has reached large proportions in the United States. A relatively small amount is made into disodium and trisodium phosphate for silk weighting and for baking powder. Additional small amounts are used in the manufacture of other phosphorus compounds, in photography, in medicine, etc.

A new method of calcining phosphate at a high temperature (1400° C.) drives off the fluorine and converts it into a citrate soluble form.

Foreign Deposits (9)—Next to the United States, North Africa ranks as an important producer, the deposits of Algiers, Tunis, and Morocco being of considerable extent. These lie chiefly on the boundary between the Cretaceous and Tertiary, and consist of phosphatic beds, with phosphate nodules, teeth, and bones, and gypsum, interstratified with phosphatic marls and limestones.

In France there are a number of producing localities, most of which yield phosphate from bedded deposits of Cretaceous age, or in the Pyrenees, beds of upper Devonian age. An exception is formed by the Quercy phosphates, which occur as veins in limestone.

The Belgian deposits are also bedded and found in the Cretaceous.

Production of Phosphate.—The shipments of phosphate rock in the United States in 1940 was 4,002,700 long tons, valued at $12,334,662, but the tonnage was about the same as that of 1930. The average value per long ton was $3.08, and the price has decreased steadily in the last 10 years.

Of the 1940 tonnage, Florida supplied about 68 per cent, Tennessee, about 27.5 per cent, and the Western states, about 4 per cent. Relatively little phosphate has been imported into the United States in recent years, the imports having declined from a post war maximum of 45,812 long tons in 1928. Russia in 1936 exported to the United States 3,100 long tons of apatite valued at about $28,000. The 1940 exports of phosphate were 751,495 long tons valued at $3,845,495.

Canada is of little importance as a phosphate producer. The apatite deposits of Quebec have been little worked since 1899, as the product from these was unable to compete with the United States and African rock phosphate. The bedded deposits of rock phosphates in British Columbia, which are of similar occurrence to those of Montana, have been neither large nor constant producers.

The Canadian imports of rock phosphate in 1939 were 124,901 tons valued at $477,317. The imports of manufactured phosphates amounted to about 104,645 short tons, valued at $1,076,627.

Of the world's producers in 1939, United States was first, Tunisia second, and French Morocco third.

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CHAPTER IX

ABRASIVES

Introductory. — Under this heading are included those natural products which are employed for abrasive purposes. Since the main use of some is not for work of abrasion, they are simply referred to briefly in this chapter, the detailed description of them being given on other pages. Brief reference will also be made to some artificial compounds which come into serious competition with the natural ones.

While some abrasive substances occur as constituents of veins, or in disseminated form, the great majority constitute a part of rocks of either sedimentary, igneous, or metamorphic origin, and of various degrees of consolidation. As a result massive ones can be used as quarried, while others have to be separated from the containing rock. They are widely distributed both geologically and geographically, but the producing localities change from time to time.

Millstones and Buhrstones[1] are stones of large diameter used for grinding cereals, paint ores, cement rock, barite, fertilizers, etc. The American stones are either coarse sandstone or quartz conglomerate, and are quarried at several points along the eastern side of the Appalachian Mountains from New York to North Carolina, the most important being the Shawangunk Grit (Silurian) quarried in the Shawangunk Mountains of eastern New York (43). Some are also quarried in Minnesota, North Carolina, and Virginia (44). The material adapted to millstones is very limited in extent. Owing to the use of improved grinding machinery the demand for millstones has fallen off greatly in recent years, but some are still used especially for grinding paint.

Some buhrstones are imported from France, Belgium, and Germany. Those from the first two localities are hard, cellular rocks, consisting of a mixture of fine quartz particles and calcareous material; but the German buhrstone is basaltic lava.

Grindstones and Pulpstones (38).—Grindstones are made from sandstones of homogeneous texture and sufficient cementing material

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[1] The term buhrstone belongs properly to those millstones made of a chalcedonic rock, full of cavities, some of them representing casts of shells.

to hold the quartz grains together, but not enough to so fill the pores as to make the rock wear smooth under use. Most of the grindstones produced in the United States are obtained from the Berea grit of Ohio (Pl. XXVII, Fig. 1), certain layers of which are highly prized for this purpose. West Virginia also contributes to the output.

Pulpstones, which have a diameter of 48 to 56 inches, a thickness of 16 to 26 inches, and a weight of 2300 to 4800 pounds, are a thicker variety of grindstone. They are used for grinding wood pulp in paper manufacture, and hence have to withstand continual exposure to hot water. The domestic supply comes from Ohio, Washington, and West Virginia (38). Artificial stones have in recent years become serious competitors with the natural ones.

Whetstones, Oilstones (39), etc. — The term "whetstone" includes those stones used for sharpening tools, the term "oilstone" being often applied when oil is placed on the stone to prevent heating and clogging of the pores by grains of steel. The stones used for making whetstones are either sedimentary or metamorphic in character, and include sandstone, quartzite, mica schist, and novaculite. The stone selected will naturally vary somewhat with the exact use to which it is to be put, but even texture and comparatively fine grain are essentials. A small amount of clayey matter adds to the fineness of grinding, but an excess lowers the abrasive efficiency of the stone. In the schists used, abrasive action is due to the grains of quartz, or sometimes garnet, which are embedded among the fine-grained scales of mica.

Scythestones and whetstones are made chiefly from Ohio and Indiana sandstone and a fine-grained even-textured schist from Vermont (Pl. XXIV, Fig. 2).

For some years the natural stones have had to compete with artificial ones.

The novaculite quarried in Garland and Saline counties, Arkansas (39), represents a unique type, much prized for high-grade oilstones for sharpening small tools, and in demand both at home and abroad. It is an extremely fine-grained sandstone made up of finely fragmental quartz grains, visible under the microscope. The rock is chert-like in superficial appearance and has a conchoidal fracture. While the deposits, which are stratified, have a total thickness of over 500 feet, the commercial novaculite is found only in thin beds varying from a few inches to 15 feet in thickness. The beds have a steep dip (Pl. XXVIII and Fig. 82), and are cut by several series of joints, which greatly interfere with the extraction of large blocks, and sometimes even with small ones. There are also structural irregularities

Plate XXVII

Fig. 1.—Grindstone quarry, Tippecanoe, Ohio. (*J. H. Pratt, photo.*)

Fig. 2.—View in Diatomite quarry, Lompoc, Calif., showing machine cutting bricks from solid. (*H. Ries, photo.*)

and almost invisible flaws, so that much waste is caused in quarrying the rock. The rock has been variously regarded as a metamorphosed chert, a siliceous silt, or a silicified limestone.

FIG. 82.—North-south section through Missouri and Statehouse Mountains showing folded character of novaculite and slate-bearing formations of Arkansas. *a*. Bigfork chert; *b*. Polk Creek shale; *c*. Missouri Mountain slate; *d*. Arkansas novaculite; *e*. Stanley shale. (*After Purdue, Ark. Geol. Surv.*, 1909.)

Pumice and Volcanic Ash (30).—The term "pumice," as used in the geological sense, refers to the light spongy pieces of lava, whose peculiar texture is due to the rapid and violent escape of steam from the molten lava. It is put on the market either in lump form, or ground to powder, or in compressed cakes of the ground-up material. The term *pumicite* is used to refer to volcanic ash (Fig. 83).

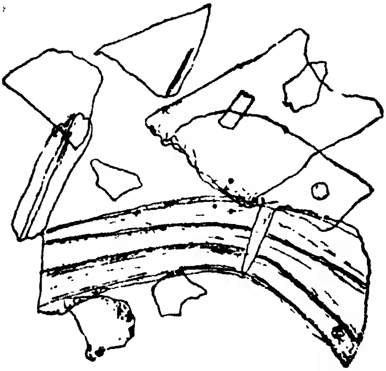

FIG. 83.—Volcanic ash from Madison County, Mont. (*After J. P. Rowe.*)

Deposits of pumice and pumicite are abundant in many western states, for example, in Nebraska (27), Utah, Montana (32), Oregon (31), Wyoming (29), Colorado (33), Kansas, etc. The domestic production of pumicite comes chiefly from Kansas. The deposits are very abundant also in Nebraska, as Barbour remarks that nearly the whole of it is underlain by pumice beds as far east as Omaha.

Much pumice has been inported from the Lipari Islands. Artificial pumice is made in Germany from obsidian.

Diatomaceous Earth.[1]—This material has been used to some extent for abrasive purposes, either in the form of polishing powder or in scouring soap. Since it has many other and more important possible applications, it is described separately on a later page.

Tripoli. (See p. 340.)—Some of the Missouri tripoli is ground and sold as tripoli flour. This flour is employed as an abrasive for

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[1] Infusorial earth and tripoli are terms sometimes applied to diatomaceous earth. Both are incorrect. Fossil flour and fossil meal are other names.

PLATE XXVIII.—View in Arkansas novaculite quarry. (*Photo. lent by Pike Manufacturing Co.*)

general polishing, burnishing, and buffing, as well as an ingredient of scouring soaps.

The so-called "silica" obtained in Union County, Illinois, is similar to tripoli, and may have had the same origin.

Both of these run high in silica, and in that respect are different from a so-called tripoli, obtained in Johnson County, Tennessee, and representing a leached Cambrian limestone. It carries about 68 per cent silica (Ref. p. 342).

Crystalline Quartz.—Some of the vein quartz quarried in the United States, and also quartzite, is pulverized and used for abrasive purposes. Considerable quartz sand is employed by stone cutters as an abrasive in sawing stone, and a small quantity is utilized in making sandpaper. (See further, under Quartz.)

Feldspar.—This also is used to some extent for abrasive purposes, but since it has other and more important uses it is discussed separately on p. 264.

Garnet (21, 22).—The garnet group includes several mineral species which are essentially silicates of alumina with iron or lime, magnesia, manganese, and chromium. They crystallize in the isometric system, and have a hardness of 6.5 to 7.5 and a specific gravity of 3.55 to 4.30.—Their color is variable, but commonly a shade of red or brown. The two varieties of value are *almandite* [$Fe_3Al_2(SiO_4)_3$] and *rhodolite* [$2Mg_3Al_2(SiO_4)_3 \cdot Fe_3Al_2(SiO_4)_3$] (from N. Ca.).

Garnet is a common mineral in many metamorphic rocks, and though ordinarily a subordinate constituent of these, it may in some cases become the chief one.

Garnet is of value as an abrasive because of its hardness, toughness, and cleavage. The best material is that which is well crystallized and relatively free from impurities, for it has greater strength and stands up better under conditions of service than finely granular material, or that containing inclusions of other minerals. The common impurities found in garnet are hornblende, chlorite, mica, and pyroxene. The parting or imperfect cleavage which garnet possesses causes it to break with smooth surfaces and sharp edges, the latter adding to its abrasive value. Garnet sand is of no value unless coarse.

Few deposits of economic value are known; in the United States the most productive deposits are found in the Adirondacks, but others are worked in New Hampshire and North Carolina. The industry has suffered from competition with artificial abrasives.

New York (20, 22).—The garnet industry is an important one in the Adirondack region, a steady production having come from Warren and Essex Counties. The garnet, which is almandite, may occur in several different ways, viz.: 1. As crystals or grains in Grenville gneisses, and representing a crystallization product of the metamorphism of sediments. 2. As distinct crystals in intrusive rocks. 3. As large, more or less rounded masses with distinct hornblende reaction rims, occurring in long, lens-like inclusions of Grenville hornblende gneiss in syenite or granite. 4. As more or less distinct crystals, without hornblende rims, in a certain special basic syenite or a diorite-like rock.

At the largest mine the garnets form 7 to 8 per cent of the gneiss mined. The rock is crushed, and the garnet concentrated by jigs and pneumatic separators.

New Hampshire (19).—Deposits of almandite garnet occur near north Wilmot, Merrimack County, and have been worked since about 1911. The garnet occurs in a porphyritic schist, which is a metamorphosed sediment, near its contact with the Meredith porphyritic granite. They are believed to have been formed by solutions emanating from the granite. The garnet bodies are generally 100 to several hundred feet long, a few feet to a hundred wide, and so far as known not over 30 feet deep. The more promising aggregates average about 50 per cent garnet, with a range of 30–80 feet.

Pegmatite and trap dikes cut the deposits in places.

North Carolina is also a producer.

Uses.—Garnet is used in making garnet paper or cloth, being a valuable abrasive for leather and wood. It has also been employed in polishing and grinding brass. Attempts have been made to use it as a substitute for corundum in the manufacture of emery wheels, for, although softer, it possesses the advantage of having a splintery fracture, which prevents it from wearing smooth.

Corundum and Emery (2–16).—*Corundum* (Al_2O_3) is, next to diamond, the hardest of the natural abrasives known, having a hardness of 9, but varying slightly from this.

Its fracture is irregular to conchoidal, and gives a good cutting surface, but the presence of parting planes decreases its value.

Corundum may occur in masses, crystals, or irregular grains. It is found in both igneous and metamorphic rocks, as well as in alluvial deposits derived from them, although the last supply but little abrasive corundum.

Distribution.—With the exception of a few western localities, the chief production of corundum in the United States formerly came from the Appalachian region, North Carolina (10) and Georgia (8) having been producers. No production, however, has been recorded since 1918, and that now produced in the United States is artificial material sold under trade names.

Corundum deposits were formerly worked at Craigmont, Ontario (2), where the material occurred in a syenite pegmatite.

The world's supply now comes almost entirely from the Transvaal, where it is found in syenite pegmatites.

Emery.—This is a mechanical mixture of corundum and magnetite, with hematite, or of these with spinel added. The former may be regarded as true emery, the latter as spinel emery. The emery in four of the five chief commercial areas known is closely associated with igneous rocks.

The Peekskill, N. Y., area (11, 5) has for some years been the most important domestic producer. This is in the Cortlandt series of basic igneous rocks, which has intruded the Manhattan schists. According to Butler (5) the former shows endomorphism while the latter have been exomorphosed. The emery, which consists when pure of pleonaste, corundum, and iron ores, forms pods and lenses, which occur in the exomorphosed Manhattan schist or in mineralized xenoliths of schist in the basic igneous rock. Butler believes that the emery is to be regarded as a contact metamorphic deposit formed mainly in the schist by emanations from the Cortlandt magma during its intrusion. The xenoliths represent ore engulfed by the magma as it advanced.

The contact metamorphic idea in somewhat different form has been expressed by others (15).

At Whittles, Pittsylvania Co., Va., deposits of spinel emery occur as lens-shaped bodies, chiefly in schist, but partly in granite which intrudes it, their formation being the result of contact-metamorphic action. It is not worked at present (14). Another locality no longer worked is at Chester, Mass.

The Grecian deposits on the Island of Naxos and the Turkish deposits near Smyrna are found as pockets in crystalline limestone, not far from granite.[1] The Grecian emery is good for abrasive wheels, but the Turkish is best adapted for use in loose grains or in emery cloth (16).

The chief use of this material is as an abrasive, and for this purpose it is used in the form of wheels and blocks, emery paper or cloth, and powder.

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[1] Papavasilicou, S. A., Zeitschr. Deut. Geol. Ges., LXV: 1, 1924.

Diamonds (18).—Abrasive diamonds are of two types: 1. Carbonados or black diamonds, obtained chiefly from the State of Bahia, Brazil (17), which are harder than gem varieties, and particularly valuable for cutting tools since they have no cleavage. They are found in stream gravels and conglomerates. 2. Borts, obtained chiefly from South Africa, and consisting of cull stones from gem diamonds. Some abrasive diamonds have been obtained from near Murfreesboro, Ark. Both kinds are used for abrasive purposes. Some are set in drill bits for boring hard rock; others are set in saws for cutting dimension stone. Diamond powder is also used as an abrasive for cutting other diamonds, gems, glass, and other hard materials which cannot be cut by softer and cheaper substances.

Pebbles for Grinding (24, 26).—These are used for grinding minerals, ores, cement clinker, etc., and those employed in the United States have been chiefly flint pebbles obtained from the chalk formations of Denmark and France, but not a few have been imported from other foreign countries. The value of flint pebbles lies in their hardness and uniform character.

The decrease in foreign supply, due to the European war, stimulated search for domestic sources of supply with some results. Stream pebbles of quartz have been tried in California gold mills; dense silicified rhyolite has been used in some mills of Nevada, and basalt in Oregon. Belgian flint for tube-mill linings is also used.

Flint pebbles have been obtained from the beach near San Diego, Calif. Quartzite, for cubes and tube mill linings is quarried at Jasper, Minn.

Artificial Abrasives.—Several artificial abrasives are now much manufactured. Prominent among these is carborundum, which is produced by fusion in the electric furnace of a mixture of silica, coke, and sawdust, the reaction being $SiO_2 + 3\ C = CSi + 2CO$.

Artificial corundum, or alundum, is made by fusing bauxite in the electric furnace. It is put on the market as grain, powder, or made up into special shapes. Aloxite, exolon, lionite, and caralox are similar to alundum.

A new artificial abrasive, norbide (boron carbide), is almost as hard as diamond. It is made from a mixture of borax and coke.

Production of Abrasives.—The total value of natural abrasives (excluding diatomite and oilstones) produced in the United States in 1940 was $3,852,887. This was made up of the following items: tripoli, $366,569; quartz, $176,390; ground sand and sandstone, $2,088,314; grindstones and pulpstones, $496,448; millstones, $6,558;

pumice and pumicite, $449,914; emery, $9,349; garnet, $259,345. The value of total production dropped from 1925 to 1931, but has risen since that time. Artificial abrasives produced in the same year had a value of $10,142,691.

The domestic imports in 1940 were valued at $11,517,117, of which 86 per cent were abrasive diamonds. The exports for the same year were $1,605,961.

In Canada the total production of natural abrasives for 1939 was valued at $25,666, being roughly 54 per cent diatomite (chiefly Nova Scotia), and 45 per cent grinding stones (chiefly New Brunswick).

The production of artificial abrasives in Canada for the same year was valued at $9,275,143. Imports of all kinds of abrasives were valued at $5,347,347; the exports were $4,567,741.

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CHAPTER X

MINOR MINERALS—ASBESTOS—GLASS SAND

Asbestos Minerals (3, 8).—The minerals which have been mined and sold under this name include: chrysotile, the fibrous form of serpentine ($H_4Mg_3Si_2O_9$), actinolite [$Ca(Mg,Fe)_3(SiO_3)_4$], anthophyllite $(Mg,Fe)SiO_3$, crocidolite ($NaFeSi_2O_6 \cdot FeSiO_3$) and amosite.

The following table gives the chemical composition of the different ones:

Analyses of Asbestos Minerals

	I	II	III	IV	V	VI	VII	VIII
SiO_2	40.30	39.05	40.87	55.81	61.82	57.12	52.11	47.68
Al_2O_3	2.27	3.67	.90	1.66	1.12	.75	1.01	trace
FeO	.87	2.41	2.81	6.81	6.55	6.36	16.75	36.00
Fe_2O_3	—	—	—	—	—	—	20.62	4.84
MgO	43.37	40.07	41.50	21.09	23.98	29.44	1.77	6.20
CaO	—	—	—	12.74	1.63	—	—	trace
Na_2O	—	—	—	—	—	—	6.16	.28
Ignition	13.72	14.48	13.55	1.81	5.45	5.47	1.58	4.71

I. Chrysotile, Italy;
II. Chrysotile, Thetford, Que.;
III. Chrysotile, Broughton, Que.;
IV. Amphibole, Roanoke County, Va.;
V. Actinolite, Hastings County, Ont.;
VI. Anthophyllite, Sall Mtn., Ga.;
VII. Crocidolite, S. Afr.;
VIII. Amosite, S. Afr.

Mode of Occurrence.—Asbestos may occur in three different ways, viz.:

1. Cross fiber found in fissures with the fibers transverse to the wall. It consists usually of chrysotile, crocidolite, amosite, and rarely anthophyllite.

2. Slip fiber lying in slipping planes with the fibers parallel to the walls. It may be either chrysotile or amphibole.

3. Mass fiber with the fiber occurring in bundles or groups. This is always anthophyllite.

Comparison of Types.—The commercial value of asbestos depends on the fineness, fiber length, flexibility, heat resistance, acid resistance, electric and heat insulating value, tensile strength, and spinnability. Chrysotile is usually taken as the standard, ranking well in everything except acid resistance. Crocidolite is equal to it in most respects but is lower in heat resistance and spinnability. Amosite fiber is harsher than chrysotile. Anthophyllite equals chrysotile in resistance to heat and acid, but is inferior in insulating qualities, as well as flexibility and length of fibers.

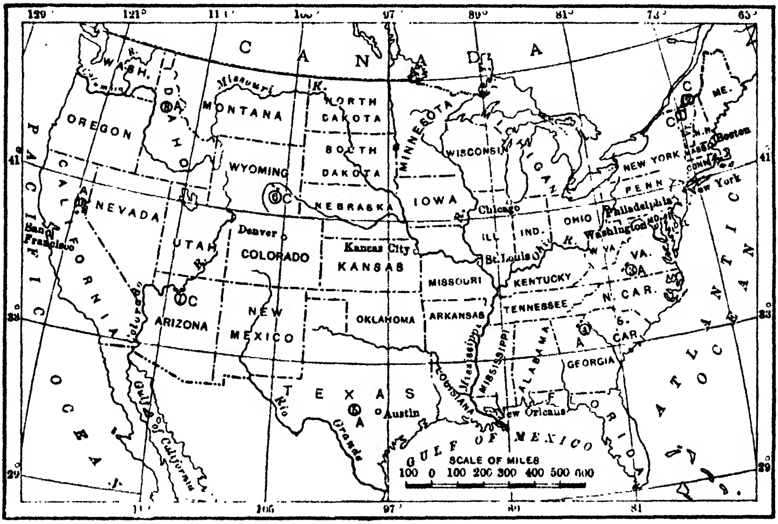

FIG. 84.—Map showing asbestos districts of the United States. (*After Diller, U. S. Geol. Surv., Min. Res.* 1913.)

1. Lowell, chrysotile; 2. Thetford, Que., chrysotile; 3. Rocky Mount, Va., Amphibole slip fiber; 4. Sall Mountain, Ga., anthophyllite; 5. Llano, Tex., amphibole; 6. Casper Mountain, Wyo., chrysotile; 7. Grand Canyon, and Globe, Ariz., chrysotile; 8. Kamiah, Idaho., anthophyllite; 9. Towle, Calif., amphibole.

Amosite fibers are said to run 9000 per inch; crocidolite, 14,500; and chrysotile very much finer.

Distribution in the United States.—The ancient crystalline rocks in which the famous Quebec deposits occur, extend southwestward through the eastern states, as far as Alabama, and although a number of small deposits of asbestos are known, yet nowhere are there any large ones; moreover, most of the deposits are of the amphibole type.

Vermont (11, 13).—Chrysotile deposits occur in the Missisquoi Valley in north-central Vermont, on or near Belvidere Mountain, not far from the Canadian border. The serpentine belt is bounded on the west by gneiss of pre-Cambrian or early Paleozoic age, and on the east by graphitic slate of early Paleozoic age.

In addition to serpentine, peridotite is present. Granite cuts the slates and serpentine in places, and has altered the latter to talc along the contact. While both the serpentine and peridotite show fracture cleavage, the chrysotile veins are found in torsion cracks produced by a later shifting of the fracture cleavage blocks. Keith and Bain believe that the chrysotile has been deposited mainly by fracture filling and that the material came from outside of the immediate vicinity of the deposit.

Vermont was the chief domestic producer in 1935.

FIG. 85.—Asbestos vein in serpentine. (*Photo. by G. P. Merrill.*)

Georgia. (9).—Sall Mountain, Georgia, was for some years a producer of anthophyllite, which formed lens-shaped masses in peridotites and pyroxenites, that are associated with pre-Cambrian gneisses, the largest lens exploited being 70 by 50 by 50 feet. The fibers are 1¼ inches or less in length, but break into shreds of ¼ to ⅒ inch. Pyrite, magnetite, talc, calcite and dolomite are the impurities. It is supposed that the anthophyllite has been formed by the alteration of olivine and enstatite of the igneous rocks. By hydration and oxidation both the anthophyllite and any unaltered olivine may be converted into serpentine, and the latter partly into talc. The deposit has not been worked since 1932. Anthophyllite is used for heat insulating, flooring, and plastering.

Virginia (24).—Amphibole asbestos is found in slip-fiber veins near Bedford, Va. The prevailing rock, which consists of hornblende and olivine, or in some

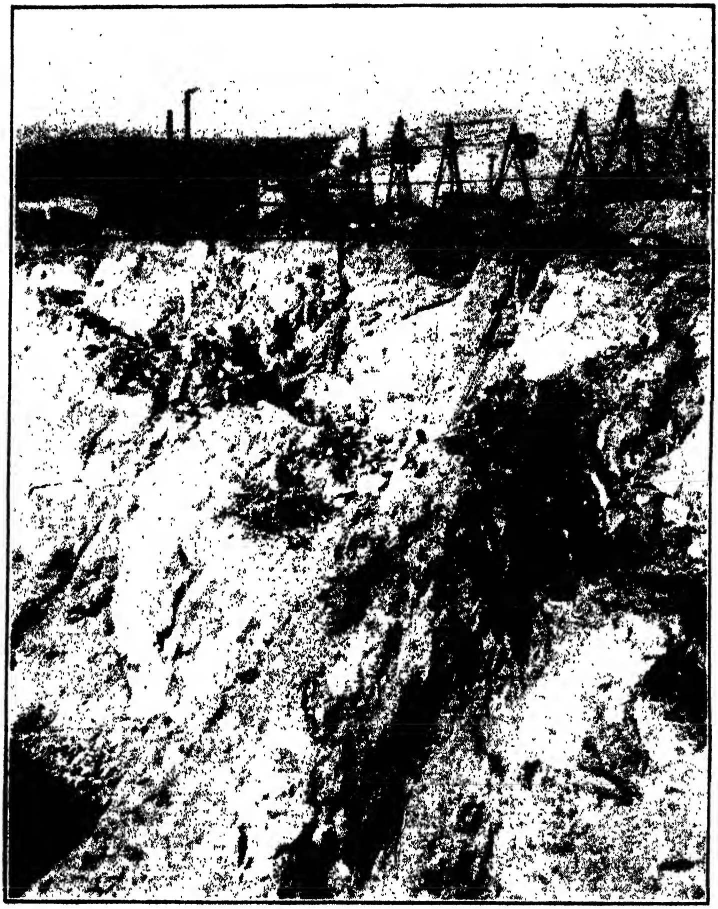

PLATE XXIX.—General view of asbestos quarry, Thetford Mines, Que. (*H. Ries, Photo.*)

cases pyroxene and olivine, is cut by occasional shear planes along which the slip fiber has developed.

Arizona (2).—Asbestos was discovered about 25 miles northeast of Globe in 1913. It forms cross-fiber veins associated with serpentine, in limestone, overlying diabase, the higher-grade veins being associated with a diabase dike.

Somewhat similar is the occurrence in the Grand Cañon of the Colorado River, near Grand View, where the asbestos forms veins in a serpentinous layer, enclosed in limestone, not far from a diabase sill. Diller has suggested that the serpentine is derived from some mineral in the limestone, while the asbestos veins postdate the serpentine and may represent a phase of contact metamorphism.

Idaho (1).—Near Kamiah, the anthophyllite asbestos forms lenticular bodies in ultra-basic intrusions, particularly dunite, which it has replaced owing to hydrothermal solutions which emanated from the Idaho batholith.

Wyoming (1).—South and southeast of Casper are pre-Cambrian intrusives consisting of hornblende schist, diorite, granite and serpentine, the last-named being much crushed and sheared, and containing both cross and slip-fiber veins of chrysotile. Maryland produces some amphibole asbestos.

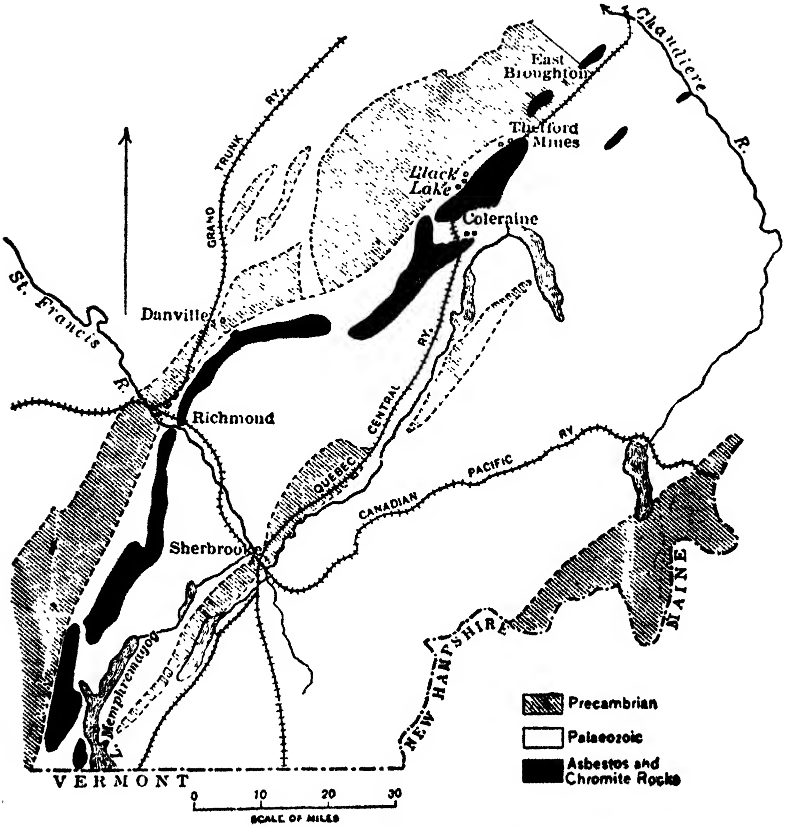

FIG. 86.—Map of Quebec asbestos area. (*After Dresser, Can. Min. Inst., Trans. XII.*)

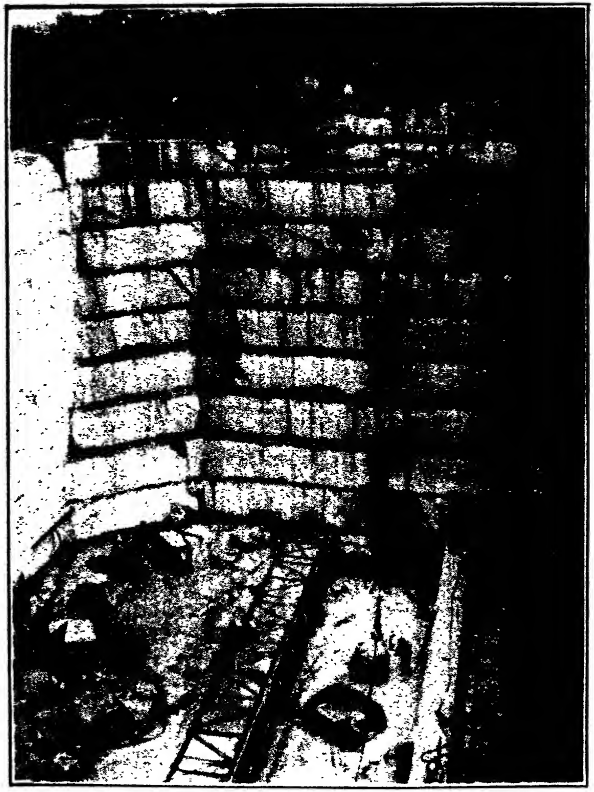

Plate XXX.—Fig. 1.—Soapstone quarry, Alberene, Va. (*H. Ries, photo.*)

Fig. 2.—Richardson feldspar quarry, near Godfrey, Ont. (*H. Ries, photo.*)

Quebec, Canada (4, 5, 6, 7, 17).—This district has been one of the important world's sources of supply for some years. Thetford and East Broughton are important localities (Fig. 86).

The geology of this area has been variously interpreted. According to the latest work by Cooke (4), the oldest rocks consist of Cambrian (Caldwell series) quartzites, slates, and lavas, overlain unconformably by Ordovician (Beauceville series) slates and impure quartzites. All of the sediments are closely folded along northeast axes. These formations have been intruded by peridotite, pyroxene, and gabbro, the last named being later than the other two. Their intrusion postdates the folding. Granite and alaskite dikes cut the basic intrusives.

Cooke states that the entire peridotite is serpentinized to an extent of 40 to 60 per cent by magmatic water. Certain portions associated with fractures are completely serpentinized. The known asbestos deposits occur fairly close to the northwest borders of the peridotite.

The asbestos is found forming veins in serpentine, varying from a fraction of an inch to 3 inches in width.

The recovery averages 5 to 6 per cent of the rock mined, with a range of 2 to 11 per cent. The deposits, which were at first worked by open pits, are now also worked by underground methods, and mining has extended to a depth of 400 feet.

Origin of the Asbestos.—There has been some difficulty in satisfactorily explaining the origin of the asbestos veins, and a number of theories have been advanced, the advocates of each having sometimes adopted a rather unyielding attitude. Not all of the theories advanced (2, 5, 11) can be mentioned here. Most investigators agree on the wall rock being the source of the chrysotile. Dresser (6) and Graham (7), while admitting the filling of the veins by infiltration, suggest that they have been enlarged by replacement of the walls (Fig. 87). Dresser points out that the veins usually show a middle parting of metallic oxides, and furthermore, that microscopic study indicates that the fibers have grown outward from each side of the seam of ore, indicating alteration and recrystallization of the serpentine *in situ*. The fractures are regarded as joints, and it is claimed that the completely serpentinized band on either side of the fracture shows a definite ratio (6:1) to the width of the vein.

Taber (23), on the other hand, believes that solutions rising along the fractures entered the walls, serpentinizing the peridotite, and that some of the serpentine was taken in solution, and reached the fractures by diffusion where it crystallized as asbestos. These crystals grew at the base, and the force exerted by them as they grew is considered to have forced the walls apart.

Cooke (4) advances the theory that the partly altered peridotite was intensely faulted by thrust movements. When interfault blocks were placed under strain by the drag of one fault face on another, many tension cracks of variable length were formed. Heated solutions entering along fault fissures penetrated the wall rock, changing it to serpentine, and bringing the excess into the fissures. There crystallization of the fibers pushed the walls apart, being assisted by existing tension. It is interesting to note that Cooke believes that asbestos solutions might flow along fissures and crystallize on walls not serpentine. This last is in line with a view expressed by Bain for the Vermont deposits.

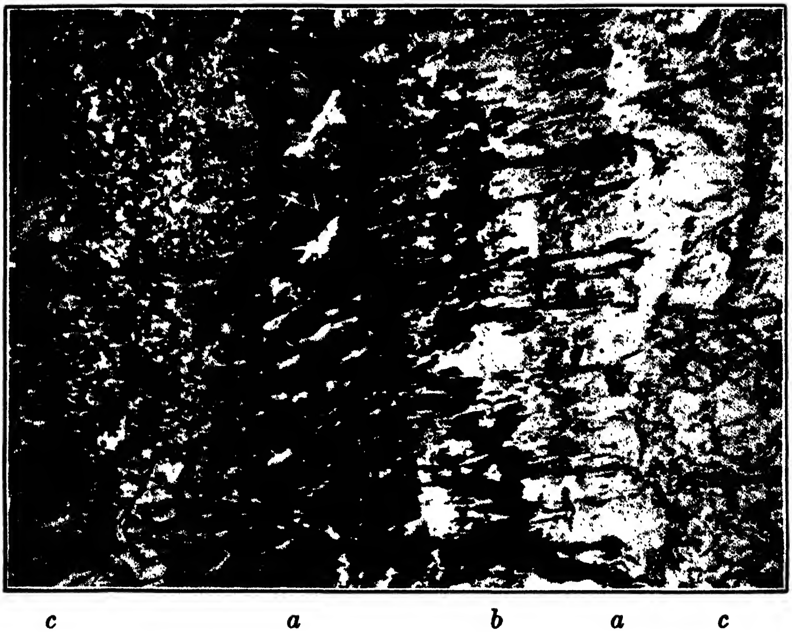

Fig. 87.—Photomicrograph showing vein of asbestos (*a*), with irregular margins, and mid streak of magnetite (*b*). Serpentinized rock (*c*) on either side. (*After Dresser, Can. Geol. Surv., Mem.* 22.)

As stated by Ries (16), it seems not unreasonable to assume that regional stresses which produced the fractures may have slowly widened them, thus permitting the deposition of chrysotile.

Any broad consideration of the origin of asbestos should take into account at least the different important deposits of the world.

Other Foreign Deposits.—In South Africa the Cape belt passing through Prieska and Tsenin (8, 15) contains only crocidolite, while the Lydenburg and Pietersburg belt in the Transvaal supplies amosite in addition.

Both belts contain a series of siliceous iron stones overlying a series of dolomites, of the Transvaal system (Pre-Devonian). The Transvaal belt is within the contact aureole of the Bushveld Igneous Complex, but there is no similar igneous body near the Cape Belt.

The crocidolite which occurs in the Lower Griquatown Series is associated with fine-grained siliceous, ferruginous slates or quartzitic ferruginous and jasper rocks, often referred to as banded ironstones. The typical crocidolite is lavender blue, and the bands pinch and swell owing to undulations of one side of the seam. The fiber length is commonly ½ to 1 inch.

The crocidolite seams always lie parallel to the bedding of the banded ironstones, showing sharp contacts with the latter, which may be wavy or straight. The seams vary in width up to 5 inches with an average of three-quarters of an inch, the fibers being often perpendicular to the walls. Associated with the blue crocidolite is a bluish non-fibrous material of similar composition which has been called potential crocidolite.

The crocidolite is similar in composition to the associated rock except for its high soda content. Its origin has not been satisfactorily settled.

Amosite occurs at the same horizon as the crocidolite of the Cape Belt, but is found entirely within the Transvaal belt, and in similar rocks. It forms cross-fiber veins, sometimes 4 to 7 inches thick, with a maximum recorded length of fiber of 11 inches.

The Shabani district of Southern Rhodesia (10) is one of the important world's producers, which presents some interesting features. The dunites and periodites have been intruded by granite, and serpentinized by solutions emanating from it. In a subsequent hydrothermal stage the cracks in the altered dunite became filled with a saturated serpentine solution, from which asbestos later crystallized. Dynamic stresses caused by a subsequent settling of the granite caused shearing, followed by deposition of talc and magnesite which encroach on the asbestos zone. The asbestos is mostly of the cross-fiber type.

Cross-fiber chrysotile is worked on the island of Cyprus where it occurs in narrow seams associated with serpentine and peridotite (25).

Russia is an important producer of chrysotile.

Uses of Asbestos.—Asbestos can be divided into two types—spinning and nonspinning. The chief use of spinning fiber is for fabrics and packings, most important being automobile brake-band linings. The chief use of nonspinning fiber is in the building trades. Asbestos paper, asbestos-cement-shingle, and millboard call for the longer grades of fiber, while the shorter is used for asbestos cement. An increasing amount of the better grades of nonspinning fiber is used for molded brake linings.

In 1940, the value per ton of the several grades of Canadian was as follows: Crude No. 1, $700–$750; Crude No. 2, $150–$350; spinning fiber, magnesia and compressed sheet fiber, $110–$200; shingle stock, $57–$78; paper stock, $40–$45; cement stock, $21–$25; and floats, $18–$20.

The value for Rhodesian Crude No. 1 in the same year was $300; and for Russian Crude No. 1, $275.

Production of Asbestos.—The United States is the world's largest manufacturer of asbestos products, but supplies only 4 to 8 per cent of the necessary raw material.

The domestic sales in 1940 were 20,060 short tons, which were valued at $309,994. Production has risen since 1932 except for a drop in 1938.

The producing states in 1940 were Arizona, California, Georgia, Maryland, North Carolina, and Vermont.

The imports of unmanufactured asbestos in 1940 amounted to 246,613 short tons valued at $10,034,433, and came mostly from Canada. Cyprus and Africa contributed appreciable amounts. No data for Russia are available since 1938.

The exports of unmanufactured asbestos products in 1940 were valued at $449,105.

Canada is the largest world's producer (313,504 metric tons in 1940), followed by Russia and Southern Rhodesia.

Canada in 1939 exported 186,238 short tons of asbestos valued at $12,463,177. The exports of manufactured asbestos including roofing were valued at $479,414, while those of asbestos sand and waste were valued at $2,902,111.

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BARITE

Properties and Occurrence.—Barite, the sulphate of barium, contains, when pure, BaO 65.7 per cent, and SO_3 34.3 per cent. Its specific gravity is 4.3 to 4.6 and its hardness 2.5 to 3.5. It is commonly white, opaque to translucent, and crystalline, while the texture is granular, fibrous, or more rarely earthy. Barite is a common mineral which may be found in many kinds of rocks—igneous, sedimentary, and metamorphic. It has in nearly all cases been formed by deposition from aqueous solutions and is not found as an original constituent of igneous rocks, nor in contact metamorphic zones, or pegmatite veins. Furthermore it is not a product of dynamo-metamorphism.

Analyses of many rocks show at least small amounts of barium, and it has also been noted in orthoclase feldspars and some micas.

It has frequently been found in spring and mine waters, where it may be in solution as the chloride, carbonate, or perhaps even as sulphate.[1] Contact of solutions containing the first two with sulphate waters will form barium sulphate, although its precipitation may be retarded by the presence of chlorides. Travertine deposits containing varying amounts of barite are also known, one described from Doughty Springs, Colo., showing from a small percentage up to 95 per cent[2] barium sulphate.

These facts indicate that barite is deposited from solution, and probably most deposits are formed in this manner.

Form of Deposits.—Commercially important deposits of barite may include the following types:

I. Veins formed by the filling of fissures, by replacement, or by cementing of fault breccias, the wall rocks being limestone, quartzite, sandstone, schist, gneiss or volcanic rocks in the different occurrences (7, 12, 23, 11).
II. Bedded deposits (3).[3]
III. Irregular masses, occurring as replacements of limestone (11).
IV. Lumps in residual clays (29).
V. Filling the interstices of brecciated masses (11, 28).

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[1] Barium sulphate has a solubility of 1 part in 400,000 of water, but the natural compound is said to be six times more soluble than the artificial.

[2] Headden, Col. Sci. Soc., Proc., VIII: 1, 1905.

[3] Bergeat, Neues Jahrb. Min. Geol., XXXIX, B. B., 1914.

Associated Minerals (7, 12, 11).—These vary with the individual deposit. The vein and replacement types often contain metallic sulphides, especially galena, but sometimes sphalerite, chalcopyrite, and pyrite. Galena is harmful, since it discolors the ground product, and other sulphides may cause similar trouble. Quartz, calcite, and fluorite are also at times abundant, the last-named being especially noted in Kentucky and Tennessee veins as well as in some of the Great Valley occurrences of Virginia.

Residual deposits especially may carry considerable iron and manganese oxides, as well as quartz. Small amounts of iron oxide can be removed by treating the ground product with H_2SO_4, but the manganese is more difficult to eliminate (11, 18).

Barite veins have not been sufficiently worked in the United States to determine whether there is much change with depth, but this has been noted in several European ones (3).

Geologic Age of Associated Rocks.—This, in the case of the deposits of the United States and Canada, may be briefly summarized as follows:

Triassic. Virginia.

Mississippian. Western Kentucky.

Devonian. Five-Islands, N. S.

Ordovician. Missouri.

Cambro-Ordovician. Central Kentucky, Tennessee, Appalachian Valley region of Virginia, Georgia, Alabama, Maryland, and Pennsylvania.

Of these the deposits of the Cambro-Ordovician are the most important, practically all the United States production coming from Missouri and the Appalachian states.

Distribution of Barite in the United States.—The more important locations may be briefly referred to since they represent several different types of occurrence.

Missouri (26, 27, 30).—The chief producing district is in Washington County, where barite is obtained from residual clays derived chiefly from the Potosi (Cambrian) limestone. Associated with it are chert and quartz. In the parent rock it is found in veins, lumps, and solution cavities, but these are not commercially important. There is a difference of opinion as to whether the barite was originally deposited by magmatic or meteoric waters.

Georgia (9, 17).—Barite deposits are known to occur near Cartersville, Ga. The bed rock consists of the Shady (Cambrian) limestone and Weisner (Cambrian) quartzite, and in these there are found veins

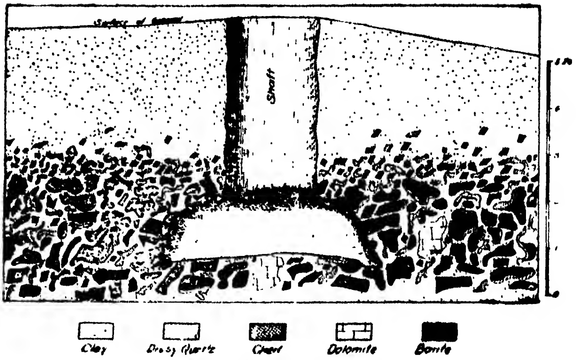

FIG. 88.—Barite deposit in residual clay near Mineral Point, Mo. (*After Buckley, Mo. Bur. Geol. and Mines, IX.*)

and replacement deposits, but they are of no commercial value. The main source of supply is colluvial, and alluvial sands and gravel (Fig. 92), the barite in them having been derived by weathering of the bed rock. The deposits have been worked for a number of years.

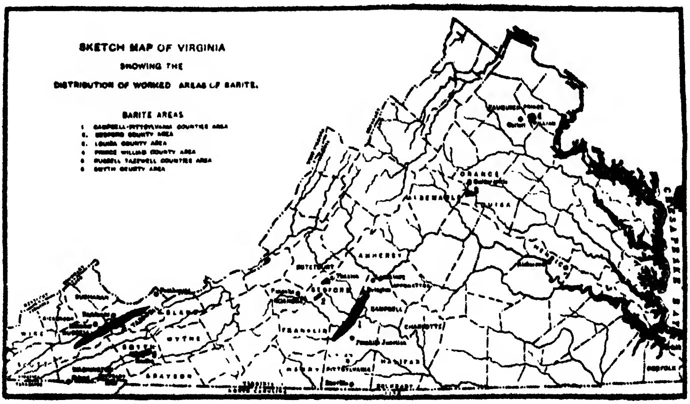

FIG. 89.—Map of Virginia showing location of worked areas of barite. (*After Watson, Min. Res. Va.*, 1907.)

Virginia (11, 29).—Barite occurs in many parts of the state (Fig. 89) but few of the deposits have been worked on a large scale, except those near Evington.

The types of occurrence recognized are: (1) fissure veins, generally banded; (2) replacement masses of lenticular form with gradational boundaries, chiefly in limestone or marble; (3) breccia zones; and

(4) residual deposits which have been the chief source of barite in this state.

The veins of the Piedmont area which are associated with pre-Cambrian marble and granite gneiss, are particularly interesting as there the barite carries tourmaline, epidote, chlorite, hornblende, and biotite, as well as showing propylitization of the wall rock, thereby indicating the magmatic origin of the deposits. In addition barite has also been found as a constituent of some of the pegmatites of this region. The magmatic origin of the deposits in the Appalachian Valley region is probable, but not equally clear. It is assumed that the barite deposition may be associated with Triassic igneous activity.

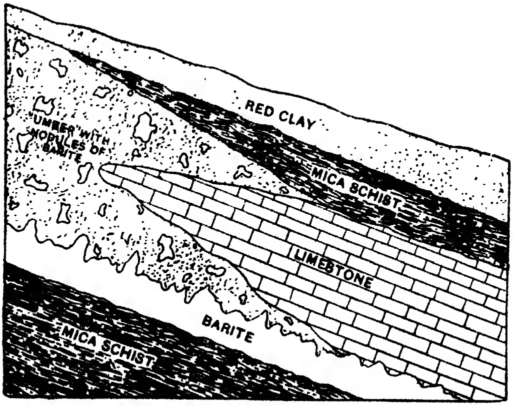

FIG. 90.—Ideal section in Bennett Barite Mine, Pittsylvania County, Va. (*After Watson, Min. Res. Va.,* 1907.)

Kentucky (12, 21).—The vein type of occurrence is well developed in this state, there being two areas. Those veins in the central part of the state (Fig. 91) are confined to the Ordovician, and are found filling simple fissures, or fault fractures, the chief associates being calcite, fluorite, sphalerite, and galena. They are from 1 to 3 feet in width, with a maximum of 24 feet, and have been mined to depths of 100 to 325 feet. In the western area, fluorspar is the chief mineral, with barite of secondary importance, and the veins occurring in Mississippian limestone.

Arkansas (20).—A bedded deposit of barite is found in Hot Springs County, where it occurs on the north flank of a closed syncline at its extremity. The laminated appearing barite is interbedded with layers of clay, and contains some pyrite parallel to the bedding. The rock which carries the barite is a Mississippian sandstone and shale. It is suggested that the barite is a hydrothermal replacement caused by solutions rising along the beds from the Magnet Cove igneous area.

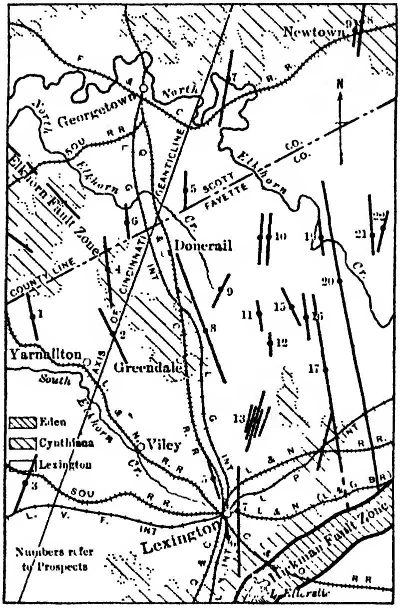

Fig. 91.—Map of barite veins near Lexington, Ky. (*After Fohs, Ky. Geol Surv., 4th Ser., I:* 441, 1913.)

Other Occurrences.—In Tennessee (15, 16) barite is obtained from residual deposits in the Sweetwater district, and Fentress County. It is also found in North Carolina (25). California (5) is an important producer, the deposits near El Portal which are replacements of limestone being of interest because

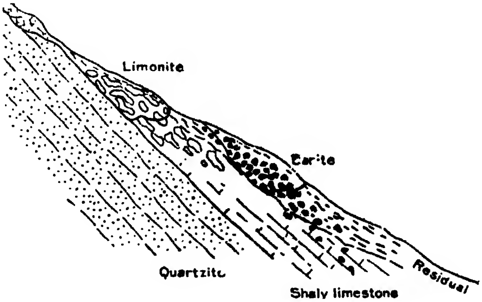

Fig. 92.—Sketch section showing relations of barite and limonite to underlying formations near Cartersville, Ga. (*After Hayes and Phalen, U. S. Geol. Surv., Bull.* **340.**)

they grade from barite downward into witherite, and the latter into lime silicates as the underlying granite is approached. Some barite has been formed by sulphuric acid from weathering pyrite, attacking witherite and changing it to barite (13). Veins are also worked in Nevada, the product from some being of a dark gray color.

ANALYSES OF BARITE

	I	II	III	IV	V	VI	VII
BaO	64.72	54.95	98.54[1]	94.20[1]	98.82[1]	93.59[1]	97.56[1]
Fe_2O_3.	.06	.06	—	.11	.33	.32	.42
SiO_2	.25	.55	.95	.05	.27	4.76	.41
CaO	tr.	.20	.02	4.44[2]	—	—	—
SrO	tr.	6.75	—	—	—	—	—
SO_3	33.82	34.22	—	—	—	—	—
ZnO	—	1.23	—	—	—	—	—
MgO	—	—	.22	—	—	—	—
F	—	.14	—	—	—	—	—

[1] $BaSO_4$ [2] $CaCO_3$

I. Mexico, Ky.; II. Danville, Ky.; III. Five Islands, N. S.; IV. Lake Ainslee, Cape Breton; V. Eton, Murray Co., Ga.; VI. Cherokee Co., S. Ca.; VII. Sweetwater district, Tennessee. All from Reference 11.

Canada (19, 23).—Barite production in Canada during former years has come mostly from the deposits at Lake Ainslie, Nova Scotia. Here the barite is found in veins in pre-Cambrian felsite. Calcite and fluorite are occasional associates. Some bituminous matter is also present.

Other Foreign Deposits.[1]—Barite deposits are widely distributed, but those of Germany (3) are probably the most important. They include: 1. A curious bituminous barite deposit, near Meggen, Westphalia, supposed to have originated by the replacement of portions of a bedded Devonian pyrite which in turn grades into limestone. 2. Vein deposits closely associated often with the Permian, and showing a considerable variety of metallic minerals. The barite is of higher grade than the Meggen product. Among other European deposits may be mentioned the replacement ones in Carboniferous limestone of Belgium, as well as minor vein deposits of France, Italy, Hungary, and Czechoslovakia, and Great Britain.

Origin of Barite.—Sulphate of barium is but slightly soluble, but is perceptibly decomposed by a dilute solution of carbonated alkali. If present in one of the silicates (feldspar) in granite it might be de-

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[1] Dammer und Tietze, Nutzbaren Mineralien, 2d. ed., II, 1927.

composed by sulphates of the alkalies, lime sulphate, or magnesium sulphate, resulting in precipitation of barium sulphate.

Buckley believes that the Missouri barite was possibly derived from solutions of the bicarbonate, precipitated with alkaline sulphates, but Tarr thinks igneous rock a probable source (27).

Watson (29) suggested that in the case of the Virginia barite it was probably taken into solution as the soluble bicarbonate, and precipitated under favorable conditions as the insoluble sulphate. Laboratory experiments by Dickson (10) with solutions of barium carbonate on selenite crystals and pure anhydrite in presence of CO_2, and on pyrite crystals in presence of an oxidizing agent, water caused precipitation of barium sulphate in each case.

Mining, Preparation, and Uses (22).—Residual deposits are usually worked as open pits, using steam shovels if the size of the operation warrants. Vein deposits may be worked as open cuts, or even by underground methods. No veins in this country have been worked to depths greater than 200 or 325 feet.

The removal of impurities from merchantable barite includes hand cobbing, sorting or grading, washing and crushing. Ground barite requires bleaching with sulphuric acid to remove iron, drying, and grinding.

Since the barite deposits are usually small and pockety, the mill must be located to permit its drawing on numerous and changing sources of supply.

Ground barite in its bleached or unbleached form is used in the manufacture of soft rubber. Much unbleached barite is used in molded goods, as buttons, hard rubber articles, and possibly phonograph records. In its bleached form barite is employed as a filler in paper where weight and smooth finish are desired. A small amount is used as an extender and loader in paints, as well as a base for lake colors. If very low in iron it may serve as an ingredient of certain glass mixtures.

Barite is used as a source of barium in the manufacture of *lithopone* pigment (7 per cent $BaSO_4$ and 30 per cent ZnS). Titanium pigment contains from 65 to 70 per cent $BaSO_4$. Barium chloride is employed in the leather industry, barium hydroxide in sugar and petroleum refining, and barium dioxide in hydrogen peroxide manufacture.

Production of Barite.—The quantity of barite sold in the United States in 1940 was 409,353 short tons, valued at $2,596,743, with an average value of $6.34 per short ton. The production has risen steadily from a low point in 1932. Production comes from a number of states, among which Georgia, Missouri, and Tennessee are prominent. The imports in 1940 were 7,391 short tons, valued at $41,392. Exports are not separately recorded.

Canada reported no production for 1938. The imports of lithopone, barite, and blanc fixe in 1939 amounted to 13,351 short tons, valued at $831,454.

The three leading world's producers in 1938 were Prussia, the United States, the United Kingdom.

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DIATOMACEOUS EARTH (DIATOMITE)

Properties and Occurrence (5, 10).—This material when pure is made up of the siliceous cases of diatoms (Fig. 93). Chemically it is a variety of opal. It resembles chalk or clay in appearance, but is very much lighter than either of these, and can also be distinguished from the former substance by the fact that it does not effervesce with acid. A microscopic examination serves to identify it at once.

Diatomaceous earth is commonly white or light gray in color, but may be brownish, dark gray, or even black, owing to the presence of organic matter. It is exceedingly porous. If pure, it should show little else than silica and water on analysis, but most earths have at least small amounts of other substances, and some contain a large amount of clayey impurities (see analysis VI below).

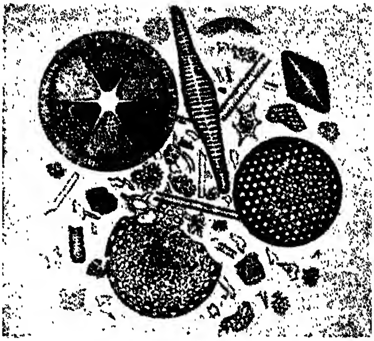

FIG. 93.—Diatomaceous earth from Lompoc, Calif. (*Calif. State Min. Bur., Bull.* 38.)

The following analyses represent the composition of a number of American earths:

ANALYSES OF DIATOMACEOUS EARTH

	I	II	III	IV	V	VI	VII	VIII
SiO_2	86.92	72.50	86.89	80.53	81.53	63.17	82.85	86.515
Al_2O_3	4.27	11.71	2.32	5.89	3.43	19.30	6.76	.449
Fe_2O_3	—	2.35	1.28	1.03	3.34	6.32	2.34	.374
CaO	1.60	.32	.43	.35	2.61	.06	.35	.120
MgO	tr.	.83	tr.	—	—	.69	1.06	12.000
Alkalies . . .	2.48	1.88	3.58	—	2.59	3.14	2.06	—
TiO_2	—	—	—	—	—	.88	1.09	—
Ign. loss . . .	5.13	9.54	4.89	12.03	6.04	6.39	3.40	—
	100.40	99.13	99.39	99.83	99.54	99.95	99.91	98.458

I. Porcelain diatomaceous shale, Point Sal, Santa Barbara Co., Calif. II. Soft shale, Orcutt, Santa Barbara Co., Calif. III. Monterey, Santa Barbara Co., Calif. IV. Lake Umbagog, N. H. V. Pope's Creek, Md. VI. Wilmot, Va.; very clayey. VII. Richmond, Va. VIII. Herkimer, N. Y.

Distribution in the United States.—Diatomaceous earth occurs as deposits of comparatively small extent in the bottoms of ponds, lakes, and swamps, sometimes mixed with organic matter, or it may form bedded deposits of marine origin and showing at times great extent as well as thickness. A few localities may be mentioned.

California (1, 6).—Important deposits of diatomaceous earth are known to occur at a number of points in the Coast Ranges of California, but the most important, perhaps, are those found in northern Santa Barbara County. There it occurs mainly in the Monterey (Middle Miocene) and in the lower part of the Fernando (Upper Miocene) formations (Pl. XXVII, Fig. 2).

The deposits range from those of high purity, through impure shaly beds, to flinty deposits. The earth is found interbedded with volcanic ash at some localities (south of Lompoc), and with limestones at others. The thickness of the diatom deposits is often remarkable, the depth of economically recoverable diatomite at Lompoc being 1000 feet (6).

New York (2, 4).—Although diatomaceous earth is known to occur at several localities, the only one recently worked is near Hinckley, Herkimer County, where it forms a bed 2 to 30 feet in White Head Lake. It is purified by washing and pressed into cakes.

Virginia (8).—In the Atlantic Coastal Plain, deposits of diatomaceous earth are not uncommon in the Miocene (Tertiary) formations, and those around Richmond have long been known. Along the Rappahannock River, especially below Wilmot, there are long exposures, the bluffs of the material standing out prominently in the sunlight.

Maryland.—Beds of diatomaceous earth occur at the base of the Calvert (Tertiary) formation, deposits being known in Anne Arundel, Calvert, and Charles counties. Few of them are worked, although some attain a thickness of at least 25 or 30 feet.

Other States.—Connecticut, Massachusetts, Florida, Nevada, Oregon (7, 9), and Washington are also producers, but the deposits are of limited extent.

Foreign Deposits.—Diatomaceous earth is known to occur at a number of Canadian localities, but the only production recorded is from Nova Scotia. Many deposits are known in Europe.[1] Large deposits are worked in North Africa.

Uses.—The uses of diatomite appear to be influenced by the size and shape of the diatoms, which in turn affect the porosity and texture of the material. It is used for polishing powders, and as a non-conductor of heat for steam-boiler backing, for wrapping steam pipes and fireproof cement. Mixed with clay, or even alone, it can be used for making porous brick or partition tile. Some of the California material is cut out into bricks by special quarry machines. A most

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[1] Dammer und Tietze, Nutzbaren Mineralien, 2d. ed., I, 1927.

important use is as a filtering medium. Processed diatomite is employed as a decolorizer for oils. It is also used as a filler for asphalt as an ingredient of talking machine records, and in the manufacture of ultramarine, various pigments, and aniline colors. All grades of matches may contain some. It is further employed in paints and varnishes as an inert filler, for reinforcing pigment for rubber, and in liquid polishes. A small amount is still used, chiefly in Europe, as an ingredient of nitroglycerine.

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FELDSPAR

Properties and Occurrence.—The feldspar group includes several species, all silicates of alumina, with one or more of the bases—potash, soda, and lime. These species may be divided into two groups, viz., the potash feldspars, and the lime-soda feldspars, a division which is not without practical value, since the two groups differ somewhat in their fusibility and mineral associates.

Orthoclase and microcline, whose composition is expressed by the formula $KAlSi_3O_8$, are the chief representatives of the first group. Expressed in percentages their composition is SiO_2, 64.7 per cent; Al_2O_3, 18.4 per cent; K_2O, 16.9 per cent. Soda may partly or wholly replace the potash. If the latter occurs, anorthoclase results. Potash-soda feldspars are usually pinkish to nearly white, but some, as that mined in Ontario, is a distinct reddish color. Nevertheless, even the strongly colored ones may calcine to a pure white color, and show a sufficiently low iron oxide content to permit their use in pottery manufacture.

The lime-soda feldspars, or plagioclases, present a series of compounds ranging from the soda feldspar, albite, through soda-lime feldspars, to the pure lime spar, anorthite, at the other end.

Albite, whose formula is $NaAlSi_3O_8$, has SiO_2, 68.7 per cent; Al_2O_3, 19.5 per cent; Na_2O, 11.8 per cent. Anorthite, $CaAl_2Si_2O_8$, has SiO_2 43.2 per cent; Al_2O_3, 36.7 per cent; CaO, 20.1 per cent

Potters prefer albite because of lower fusibility. As a rule feldspars in melting pass gradually from a solid condition to that of a very stiff fluid, but the fusion point depends on the kind of feldspar. Thus orthoclase is said by Bowen to fuse at 1170° C, albite at 1100° C, and anorthite at 1550° C.

Most of the feldspar quarried in the United States is the potash-soda type, but in some localities the soda spar, albite, may be present. If plagioclase is present in feldspar used for pottery, it is generally albite.

Feldspars are widely distributed in many igneous and metamorphic rocks, but in most cases they are so intimately mixed with other minerals that their extraction is not commercially practicable, and it is only when found in pegmatites that they are worked.[1] Of these rocks, two types are recognizable, viz., the granite pegmatites, which are very coarse-grained and carry quartz, potash feldspar, muscovite, biotite, tourmaline, etc., and the soda pegmatites, which consist mainy of albite with a little hornblende. Most of the deposits worked in the United States belong to the first type, only a few from southeastern Pennsylvania and northeastern Maryland falling in the second class.

It may be mentioned here that all pegmatite deposits are not worked for their feldspar contents, some serving as sources of other minerals, such as mica, quartz, or gems. Their value as spar deposits depends on the quantity and purity of the material present.

The pottery trade demands that the spar be free from iron-bearing minerals. Muscovite is also undesirable on account of the difficulty encountered in grinding it, while the permissible limits for quartz range from 5 to 20 per cent.

In quarrying or mining some sorting is often necessary, and in those states lying south of the glaciated area the deposit may be capped with residual clay.

Distribution of Feldspar in the United States (2).—In the United States feldspar quarries are operated in New York, Connecticut, New Hampshire (9), North Carolina (14), etc. The general form of deposit is similar in all the states, but some of those worked in Pennsylvania and Maryland are albite spar, while the others are potash spar. The

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[1] For origin of pegmatites see: Hess, Eng. Min. Jour. Press, Aug. 22, 1925; Landes, Amer. Min., p. 519, 1928; Schaller, Amer. Min. XII: 62, 1927.

wall rock is gneiss or schist, and rarely limestone (some New York (10) and Maryland).

In recent years feldspar deposits have also been developed in California, Colorado, and Minnesota.[1]

The following table gives the composition of feldspar from a number of localities:

ANALYSES OF FELDSPARS

	1	2	3	4	5	6	7
SiO_2	64.7	65.40	65.23	65.95	64.62	63.50	68.60
Al_2O_3	18.4	18.80	20.09	18.00	20.57	22.39	19.10
Fe_2O_3	—	tr.	.71	.12	tr.	.36	.14
CaO	—	none	none	1.05	.14	2.15	tr.
MgO	—	none	none	tr.	2.36	none	.28
K_2O	16.9	13.90	11.60	12.13	1.94	3.40	9.03
Na_2O	—	1.95	2.00	2.11	10.27	6.27	2.09
Loss on ignition	—	.60	.36	—	—	1.00	—
Total	100.0	100.65	99.99	99.36	99.90	99.07	99.24

1. Theoretical composition of pure orthoclase or microcline. 2. Pink orthoclase-microcline feldspar, from Bedford, Ont. Much used by American potters. 3. Cream-colored orthoclase-microcline feldspar, Georgetown, Me. 4. Pink orthoclase-microcline feldspar, Bedford Village, N. Y. 5. Soda feldspar, Chester County, Pa. 6. White feldspar, Embreeville, Pa. 7. Potash-soda feldspar, Henryton, Md.

Canada (4, 12).—The Canadian production comes chiefly from Quebec and Ontario. Manitoba has contributed some since 1933. In Quebec the mining is done in the townships of Portland, Derry, and Buckingham in the Gatineau-Lievre section of the Ottawa Valley. One deposit near Villeneuve has yielded a very white albite. In Ontario the production is chiefly in Lanark County. Some of the pegmatites worked here and to the southward (Pl. XXV) are bodies of some size. The Manitoba spar comes from pegmatite near Point du Bois on the Winnipeg River.

Recently there has been developed in Hastings County a deposit of nepheline syenite, which has a lower fusion point than feldspar. The material is crushed, freed of impurities, and finely ground. It is at present being sold for glass manufacture, but its use in pottery bodies is also contemplated.

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[1] U. S. Geol. Surv., Min. Res. 1913: 149, 1914.

PLATE XXXI

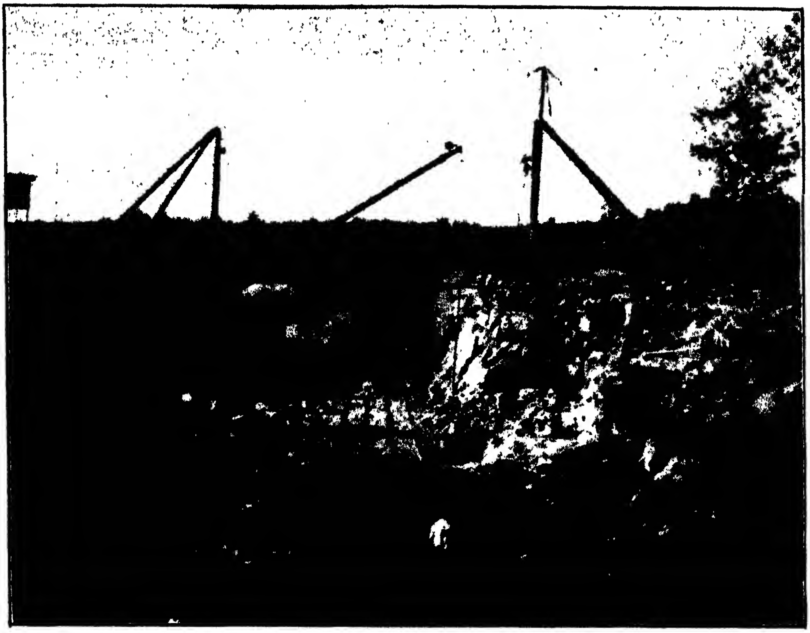

FIG. 1.—Stewart graphite mine, near Buckingham, Que. Rock on right, graphitic gneiss. On left at farther end of cut, a basic igneous rock. (*H. Ries, photo.*)

FIG. 2.—Mica mine, Sydenham, Ontario. (*Photo. lent by Can. Dept. Mines.*)

Other Foreign Deposits.—Many feldspar deposits are worked in Europe, for use in the pottery industry. Those of Norway (1) and Sweden are the largest producers, the product being exported in considerable quantity. In this connection mention may be made of *Cornish stone*, a partly weathered, coarse-grained granite, quarried in Cornwall, England, and used in some quantity by the potters of Europe and America.

Uses (3, 12).—Feldspar is used chiefly as a flux in the manufacture of pottery, electrical porcelain, and some enameled wares. For all these purposes it should be as free from iron as possible, but some of the ground commercial spar carries as much as 15 to 20 per cent free quartz.

Feldspar is also employed as a flux or binder in emery and carborundum wheels, and to some extent in the manufacture of opalescent glass. For the last purpose it can carry more quartz and muscovite than pottery spar, and does not have to be as finely ground, 50 to 60 mesh being sufficient.

As an ingredient of scouring soap, feldspar possesses advantages over quartz, because it is softer and less liable to scratch glass. Selected feldspar is used in the manufacture of artificial teeth.

The possibility of using feldspar as a fertilizer, because of its potash content, has been suggested. Nepheline syenite has become a competitor in glass manufacture.

Production of Feldspar.—The production of feldspar in the United States in 1940 was 290,763 long tons valued at $1,271,995. The price of crude spar has been about $4.37 per ton for several years. Ground domestic spar in 1940 was $10.49 per ton, while ground from imported crude sold for $18.89 per ton in the same year.

In 1940 North Carolina was the leading state, supplying 28.5 per cent of the tonnage. South Dakota and New Hampshire were respectively second and third.

The imports in 1940 were 12,522 long tons, valued at $80,274, nearly the entire supply coming from Canada. There were no exports reported.

The production of feldspar in Canada during 1939 was 12,500 tons valued at $112,300. Canada in the same year imported 865 tons mostly of ground feldspar valued at $11,681, all of it coming from the United States. In the same year she exported 7,661 tons of crude spar valued at $49,957, most of it to the United States.

In 1939 the United States was the leading world's producer with Sweden, Norway, and Canada following in the order named, but with the first-named far in the lead.

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FLUORSPAR

Fluorspar, or fluorite (CaF_2), contains 48.9 per cent fluorine and 51.1 per cent calcium. Its hardness is 4, its specific gravity, 3.18, and it has a pronounced octahedral cleavage. Fluorite shows a variety of colors, including white, green, purple, etc. The mineral is commonly found in veins which may be fissure fillings or replacements, and is often associated with ore minerals, especially lead and tin. Limestone is the most important wall rock of the American deposits, but in some districts granites, gneisses, or volcanic rocks may form the vein wall.

Distribution in the United States.—In the United States fluorite is found at a number of points in the Piedmont and Appalachian areas from Maine to Virginia, and is likewise noted (usually in small amounts) in many metalliferous veins of the west; but the most important producing districts are in Kentucky and Illinois. Colorado, New Mexico, and Tennessee are also to be included in the producing states.

Kentucky (6, 10).—In the western Kentucky district, which is one of the largest producers of the world, the fluorite occurs as vein deposits in fault fissures cutting limestones (Fig. 94), sandstones, and shales of Carboniferous age. The minerals have been deposited by (1) a filling of the fissure cavity, (2) replacing the wall rock of the fissure, or (3) cementing a breccia of the same.[1] Associated with the fluorspar are barite, calcite, galena, and sphalerite, as well as other minerals in smaller amounts. The different minerals may occur in the veins, either intimately intergrown or in separate bands; in some cases,

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[1] Currier, Ky. Geol. Surv., Ser. VI, 1923, regards them as replacements of vein calcite.

however, only one mineral may be present in the vein. The fault fissures strike northeast and northwest, but the former carry more fluorite.

It is supposed that the fluorite has been deposited by thermal waters, which were given off during cooling by the dikes of mica peridotite which are found in the district. The fissures, fault planes, and dike contacts served as trunk channels along which the waters ascended, and from which they also spread out into the adjacent rocks. Weathering has produced a disintegration of the fluorite. The veins show a maximum width of 36 feet for gravel ore and 16 feet for lump ore.

The product of the veins is divided into lump, representing the coarse product; gravel, which is the naturally or artificially disintegrated spar, and ground fluorspar. Washing and jigging are necessary to separate clay and associated minerals. No. 1 fluorite is usually white and carries 96 per cent or more of calcium fluoride; No. 2 grade has at least 90 per cent calcium fluoride and under 4 per cent silica; while No. 3 carries from 60 to 90 per cent calcium fluoride.

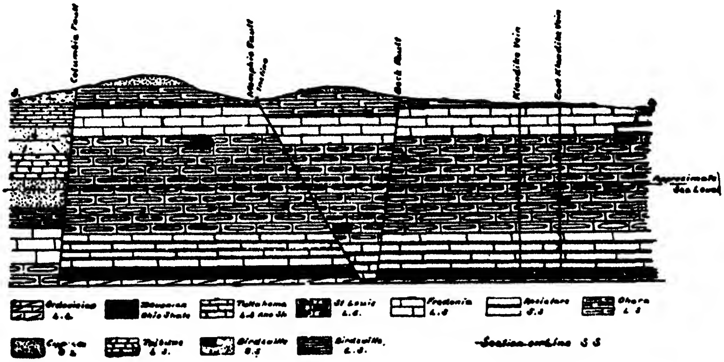

Fig. 94.—Section of Memphis mine group. (*After Fohs, Ky. Geol. Surv., Bull.* 9.)

Illinois (3, 5, 7).—Until 1898 Hardin and Pope counties, Illinois, were the only domestic sources (2), and this area continues to be an important producer. The main deposits fill fault fissures in Lower Carboniferous limestones or sandstones. Dikes of mica peridotite also occur in the district, but not in contact with the veins. These latter in some places attain a width of 45 feet and a proven depth of 1000 feet. The vein filling is chiefly fluorite and calcite, while associated with these are smaller amounts of galena, sphalerite, and occasionally pyrite or chalcopyrite. In the Cave in Rock area the fluorite occurs as horizontal masses replacing limestone. Their average thickness is 4 feet, with a maximum of 12 feet.

The origin of the fluorite is somewhat doubtful, but Bain (2) believes that it has probably been derived from heated waters of either meteoric or magmatic origin which leached the mineral from some large mass of low-lying igneous rocks of which the dikes are offshoots. These heated ascending solutions are thought to have carried fluosilicates of zinc, lead, copper, iron, barium, and calcium. The dissolved compounds were probably broken up by cold descending waters, which possibly also furnished the sulphur to combine with the metals. Spurr suggests a magmatic origin (14) for the fluorite, and Currier regards the mineral as a replacement of vein calcite (6).

Colorado (1).—In eastern Colorado fluorspar occurs in considerable quantities in a belt extending from Boulder County to Custer County. The veins, in most cases, cut granites and gneisses of pre-Cambrian age that have been intruded by later dikes, especially of quartz porphyry. Metalliferous minerals are associated with the fluorite, but in several instances the latter forms most of the vein filling. The deposits have thus far not been extensively developed, and much of the material lies rather far from the railroad. The producing counties are Chaffee, Boulder, Jackson, and Mineral. Some of the product is shipped to Pennsylvania and New York.

Shipments have been made from an interesting vein at Wagon Wheel Gap. The fluorite here occupies a fissure averaging 3 feet in width in rhyolitic tuffs and breccias. It is associated with hot springs, and contains small quantities also of barite, calcite, quartz, and altered pyrite, the last mostly in the altered wall rock. Even small amounts of gold and silver occur in the fluorite.

New Mexico (11).—Fluorspar occurs as vein fillings in igneous and sedimentary rocks and replacements in limestone, in south and southwestern New Mexico. Few of the veins have sharp walls, and where fluorite replaces the limestone, often much secondary quartz accompanies it. Silicification of the walls is common in limestone and igneous rock, but the latter also frequently shows sericitization. The chief primary minerals are fluorite, barite, calcite, quartz, galena, pyrite, chalcopyrite and occasionally specularite. The deposits are thought to be of magmatic origin and associated with Tertiary volcanic activity.

Canada (16).—The production of fluorspar in Canada is small, and has come from Ontario, and intermittently from British Columbia. The Rock Candy vein near Grand Forks, British Columbia, is said to be the most extensive fluorspar deposit thus far discovered in Canada. The deposit represents a network of closely spaced veins, whose filling consists of a mixture of fluorite, barite, chert, quartz, calcite, and

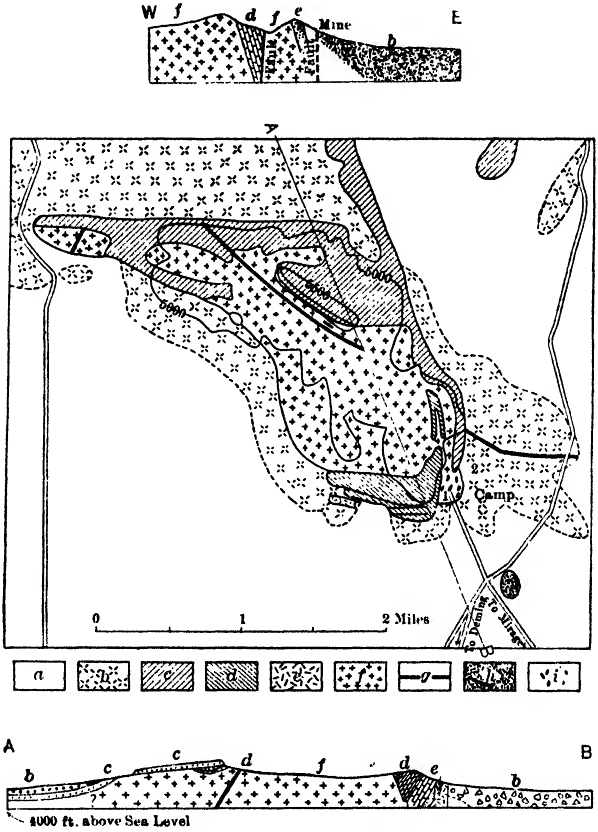

FIG. 95.—Map and sections of fluorspar deposits, Deming, N. Mex. *a*, Desert fill; *b*, andesitic agglomerate; *c*, sandstone; *d*, limestone; *e*, intrusive granite; *f*, monzonite; *g*, basalt dikes; *h*, rhyolite; *i*, fluorite veins, marked 1 and 2 on map. (*After Darton and Burchard, U. S. Geol. Surv., Bull.* 470.)

pyrite. Dolmage regards it as a replacement of syenite in the epithermal zone.

In the deposits at Madoc, Ontario, the veins which are associated with a fault fissure cut Ordovician limestone and pre-Cambrian granite, limestone, and graywacke. The chief vein minerals are fluorite, barite, calcite, and celestite. Uncommon minerals are pyrite, marcasite, chalcopyrite, quartz, and tetrahedrite. Wilson admits that they may possibly be derived from a magmatic source, but seems to think that their deposition by meteoric waters is equally reasonable.

Other Foreign Deposits.—Next to the United States, Great Britain is the largest producer, the fluorspar of Derbyshire and Durham, associated with lead-zinc ores of the Carboniferous, serving as an important source of supply. Most of the mineral comes from the tailings of lead mines, and the gob of abandoned workings.

In Germany fluorspar veins are worked, especially in the southern Harz district, Bavaria, Black Forest and Thuringian Forest. The veins may be large, and contain the common associates.

Cryolite.—This mineral, which is a sodium-aluminum fluoride, is not produced in the United States, the entire supply being imported from Ivigtut on the south coast of Greenland.[1] The cryolite forms a large mass in a porphyritic granite, partly surrounded by pegmatite. Siderite, galena, pyrite, and fluorite are associates.

The quantity of natural and artificial imported for consumption in the United States in 1940 was 258,858 long tons, valued at $1,329,788, or an average price of $76.63 per ton.

Analyses of Fluorspar.—The analyses (2, 12) given on p. 273 will indicate the variation in composition of the American product.

Uses.—Most of the domestic and imported fluorspar is used in the steel industry, being added as a flux to the furnace charge. It gives fluidity to the slag, and assists the elimination of objectionable im-

ANALYSES OF FLUORSPAR

LOCALITY	CaF_2	SiO_2	$CaCO_3$, $MgCO_3$	Fe_2O_3, Al_2O_3
Hodge Mines, Ky.	98.30	0.21	0.98	—
Nancy Hanks Mines, Ky.	96.00	0.71	3.29	tr.
Gravel Fluorspar	95.08	1.90	—	—
Rosita, Colo.	86.75	9.3	—	4.2
Jamestown, Colo.	60.9	27.	—	n.d.
	76.05	19.8	—	4.2
	86.75	8.60	—	4.46
Marion, Ky.	96.01	1.9	—	1.88
	84.25	2.98	10.28	1.28
Fairview, Ill.	88.85	3.4	—	1.45
Mirage, N. Mex.	93.68	4.68	0.76	0.74

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[1] Gordon, S. G., "Mining Cryolite in Greenland." Eng. Min. Jour. Press, vol. 12, Feb. 6, 1926, pp. 236–240. Ball, Soc. Econ. Geol., Pub. 15, 1922.

purities, as sulphur and phosphorus. The fluorspar must show at least 85 per cent CaF_2, not over 5 per cent SiO_2 or over 3 per cent S. For cupola work in the foundry, fluorspar has a similar use.

In the glass industry fluorspar is used chiefly in making opalescent, opaque, and colored glasses. That used generally contains 95 per cent CaF_2, under 3 per cent SiO_2, under 1 per cent $CaCO_3$, and not over 0.12 per cent Fe_2O_3.

Similarly high-grade fluorspar is called for in the iron enameling industry.

For making hydrofluoric acid the specifications call for fluorspar with a minimum of 98 per cent CaF_2 and a maximum of 1 per cent SiO_2. Fluorspar is also employed in the manufacture of artificial cryolite.

A small amount of fluorspar is used for optical purposes. It must be water clear, colorless, and free from inclusions or cracks.

Preparation and Grading.—The fluorspar is prepared for market by hand sorting, crushing, jigging, and sometimes fine grinding. The grades produced are:

1. American lump No. 1, with under 1 per cent silica, and sold mainly to glass, enameling, and chemical industries.

2. American lump No. 2, which includes colored spar and may run as high as 4 per cent silica, though usually sold under a 3 per cent guaranty. It is used by blast furnaces in the production of ferrosilicon and ferromanganese, and in basic open hearth steel furnaces.

3. Gravel spar, including all with over 4 per cent silica, and spar mixed with calcite. It is used in iron and brass foundries.

Production of Fluorspar.—The production of fluorspar in the United States in 1940 amounted to 244,000 short tons, while the shipments were 233,600 short tons, valued at $4,744,808. The average value at mine for eastern spar was $18.93 to steel plants and $26.10 to acid manufacturers. The production has tripled since 1933. Kentucky and Illinois together produced about 89 per cent of the total tonnage. Other producing states were Colorado, New Mexico, California, and Nevada.

The imports into the United States in 1940 were 11,871 short tons, valued at $142,931, and came mostly from Germany. The exports in 1940 were 8,482 tons valued at $178,467.

Canada in 1939 produced but 240 short tons, valued at $4,995, the entire production coming from Ontario. The imports for the same year were 16,332 tons valued at $258,796.

The United States, Germany, and the United Kingdom are the three leading producers.

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FOUNDRY SANDS

Definition.—Under the term *foundry sand* are included (1) sands for making the mold proper into which the metal is cast, and (2) core sand, utilized for making the cores which occupy the hollow spaces of the cast piece.

The molding sands proper are usually of finer texture and more loamy character than the core sands, still the two grades overlap, and both show considerable range of texture. In selecting molding sands, the fine-grained ones are used for small castings while the coarser grades are employed for heavy castings. The core sands have but little cohesiveness, owing to their lack of bonding material, and hence require the addition of an artificial binder.

Requisite Properties.—The requisite physical qualities of foundry sands are: (1) sufficient cohesiveness to make the grains cohere when pressed together to form the parts of the mold, the deficiency in this respect in core sands being supplied by artificial binders; (2) sufficient refractoriness to prevent extensive fusion in the sand when exposed to the heat of the molten metal; (3) texture adapted to the grade of casting to be poured in it; (4) sufficient porosity and permeability to permit the escape of the gases given off by the cooling metal; (5) durability, or sufficient length of life, to permit as much of the sand as possible being used over again.

The laboratory examination of foundry sands may include the determination of (1) texture (by sieve test), (2) permeability to gases,

(3) bonding strength, (4) dye absorption (to determine quality of bond), (5) refractoriness, and (6) life. These tests have been to a large extent standardized.[1]

These physical properties of the sand determine the size of casting for which the sand can be used, smoothness of finish, and to some extent the kind of metal that can be cast in it. The variation in the physical properties has resulted in the sands being graded, and although at present the grades have not been standardized, efforts to accomplish this are now under way. Chemical analyses of foundry sands are of little or no value.

Mixtures of sands are often used, and even synthetic sands consisting of silica sand and fire clay, or bentonite, mixtures, may be employed.

Distribution in the United States.—Many thousands of tons of foundry sand are used annually by foundries, scattered all over the United States and Canada. In most cases sands are obtained from nearby sources, but in others they may be brought from a considerable distance, the latter being especially true of the finer-textured sands, employed for casting brass and stove plate. Certain varieties, such as those used for casting bronze, may be even imported from Europe.

The region north and south of Albany, N. Y., has a high reputation because of the finer grades of molding sand which it produces and which are shipped to different parts of the United States and even Canada. The Newport, Ky., district, and Danville, Pa., yield similar grades, all from Pleistocene formations.

The Cretaceous and Tertiary beds of New Jersey also form the basis of an extensive foundry sand industry, yielding much medium and coarse molding and core sand. Still other important districts are in Ohio, Indiana, and Michigan.

Dune sand for core work is obtained at a number of localities. Soft high-silica sandstone is quarried and crushed for core and steel work in eastern Ohio, Ottawa, Illinois, and other localities.

The sand beds often vary greatly in thickness, and several grades may occur in the same deposit, necessitating careful sorting at the pit.

The quantity of molding sand produced in the United States annually amounts to several million tons, with an average value of about a dollar a ton.

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FULLER'S EARTH (BLEACHING CLAY)

Properties.—Fuller's earth (12) may be regarded as a peculiar type of clay which has the property of decolorizing or clarifying (bleaching) oils and fats. Such earths are also known as active clays. Some clays are not active in their natural condition, but may be activated by partial acid leaching, and the most powerful bleaching clays belong to this type.

Fuller's earth (8, 9) is usually of bentonitic character, but not all so-called bentonites are activable, although they supply our most efficient activable clays.

Bleaching action is said to be due to the selective adsorption of coloring matter on the exposed particle surfaces which are in contact with the liquid to be decolorized. Nutting (9) believes that the selective adsorption is due to the presence of chemically open bonds or free valences on the surface. Contributing factors may be platy structure, fineness of grain, and individual bonding of atoms within the clay material.

More than 90 per cent of the fuller's earth produced in the United States is said to be used for decolorizing mineral oils, 6 per cent for vegetable and animal oils, and under 1 per cent for fulling cloth. The naturally active clays are employed chiefly for bleaching edible oils, while the activated clays find their chief use for mineral and vegetable oils and animal fats.

All domestic bleaching clays are of sedimentary origin, and probably originated from the alteration of volcanic ash. Montmorillonite is therefore their dominant mineral constituent.

Some clays grade from active ones at the top of the deposit to activable ones at their base, a change which is believed to be due to weathering.

Some bentonites absorb several times their weight of water and swell considerably, but these are said to be generally less activable than non-swelling types. Activable clays commonly slake in water, while most active ones do not.

Bleaching clays are of variable color and hardness, but are usually fine grained.

Distribution in the United States.—Originally the fuller's earth used in the United States was imported from England, and some is still obtained from Europe.

The domestic supply is obtained chiefly from Tertiary and Cretaceous formations. Georgia (2) is the largest producer, the most important deposits of both fuller's earth and bentonite being found in Miocene deposits in Decatur County. Here there occur high-grade naturally active clays. Fuller's earth is also dug in Twiggs and Wilkinson counties.

Florida (7, 13), which ranks next to Georgia in point of production, has deposits in Gadsden and Marion counties, the former being just across the border from Decatur County, Georgia. Those are also of Miocene age.

Other producing states are Alabama, California, Colorado, Illinois (5, 11), Indiana, Nevada, and Texas.

Foreign Deposits.[1]—The best known foreign deposits are those of England. They are worked chiefly in the Lower Cretaceous at Woburn Sands, and in the Lower Oölite (Jurassic) at Bath. The German deposits, though of low yield, are interesting because those of the most important or Westerwald district are a weathering product of basalt, while some of the Saxon ones come from the decay of gabbro and amphibolite.

Production of Fuller's Earth.—The production of fuller's earth in the United States in 1940 was 146,568 short tons valued at $1,471,083. The production has fallen since the peak in 1930 as activated bentonite and bauxite have become strong competitors in oil refining. Georgia, Florida, and Texas were the leading producers.

The imports in 1940 were 474 short tons valued at $6,105, and came almost entirely from the United Kingdom. The exports in 1940 were 6,290 short tons valued at $53,886. About 30 per cent of this went to Canada.

Canada in 1939 consumed 10,700 short tons, valued at $335,138. Most of it was used in the petroleum industry.

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[1] Dammer und Tietze, Nutzbaren Mineralien, II, 1927.

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GLASS SAND

Glass sand is obtained from quartzose sands, sandstones, or quartzites. When sand is employed, it is sometimes necessary to put it through a washing process in order to separate the impurities, while in the case of sandstone or quartzite, at least a preliminary crushing and screening are usually necessary.

Chemical Composition.—Since silica is the major ingredient of the sand, it influences the character of the ware to a marked degree. Sand with impurities is therefore to be avoided, especially if it is to be used for the higher grades of glassware. Chemical analysis of almost any sand may show at least traces of iron oxide, alumina, titanium oxide, lime, magnesia, and organic matter, but most of these are included in mineral grains other than quartz.

Iron oxide, even in small amounts, colors the glass green, and is avoided by a selection of the whitest sand, although whiteness does not necessarily indicate freedom from impurities. Washing may remove much of the iron, and the iron color may also be counteracted to some extent by the addition of arsenic. Magnesia causes trouble by rendering the batch less fusible, but it is more likely to be introduced through the limestone than the sand. Clay is undesirable, since it tends to cloud the glass.

Physical Properties (9).—Contrary to the belief of glass manufacturers that rounded grains are best, much good glass is made from sands of angular or subangular grain. Uniformity of grain is highly desirable, and should range between 30 and 120 mesh. If larger than 30 mesh, the sand is more difficult to fuse; if finer than 120 mesh, it is said to "burn out" in the batch.

CHEMICAL ANALYSES OF GLASS SANDS

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO		TOTAL
1. Ottawa, La Salle County, Ill.	99.45	.30		.13	tr.	—	99.88
2. Klondike, Mo.	99.97	.03	—	—	—	—	100.00
3. Grays Summit, Mo.	99.839	—	.0014	—	—	H O .154	99.9944
4. Flora, Grant Co., Wis.	99.17	.25	.22	—	—		99.64
5. Coxville, Ind.	98.61	.74	.22	12	tr.	Ign. .32 Und.	100.01
6. Massillon, O.	97,50	1.50	.50	—	.50	—	100.00
7. Niles, O.	99.915	.062	.0019	021	tr.	—	99.999
8. Berkeley, W. Va. (Oriskany sandstone)	98.99	.7717	.0383	—	—	—	99.80
9. Columbia, Pa. (Oriskany)	99.5044	.1337	.2989			Loss etc. .062	99.9999
10. Lewiston, Pa. (Oriskany)	98.84	.17	.34	tr.	tr.	Ign. .23	99.58
11. Hanover, N. J. (Tertiary)	97.705	.755	.15	955	.442		100.007

Nos. 1–4, Ref. 3; Nos. 5–7, Ref. 4.

Few mechanical analyses of glass sands have been published but the following will serve to show the texture of several from different localities (1, 2).

MECHANICAL ANALYSES OF GLASS SANDS

LOCALITY	SAMPLE	PASSES 20 MESH	PASSES 40 MESH	PASSES 60 MESH	PASSES 100 MESH
Ottawa, Ill.	Finest grained	100	100	92	25
Ottawa, Ill.	Coarsest grained	99	6	1 −	0
Ottawa, Ill.	Crude, direct from pit.	99 +	23	3	1 −
Klondike, Mo.	Extra quality	100	90	15	1
Grays Summit, Mo.	Finished product	100	92	25	2
Crystal City, Mo.	Prepared	99 +	23	13	1
Crystal City, Mo.	Average mine run	100	55	20	1
Berkeley Springs, W. Va.	Crushed sandstone, finished product	100	98	25	1 −

Distribution of Glass Sand.—Sand for glass making is obtained from a number of different geological formations, ranging from Cambrian to Pleistocene. Those obtained from the Pleistocene deposits, as in New York (14), are not as a rule of high purity, but those from the Tertiary and Cretaceous formations are of better quality. In New Jersey there are extensive pits in the Tertiary, around Bridgeton (13), the material being used in the glass works of southern New Jersey and southeastern Pennsylvania. The Oriskany sandstone is found to be of high purity in West Virginia between Berkeley Springs and a point on the border near Hancock, Md., the locality having been worked for a number of years (12). Sandstones of the same age are also worked in Pennsylvania (Pl. XXXIII, Fig. 1) (6, 9).

The glass-sand industry of Illinois (1), is developed mainly in La Salle County, the rock used being the St. Peter (Ordovician) sandstone. Much of it is very soft. Sandstone of similar age is worked in Missouri (1), in a belt between Klondike on the Missouri River and Crystal City on the Mississippi River. Indiana (2) contains sandstone suitable for glass manufacture in the Silurian, Devonian, Carboniferous, and Tertiary formations, but most of it comes from the Mansfield sandstone of the Carboniferous in the southwestern part of the state. Beds of high-grade sandstones occur interbedded with Silurian limestones in northwestern Ohio (2), but the most important deposits are found in the Mississippian, Pottsville, and Lower Coal Measures in the eastern portion of the state.

In eastern Canada the Oriskany sandstone is used.

Production of Glass Sand.—The production of glass sand in the United States in 1940 was 2,759,544 short tons, with an average value of $1.77 per ton. Pennsylvania, West Virginia, Illinois, Ohio, and Nevada were all large producers.

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CHAPTER XI

MINOR MINERALS—GRAPHITE—MONAZITE

GRAPHITE

Properties and Occurrence.—Graphite, or black lead, as it is often termed popularly, is a form of carbon, of which two varieties are generally recognized, especially in the trade. The first of these, the *crystalline*, has a lamellar or flaky structure, and is of high purity, while the other form, which is classed as *amorphous*, lacks crystalline structure, and may be quite impure. However, even the purest graphite may contain at least a few tenths per cent ash and volatile matter, and commercial graphite often contains an appreciable content of impurities. Those containing 90–95 per cent graphitic carbon meet the requirements of the general trade, but for many purposes, especially paint-making, graphites with as low as 30 to 35 per cent graphitic carbon can be employed.

The following analyses of graphite from a number of localities (24) show the variation in its composition, but probably do not in all cases represent commercial samples.

ANALYSES OF GRAPHITE

LOCALITIES	SP. GRAV.	VOLATILE MATTER	CARBON	ASH
Cumberland, first quality	2.3455	1.10	91.55	7.35
Passau, Bavaria	2.3032	7.30	81.08	11.62
Passau, Bavaria	2.3108	4.20	73.65	22.15
Mugrau, Bohemia	2.1197	4.10	91.05	4.85
Ceylon crystals	2.3501	5.10	79.40	15.50
Ceylon, commercial quality	2.2659	5.20	68.30	26.50
Gulf of Spencera, S. Australia	2.3701	2.15	25.75	72.10
Gulf of Spencera, S. Australia	2.2852	3.00	50.80	46.20
Buckingham, Can.	2.2863	1.82	78.48	19.17
Madagascar	2.4085	5.18	70.69	24.13
Pissic, Dep. Hautes Alpes	2.4572	3.20	59.67	37.13
Ural Mts., Russia	2.1795	.72	94.03	5.25
Ticonderoga, N. Y., vein graphite	2.2647	.818	97.422	1.76

Graphite is usually easily recognized by its peculiar physical properties, such as extreme softness, steel-gray to blue-black color, greasy feel, and black streak. The specific gravity is 2.20 to 2.27. The luster is metallic in the leafy form, but earthy when the graphite is in a finely divided state. In such event it may be difficult to tell it from amorphous carbon, although graphite can be told by its property of forming graphitic acid, when treated with nitric acid. Molybdenite is the only mineral with which it might be confused, but this has a bluish or greenish tinge and a greenish streak.

Mode of Occurrence.—Graphite always occurs in igneous or metamorphosed rocks, especially the latter. The different occurrences include schist, gneiss, quartzite, crystalline limestones, granulite, syenite, etc,

The shape of the deposit is also varied. Thus the graphite may form: (1) disseminations in metamorphic rocks; (2) pockets in metamorphic or in igneous rocks; (3) veins; and (4) bedded deposits.

The gangue minerals are important, since they affect the process of separation, and are in general those common to the country rock, except in the case of veins, when they may be different. Mica and chlorite are undesirable, as they are hard to separate. Both quartz and calcite may be common gangue minerals, and the less abundant may include rutile, titanite, apatite, etc.

Genetic Occurrence.—It seems probable that graphite may be of either igneous or sedimentary origin, although the latter is possibly the more important. The following cases are recognized:

1. *In Igneous Rocks.*—Not all geologists are agreed that graphite may represent an original constituent of igneous rocks, formed by the cooling and crystallization of a magma. Its occurrence in meteorites is pointed to as possible proof of such origin. Where found in igneous rocks as in Siberia, there is sometimes evidence that these may have passed through metamorphosed graphitic sediments and obtained their carbon from this source. This fact has been pointed out also for a graphite-bearing pegmatite from Maine,[1] and another from New Jersey.[2]

2. *In Veins.*—This manner of graphite occurrence affords a puzzling problem. The veins appear to represent fissure filling, and may be several feet in width. They are found not only in igneous rocks such as granites and pegmatites, but also in metamorphosed sediments, and while they were probably formed at considerable depths,

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[1] Smith, U. S. G. S., Bull. 285: 280, 1906.

[2] Spencer, U. S. G. S., Geol. Atl. Fol. 161, 1908.

it has been suggested that in some cases at least, the temperature did not exceed 575° C.[1]

The mode of introduction of the graphite presents a puzzling problem. One view is that the graphite was brought in by magmatic solutions, which it has been suggested were of an alkaline nature (4), a fact that in some cases seems to be corroborated by the deposition of sericite with the graphite. There is no doubt that in some instances the graphite was brought from below, as when it occurs filling fractures in igneous rocks (8). In veins where the graphite has been brought up by pegmatite solutions it is found replacing the silicates. This is true in the Ceylon graphite veins.

Winchell has suggested that the graphite has been derived from gaseous constituents of the magma, it being pointed out that, if CO and H are present, they will react below 500° C. according to the equation

$$2CO + 2H_2 \rightleftharpoons 2C + 2H_2O$$

3. *Regional Metamorphism* (2, 6, 9).—Graphite is found in disseminated flakes in some schists, gneisses, and limestones, in which case, where these rocks represent metamorphosed sediments, it seems quite clear that the graphite is metamorphosed bituminous or carbonaceous matter.

This type of occurrence forms the chief source of supply in the United States and many other countries.

4. *Contact Metamorphic Deposits.*—Graphite occurs in some rocks adjacent to intrusive ones, that is, in the zone of contact metamorphism, and its source in such cases has been supposed by some to be the intruding magma. Weinschenk was particularly in favor of this theory, believing that the carbon came from the magma as metallic carbides or cyanogen compounds (29).

Winchell suggests that the carbon may have come from the breaking down of $CaCO_3$ of limestone in the contact zone, the CO_2 reacting with H to yield C.

At Calabogie, Ontario (32), the graphite occurs intergrown with contact metamorphic silicates in limestone, the latter being nongraphitic away from the contact.

The intrusion of igneous rocks into or near coal appears in some cases to have produced crystalline (25, p. 41), in other instances amorphous graphite.[2] As an example of the latter we may refer to deposits

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[1] Bastin, Econ. Geol., V: 152, 1910.

[2] Bastin, U. S. Geol. Surv., Min. Res., 1908.

in central Sonora, Mexico, where coal beds up to 24 feet in thickness, enclosed in sandstone, have been metamorphosed by granite.

Distribution of Graphite in the United States.—Crystalline graphite is widely distributed in the United States, occurring in contact zones between igneous and sedimentary rocks, in metamorphic rocks, etc., but the known deposits of commercial value are few in number.

The domestic supply has in the past been obtained from different states.

New York (2, 6, 16).—The deposits are located on the southeastern side of the Adirondacks in Essex, Warren, Washington, and Saratoga counties, but they are not now worked.

The graphite occurs in the following ways: 1. In pegmatite veins, forming bunches, associated chiefly with quartz, but also feldspar, pyroxene, hornblende, mica, calcite, scapolite, apatite, sphene, etc. This type of deposit is of little commercial value. 2. Veinlets of graphite with quartz in gneiss. 3. Graphitic quartzites, representing metamorphosed pre-Cambrian sediments. These are the most important type. 4. Graphitic disseminations in Algonkian limestones.

Rhode Island (3).—Amorphous graphite, graphitic anthracite, or graphitic shale, as it has been variously called, has been known for many years to occur in the metamorphosed Carboniferous rocks near Providence and Tiverton, Rhode Island, but the production has been irregular. At the Cranston Mines near Providence the section shows a series of interbedded, sandy, carbonaceous, and graphitic shales, something over 300 feet thick, all folded and perhaps faulted. The main graphitic bed is 30 feet thick.

Ashley has characterized the material as a high-ash, high-moisture, graphitic anthracite coal of high specific gravity (1.65–2.45), which cannot be used successfully as a fuel, unless it can be mined and delivered at the furnace in Providence or Boston for less than one-half the wholesale price of competing coals.

The material is used chiefly for paint and foundry facings.

Pennsylvania (19).—Crystalline graphite has been mined at several localities in eastern Pennsylvania, where it occurs in crystalline rocks.

Alabama (9).—Crystalline graphite forms bands of graphite schists in Clay, Chilton, and Coosa counties. The graphite-bearing schists, which dip steeply to the southeast, are of pre-Cambrian age, and form lenses of variable size in a garnet schist. Granite intrusions are present in the schists, but their genetic relations to the graphite are not definitely established. The schist is said to run about 2½ per cent graphite, and mining is not carried below the zone of weathering.

New Mexico (17).—Amorphous graphite is known to occur in the cañon of the Canadian River, about 7 miles southwest of Raton, and represents a coal bed metamorphosed by a diabase dike. The graphite is said to occur in pockets or irregular masses in the diabase, and is columnar normal to the faces of the igneous rock. It has been mined somewhat and sold for the manufacture of mineral paint.

Montana (33).—Near Dillon, Mont., there is a deposit somewhat similar to those of Ceylon, for the graphite occurs in veins. These may be irregular, forming a network, or some of the narrow ones appear persistent. They occur in schists and crystalline limestones, which have been penetrated by pegmatite. The graphite is said to be softer than the Ceylon product.

Other States.—Developments of graphite have been made in other states, such as Michigan, Wisconsin, Virginia (28), Wyoming (5), Maine (22), Georgia (12), California (8), etc., but the output is not steady.

Canada (24, 32).—Mining for graphite in Canada began in 1847, and has continued since, the production coming from rocks of the Hastings-Grenville series of eastern Ontario and the adjoining portions of Quebec. Canadian graphite occurs in the following five ways: (1) as disseminations in gneiss, quartzite or schist, the beds being sometimes more highly graphitic, where pierced by intrusives; (2) as usually narrow or irregular veins, in or near igneous rocks; (3) as veins or irregular masses in limestone near igneous rocks; (4) as a constituent of pegmatite veins cutting the Grenville series; (5) as a contact metamorphic deposit in limestone. The production comes chiefly from Calabogie, Ontario, where the graphite is found associated with silicates in a limestone adjacent to an intrusive rock.

Other Foreign Deposits.—Ceylon (2, 5) was the leading graphite-producing country of the world, the chief mines being located in the mountainous area of the southwestern and south central part of the island. The chief rocks are gneisses with some interbedded dolomites, and some intrusives, especially granite pegmatites. While some disseminated graphite is found in gneiss and limestone, the commercially important deposits are veins of irregular width, occurring along fracture planes. In small veins the graphite forms an aggregate of parallel needles at right angles to the wall, but in the larger veins a coarse platy structure is observed. Pyrite and quartz are not uncommon, while biotite, orthoclase, pyroxene, apatite, allanite, and rutile are more rare.

Bavaria (25) is another important producer. There, in the Passau district (Fig. 96), the country rock is cordierite gneiss, surrounded by granite, and containing bands of schist, and limestone, as also some intrusive rocks. The graphite forms lenses conformable with the gneiss and schist, with often a foot wall of limestone and syenite, and a hanging wall of granite. Both the country gneiss and graphite are strongly decomposed. Weinschenk advanced the theory that the graphite was deposited by exhalations from the granite, and that the kaolinization was due to the same cause. The first is disputed by some, who consider the carbon to be original in the rock, while the latter is very unlikely, the kaolin being an ordinary product of weathering.

Austria is the largest producer in Europe, the deposits of southern Bohemia being similar to those of Bavaria. The Styrian ones form thin beds in schist, and those of Mähren occur in crystalline limestone which is interbedded with schists, gneisses and quartzites. The Madagascar[1] deposits of crystalline graphite, and Korea[2] deposits of amorphous graphite, are also important.

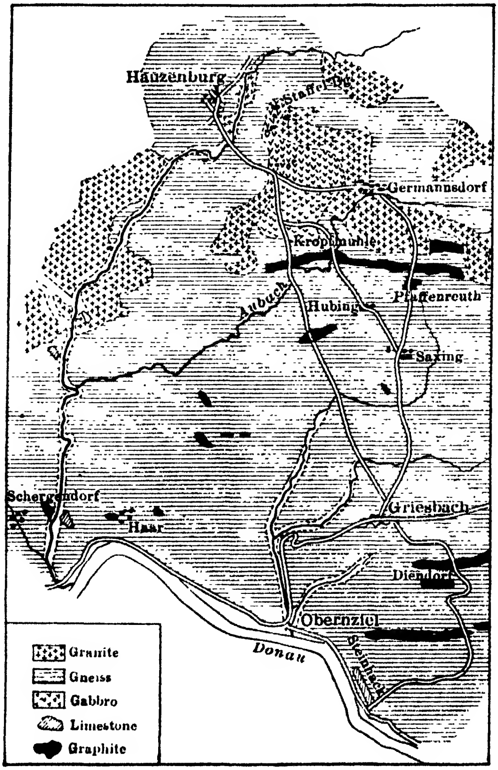

FIG. 96.—Geologic map of Passau, Bavaria, graphite district. (*After Gümbel-De Launay, from Stutzer, Die Nicht-Erze.*)

Uses (27).—The consumption of graphite in the United States gives an idea of the amount used for different purposes, and this is, roughly: crucibles, 20 per cent; foundry work, 40 per cent; pencils or crayons, 15 per cent; lubricants, 15 per cent; paints, stove polishes, and miscellaneous, 10 per cent.

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[1] U. S. Geol. Surv., Min. Res., 1913: 23, 1914.

[2] *Ibid.*, p. 238.

Crucibles are made of a mixture of the best-grade crystalline graphite and a refractory bond clay. The graphite for this purpose was formerly obtained chiefly from Ceylon, but in recent years Madagascar has become an important competitor. Furthermore the use of graphite crucibles has decreased greatly, partly because less steel is smelted in them, and because of competition of other materials for crucible manufacture.

Pencils are made of a mixture of amorphous graphite and clay, and most of the former comes from Mexico. For foundry work, which is now the most important use, either crystalline or amorphous graphite may be employed.

Artificial graphite is used for the manufacture of electrodes, dry batteries, lubricants, etc.

Crystalline graphite is put through a concentrating process before shipment to market. This is necessary in order to free it from the associated minerals. Both wet and dry methods of separation are employed, and more recently air separation has been tried with some success.

Graphite Industry.—In spite of the importance of graphite, the United States produces practically no graphite at the present time, although many deposits have been worked for a short period. Considerable Madagascar graphite, which is of the flake variety, is imported into the United States. It is cleaned after being received here. Korean amorphous graphite is also imported. There is large production of artificial graphite but statistics are not published.

Production of Graphite.—Many graphite operations have been started in the United States but few have developed into permanent producers, and the Minerals Yearbook does not give any figures of production for 1940. The imports for the same year amounted to 31,329 short tons valued at $891,285. Of this amount 23,766 short tons was natural amorphous graphite with a value of $487,675 and 7,303 short tons of crystalline graphite valued at $394,423. Some artificial graphite is also imported.

Ceylon lump averaged about 10 cents per pound in New York, Madagascar flake between 5 and 6 cents, and amorphous graphite from $10 to $20 a ton.

The exports of natural graphite in 1940 were 1,632 short tons valued at $148,639.

The production of graphite in Canada in 1939 was valued at $61,684, and came almost entirely from Renfrew County, Ontario. The Canadian imports of manufactured and unmanufactured graphite in 1939 were valued at $160,329, while similar exports had a value of $818,948.

Of the world's producers in 1938, Chosen ranked first, Bavaria second, and Austria third. The world's production in 1939 was about 112,000 metric tons (partly estimated).

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LITHIUM

The minerals now used as sources of lithium are: *amblygonite* ($Li(AlF)PO_4$), *spodumene* (LiO_2, Al_2O_3, $4SiO_2$) and *lepidolite* ($3LiO_2$, $3Al_2O_3$, $12SiO_2$, $2K_20 \cdot 8F$). Both amblygonite and spodumene are obtained from pegmatite veins in the Black Hills of South Dakota (3), the former mineral being found in compact masses, the latter as crystals often of large size. Lepidolite is found especially in pegmatite veins of Southern California where it occurs as lenses of compact fine scaly nature (1).

Lithium minerals have also been mined in New Mexico. Southern

Manitoba (4, 6) contains lithium-bearing pegmatites, but there has been no commercial production.

Uses.—Lithium and its compounds are increasing in commercial importance. For some years there has been a steady output of lithium for use as a hardener in bearing-metal alloys. Lithium salts are efficient as dehumidifiers, and lithium hydroxide is used in alkali storage batteries. Some compounds are used in certain glasses, glazes and enamels, in photography, and in fireworks.

Production.—The production of lithium minerals in the United States has fluctuated owing to the erratic demand for lepidolite, which was produced in California, later from South Dakota and North Carolina. The domestic production in 1940 was 1,961 short tons valued at $79,679.

There were no exports in 1940. Canada reports probable production in 1940 from Manitoba.

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LITHOGRAPHIC STONE

Properties.—Lithographic stone (1, 3) is a very fine-grained, homogeneous limestone, used for lithographic purposes. It may be either pure lime carbonate or magnesian limestone, but so far as known this difference in composition exerts no important influence on its physical character. The two following analyses will serve to indicate this difference in composition, No. 1 being the standard Bavarian stone and No. 2 the Brandenburg, Ky., rock:

	Insoluble in HCl			Soluble in HCl							
	SiO_2	$(AlFe)_2O_3$	CaO	Al_2O_3	FeO	MgO	CaO	Na_2O K_2O	Moist.	H_2O	CO_2
1.	1.15	.22	Trace	.23	.26	.56	53.80	.07	.23	.69	42.69
2.	3.15	.45	.09	.13	.31	6.75	44.76	.13	.41	.47	43.06

The physical character of the stone is of prime importance, for in order to yield the best results it should be fine-grained, homogeneous, free from veins or cracks, or just sufficient porosity to absorb the grease holding the ink, and soft enough to permit its being carved with the engraver's tool. Owing to these strict requirements but few localities have produced good stone.

Sources of Supply.—Lithographic stone is not confined to any one geologic formation, and deposits have been reported from many states both east and west. Some of these appear to be of inferior quality, while others are too far from railroads. One promising deposit was found at Brandenburg, Ky. (2, 6). Another bed of good quality has also been described from Iowa (1).

The main source of the world's supply is obtained from the Jurassic limestone of the Solenhofen district in Bavaria (4), in which the quarries have been worked for a number of years, but the supply is said to be becoming unsatisfactory and unreliable. The stones are trimmed at the quarries, and sizes of 22 or 28 by 40 inches are in the greatest demand. From these they range up to sizes 40 by 60 inches. The best-quality stones sell for 22 cents per pound.

The domestic demand is not large, and it is probable that one or two well-developed and well-managed native quarries could satisfy it.

The successful substitution of zinc or aluminum plates for certain classes of lithographic work is said to have had a noticeable influence on the demand for lithographic stone. Onyx has also, in some cases, been found to make a good substitute.

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MAGNESITE

Properties and Occurrence.—This mineral, which is a carbonate of magnesium with 47.6 per cent magnesia (MgO), has a hardness of 3.5 to 4.5 and a specific gravity of 3 to 3.12.

Magnesite deposits may show one of the four following modes of occurrence:

1. Sedimentary deposits, in which the magnesite occurs as beds. One example is known from Kern County, California, where the magnesite is interstratified with clay (3).

Other bedded deposits are known to occur in the Muddy Mountains of Nevada. The magnesite here is interbedded with shales (10).

A third deposit, in this case hydromagnesite, occurs at Atlin, B. C., and seems to represent a lake deposit (22).

2. Vein deposits, several of which are known in Canada, but are of no economic value (1), and some of which may belong to group 4.

3. Dolomite type, forming irregular or lenticular masses occurring as replacements of limestones, usually of dolomitic character, and sometimes accompanied by serpentine or talc. The magnesite is crystalline and has occasionally been mistaken for marble. Its origin is commonly ascribed to magmatic solutions, but whether from acid or basic magmas has been disputed. This represents a worldwide type. The most important deposits commercially are those near Veitsch, Austria, and Mittendorf, Styria, which occur in Carboniferous dolomites. Others are in Argenteuil County, Quebec (20–21), Stevens County, Washington (9), and Russia. Very extensive deposits are also known in Manchukuo (12).

4. Serpentine type (7, 18), in which the magnesite (Pl. XXXII, Fig. 2) forms veins or lenses in serpentine, and has been derived from the latter or possibly from a mineral that altered to serpentine. The process is supposed to be due to the action of water carrying CO_2, but whether it was of surface or magmatic origin is disputed. Some of the silica set free in the decomposition of the serpentine was precipitated near it as veins of opal or chalcedony. The magnesite is fine-grained, dense or massive, and white when pure.

This type is also of worldwide distribution, the largest deposits known being on the island of Euboea, Greece (18).

California (7).—Deposits of magnesite (Fig. 97) are scattered along the Coast Range from Mendocino County at least to a point south of Los Angeles, and along the western slope of the Sierra Nevada from Placer County to Kern County. The greatest production comes from near Porterville in Tulare County (Fig. 97). The deposits, with one known exception,[1] all occur as veins in serpentine, the larger number being in the Coast Range.

The much-fractured and faulted serpentines of the Coast Ranges, which are probably of Lower Cretaceous age, appear to have been derived from olivine-pyroxene rocks, and the magnesite may have been formed from both the serpentine-making minerals and the serpentine itself. In some cases the magnesite forms a network of veins

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[1] A sedimentary deposit at Bissell, Kern Co.

PLATE XXXII

FIG. 1 — Finch magnesite quarry near Chewelah, Wash. (*Courtesy Northwest Magnesite Company.*)

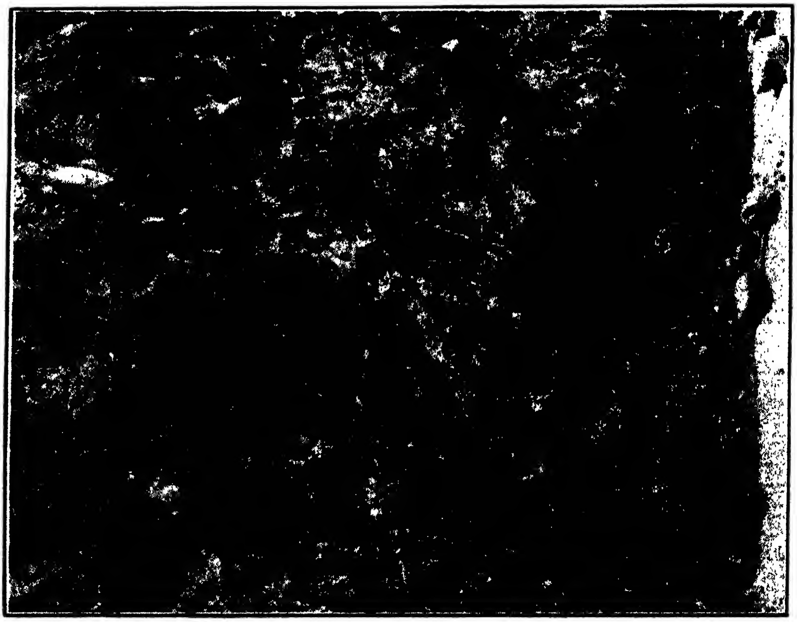

FIG. 2.—Network of magnesite veins in Serpentine, Winchester, Calif. Not a commercial deposit. (*H. Ries, photo.*)

in the serpentine, but since its origin is due to the action of surface waters, the deposits may be of limited depth. As the magnesite

FIG. 97.—Map of part of California showing distribution of magnesite deposits. (*After Yale and Gale, U. S. Geol. Surv. Min. Res.* 1913.)

weathers less readily than the serpentine, the vein outcrops often stand out in bold relief.

The following analyses show the composition of the magnesite from several localities:

Analyses of Magnesite

	1	2	3	4	5	6	7
SiO_2	7.67	.73	2.28	1.67	2.24	6.48	1.60
Al_2O_3	.26	.14	.03	3.47	2.05	4.20	1.81
Fe_2O_3	.29	.21	.26	4.68			
CaO	.04	.40	1.32	2.94	2.48	2.52	7.89
MgO	43.42	46.61	45.17	86.90	93.63	41.53	39.25
CO_2	48.08	51.52	50.74	......	......	53.60	49.7
	99.76	99.61	99.80	99.66	100.40	98.33	100.27

1. Siliceous Magnesite, 8 m. north of Cazadero, Sonoma County. 2. Alameda claim, Santa Clara County. 3. Four miles northeast of Porterville, Tulare County. Too high in lime for good cement. Used in wood-pulp whitening. 4. Calcined magnesite, Nyustya, Hungary. 5. Calcined magnesite, Greece. 1–5 from Ref. 1. 6. Stevens County, Wash. 7. Quebec.

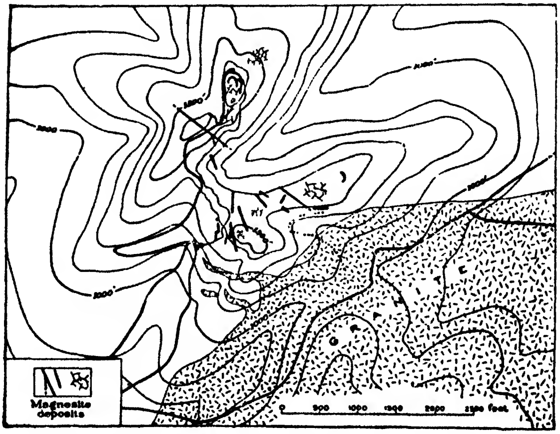

Fig. 98.—Plan of magnesite veins and workings 4 miles northeast of Porterville, Calif. (*After Hess, U. S. Geol. Surv., Bull.* 335.)

Washington (9, 20).—Magnesite lenses are irregularly distributed through the metamorphosed dolomites which form the lower member of the Stevens Series in Stevens County, Washington. Some of the bodies are 500 feet or more in length, 300 feet wide, and 200 feet thick. The magnesite may be traversed and displaced by faults, and along these there may be an abrupt change from magnesite to dolomite. There has been some difference of opinion regarding the origin of these deposits. Some have suggested that they may represent dolomite which has been enriched by magnesium-bearing waters emanating from the basic intrusives found in this region, while Whitwell (20) believes that they represent sedimentary deposits of mixed salts of calcium and magnesium carbonates which were leached of their calcium carbonate before being metamorphosed. The reserves are large, but the Washington product finds difficulty in competing with imported material, partly on account of freight rates.

Vermont (4).—It has been known for some time that the Vermont talc deposits carried a white carbonate mineral as gangue, but it was considered to be dolomite. Recent investigations have shown it to be magnesite (4), and concentration tests by the Bureau of Mines indicate that it can be separated from the talc.

Canada.—*Quebec* (21).—Magnesite has been worked for a number of years in Argenteuil County, Quebec. The material lies in the Grenville formation, and forms extensive masses which are associated with bands and lenses of serpentine. Serpentine is also disseminated through the magnesite, and there is more or less included dolomite, and other minerals including diopside, talc, quartz, and pyrite.

Wilson believes that the rock was originally a limestone which was successively silicated and dolomitized. Later the dolomite was replaced by magnesite.

The product is classed as a magnesitic-dolomite.

Uses.—Caustic calcined magnesite is that which has been calcined at a comparatively low temperature and contains from 2 to 7 per cent CO_2. This is used in the manufacture of *oxychloride cement* (a mixture of magnesia and magnesium chloride). It may deteriorate on exposure, recarbonating to some extent. About two-thirds of the caustic magnesite used in the United States is from domestic sources, chiefly California, and to a lesser extent from Washington. Its chief use is for making flooring and wallboard, although another use is as a chemical accelerator in rubber. Caustic magnesite should be low in Fe_2O_3.

Dead-burned magnesite has been calcined at a higher temperature, and contains under 1 per cent CO_2. It does not recarbonate, and is made from both the dolomitic and serpentine type of magnesite. The dead-burned magnesite is used entirely for refractory purposes and should contain several (4–7) per cent Fe_2O_3. Magnesite is also used for the manufacture of metallic magnesium, although the metal may be made from magnesium-bearing brines.[1] Basic bricks are now made of chromite or olivine mixed with magnesite.

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[1] Martin, Mich. Geol. Surv., Pub. 32: 46, 1922; Niinomy, Econ. Geol. XXXI: 767, 1936. (Korea.)

Production of Magnesite.—In 1940 the United States produced 333,166 short tons of magnesite, valued at $2,487,969, at an average price of $15.38 per ton. Dead-burned Washington magnesite sold at $19.92, and best domestic ground caustic at $31.52 per ton. California and Washington are the two producing states, with deposits being developed in Nevada.

The imports in 1940 consisted of a little crude, an appreciable amount of caustic magnesite, and a much larger amount of dead-burned magnesite, the total value being $573,592. They came chiefly from central Europe and Russia. Manchuria has supplied an appreciable amount. No exports were listed.

The Canadian production of calcined magnesitic-dolomite in 1939 was valued at $474,418. The imports of burned and manufactured magnesite were valued at $862,932. Exports of magnesitic-dolomite were valued at $183,034.

Among the world's producers in 1940, Russia, Austria, and the United States were important.

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MEERSCHAUM

Meerschaum or *sepiolite*, which is well known on account of its use for making pipes and other smoker's articles, has for many years been obtained mainly from Asia Minor, although other occurrences are known.

FIG. 1.—Oriskany sandstone quarry, worked for glass sand, Lewistown, Pa. (*H. Ries, photo.*)

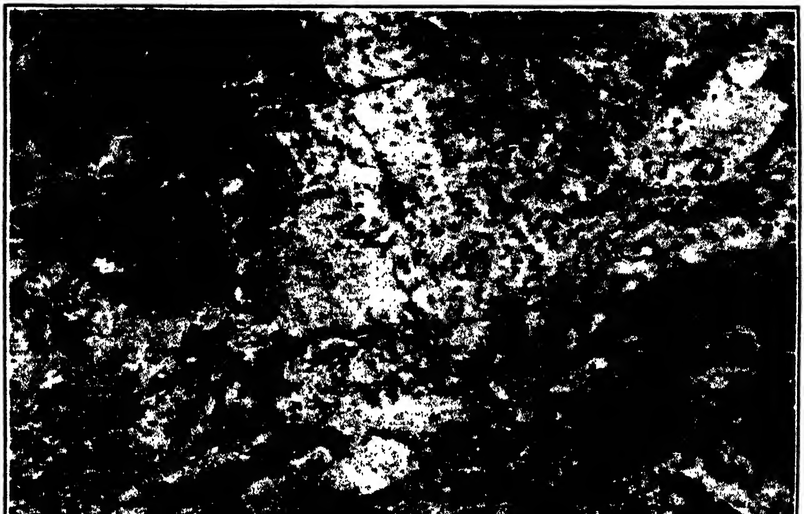

FIG. 2.—Face of garnet quarry, North Creek, N. Y. Shows numerous garnets. (*H. Ries, photo.*)

Sepiolite has a probable composition of $H_4Mg_2Si_3O_{10}$, and when pure is a white, porous mineral, with a specific gravity of about 2. It absorbs water readily, becoming somewhat plastic, but hardens again on drying. It has a hardness of 2 to 2.5, great toughness, and earthy or conchoidal fracture, the toughness being most pronounced in those forms having a leathery or fibrous texture. Its peculiar physical properties make it of great value for carving into pipes.

Occurrences have been reported from New Mexico (1, 2), but there is no domestic production, and the main supply comes from Asia Minor (3).

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MICA

Properties and Occurrence.—There are few minerals more widely distributed in crystalline rocks than mica, and yet deposits of economic value are rare because the mica flakes are either too small, or too intimately mixed with other minerals for profitable extraction. Only two of the several known varieties of mica, muscovite ($H_2KAl_3Si_3O_{12}$) and phlogopite ($H_6K_2Mg_7Al_2(SiO_4)_7$), are of value as sheet mica, the former only being found in deposits of commercial value, as sheet mica, in the United States. Both phlogopite and muscovite are found in Canada, but only the former is of much commercial importance. The India and Madagascar micas; both of which are shipped to the United States, are muscovite.

Biotite and chlorite are of no value as sheet mica, but schists composed almost exclusively of these minerals may be worked as a source of ground mica.

The commercial deposits of muscovite are found in pegmatites, cutting granites, gneisses, and schists. In these the mica is associated with quartz and feldspar (usually orthoclase or microcline, more rarely plagioclase), being found in rough crystals called blocks or *books*, which are either irregularly distributed through the vein or collected near its sides. The value of the deposit depends more on the abundance and quality of the mica than the size of pegmatite body.

The best mica is obtained from the more coarsely crystalline rocks; but the widest veins do not necessarily contain the largest blocks. As a rule the mica does not form more than 10 per cent of the vein, and usually not more than 10 or 15 per cent of that mined can be cut into plates, the rest being classed as scrap mica.

The phlogopite mica of Canada is found in veins or dikes of pyroxene cutting gneiss or limestone. Its chief associate is apatite, occurring in a granular form or large rough crystals. Other minerals present in smaller amounts are calcite, scapolite, tourmaline, titanite, and even sulphides. The deposits are genetically similar to the apatite scapolite veins of Norway. In these the phlogopite occurs in the same irregular manner as the muscovite in pegmatites.

The value of a mica deposit depends on the abundance and size of the books, perfection of cleavage, color, and clearness. Large sheets of mica are the exception rather than the rule.

Mica may show several internal structures which affect its market value. These are:

(1) "A" structures, which are striations or slight ridges appearing on cleavage faces, and following definite crystallographic lines, meeting to form a "V." (2) Herring-bone structure, similar to the preceding, but with a third set of striations bisecting the obtuse angle of the "A." (3) Ruled mica, resulting from the development of partings, and forming a series of straight, sharp, parallel cracks which cut through the book, at an acute angle to the cleavage face.

Large mica crystals may include smaller ones, or also grains or crystals of other minerals. Mica containing minute inclusions is known as *specked mica.* These inclusions may be dendritic in character.

Distribution in the United States.—Deposits of mica have been worked in a number of states both east and west, and yet but few are steady producers. The more important ones may be described.

New Hampshire (8).—This state, which now ranks second in point of domestic production, produces both sheet and scrap mica. The mica occurs in pegmatites, and appears to be most abundant in those bodies containing little feldspar, although some deposits supply both minerals. The country rock is schist.

North Carolina (11).—The mica mined in this state comes from three belts (Fig. 99). Owing to a frequent capping of residual soil, discovery of the deposits is difficult. This state is the leading domestic producer.

The mica-bearing pegmatites occur in mica, garnet, cyanite, hornblende, and granite gneissses and schists, all of Archæan age, the important formations being the Carolina and Roan gneisses. The rocks of these two are interbanded with, and cut by, streaks of granitic or pegmatitic material, the latter forming lenticular bodies or vein-like

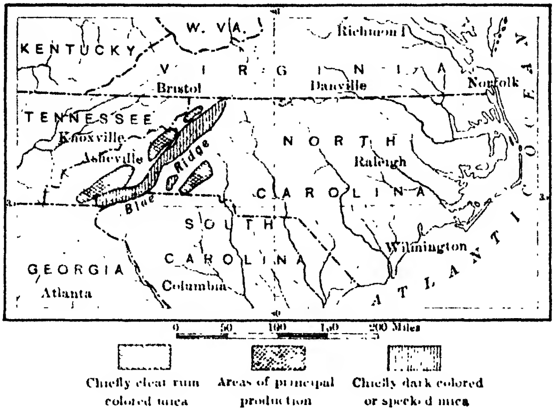

FIG. 99.—Map showing areas in North Carolina in which mica has been mined. (*After Sterrett, U. S. Geol. Surv., Bull.* 315.)

deposits, which may or may not be conformable with the schistosity of the country rock.

While they vary in size, 1 to 2 feet seems to be the minimum

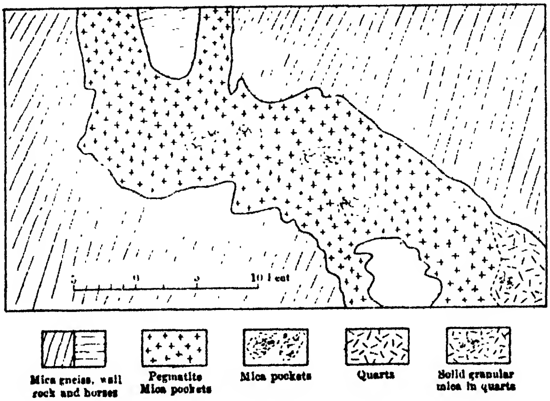

FIG. 100.—Section across pegmatite at Thorn Mountain mine, Macon Co., N. Ca. (*After Sterrett, U. S. Geol. Surv., Bull.* 315.)

workable limit for rich and regular "veins." The muscovite, which is the main mica present (biotite being the other), shows a variable mode of occurrence. At one time it is evenly distributed through the pegmatite; at another large crystals are found in clusters scattered through the vein (Fig. 100).

The better grades of North Carolina mica are used for the glazing industry, while the less perfect sheet material is employed for electrical work. The pegmatite veins also carry a number of rare minerals.

Other States.—Mica has from time to time been worked in other states, including South Dakota (11), Colorado (11), Virginia (13), Georgia (5), and Texas.

Distribution in Canada (10).—Muscovite deposits are found quite widely distributed over the Dominion, where the pre-Cambrian crystalline rocks are exposed. They have been worked at a number of localities, but are of little commercial importance at the present time.

Phlogopite deposits are confined to two areas, viz.: (1) the Quebec area lying mainly between the Gatineau and Lièvre rivers; and (2) the Ontario area lying principally north of Kingston.

The most important mine in Canada is that located near Sydenham, Ont. (Pl. XXXI, Fig. 2), which has attained a depth of nearly 200 feet. The only other important active one is in Templeton township northeast of Ottawa.

In the Loughborough mine near Sydenham the mica "lead" varies from a few inches to 25 feet in width, being at times almost a solid mass of enormous mica crystals. The mica is mottled, wine-amber, and occurs in a greenish-gray pyroxenite. One crystal found in this mine was 9 feet in diameter. Branches of massive apatite are occasionally met, and these are mixed with white calcite.

Other Foreign Deposits.—India (2, 4) yields a large percentage of the world's supply of sheet mica, from pegmatites. It enjoys its commercial position because of the richness of the deposits, low labor costs, and high quality of the product. Madagascar, which produces both amber and white mica, and the Transvaal have been increasing their output in recent years. Other foreign countries are also producers.

Mining and Uses (6).—The irregularity of its occurrence makes mica mining somewhat uncertain. This often leads to the type of mining known as ground hogging or gophering. The rough crystals obtained from the mine range in size from small crystals to blocks several feet across. These rough crystals are cobbed and cleaned, and then split into plates about $\frac{1}{16}$ inch thick. The plates then have the rough edges cut off, and after grading as to size and quality are ready for further splitting and trimming.

There may be as much as 90 per cent loss in splitting and trimming, and this waste is used for grinding. Mica may be wet or dry ground.

Mica may be classified as punch, or pieces which will yield a circle of clear material up to 1¼ inches diameter; circle, or pieces up to 2 inches diameter; and rectangles, which range in size from 1½ × 2 inches up to 8 × 10 inches or larger.

Splittings are small irregular sheets of mica that are glued together to make large sheets, which can be bent, rolled, or punched and used for the same purposes as sheet mica.

The chief use of sheet mica is for electrical purposes, it being employed as an insulating material in all types of electrical apparatus.

That used for electrical work must be free from metallic minerals.

Clear mica has been used for lamp chimneys, stove doors, and other openings where a clear material resistant to heat is required. Much ground mica is employed in the wall paper and rubber industries, and also for coating roll roofing.

It is claimed that the addition of mica to paints increases their durability and protective qualities. A process has also been developed to substitute mica for felt in making asphalt shingles.

The increasing use of ground mica has led to the development of other sources of supply. Formerly all ground mica was obtained by grinding scrap, but now 35 per cent of that used is obtained from kaolin washing plants, and by grinding mica schists.

Vermiculite (13).—This name is applied to a group of micaceous minerals that are alteration products of mica. They possess the curious property of expanding at right angles to the cleavage, the volume increase amounting to as much as 16 times the original. The color also changes to a silvery or golden hue, depending on temperature and exposure to air. The material which has been formed by the alteration of biotite is found associated with ultrabasic igneous rocks.

The only deposit of importance which has been worked in this country is north of Libby, Mont., and the marketed product is known as zonolite (2).

It is claimed that material which weighs over 6 pounds per cubic foot when expanded cannot be marketed successfully, and many occurrences of the material do not meet this requirement.

In addition to the Montana deposits, attempts are being made to develop others in Wyoming, North Carolina, and Colorado.

The main use of vermiculite at present seems to be as an insulator, but many other uses have been suggested. When used for insulation it has to compete with mineral wool.

Production of Mica.—The United States is the largest consumer of mica, but produces normally only 15 to 35 per cent of its requirements of sheet mica larger than punch size, and under 2 per cent of its requirements of splittings. Its output of scrap and punch mica is practically enough to supply domestic needs.

The United States in 1940 produced 1,625,437 pounds of uncut sheet and punch mica, valued at $291,685, and 22,386 short tons of scrap mica, valued at $314,565. Of the latter about one-third of the tonnage came from kaolin mines and schists. North Carolina was the leading producer, with Connecticut far behind. New Hampshire has been dropping off for several years.

The quantity of ground mica sold by domestic producers in 1940 was 27,984 tons valued at $1,016,628. Under this, however, are included ground schists The increased sale of ground mica is due to a growing use in roll roofing, wall paper coating, rubber trade, and architectural plastic manufacture.

The imports of mica of all kinds in 1940 amounted to 7,688 short tons valued at $2,484,128. Most of this came from British India, with Canada second. South America is replacing British India.

The production of mica in Canada in 1939 amounted to 2,135,356 pounds valued at $147,321. About two-thirds in quantity came from Ontario, and about one-third from Quebec, with a very small amount from British Columbia. The value of the Quebec material, however, was nearly nine-tenths of the total, being nearly all phlogopite.

The imports of mica and manufactures in 1939 were 61,835, while exports of similar materials were valued at $165,252.

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NATURAL MINERAL PIGMENTS

Under this head are included a number of mineral substances which are used in the manufacture of paints, and most of which contain varying amounts of iron oxide as the coloring agent, and usually clay as the base or filler.

Those colored by iron oxide or iron hydroxide give a series of yellow, red, brown, or even black colors. The brilliancy of the color does not depend on the iron content of the material. Some may contain as much as 80 to 90 per cent Fe_2O_3. The color may also be improved by roasting.

Ocher is a mixture of iron oxides (usually hydrated) with clay, hence the yellow or yellowish-brown color. If heated it becomes red or reddish brown.

Umber and Sienna are naturally occurring mineral pigments consisting of clay and hydrated iron oxide, but in addition they contain hydrated manganese oxide, which gives them a brown color.

Sienna may, on the one hand, grade into ocher, and on the other, with an increase in manganese, into umber.

Burnt sienna and burnt umber are derived from the corresponding raw materials by calcination.

Mineral red is a natural red pigment derived from hematite. Persian red from Ormuz Island in the Persian Gulf and Spanish red from Spain are examples.

Mineral browns are produced chiefly by calcining limonite or siderite ores.

Mineral pigments and iron ore may or may not occur in the same deposit. Thus, in residual limonite, the clay washed off the ore lumps may sometimes be suitable as a mineral pigment.

The Clinton iron ore at Clinton, N. Y., was worked for a number of years as a source of red paint (9).

Georgia and Pennsylvania (8) have produced a considerable amount of ocher. In Georgia it is associated with the Weisner quartzite, in which it is thought to have been deposited by replacement (13). It has been used in linoleum manufacture and paint.

Pennsylvania (8) has produced yellow ocher from residual clays, particularly in the eastern part of the state.

Umber deposits of similar geological occurrence have also been worked at several localities in the same general region.

The most continuously mined paint ore in Pennsylvania is that of the Lehigh Gap area (8). The material appears to be a ferruginous limestone, which is ground and calcined for market.

Vermont has also produced ochers from residual clays in Bennington and Rutland counties (3, 16).

In some states slates and shales of the proper color have been ground for paint, but the production has not been steady.

The chief use of the ordinary mineral pigments is for painting iron and steel, also for wooden surfaces as barns and freight cars. Umber and sienna are used as pigments in paints and for wood stains.

The government has not published any statistics of production since 1915. There is some exportation to the United States from foreign countries.

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MONAZITE

Properties and Occurrence.—This mineral is an anhydrous phosphate of the rare earth metals, cerium, lanthanum, praseodymium and neodymium; but its economic value has been due chiefly to the small amount of thoria which it contains. The percentage of thoria in monazite ranges from less than 1, to 20 or more, and in commercial monazite varies between 3 and 9 per cent. Although grains of monazite are found scattered through many granites and gneisses, still no occurrences of this type have thus far proved to be of commercial value. The economically valuable deposits have all been found in stream gravels or beach sands derived from the disintegration of monazite-bearing rocks. Monazite is usually light yellow to honey yellow, red, or brown in color, has a resinous luster, a specific gravity of 5.203 (Penfield and Sperry), and a hardness of 5 to 5.5. It is very brittle. Its gravity and color aid in its ready determination.

Monazite has been produced on a commercial scale in the Carolinas, Idaho, and Florida, but no domestic production has been reported since 1925. Brazil exported several thousand tons annually to the United States for some years, but this dropped off after the high-thoria sand from Travancore, India, was put on the market.

Uses of Monazite.—Monazite was formerly marketable because of its thoria content, but with the decline in gas mantle manufacture, for which it was used, the demand has dropped off. Monazite is now used as a source of ceria, and the thoria is finding other uses than the original one, since it is refractory and resistant to chemical action. Objections to it are the high price and its sensitiveness to sudden temperature changes.

Production of Monazite.—The production of monazite is very erratic, and so are the imports. Thus the amounts for several years, given in short tons, were: 1932, 1569; 1933, 56; 1934, 112; and 1935, 1299. Practically all of it comes from India. The average price based on an 8 per cent thoria content is $60–$65 a short ton.

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CHAPTER XII

MINOR MINERALS—PRECIOUS STONES—ZIRCON

PRECIOUS STONES

The names *gems* and *precious stones* (3, 5) are applied to certain minerals which, on account of their rarity, as well as hardness, color, and luster, are much prized for ornamental use. The hardness is of importance as influencing their durability, while their color, luster, and even transparency affect their beauty. A distinction is sometimes made between the more valuable stones, or gems (such as diamond, ruby, sapphire, and emerald), and the less valuable, or precious stones (such as amethyst, rock crystal, garnet, topaz, moonstone, opal, etc.).

Gems may occur as constituents of igneous rocks, placer deposits, pegmatites, contact and regional metamorphic deposits, or of deposits formed by magmatic or meteoric waters.[1] The first group yielding diamonds and sapphires are the most important, while the placer deposits are second in point of value produced.

Many different minerals are used as gems (3, 5), but only a few of the more important ones can be mentioned here, and the number of the more valuable kinds found in the United States is very limited (7, 25). Reference to new discoveries has been made in the Mineral Resources of the United States published formerly by the United States Geological Survey, or Minerals Yearbook published now by the United States Bureau of Mines.

Diamond.—This mineral, which is the hardest of all known natural substances, is pure carbon, crystallizes in the isometric system, and has a specific gravity of 3.525. It occurs in many different colors, of which white is the commonest, and is found either in basic igneous rocks or in alluvial gravels.

The massive forms, known as *bort* or *carbonado*, have little or no cleavage, and are of value only as an abrasive (Chapter IX).

The greatest number of diamonds come from Africa, but other deposits of commercial value occur in India, Borneo, Brazil, and British Guiana.

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[1] Ball, Econ, Geol., XVII: 575, 1922.

In the United States a few scattered diamonds have been found in the drift or soil of the southern Alleghanies, California, Wisconsin, and Indiana, but they are all small (19, 25, 24).

Arkansas.—The only and first locality in North America where diamonds have been found in place is in Pike County, Arkansas (17), where, near Murfreesboro, several areas of peridotite are known to occur (Fig. 101). The first diamonds were found in 1906, and up to 1925, over 10,000 stones had been found. The largest was 40¼ carats. About 1 carat is obtained from 8 tons of rock.

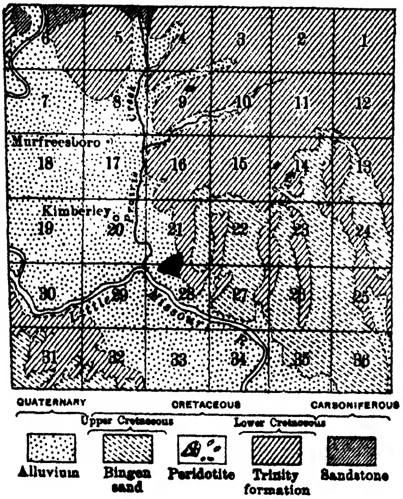

FIG 101.—Map of Arkansas diamond area. (*After Miser, U. S. Geol. Surv*, *Bull.* 540.)

The sedimentary rocks of this area consist of strongly folded Paleozoic ones, overlain by Cretaceous beds, and these have been intruded by the peridotite. This has in most places disintegrated to a soft earth, whose topographic features, however, do not differ from those of Trinity (Cretaceous) clays.

The residual clay derived from the peridotite is usually yellowish green above and bluish green below, the solid rock being in some cases as much as 30 feet down.

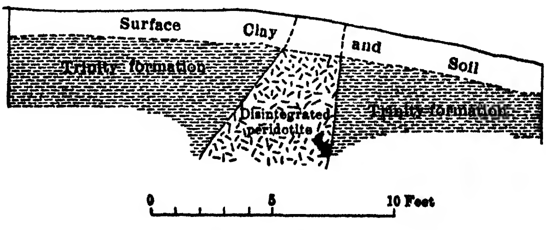

FIG. 102.—Section in Arkansas diamond area. (*After Miser.*)

Africa (8, 40).—On this continent diamonds were first obtained in the Union of South Africa from volcanic pipes of kimberlite which pierce a series of sandstones, lavas and shales, ranging from Carboniferous to Triassic in age. In the kimberlite there are fragments of the country rock. The upper part of the pipe to a depth of 35-140 feet is well-weathered *yellow ground,* below which one finds less altered and oxidized rock known as *blue ground,* which disintegrates on exposure to the weather, while still lower is the *hardebank* or well-preserved kimberlite.

The pipes range in diameter from over ½ mile (Premier mine) to less than 100 feet. Most of the important pipes are in the region around Kimberley, but the largest is near Pretoria.

These pipes are regarded as being the products of successive eruptions, the great kimberlite one having been formed by the coalescence of three distinct chimneys. Following this, rising magmatic waters produced considerable hydrothermal alteration of the wall rock. The diamonds are regarded as normal constituents of the kimberlite (40).

The diamonds range in size from minute ones to the Cullinan stone which weighed 3025 carats. The diamond content of the blue ground ranges from 5 to 30 metric carats (1 carat = 200 milligrams), but the richness diminishes with depth. About 150 pipes have been found, but only 25 have been worked, and the bulk of the production has come from 7. The pipe mines were closed in 1934.

More recently the diamonds found in gravels have become of greater importance, and the stones command a higher average price. In the Union of South Africa these diamantiferous gravels have been developed: (1) in valleys, between Prieska and Potchefstrom; (2) on the high plains of west Transvaal; and (3) on the coast of Namaqualand where they are found along an ancient coast line (38).

On the coast of Southwest Africa the diamonds occur in windblown sands (4). In addition, gravels are also worked in Angola, Belgian Congo (12), Tanganyika, and Rhodesia.

In 1935 the Congo, Gold Coast, and South Africa were the leading producers in the order named.

Brazil.—Diamonds have been produced from stream placers for a number of years. Their immediate source was a conglomerate (17, 29).

Emerald.—This gem is a variety of beryl, essentially a glucinum-aluminum silicate. Its hardness is 7.5 to 8, and its specific gravity 2.5 to 2.7. Its brilliant green color is attributed by some to chromium, by others to organic matter. Brazil, Hindostan, Ceylon, and Colombia are sources. In the United States a few have been found in western North Carolina (24) in gravel deposits. Flawless emeralds are rare, and equal in value to diamonds. The best ones come from Brazil.

Aquamarine and *oriental cat's-eye* are also varieties of beryl. *Brazilian emerald* is a green variety of tourmaline, and *lithia emerald* an emerald-green spodumene (11).

Beryl.—Gem beryl has been found at many localities in New England, and while at some of these it has been obtained as an accessory mineral in feldspar mining, at others the veins have been worked for the gem mineral alone. Thus in Connecticut golden beryl has been obtained near New Milford, and good aquamarine near East Hampton. Other localities have been worked in Maine, Massachusetts, and New Hampshire (32).[1]

Garnet.—Of the several varieties of garnet, three are well known as gem stones, viz., the precious garnet, or almandite; Bohemian garnet, or pyrope; and manganese garnet, or spessartite. The first two are of deep crimson, the last of orange-red or light red-brown color. India is the main source of supply. All three varieties mentioned are found in the United States, but there is a regular production only of the pyrope from Arizona and New Mexico, and a purple-red garnet known as rhodolite from North Carolina (7, 24).

Those found in the southwest have for many years been collected by the Navajo Indians. Clear red garnets associated with peridot gems, which have been weathered out of basic igneous rocks, have been found at several places around and north of Fort Defiance, Ariz., but those obtained from these localities are small and not worth cutting.

Opal, which is hydrous silica chemically, is amorphous, with conchoidal fracture, yellow, red, green, or blue color, and often showing considerable iridescence. The varieties recognized are the precious opal, fire opal, girasol, and common opal. The finest examples of precious opal are obtained from Hungary and New South Wales. Others are also found at Queretaro, Mexico, and in Oregon and Washington. The United States production is small, although it is thought that there are many scattered occurrences in the igneous rocks of Washington, Idaho, Oregon, California, Nevada, and Utah (7, 11, 23).

In 1913,[2] considerable prospecting was done in the opal field of Virgin Creek, Humboldt County, Nevada, a region that was discovered in 1908. The formations consist of tuffs, ashes, and rhyolitic lavas, which have been broken by block faulting and tilting, and the opal occurs in the ash beds, mostly associated with the petrified wood. It is found as casts of different parts of the trees, and as coatings and filling in cracks in the silicified wood.

Peridot.—This name is applied to a deep olive-green variety of chrysolite, a silicate of magnesium and iron. Peridot has a low hardness (6.75) as compared with other gems, while its specific gravity, 3.3 to 3.4, is relatively high.

Gem peridot is found in two regions in Arizona, viz., north of Fort

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[1] Min. Res., U. S. Geol. Surv., 1913, p. 656.

[2] Merriam, Science, n. s., XXVI: 380, 1907, and Sterrett, U. S. Geol. Surv., Min. Res., 1913, p. 677.

Defiance in the Navajo Indian Reservation, and near Rice in the White Mountains Apache Indian Reservation. In the former district the peridot is plentiful, and is found associated with volcanic rocks. These are monzonite porphyry, orthoclase basalt, and peridotite agglomerate. The peridot, which appears to have been derived from the agglomerate, is found in the soil, and associated with it are such minerals as garnet, diopside, quartz, calcite, titanic iron, etc. Gems of 1 to 2 carats' weight are fairly abundant, and some of 3 to 4 carats are found. Those of dark yellowish-green color are commonest.

Ruby.—A red, transparent variety of corundum (Al_2O_3), having a hardness of 9 and a specific gravity of 4. The most valuable color in ruby is a deep, clear, carmine red. Rubies of large size are scarce, so that a 3-carat stone of good color and flawless is worth several times as much as a diamond of the same size. The best ones come from Burma. In the United States they have been found in the stream gravels of Macon County, North Carolina, but the production is not a steady one. Those found in Arizona and other western states are not true rubies, but a variety of garnet (7, 11).

Sapphire is a blue, transparent variety of corundum (Al_2O_3). It is of slightly greater hardness and specific gravity than the ruby, though of similar composition. Sapphires of good color and size are more common than rubies and cheaper. The best sapphires come from Siam. In the United States they have been found in the gravels of Cowee County, North Carolina, but Yogo Gulch, Montana, has been a more important source of domestic supply. They range in weight from under 1 up to 4 or 5 carats (7, 11, 33).

The Montana sapphires were first found in gravel bars on the Missouri River, but subsequently they were discovered in dikes of basic igneous rock cutting Carboniferous (?) limestone in southwestern Fergus County. The rock is of somewhat basic character belonging to a type known as monchiquite, and the sapphires are obtained from the somewhat decomposed portions of the dike.

The deposits are not worked at present. Kashmir, India, has been a large producer.

Spodumene.—A remarkable transparent lilac-colored and pale pink to white spodumene, known as *kunzite* (22) has been found in California not far from the rubellite locality, and occurring in a pegmatite dike, where it is closely associated with gem tourmalines.

Topaz.—This is a fluosilicate of alumina, crystallizing in the orthorhombic system, with a hardness of 8, specific gravity of 3.5, vitreous luster, and yellow, green, blue, red, or colorless. It occurs in gneiss or granite, as well as in other metamorphic or igneous rocks, and is associated with beryl, mica, tourmaline, etc. It is also found in alluvial deposits. The best gem stones come from Ceylon, the Urals, and Brazil. In the United States they have been found in small quantities in Maine, Colorado, California (22), and Utah (11).

In Utah topaz (31) is found in the Thomas range of mountains about 40 miles north of Sevier Lake, at a locality known as Topaz Mountain. The transparent crystals occur in lithophysæ in rhyolite, and vary from colorless to wine color. Rough opaque crystals are scattered through the solid rhyolite. The crystals are believed to have been formed by vapors or solutions contemporaneous or nearly so with the final consolidation of the rock. In the weathering of the rock the crystals fall out and become mixed with the soil, the colored ones fading on exposure to the light.

Topaz is obtained from pegmatite veins near Ramona, San Diego County, where it occurs in pockets in albite and orthoclase. The topazes are white, yellow, sea-green, and sky-blue, some of them being of large size (22).

Tourmaline.—This is a complex silicate, of aluminum and boron, with usually varying amounts of iron, magnesium, alkalies, and water. It has a hardness of 7 to 7.5 and a specific gravity of 2.98 to 3.20. The color is variable, and this variation may exist in the same crystal (11).

The opaque, black, or brown tourmaline is a somewhat common mineral in many metamorphic rocks, as well as in granite and other eruptive rocks, but this variety has no value as a gem.

Gem tourmalines are, however, rather rare, being known in Brazil, Russia, and Ceylon, and in this country in the states of Maine, Connecticut, and California. Of the gem tourmalines the red ones are most highly prized, especially the darker ones; the green ones are usually dark green.

A large number of green tourmalines have been obtained from a pegmatite granite at Paris, Me., and many are found in a belt extending from Auburn to Newry (37). The gems here are likewise found in pegmatite, and are associated with beryl.

An interesting occurrence of red tourmaline (*rubellite*) has been worked at Pala, San Diego County, Calif. The crystals here form radiating groups in lepidolite, and the earlier discovered ones were clear enough for cutting. Valuable crystals, many of gem character, have since been found in pegmatite veins near Pala, and near Mesa Grande (22).

Turquoise is a massive hydrated aluminum copper phosphate, of waxy luster, blue to green color, and opaque. Its hardness is 6, and specific gravity 2.75. It usually occurs in streaks and patches in volcanic rocks. The best varieties are obtained from Persia, but it is also obtained from Asia Minor, Turkestan, and Siberia. In the United States turquoises have been found in the Los Cerillos Mountains near Santa Fé, N. M., and Turquoise Mountain, Arizona, as well as in Colorado (11).

It is interesting to note that turquoise was hardly known in the United States in 1890, but some comes from the southwestern states (20, 42).

The production of turquoise in the United States has at different times come from New Mexico, Nevada, Arizona, California, and Colorado.

Turquoise mines have been operated in the Burro Mountains, 15 miles southwest of Silver City, N. M. The country rock of granite, which is cut by andesite-porphyry, andesite, and dacite, is much altered, and the turquoise is found in a vein or fissured zone, which contains kaolinized feldspar and secondary quartz.

In this strip, which is 40 to 60 feet wide, the turquoise occurs as veins and nuggets, the former filling cracks in the granite 1/16 to 3/4 inch wide, and the latter in the kaolin. The veinlets often cross and indicate successive periods of deposition.

A diversity of opinion exists regarding the origin of the turquoise. Silliman (Amer. Jour. Sci., 1881, July, p. 67) believes it to have been formed by heated water and vapors, which destroyed the original character of the rock and produced new compounds. Clarke and Diller suggested that the turquoise represents a replacement of the apatite of the granite. Johnson (20) advanced the theory that gases played a rôle in the decomposition of the rock, and called attention to the association of fluorite with the turquoise. The alumina of the turquoise, he thinks, was derived from the feldspar, the phosphorus from the apatite, and the copper from cupriferous solutions which formed the ores in that region.

Zalinski (42) believes that hot solutions, coming from below, caused a kaolinization of the granite, the silica set free in this connection being deposited in cracks and fractures with the turquoise. Solutions carrying aluminum phosphate rose along fissures parallel with the walls, while the copper solutions came along an intersecting series. Intermingling of the two solutions formed the turquoise.

In Mohave County, Arizona, the turquoise is found in the younger intrusive porphyries and granite, both of which have been more or less altered, especially around the turquoise deposits. This alteration consists of kaolinization, but there has also been some silicification, as shown by a deposition of quartz in joints and between the grains. Some of the turquoise seems to have been derived from the kaolin by the addition of phosphoric acid and copper, but much of it has been deposited from solution, as it occurs as seams and veinlets, as well as in patches or streaks in quartz seams and veinlets. The nodular turquoise is less common.

The Colorado turquoise deposits are associated with trachyte, but they show relations similar to the Arizona material.

In the district of northeastern San Bernardino County, California, where several large mines have been operated, the turquoise occurs in a coarse porphyritic granite, and a monzonitic (?) porphyry. These have been fractured, and then sericitized and kaolinized, as well as stained with limonite. Later solutions carrying the elements of turquoise passed through the same fissures where kaolinization occurred and deposited the turquoise in seams and veinlets, as well as in nodular masses in the kaolinized and sericitized rock.[1]

Variscite.—This mineral alone is not used as a gem stone, but it is cut with its associated matrix. This mixture, which is sometimes called **amatrice** (43), is composed of variscite, wardite, and probably other associated minerals such as chalcedony and quartz. The first two are hydrous phosphates of aluminum, showing varying shades of green, of compact, tough character and having a hardness of 4 and 5 respectively. The matrix consists of chalcedony and quartz with other minerals, among them yellowish gray and white phosphates. The decorative value of the material lies in the variety and arrangement of its colors.

Production of Precious Stones.—The domestic production of precious stones in 1940 had a roughly estimated value of $340,000. The value of diamonds imported into the United States in 1940 was as follows: rough, uncut, $11,595,703; cut but not set, $22,001,719. Emeralds, rough and cut, $401,019. Other precious stones, cut and uncut, $2,345,371.

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QUARTZ

Although this material has been briefly referred to under abrasives and glass sands, it is sufficiently important to require treatment as a special topic.

Silicon is the second most abundant constituent of the earth's crust, and quartz, of which it is an important ingredient, is the most abundant of all minerals, but varies greatly in its mode of occurrence and uses. Thus some varieties, such as rose or smoky quartz, amethyst, etc., are used as gems. Quartz in the form of sand is employed for foundry sand, building, glass-making, and pottery manufacture, etc. In the form of sandstone and quartzite (Chapter III) it is of value as a structural material.

The forms of quartz considered here are the massive crystalline quartz (often known as vein quartz), flint, and quartzite used for purposes other than building or paving.

Vein Quartz (1, 8).—This form of quartz, which is white, or less often rose or smoky, occurs in veins or dike-like masses, usually in metamorphic rocks. It may be of high purity, or may be mixed with feldspar, mica, etc., as an ingredient of pegmatite, in which case it is obtained as a by-product in the mining of feldspar. Vein quartz is produced in Connecticut, New York, Pennsylvania, and Maryland. A crystalline quartz, not of vein character, obtained in southern Illinois is referred to under Tripoli (p. 340).

Quartzite.—This rock is quarried at a few localities for special purposes. Thus in Cherokee County, North Carolina, a vitreous Cambrian quartzite has been quarried for use as a flux in copper smelting. Large quantities of a hard brittle quartzite have also been quarried near Wausau, Marathon County, Wisconsin, the ground product being used for sandpaper and other abrasive purposes, filters, bird grit, wood filler, etc. It analyzes 99.07 per cent silica. Much quartzite is used for silica brick and glass.

Flint or Chert.—This term is applied to lusterless quartz of very compact texture and conchoidal fracture, which often forms nodules in limestone or chalk. In some cases these concretions may represent silicified fossils. Flint nodules are found in many formations in the United States, but little of the domestic material has been utilized except for road metal. The entire supply of true flint demanded by this country for special purposes is obtained from France, England, Norway. The smaller nodules are used in tube mills, but much of the supply is calcined to whiteness and then ground for use in pottery manufacture. It is also used as a substitute for abrasive garnet.

Uses of Quartz.—Quartz is extensively used in pottery manufacture to diminish the shrinkage of the ware in burning, and for this purpose it should have under 1 per cent of iron oxide. In recent years quartzite and sandstone have been more used than vein quartz. It is also employed in the manufacture of wood filler, paints, scouring soaps, sandpaper, filters, and tooth powders. Blocks of massive quartz and quartzite are employed as a filter for acid towers, and tube mill linings.

Quartz is also used as a flux in copper smelting and in the manufacture of silicon and ferrosilicon. Much chemical ware is now made of fused quartz.

Production of Quartz.—The production of quartz in the United States in 1940 amounted to 31,865 short tons, valued at $176,390.

In Canada the production of "Quartz" for 1939 included natural silica, quartzite, siliceous fluxing gravel, lode quartz and natural silica sand, the total being 1,582,935 short tons, valued at $1,100,214. This production was contributed by all the provinces except Alberta and New Brunswick.

The imports of silex or crystallized quartz, ground or unground, were 2,751 short tons, value $61,497.

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SILLIMANITE GROUP

Andalusite, kyanite, and sillimanite all have the formula $Al_2O_3 \cdot SiO_2$, while dumortierite is closely related but in addition contains boron. A characteristic feature of all these minerals is that when heated above 1545° C. they change to mullite ($3Al_2O_3 \cdot 2SiO_2$) and glass. Above 1810° C. the mullite breaks up to corundum and liquid. For many years needle-like crystals were noticed in thin sections of fired whiteware bodies but they were mistaken for sillimanite, until Bowen and Greig discovered that they were mullite.[1]

Distribution in the United States.—Kyanite is widely distributed in the states of Virginia, North Carolina, and Georgia, while andalusite occurs in California and dumortierite in Nevada.

Virginia (3).—The kyanite is found in central Virginia in the Wissahickon quartzite, and in southwestern Virginia in pegmatite. In the quartzite it is believed to have originated by regional metamorphism, but in the pegmatites it is thought to have come from a

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[1] Amer. Ceram. Soc., Jour. VII: 238, 1924.

magmatic source. The quartzite carries from 20 to 80 per cent kyanite, with an average of 30 per cent. There has been no steady commercial production.

North Carolina (12).—In this state the kyanite is widely distributed in the Piedmont Plateau and Appalachian Mountain sections. The mineral occurs as disseminations in Archæan to Cambrian gneisses and schists, and as rounded masses or lenses in quartz veins and pegmatite dikes.

Stuckey, who has made a careful study of the deposits in this state is not in complete harmony with the theories expressed by those who have studied the Virginia deposits. He presents rather definite evidence to show that the North Carolina kyanite probably owes its origin to replacement by magmatic solutions. It was accompanied by the deposition of muscovite, biotite, tourmaline, and garnet. The deposits carry from 5 to 50 per cent kyanite with an average of 20 per cent. Substantial shipments are said to have been made, mostly from the pegmatite deposits.

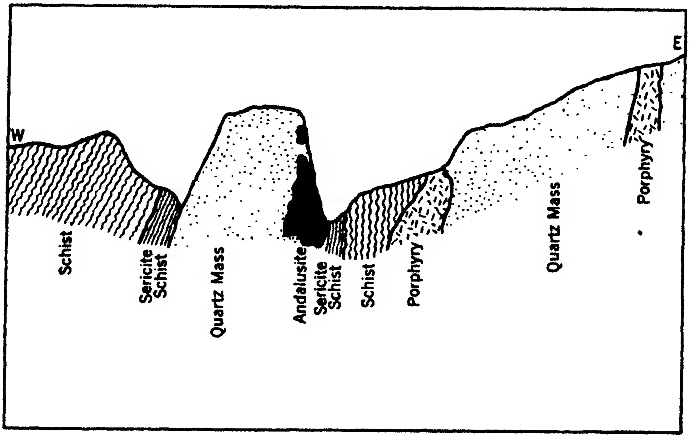

FIG. 103.—Section of andalusite deposit near White Mountain, California. (*After Kerr, Econ. Geol. XXVII*, 1932.)

Georgia (9, 11).—The kyanite deposits occupy a curved belt about 30 miles long in Rabun and Habersham counties. This is near the northern edge of the Piedmont upland in pre-Cambrian metamorphics of sedimentary origin, intricately folded, and intruded by igneous rocks. The kyanite occurs as scattered crystals in mica schist, and aggre gates of crystals in quartz veins. The schist deposits are low grade, averaging about 6 per cent plus in places favorable for mining. Some material has been obtained from residual clay.

California (5).—Kyanite is worked near Ogilby where it is said to form a vein 10 to 200 feet wide in mica schist. The product is shipped to Los Angeles.

Andalusite is being steadily produced from a deposit at 9000 feet altitude near White Mountain, California. The mineral occurs as irregular segregations in a great lenticular quartz mass, which is bordered on either side by sericite schist (Fig. 103) that is free from andalusite. While much of the quartz contains andalusite, only limited areas are rich enough to work. These are of irregular shape and occur in a zone 10 to 50 feet thick. The majority of the associated minerals contain silica and alumina, so that aside from excessive quartz a separation is not necessary. The common associates are corundum, quartz, muscovite, pyrophyllite, diaspore, alunite, rutile, and lazulite.

The country rock in the immediate vicinity is quartz-sericite schist, quartz-mica-tourmaline schist, and porphyry. The schists are regarded as metamorphosed trachytes, with an intervening layer of aluminous volcanic material. The andalusite is thought to be due to metamorphism accompanying the porphyry intrusion. There were two periods of mineralization: (1) introduction of andalusite, corundum, and diaspore; and (2) pyrophyllite, muscovite, alunite, and lazulite.

The product of these mines is shipped to Detroit, Mich.

Nevada (4).—In the Humboldt Range, 5 miles east of Oreana, Nev., there is a most interesting deposit of dumortierite and andalusite. The mineralization is concentrated along two parallel zones in a quartz-sericite schist in which there occur irregular lenses of andalusite partly or entirely altered to dumortierite. The schists are metamorphosed tuffs. It is thought that the minerals were deposited in two stages, as follows: (1) pneumatolytic, which gave the andalusite concentration, and (2) hydrothermal stage in which areas of fibrous or matted dumortierite were formed by replacement of andalusite. The solutions are believed to have emanated from intrusions to the north. The product of these mines is shipped to Detroit.

Foreign Countries (2, 7).—British India appears to be the only important foreign source of supply. Kyanite has been shipped from Kharsawan about 175 miles west of Calcutta. The recent output has been from the Singhbhum district. There are also reported to be large reserves in the Khasi Hills and at Pipra, but they are too remotely located to be workable at present.

South Africa is also known to contain scattered deposits.

Uses (8, 10).—The sillimanite group of minerals as it is sometimes called is of special value in the manufacture of spark plugs, chemical ware, and special refractories. Kyanite differs from the other members of the group, in expanding when changing to mullite, and this is regarded by some as an undesirable feature, but this trouble may be overcome by precalcining. This is said to make it more difficult to bond than raw sillimanite and andalusite. It is suggested, however, that the swelling of kyanite may serve to counteract the clay shrinkage where it is used in making refractory brick.

Some kyanite is also used in glass manufacture. Where the minerals form only a small portion of the rock mined, concentration is necessary.

Production of Sillimanite Group.—The production in 1940 was over 7000 tons. An equal amount of kyanite was imported.

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STRONTIUM

Sources and Occurrence.—The two minerals serving as sources of strontium salts are celestite ($SrSO_4$) and strontianite ($SrCO_3$). Of these two the former is the more important, but the latter is the more valuable, as the strontium salts can be more easily extracted from it.

Two commercial sources of strontium minerals are said to occur in Ontario (6).

Potential supplies of strontium minerals in the United States may be greater than was originally believed.

In the region around Boulder Dam (1) there are a number of deposits, one of which, near Argus, Calif., is said to contain over

600,000 tons. The deposits in this region are said to carry from 70 to 90 per cent strontium sulphate contaminated chiefly by silica.

Potential sources of celestite are said to occur in Texas and other western states.

Nearly all the strontium salts now used in the United States are imported from England, which is the largest producer of celestite, and Tunisia.

Uses.—Strontium salts are used in sugar refining, in fireworks manufacture, signal flares, and to a small extent in medicine.

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SULPHUR AND PYRITE

These two minerals are discussed in the same chapter because both serve as sources of sulphur or sulphuric acid.

SULPHUR

Native sulphur may be formed in several different ways as follows:

Solfataric Type.—Sulphur is often found in fissures of lava and tuff around many active and also extinct volcanic vents.[1] When thus formed as a volcanic sublimate it may be a product of reactions between sulphur dioxide and hydrogen sulphide. It may also be formed by incomplete combustion of hydrogen sulphide, probably as follows: $2H_2S + O_2 = 2H_2O + 2S$. This latter change probably occurs at least a short distance below the surface, where oxygen is deficient, as at the surface the H_2S may form H_2SO_4.

Deposits of the solfataric type are rarely of commercial importance, but they are worked in Japan, and have also been worked in the crater of Popocatepetl in Mexico.

Mineral Spring Deposits.—Sulphur is not an uncommon deposit around mineral springs, its deposition being due to imperfect oxidation of hydrogen sulphide, the sulphur appearing in the spring waters as a whitish powder. It has been noticed, however, that the associates of this type of sulphur deposit are often some form of lime carbonate,

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[1] For deposition of sulphur in crater lakes see Oinouye, Jour. Geol. XXIV, 806, 1916.

or gypsum, and that the sulphur depositing springs sometimes rise through fissures in limestone, leading to the belief that a reaction like the following may occur:[1]

$$2CaCO_3 + 2H_2S = Ca(SH)_2 + H_2Ca(CO_3)_2$$

The calcium hydrosulphide formed will yield calcium carbonate or gypsum on the escape of the H_2S as follows:

$$Ca(SH)_2 + 2O_2 + 2H_2O = CaSO_4 \cdot 2H_2O + H_2S$$
$$Ca(SH)_2 + CO_2 + H_2O = CaCO_3 + H_2S$$

This accounts for the travertine and gypsum found with some mineral spring deposits (p. 327). It is possible also that some of the sulphur is deposited by sulphur bacteria.[2] These have the power of oxidizing H_2S to H_2SO_4, and retaining free sulphur in their cells, if there is an excess of H_2S. The H_2SO_4 formed will in turn attack calcium bicarbonate, which the cell takes up from the water and converts it into calcium sulphate. Sulphur under favorable conditions may also be carried in the colloidal form, and be later precipitated.[3]

Gypsum Type (2, 8, 20).—This type, which is of world-wide distribution, is so called because of its constant association with gypsum, but the exact relationships are not the same in all cases.

In the Sicilian deposits (q. v.), which represents one sub-type, bedded deposits of limestones, marls and bituminous matter are found with the sulphur. In the Louisiana sub-type (q. v.) the sulphur shows peculiar relations to limestone, anhydrite and salt. Because of the definite relation of these sulphur deposits to volcanic activity, and their association with rocks deposited from water, the true explanation of the origin of these deposits has been somewhat difficult to find.

The theories advanced to explain the Sicilian deposits may be briefly stated as follows:

1. The sulphur is thought to have been formed by the reducing action of bituminous matter on gypsum according to the following reactions:

$$CaSO_4 + 2C = CaS + 2CO_2$$
$$CaS + CO_2 + H_2O = CaCO_3 + H_2S$$
$$H_2S + O = H_2O + S$$

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[1] Bechamp, Ann. chim. phys., 4th ser., XVI: 234, 1869.

[2] Winogradsky, Botan, Zeit, XLV, No. 31–37, 1887.

[3] Raffo and Marncini, Zeitschr. Chemie Ind. Kolloide, IX: 58, 1911.

This theory was first suggested by G. Bischof,[1] and is still held by many.

2. Stutzer (20) has suggested that the sulphur is of purely sedimentary origin. He bases his belief on: (*a*) its stratified structure; (*b*) the interstratification with limestone, and in the Sicilian deposits at least, its absence in the gypsum; and (*c*) the presence of interbedded clay layers, which would prevent circulation, and preclude the deposition of the sulphur by permeating waters.

In accordance with this view he assumes that decaying organisms in the water yielded hydrogen sulphide, or that it might have been formed by the action of hydrocarbons on calcium sulphate. The oxidation of the hydrogen sulphide was brought about either by the oxygen of the air, or by sulphur bacteria.

3. A third theory is that the hydrogen sulphide was supplied by cold springs discharging into fresh-water lakes,[2] or by hot springs flowing out over the ocean floor.[3]

4. Hunt (8), after noting that the sulphur of Sicily forms basin-like deposits, underlying the more continuous gypsum which contains occasionally lens-shaped masses of secondary sulphur, suggests the following:

The sulphur was collected in small basins, whose water had a comparatively high average temperature, and a high sulphate content. Bacterial reactions extending over a period of years caused a copious production of H_2S from decomposition of sulphates, and reactions similar to those mentioned under *Mineral Springs Deposits* (q. v.), might cause a simultaneous precipitation of sulphur and calcium carbonate. Some of the sulphur would, however, be absorbed by the $Ca(SH)_2$, forming an unstable polysulphide, which would yield copious precipitations of free sulphur from time to time. Continued evaporation of the basin waters eventually rendered them so saline as to check bacterial action and also precipitate the overlying gypsum.

5. Sagui (19) believes that the sulphur owes its origin to H_2S waters of volcanic origin, which mingled with the ground water and that its deposition was contemporaneous with the limestone. Its present irregular distribution he thinks is due to its solution and redeposition later.

6. In the case of the Texas-Louisiana deposits (2), one prominent suggestion is that the sulphur may have been formed by the carbon

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[1] Chem. u. Phys. Geol. II: 144, 1851.

[2] A. von Lasaulx, Neues Jahr. Min., 1879, p. 490.

[3] G. Spezia, Neues Jahrb. Min. 1893, I: 38.

or hydrocarbon compounds, derived from associated petroleum, acting on calcium sulphate, in which case the sulphur would be of later age than the associated rock.

Metallic Sulphide Type. Sulphur may result from alteration of pyrite, marcasite, or related sulphides, possibly through action of bituminous matter. Gypsum is a common associate. No deposits of economic value have been formed in this manner.

Distribution of Sulphur in the United States.—Louisiana and Texas are the most important producers, smaller quantities coming from other western states, especially Wyoming.

Louisiana—Texas (2, 9, 13).—The deposits of sulphur found in these two states supply over 99 per cent of the domestic production. Sulphur was first discovered in 1865, in drilling for oil near Lake Charles, La.

The sulphur is found in the cap rocks overlying salt domes (Fig. 104). This cap rock consists of anhydrite, and sometimes gypsum, these being overlain by calcitic limestone. The sulphur occurs irregularly and mainly in the limestone, but is not always present in commercial quantities. It may vary in thickness from a few inches

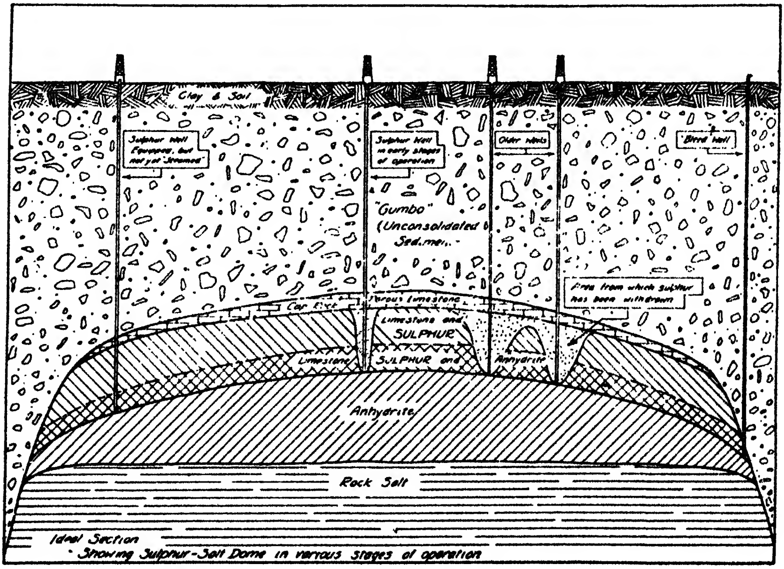

FIG. 104.—Idealised section of salt dome showing extraction of sulphur. (*Gulf Sulphur Company.*)

to more than 100 feet, and forms from 20 to 40 per cent of the rock worked.

The sulphur is encountered at depths varying from 450 to 1500 feet.

Ten salt domes have been developed up to the present time, most of them in Texas.

The reserves are no doubt large, but there has also been a large production.

Owing to the quicksand-like character of the overlying beds, attempts to sink a shaft to the deposit were unsuccessful. It is now obtained by pumping superheated steam down through pipes, melting the sulphur, and drawing it to the surface, where it is discharged into vats to cool and solidify.

Utah (11).—Sulphur of the solfataric type has been mined at Sulphurdale in central Utah for some years. In this district there are found a series of rhyolites and andesites, overlain in places by basalts, the whole resting probably on Paleozoic sediments.

The sulphur occurs mostly as disseminations in the porous tuff, and cementing it. The crude material varies greatly in richness, rock running as low as 15 per cent sulphur being workable. There seems no doubt that it is of volcanic origin, having been formed from hydrogen sulphide, which can be noticed escaping from openings in the tuff.

Wyoming.—Native sulphur has been mined in Wyoming near Cody (22), and near Thermopolis (23), the mode of occurrence at the two localities being almost identical. At the latter locality the deposits are found in the altered Embar (middle Carboniferous) limestone which immediately underlies a travertine deposit (Fig. 105).

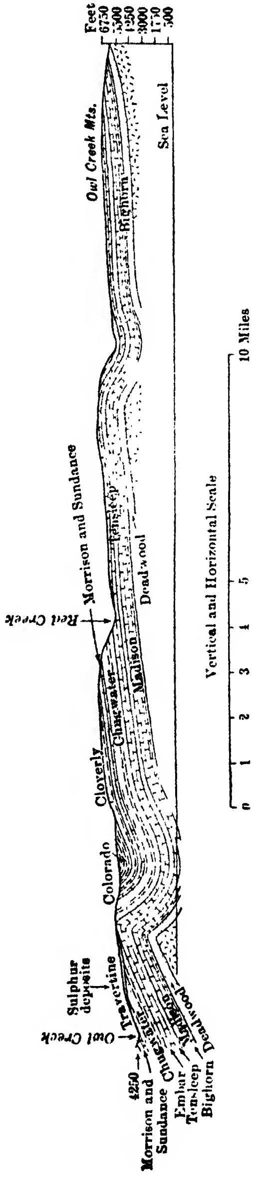

FIG. 105.—Section showing stratigraphy and structure from crest of Owl Creek Mountains to Owl Creek, and relations of sulphur deposits near Thermopolis, Wyo. (*After Woodruff, U. S. Geol. Surv., Bull.* 380.)

The sulphur occurs in small yellow crystals filling veins or cavities in the rocks, and in massive form as a replacement of calcium carbonate by sulphur, the original structure of the limestone being retained.

The distribution of the sulphur appears to be very irregular, and confined to those portions of the limestone surrounding the channels of the hot springs that deposited the travertine. The attempted explanation of the origin of the deposits is that surface waters worked their way downward along the sandstones from the Owl Creek Mountains (Fig. 105), and came into contact with some uncooled body of igneous rock, which not only heated them, but also supplied them with hydrogen sulphide. Following this they passed upward through the much-fractured beds of the anticline with which the deposits are associated. As these waters approached the surface, the sulphur was precipitated by oxidation, or by other processes mentioned under *Mineral Springs Deposits* (q. v.). Hot springs carrying both H_2S and CO_2 exist there at present.

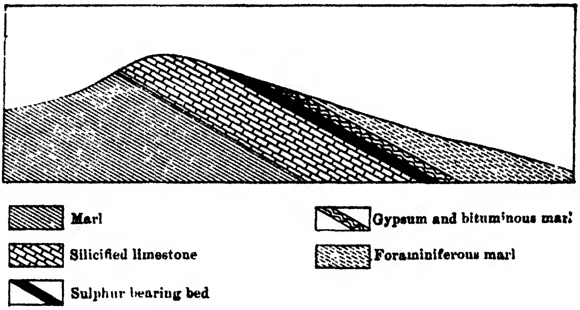

FIG. 106.—Section in Sicilian sulphur deposits. (*After Mottura, from Stutzer, Die Nicht-Erze.*)

FIG. 107.—Banded sulphur-bearing rocks from Sicily; black, sulphur; dotted, limestone; white, calcite. (*From Stutzer, Die Nicht-Erze.*)

The depth of the deposits at these two localities is not believed to be great, but in the rich pockets the sulphur may form 30 to 50 per cent of the rock.

Other States.—Sulphur deposits have been worked in Colorado, Nevada (1), and California.

Sicily (8, 20).—In the Sicilian sulphur-producing region the sedimentaries include (1) sands, sandstones, and shell breccia of Upper Pliocene; (2) foraminiferal limestone of Lower Pliocene; and (3) Upper Miocene sulphur-bearing series, consisting of: (*a*) an upper gypsum member with occasional lenses of secondary sulphur, and (*b*) a series of beds of sulphur-bearing limestone, separated from each other by bituminous, salty clays, and shales (Fig. 106). The individual sulphur beds may vary from one to thirty (exceptional) meters in thickness. Associated with the sulphur are celestite and calcite, less often barite, also bituminous matter. The whole series has been disturbed by folding and faulting.

Uses of Sulphur.—The most important use of sulphur is for the manufacture of sulphuric acid and in paper manufacture. Some is also used in making matches, for medicinal purposes, and in making gunpowder, fireworks, insecticides, for vulcanizing India rubber, etc. It is also used as a fertilizer.

In recent years pyrite has been largely replaced by domestic sulphur for the manufacture of sulphuric acid, and the importation of Sicilian sulphur has decreased.

Production of Sulphur.—The amount of sulphur shipped in the United States in 1940 was 2,558,742 long tons, valued at about $40,900,000. The price in 1940 was $16 per ton. The production has fluctuated greatly since 1925, reaching a peak in 1930, a large drop to 1932, and a slight rise since then. In 1940 Texas yielded 81 per cent of the domestic output, Louisiana, 18.7 per cent, and the balance from California and Utah.

The imports in 1940 amounted to 27,845 long tons, and the exports were 19,745 long tons.

At the present time not only is sulphur produced from native sulphur, but there is also a production of elemental sulphur from sulphide ores.

The United States is the largest world's producer, and has competed actively with foreign countries. Through a market agreement between Italy and the United States, the world's markets have been divided. Italy is the second largest producer and Japan third. Norway and Spain have both produced elemental sulphur from pyrite. Anhydrite has been used in England for the same purpose.

Canada is an important producer of sulphur in the form of sulphuric acid from smelter gases, and a large tonnage has been recovered from the smelters at Copper Cliff, Ontario, and Trail, British Columbia; at the latter locality elemental sulphur has also been produced. In 1939 Canada imported 3,044,329 cwt. of sulphur and brimstone.

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PYRITE

Properties and Occurrences.—Pyrite, FeS_2, when chemically pure, has 46.6 per cent iron and 53.4 per cent sulphur, and occurs in well-defined cubes or modifications of the same, in irregular grains or as granular masses, of a brassy yellow color.

It is widely distributed in nature, being found in many kinds of rocks and in all formations, and in these may occur as disseminated grains, in contact zones, as concretions in sedimentary rocks, in fissure veins, and as lenticular bodies of variable size usually in metamorphic rocks.

Pyrite as mined is never chemically pure, but contains admixtures of other sulphides, as well as nonmetallic minerals.

If chalcopyrite is present in sufficient quantity to bring the copper content of the ore above 3 or 4 per cent, the material may be sold for copper making instead of acid manufacture. Pyrrhotite is abundant in some of the Virginia deposits. In some regions the pyrite carries enough gold to render its extraction profitable, but such deposits are not worked for their sulphur content.

Pyrite as offered to the trade rarely contains over 43 per cent sulphur, and if the content falls below 38 per cent, the acid makers object. Careful sorting and jigging of the pyrite is usually necessary. Lead, zinc, arsenic, antimony or selenium are objectionable.

The pyrite produced in the United States is obtained from (1) massive deposits, often of lenticular form and disseminations occurring in gneisses or schists (Virginia); (2) from the lead and zinc mines of the Upper Mississippi Valley; and (3) formerly from the coal mines of Indiana and Illinois.

When pyrite is roasted SO_2 is given off, which is changed to SO_3 by mixing with fumes given off from a mixture of $NaNO_3$ and H_2SO_3 in properly constructed lead chambers. In thoroughly roasted pyrite there remains a residue of iron oxide, which is known as "blue billy" or purple ore, and can be used in the blast furnace for iron manufacture. The roasted chalcopyrite is sometimes also used for copper making.

Distribution in the United States.—The most important domestic occurrences are found in a belt of pre-Cambrian metamorphic rocks extending from New Hampshire to Alabama (5), in which the pyrite occurs in lenticular deposits. Virginia and New York have been the most important eastern sources. California has been the only western state producing appreciable quantities.

Virginia (16).—The counties of Louisa and Prince William contain workable deposits of pyrite, which at one time were extensively worked, and yielded a considerable portion of the domestic production.

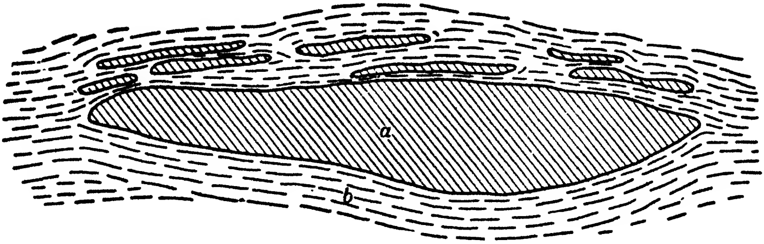

FIG. 108.—Plan of pyrite lens (*a*), showing stringers of pyrite, interleaved with schists (*b*) on hanging wall. Arminius mine, Louisa County, Va. (*After Watson, Min. Res., Va.*, 1907.)

In these counties the pyrite occurs as bodies of lenticular shape (Fig. 108), in quartz-mica schists, which may contain more or less hornblende and garnet locally developed.

The pyrite is massively granular, and the associated minerals in the order of their importance are sphalerite, chalcopyrite, galena, pyrrhotite, and magnetite. Calcite, quartz, green hornblende, and red garnet are present, but the last two rather favor the margin of the ore bodies.

The lenses of pyrite follow each other along the strike, sometimes overlapping, and may also be connected by stringers of ore (Fig. 108). The main bodies may be several hundred feet long, indeed one in Louisa County has a length of 700 feet and a thickness of 60 to 80 feet. Another in Prince William County is 1000 feet long. Pinches and swells are common, and while the pyrite bodies are usually sharply defined, they may at times grade into the country rock.

Watson considered that the inclosing schists are undoubtedly metamorphosed sedimentary limestones, as shown by the presence of bands and stringers of impure limestones and the abundant development of lime-bearing silicates. The pyrite is believed to have been formed by replacement.

New York (4, 14).—Pyrite deposits were worked near Canton and Gouverneur, St. Lawrence County. The pyrite was low grade, carrying 20 to 35 per cent sulphur which was raised to 45 to 50 per cent by concentration. The ore deposits, which are associated with crystalline limestones and schists of the Grenville series, appear to represent impregnation zones in the schist, which by local enrichment may give lens-like accumulations.

Massachusetts (12).—Pyrite was produced near Davis, Franklin County. The material forms a somewhat tabular deposit of irregular width in steeply dipping, northeasterly striking, crystalline schists.

Other States.—Some pyrite was produced from deposits in crystalline schist in Clay County, Alabama, near Acworth and Villa Rica, Georgia, and in California (1). In Indiana, Illinois, and Ohio some has been obtained as a by-product in the mining of coal (15).

Some pyrite (marcasite) has been obtained from the Wisconsin-Illinois lead-zinc district. Some of it is a by-product of the separating plants, but the greater part is shipped as mined, and may average 45 per cent sulphur. New York zinc ores supply some.

Canada (17).—Pyrite deposits are known at a number of points in Canada, especially in Ontario and Quebec, but comparatively few of them are in active operation.

The pyrite at present is produced from the concentration of sulphide ores. One deposit which has been worked for a number of years is the Eustis Mine at Weedon, Quebec (2), which is described under Copper. The ore averages about 56 per cent pyrite, and the pyrite concentrates are exported. Another deposit is worked in Boischâtel township, Quebec.

Concentrates have also been produced at Britannia Beach, north of

Analyses of Pyrite and Pyrrhotite

	I	II	III	IV	V	VI	VII	VIII	IX
S	9.27	32.10	44.95	47.00	34.060	48.00	49.00	45.00	44.78
Fe	43.62	35.94	41.14	44.00	53.150	43.00	43.55	42.50	37.49
Cu	1.50	0.30	0.28	1.50	0.866	1.6	3.20	3.50	—
Zn	0.38	4.68	3.58	tr.	—	1.5	0.35	0.25	4.23
Insol.	4.23	[1]13.42	[1]2.54	[1]3.00	[1]2.99	[1]5.0	1.70	—	11.08
CaO	1.32	1.00	—	—	—	—	0.14	0.10	0.87
MgO		0.59	0.70	—	—	—	—	—	0.20
As	—	0.04	0.04	—	—	—	0.47	—	0.07
Pb	—	0.50	0.40	—	—	—	0.93	0.20	0.14

[1] SiO_2.

I. Louisa County, Va. II. Crude ore, Louisa Co., Va. III. Concentrates, Louisa Co., Va. IV. Concentrates, Davis, Mass. V. Pyrrhotite, Virginia. VI. New Hampshire. VII. Rio Tinto, Spain. VIII. Sulitjelma, Norway. IX. Meggen, Ger.

Vancouver. Additional production of sulphur is obtained from smelter gases.

Other Foreign Deposits.—France, Germany, Italy, Norway, Portugal, and Spain are all large producers of pyrite, but only the last-named country has shipped much ore to the United States.

The Huelva deposits of Spain, with Rio Tinto as an important producing town, consist of lenticular ore bodies in schist. The ore is said rarely to fall below 47 per cent sulphur (3).

Some of these are referred to in more detail under Copper (Chapter XV).

Uses of Pyrite (11).—Pyrite was formerly used chiefly and in large quantities for the manufacture of sulphuric acid. The production came in part from pyrite, marcasite and pyrrhotite, while the rest represented by-product acid made in connection with roasting copper and zinc ores.

This acid is used in the manufacture of superphosphates and explosives, in refining crude oil, and other ways.

Production of Pyrite.—The production of pyrite in the United States in 1940 amounted to 617,513 long tons, valued at $1,892,000. Tennessee was the leading state; other producers were California, Colorado, Illinois, Indiana, Missouri, Montana, New York, Virginia, and Wisconsin. That obtained in Illinois and Indiana was coal brasses, while the pyrite produced from the others was in part a by-product obtained in ore concentration.

The imports to the United States in 1940 were 407,004 long tons, valued at $1,351,367, and came mostly from Spain. No exports are given.

The sulphur content of pyrites produced in Canada in 1939 amounted to 211,278 short tons valued at $1,668,025. No imports are recorded, but the exports are stated as the equivalent of 110,142 tons of sulphur contained in pyrite, valued at $793,466.

Among the world's producers of pyrite for 1938, Norway, Italy, Cyprus, Portugal, United States and Germany are listed as large contributors.

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TALC AND SOAPSTONE

Properties (10).—Talc, a hydrous magnesium silicate [$H_2Mg_3(SiO_3)_4$] is characterized by its extreme softness and soapy feel. It is white, gray or green in color, and has a foliated or micaceous structure. *Steatite* is the name applied to the massive, compact, cryptocrystalline to finely granular variety. *Agalite* is a fibrous talc from New York state. *Soapstone* is a term ordinarily applied to a dark-gray bluish or greenish rock, composed essentially of talc, but containing other minerals as impurities, such as chlorite, serpentine, amphibole, enstatite, and also quartz, magnetite, pyrrhotite, and pyrite. It is usually somewhat foliated, and like talc is soft enough to be easily cut with the knife.

Occurrence (5, 19).—Talc or soapstone deposits are always found in metamorphic rocks, and the following types of occurrence may be recognized:

1. White or light colored talc, usually associated with crystalline dolomite. Tremolite, actinolite, etc., are common associates.

2. Gray or green talc, usually impure, and associated with basic, igneous rocks. Soapstone deposits come under this heading.

3. Replacements in schists or gneisses.

4. Foliated talc in veins, usually of narrow width, which may cut soapstone, steatite, or serpentine. Though very pure they are of no commercial importance.

Origin (5, 7, 13).—Talc is essentially an alteration product of other minerals found associated with igneous or metamorphic rocks. It seems highly probable that it forms under conditions of lower temperature and pressure than the anhydrous silicates such as olivine, enstatite and tremolite, and under conditions of higher temperature and pressure than those accompanying the processes of surface weathering.

Various theories have been advanced to explain the origin of talc and soapstone, but these may be summarized as follows:

1. Metamorphism of a dolomitic limestone to silicates, such as actinolite and tremolite, and these in turn altered to talc. This might be brought about by regional metamorphism aided by water bearing carbon dioxide, by contact metamorphism of granite on dolomite, or from siliceous dolomite by regional metamorphism (19).

2. Alteration of ultrabasic igneous rocks to talc, either directly or through an intermediate stage of amphibole or serpentine. The agents which have been suggested are regional metamorphism, or the action of meteoric or magmatic waters carrying carbon dioxide and silica (5).

3. Replacement of schists or gneisses first by chlorite or amphibole, and these in turn by talc. The process is supposed to be due to magmatic waters.

4. Deposits from solution in veins, the agent being meteoric or magmatic water, according to differing observers.

5. By weathering of magnesium-bearing minerals.

It would seem safe to say that at the present time the majority of geologists believe that the formation of talc and soapstone is due usually to the action of magmatic solutions, the talc being formed in dolomitic crystalline limestones, schists, gneisses, or basic igneous rocks.

The fact that the talc is intimately associated with minerals of moderate to high temperature conditions indicates that it must have been formed below the zone of meteoric circulation; moreover the random instead of parallel orientation of the talc foliæ shows, according to some investigators, that it cannot be a product of regional metamorphism alone.

Distribution in the United States.—The production of talc and soapstone is limited almost exclusively to the belt of old crystalline rocks forming the axis of the Appalachian Mountain system, and although they are quarried in eight or ten states, but few are important producers, and these are mentioned below.

Deposits of talc and soapstone are known in some of the western states, but commercial conditions have not been favorable for their development. Small quantities of talc have been produced in the past in both California and Washington.

Vermont (5, 9).—The talc deposits which occur in two north-south belts in central and eastern Vermont form lenses in crystalline rocks. Some are associated with serpentine masses representing altered basic intrusives; others are in schists or gneisses. In all the deposits found in schist the talc is bordered by a chlorite zone called black wall. Dolomite is a constant associate, and other minerals commonly found with the talc are biotite, actinolite, apatite, magnetite, and pyrrhotite. Gillson (5) believes that the chlorite replaces the country rock, and in turn has been replaced by talc, the process being due to magmatic solutions from either a basic or acidic magma.

Virginia (1).—This state is the most important producer of soapstone, and while the material is found at a number of localities in the state, nearly the entire production comes from a narrow northeast belt at least 30 miles long, extending from Nelson into Albemarle counties.

The soapstone occurs in a number of lenses of variable size, whose major dimensions are conformable to the dip and strike of the country rock. The latter is schist and micaceous quartzite, containing belts of altered ultrabasic igneous rocks, and the soapstone deposits occur in or along the borders of the intrusives.

The soapstone varies in color from light bluish gray to dark greenish gray, the former or higher grade containing the most talc, and being the easiest and most satisfactory to work.

Under the microscope the better grade is seen to consist mostly of talc, with small quantities of chlorite, carbonates, and magnetite, as well as traces of amphibole and pyroxene. The dark green soapstone owes its color to chlorite and serpentine and its greater hardness to other silicates, such as hornblende and pyroxene. According to J. D. Burfoot the soapstone was formed chiefly by magmatic waters carrying carbon dioxide and silica, which altered the pyroxene and olivine directly or indirectly to talc. Amphibole and serpentine are common intermediate minerals in the process of alteration. There is no clear evidence that the soapstone has been formed by the replacement of schist. The product is used mainly for laundry tubs, but smaller amounts are converted into table tops, sinks, and switch boards. Much of it is shipped to foreign markets.

New York (13).—All the talc mined in the state is obtained from the region around Gouverneur, St. Lawrence County. The most abundant country rocks of this area are pre-Cambrian gneisses, in which there occur irregular northeast-southwest belts of crystalline limestone, the greater portion of which is impure. The limestones have been replaced locally by tremolite and enstatite, caused by magmatic solutions emanating from an underlying granite. Later these two minerals were altered to talc, this change being represented by the following equations:

$$\underset{\text{Enstatite}}{4\ MgSiO_3} + H_2O + CO_2 = \underset{\text{Talc}}{H_2Mg_3Si_4O_{12}} + MgCO_3$$

$$\underset{\text{Tremolite}}{CaMg_3Si_4O_{12}} + H_2O + CO_2 = \underset{\text{Talc}}{H_2Mg_3Si_4O_{12}} + CaCO_3$$

The first alteration was produced at a higher temperature than the second one. It forms lenses of variable size, and the mineral exhibits a bladed or fibrous structure. It is used mainly as a filler for writing papers, but has numerous other uses.

Washington (20).—Talc and soapstone occur as isolated bodies in pre-Tertiary metamorphic rocks in the northern part of the state, having been formed either by silication of dolomites or magnesites in eastern Washington, or by hydrothermal alteration of peridotite soapstone has been developed in Skagit County.

North Carolina (16).—The talc deposits of this state form an interesting contrast with those of Virginia, for here the material occurs as a series of lenticular masses and sheets in blue and white Cambrian marbles, thus indicating its probable derivation from a sedimentary rock. In other deposits the talc is found in a Cambrian conglomerate, in Archæan rocks associated with peridotite, showing an undoubted derivation from igneous rocks. Most of the North Carolina talc is ground to powder, but some is sawed into slabs, or made into pencils, crayons, gas tips, etc.

New Jersey (11).—Talc has been found at a number of points in the vicinity of Phillipsburg, N. J., and also across the river near Easton, Pa. The talc occurs with serpentine in dolomite and near pegmatite intrusions. The latter by contact metamorphism developed tremolite, white pyroxene, and phlogopite in the limestone. Later, during break-thrust faulting, accompanying minor folding, squeezing, and faulting in this area, the magnesian silicates were altered by water to talc and other products.

The following analyses from several localities show the kind and quantity of impurities which good talc may contain:

ANALYSES OF TALC

	I	II	III	IV	V	VI	VII	VIII	IX
SiO_2	62.42	60.15	63.07	60.26	57.08	61.85	60.60	60.20	63.36
Al_2O_3	1.43	0.74	1.56	0.31	8.40	2.61	0.30	1.25	0.46
Fe_2O_3	2.38	0.09	—	—		—	—	2.50	—
FeO	—	5.05	0.67	0.12	—	—	0.60	—	0.30
MgO	30.24	28.71	28.76	33.04	27.16	34.52	35.30	27.98	27.60
CaO	tr.	0.04	0.30	0.28	1.72	tr.	0.40	2.60	3.49
Na_2O	—	0.22	0.79	0.24	—	—	2.80	—	—
K_2O	—	0.32	tr.	—	—	0.17	—	—	—
H_2O ign.	3.35	4.11	4.36	5.01	5.15	0.60	—	5.70	3.92

I. Foliated talc, Burton, Rabun Co., Ga.; II. Pencil grade talc, Chatsworth, Murray Co., Ga.; III. Kinsey Mine, North Carolina; IV. Fibrous talc, New York; V. Vermont; VI. Luzenach, France; VII. Valley of Pignerolles, Italy. Nos. I to VII quoted in Ref. 10. VIII. Sheep Creek, Calif.; IX. Seven miles southeast Riggs Station, Calif., Nos. VIII, IX, Ref. 4.

Georgia (7).—Talc formed from limestone is found in Fannin and Gilmer counties, but is not extensively worked. Deposits of greater importance, are those worked in Murray County. These occur in the Ocoee (Cambrian) series, the talc-bearing formations dipping 45° southeast. The talc occurs as lenses associated with a harder impure form known as blue john, between walls of quartz schist. It is supposed to be derived from igneous rocks.

California (3).—Talc deposits which occur in San Bernardino and Inyo counties, California, have recently undergone considerable development. The talc is usually quite white, and lies on the contact between diorite and banded limestone, but is very irregular in its thickness. Tremolite and serpentine are found in association with the talc. It has been used chiefly in the manufacture of tiles.

Canada (14, 19).—Talc is mined only in Madoc township, Hastings County, Ontario. The material, which is massive and white, occurs in a brown quartzose limestone of the Grenville series. It varies from 25 to 40 feet in width, and has been mined for a horizontal distance of about 500 feet. There seems to be no doubt that the talc has been formed by the alteration of magnesian limestone, although the exact process is not clear, except that the neighboring granite intrusion may have yielded silica-bearing solutions. British Columbia has also produced some talc. Soapstone deposits are worked intermittently in southern Quebec (19).

Other Foreign Deposits (2).—The largest European talc deposits are those on the north side of the Pyrenees in southern France. The material lies between mica schists and Ordovician slates, and contains beds of limestone, as well as scattered granite blocks. Another important occurrence is that found in Styria, where, in a saddle-shaped fold, the talc lies between an underlying graphite slate and an overlying limestone of Silurian age. The talc is supposed to have been derived by the alteration of the graphitic slate and grades into it. A similar and important occurrence of pure talc is worked near Pinerolo in northern Italy. Numerous other foreign deposits are known, but they are much less important than the above-mentioned ones.

Uses.—Talc is marketed as rough talc, sawed slabs, or ground talc. Its peculiar physical character, extreme fineness, softness, and freedom from grit adapt it to a number of uses, of which the following are most important: fireproof paints, foundry facings, boiler and steam-pipe coverings, soap adulterants, toilet powders, dynamite, in wall plasters, for dressing skins and leathers, as a base for lubricants, as a filler for paper, and for sizing cotton cloth. It has been used to a slight extent for adulterating food. Soapstone can, on account of its softness, be easily sawed or carved, and is extensively used for washtubs, sanitary appliances, laboratory tanks and tables, electrical switchboards, hearthstones, mantels, footwarmers, etc. Virginia is the chief source. New York fibrous talc is much used as a paper filler, being better suited for it than the North Carolina product. The compact varieties of pure talc are employed for pencils, and for coal- and acetylene-gas tips.

Talc has attracted attention recently as an ingredient of ceramic bodies, because it is a cheap source of magnesia which acts as a flux, imparts resistance to thermal shock and high electrical resistance at elevated temperatures. On the other hand it decreases the firing range. An addition of 5 per cent is said to strengthen concrete. Pyrophyllite has similar uses to talc.

Pyrophyllite differs from talc chemically, being a hydrous aluminum silicate, instead of a magnesium silicate, but when sufficiently free from grit, it is put to the same use as talc. It is sometimes incorrectly called agalmatolite, because of its resemblance to the true mineral of that name. Deposits, more extensive than those of talc, are found near Glendon, North Carolina (17). It varies from green and yellowish white to white, and replaces metamorphosed acid volcanic rocks along a shear zone. It is sold for the same uses as talc.

Production of Talc and Soapstone.—The sales of talc, pyrophyllite and ground soapstone in the United States in 1940 amounted to 281,375 short tons valued at $3,008,320. New York, California, and

North Carolina were the leading states in the order named, the first one supplying about 46 per cent of the value.

The imports in 1940 were 28,363 short tons, valued at $487,267. The tonnage came from Italy, Canada and France. Exports were valued at $1,113,522.

The Canadian production of soapstone in 1939 was valued at $41,471, while the talc output was 13,144 tons valued at $128,595. The imports of talc and soapstone were 3,193 tons, valued at $51,380, while the exports of talc amounted to 7,184 tons, with a value of $74,560.

The United States in 1938 was by far the largest producer of talc and soapstone, with Italy and Norway next. British India is fourth and Canada fifth.

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TRIPOLI

Properties and Occurrence.—The term *tripoli* is somewhat loosely used to include many siliceous substances used for abrasive purposes, but in this place it is restricted to certain siliceous rocks, found in Missouri (2, 4), Illinois (1, 3), and Tennessee.

The Missouri tripoli is a light, porous, siliceous rock which has been extensively quarried near Seneca, Mo., but it is known at other localities in the state, and even in Oklahoma.

The deposits occur in the Boone (Lower Carboniferous) formations (4), consisting of alternating limestones and cherts having an average thickness of 350 feet, and with only an oölitic limestone as an easily recognized bed. The tripoli beds, which occur mostly above the last, are 4 to 12 feet thick, and overlain by chert, gravel, and red clay. Chert may also occur in the tripoli itself, and even form a large proportion of it.

The tripoli is an even-textured, finely porous rock, whose grains are mostly under 0.01 mm. in diameter, and are probably chalcedony. The following analyses represent the composition of the stone from Seneca, Mo.:

Analyses of Tripoli from Seneca, Mo.

	1	2	3
SiO_2	98.28	98.10	98.10
Al_2O_3	.17	.24	.24
Fe_2O_3	.53	.27	.27
CaO	tr.	.184	.33
K_2O	.17	——	——
Na_2O	.27	.23	.23
Ign.	.50	1.16	1.17
Org.	——	.008	——
	99.92	100.192	100.34

1. R. N. Brackett, Ark. Geol. Surv., V: 267, 1892. 2. W. H. Seaman, Sci. Am. Supp., July 28, 1894: 15487. 3. Mo. Geol. Surv., VII: 731, 1894.

A commonly accepted theory is that the tripoli results from the decomposition of chert, but while chert is in the tripoli beds, it is not possible to find a transition from tripoli laterally to unaltered rock. It is also difficult to see how the common chert of this region could form the massive, non-fossiliferous tripoli.

Siebenthal (4) believes the tripoli to have been derived by the leaching of lime carbonate from beds like certain gray, dull, massive limestones now found in this region.

In southern Illinois, in Union and Alexander counties, there are beds of fine-grained silica, which may be similar to the Missouri tripoli. Its origin and extent are, however, imperfectly known. An analysis yielded SiO_2, 98.00; MgO, 0.20; Al_2O_3, 1.21; moist., 0.15; und., 0.44. The silica consists of minute particles from 0.50- to 0.2-mm. diameter, of crystalline structure, transparent character, and irregular shape, loosely cemented by a small amount of clay. It may be used for wood polishing and other purposes.

Another deposit of tripoli is that found near Butler, Tenn. (5). It represents leached beds of Cambrian limestone, and forms a soft chalk-like or pulverulent mass, whose grains range from 0.01 to 0.06 mm. in diameter.

The composition is: SiO_2, 67.85; Al_2O_3, 16.80; FeO, 5.06; CaO, 0.32; MgO, 0.60; K_2O, 5.40; Na_2O, 1.23; ignition, 3.47.

Uses.—The rough blocks are sawed up into filter stones, while the spalls and small pieces are ground up for tripoli flour. Tripoli stone is used to some extent for blotter blocks and scouring bricks. Tripoli flour is used as an abrasive for general polishing, burnishing, and buffing, and also as an ingredient of scouring soaps. The production of tripoli in 1935 was 27,375 short tons valued at $383,416.

REFERENCES ON TRIPOLI

1. Bain, Ill. Geol. Surv., 4: 185, 1907. (Illinois.) 2. Hovey, Sci. Amer. Suppl., July 28, 1894, p. 15487. (Missouri.) 3. Perry, Okla. Geol. Surv., Bull. 28, 1917. (Okla. and general.) 4. Siebenthal and Mesler, U. S. Geol. Surv., Bull. 340: 429, 1908. (Missouri.) 5. Glenn, Res. Tenn., IV: No. 1, 1914. (Tenn.) 6. Santmyers, U. S. Bur. Mines, Inf. Circ. 6474, 1931.

ZIRCON

There are two minerals which may serve as a source of zirconium oxide, zircon ($ZrSiO_4$) and baddeleyite (ZrO_2), but commercial deposits of either of these minerals are scarce. At one time it was obtained from sands at Pablo Beach south of Jacksonville, Fla., where it occurred with other heavy minerals (see Titanium) from which the zircon was separated (2), but these deposits were abandoned in 1929, after having produced a maximum of 3,646 short tons in 1927. A zirconiferous sandstone of Miocene age is known in Virginia but it has never been worked (8). Some has also been obtained from a weathered pegmatite in Henderson County, N. C. (3).

In recent years the demands of the United States, which are very irregular, have been supplied chiefly by Brazil (21, 5) and British India. The deposits of the former country carry baddeyelite, and the latter zircon.

The Travancore, India, deposits are worked chiefly for ilmenite, but the zircon is saved as a by-product and in 1933 amounted to 603 tons.

There are also plans to develop alleged extensive sand deposits at Byron Bay, New South Wales, which are said to carry 64 per cent zircon.

Uses of Zirconium.—There is an increasing demand for zirconium-bearing minerals. Although zircon is a widely distributed mineral, natural concentrations of it are rare. It is used in the manufacture of refractory brick, on account of its high fusion point and chemical inactivity. As an alloy with iron its use is small but increasing. In metallic form it is employed in flashlight mixtures and ammunition primers. There is also some demand for it as an opacifier in enamels and lacquers.

Production.—There is no production at present in the United States. The imports in 1940 of zirconium ore were 33,690,506 pounds valued at $252,749. Those of ferrozirconium, zirconium, and zirconium-silica amounted to 533,055 pounds valued at $37,126.

About half of the imports are mixed zircon rutile concentrates from Australia.

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1. Fox, Min. and Geol. Inst., Ind., Trans., XX: 176, 1925. (India.) 2. Hevesy, Ztschr. anorg. allgem. Chem., CCXVI: 305, 1934. (Occurrence.) 3. Martens, Fla. Geol. Surv., 19th Ann. Rept.: 124, 1928. (Fla.) 4. Pratt, N. C. Geol. and Econ. Surv., Bull. 25, 1916. (N. C.) 5. Ries, Mineral Foot-notes, III, No. 6: 3, 1919. (History, chemistry.) 6. Sterrett, U. S. Geol. Surv., Min. Res., 1906-1911. 7. Watson, Amer. Inst. Min. Engrs., Trans., LV: 936, 1917. (Va. pegmatite.) 8. Watson and Hess, Va. Univ. Phil. Soc., Bull., sci. ser. 1: 267, 1912. (Zirconiferous sandstone and general.) 9. Youngman, U. S. Bur. Mines, Inf. Circs. 6425, 6455 (General), and 6456, 1931 (deposits.) 10. Chem. Eng. and Min. Rev., XXVI: 388, 1934. (N. S. W.)

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PART II

ORE DEPOSITS

CHAPTER XIII

ORE DEPOSITS

Definition.—The term *ore deposits* is applied to concentrations of economically valuable metalliferous minerals found in the earth's crust, while under the term *ore* are included those portions of the ore deposit of which the metallic minerals form a sufficiently large proportion and are in the proper combination to make their extraction possible and profitable. The term *ore mineral* can be applied to those minerals carrying the desired metallic elements which occur within the deposit. In some cases they make up the entire mass of the ore. *Protore* is metalliferous rock too low grade to work.

A metalliferous mineral or rock might therefore not be an ore at the present day, but become so at a later date, because improved methods of treatment or other conditions rendered the extraction of its metallic contents profitable.

A few metallic minerals serving as ore minerals, such as gold, copper, platinum, and mercury, sometimes occur in a native condition; but in most cases the metal is combined with other elements, forming sulphides, oxides, carbonates, sulphates, silicates, chlorides, phosphates, or rarer compounds, the first five of these being the most numerous. A deposit may contain the ore minerals of one or several metals, and there may also be several compounds of the same metal present.

Gangue Minerals.—Associated with the economically valuable metallic minerals there are usually certain common ones, of metallic or non-metallic character, which carry no values worth extracting. These are termed the *gangue minerals.* They often form masses in the ore deposit which can be avoided or thrown out in mining, but at other times they are so intermixed with the valuable metalliferous minerals that the ore is crushed and the two separated by special methods.

Quartz is the most abundant gangue mineral, but calcite, barite, fluorite, and siderite are also common, while dolomite, hornblende, pyroxene, feldspar, rhodochrosite, etc., are found in some ore bodies.

Origin of Ore Bodies.—The fact that metallic minerals occur as ore deposits in rocks is explainable in two ways: either they have been formed at the same time as the inclosing rock (*contemporaneous* or *syngenetic*); or else they have been formed by a process of concentration at a later date (*subsequent* or *epigenetic*). The first theory is found to be applicable to some ores in igneous rocks, and to some sedimentary ones; the second applies to most ore deposits, regardless of the character of the inclosing rock.

It must not be inferred from this, however, that the origin of all known ore bodies has been definitely settled, for a strong difference of opinion sometimes exists among geologists regarding the same deposit, and some have been placed first in one class and then in another; but with all this shifting the number of occurrences falling in the syngenetic class has not increased considerably although it includes some large and important ore deposits.

Syngenetic Deposits.—These may be divided into two groups, viz., those of magmatic origin, and those of sedimentary origin.

Magmatic Segregations (45, 47, 54).—Under this heading is included a relatively small class of ore deposits, whose occurrence in igneous rocks and intimate association with them seems to indicate beyond a doubt that the ore minerals were constituents of the original magma and separated from it during the process of cooling and crystallization.

In some cases the metallic minerals may be found more or less uniformly mixed with the silicates of the igneous rock, but in others they have been segregated or concentrated during cooling so as to form workable masses of ore. These deposits have been variously referred to as magmatic segregations, magmatic ores, and liquid-magmatic ores (Lindgren).

The deposits contain the simpler and less volatile oxides and sulphides, such as iron, nickel, chromium, titanium, platinum, and copper.

Separations of the heavy metals appear to be characteristic of igneous magmas deficient in acid-forming constituents. In some cases, however, metallic concentrations occur in acid rocks.

In these segregations it is seen that the metallic minerals which have gathered together to form the ore deposits are simply common accessory, and not important, constituents of the igneous rocks. That is, the ore body and the country rock contain the same minerals, but the relative abundance of the silicates and metallic minerals is reversed. As an example: the average percentage of chromium in the rocks of the earth's crust is about 0.01 per cent. In a peridotite magma it forms about 0.2 per cent, but in segregations within the magma we find 40 to 60 per cent Cr_2O_3.

Ores formed by magmatic segregation show a crystalline texture

(Fig. 138), usually of coarse, but sometimes fine, grain. Graphic intergrowths may occur, and while some believe it to indicate that the magma contained a eutectic mixture of two minerals which crystallized at the same time, this view is not held by all geologists.

Paragenesis.—The oxides and sulphides were formerly considered to be among the earliest products of crystallization. As they crystallize, however, they may become more soluble in the residual magma, so that both oxides and sulphides, including some that remained in solution, may be among the late products of crystallization.

FIG. 109.—Chromite in olivine (in part altered to serpentine), from Kraubath, Austria. ×15.

Tolman and Rogers were among the first to emphasize this fact,[1] and after a study of many supposed magmatic sulphides, they suggested that the succession of events was: (1) formation of olivine, pyroxene, and feldspar; (2) magmatic alteration of silicates as pyroxene to hornblende; (3) metallic minerals separating out and replacing silicates.

The ore minerals, according to them, were formed in the sequence magnetite, ilmenite, pyrrhotite, pentlandite, and chalcopyrite. They considered also that in titaniferous magnetites the silicates crystallized out first, and Singewald corroborates this view.

Chromite in different deposits has in some cases been classed as early magmatic and in others as late magmatic.[2]

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[1] Magmatic Sulphides, Stanford University Publications, 1916.

[2] Fisher, Econ. Geol., XXIV: 691, 1929.

Chalcopyrite in igneous rocks always separates out as one of the latest minerals.[1]

Graton and McLaughlin suggest the term *orthotectic* for clearly magmatic ores, and *pneumotectic* for slightly later processes, in which mineralizers played a rôle in the formation of the metallic minerals.[2]

Methods of Segregation.—The following processes have been suggested to explain the segregation of the ore minerals in igneous rocks.

Gravitative Differentiation. This theory supposes that a magma may separate into two portions, a lighter upper part, and a denser lower one. In addition as the less soluble minerals begin to crystallize out of the fluid magma, they will settle towards the bottom of the magmatic reservoir. The lower denser stratum, called the proto-enriched magma (54), represents a basic differentiate from the original magma. The nickel-bearing sill at Sudbury, Ontario, with sulphide ore bodies in its basal portion, is supposed to be an example.

As a result of crystallization and removal of the the more basic minerals, there is left a concentration in the still fluid magma, of the more acid constituents, gases, and mineralizers, as well as precious and base metals, whose crystallization develops a series of acid extracts, that may form pegmatites, and contribute to ore veins. This is what Vogt calls the rest magma (54).

Segregation by Diffusion (45).—This process is based on Soret's principle, which states that if two parts of a solution are at different temperatures there is a tendency towards selective concentration of certain constituents in the cooler portion. To interpret and apply this to ore deposits means that, since the peripheral portion of the magma cools first, the ingredients crystallizing out first will tend to concentrate there.

Liquid Immiscibility—This theory assumes that in a solution like a magma certain elements may be fully miscible with the silicates at higher temperatures, but with a lowering of the latter this condition does not persist, and these minerals separate out. It seems to be specially adapted to the concentration of sulphides, and in this connection it is interesting to point out that in the blast furnace the sulphides are soluble in the slag at higher temperatures, but separate out as cooling begins.

Segregation by Gas Transfer.—This is based on the assumption that: (1) there are gases rising through the magma in considerable amounts; (2) these may react with constituents of the magma, prob-

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[1] Newhouse, Geol. Soc. Amer., Bull. XLVII: 1, 1936.

[2] Econ. Geol., XIII: 85, 1918.

ably causing volatile compounds, and (3) the gas bubbles may attach themselves to crystals or drops of sulphides and float them off (51). The distribution and movement of the gases will be influenced by their vapor pressure, which in turn will be affected by the quantity of gas present and the temperature.

Where the metallic minerals crystallize out and segregate, the ore body forms a portion of the igneous mass, and usually grades off into it, but in some cases the ore minerals have not only become differentiated from the parent magma, but this separated portion has been forced up from below, independent of the rest of the igneous mass, thus forming a true dike. (Kiruna, Chap. XIV.)

Form of Magmatic Ore Bodies.—Ore deposits formed by magmatic segregation vary in richness, size and form. Some like those of Kiruna, Sweden, are of large size (Fig. 136); indeed, much larger than any of this type known in North America, the nearest approach to them being the nickel deposits of Sudbury, Ontario, not accepted as syngenetic by all geologists.

Magmatically segregated ore bodies may occur: (1) as irregularly distributed deposits, which show a transition into the surrounding igneous rock; (2) as deposits on the border of the igneous rock, but lying mainly within the former and sending tongues out into either; or (3) as dikes in the igneous rock. In the latter case they might be regarded as very basic differentiates, which have been forced up from below, subsequent to the intrusion of the basic rock itself (p. 435).

The following types can probably be referred to this class: 1. Titaniferous iron ores in basic igneous rocks (p. 432), and perhaps some iron ores in acid eruptives (p. 426). 2. Chromite in peridotites and the secondary serpentines. 3. Some sulphide ores (Sudbury). 4. Nickel-iron ores in eruptive rocks (no value). 5. Platinum in basic eruptives (q. v.). 6. Tin ores in some pegmatites (South Carolina). 7. Some gold ores in quartz veins (Silver Peak, Nev.).

Syngenetic Deposits of Sedimentary Origin.—If ores in sedimentary rocks are of contemporaneous origin they must have been formed at the same time as the rock in which they occur, the process being either a chemical or mechanical one, similar to that by which the different kinds of stratified rocks have been formed. Two classes might be recognized, viz.: (1) interstratified deposits, and (2) surficial deposits or placers.

Interstratified Sedimentary Deposits.—These may have originated by processes analogous to those which have formed the inclosing rocks. Some may have accumulated by precipitation from sea water or fresh water, a process which is going on even at the present day, as shown by the deposition of limonite in ponds, or the formation of nodules of limonite, pyrite, or manganese on the ocean bottom.

Others may be of mechanical origin, the grains of metallic minerals having been set free by disintegration of rocks on the land, and the particles later becoming segregated, as in the case of magnetite or ilmenite sands, formed along the beaches by wave action. Both types may be subsequently covered up by other sediments, or in rarer cases by igneous flows.

Sedimentary deposits of the two types just mentioned are of tabular form, and thin out horizontally in all directions, but many of them are of great extent and even of curiously uniform character, as for example the Clinton ores of the eastern United States (q. v.), the bedded limonites of France and Germany (q. v.), the limonites and siderite of England, or the hematite of Newfoundland (q. v.). They are sometimes sharply separated from the inclosing rocks, or at others grade into them. Further characteristics to be noted are the absence of fragments of the overlying country rock in the ore and of veinlets branching off from the bed. If folding of the rocks has occurred, the beds follow the folds. Sedimentary deposits are occasionally enriched by water circulating through the beds and causing a concentration of the contents by removal of soluble elements. Syngenetic bedded deposits often show a fine-grained texture. In cases they are oölitic or even fossiliferous, the metallic minerals in part replacing the fossils. Some may show finely crystalline quartz and also finely crystalline secondary minerals.

Placer Deposits.—This term is applied to deposits of gravel, sand, or even clay, containing heavy metallic minerals like gold, cassiterite, platinum, etc., concentrated usually by mechanical agents such as streams, waves or wind.

When the products of rock decay are washed down the slopes and into the streams, the lighter material is carried off to sea, while the heavier particles such as pebbles and metallic mineral grains remain behind in the stream channels. The metallic fragments by reason of their higher specific gravity settle to the bottom of the channel, and all become more or less rounded by the rubbing action they are subjected to while being moved along by the stream current.

Placer deposits may also be formed along beaches by wave action, while a rare type are those which originate in dry climates by the disintegration of rock, little of the material being removed, except sandy particles which are blown away by the wind. A somewhat special type, called *eluvial* placers, originates by the weathering of gold-bearing rocks, the residual products remaining at the point of origin, or migrating a short distance down grade. The gold in these is rough and angular. Eluvial places are known in the southern Appalachians.

It is not to be assumed that placer deposits did not form in the past, for they did, and are known to exist in sedimentary formations as far back as the Cambrian. (See Gold, South Dakota.) Owing to their surface origin the ancient ones may have been destroyed by erosion.

Epigenetic Ore Deposits.—These, as previously stated, are of later age than the inclosing rock. In other words, they have been concentrated in the rocks by circulating waters of magmatic or meteoric origin.

In order to demonstrate this it is necessary to show: (1) the source of the metals found in the rocks; (2) the existence of a carrier which could transport the metals, in solution probably; and (3) the existence of conditions favorable to the precipitation of the ore.

Occurrence of Metals in the Rocks.—It is well known that metallic minerals in small quantities are widely distributed, in both igneous and sedimentary rocks. Sandberger,[1] for example, has shown by analyses the presence of nickel, copper, lead, tin, and cobalt in such minerals as hornblende, olivine, and mica; and Curtis has found traces of silver, gold, and lead in the quartz-porphyries at Eureka, Nev.,[2] and silver, arsenic, lead, copper, and gold in the granite at Steamboat Springs, Nev.[3] Grout[4] found 0.029 per cent copper in Keweenawan traps of Minnesota, while Lewis[5] recorded 0.025 per cent CuO in the New Jersey diabase. Winslow has pointed out the presence of small quantities of lead and zinc in the limestones of Missouri and Wisconsin (see lead and and zinc references), and Wagoner has made similar tests on California sediments (173). Since, however, the sediments were originally derived from the igneous rocks, it follows that the latter must be the original source of the minerals.[6] It is interesting to note that even in the igneous rocks the metals are not impartially distributed, but that certain metals seem to favor certain rocks.[7] Thus

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[1] Untersuchungen über Erzgänge, 1882.

[2] U. S. Geol. Surv., Mon. VII: 80.

[3] *Ibid.*, Mon. XIII: 350.

[4] Econ. Geol., V: 471, 1910.

[5] *Ibid.*, II: 242, 1907.

[6] For a most interesting discussion of this see Siebenthal, U. S. Geol. Surv., Bull. 606; 67, 1915.

[7] De Launay, Ann. d. Min., Aug., 1897.

iron, manganese, nickel, cobalt, chromium, and platinum seem to favor basic rocks; while tin, tungsten, and some rarer metals favor the acid ones. Titanium has been found in both acid and basic.

While the occurrence of metallic minerals in the rocks of the earth's crust is widely recognized, few, perhaps, realize the small percentage existing outside of those concentrated portions, the ore deposits; and the following table, showing the average composition of rocks of the earth's crust,[1] will serve to emphasize this point:

Oxygen	46.46	Carbon	0.09
Silicon	27.61	Phosphorus	0.12
Aluminum	8.07	Manganese	0.09
Iron	5.06	Sulphur	0.06
Calcium	3.64	Barium	0.04
Magnesium	2.07	Chlorine	0.05
Potassium	2.58	Fluorine	0.03
Sodium	2.75	Strontium	0.02
Titanium	0.62	All other elements	0.50
Hydrogen	0.14		

An examination of the above figures shows that, of some twenty metals that are of importance to us for daily use, only three, viz., aluminum, iron, and manganese, are included in the above list, and that the others must be present in amounts of less than 0.01 per cent.

Professor Vogt[2] has endeavored to estimate the approximate average amount present of other important (economically) metals, not included in the preceding table. According to him, the percentage amount of tin, zinc, and lead is expressed by a digit in the third or fourth decimal place, copper in fourth or fifth, silver in sixth or seventh, gold and platinum in seventh or eighth. Mercury would show a slightly larger percentage than silver, and arsenic, antimony, molybdenum, and tungsten, between copper and silver. Bismuth, selenium, and tellurium would be placed between silver and gold in the list.

Lindgren (10) differs somewhat from Vogt, and would place the percentage of copper at 0.01 to 0.005, zinc at 0.004 per cent, and lead at 0.002 per cent. He suggests that silver may constitute 0.00001 per cent of the earth's crust, and gold 0.0000005 per cent.

As actual examples of the amounts present, we may quote the following determinations made on eruptive rocks from several localities:

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[1] Clarke, U. S. Geol. Surv., Bull. 770: 36, 1924.

[2] Zeitschr. prak. Geol., July and Sept., 1898.

Metal	Per cent	Locality
Copper	0.0009	Missouri
Copper	0.029	Minnesota
Lead	0.0011	Colorado
Lead	0.004	Missouri
Zinc	0.009	Missouri
Silver	0.00007	Leadville, Colo.
Silver	0.00016	Eureka, Nev.
Gold	0.00002	Eureka, Nev.
Gold	0.00004	Owyhee Co., Idaho.

It is quite evident that the percentage of metal normally distributed in the rocks of the earth's crust, as indicated above, is far too low to be regarded as workable ore, for, in order to be classed as such, the rock must contain at least a certain percentage of the metal, which varies not only with the kind of metal, but even with the same one under different conditions, such as location and nature of ore.

Iron ores, for example, especially low-grade ones, cannot be successfully worked, unless favorably located; whereas gold ores, being of higher unit value, are much less affected by this factor. Again, the nature of the ore has to be considered, some being quite easily treated, but others less so, and here the manner of association comes into consideration. The introduction of the flotation process has made possible the concentration of some metal-bearing rock not previously worked. Lastly, with changed conditions, a rock which was formerly of no economic value may become a profitable ore to work, partly because improved methods of treatment have lowered the cost of production. The quantity of metal necessary in an ore for profitable working is referred to under "Value of Ores" in this chapter.

Source of Water in the Earth's Crust (166, 165, 167, 168, 173).—Water is known to be widely but not uniformly distributed in the rocks of the earth's crust, and much of it is in slow but constant circulation. Geologists admit that this *ground* water has been an important ore carrier, but there has existed a strong difference of opinion, regarding its source, or at least the source of that portion which has been active as an ore carrier.

Three types of ground water are recognized, viz. (1) *meteoric,* (2) *connate,* and (3) *juvenile* or *magmatic.*[1]

Meteoric Water.—A variable portion of the rain falling on the

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[1] See Daly, Econ. Geol., XII: 487, 1912.

earth's surface penetrates the pores and other cavities of the regolith and bed rock, forming a more or less saturated zone, whose upper limit is known as the *water table.* While the latter follows in a general way the surface contours, it may approach close to the surface under the valleys, and lie at a greater depth below the hills. In moist regions the average depth of the water table is shallow, but in arid regions it may lie deep, sometimes 2000 feet or more.

Between the surface and the water table is a zone of descending oxidizing waters, as well as one containing altered rocks and minerals. This zone has been variously called the *vadose region* (Posepny), *belt of weathering* (Van Hise) and *gathering zone* (Finch).

Below the water table, the meteoric water penetrates to variable but probably not great depths, although this is influenced by the character of the rock and its structure. Some, like Van Hise, believed that it might go as deep as cavities existed, in other words to the bottom of the zone of fracture or cavities. There seems strong doubt, however, as to whether surface waters penetrate to any such depth, for not only do observations in mines indicate frequently a decrease in water with depth, but the bottoms of some deep ones are dry and dusty. We find water in oil sands 8000 to 10,000 feet deep, which is probably not all connate water (203).

Finch suggests dividing the water below the water table into two zones. The upper one he calls the discharge zone, and in this the water is in lateral motion toward some lower discharge level. The lower is called the *static* zone, and in this the water is stationary or nearly so.

That meteoric waters were the most important, if not the only collecting agents of ores, was advocated by many of the earlier geologists, including J. Le Conte,[1] F. Posepny,[2] and L. De Launay,[3] and in later years this theory of ore formations was strongly urged by Van Hise (18).

There is no doubt that the circulation of meteoric waters is quite extensive, and it plays an important rôle in the secondary concentration of ores, by downward-moving solutions, but its effects as a factor in the primary concentration of ore deposits are probably unimportant except in a few regions.

Connate Water (168).—This is water which is indigenous to the rocks containing it, such as original sea water in a sedimentary rock.

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[1] Amer. Jour. Sci., July, 1883, p. 1.

[2] Trans. Amer. Inst. Min. Engrs., XXIII, p. 213.

[3] La recherche, captage, et aménagement des sources thermo-minérales.

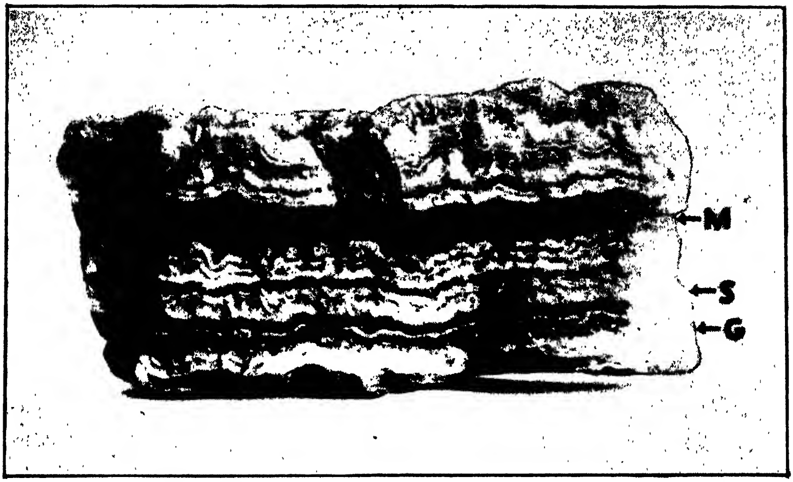

FIG. 1.—Specimen from Moresnet, Belgium, showing crustified structure. Light bands, sphalerite (S); dark bands, pyrite (M); light grains, galena (G). (*From specimen in Cornell collection.*)

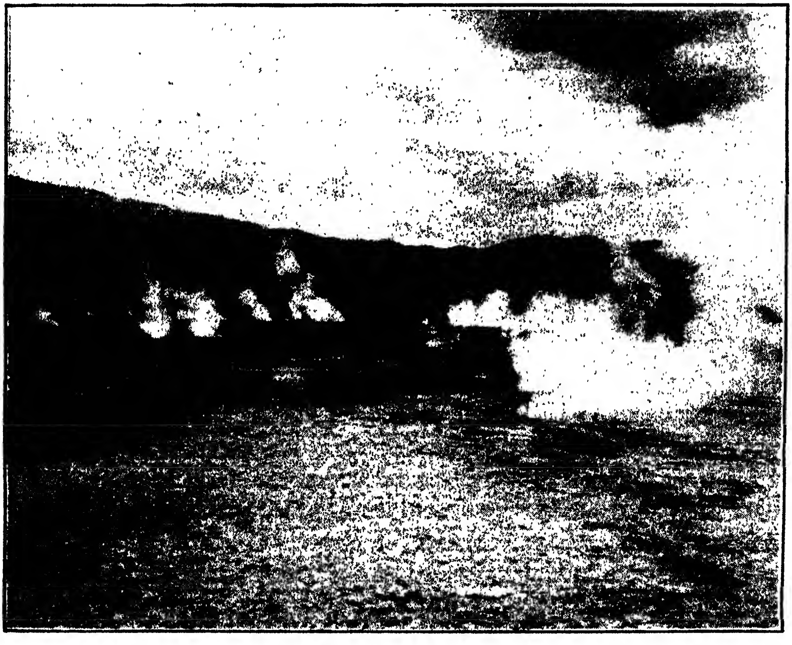

FIG. 2.—Steamboat Springs, Nev. The white deposit is siliceous sinter carrying mercury and antimony. Steam rises from numerous fissures whose sides are coated with sulphur crystals. (*H. Ries, photo.*)

It is found chiefly in sandstones and sands, the brines of the Lower Carboniferous and some other formations being examples of it.

Igneous rocks may retain some of their magmatic waters on consolidation, and it is possible that some of the changes which go on in them after solidification depend on this residual liquid (10).

Submarine lava flows may absorb ocean water, and that found in some deeply buried lava flows may be of this nature. Lane (169), in his work on the copper deposits of the lava flows on the Keweenaw peninsula, Michigan, has called attention to the relatively large calcium chloride content of the mine waters at depths of 600 to 1600 feet, and believes that it must be of marine origin. In fact, both sodium and calcium chlorides are in evidence with depth, the former preponderating at first, but deeper down yielding to the latter.

Magmatic Water (44, 76, 84, 87, 167, 168, 173).—The majority of geologists now believe that the primary concentration of ores has in most cases been performed by magmatic waters.

This theory, although it has grown greatly in recent years, is not a new one, for it was suggested by Elie de Beaumont as early as 1850;[1] but its full significance was not grasped until some years later, when the writings of Vogt[2] (in 1894), Spurr,[3] Lindgren, and especially Kemp (84) did much to emphasize its importance.

The general theory is that deep-seated masses of igneous rock have dissociated water as well as other gaseous elements, the water- and gas-filled cavities in quartz indicating this. In addition, there may be chemically combined water. As the magma solidified, the water (possibly in gaseous form) was expelled, carrying along dissolved substances.

Some have claimed, of course, that the water contained within the magma may have come from external sources in at least two ways as follows: 1. By infiltration of sea water to the igneous mass—a somewhat unlikely process, as the heat would drive it out. 2. By the absorption of hydrated rocks, which became engulfed in the rising magma as it forced its way upward, a phenomenon regarding which field evidence is lacking. Daly calls this *resurgent water* (162).

One thing seems certain, and that is that the igneous rocks give off water in vaporous form during cooling. Evidence of its presence is found in volcanic emanations, as most convincingly shown by Day and Shepherd (43), by the analyses published by F. C. Lincoln (44),

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[1] Geol. Soc. France, Bull. IV: 1249.

[2] Zeitschr. für prak. Geol. II.

[3] U. S. Geol. Surv., 16th Ann. Rept., II.

and the work of R. T. Chamberlin.[1] As against this evidence there is the statement of P. Brun (41), based on possibly insufficient field data, that water is not given off by magmas.

Many of the points brought out by the advocates of magmatic waters as ore-concentrating agents have been used as arguments against the possible efficiency of meteoric ones. These include the following: Meteoric waters do not reach great depths, in fact probably not more than 2000 feet or sometimes less from the surface, and when they do penetrate to a greater distance, it is because they have followed some fissure. The lower levels of many deep mines are so dry as to be dusty. Ores have been concentrated at a much greater depth than that reached by surface waters. It is perfectly reasonable to regard igneous rocks as an important source of water, and the experiments of Daubree have shown that a molten granite contains a large amount of vapor which it retains while at great depths, but gives off on approaching the surface and cooling.

It is an undeniable fact that most metalliferous veins are found in areas of igneous rocks, and Lindgren (see Metallogenetic Epochs on a later page) has shown that in the case of the gold deposits of North America the periods of vein formation agreed closely with those of igneous activity. It is also a noteworthy fact that, with the exception of some deposits of commoner metals, such as some iron, copper, lead, and zinc, ores are found in close association with igneous intrusions, which seems to postulate a close connection between igneous rocks and ore deposits, as advocated by such authorities as Weed, Kemp, Lindgren, and Emmons. While the importance of magmatic waters as agents of primary deposition is quite generally admitted, it is true that the metalliferous minerals as originally deposited have not always been sufficiently concentrated to serve as ores, but they have become concentrated at a later date by meteoric waters, as shown by many copper deposits. Posepny (89), in his work on the Genesis of Ore Deposits, distinguishes between descending surface waters, or *vadose* circulations, and ascending waters from great depths. It is the former that have been active in the secondary concentration of ores.

Composition of Ground Waters (5, 10, 163, 166, 168).—The waters show a variable temperature and always a variable quantity of dissolved matter.

The waters of sedimentary rocks, beyond the influence of igneous intrusions, are mainly of carbonate character. In chloride waters,

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[1] Carnegie Institution, 1908.

sodium and calcium are prevalent, and even calcium and sulphate ones are not uncommon, but sodium carbonate waters are rare in mining regions. The waters are chiefly cold, although many tepid ones and even some hot ones occur. Both hydrogen sulphide and carbon dioxide may be present in either hot or cold waters.

In the older igneous rocks, where the effects of vulcanism have subsided, there is less variation. The surface waters in these, where free from disturbing influences, are of the calcium carbonate type, but may often show sodium chloride, ferrous and magnesium carbonates, and even much silica. If the rocks contain pyrite, sulphuric acid may be present locally, together with sulphate of lime, alumina, and iron.

Where acid waters reach the surface, their acidity may be due to: (1) oxidation of sulphides or sulphur, (2) oxidation of H_2S in ascending hot waters, or (3) acid emanations from shallow volcanic sources mingling with surface waters.

Ascending waters in igneous rocks of recent or Tertiary volcanic activity are often tepid or hot. They may carry sodium chloride, or sodium carbonate with carbon dioxide.

Mine Waters (124, 163, 169).—These are usually surface waters, whose composition is modified by the presence of soluble salts derived from the decomposing minerals of the ore body, or igneous sources. They may therefore contain both metallic and non-metallic elements, and show the power of water to transport different elements in solution. The analyses on p. 361 will serve for purposes of illustration.

Metalliferous Deposits from Springs (164, 170, 171, 174).—The composition of many spring waters also affords further testimony of the ability of underground waters to serve as ore carriers. Moreover, occasional examples of metalliferous deposits now being formed by springs are sometimes found as shown below.

Weed has described a hot spring near Boulder, Mont. (174), which is depositing auriferous quartz, and the deposit is pointed out by him to be identified with silver- and gold-bearing quartz veins of the region between Butte and Helena, Mont. Of still more interest is the collection, by evaporation, of copper from certain Javan hot springs, in which the metal occurs as iodide of copper.[1]

Lindgren has also called attention to the occurrence of certain mineral springs near Ojo Caliente, New Mexico (171), whose strongly alkaline water contains much sodium carbonate as well as fluorine, boron, and barium, the last being present in considerable amount.

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[1] Stevens, Copper Handbook, IV: 156, 1904.

ANALYSES OF MINE WATERS
(Parts per million)

	I	II	III	IV
SO_3	406.5	2672	43.2	2039.51
Cl	6.8	23	7.9	8.16
CO_3	13.2	——	110.5	——
NO_3	——	——	——	——
PO_4	tr.	tr	tr.	——
B_4O_7	——	tr.	——	——
Br	——	tr.	——	——
F	——	tr.	——	——
SiO_2	23.2	47.7	25.9.	13.80
K	7.1	13.1	10.6	70.0
Na	16.2	39.6	36.4	106.27
Li	tr.	——	tr.	——
Ca	151.2	132.5	37.4	187.15
Mg	28.2	61.6	12.25	93.50
Al.	——	83.5	0.4	3.12
Mn	0.5	12.0	0.8	155.58
Ni	——	0.5	——	——
Co				
Cu	tr.	59.1	tr.	77.05
Zn	0.3	852	0.2	49.66
Fe'''	1.8	159.8	0.7	164.82
Fe''				
Cd	——	41.1	——	——
Pb	——	——	tr.	3.44
CO_2	——	——	37.2	——

I. Green Mountain Mine, Butte, Mont., 220-foot level fissure in granite, remote from known veins; II. St. Lawrence Mine, Butte, Mont.; III. Geyser Mine, Custer Co., Col.; IV. Stanley Mine, Idaho Springs, Col. All quoted by Emmons, U. S. Geol. Surv., Bull. 529, pp. 60, 62 and 63, 1913.

The pre-Cambrian gneiss near by contains veinlets of colorless fluorite, probably deposited when the spring waters issued at a higher level. Higher up the slope is a narrow vein, carrying small amounts of gold and silver in a gangue of colorless fluorite and some barite, and capped by a calcareous tufa. The latter is supposed to have been deposited at the surface while the fluorite was precipitated farther down in the vein fissure.

At Steamboat Springs, Nev., the hot chloride waters are depositing siliceous sinter (Pl. XXXIV, Fig. 2), which contains mercury and antimony in small amounts, while stibnite crystals have been found in some of the spring basins.

Mode of Concentration.—From what has been said above we see that water not only is widely distributed in the rocks, but also serves as a carrier of mineral matter. It is, therefore, an important concentrating agent, whatever its source. While cold water, free from impurities, has comparatively little solvent power, the presence of acids or alkalies materially increases its solvent capacity, while heat and pressure have also a great influence.

Before considering the causes governing the precipitation of ore minerals in cavities or solid rocks, we may turn to a discussion of the deposits formed by waters of magmatic origin.

Deposits from Magmatic Emanations.—Under magmatic emanations are included gases, vapors, or liquids, given off by molten magmas during cooling.

These emanations (41–44), may be determined from those actually in process of emission from cooling igneous magmas, or from those which remain imprisoned in the rocks.

As evidence of the variety of the former we may list the following emanations identified at two well-known volcanoes:

Vulcano, S, Te, As_2S_2, B_2O_3, NaCl. NH_4Cl, $FeCl_3$, Na_2SO_4, $CaSO_4$, $Li_2(SO_4)_2$, $Al_2(SO_4)_3$, Tl, Rb. Ce, Co. Zn, Sn, Bi, Pb, Cu, I, P.

Vesuvius, 1895. HCl, SO_2, H_2S, CO_2, S, $CaSO_4$, iron and copper chlorides. NaCl, KCl, Na_2SO_4. K_2SO_4, NH_4Cl, CuO, Fe_2O_3, Se, HF, HBr, $NaHCO_3$.

The springs of Carlsbad, Bohemia, which are supposed to be of magmatic derivation show CO_2 and salts of the elements Cl, F, B, P, S, Se. Tl, Rb, Cs, As, Sb, Zn, Na, K, Li, Ca, Mg, Sr, Ba, Fe, Mn, Al, and Si.

In order to point out more clearly the several processes by which ores may be deposited from magmatic emanations it may be well to turn for a moment to the molten magma and consider certain changes which take place during the period referred to.

A study of large intrusive masses has shown us that the molten mass after coming to rest sometimes tends to separate into two portions, viz., a basic part, usually the lower, and an acid portion, usually the upper.

Into the upper portion, then, there will rise not only the lighter constituents like silica and feldspars, but also gaseous ones. All metals which have an affinity for acidic constituents, as well as those which form liquid or gaseous compounds with the halogens, will be carried towards the surface.

Lindgren divides the lighter and volatile accumulations of the magma into: (1) salic extracts represented by the pegmatites, and (2) gas-fluxing components which appear as gases and sublimates near the surface, or as veins and replacements at depth. The solutions then which escape from the magma are of an acid nature, and it is these which traverse the rocks and attack many minerals, and, according to Bowen (1), are the chief agents of ore formation.

Bowen believes that oxides and sulphides are easily transported in acid solutions. The silica is thought by some to be transported as some volatile form of silicic acid, while Lindgren suggests its transfer in colloidal solution (87).

As these solutions ascend towards the surface and attack minerals and rocks they become neutral or alkaline, and may remain so to the surface.

With regard to what happens to the sulphides when the waters become alkaline, Lindgren believes that the oxy-salts of the heavy metals are transformed into colloidal sulphide solutions, with silica sol acting as a protecting agent. The sulphide sols coagulate, singly, in combination, or as solid solutions.

This usually takes place in a definite order as shown by the paragenesis, which is much the same for hypothermal, mesothermal, or epithermal conditions.

The precipitated gels form fine-grained metacolloids, or sometimes well-developed crystals may form directly from sols, but this is thought to occur mainly at high temperatures.

With sufficiently high temperature, silicates such as chlorite, sericite, and tourmaline are formed first, later cassiterite and wolframite, then sulphides, and finally tellurides and gold.

Relation of Ore Bodies to Intrusives (16, 183).—It would seem as if the volatile constituents of a magma which carry the metals tend to escape chiefly from the upper part of the intrusive mass. Thus Butler (75), in his study of the ore deposits of Utah, pointed out that, in the case of stocks which had been but little cut off by erosion, the associated ore deposits were of greater importance, but that where the stocks had been deeply truncated relatively few ore deposits were associated with them. A similar view has been expressed by Billingsley and Grimes for the Boulder batholith in Montana.[1] Emmons (183) states that of the veins and related deposits precipitated from solutions, originating in cooling intrusives, more than 95 per cent of all

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[1] **Amer. Inst. Min. Engrs., Trans., LVIII: 284, 1918.**

the lode ores are related to intrusives more acid than diorite, and that nearly all of them are either known to be, or presumably are, associated with granite batholiths. The vast majority of these lodes he claims are features of their roofs.

Types of Ore Deposits of Magmatic Origin (80, 87).—Bearing in mind the fact that as the magmatic solutions leave the magma and rise towards the surface they pass through different conditions of environment, especially as regards temperature and pressure, both of which decrease, and which exert an important influence on the kind of minerals formed, several types of deposits originate.

Those suggested by Lindgren starting from the intrusive and going upward are: (1) pegmatites, (2) contact metamorphic (pyrometasomatic), (3) hypothermal or high-temperature veins, (4) mesothermal or intermediate veins, and (5) epithermal or shallow veins. More recently it has been suggested by Graton (1, 80) that two additional zones be added, viz., *leptothermal* between 4 and 5, and *telethermal* (above 5).

The different vein zones are characterized by their mineral compounds, as well as conditions of texture, structural features, and wall rock alteration.

The total thickness of these hydrothermal zones must be very great, and at no point is there found a continuous vein which shows the characteristics of several vein zones from top to bottom. In some cases a difference in character of mineralization may be noted which indicates that the upper or lower end of the deposit may be near a transitional stage into the next zone above or below.

The vertical range of any one zone depends probably on the depth of the magma below the surface existing at the time of its intrusion.

The evidence of these conditions is shown by the presence of essentially high-temperature minerals, some of which crystallize only in the presence of mineralizers. These include pyroxenes, amphiboles, garnets, apatite, ilmenite, tourmaline, topaz, brown and green micas, spinel, soda-lime feldspars, cassiterite, arsenopyrite, pyrrhotite, and some others.

A characteristic feature of these veins is the frequently intense metasomatic alteration of the wall rock, which may result in the conversion of the latter into a coarse-grained mineral aggregate. Extensive replacement deposits are not abundant.

Pegmatites.—These represent the last unconsolidated portions of an intrusive magma—the rest magma—and may be forced out from the parent mass to form dikes which may be either of basic or acid character depending on the composition of the parent magma. They are characterized by an abundance of water. Basic rocks like gabbros may be accompanied by pegmatites containing chiefly plagioclase feldspar and pyroxene, while granites are accompanied by those consisting chiefly of microcline and quartz.

In complex pegmatites there may be a number of other minerals such as albite, beryl, topaz, cassiterite, micas, tourmaline, rare earth minerals, etc.

It is generally assumed that the simple pegmatite resulted by crystallization from the magma, and that these earlier minerals were acted on later by hydrothermal solutions from which other minerals were deposited by replacement of the earlier ones.

Thus the earlier microcline has been replaced to a varying degree by albite, quartz, and muscovite, and by other less common ones such as tourmaline, lepidolite, beryl, columbite, and cassiterite.

Minerals of commercial value may therefore be added to pegmatites which have undergone hydrothermal alteration.

While pegmatites have been worked for tin, gold, bismuth, molybdenite, and rutile, they do not carry large amounts of sulphides.[1]

If this depth is relatively small, the several depth zones may be correspondingly thin, but if it is great, then each zone may be expected to have a greater vertical extent, and the change from one zone to the other may be gradual.

It is impossible, of course, to state definitely the depth of their range in feet. Graton (80) makes a speculative estimate that the hypothermal zone may have had a vertical depth of 50,000 feet (80). The other zones were probably less deep.

Hypothermal Veins.—The high-temperature veins represent magmatic products forced out from a cooling magma, consisting probably of a mixture of water and gases, with other substances in solution, the whole being under high pressure and temperature. The latter is probably not in excess of 573° C., the inversion point of α to β quartz,[2] nor is it supposed to have been below 300° C. Most vein quartz was deposited as α quartz.

Hypothermal veins are often of very irregular shape, and since they have been formed at depths where the rock pressure is too great to permit cavities to remain open, Graton has suggested that intrusive

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[1] Schaller, Ore Deposits Western United States, p. 144, 1933; Landes, Amer. Mineral., XVIII: 355; 33 and 95, 1933.

[2] F. E. Wright and E. S. Larsen, Quartz as a Geologic Thermometer, Amer. Jour. Sci., XVII: 147, 1909.

pressure transmitted to the walls by the mineral-bearing solutions was the cause of forcing them apart (80).

The veins have been formed at great depth, and while in some cases they are close to the intrusive, or even within it, at others they may be some distance from it, but still initially at such depth as to maintain the conditions of temperature and pressure.

Several classes of veins seem to belong to this group, as follows: [1]

1. Veins of cassiterite, wolframite, and molybdenum, the first named being specially important.
2. Gold-bearing veins in crystalline schists as those of the southern Appalachians, southern Brazil, southeastern Alaska, Ontario, Lead City, S. Dak., and Kalgoorlie, W. Australia.
3. Copper-gold-tourmaline deposits, represented by those of Cornwall, Eng.; [2] Cactus Mine, Utah; [3] Rossland, British Columbia; and Meadow Lake, Calif.[4]
4. Lead-silver tourmaline veins associated with the Helena batholith, Montana.[5]
5. Cobalt-tourmaline veins of San Juan, Chile.[6]

Pyrometasomatic Deposits (29–40).—These include masses of metallic minerals and silicates which are found in some sedimentary rocks, chiefly calcareous ones, near their contact with igneous intrusions, specially those of a more or less acidic character (Fig. 110).

It has long been known that an igneous mass may often exert considerable effect on the rocks which it has penetrated, sandstone, for example, being altered to quartzite, clay or shale to hornstone, and limestone to marble. Moreover, the contact-metamorphism is accompanied by the development of new minerals in the wall rock.

Thus in limestone there may be formed garnet, wollastonite, epidote, diopside, amphibole, wernerite, vesuvianite, etc.; while in aluminous rock such as shale and slate we find andalusite, sillimanite, biotite, etc.

It was formerly believed by many that these silicates, as in the limestones, must be segregated and recrystallized impurities, and hence could form only in impure rocks, the pure limestones yielding simply a marble.

Investigation of these contact zones has shown us, however, that they contained many elements which were not found in the limestone

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[1] Those not referred to in the following footnote are discussed in subsequent chapters on those metals.

[2] Beyschlag, Vogt and Krusch, Ore Deposits, Translation, I: 431.

[3] Butler, U. S. G. S., Prof. Pap. 80.

[4] Lindgren, Amer. Jour. Sci., XLVI, 201, 1893.

[5] Knopf, Econ. Geol. VIII: 105, 1913.

[6] Stutzer, Zeitschr. prak. Geol., XIV: 294, 1906.

outside of this belt of metamorphism, and we are therefore driven to the conclusion that they represent to a large extent substances which have been given off by the magma and lodged in the lime rock.

The theory usually advanced to explain the origin of these contact-metamorphic deposits is that the original magma contained various volatile substances in solution, such as water, carbon dioxide, sulphur, boron, chlorine, and fluorine, which on the cooling and solidification of the magma are forced out into the surrounding rocks. The watery vapor was evidently heated above its critical temperature (365° C.).

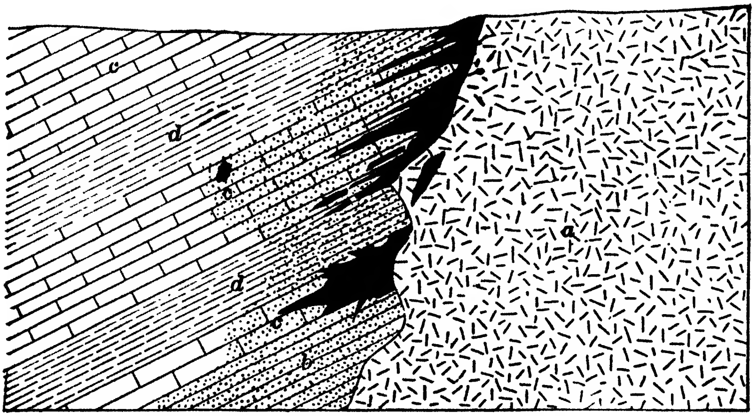

Fig. 110.—Section through a contact-metamorphic zone; showing (*a*) intrusive rock; (*b*) quartzite; (*c*) limestone; (*d*) shale. Contact-metamorphic zone shown in stippled area, including ore in black. (From *Ries and Watson, Engineering Geology*.)

The metals and many of the other elements found in contact-metamorphic deposits are supposed to have been carried out by these vapors, but their exact form of combination during emission is not known, although it has been suggested that some were combined with fluorine or boron.

These were forced out into the fissures or pores of the limestone, and replaced the latter wholly or in part, the silica, alumina and iron combining with some of the lime to form different silicates.

While contact-metamorphic effects may extend to a distance several thousand feet from the eruptive, ore deposits rarely extend more than a few hundred feet, and often terminate suddenly.

Normal granites or other highly acid intrusives may produce contact metamorphism, but do not as a rule form ore deposits. Intrusives like monzonite, quartz-monzonites or granodiorites are important associates of contact-metamorphic ores, as can be seen by the numerous occurrences in the Cordilleran region of the United States. The more basic rocks are of less importance, although they sometimes yield contact-metamorphic ores in limestones as in the case of gabbro at Hedley, British Columbia, and diabase at Cornwall, Pennsylvania.

Contact-metamorphic deposits were probably formed at depths of several thousand feet, and possibly in most cases within the zone of fracture. The temperature according to Lindgren was probably high, from 300° C. to 600° C.

Contact-metamorphic deposits are usually of irregular shape and somewhat bunchy in character, but very little can be said regarding the depth to which they may extend. Where the development has followed certain beds a tabular structure often results.

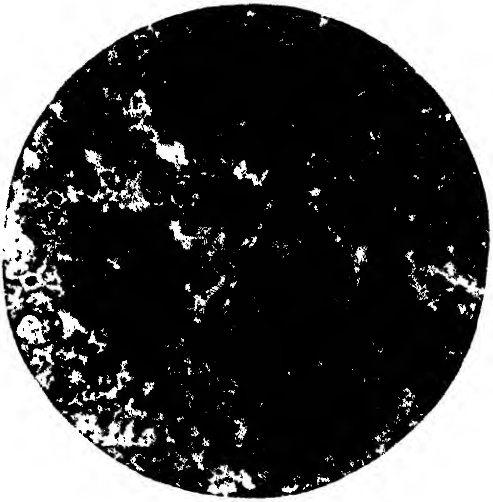

FIG. 111.—Section of garnetiferous limestone from Silver Bell, Ariz. Dark gray, garnet; black, sulphides.

The common ore minerals found are magnetite and specularite, together with such sulphides as bornite, chalcopyrite, pyrite, pyrrhotite, and more rarely galena and zinc blende. Some gold and silver may be present, but tellurides are probably very rare. Molybdenite and tetrahedrite are known.

The gangue minerals are in general lime-alumina silicates, and include garnet[1] (Fig. 111), wollastonite, epidote, tremolite, diopside, hedenbergite, zoisite, vesuvianite, ilvaite, quartz and calcite. The first

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[1] Mainly andradite, the iron-lime garnet, and less often grossularite, the lime-alumina garnet.

of these is especially abundant and may form nearly the entire mass of the rock. There may also be present minerals containing boron, fluorine, and chlorine, such as axinite, tourmaline, fluorite, scapolite, and danburite.

Some difference of opinion exists regarding the details of the contact-metamorphic process.

Thus, while most geologists are agreed that most of the constituents of the ore body are derived from the magma, others like Leith, though admitting some magmatic emanations, hold that the silicate gangue minerals are mainly the result of the recrystallization of original constituents of the limestones. This means the removal of an excess of certain constituents and a consequent reduction of volume, a fact which is said not to be proved by the field evidence.

In strong contrast to the usually accepted theory of the formation of contact-metamorphic deposits is that advanced and energetically defended by A. C. Lawson (35), who contends that they originate by the action of meteoric waters. According to him any circulation of groundwater will be profoundly disturbed by igneous injections into sedimentary terranes. As a result of this there would be developed an upward circulation following along the periphery of the heated mass, and competent, he considers, to form the characteristic lime-silicate zones.

W. O. Crosby has also suggested that contact-metamorphic deposits are the work of meteoric waters (31), while Klockman believes that they represent pre-existing ore bodies altered by intrusives (34).

The order of succession of the minerals is certainly not always the same, and according to different observers the sulphides sometimes follow the silicates, or at other times are contemporaneous with them.

Contact-metamorphic deposits, though sometimes rich enough to mine where not secondarily enriched, need this process in many cases to make the ore workable. This was well illustrated in the case of the Morenci, Arizona, copper ores.

It is a question in the minds of some whether pyrometasomatic deposits should be classed as a separate group of the hydrothermal series, or as a subdivision of the hypothermal ones, with which they have many significant minerals and other features in common, their rather special character being due to the nature of the wall rock.

Although this class of deposits was recognized by von Groddeck, as early as 1879, he failed to appreciate the true importance of the associated intrusive. In more recent years the writings of Vogt, Kemp, Weed, Lindgren, and Barrell have greatly increased our knowledge of the true nature of these interesting deposits, and we now know, moreover, that they form a very important and somewhat common type, which in the United States is restricted mainly, however, to the Pacific Cordilleras. They are also known in Canada, the Yukon, Alaska, and many other countries.

Contact metamorphic deposits may be classified as follows (10):

1. Magnetite deposits.
   Examples: Iron Springs, Utah,[1] Fierro, N. Mex.,[2] and Cornwall, Pa.[3]
2. Chalcopyrite deposits. Chief ore minerals, chalcopyrite, pyrite, pyrrhotite, sphalerite, molybdenite and specularite.
   Examples: Clifton, Ariz.,[4] San Pedro, N. Mex.,[5] and Cananea, Mex.[6]
3. Galena-blende deposits.
   Examples: Magdalena Mines, N. Mex.[7]
4. Arsenopyrite-gold deposits. Chief minerals, arsenopyrite and pyrrhotite.
   Examples: Hedley, Brit. Col.[8]
5. Gold deposits.
   Examples: Cable Mine, Mont.[9]
6. Cassiterite deposits.
   Examples: Pitkaranta, Finland,[10] Seward Peninsula, Alas.[11]

Mesothermal or Intermediate Depth Deposits.—Following the succession of deposits formed under conditions of gradually decreasing temperature and pressure, there has been recognized another group formed presumably at intermediate depths, deposited by ascending hot waters, and evidently genetically connected with intrusive rocks.

It is difficult, of course, to tell the exact depth of their formation, which Lindgren has estimated within a somewhat wide range of 4000 to 12,000 feet; but it can sometimes be approximately judged by determining the thickness of overlying rock removed by erosion. An important character of these deposits is the absence of high-temperature minerals.

The deposits are often fissure veins or a related type, and while the minerals frequently fill open fissures, replacement deposits are not

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[1] Leith and Harder, U. S. Geol. Surv., Bull. 338, 1908.
[2] Graton, *Ibid.*, Prof. Pap. 68: 313.
[3] Spencer, *Ibid.*, Bull. 430.
[4] Lindgren, *Ibid.*, Prof. Pap. 43, 1905.
[5] Lindgren and Graton, *Ibid.*, Prof. Pap. 68.
[6] Perry, Copper Resources of World, p. 413, 1935.
[7] Lindgren, U. S. Geol. Surv., Prof. Pap. 68: 241.
[8] Camsell, Can. Geol. Surv., Mem. 2, 1910.
[9] Emmons, W. H., U. S. Geol. Surv., Bull. 315: 45, 1907.
[10] Vogt, Krusch and Beyschlag. Lagerstätten.
[11] Knopf, U. S. Geol. Surv., Bull. 358, 1908.

uncommon and, where limestone is the country rock, may be of considerable extent. They may show banding.

The most important metals in these deposits are gold, silver, copper, lead, and zinc, but the deeper-formed members of the series may carry molybdenum, bismuth, tungsten, and arsenic. Sulphides, arsenides, sulpharsenides, and sulphantimonides are the prominent compounds, while oxides are rare. Quartz is the chief gangue mineral, but carbonates are common.

The country rock usually shows intense alteration next to the ore, feldspathic and ferromagnesian rocks yielding sericite, carbonates and pyrite, and calcareous rocks often showing silicification. The last-named process may also be accompanied by dolomitization.

The following types, with examples added, may be enumerated as belonging to this class:

1. Gold quartz veins of California and Victoria type. Sierra Nevada,[1] Interior Cordilleran region;[1] Victoria, Australia,[1] and Nova Scotia.[1]

2. Gold-bearing replacements in limestone. Mercur, Utah;[1] siliceous gold ores of Black Hills, S. Dak.[1]

3. Gold-bearing replacements in quartzite. De Lamar Mine, Nevada.[2]

4. Gold-bearing replacements in porphyry. Cripple Creek, Colo. (in part). Little Rocky Mountains, Montana.[3]

5. Silver-lead veins, including
    a. Quartz-tetrahedrite-galena veins. Organ, N. Mex.[4]
    b. Tetrahedrite-galena-siderite veins. Wood River, Idaho.[5]
    c. Galena-siderite veins. Cœur d'Alene, Idaho.[6]

6. Lead-silver veins with calcite, siderite and barite. Clausthal, Germany, and Prz'bram, Bohemia.[6]

7. Pyritic-galena-quartz veins. Freiberg,[7] Saxony; Cerbat range, Arizona.[8]

8. Silver-lead replacements in limestones. Aspen[6] and Leadville, Colo.;[7] Eureka, Nev.;[6] Lake Valley, N. M.;[6] Park City and Tintic, Utah;[6] Sierra Mojada, N. Mex.[6]

9. Tungsten veins. Boulder County, Colo.[9]

10. Native silver veins. With cobalt and nickel as at Cobalt, Ontario,[10] and Annaberg, Saxony;[10] with zeolites, as at Kongsberg, Sweden.

11. Copper veins. Butte, Mont.,[11] and Virgilina, Va.[11]

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[1] See references under Gold.
[2] Emmons, S. F., Amer. Inst. Min. Engrs., Trans., XXXI: 658, 1901.
[3] Emmons, W. H., U. S. Geol. Surv., Bull. 340: 98, 1908.
[4] Lindgren and Graton, U. S. Geol. Surv., Prof. Pap. 68: 209.
[5] Lindgren, *Ibid.*, 20th Ann. Rept., Pt. 3: 190, 1900.
[6] See under Lead-Zinc ores.
[7] See under Lead-Zinc ores.
[8] Schrader, U. S. Geol. Surv., Bull. 397, 1909.
[9] See under Tungsten.
[10] See under Nickel-Cobalt.
[11] See under Copper.

12. Pyritic replacement deposits. Rammelsberg, Harz;[1] Mt. Lyell, Tasmania;[1] Rio Tinto, Spain;[1] Shasta County, Calif.;[1] Tyee, Vancouver Island.[1]

Leptothermal Zone Deposits (80).—This zone is made by taking a little off the bottom and top of the epithermal and mesothermal zones respectively. It may contain both simple sulphides and complex sulpho-salts found in mesothermal zone, but the silver-bearing minerals are not of the richer varieties, nor abundant. Silver is obtained, mainly as a by-product. Native gold and tellurides are subordinate. Quartz is common as a gangue, and there may be more or less barite and carbonate, the latter usually manganiferous. Grain size averages smaller but more variable than in mesothermal ores. Vugs and druses are common. Rock alteration is from sericitic to propylitic.

As examples Graton (80) notes San Juan, Colo., Michigan copper; the outermost zone at Butte, and Cobalt, Ontario.

Epithermal or Shallow Zone Deposits (10, 19).—These include a number of fissure-vein deposits, found in the Cordilleran region, and carrying gold with much silver, as well as subordinate amounts of lead. zinc, and copper. The fact that they are found in flows of volcanic origin indicates their formation at comparatively shallow depths, that is, from a few hundred to four or five thousand feet. They include most of the veins of western Nevada, the San Juan region of Colorado, Cripple Creek, Colorado, district, etc.

Gold and silver are prominent, although the former is more abundant and the native gold usually more finely divided.

Like the deeper veins, they may carry pyrite, galena, and sphalerite, but in addition chalcopyrite, arsenopyrite, argentite, and stibnite are characteristic ore minerals. Quartz is a common gangue mineral, and calcite, dolomite, siderite, barite, and fluorite are also found. Adularia is also widespread as a gangue mineral.

Metasomatism varies somewhat with the different rocks. In moderately acid rocks sericitization and even pyritization seem to be common near the vein, and propylitization farther away. In basic igneous rocks, propylitization may extend close to the vein, but sericitization occasionally takes its place. Silicification of the wall rock may occur, especially in rhyolites and sometimes in calcareous rocks.

A change in the character of the vein mineralization is sometimes shown, as when earlier calcite gangue is replaced by quartz and adularia.

Since these ores are of shallow origin, they are formed in the zone

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[1] See under Copper.

of fracture, and are therefore found filling cavities of varied origin and wide distribution.

The veins are usually strong, and show a tendency to branch upward. A noteworthy characteristic is the low ratio of sulphides to gangue, hence workability may depend on the precious-metal content. The dominance of gold over silver may be due to instability of silver minerals in a sulphuric acid solution.

Deposits formed at shallow depths may be separated into different types as follows:

1. Quicksilver deposits.[1]
2. Stibnite deposits.[2]
3. Gold-quartz veins.[3]
    - *a.* In andesite, Brad, Transylvania; Hauraki Peninsula, N. Z,
    - *b.* In rhyolite. De Lamar, Idaho.
4. Argentite-gold-quartz veins.[3] Tonopah and Comstock Lode, Nev.
5. Argentite veins.[3] Pachuca and Guanajuato, Mexico.
6. Gold-telluride veins.[3] Cripple Creek, Colorado.
7. Gold-selenide veins.[3] Republic, Washington.
8. Base-metal veins.[3] San Juan region, Colorado.
9. Gold-alunite veins.[3] Goldfield, Nevada.

Telethermal Zone Deposits (80).—This group represents the upper member of the hydrothermal series. The ores which may show little evident connection with igneous rocks were deposited by relatively inactive solutions, which at times came in contact with a favorably reactive rock, and deposited their minerals slowly.

As examples of this class Graton cites certain lead and zinc deposits in limestones, the copper ores of the Red Beds in the southwest, and possibly some mercury and antimony ores.

Vein-dikes (6, 88).—Most geologists believe that ore deposits derived from igneous rocks have been deposited by solutions of magmatic origin, and possibly varying degrees of concentration. In strong contrast with this view is that advanced by Spurr, who maintains that the ores have been deposited from thick, highly concentrated solutions, which represent a differentiate from the parent magma. Spurr believes that this "ore magma," as he calls it, is of a highly viscous nature, like a gel, and that it has been forced into the fissures which it fills. Replacement veins he considers have originated from thinner,

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[1] See under Mercury.

[2] See under Antimony.

[3] See under Gold-Silver.

but nevertheless concentrated, solutions. To the deposits filling fissures he applies the name *Vein-dikes.* Spurr asserts that the presence of such a viscous filling satisfactorily explains the existence of apparently unsupported angular rock fragments (inclusions) in the vein, which could not have remained suspended in thin solutions. This point is not agreed to by all geologists.

The unsupported angular fragments may in reality, however, be supported at some point not in the plane of the surface exposed, or they may have been detached from the wall of the fissure and dropped into the vein cavity when it was partly filled. In some cases angular fragments are formed by replacement (110).

Zonal Distribution of Ores (180–192).—Attention has been called to the fact, notably by Spurr and Emmons in the United States, that, in some districts where two or more kinds of ore occur, these show a zonal arrangement, being sometimes arranged concentrically around the intrusive in successive zones, in going away from the parent mass.

The sequence from the outer zone towards the center is the same as from the surface downward. The order given by Spurr is Hg, Pb, Zn, Ag, Cu, Au, W, Mo. If, according to Spurr, an ore magma reaches the surface, it cools so quickly, that when the ore magmas (or solutions) penetrate these rocks the ores of the different vein-zones are deposited in the same vertical range, and these he terms "*telescoped deposits.*"

Emmons (183) has also stressed the zonal arrangement of ores and makes sixteen subdivisions, admitting, however, that the entire series may not be shown in any one vein.

Only time will tell whether the zonal theory will be universally accepted. Some deposits like those of Cornwall, England, where tin grades upward into copper, and the latter in turn to lead and zinc, seem to be good examples, but there seem to be so many exceptions as to make one skeptical of its general application.

Formation of Cavities.—The deposition of ores in the rocks is greatly facilitated by the presence of cavities along which the ore-bearing solutions freely pass, and consequently a great many ore deposits occur in such spaces. There are a number of different ways in which cavities may be formed in rocks. The percolation of surface water through certain ones, such as limestones, often results in the formation of solution cavities, these in many instances attaining the size of veritable caverns; a soluble rock may contain more or less insoluble material, such as clay or chert, which collapses when the surrounding rock is dissolved, and partly fills the cave thus formed. At times the more resistant parts are so bound together that they remain in their original position, forming a porous mass, in the cavities of which mineral matter is later deposited.

Dynamic disturbances produce cavities of variable extent in many different rocks. These range from microscopic cracks, like the rift planes of granite, to enormous faults of great depth and linear extent, and include the joint planes so common in the rocks of almost all regions. Fault fissures form one of the most important types of passageways for ore-bearing solutions. They are often irregular, branching, and partly filled by fault breccia, caused by the breaking of the rock during the movement along the fault plane. A third important group of cavities in the rocks are those resulting from shrinkage of the mass, which may be due to (1) shrinkage during cooling, as in igneous rocks; (2) shrinkage during certain forms of replacement. For example, the change of calcite to dolomite may be accompanied by a shrinkage of the mass, which renders the dolomite more porous than the original rock; and in the alteration of siderite to limonite there is a shrinkage of fully 20 per cent (162). A fourth type of channelway for the passage of underground water is the contact plane between two quite different kinds of rock, one of them fairly dense and impervious. Gas cavities of lavas and the pore spaces of pyroclastic rocks may also serve as openings for ore deposition.

Deposition of Ore in Open Cavities.—Open cavities may, according to general belief, exist to a depth of many thousands of feet below the surface. If rock pressure alone were active, they could not theoretically exist below the zone of fracture, but it seems possible that hydrostatic pressure due to various causes might to some extent counteract rock pressure.

There is evidence to show that some large cavities must have existed at great depths, and the force of crystallization has been appealed to, Becker and Day having demonstrated the actual existence of such a force.[1] Lindgren points out that it seems scarcely possible to attribute such power to it as would be necessary to open deep-seated crevices sufficiently to form room for the crystals, or that under these conditions comb structure and coarse, even-grained quartz could be produced. Graton (80) suggests the crevices formed below the zone of fracture have been opened by the pressure of solutions forced out of the cooling magma.

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[1] Proc. Wash. Acad. Sci., VII: 283.

Precipitation of Metals from Solution.—In some cases the metalliferous and other minerals found in ore deposits have no doubt been taken into solution by surface waters, and precipitated at no great depths; but in the majority of instances the metals were taken into solution at some point considerably below the point of precipitation, where heat and pressure were evidently high. The ascent then of these solutions toward the surface where temperature and pressure were low would reduce the solvent capacity of the liquid and cause deposition.

As has been pointed out by Lindgren (87) the physical conditions during deposition, especially temperature and pressure, are of great importance in determining the mineral association in ores formed by deposition from solution, in fact this feature is made use of in his classification of ore deposits (p. 405).

Certain minerals, for example, are very stable under high pressure and temperature, and could not therefore exist under conditions prevailing near the surface. That is to say, that the different minerals have their "critical level," above or below which they cannot form or exist. Other minerals are termed "persistent minerals," because they have a large interval of existence.[1]

The deposition of the metals may have been due, however, to other causes, such as the mingling of waters, resulting in chemical reactions, contact of the solution with reducing agents such as carbon, ferrous sulphate, or hydrogen sulphide; or where the precipitation occurs near the surface, by oxidation.

Other conditions may, however, operate to cause precipitation, for, as shown by Sullivan (92), the natural silicates have the power of precipitating metals from solution of salts, "while at the same time the bases of the silicates are dissolved in quantities nearly equivalent to the precipitated metals." The bases which most commonly replace metals in such a process are potassium, sodium, magnesium, and calcium, and the metals are precipitated as hydroxides or basic salts. Cupric sulphide, for example, is precipitated as a basic cupric sulphate similar to brochantite or langite.

Colloidal Precipitates (21–28).—While most minerals in ore deposits are precipitated in crystalline form, it seems quite evident that some are separated out from solution in a colloidal condition, forming gelatinous or flocculent masses. This colloidal material after solidification tends to change to a crystalline condition, and is then called a *metacolloid* (25).

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[1] A. Grubenmann, Die Kristallinen Schiefer, Berlin, 1904, p. 55.

Colloidal precipitates when hardened often form rounded masses, called *colloform*, and this shape may be retained by the metacolloid.

Colloidal precipitation of silica, ferric hydroxide, and aluminum hydroxide are common, and the same seems to be true of a number of other minerals (Pl. XXXIV, Fig. 1). Colloidal deposition is most widespread at or near the surface, but it seems evident that it may take place at greater depths, even down to the mesothermal zone (10). Examples of it seem to be shown by the veins of Cobalt, Ontario, Freiberg, Saxony, and the tin-bearing veins of Rhyolite, Nevada. Beautiful examples of it are observed in the zone of weathering, and in some secondary enrichment ores.

FIG. 112.—Vein breccia from Freiberg, Germany.

The specimen shows fragments of altered schist (*S*), which are in some cases surrounded, and in others more or less completely replaced by sphalerite (*Z*), and cemented by quartz (*Q*). Scattered grains of pyrite (*P*) are also present. (*Specimen in Cornell collection.*)

While the deposition of either metallic or non-metallic minerals may be precipitated in colloidal form in cavities, it seems quite clear that in some cases solid rock has been replaced by such material as silica gel (116), which subsequently changed to chalcedony. Metalliferous solutions may furthermore have deposited sulphides in the gel.

Replacement, or Metasomatism (109–120).—It is a well-known fact that under favorable conditions mineral-bearing solutions may attack the minerals of the rocks which they penetrate, dissolving them wholly or in part, and depositing some of the original burden in place of the material removed. This replacement, termed "*metasomatism*," is an important factor in the formation of many ore deposits, and may involve a total or partial loss of certain constituents of the rock attacked and a gain of others, even to the extent of introduction of entirely new compounds and elements.

While some (112) believe that replacement may be accompanied by a volume change, others (114) assert that it proceeds independent of molecular weight, molecular volume, and specific gravity. The latter seems the more correct view.

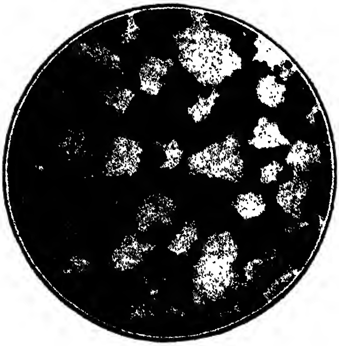

FIG. 113.—Photomicrograph of a section of quartz conglomerate, showing replacement of quartz (white), by pyrite (black), ×25 diam. (*After Smyth, Amer. Jour. Sci., XIX*, 1905.)

The replacing solutions gain entrance to the rock mass, along fractures of different sorts, and penetrate the rock first along the smallest cracks, and then work their way into the individual mineral grains along their cleavage planes until they finally permeate the entire mass (Figs. 113, 114, and 116). The reactions between the dissolved mineral, and the original rock probably take place in films of the solution coating the grains.

Metasomatic processes show great variety, and are not confined to one kind of rock or mineral. In its simplest form the result of metasomatism may often be seen in fossiliferous rocks, where organic remains have been replaced by common mineral compounds, as in the replacement of the lime carbonate of corals by quartz, or the replacement of molluscan shells by pyrite. From such simple conditions there is every gradation to the complete replacement of extensive areas of rock by ore, or to the extensive operation of metasomatism along the walls of fissure veins.

The complexity of metasomatic processes referred to above may

FIG. 114.—Pyrite replacing hornblende, Mineral, Louisa County, Va. ×35. Black, pyrite; gray, hornblende; white, quartz.

be due to variations in temperature, character of rock, and nature of solution. Metasomatism may take place through a wide range of temperature, but heat greatly aids the process, and the replacing solutions while usually liquid, may also be gaseous. Of the many different rocks affected, limestones are most favorable to replacements, while those high in alumina are least easily attacked.

FIG. 115.—Replacement vein in syenite rock, War Eagle Mine, Rossland, B. C. (*a*) granular orthoclase with a little sericite; (*b*) secondary biotite; (*q*) secondary quartz; (*c*) chlorite; *black*, secondary pyrrhotite. (*After Lindgren, Amer. Inst. Min. Engrs., Trans. XXX.*)

The original structure and even the texture of the rock may be preserved, although its mineral composition is completely altered, illustrations of the former being sometimes seen in silicified limestones, or of the latter in replaced porphyritic rocks, in which the outlines of the phenocrysts are still preserved.

The replacing mineral is called the *metasome,* or if with crystal outlines a *metacryst*. Some minerals show a strong tendency to develop metacrysts. Boydell calls the host rock the *palosome.* The replacing mineral may also be deposited as a gel (116).

Replacement at high temperatures is usually indicated by complete recrystallization, the development of silicate minerals with little or no water, and coarse texture. That performed at lower temperatures commonly results in a much finer-textured mass.

To decide definitely whether replacement has occurred, both field and laboratory study is often necessary. In hand specimens it is not always possible, without examination of a thin section under the microscope, to decide whether the minerals present are due to replacement or to simple interstitial filling.

Certain criteria representing both field and laboratory features have been suggested (112), although all are rarely applicable to a single deposit. These are: (1) presence of complete crystals in foreign rock masses; (2) preservation of rock structures; (3) intersection of rock structures by replacing mass; (4) absence of crustification; (5) presence of unsupported nuclei; (6) relation of replacement to fissures and other cavities; and (7) form of deposit.

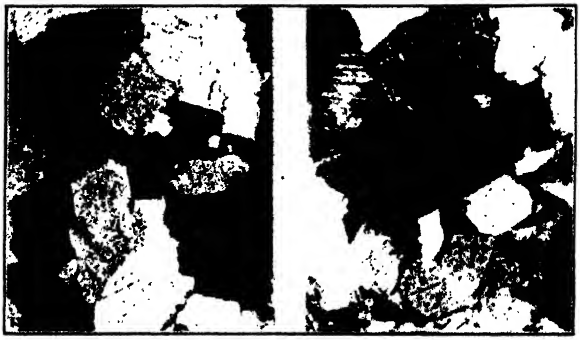

FIG. 116 FIG. 117

FIGS. 116 and 117.—Photomicrographs of thin sections of ore from Austinville, Va., mines. ×20 diam. crossed nicols. Shows crystalline granular dolomitic limestone, and the filling of fine cracks accompanied by replacement of limestone grains along crystallographic directions by the sulphides. Very dark irregular areas in center represent sulphides. Reëntrant angles along margins of the sulphides and the spider-like arrangement of the sulphide areas as a whole are well shown. (*After Watson, Va. Geol. Surv., Bull. I.*)

As mentioned before, metasomatic processes show endless variety. Non-metallic minerals may replace each other as quartz replacing calcite, or metallics may replace nonmetallics, as galena in limestone

PLATE XXXV

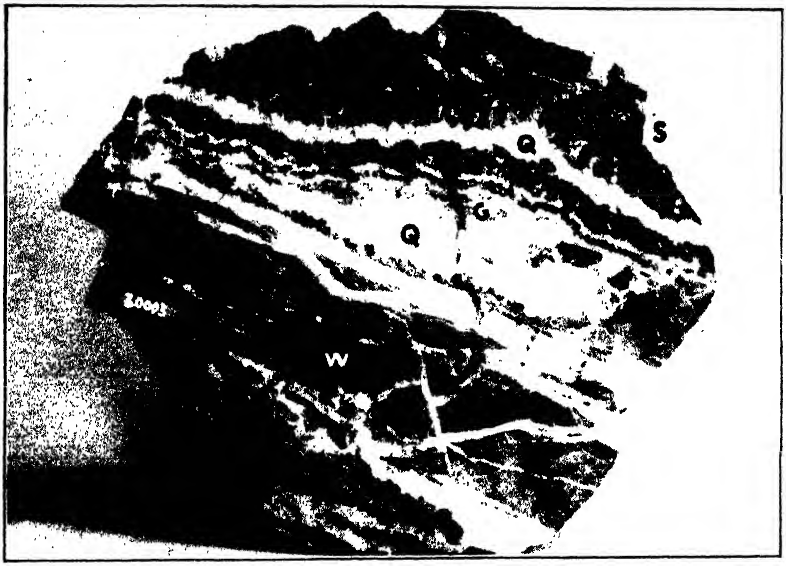

FIG. 1.—Banded vein from Clausthal, Germany. Sphalerite, *S*; quartz, *Q*; argillite wall rock, *W*, fragments of which have been separated by quartz crystallizing in the cracks.

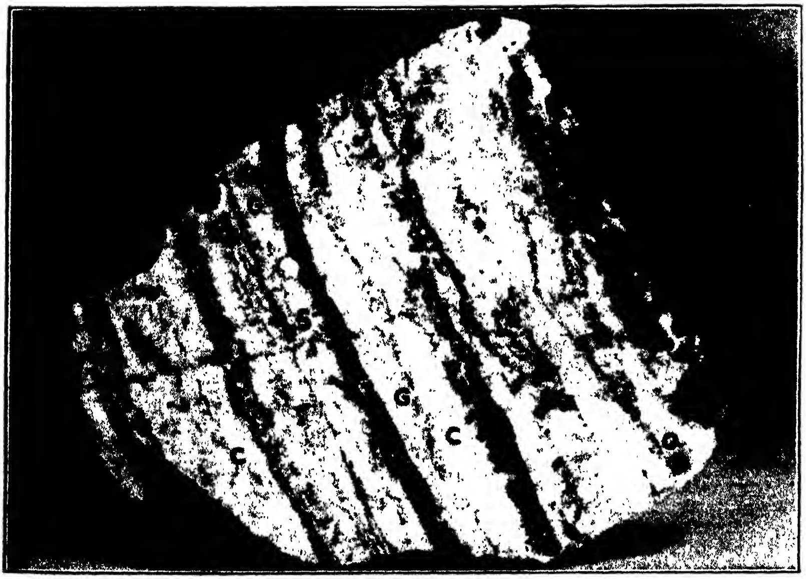

FIG. 2.—Banded vein, same locality. Sphalerite, *S*; galena, *G*; chalcopyrite, *C* (black); calcite, *C* (white); streak of later quartz, *Q*.

or pyrite in hornblende (Fig. 114); and lastly one sulphide may be replaced by another, as pyrite by chalcocite (Pl. XXXVII), or sphalerite by chalcocite. More rarely non-metallic minerals may replace metallic ones, although few definite cases of this have been noted in the literature.

Although the process of metasomatism was recognized by Charpentier as early as 1778, it was generally disregarded, and not widely accepted or recognized until many years later, and geologists continued to assume that ores precipitated from solution were deposited in cavities. Replacement was, however, finally recognized in the United States, being applied by Pumpelly to the Lake Superior copper deposits in 1873; by Emmons to Leadville in 1886, and by Irving and Van Hise to the Gogebic Range in 1887 to 1888.

Ore deposits of great size, as those of Leadville, Colo., or Bisbee, Ariz., may be formed by replacement, and a frequent expression of it is seen in the alteration of the wall rocks of many fissure veins. (See Hydrothermal alteration.)

Unmixing (136–142).—Study of polished ore surfaces sometimes shows that a crystal or large grain of one metallic mineral may have distributed through it, sometimes crystallographically oriented, grains of another mineral. A common case is the occurrence of dots and rods of chalcopyrite in sphalerite.

At the present day this is often explained by the term *unmixing*. It assumes that if a mineral has crystallized at high temperatures the other constituents in it remain in solid solution, but if the mixture cools slowly the impurities may separate as inclusions of the host mineral. The process is supposed to be analogous to what happens in metallic alloys. If such unmixed material were heated and then cooled suddenly, it should again form a solid solution. This has been done experimentally.

Unmixing may bear a resemblance to replacement, and care should be taken not to confuse the two.

Forms of Ore Bodies (199).—Ore bodies vary greatly in their form, and this character has at times been used as a basis of classification by some writers; but the more modern tendency is to use genetic characters instead, making shape of secondary importance in the grouping. Certain forms of ore bodies are so numerous as to deserve special mention.

Fissure Veins (3, 19, 145, 147, 152, 155, 161, 199).—A fissure vein may be defined (90) as a tabular mineral mass occupying or closely

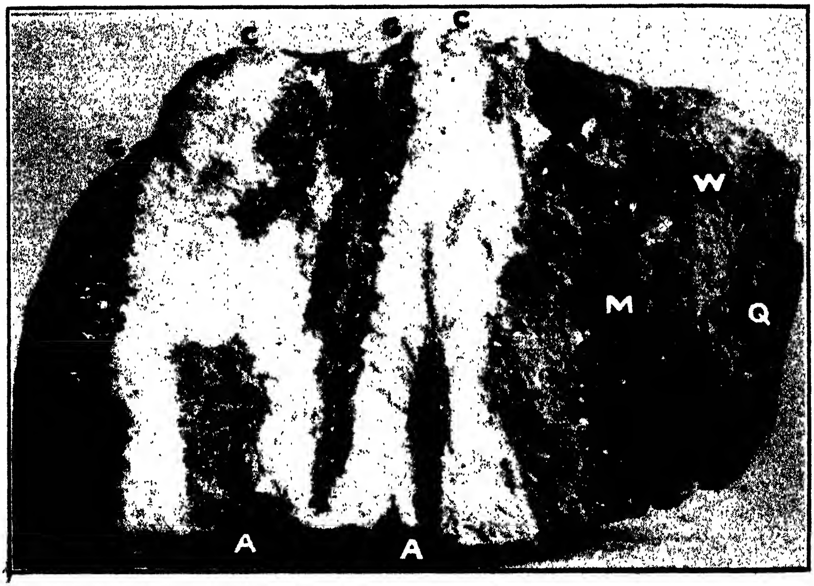

FIG. 1.—Vein specimen from Przibram, Bohemia; galena, *G*; stibnite and quartz, *A*; galena and quartz, *M*; dolomite, *C*; quarts, *Q*; fragments of graywacke wall rock, *W*.

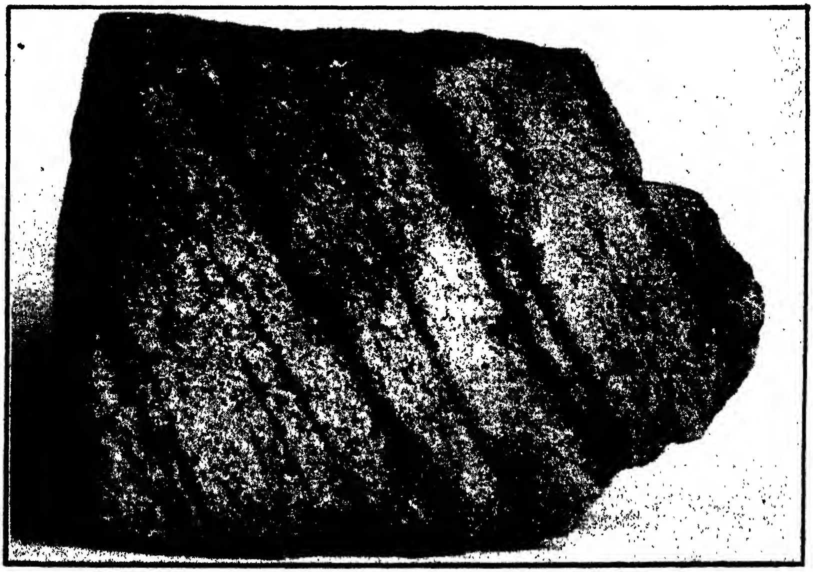

FIG. 2.—Veinlets of ore in granite, Altenberg, Saxony.

associated with a fracture or set of fractures in the inclosing rock, and formed either by filling of the fissures as well as pores in the wall rock, or by replacement of the latter (metasomatism). When the vein is simply the result of fissure filling, the ore and gangue minerals are often deposited in successive layers on the walls of the fissure (Rico, Colo.), the width of the vein depending on the width of the fissure and the boundaries of the ore mass being sharp. In most cases, however, the ore-bearing solutions have entered the wall rock and either filled its pores or replaced it to some extent, thus giving the vein an indefinite boundary. Therefore the width of the fissures does not necessarily stand in any direct relation to the width of the vein (161) (Butte, Mont.). The term *vein material* is best used to apply to the aggregate of materials which make up the ore body. *Vein stone*, though sometimes used, is less desirable (Emmons).

Veins formed by the simple filling of a fissure often show a banded structure of varying regularity termed *crustification*[1] by Posepny (Pl. XXXIV, Fig. 1, and Fig. 118), which may sometimes be brecciated by later movements along the fissure.

Some veins exhibit a beautifully banded structure, and while it is intimated that this may be caused by a change in the character of the solutions moving through the fissure, it seems hardly a satisfying explanation, especially where the bands may be due to alternating deposition of two minerals. One suggestion is that it is due to rhythmic fractional crystallization (154). Attention has also been called to the fact (155) that the minerals of one band may in part replace those of the next earlier one. Secondary bands may be formed after reopening of the fissures (Fig. 118), and such a movement may cause brecciation of the vein material. There are many filled fissure veins in which banding is absent, the ore minerals and gangue being intermixed, but so related as to indicate probably simultaneous deposition of the two. Later movement along the vein wall may sometimes form a layer of soft, clayey material, known as *gouge* or *selvage*, between the vein and the country rock, but where the vein filling adheres closely to the country rock it is said to be *frozen to the walls*. Where the fissure has not been completely filled, thus leaving a central space into which the crystals of gangue project, a *comb structure* is formed. The bands in a filled fissure may consist of gangue and ore alternating, or of different ores. Among the commonest ore minerals

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[1] The replacement of certain layers only in a bed of stratified rock may also produce a banded structure.

seen in these fissure veins are pyrite, chalcopyrite, galena, blende, and sulphides of silver. Some regions afford especially fine examples of banded veins, notably those of Grass Valley, California, and Rico, Colo. Abroad the mines of Freiberg, Saxony, and Clausthal, Prussia, also often yield magnificent specimens. Even in a single vein the ore may follow certain streaks which are termed *shoots* (*q.v.*) or again it may be restricted to pockets of great richness, which are known as *bonanzas.*

FIG. 118.—Section of vein in Enterprise mine, Rico, Colo. The right side shows later banding due to reopening of the fissure. (*After Ransome, U. S. Geol. Surv., 22d Ann. Rept., II.*)

In some veins the friction breccia or dragged in fragments of the country rock form a considerable portion of the vein filling, and the ore has been deposited in layers around these fragments.

Fissure veins in which metasomatic action has predominated show great irregularity of width and an absence of well-defined boundaries; they also lack as a rule the symmetrical banding and the breccias cemented by vein material. There are all gradations between these two types of fissure veins; and even in a single vein simple filling may occur in one part and replacement in another, Veins often split or intersect, and at the point of intersection or splitting the ore is likely to be richer. There are other reasons for variations in richness, among the most important being the character of the wall rocks, some kinds being more easily replaceable or more porous than others. Their physical character will, moreover, exercise considerable influence on the shape and size of the fissure. Tough rocks like gneiss, for example, give a clean-cut fissure, but in brittle rock the fissure is apt to split frequently, and therefore a vein may be workable in one kind of rock, but becomes worthless when passing to another, since the profuse branching interferes with economical mining (Fig. 119). A dike may also cause local irregularities, and in a given region the fissures not uncommonly show great variation in their direction. Thus at Butte, Mont. (*q.v.*), east-west veins predominate, while in the Silverton district of Colorado they cut the rocks in all directions, but the majority show a north of east trend. In the Monte Cristo, Wash., district the veins with northeast trend are predominant (Fig. 120).

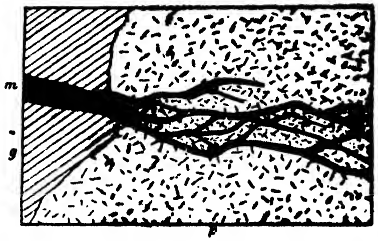

Fig. 119.—Section showing change in character of vein passing from gneiss (*g*) to quartz porphyry (*p*). (*After Beck, Lehre von der Erzlagerstatten:* 135.)

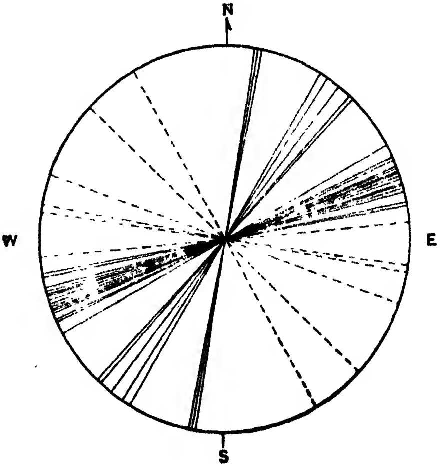

Fig. 120.—Tabulation of strikes of principal veins in Monte Cristo, Wash., district. (*After Spurr, U. S. Geol. Surv., 22d Ann. Rept., II.*)

Fissure veins vary considerably in their width, swelling at some points and pinching or narrowing at others. They also at times show lateral enrichment (Ouray, Colo.); for instance, where the ore cuts through stratified beds, into which the ore-bearing solutions have spread out laterally along the planes of stratification or other planes. It has been noticed in some veins, especially those formed by replacement, that the filling varies with the wall rock, at times changing suddenly; but where the vein is formed wholly by the filling of an open fissure, the rock exerts no influence on the character of the ore (161). If the vein is inclined, the lower wall is spoken of as the *foot wall* and the upper one as the *hanging wall.*

A *horse* is a mass of rock broken off from the vein wall, and held between the walls of the fissure. It is often surrounded by ore, and may itself sometimes be mineralized to a varying degree.

Parallel fissures are not uncommon, but the several veins do not necessarily show an equal degree of richness. Where the vein is of composite character—that is, consisting of closely spaced parallel fissures accompanied sometimes by a mineralization of the intervening rock—it is termed a *lode.*

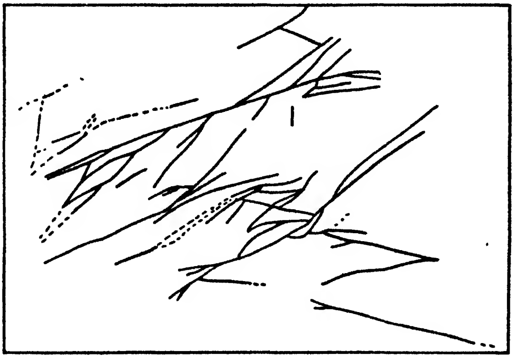

FIG. 121.—Linked veins. (*After Ordonez.*)

The term *vein systems* is suggested for a larger assemblage of vein fissures, which may include several lodes.

Subordinate fractures, such as little veins, that cross the material included within the vein walls, are called *veinlets* or *stringers.*

The top of the vein is called the *apex,* and is occasionally traceable for a long distance. It does not necessarily outcrop at the surface; indeed a vein might apex some distance below it.

Linked veins represent a type in which the parallel fissures are connected by diagonal ones (Fig. 121), giving a series resembling the links of a chain.

Gash veins are a special type of fissure vein of limited extent. Some are formed by the enlargement of joint planes and sometimes bedding planes. They are characteristic of the upper Mississippi

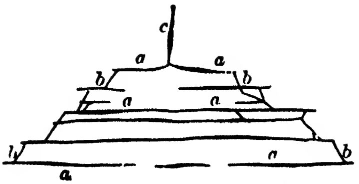

Fig. 122.—Gash vein with associated "flats" (*a*) and "pitches" (*b*). Wisconsin zinc region. (*After Grant, Wis. Geol. and Nat. Hist. Surv., Bull. IX.*)

Valley lead and zinc region, but are usually of limited extent and local importance. In the simplest form they are a vertical fissure, but develop into types shown in Fig. 122. Other gash veins may be the result of torsional strain, as those accompanying the Catoctin type of copper ores.

Bedded Vein.—This term is sometimes applied to a deposit conforming with the bedding. It is also called *bedded deposit.* Among miners the term *blanket vein* is commonly applied to any nearly flat deposit.

Bedded deposits are those found parallel with the stratification of sedimentary rocks, and sometimes of contemporaneous origin (Clinton iron ore).

Cross veins is a term applied to those which cross the stratification.

Lenticular veins are short lenses, frequently found in metamorphic rocks, and often scattered along a line, or lying more or less parallel in a zone.

Filling of Fissure Veins.—The manner in which fissure veins have been filled, and the source of the metals which they contain, formed a most fruitful subject of discussion among the earlier geologists. The several theories advanced and the arguments for and against them are well set forth in Kemp's book, and it may simply be said here that most geologists now believe that the primary deposition of ores in fissure-vein deposits was accomplished by solutions ascending along the fissures, which sometimes spread out into the wall rocks, to a variable distance.[1]

Other Forms of Ore Deposits.—*Chimmey* is a term applied to ore bodies which are rudely circular or elliptical in horizontal cross-section, but may have great vertical extent. A *stock* is a somewhat similarly shaped ore body, but of greater irregularity of outline. *Fahlband* is a term originally used by German miners to indicate certain bands of schistose rocks impregnated with finely divided sulphides, but not always rich enough to work. It is occasionally used in this country. *Stockwork* is the term applied to a rock mass broken in different directions by short fissures, which may be mineralized. *Impregnation* is a term indicating the occurrence of minerals in a finely disseminated condition in rocks, either as a filling of open spaces or as

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[1] See also Spurr (16).

a replacement of certain minerals. *Disseminated deposits* (Fig. 123) is regarded as a better term by some. *Contact-metamorphic deposits,* as now understood, represent ore bodies formed along the contact of a mass of igneous and country or invaded rock (usually calcareous), the ore having been derived wholly or in part from the intrusive mass (Clifton, Ariz., in part). If the term *contact-metamorphic deposit* is used for this type, it would not necessarily conflict with the term *contact deposit,* applied to any ore body occurring along the boundary between two formations or two kinds of rock. *Ore channels* include those ore bodies formed along some path which the mineral solutions could easily follow, as the boundary between two different kinds of rock (Mercur, Utah).

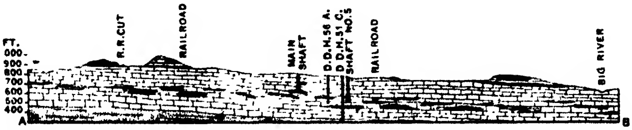

FIG. 123.—Section at Bonne Terre, Mo., showing ore disseminated through limestone.

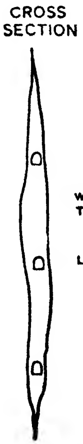

FIG. 124

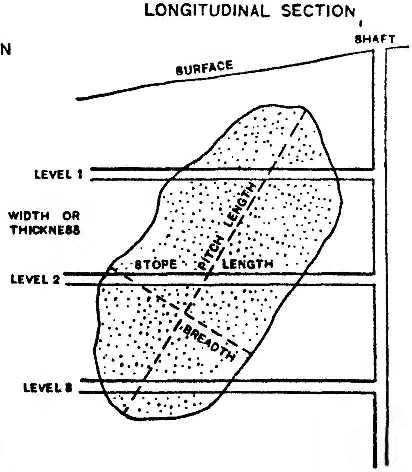

FIG. 125

FIGS. 124 and 125.—Sketch showing dimensions of an ore shoot. (*After Lindgren and Ransome.*)

Shear zones or *sheeted zones* represent a zone of rock broken by numerous parallel and often closely spaced fractures, which may be mineralized as at Cripple Creek, Colo.

Ore Shoots (97–102).—Few ore deposits are of uniform character throughout; indeed, the occurrence of pay ore is apt to be more or less irregular, the richer material being often somewhat restricted in its occurrence. These richer portions, if small, may be called nests, or *pockets,* but if large, the term *ore shoot* is commonly applied to them. According to some authors the ore shoot includes only the richer portion of the workable ore. (Van Hise.)

Other writers, among them Emmons, Lindgren, and Ransome, employ the term ore shoot or pay shoot to signify the workable part of a lode or similar deposit.

Ore shoots are commonly of irregular shape, and usually steep dip, although they may be nearly horizontal.

According to Emmons the ore shoot, as a rule, has a longer axis that forms a large angle with a horizontal plane. This longer axis may be called the *pitch length,*[1] and the horizontal dimensions along the level the *stope length.* Ore shoots are evidently caused by varying chemical and physical conditions in different parts of the deposit, at the time the ore was formed, thus causing a more abundant precipitation of the ore minerals in certain parts of the deposit. More abundant fissuring, or brecciation, in certain parts of the rock may operate to promote deposition in those parts of the mass; clay walls may be influencing factors in guiding the ore solutions towards certain spots; or intersecting fissures may permit the mingling of reacting solutions, thereby bringing about more abundant precipitation of ore at these crossing points. The existence of fissures in certain parts of the ore body might produce additional deposition in those parts, by serving as a guiding channel to either ascending or descending enriching solutions.

The examples cited above apply especially to epigenetic deposits; but if the term *ore shoot* is used in its broadest sense, one might reasonably include ore masses formed by magmatic segregation.

Several attempts have been made to classify ore shoots, all of them being on a genetic basis. Thus Van Hise[2] divides them into three groups as follows: (*A*) those explained largely by structural features; (*B*) those formed by the influence of wall rocks; and (*C*) those formed by secondary concentration by descending waters.

Irving (98) has classified them as (1) shoots of variation, or those which vary from the inclosing material only in relative richness of the ore; and (2) shoots of occurrence, or those which occur in isolated positions with no other ore of any kind about them.

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[1] Lindgren and Ransome.

[2] Amer. Inst. Min. Engrs., Trans. XXX: 27.

Winchell[1] makes a division into (1) paragenetic shoots, or those developed mostly at the time of the original formation of the ore deposit inclosing them; and (2) postgenetic shoots, or shoots developed mostly after the original formation of the inclosing ore deposit.

Secondary Changes in Ore Deposits (121–135).—Ore deposits are often changed in their upper parts, and sometimes to a considerable depth, by weathering agents, while the lower-lying portions, below the groundwater level, are often enriched by secondary processes.

The two zones each show a somewhat characteristic set of compounds. Thus in the weathered zones we find sulphates, carbonates, silicates, oxides, chlorides, arsenates, and native metals; while in the lower zone the compounds are sulphides, tellurides, arsenides, and antimonides.

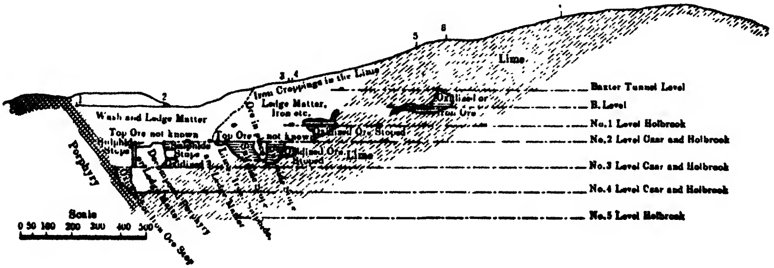

FIG. 126.—Section through Copper Queen Mine, Bisbee, Ariz., showing variable depth of weathering. (*After Douglas, Amer. Inst. Min. Engrs., Trans. XXXIX.*)

Weathering may disguise the true character of an ore body most effectually. For example, the ore found in the outcrop may be a gold ore, and mills are sometimes erected and operated for a period on such ore, without any suspicion that beneath there may be great bodies of copper or lead sulphides. Such a change has been found at Bingham, Utah; Butte, Mont.; or Mount Morgan, Australia. The last has been one of the world's greatest gold mines, but later produced copper from its lowest levels. In other cases, the base metals may all have been leached out of the upper part of the ore body, and too little gold remains in the gossan to make it profitable. Butte, Mont., is a well-known example of this, for the nearly barren outcrops gave little clew to the great sulphide ore bodies lying below, which might never have been discovered but for the presence of another system of closely associated veins carrying silver.

Weathering or Superficial Alteration (175–179).—Nearly all minerals are attacked by the weathering agents, but most metallic min-

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[1] Econ. Geol., III: 425, 1908.

erals are more easily and more profoundly affected than the non-metallic ones.

This weathering process involves both chemical and physical changes similar to the decay and disintegration of common rocks, but in ore bodies the great number of minerals involved, including many with a metallic base, give rise to a large number of intricate chemical reactions.

As a result of weathering worthless minerals may be removed, leaving the weathered part more porous, and this may increase the richness, because we have a greater quantity of metals per ton of rock.

The character of the outcrop in non-glaciated areas depends on the relative resistance to weathering of the ore and wall rock. Hard quartz veins, silicified ledges (Pl. L, Fig. 2), or dense fine-grained garnet rock are usually more resistant than the country rock, and may remain standing in more or less strong relief. Pyritic deposits weather more easily usually than the wall rock, and hence a depression may be developed.

A mixture of quartz and pyrite will yield a mass of rusty honeycombed quartz, or a hard porous limonite, such a mass being known as *gossan* or iron hat (French, *chapeau de fer;* German, *Eisener Hut*). Solid sulphide ore bodies also are often capped by a gossan.

The weathering of an ore body is a comparatively slow process, so that, in glaciated areas, unweathered ore may extend close to or actually up to the surface, because since the retreat of the ice the time has been too short to permit much weathering.

Oxidation in general extends to the water level, although there may be a number of exceptions to this rule. It may hence show great variation in depth due to this cause alone, but aside from this other factors exert an influence, such as topographic conditions, rainfall, nature of the rock, whether fissured, porous, or dense, kind of ore minerals, climate, etc. Even in the same deposit oxidation may extend to greater depths in one place than another (Fig. 126), because of the presence of fissures which permitted local penetration of the surface waters.

As examples of the maximum depth to which weathering may extend in some parts of an ore body the following can be mentioned:

Bisbee, Ariz.	1600 feet in places
Tintic, Utah	2000
Bingham, Utah	1300
Tonopah, Nev.	1200
Ducktown, Tenn.	100
Butte, Mont.	400

As a result of oxygen-bearing surface waters entering the ore body, chemical changes begin, oxidation and hydration being important; and these, together with other changes, produce many soluble compounds. The oxidation of pyrite, for example, gives sulphuric acid, and the latter is active in the formation of ferrous and ferric sulphates, of which the last-named is important as an oxidizing agent.

Not all of the sulphides appear to be attacked with equal readiness, and the same mineral may show different degrees of resistance under different conditions. That the order of resistance does not seem to be the same in all cases is indicated by the table below.

Whatever the order in which the sulphides succumb to the attacks of the weathering agents, they all yield, forming new compounds stable under surface conditions, and sometimes of soluble character, which permits their removal.

Among the compounds found in the oxidized zone are the hydrous oxides of iron, hematite, manganese oxides, free gold under favorable conditions, silver chloride, silicates, carbonate and sulphate of lead, and oxidized compounds of zinc and copper.

Order of Oxidation of Sulphides, According to Several Authorities

1	2	3	4	5	6	7	8
Iron	Arsenopyrite	———	———	———	———	Pyrrhotite	Marcasite
Copper	Pyrite	———	———	———	Sphalerite	Sphalerite	Pyrite
———	Chalcopyrite	———	———	———	Chalcocite	———	Pyrrhotite
Zinc	Sphalerite	Chalcocite	Chalcocite	Chalcocite	Galena	Galena	Chalcopyrite
Lead	Galena	———	———	Bornite	———	———	Bornite
Silver	Chalcocite	———	Pyrrhotite	Pyrrhotite	Pyrite	———	Millerite
———	———	———	———	Chalcopyrite	Chalcopyrite	Chalcopyrite and pyrite	Chalcocite
———	———	Pyrite	Pyrite	Pyrite	Argentite	———	Galena Sphalerite

1. Van Hise, Amer. Inst. Min. Engrs., Trans., XXX: 101, 1901; 2. Weed, *Ibid.*, XXX: 429, 1901; 3. Lindgren, U. S. Geol. Surv., Prof. Pap., 43: 180, 1905; 4. Emmons and Laney, U. S. Geol. Surv., Bull. 470: 151, 1911; 5. Vogt, Amer. Inst. Min. Engrs., Trans., XXXI: 125, 1902; 6. Gottschalk and Buehler, Econ. Geol., IV: 28, 1910; 7. Wells, U. S. Geol. Surv., Bull. 529: 76, 1913; 8. Beck (Weed), Nature of Ore Deposits, p. 337.

Tolman claims that the zone of weathering can be divided into three subzones, which beginning at the surface are: (1) zone of complete oxidation; (2) zone of complete leaching; and (3) zone of oxide enrichment which is of variable thickness and lying immediately above the sulphides.

The first represents complete oxidation and includes the iron cap. It shows limonite, hematite, residual silica, and sometimes residual gold, as well as silver chloride. Lead, zinc, and copper oxidation products may be present. The second is usually somewhat thoroughly leached of its metallic contents, but the gold and less often silver may extend down into it. The third may contain partly oxidized minerals, and include native elements, oxides, carbonates, and silicates brought from above. Some authors do not agree to this constant zonal division of the weathered zone.

Reactions of Oxidized Zone.—The reactions that take place in the oxidized zone are primarily those taking place between the sulphides, oxygen, water, carbon dioxide, and sulphuric acid. These may be followed by reactions between the products so formed or between these and other minerals, the result in some cases being the formation of minerals of stable and slightly soluble character, which are evidence of weathering reactions. Some of the possible reactions follow:

$$\begin{aligned} FeS_2 + 4O &= FeSO_4 + S \\ FeS_2 + 7O + H_2O &= FeSO_4 + H_2SO_4 \\ FeS_2 + 6O &= FeSO_4 + SO_2 \end{aligned}$$

Ferrous sulphate, however, oxidizes to ferric sulphate:

$$2FeSO_4 + H_2SO_4 + O = Fe_2(SO_4)_3 + H_2O$$

But the ferric sulphate is not very stable near the surface, although deeper down this salt together with ferric chloride and even other ferric salts may remain in solution, and serve as oxidizing agents.

Both ferric and ferrous sulphates may yield limonite as follows:

$$\begin{aligned} &6FeSO_4 + 3O + 3H_2O = 2Fe_2(SO_4)_3 + Fe_2(OH)_6 \\ &Fe_2(SO_4)_3 + 6H_2O = 2Fe(OH)_3 + 3H_2SO_4 \\ &4Fe(OH)_3 = 2Fe_2O_3 + 6H_2O = 2Fe_2O_3 \cdot 3H_2O + 3H_2O \\ &2Fe_2(SO_4)_3 + 9H_2O = 2Fe_2O_3 \cdot 3H_2O + 6H_2SO_4 \end{aligned}$$

As evidence of the oxidizing effect of ferric sulphate we have

$$FeS_2 + Fe_2(SO_4)_3 = 3FeSO_4 + 2S$$

and $2S + 6Fe_2(SO_4)_3 + 8H_2O = 12FeSO_4 + 8H_2SO_4$

Again the ferric sulphate may break up in the presence of water as follows:

$$Fe_2(SO_4)_3 + H_2O = 2FeSO_4 + H_2SO_4 + O$$

the atom of oxygen liberated being free to attack oxidizable substances.

Another important rôle played by ferrous and ferric salts is as solvents and precipitants of gold (Emmons).

Gold forms no soluble compound in the oxidized zone, and it is not soluble in sulphuric acid; nor is it soluble in ferric sulphate as has been sometimes stated.

If gold is in solution as the chloride, it is precipitated by ferrous sulphate, formed in manner indicated above, but if much manganese oxide is present, the ferrous sulphate is oxidized to ferric sulphate, which does not precipitate the gold. The presence of manganese oxides therefore favors the dissolving of gold in acid solutions, and it may be carried downward. On meeting a reducing environment, however, both the gold and manganese are precipitated.

Copper sulphides also are subject to oxidizing action, thus:

$$CuFeS_2 + 8O = CuSO_4 + FeSO_4$$

At times, however, a reduction may occur, as shown by the next equation:

$$CuSO_4 + 2FeSO_4 = Cu + Fe_2(SO_4)_3$$

The copper sulphate may be held in the oxidized zone as a result of the following reactions:

$$2CuSO_4 + 2H_2Ca(CO_3)_2 = CuCO_3(CuOH)_2 + 3CO_2 + 2CaSO_4 + H_2O$$

$$3CuSO_4 + 3H_2Ca(CO_3)_2 = 2CuCO_3(CuOH)_2 + 3CaSO_4 + 4CO_2 + 2H_2O$$

$$2CuSO_4 + 2FeSO_4 + H_2O = Cu_2O + Fe_2(SO_4)_3 + H_2SO_4$$

$$Cu_2O + H_2SO_4 = Cu + CuSO_4 + H_2O$$

$$CuSO_4 + H_2Ca(CO_3)_2 + H_4SiO_4 = CuO\ H_4SiO_4 + CaSO_4 + H_2O + CO_2$$

If zinc sulphide is present unaccompanied by pyrite the reaction will be:

$$ZnS + 4O = ZnSO_4$$

If, however, pyrite or some other source of $Fe_2(SO_4)_3$ is present, then the reactions may be more complicated, as shown by the following:[1]

$$ZnS + Fe_2(SO_4)_3 = 2FeSO_4 + ZnSO_4 + S$$

$$3ZnSO_4 + 3Na_2CO_3 + 4H_2O = ZnCO_3 \; 2Zn(OH)_2 + 3Na_2SO_4 + 2H_2CO_3$$

$$ZnSO_4 + Ca(HCO_3)_2 = CaCO_3 + ZnCO_3 + H_2SO_4$$

$$ZnSO_4 + 2NaHCO_3 = ZnCO_3 + Na_2SO_4 + H_2CO_3$$

Smithsonite is very likely to develop and replace limestone. Indeed in some cases it may be found lower than the sulphides.[2]

Downward Secondary Sulphide Enrichment (121–135).—In many ore bodies there is found below the oxidized zone a second one in which the ore may be richer than that above or below it. This zone, known as the *secondary sulphide zone*, has been enriched by the deposition of secondary sulphides, is of variable thickness and richness, and represents the results of important processes which have often converted a non-workable ore deposit into a workable one.[3]

The process of downward sulphide enrichment briefly stated is as follows: Ore minerals in the zone of weathering become converted into soluble compounds (sulphates chiefly), and these, on being carried down towards or below the water level, come in contact with unaltered sulphides or other reducing agents which reduce them again to insol-

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[1] Wang, Y. T., Amer. Inst. Min. Engrs., Bull. Sept., 1915.

[2] Loughlin, Econ. Geol., IX: 1, 1914.

[3] In this book, the term secondary sulphide enrichment is applied to the precipitation of sulphides below the oxidized zone, from meteoric waters, penetrating the ore body from above, and taking metallic salts from the oxidized to the unoxidized zone. Emmons (124) applies the term *primary* to all ore bodies whose chemical and mineral composition have remained essentially unchanged by superficial agencies since the ores were deposited. A *secondary* ore he classes as one that has been altered by superficial agencies.

Tolman classifies the minerals of an ore deposit into *original* minerals of the rock; *primary* minerals introduced by vapors and waters of deep-seated or igneous origin, and *secondary* minerals contributed by descending surface waters.

Rogers would apply the name secondary to a mineral formed at the expense, or by the replacement of, an earlier formed mineral. He then uses the term *upward secondary enrichment* for sulphides deposited from rising solutions, and *downward secondary enrichment* to those deposited from descending solutions. These two terms correspond respectively to Ransome's *hypogene* and *supergene*. (U. S. Geol. Surv., Bull. 540: 52, 1914.)

In the case of copper ores which Rogers has studied he states that the criteria of downward chalcocite enrichment may be summarized as: (1) comparatively regular replacement along anastomosing channels; (2) the presence of quartz veinlets related to chalcocite deposition; (3) the association of melaconite with chalcocite along veinlets. Criteria of upward chalcocite enrichment may be summarized as follows: (1) irregular intricate replacements; (2) the presence of so-called graphic intergrowths of bornite and chalcocite; and (3) presence of sericite related to chalcocite deposition.

uble sulphides. Thus they bring about a secondary enrichment of the ore body.

Important as this process is, it was not clearly recognized until a comparatively late date, when the writings of De Launay [1] in France, and of S. F. Emmons (23), Weed (135), and Van Hise (94), in the United States did much to increase our knowledge of the subject.

Not all ore minerals are subject to the process of secondary enrichment as outlined above, it being most often seen in ores of copper, gold, and silver.

Secondary sulphide enrichment like weathering may be affected by a number of, and sometimes the same, factors. These include climate, altitude, relief, permeability, geologic history of the locality, and chemical and mineral composition.

Warm climates favor chemical reactions, and cold climates not only retard them, but freezing temperatures prevent solution. Secondary-enrichment zones are rare in north latitudes as compared with southern ones. If formed in the past under different climatic conditions they may have been removed by glaciation.

Rainfall in abundance may be favorable, because of its stimulating effect on groundwater circulation, but scarcity of rainfall does not preclude the possibility of finding secondary ores, as a moderate supply of water acting through a long period of time may have yielded favorable results.

High altitude may act unfavorably because of rapid erosion and low temperatures, but under favorable conditions enrichment may occur.

Strong relief favors deep and rapid underground circulation and hence may cause relatively deep enrichment, while in a base leveled area the circulation will be sluggish, and the waters will not descend far before losing the metals dissolved higher up.

Slow erosion means a longer exposure of outcrop, hence long weathering and thorough leaching, but if the process continues there may be a downward migration of both the oxidized and secondary enrichment zone; the products of secondary enrichment may therefore be derived from portions of the ore body long since removed.

Permeability is an essential factor, because, unless the solutions can penetrate the unweathered part of the ore body, secondary enrichment cannot occur. The permeability may be due to original porosity of the ore, or to fractures caused by post-mineral movements. Comparatively small openings sometimes appear sufficient for permeation.

An important point to consider is the past topography, for the enrichment may have taken place when physiographic conditions were quite different from what they are now, and hence the zone of secondary sulphides shows no rational relationship to the present land surface.

Under normal conditions the secondary sulphides would be deposited at or

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[1] Les variations des filons métallifères en profundeur, Revue générale des Sciences, etc., Apr. 30, 1900, No. 8.

below water level, but subsequent changes in the latter, too rapid for the chemical changes to keep pace with, may result in secondary sulphides extending above the water level.

Criteria of Downward Secondary Sulphide Enrichment (126, 131).—These may be geologic, mineralogic, and textural. Any one alone will not necessarily afford conclusive evidence. The geologic criteria include suggestive surface conditions such as a leached ferruginous gossan, underlain by chalcocite and this in turn by cupriferous pyrite. Or the weathered zone may show argentiferous galena, more or less altered to cerussite, with deeper down the appearance in increasing quantities of sphalerite and pyrite. Assay maps of an ore body showing a lean zone above, passing downward into one of relatively greater richness, and this in turn into a much poorer zone, are also suggestive.

It is difficult to name any mineral as distinctively characteristic of secondary enrichment. Even chalcocite which at one time was regarded as typical of this process is now known to be formed by primary deposition.[1]

Textural criteria may be of value. Thus we find veinlets of rich ore in leaner material; the irregular replacement of one mineral by another (Pl. XXXVII); evidence of solution followed by deposition of fresh material; or grains of primary sulphide surrounded by secondary ones, as chalcocite surrounding pyrite. No one of these, however, should be used alone.

Chemistry of Secondary Sulphide Enrichment (124, 133).—The exact equations of secondary sulphide enrichment are not always known. Reference has already been made to some of those that may occur in the zone of weathering, resulting in the formation of soluble sulphates, chlorides or bicarbonates.

Precipitation below the water level may be due to: (1) reduction of sulphates to metallic sulphides by carbonaceous matter; (2) reduction by hydrogen sulphide; and (3) reaction of salts with sulphides.

With regard to the precipitation of sulphates by sulphides, it has been found that this agrees somewhat closely with Schuermann's law which arranges the metallic sulphides in a series, any member of which will be precipitated at the expense of any sulphide lower in the series.[2] His series was Hg, Ag, Cu, Bi, Cd, Pb, Zn, Ni, Co, Fe, Mn. According to this, pyrite, for example, would precipitate copper, lead, zinc, or

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[1] Tolman, Amer. Inst. Min. Engrs., LIV: 402, 1917. Etch figures of chalcocite.

[2] Liebig's Ann. der Chemie, CCXLIX: 326, 1888.

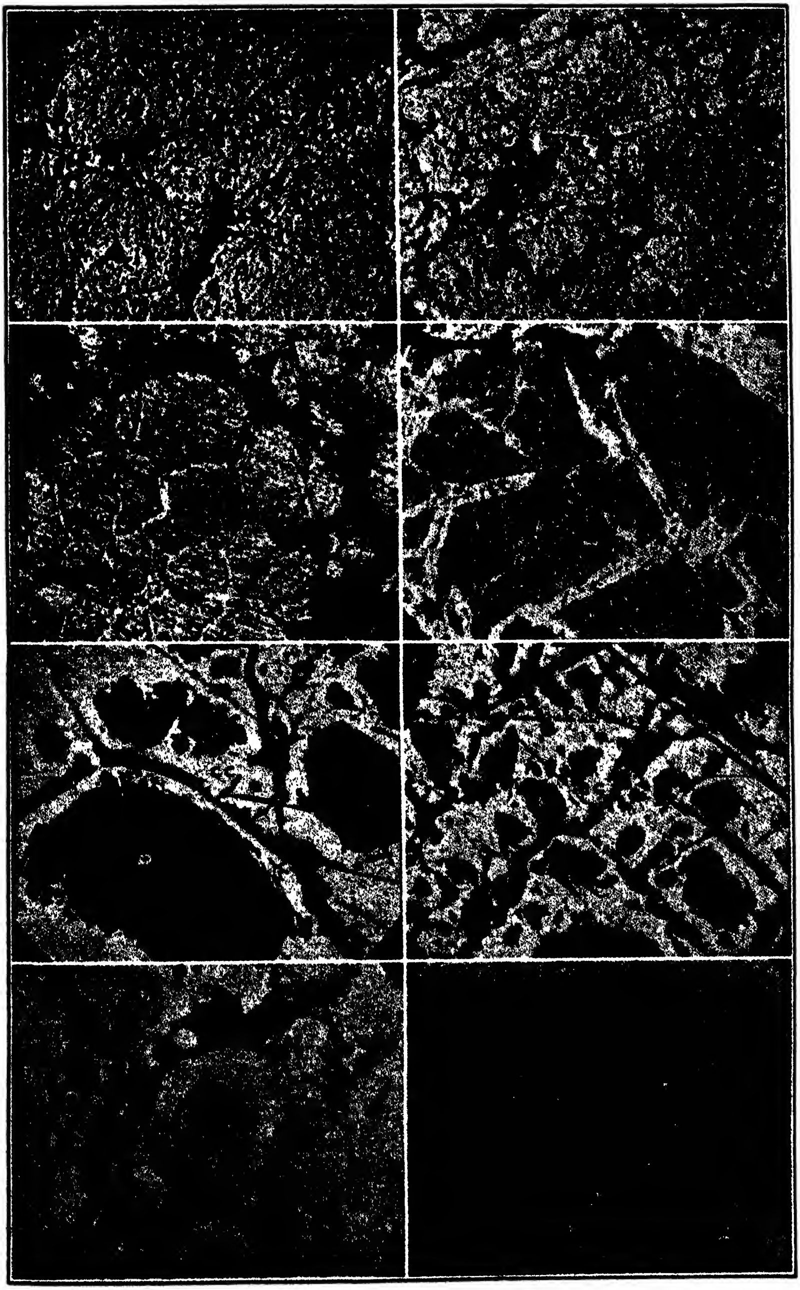

Plate XXXVII.—Photomicographs of polished specimens of ore from Burro Mountains, N. Mex., showing progressive replacement of pyrite (*p*) by chalcocite (*cc.*). ×40. (*R. E. Somers, photo.*)

others in the series above it. Again if we had descending solutions carrying copper, lead, and silver, the order of precipitation of the sulphides of these would be silver, copper, and lead sulphides.

The order of precipitation mentioned above may not hold under all conditions, for as mentioned by Tolman, on account of mass action, a strong solution of a metallic salt may cause a precipitate at the expense of a member of the series higher up.

Reactions of Secondary Sulphide Deposition (124).—Various reactions have been written to explain the precipitation of metallic sulphides in the zone of secondary enrichment. It is probable that some of them do not always state the case exactly, and that the change instead of being a simple and direct one may involve several intermediate steps. Thus, for example, chalcocite is found as a secondary mineral, precipitated by pyrite, but careful work by Graton and Murdock (126), corroborated by experimental work performed in the Carnegie Geophysical Laboratory at Washington,[1] has shown that the change from pyrite to chalcocite is not a direct one, but that there may be intermediate stages so that the order of formation in some cases at least is: Pyrite → Chalcopyrite → Bornite → Covellite → Chalcocite. These changes result from the action of copper sulphate solutions on sulphides, and at low temperatures are probably exceedingly slow.

For copper some of the enrichment zone reactions published are:

$$2CuSO_4 + 2FeS_2 = Cu_2S + 2FeSO_4 + 3S$$

or

$$14CuSO_4 + 5FeS_2 + 12H_2O = 7Cu_2S + 5FeSO_4 + 12H_2SO_4$$

$$4CuSO_4 + FeS_2 + 3SO_2 + 6H_2O = 2Cu_2S + FeSO_4 + 6H_2SO_4$$

$$CuSO_4 + CuFeS_2 = 2CuS + FeSO_4$$

or

$$2CuSO_4 + CuFeS_2 + SO_2 + 2H_2O = Cu_2S + CuS + FeSO_4 + 2H_2SO_4$$

$$CuSO_4 + 2FeS_2 + 2O = CuFeS_2 + FeSO_4 + SO_2$$

$$CuSO_4 + ZnS = CuS + ZnSO_4$$

$$CuSO_4 + H_2S = CuS + H_2SO_4$$

For zinc the equations may be:

$$ZnSO_4 + FeS_2 = ZnS + FeSO_4 + S$$

or

$$2ZnSO_4 + FeS_2 + H_2O = 2ZnS + FeSO_4 + H_2SO_4 + O$$

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[1] Day, Min. and Sci. Pr., CX: 841, 1915.

or

$$7ZnSO_4 + 4FeS_2 + 4H_2O = 7ZnS + 4FeSO_4 + 4H_2SO_4$$

For lead we have

$$PbSO_4 + FeS_2 + O_2 = PbS + FeSO_4 + SO_2$$

$$PbSO_4 + ZnS = PbS + ZnSO_4$$

It is difficult to distinguish secondary lead and zinc minerals from primary ones, because they are the same in each case, and while they no doubt occur, few well-defined cases have been described.[1]

Sphalerite has apparently not been found replacing pyrite, an exception being the deposits of supergene zinc at Balmat, N. Y. (Lead Zinc Ref. 63). Wurtzite has been found at several localities in the United States and may be of secondary character.

Secondary silver sulphides undoubtedly occur. The compounds said by Ransome to be more often secondary than primary are stephanite, polybasite, argentite, pyrargyrite, and proustite.

Hydrothermal Alteration (10, 19, 115).—The hot ascending solutions of varying composition often bring about a most profound alteration of the rocks which they traverse, extracting, it may be, certain elements and adding others. Indeed in some cases the alteration is so extensive that the rock affected bears no resemblance to its former self.

Alteration is usually most intensive along the fissures which guided the solution, but if the rock is extensively fractured it may be affected over a large area.

The changes produced will vary not only with the composition of the solution, but also with the temperature and pressure, and in some cases similar changes may be wrought by cold solutions of non-magmatic character.

The types of hydrothermal alteration which are well recognized are *propylitization, sericitization, silicification, alunitization,* and *greisenization*; others are *carbonatization, tourmalinization,* and *pyritization.*

Two of these may sometimes occur in the same rock.

Propylitization (19, 115).—This is a common type of alteration. It results in a change of the silicates to abundant chlorite, and pyrite, as well as epidote in some cases. Carbonates are likewise formed,

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[1] See Finlayson, Econ. Geol., V: 421, 1910; Weed, Amer. Inst. Min. Engrs., XXX: 424, 1911; Irving and Bancroft, U. S. G. S., Bull. 478: 97, 1911; Umpleby, *Ibid.*, Prof. Pap. 97: 87, 1917; Butler, *Ibid.*, Prof. Pap. 80: 154, 1913; Blow, Amer. Inst. Min. Engrs., Trans., XVIII: 172, 1890; Graton, U. S. G. S., Bull. 430, 71; 1910; Ransome, *Ibid.*, Prof. Pap. 75: 169, 119.

and in some cases there may also be sericite. The rocks so changed are usually of a greenish-gray color, but may preserve their original texture. The process may involve extraction of soda and potash, as well as silica, and even lime, and magnesia unless carbonates are formed, while the additions consist chiefly of sulphur and water.

Propylitization is developed chiefly in the epithermal zone and is a common accompaniment of some western gold and silver veins. It is found in the wall rocks at Virginia City and Tonopah, Nev., Cripple Creek, Colo., and other places. It also develops in mesothermal veins.

Sericitization.—This is a common type of hydrothermal alteration, which is often seen near veins, but may pass outward into propylitic alteration. The rocks so altered are white or light yellow in color, and the mass often appears clay-like. Indeed sericite masses are sometimes mistaken for kaolin, and it is difficult to distinguish sericite from kaolinite, under the microscope.

Sericitization involves a loss of soda and a gain of potash. Silica may be reduced or increased in amount, and carbonates may be formed, while pyrite is usually added. The resultant product is a fine-grained mixture of sericite, adularia, and pyrite, with sometimes calcite and quartz, the first-named of these being developed from both quartz and feldspar. Close to the vein, silification sometimes overshadows sericitization. The latter process may take place in veins of both shallow and intermediate depth; moreover although chlorite may be developed first, sericite may crowd it out later (Butte, Mont.).

Silicification.—This is also a common form of alteration associated with the deposition of ores, being more often noticed in acid than in basic rocks. Rhyolites may often show it, both the groundmass and phenocrysts being affected. At Goldfield, Nev., the silicified ledges so prominently associated with the ore bodies are formed by the alteration of andesite (Pl. LVIII, Fig. 2). The quartz thus formed is of cherty character, but the original structure of the rock may be clearly preserved. Limestones and other calcareous rocks may also be silicified, as in some contact metamorphic deposits. (See Bisbee and Miami, Ariz.)

In some cases silicification may be brought about by meteoric waters.

Alunitization.—This type of alteration, which is not a very common one, was first noticed at Goldfield, Nev., where the feldspars have been somewhat extensively altered to alunite. It is a change that takes place at shallow depths, and is thought to be due to the action of sulphuric waters.

The alunite at Goldfield occurs not only as a massive crystalline constituent of the altered rocks, but also intergrown with pyrite, gold, tellurides, and other minerals of the ore.

Alunitization has since been noticed at a number of other western localities. (See references under Potash.)

Greisenization.—The granite walls of many tin veins show a strong and characteristic alteration, the feldspar and muscovite being attacked by water vapors carrying fluorine and boric acid, resulting in the development of a mass of quartz, topaz, tourmaline, and lepidolite, to which the name *greisen* is applied. Cassiterite may also be present in the altered wall rock.

Value of Ores.—The terms *rich* and *poor*, as applied to ores, are used with great frequency, although most indefinite and often meaningless. Under very favorable conditions it is possible to work profitably an ore of given value at one locality, while if found under other less favorable conditions at another point it might be almost worthless.

Those who have not given special study to ore deposits often fail to realize that in the majority of ores the percentage of metal contained in the ore falls considerably below the theoretic percentage of the metallic contents of the ore-bearing minerals, owing, of course, to the presence of a greater or less quantity of gangue minerals which tend to dilute the metallic values of the vein. Many low-grade lead ores are profitably mined because their gold and silver contents more than pay the cost of metallurgical treatment. In many cases the metallic content of the ore is increased by mechanical concentration, by flotation, or by roasting (in the case of sulphides), or all three, before the ore is smelted.

Allowable Minimum of Metal in an Ore.—Iron ores are of little value, whereever they may be located, unless they contain at least 30 per cent of iron when charged into the furnace. They may in some cases be concentrated by washing, roasting, or magnetic separation.

Copper has an average minimum of probably under 2 per cent, but the Lake Superior ores, because of their peculiar characteristics, can be operated on a lower percentage. Some of the western disseminated copper sulphides, which are worked on such an extensive scale, average less than 2 per cent. In the case of these low-grade ores the metallic contents are raised by concentration or roasting, or both, before entering the furnace.

Lead.—In southeastern Missouri lead ores are profitably mined when carrying as little as 5 to 10 per cent metal, but the concentration raises the percentage up to 65 or 70 per cent.

Zinc ores on entering the furnace should have a minimum of 25 to 30 per cent zinc, but the contents are sometimes raised to 60 or more per cent by concentration, the concentrates being sold on a percentage basis. Some of the Missouri zinc ores as mined run as low as 3 per cent zinc.

Gold and Silver.—The metallic contents of these ores are expressed, not in percentages, but in troy ounces per ton, a troy ounce in a ton being 1/300 per cent. The market value of silver is, in round numbers, 75 cents per ounce, while gold in round numbers is figured at $35 per ounce. These prices, which are higher than formerly and due to government action, have resulted in the reopening of many mines.

Silver rarely occurs alone, and the ore may be treated primarily for its associated lead and copper.

Most of the gold and silver mined in the United States is rather low grade. In 1933 the average gold content was 0.18 ounce per ton, and silver 0.42 ounce. A large amount of these two metals is obtained from mixed ores, and the average is even lower except for silver in lead and lead-zinc ores.

Gold gravels containing as little as 4 or 5 cents gold per cubic yard may be worked by hydraulicking, and 10 to 15 cents by dredging.

Tin.—For this metal the crude ore commonly ranges from 1.5 to 3 per cent, but by concentration it can be raised to 70 per cent.

Nickel should reach 2 to 5 per cent in the crude ore.

Platinum.—Owing to the scarcity of this metal, few figures are available, but in Russia placers are worked which carry 1/40 ounce per cubic yard, which is the equivalent of 1/60 ounce per ton or 5.5 hundred-thousandth per cent.

Manganese to be considered of commercial grade must contain at least 35 per cent manganese and otherwise conform to the specifications of the trade in which the ore is used.

Chromium ore should carry 45 per cent Cr_2O_3.

Classification of Ore Deposits.—Many attempts have been made to develop a suitable classification of ore deposits, and many schemes have been suggested (19). These are usually based either on form, mineral contents, or mode of origin. The first is perhaps the most practical from the miner's standpoint; the second is undesirable because several kinds of ore may often be found in the same ore body; the third is the most scientific, and is of value to the mining geologist and engineer.

Those desiring to look into this phase of the subject in more detail are referred to the bibliography at the end of this chapter, especially the papers by Kemp (77), Posepny (89), Van Hise (18), and Lindgren (10).

The classification given here is that of W. Lindgren. It is based chiefly on genetic characters, and also attempts to indicate more definitely the physical conditions of deposition.

CLASSIFICATION OF ORE DEPOSITS (AFTER LINDGREN)

I. Deposits produced by mechanical processes of concentration. (Temperature and pressure moderate.)
  Ex. Placers of gold, platinum, etc.

II. Deposits produced by chemical processes of concentration. (Temperature and pressure vary between wide limits.)

- A. In bodies of surface water.
  - 1. By interaction of solutions:
    - *a.* Anorganic reactions. Clinton iron ore.
    - *b.* Organic reactions. Ex. Bog iron ore.
  - 2. By evaporation of solvents. (No metallic examples.)
  - Temp., 0°–70°±. Pressure moderate.
- B. In bodies of rocks.
  - 1. By concentration of substances contained in the geological body itself.
    - *a.* Concentration by rock decay and residual weathering near surface. Ex. Residual iron and manganese ores. — Temp., 0°–100°±. Pressure moderate.
    - *b.* Concentration by ground water of deeper circulation. Ex. Lake Superior iron ores. — Temp., 0°–100°±. Pressure moderate.
    - *c.* Concentration by dynamic and regional metamorphism. Ex. Fahlbands in some schists? — Temp. up to 400°. Pressure high.
    - *d.* Zeolitization of surface lavas. Ex. L. Superior copper ores. — Temp., 50°–300°. Pressure moderate.
  - 2. Concentration effected by introduction of substances foreign to the rock.
    - *a.* Origin independent of igneous activity.
      - By circulating atmospheric waters at moderate or slight depth. Ex. Miss. valley lead and zinc ores. — Temp., to 100°. Pressure moderate.
    - *b.* Origin dependent upon the eruption of igneous rocks.
      - a. By hot ascending waters of uncertain origin, but charged with igneous emanations.
        - 1. Deposition and concentration at slight depth. Ex. Goldfield, Nev. — Temp., 50°± – 150°±. Pressure moderate.

2. Deposition and concentration at intermediate depth. Ex. Leadville, Colo.; Cobalt, Ont.	Temp., 150° ± – 300° ±. Pressure high.
3. Deposition and concentration at great depth or at high temperature and pressure. Ex. Tin veins; Ontario quartz veins.	Temp., 300° ± – 500° ±. Pressure very high.
b. By direct igneous emanations.	
1. From intrusive bodies. Contact metamorphic deposits and allied veins.	Temp., probably 300° ± – 800°. Pressure very high.
2. From effusive bodies. Sublimates, fumaroles. No ore deposits.	Temp., 400° ±. Pressure atmospheric to moderate.

C. In magmas, by processes of differentiation.
  a. Magmatic deposits proper. Temp., 700°–1500°. Pressure high.
    Ex. Titaniferous iron ore. Chromite.
  b. Pegmatites. Temp. about 575°. Pressure very high.
    Ex. Molybdenum ore.

Metallogenetic Epochs (55–62).—The term metallogenetic epoch refers to a period of time during which a deposition of metals was taking place, and usually accompanied or immediately followed periods of igneous activity. This process has been active, during a number of periods in the past, as shown by the geologic records, and the available data for North America have been summarized by Lindgren as follows (59).

Pre-Cambrian Period.—The pre-Cambrian rocks, which underlie a number of extensive areas in the United States, include not only metamorphosed schists and gneisses, but also various types of intrusives, the characteristic metals being iron, copper, nickel, gold, and silver. Lead and zinc are less abundant than they are in the later periods, while quicksilver and antimony are rare.

The ilmenites and magnetites of the eastern states are chiefly of igneous origin, while the hematites of Lake Superior are partly igneous and partly sedimentary, but subsequently oxidized and concentrated by surface waters, a process which is believed to have gone on in pre-Cambrian times. The copper and nickel ores are associated with basic igneous rocks, some of these, as in Michigan, being of effusive nature. This copper concentration Lindgren suggests must have gone on in pre-Cambrian times, following the close of Keeweenawan (Algonkian) volcanic activity. Of similar age are the cobalt-silver veins of Ontario. The auriferous-quartz veins of the southern states, whose deposition followed that of granitic intrusions in schists, are also to be placed here, although some writers would date them later.

In the Cordilleran region the pre-Cambrian was productive of gold and copper deposits, which are found at many points from South Dakota and Wyoming to Arizona. These gold ores are usually lenticular quartz veins in schists, associated with such gangue minerals as tourmaline, garnet, etc. The copper ores often contain chalcopyrite, and form veins or irregular masses, which are probably of magmatic origin, and have been modified by dynamo-metamorphism. Sphalerite may accompany the chalcopyrite, but lead is almost entirely wanting.

In Ontario a careful study of the pre-Cambrian rocks by Miller and Knight[1] (60) has shown the possibility of recognizing at least five metallogenetic epochs as follows:

1. Grenville.—Epoch of extensive deposition of "iron formation," as a chemical precipitate among other sediments.

2. Timiskanian.—Epoch of minor deposition of "iron formation" as a chemical precipitate.

3. Algoman.—Epoch following granite intrusions, of gold at Porcupine and other localities, and of auriferous mispickel. Preceding granite intrusions, basic intrusions of probable post-Timiskanian age, gave rise to nickel, titaniferous and non-titaniferous magnetites and chromite.

4. Animikean.—Epoch of deposition of "iron formation" as a chemical precipitate.

5. Keweenawan.—Epoch following basic intrusions of: (*a*) silver, cobalt, nickel and arsenic at Cobalt and elsewhere; (*b*) nickel and copper at Sudbury and copper elsewhere.

Paleozoic.—During this time a number of granitic intrusions occurred from New York and New England northward to Quebec and Nova Scotia, and these were accompanied by the formation of some gold-quartz veins; but little metallization occurred in the West during this period.

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[1] For classification used here, see Geol. Soc. Amer., Bull. XXVI: 87, 1915.

Two periods of iron-ore formation occurred during Paleozoic time in the East. One of these was in the Silurian, when the persistent beds of low-grade Clinton hematite were formed; the other was during the Carboniferous, when the layers of carbonate black-band ores were deposited.

Mesozoic.—During the Triassic, small deposits of copper and iron ores were formed in the eastern states, along the contact of the trap sheets and sedimentary rocks. The deposits were in part veins and in part of contact-metamorphic character.

In the West important accumulations of ores were beginning, for during the Triassic there began a series of eruptions which continued through the Jurassic, the products of these being basic lavas which were extruded from California to Alaska. The metallization accompanying or following these yielded copper deposits, which include some of those found in California, British Columbia, and those of the Copper River region in Alaska.

Another important metallization epoch followed the intrusion of the great early Cretaceous quartz-monzonite or grano-diorite batholiths of the Pacific coast.

These injections were of vast extent, one batholith extending through California, and another from Washington up through British Columbia to Alaska, while other smaller masses occur in several of the western states. These intrusions were followed by intense metallization, mineral deposits being formed in abundance around the margin of the batholiths, as in the gold belt of California. Gold was the chief metal formed, with copper next. Along the Pacific coast, where there is little limestone in the intruded sediments, lead is rarely found, but in the interior (Nevada and Idaho) where limestones were present, lead and zinc both occur. Silver is everywhere present, but is rarely important unless associated with lead; arsenic and antimony are rare; and mercury is wanting in commercial quantities.

Early Tertiary.—About this time, perhaps a little earlier, or a little later, important concentrations of lead and zinc took place in the Mississippi Valley, but they show no close connection with igneous intrusions, and have been thought by most geologists to represent the work of surface waters, the ultimate source of the metals being the pre-Cambrian rocks.

At the close of the Cretaceous violent outbursts began along the eastern margin of the Cordilleran region, the magmas being of intermediate character and laccolithic form. They occur from British Columbia through Montana, Colorado, New Mexico, and eastern Arizona down into Mexico.

There ensued then another or third epoch of Cordilleran metallization, during which many contact-metamorphic deposits and veins were formed around the margins of the laccoliths. Gold and silver are the characteristic metals, with abundant lead and zinc, especially where the intrusions cut limestones. The latter may also show copper and iron along the contact. Arsenic and antimony are more common than they were in the earlier epochs, but mercury is still rare.

Late Tertiary.—After a period of mountain-making disturbances, uplift, warping, and dislocations, there were extruded a series of lava flows which spread over a large area in the far West, and are prominent in California, Washington, Oregon, Idaho, Colorado, Utah, Nevada, New Mexico, and Arizona. Andesites and rhyolites predominate. This was accompanied by a fifth metallization, whose characteristic metals are gold and silver, forming deposits often of great richness; lead and zinc are not abundant, except in limestone, and neither is copper. Tellurium and antimony are common; not that they are absent in older metallizations, but the tellurium seems to be especially characteristic of this epoch. The metallic deposits seem to be somewhat restricted, occurring mainly near the foci of igneous activity.

Post-Pliocene.—There came finally an epoch of metallization at a late date, restricted, however, to the Pacific coast line, and characterized by the mercury deposits of the Pacific coast belt.

Cretaceous or Later Copper Epochs.—These, being of wide time range, cannot be included in the previous classes. They represent disseminations of copper in sandstones, shales or conglomerates, and carry in most cases primary chalcocite with a little silver.

Summary.—The following table of Lindgren (p. 410) summarizes the conditions for the western states.

Metallographic Study of Ores (63–72).—Due to the opaque character of most ore minerals these cannot be examined in thin sections by transmitted light, as is done with non-metallic minerals.

Another method of study, known as *Mineragraphy*, has therefore been developed and consists in examining polished surfaces of the ore under the microscope by reflected light. By this means the relationships of the different metallic minerals in the ore can be quite satisfactorily studied, and differentiated by means of their color, microchemical tests, etc. Pl. XXXVII shows a series of ore specimens examined and photographed in the manner described above. This method of

	Principal Metals	Principal Rocks Associated with Deposits
1. Deposits of the pre-Cambrian period	Gold and copper	Granites, diorites, gabbro
2. Deposits of the early Mesozoic epoch	Copper	Basalt, diabase, gabbro
3. Deposits of the late Mesozoic epoch	Gold	Grandiorite, quartz-monzonite
4. Deposits of the early Tertiary epoch	Gold, silver Copper, lead, zinc	Grandiorite, quartz-monzonite, monzonite
5. Deposits of the late Tertiary epoch	Gold, silver	Andesite Rhyolite,
6. Deposits of the Post-Pliocene epoch	Quicksilver	Basalt
7. Cretaceous or later concentrations in sedimentary rocks	Copper	Sandstone, shale, conglomerate

study has been most helpful in studying genetic problems, secondary enrichment processes, etc.

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CHAPTER XIV

IRON ORES

Iron is an abundant constituent of the earth's crust, and yet few minerals are capable of serving as ores of this metal, because they do not contain it in the right combination or in sufficient quantity to make its extraction possible or profitable.

The iron ores having the greatest commercial value at the present day are usually those which are favorably located, of high quality, in considerable quantity, and possessing a structure such as to render their extraction easy. These four requirements have been met to such an eminent degree by the deposits located in the Lake Superior district that they now form the main source of supply for furnaces in the eastern and central states, and many of the iron mines in the eastern part of the United States have found it difficult to compete with them, although it is true that a number of deposits are worked to supply local demand, owing to their proximity to furnace, flux, and coal, or because they possess certain desirable characteristics.

Iron-ore Minerals.—The ore minerals of iron, together with their composition and theoretic percentage of metallic iron, are:

MAGNETITE.	Magnetic iron ore, Fe_3O_4	72.4%
HEMATITE.	Specular iron ore, red hematite, fossil ore, Fe_2O_3	70%
LIMONITE[1]	Brown hematite, bog ore, brown ore, $2Fe_2O_3$, $3H_2O$	59.89%
SIDERITE.	Spathic ore, blackband, clay-iron stone, kidney ore, $FeCO_3$	48.27%

Of subordinate value:

PYRITE.	FeS_2	46.6%
FRANKLINITE.	$(Fe, Zn, Mn)O, (Fe, Mn)_2O_3$	±44.1%
PYRRHOTITE.	Chiefly FeS	±61.6%

Chamosite and thuringite, both iron-rich chlorites are common in some European bedded iron ores.

Magnetite is black, often granular with a metallic luster. It has a black streak, hardness of 5.5–6.5, specific gravity of 5.5–6.5, and is strongly magnetic. Some occurrences may run high in titanium, especially those found in basic igneous rocks. Hematite is red to brownish red, steel-gray, or even black. It

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[1] The group name "*brown ore*" may include several hydrous oxides, such as limonite, turgite, and göthite. See also Amer. Jour. Sci., XLVII: 311, 1919.

is commonly fine-grained, but the specular varieties may be quite coarse. It ranges from massive to powdery, and has a specific gravity of 5.2. Limonite is never crystalline, and varies widely in appearance; some forms are powdery others massive, and these may be porous, vesicular, stalactitic, or even, though rarely, solid. The specific gravity is 3.8. The color is brown to brownish yellow on the fracture, but may be black and shiny on the natural surface. Göthite (Fe_2O_3, H_2O) and other hydrous oxides with less water than limonite are sometimes associated with it. Indeed much of the commercial limonite or brown ore is an intimate mixture of several of the hydrous oxides of iron. Siderite, when occurring in commercial quantities, is rarely in cleavable form, but occurs as a fine-grained mass, with impurities. Hematite is by far the most valuable of the iron-ore minerals, chiefly on account of its easier reduction, but also because of the greater richness of the known important deposits.

The deficiency in iron content shown by many ores is due to the presence of common rock-forming minerals in the gangue, the impurities which they supply being alumina, lime, magnesia, silica, and also metallic minerals which have titanium, arsenic, copper, phosphorus, and sulphur. The effect of the last four is in general to weaken the iron.

Silica is objectionable because it displaces iron, and because just so much lime is required to flux it, but some furnaces turn out iron for foundry purposes containing 10 or more per cent. Ores carrying as high as 40 per cent SiO_2 are used in small quantities. Lime in small amounts does no harm, but in large quantities needs to be fluxed off. It is not present in any quantity in limonite, but may run high in the Clinton red ores. Alumina may run somewhat high in limonites, because of admixed clay. Pyrite is the common source of the sulphur, but in some limonites it may come from gypsum or barite. Titanium, a common ingredient, is found in some quantity in many magnetite deposits (see Titaniferous magnetites, also refs. 34, 41) and up to the present time has rendered them practically useless, not because it interferes with the quality of the iron, but because it makes the ore highly refractory, and drives much of the iron into the slag. Experiments have been made looking towards the utilization of these titaniferous magnetites for the manufacture of ferrotitanium; indeed these have been used for several years in the manufacture of this alloy, for although rutile is preferred it is too expensive. Manganese, when present, is found mostly in the limonite ores and for certain purposes is desirable. It is also prominent in some of the Lake Superior ores. Apatite yields the phosphorus. As this cannot be eliminated in either the blast furnace or the acid converter used in making Bessemer steel, and as the allowable limit of phosphorus in pig iron used for this purpose is $\frac{1}{10}$ per cent, a distinction is usually made between Bessemer and non-Bessemer ores, the maximum amount of phosphorus permissible in iron ore to be used for this purpose being $\frac{1}{1000}$ of the percentage of metallic iron contents of the ore. The phosphorus contents of many high-grade ores falls considerably below the allowable limit.

Classification.—Iron-ore deposits have originated in a number of different ways, including: 1, Magmatic segregation deposits (Lake

Sanford, New York, etc.). 2. Contact-metamorphic deposits (Iron Springs, Utah, etc.). 3. Sedimentary ores (bedded hematite and limonite, bog ores, etc.). 4. Ores concentrated by meteoric waters, and deposited as replacements (some Lake Superior hematites, Oriskany limonites), or in residual materials (Virginia Cambro-Silurian limonites). 5. Lenticular masses in metamorphic rocks, of variable origin (some magnetite and pyrite deposits). 6. Gossan ores (limonite capping of many sulphide ore bodies). 7. Replacements by ascending waters. 8. Placer deposits (magnetite sands).

Iron-ore bodies may show a variety of form, but many of the important deposits known in this country are lens- or basin-shaped in outline. Irregular masses and beds are not uncommon.

Iron ores show a wide geologic distribution, those found in the United States, for example, ranging from pre-Cambrian to Recent. The occurrences of the different kinds of ore are best discussed separately, and for practical as well as for other purposes a mineralogic and geographic grouping seems better in this case than a genetic one.

MAGNETITE

United States.—Magnetite occurs (Fig. 127) (1) as lenticular masses commonly in metamorphic rocks; (2) as more or less lens-shaped and tabular bodies in igneous rocks; (3) as sands on the shores of lakes and seas; (4) as contact-metamorphic deposits; (5) as replacements in limestone, not of contact-metamorphic character; (6) as veins, and (7) in residual clays.

The first class includes the most important deposits now worked in this country. The second [1] and third groups run too high in titanium to have any commercial value at the present time, but the second may become of importance in the future, and moreover some of its representatives are of large size. Examples of the fourth class are known at a number of points in the West, and while few of them are worked, they may some day become of great importance. They carry hematite in addition to magnetite. The fifth, sixth, and seventh groups are unimportant.

Distribution of Magnetites in the United States [2] (Fig. 127). **Non-titaniferous Magnetites.**—These are usually found in the form of lenticular deposits in metamorphic rocks. The most important series of

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[1] This is not true of all the European deposits.

[2] Magnetites in general fall into two classes on basis of titanium content, viz., the non-titaniferous and titaniferous.

occurrences lies in the crystalline belt of rocks extending from New York into Alabama, deposits being known in New York, New Jersey, Pennsylvania, Virginia, and North Carolina.

The lenses, which are interbedded with gneisses of either acid or basic character and often conform with the latter in dip and strike, are of variable size, and may occur either singly or in series, the ore body commonly showing pinching and swelling, or even faulting. Well-defined boundaries are sometimes wanting. Feldspar, hornblende, and quartz are common gangue minerals, while apatite is prominent in some. Although the ore as mined is frequently of sufficient purity to be shipped direct to the blast furnace, in some instances it is so lean as to require concentration by magnetic methods. A description of one or two occurrences will serve as types:

FIG. 127.—Map showing distribution of hematite and magnetite deposits in the United States. (*After Harder, U. S. Geol. Surv., Min. Res.*, 1907).

Adirondack Region, New York (24, 37).—The rocks of the Adirondack region (Fig. 128) are almost exclusively of pre-Cambrian age, with occasional inliers of the bordering Paleozoic strata, whose basal member, the Potsdam sandstone, rests unconformably on the older crystallines. The latter have in most cases been subjected to powerful compression, and sometimes greatly changed by metamorphism, in fact so much so that their original character is determinable with difficulty.

The following members are recognized, beginning with the oldest: I. *Metamorphic Rocks.*—1. *Sedimentary or Grenville Series.* These consist of limestones and dolomites, often impregnated with pyrite, graphite, and silicates, and by an increase in the latter may pass into schists. Both rock types occur in long narrow belts, bounded by sedimentary gneisses. 2. *Gneisses of acid to basic character*, often showing garnet, sillimanite, graphite, kyanite, pyrite, etc. 3. *Amphibolites*, which are composed mainly of hornblende and feldspar, and which may be metamorphosed dikes or magnesian shale. 4. *Quartzites* of infrequent occurrence. 5. *Gneisses* of doubtful relationships.

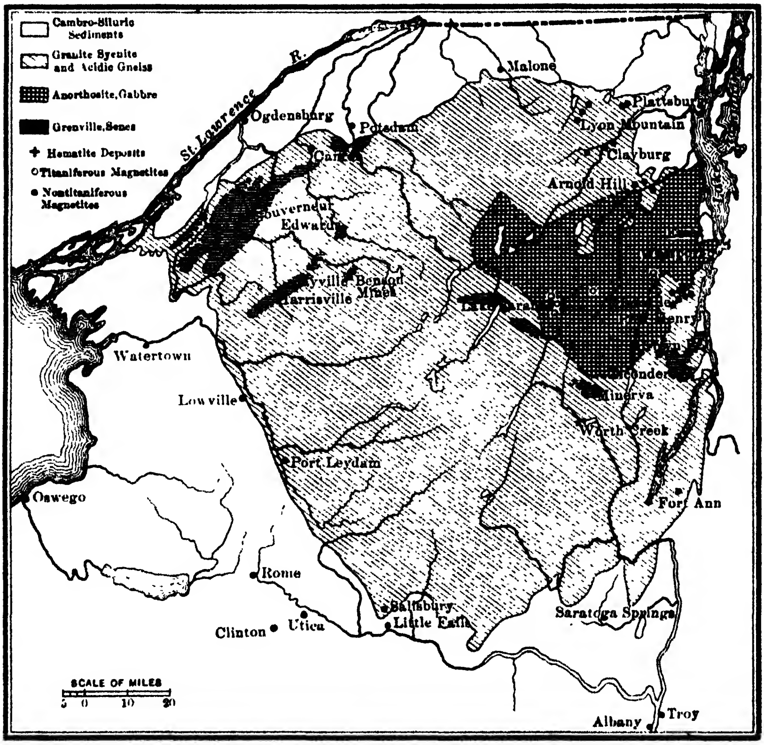

FIG. 128.—Geologic map of Adirondack Region, New York, showing location of iron-ore deposits. (*After Newland, Econ. Geol., II.*)

Igneous Rocks (55).—These include: (1) anorthosite (the earliest), gabbro, syenite, and granite, all connected by intermediate rock types and probably representing derivations from the same magma. (2) Dikes, mostly diabase.

Ores.—The non-titaniferous magnetites are the most widespread of the Adirondack ores, and occur on both the eastern and western sides of the mountains.

The ores vary from impure lean varieties, consisting of magnetite mixed with the country-rock minerals (*i.e.*, quartz, feldspar, pyroxene, hornblende, etc.), to pure magnetite. The richest ore averages 60 to 70 per cent iron, and comes chiefly from Mineville, while those ores carrying under 50 per cent have to be concentrated. The phosphorus content is variable, but seems to be lower in the leaner ones, while in the non-Bessemer ores it may exceed 2 per cent. The amount of sulphur is also variable, but is highest in those ore bodies found in the Grenville gneiss.

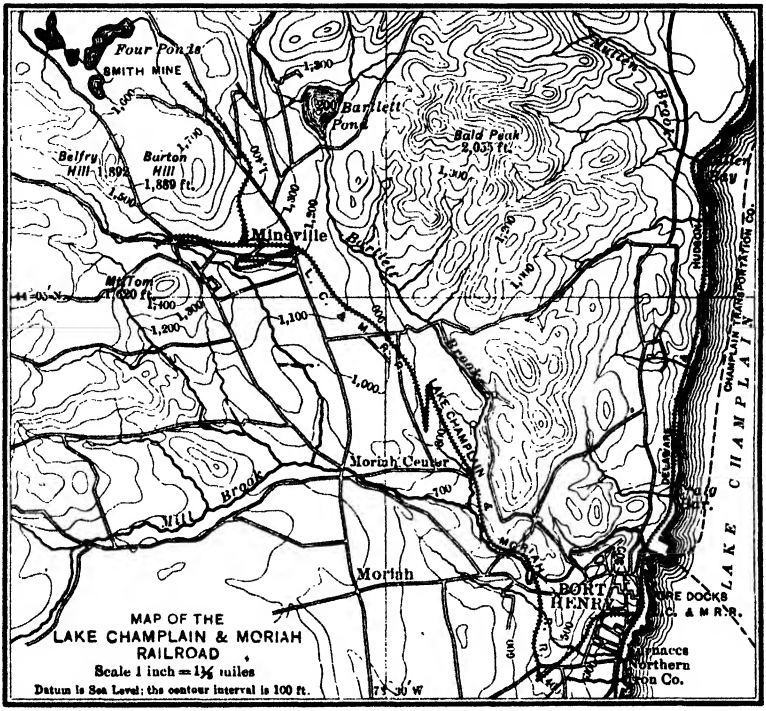

FIG. 129.—Map of Mineville, N. Y., iron-ore district. (*After Granbery, Eng. and Min. Jour., LXXXI.*)

While the ore bodies are variable in shape they show in general a somewhat lenticular cross-section, with the tabulation extending parallel with the strike; but regularity is more common on the north and west sides of the province, for in the eastern districts there is the greatest irregularity due to a complexity of pinches, swells, and compressed folds. The wall rocks include gneisses of granitic, syenitic, and dioritic composition, as well as schists and occasionally limestones.

Mineville, New York (37).—The ore bodies at this locality are the largest and most productive in New York State at the present time. They are of lenticular character, but in some cases the lenses are so flat and of such extent as to be commonly spoken of as beds; moreover, some of them have been bent over into a southwesterly pitching fold, whose crest has been stretched and pinched, while faulting at the northern end of this has complicated the structure.

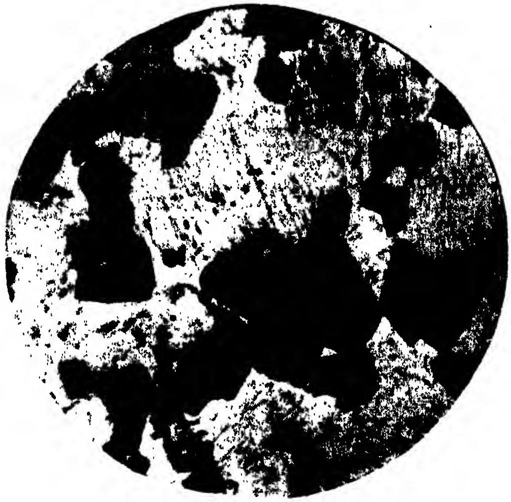

FIG. 130.—Thin section of magnetite gneiss, Lyon Mountain, N. Y. Magnetite (black); feldspar (gray); pyroxene (crossed cleavage). ×30.

The ores occur as integral members of the syenite series, and are in the form of layers conformable to the banding or foliation of the inclosing rocks.

There are at least three large ore bodies (Fig. 131), viz.:

1. The Barton Hill ore body, forming a practically continuous bed, whose outcrop is approximately 3500 feet long in a direction a little east of north. Iron content, 30–35 per cent; concentrates, 65 per cent; Fe, 0.025 per cent P.

2. The Harmony bed, lying to the southwestward of Barton Hill, and striking northwest, with a rather flat southwest dip. It is 10 to 20 feet thick and cut by several narrow trap dikes which occupy fault planes of 10 to 50 feet displacement.

PLATE XXXVIII

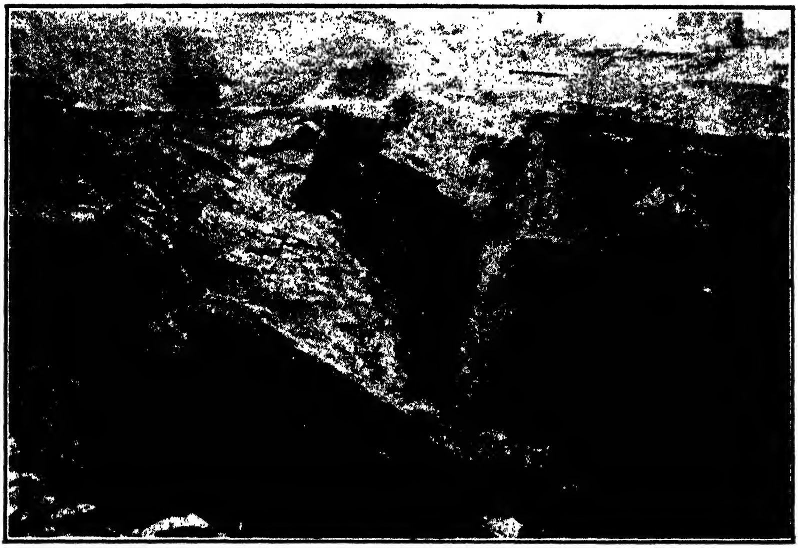

FIG. 1.—View of open cut in magnetite deposit, Mineville, N. Y. The pillars are left to support the gneiss hanging wall. (*After Witherbee, Iron Age, Dec.* 17, 1903.)

FIG. 2.—General view of magnetic separating plants and shaft houses, Mineville, N. Y. (*After Witherbee, Iron Age,* 1903.)

3. A large ore body which appears to be made up of three principal and separated parts, known as the Miller, the Old Bed or Mine 23, and the "21"-Bonanza-Joker. This is the chief source of the ore. There is some doubt whether there is any connection between the Joker and the Harmony. This Old Bed group extends in a practically unbroken

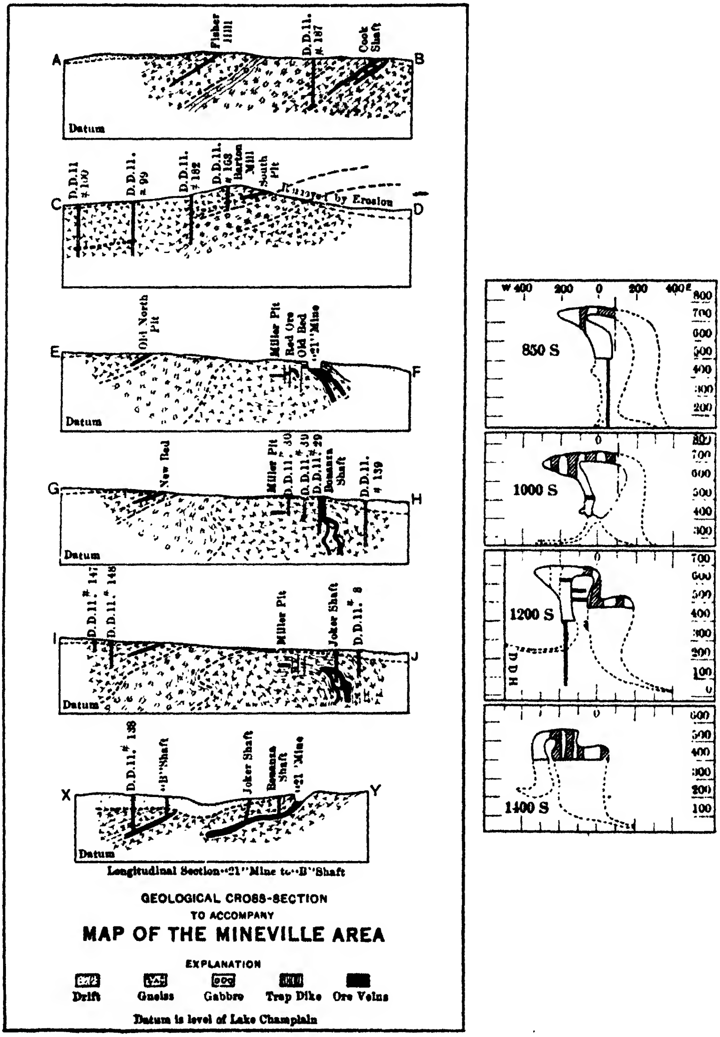

Fig. 131.—Sections of the old, "21"-Bonanza-Joker ore beds, Mineville, N. Y. (*After Granbery, Eng. and Min. Jour., LXXXI.*)

stretch for about a half-mile, exhibiting at the same time a most complex fold, referred to above.

The ores are granular masses of magnetite which in the Barton Hill group were prevailingly of Bessemer grade, but which in the Old Bed series are high in phosphorus.

The lean ores are mixed with the minerals of the wall rocks, and among these the basic syenite is the chief one.

At Lyon Mountain (36) the ore is a lean magnetite traceable for 6 miles and from 20 to 200 feet wide, and occurs in a rock intermediate between granite and syenite. Most of the ore is low in phosphorus, the concentrates carrying about 0.008 per cent P and 65 per cent Fe.

New Jersey.—In northern New Jersey, the magnetite deposits form layers or bands in the Franklin (pre-Cambrian) limestone, or as flat lenses in the associated gneisses.

The ore, according to Bayley (26), consists mainly of magnetite, hornblende, pyroxene, and apatite, sometimes intimately mixed. Pyrite and quartz are not uncommon, and all the associated minerals occur in the country gneiss.

The ore bodies, which are lens-shaped, lie with their longer axes conforming to the foliation of the gneisses, and the ore usually grades into the gneiss, although sharp boundaries are in some cases known. Several lenses may overlie each other, and then the intervening rock may be either gneiss, pegmatite full of magnetite, or coarse-grained hornblendic rock, with ore veinlets paralleling the foliation of the gneiss. This series of magnetites extends northeastward into the Highland region of New York.

Origin of Magnetites.—The origin of the magnetites found in the gneisses has formed a puzzling problem to geologists, whose correct solution depends in part at least on the correct interpretation of the origin of the inclosing rocks.

If the gneisses are of sedimentary origin, then it is possible that the ores may represent metamorphosed deposits of magnetite sands, limonite, or siderite, and the parallelism of the ore bodies with the foliation of the gneisses might be regarded by some as evidence in favor of such a view.

But even if the gneisses were of sedimentary origin, it might still be possible that the ores were of later introduction, as has been suggested by some. Thus Keith held the view that the North Carolina magnetites were replacement deposits, while Kemp formerly advanced the theory that the ore bodies at Mineville (37) have been formed by iron-bearing magmatic waters, which were given off from the neighboring gabbros and penetrated the gneisses while the latter were probably still at great depths, and before their metamorphism was complete. The presence of apatite and fluorite was thought to show that mineralizing vapors also played a part. A similar origin was suggested by Spencer for the New Jersey magnetites (45). Colony (28) and Smith (43) have both suggested that the magnetites of southeastern New York and northern New Jersey respectively have been brought in by hydrothermal solutions following the injection of the associated pegmatites.

Studies by Kemp and Newland in the Adirondacks (37) seem, however, to indicate that the acid gneisses are probably of igneous origin, and that the magnetites themselves are products of magmatic differentiation. Newland points out that there is no obstacle to this because the acid igneous rocks of the region contain a large excess of iron over the amounts combined with the lime and magnesia to form silicates. The peculiar form of some of the ore bodies is likewise perhaps explainable only by this theory. A fact not to be overlooked, however, is the occurrence of fluorite, apatite, hornblende, etc., intercrystallized with magnetite, or the frequent association of the latter with pegmatite or vein quartz, a group of conditions which are sug-

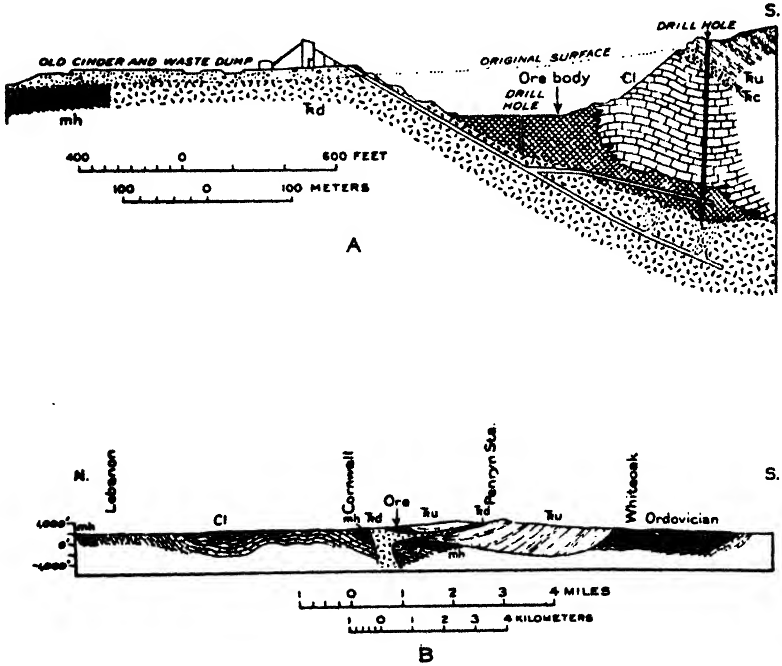

FIG. 132.—Section through iron ore deposit, Cornwall, Pa. (*After Cummings, XVI, Internat. Geol. Cong., Guide Book 8.*)

ŦC, Triassic conglomerate; Ŧu, Triassic undifferentiated; Ŧd, intrusive diabase; Cl, Cambrian limestone; mh, "Mill Hill slate."

gestive of mineralizing agents, and their deposition by pneumatolytic or aqueous action, as Alling has suggested (24).

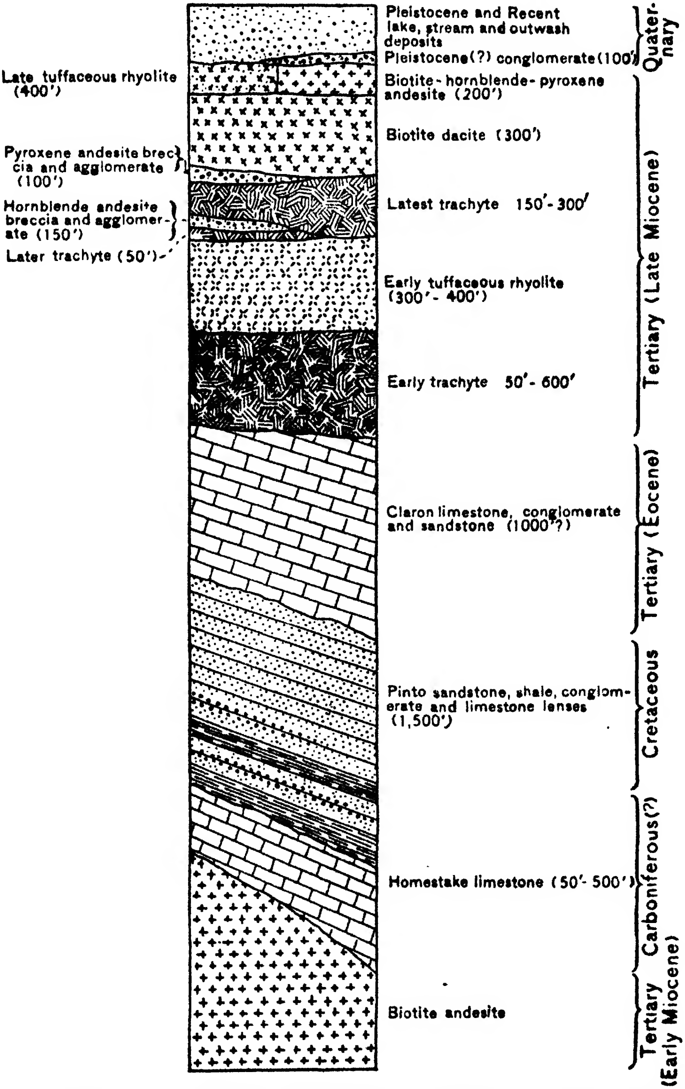

FIG. 133.—Geologic column of the Iron Springs, Utah district. (*After Leith and Harder, U. S. Geol. Surv., Bull.* 338.)

Cornwall, Pennsylvania (33).—A somewhat unique deposit occurs at Cornwall, Lebanon County, Pa., and at several other localities in southern Pennsylvania. The ore is found along the contact of Triassic diabase, with Cambro-Ordovician limestones or more rarely Triassic shales, and consists mainly of magnetite, specular hematite, pyrite, and chalcopyrite. The gangue minerals are pyroxene, garnet, tremolite, actinolite, and talc. The ore forms large and small masses of irregular shape, lying either within the sediments or along the contact. The ore averages about 45 per cent iron, is low in phosphorus, but high in sulphur, silica, lime, and magnesia. It also carries some copper.

Iron Springs, Utah (35).—Iron deposits are widely scattered over the western states, but few have been worked, owing to the limited demand in that region. They can be regarded, however, as reserves which may become of importance in the future. Among the best known of these are those of the Iron Springs district of southwestern Utah, which belongs to the contact-metamorphic type.

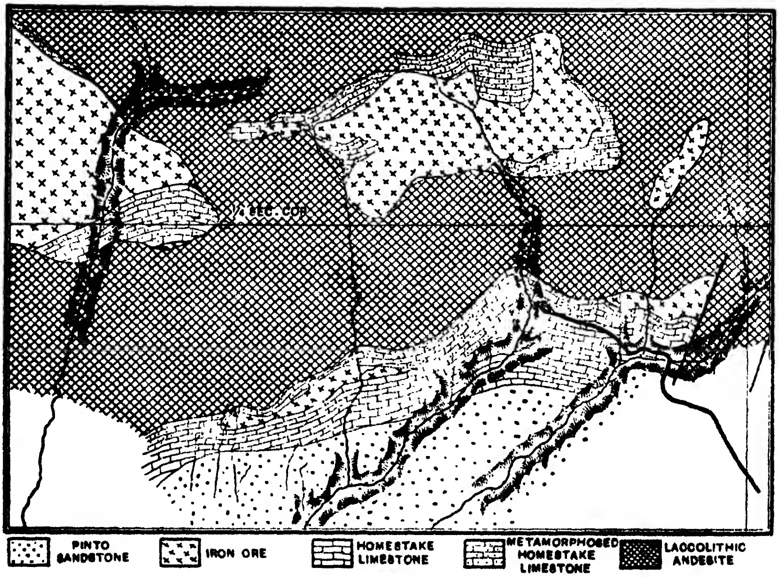

FIG. 134.—Map of a portion of the Iron Springs, Utah district, showing occurrence of iron ore in limestone near andesite contact, and also in the igneous rock. (*After Leith and Harder, U. S. Geol. Surv., Bull.* 338.)

At this locality the series of sedimentary rocks ranges from Carboniferous to Pleistocene (Figs. 133, 134), and is intruded by three laccoliths of biotite andesite, which have especially affected the Homestake (Carboniferous) limestone, and to a lesser extent the Claron (Tertiary) limestone.

The ore bodies are of three types, viz.: (1) fissure veins in andesite; (2) fissure and replacement deposits on the contact of the andesite and Carboniferous limestone; and (3) as breccia cement in Cretaceous quartzite.

The second of these is the most important, and while the ore bodies are roughly lens-shaped, with their longer diameters parallel to the contact, still there are numerous irregularities, due to faulting and other causes. The ore bodies which have been developed in recent years to supply the local industry are worked both by open pit and underground workings.

The ore consists of magnetite and hematite with a small amount of limonite, the first two, of course, being characteristic of contact-metamorphic deposits. The ore shows a hard, crystalline texture at the surface, but, as is sometimes found in arid regions, becomes softer with depth. The gangue is chiefly quartz or chalcedony near the surface, but calcite increases with depth. The contact minerals, garnet, diopside, apatite, mica, hornblende, and other silicates, are minor constituents.

While much of the ore runs above 60 per cent in iron, the average is about 56. Phosphorus is uniformly high, but sulphur, copper, and titanium are not in prohibitive amounts.

Leith and Harder believe that the ores are closely related in origin to the andesite laccolith intrusions, but do not consider that the andesite has contributed much to the ore deposit except iron. This view has been attacked by Kemp and others.

Other Occurrences.—Small deposits of magnetite are found in the limestones of the Shenandoah Group and their residual clays in southwestern Virginia (22). Magnetite representing contact metamorphosed iron formation is abundant in the eastern Mesabi range, Minnesota (56). It occurs sparingly in the Marquette Range of Michigan, where it is found in the schists. Contact-metamorphic deposits are found at a number of localities in the West, but the chief occurrences are in Colorado, New Mexico, Utah, and California. That at Fierro, N. Mex. (30) occurs in Paleozoic limestone, near its contact with a Tertiary monzonite porphyry. Another found at Heroult, Calif., lies chiefly at the contact of diorite and Triassic limestone (40).

Analyses of Magnetites.—The table on p. 429 gives the composition of non-titaniferous magnetites from a number of localities. It is not possible in all cases to obtain analyses of recent date.

Canada.—Two magnetite occurrences in eastern Canada are those at Bathurst, N. B., and Moose Mountain, Ont. Some magnetite has

ANALYSES OF MAGNETITES

	I	II	III	IV	V	VI	VII	VIII	IX
Fe . . .	60.03	60.91	61.69	59.93	56.05	64.9	56.00	61.85	80.4^1 7.5^2
SiO_2 . .	4.48	4.49	18.90	7.72	7.76	3.98	7.	4.74	2 4
P	1.635	1.548	1.30^5	0.08	0.036	0.021	0.2	0.112	0.011
S	0.021	0.027	1.23	0.19	0.06	0.071	0.057	0.015	0.099
Ti . . .	0.12	0.03	1.30	——	——	——	——	——	——
Cu . . .	——	0.007	——	——	——	0.005	0 027	——	——
Moist . .	0.28	0.25	——	——	——	——	3.	2.62	——
Mn . . .	——	——	0.55^4	0.17	none	0.158	0.196	2.42^3	0.18^4
Al_2O_3 . .	——	——	12.48	——	——	0.324	1.	0.74	——
CaO . .	——	——	4.45	——	——	1.010	4.	0.16	——
MgO . .	——	——	0.86	——	——	1.131		0.95	0.3

I. Sample 60 carloads. II. Sample 35 carloads, 21 pit, both Mineville, N. Y., N. Y. State Museum, Bull. 119 : 82. III. Warren County, N. J., N. J. Geol. Surv., Ann. Rept. 1873 : 80 IV. Philpot, Patrick County, Va., U. S. Geol. Surv., Bull. 380 : 219. V. Limestone magnetite. Abingdon, Va., *Ibid.* VI. Cornwall, Pa., Amer. Inst. Min. Engrs., Trans. XIV : 892. VII. Iron Springs, Utah, U. S. Geol. Surv., Bull. 338. VIII. Hanover, N. Mexico, U. S. Geol. Surv., Bull. 380 : 212. IX. Shasta County Calif., Econ. Geol., III : 472.

^{1} Fe_3O_4. ^{2} Fe_2O_3. ^{3} MnO_2. ^{4} MnO. ^{5} P_2O_5.

been obtained at Torbrook, N. S.,[1] and north of Lake Superior, but both of these are better discussed under Hematite.

Bathurst, N. B. (121).—The magnetite here forms three bodies, which are replacements in quartz porphyry or tuff. Both the igneous rocks and ore are more or less schistose or banded. The ore, which consists largely of magnetite with a variable amount of hematite, is fine grained, fine to coarse banded, and with sharply defined walls.[2]

Moose Mountain, Ont. (134).—This deposit is situated north of the Sudbury nickel basin (q. v.). The magnetite shows a more or less strongly banded structure, due to alternations of iron ore and silica, while epidote sometimes fills fissures in the ore, which are often bordered by hornblende that passes outwards into magnetite. The iron formation which lies in Keewatin schists is steeply tilted.

Texada Island, B. C. (128).—Contact-metamorphic deposits of magnetite with some copper, occurring in limestone near granite and diorite contacts are found on Texada Island, northwest of Vancouver, but they have not been steadily worked.

Other Foreign Deposits (1).—Two of the most remarkable deposits of magnetite known in the world are those of Kiruna and Gellivare in northern Sweden.[3]

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[1] Can. Geol. Surv., Sum. Rept., 1916: 273, 1917.

[2] See Moore, Canada's Mineral Resources, 1929, Toronto, for other deposits.

[3] Sjögren, Amer. Inst. Min. Engrs., Trans. XXXVIII: 766, 1907. Stutzer, Zeitschr. prak. Geol., XIV: 65 and 137, 1906.

That at Kiruna occurs as a great steeply dipping tabular or dike-like mass, traceable for about 8 kilometers in the hills of Kirunavaara and Luossavaara (Pl. XXXIX, Fig. 1, and Fig. 135), and has a width of 32 to 152 meters. The total tonnage as determined from outcrops and borings is estimated at 480 000,000 tons. The footwall is an orthoclase porphyry or syenite, while the hanging wall is quartz porphyry, which in turn is overlain by quartzites, clay slates, and conglomerates, supposedly of pre-Cambrian age.

The ore is a fine-grained mixture consisting chiefly of magnetite and apatite (Fig. 135).

Much discussion has been aroused over the origin of these ores. Högbom in 1898 thought them to be due to magmatic segregation, while de Launay argued for a sedimentary origin, assuming that the footwall was a submarine flow, from which iron chlorides and sulphides emanated in gaseous form and were then oxidized to ferric oxide, which later was changed to magnetite by a covering flow of quartz porphyry. Stutzer has regarded the ore as a dike, whose intrusion was preceded by the footwall syenite, and followed by the hanging wall quartz porphyry. It may also have been intruded between the syenite and quartz porphyry.

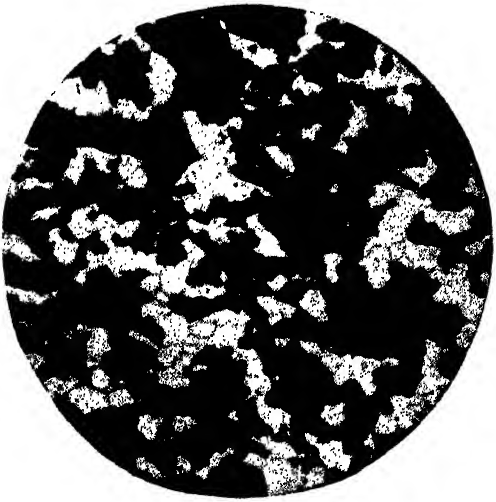

Fig. 135.—Photomicrograph of thin section of ore from Kiruna, Sweden. Black magnetite; white, apatite.

At Gellivare (Pl. XXXIX, Fig. 2), the ore is similar to Kiruna mineralogically, but coarser grained. It occurs as steeply dipping irregular lenses, in a gray or red gneiss, often surrounded by a curious hornblendic zone (*skarn*). The ore is probably similar in origin to that at Kiruna, but has been strongly altered by metamorphism.[1]

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[1] Sjögren, *loc. cit.*, and Lundbohm, Internat. Geol. Cong., Sweden, Guidebook, 1910.

Other large magnetite deposits are known in the Ural Mountains at Wyssokaia Gora and Goroblagodat.[1] Of historic and scientific interest are the contact metamorphic deposits of magnetite with some sulphides found in the province of Banat, Hungary, and first described by von Cotta.[2]

Most interesting are the Cuban[3] deposits lying in a belt stretching eastward from Santiago, and supplying ore which is chiefly magnetite, but carries some hematite and pyrite, especially in its upper parts. Prominent among the sedimentary and igneous rocks of the district is a large area of intrusive diorite which encloses fragments of an older, bedded limestone. The ore deposits consist of: (1) small streaks to larger ones in limestone, with quartz, garnet, and epidote gangue, and evidently of contact-metamorphic origin; (2) great tabular masses in diorite, but showing the same gangue minerals as the first. Kemp regards the latter as replacements along fracture zones in the diorite, while Lindgren is inclined to the view that the ore bodies are a product of contact metamorphism exerted by the diorite on included masses of limestone.

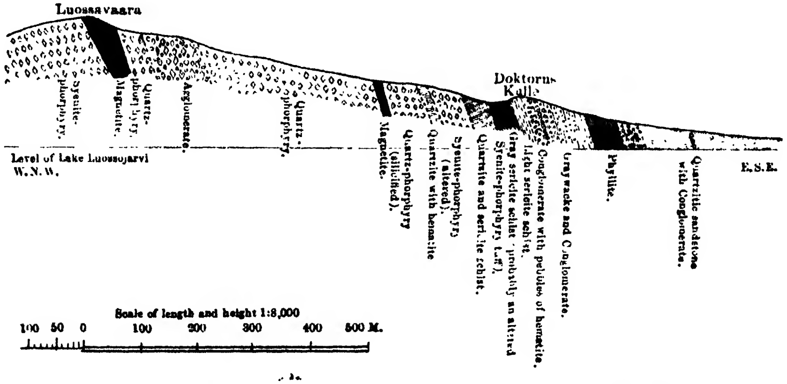

FIG. 136.—Section across Luossavaara near Kiruna, Sweden. (*After Lundbohm.*)

Titaniferous Magnetites (9, 34, 37, 41).—These form a peculiar class by themselves, and with one or two exceptions are found always associated with rocks of the gabbro family. The ore bodies usually represent products of magmatic segregation, and may occur: (1) within the eruptive mass but grading off into it; (2) as irregular bands (schlieren); or (3) as dikes which have separated from the magma at greater depth, and then forced their way upward.

An exception to any of the above is the deposit at Cebolla Creek, Colo., which is in part of the contact-metamorphic type (42).

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[1] Beck, Erzlagerstätten, 3rd ed., I: 29.

[2] Beck, *loc. cit.*

[3] Kemp, Amer. Inst. Min. Engrs., Trans. LIII: 3, 1916; Lindgren, *Ibid.*, LIII: 40, 1916; Roesler, *Ibid.*, LVI: 77, 1917; Singewald and Miller, *Ibid.*, LIII: 67,

PLATE XXXIX

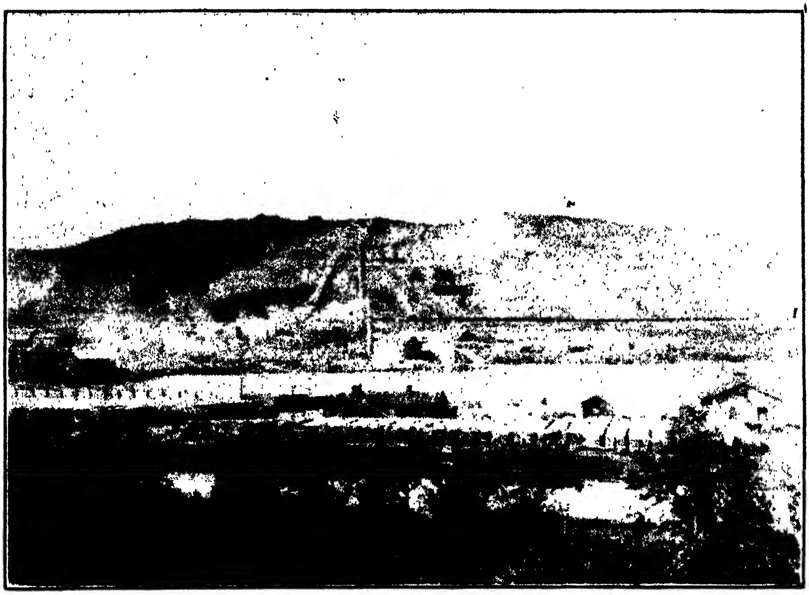

FIG. 1.—View of iron ore mines in Kirunavaara, Sweden. Open cuts near top in iron ore. Lower slopes chiefly hanging wall. (*H. Ries, photo.*)

FIG. 2.—Iron deposit at Gellivare, Sweden. Note pit in floor connecting with lower workings. Walls of cut are country gneiss and in part "skarn." (***H. Ries, photo.***)

Many titaniferous magnetites are granular aggregates of magnetite and ilmenite. The ilmenite is highly lustrous with a rougher surface, while the magnetite shows duller, black, parting surfaces. The grains of the latter sometimes have minute intergrowths of ilmenite, which show most commonly as lines and dots, the former representing sections of very small ilmenite lamellæ oriented parallel to the octahedral faces of the magnetite. Ramdohr[1] explains this apparent intergrowth as due to unmixing by slow cooling.

The gangue minerals may be pyroxene, brown hornblende, hypersthene, enstatite, olivine, spinel, garnet, and plagioclase. The ores are usually low in phosphorus and sulphur, but vanadium, chromium, nickel, and cobalt are almost always present.

Titaniferous magnetites are found in many parts of the world, the deposits being often of large size, but they have been little developed due to the fact that it is often impossible to separate the ilmenite (non-magnetic) from the magnetite (magnetic) to a sufficient degree, owing to the fine intergrowths of the two.

The analyses on the following page illustrate their composition.

United States (34, 41).—In this country titaniferous magnetites are found in New York, New Jersey, Wyoming, Minnesota, Virginia, Colorado, etc., but are not worked. The two localities of greatest importance are Sanford Hill, in the Adirondack region of New York, and Iron Mountain, Wyo.

Descriptions of two localities will serve to illustrate the mode of occurrence of these titaniferous ores.

New York (34, 37).—Titaniferous magnetite deposits of large size occur in the Adirondack region, and while they carry TiO_2 as an essential ingredient, the percentage of this element may vary considerably. Thus in the Adirondack ores it is at least 8 to 9 per cent (TiO_2), and averages 15 per cent.

The ores are closely associated with gabbro-anorthosite intrusions, and are found chiefly in Essex and southern Franklin counties. At Lake Sanford, where the most important ore bodies occur, the small deposits are found in gabbro dikes cutting the anorthosite and having a tabular form conformable with the strike of the dikes, but large ones occur in the anorthosite and may be segregations during cooling, or actual intrusions forced into the anorthosite after partial consolidation.

The ores are essentially magnetite and ilmenite, the richest showing little else and running about 60 per cent Fe. The magnetite grains are

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[1] **Festschr. 2:150, Jahrfeier d. B. A. Clausthal, 1925.**

ANALYSES OF TITANIFEROUS MAGNETITES

	1	2	3	4	5	6	7	8
FeO . . .	70.50	80.78	27.95	79.78	70.80	28.84	24.55	51.44†
Fe_2O_3 . . .	—		15.85			14.05	48.97	—
TiO_2 . . .	14.00	12.09	15.66	12.08	19.52	10.11	23.18	16.76
SiO_2 . . .	8.60	2.02	17.90	0.75	1.39	22.35	2.15	—
Al_2O_3 . . .	4.00	2.58	10.23	4.62	4.00	5.26	—	—
Cr_2O_3 . . .	—	2.40	0.51	0.32	—	Tr.	—	—
V_2O_5 . . .	—	—	0.55	Tr.	—	0.18	—	—
MnO . . .	—	—	T .	0.28	—	0.43	—	—
CaO . . .	1.60	—	2.86	0.13	—	1.17	—	—
MgO . . .	2.30	—	6.04	2.04		16.10	—	—
H_2O . . .	—	—	0.04	—	—	0.42	—	—
P_2O_5 . . .	—	0.03	0.14	—	0.022*	0.12	—	0.97*
S	—	—	—	—	0.028	0.38	0.03	—
Na_2O . . .	—	—	—	—	—	0.44	—	—
K_2O . . .	—	—	—	—	—	0.10	—	—
Zn	—	—	—	—	—	0.71	—	—
Cu	—	—	—	—	—	0.03	—	—
Ço, Ni . .	—	—	—	—	—	7.08	—	—
Pb	—	—	—	—	—	— Tr.		—

1. Grape Creek, Col. 2. Mayhew Range, Minn. 3. Split Rock, N. Y. 4. Greensboro, N. Ca.; Nos. 1–4, U. S. Geol. Surv., 19th Ann. Rept., III : 377, 1899. 5. Lake Sanford, N. Y., N. Y. State Mus., Bull. 119 : 163. 6. Cumberland Hill, R. I., Amer. Jour. Sci., Jan., 1908. 7. Iron Mountain Wyo,, U. S. Geol. Surv., Bull. 315 : 209. 8. Marksville, Va., Min. Res. Va., 1907 : 419.

* P. † Fe.

recognizable by parting planes parallel to the octahedron and smooth and but slight magnetism. Other minerals present are plagioclase, pyroxene, hornblende, biotite, olivine, garnet, pyrite, apatite, spinel, and quartz. The usual order of crystallization is reversed, being silicates, pyrite, ilmenite, magnetite. Analyses of the Sanford deposits show 70.73–87.60 Fe_3O_4, 0.87–2.46 SiO_2; 9.45–20.03 TiO_2; 0.53–4.00 Al_2O_3; 0.007–0.022 P; 0.027–0.028 S.

The following results (p. 436) were obtained by magnetic separation after crushing to 40 mesh. Finer crushing would probably improve the product.

Wyoming (25).—An occurrence of titaniferous magnetite of some importance is found at Iron Mountain in southeastern Wyoming. Iron Mountain is a ridge 300 to 600 feet wide, and 1¼ miles long, which rises sharply from the anorthosite hills to the east and pre-Cambrian uplands to the west. The pre-Cambrian complex near the iron ore dike consists of three granular igneous rocks, viz., anorthosite, iron ore, and granite, the anorthosite, or oldest, being cut by dikes and lenticular masses of iron ore and granite.

	1	2	3
	MAGNETITE	CONCENTRATE	ILMENITE AND OTHER MINERALS
Fe_2O	55.9	54.39	14.28
FeO	27.5	28.66	30.93
TiO_2	14.0	8.93	45.23

The ore, which forms a dike 1¼ miles long, 40 to 300 feet wide, and has a northerly strike, is sharply bounded on both sides by anorthosite, and paralleled by several smaller dikes. It is a black, granular, holocrystalline rock, which carries as impurities biotite, olivine, and feldspar. The iron content averages about 50 per cent.

It is suggested (Ball) that the ore and anorthosite are differentiation products from a common magma, the iron having been intruded after the complete solidification of the anorthosite; but the relationship of the two is shown by the presence in each of similar minerals, although their proportions are different.

The granite is probably the youngest of the pre-Cambrian rocks, and grades into, as well as being cut by, a biotite-pegmatite which carries some magnetite.

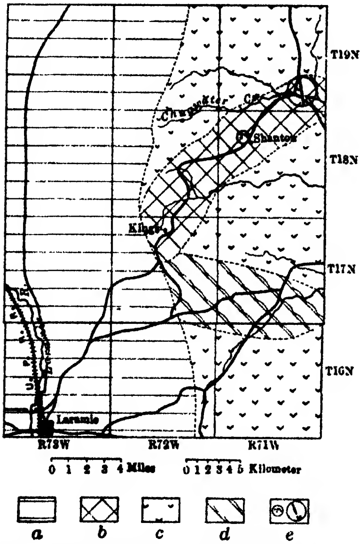

FIG. 137.—Map of Iron Mountain, Wyo., titaniferous magnetite deposit. *a*, post-Devonian; *b*, anorthosite; *c*, granite; *d*, gneiss; *e*, ore. (*After Kemp, Zeitschr. prak. Geol.*, 1905.)

Fig. 138 is a section of a low-grade titaniferous ore found in gabbro at Cumberland, Rhode Island (48).

Magnetite Sands.—These are found in those regions where the beach sands are composed of weathering products of metamorphic and igneous rocks. The sorting action of the waves serves to carry the heavy mineral grains high up on the beaches, where they form black streaks, composed mostly of magnetite (usually titaniferous), mixed with monazite, apatite, and other heavy minerals.

Deposits are known in this country on the shores of Lake Champlain, Long Island, etc., but they are of small extent as well as lacking in quality.

New Zealand,[1] Japan[2] and Brazil are said to possess magnetite sands of commercial value.

Sandstones of Upper Cretaceous age, and carrying titaniferous magnetite, are known in Montana, but are of no commercial value (46).

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[1] Aubel, Amer. Inst. Min. Met. Engrs., Trans., LXIII: 266.

[2] E. and M. J., CXXIII: 243, 1927.

Canada (120, 127).—Titaniferous magnetites have been found at a number of localities in Ontario, those of the Chaffey and Matthews mines being well known. Another large deposit occurs at St. Urbain, Quebec. (See under Titanium.)

Fig. 138.—Section of Cumberlandite (Rhodose) from Cumberland, R. I. Black ilmenite and magnetite; white, olivine. ×30.

Along the St. Lawrence River, in Saguenay County, Quebec (127), magnetite sands are somewhat abundant. Where the sands have been worked over by the waves, the magnetite grains have been concentrated into lenses distributed through the ordinary sand. Analyses of the sand, etc., are given below:

	Fe[1]	TiO_2[1]	Insoluble Residue	P	S
Crude sand	14.7	4.43	76.00	.006	.006
First concentrate	67.2	3.51	7.45	.043	.012
First tailings	8.3	4.7	——	——	——

[1] Soluble iron only.

Other Foreign Deposits.—A number of titaniferous magnetite deposits are found in Scandinavia. The best known is that of the Ekersund-Soggendal[1] on the south coast of Norway, where the labradorite rock contains some large ore bodies. Routivare in northern Sweden has a large mass of spinel-bearing titaniferous magnetite in altered gabbro, while at Taberg in southern Sweden is still another large deposit, which occurs in olivine-gabbro and was recorded as early as 1806.

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[1] Beyschlag, Vogt u. Krusch, Ore Deposits, Translation, I: 250, 1914.

HEMATITE

This is by far the most important ore of iron in the United States, having in 1935 formed over 91 per cent of the total production, and about 84 per cent of the hematite mined came from the Lake Superior region. It is also an important ore in some other countries. Hematite may occur mixed with magnetite in magmatic segregations (Kiruna, Sweden, q. v.) and contact-metamorphic deposits (35), as beds in sedimentary rocks (69–78), as replacements in limestone (Spain); as irregular deposits formed by circulating surface waters (p. 460); and as specular hematites in metamorphic rocks (L. Superior).

Distribution of Hematite Ores in the United States (Fig. 127).—At the present day there are but two very important hematite-producing regions in the United States, viz., the Lake Superior region and the Birmingham, Ala., district. Other areas which are worked will also be referred to, but they are less important.

Lake Superior Region (62, 65).—Under this head are included a great series of deposits lying in the region surrounding the south and west sides of Lake Superior (65). The rocks are of remote geologic age, and the age and names of the iron-bearing formations are as follows:

Algonkian system.
  Keweenawan series: Carries titaniferous gabbros in Minnesota but no hematite.
  Huronian series:
    Animikie group.
      Biwabik formation of Mesabi.
      Animikie group of Animikie district, Ontario.
      Ironwood formation, Penokee—Gogebic district, Michigan and Wisconsin.
      Vulcan formation, Menominee and Calumet districts, Michigan.
    Vulcan iron-bearing member of Crystal Falls, Iron River, and Florence districts, Michigan and Wisconsin.
      Gunflint formation, Gunflint Lake district, Canada, and Vermilion district, Minnesota.
      Bijiki schist, Marquette district, Michigan.
      Deerwood iron-bearing member, Cuyuna district, Minnesota.
      Negaunee formation, Marquette district, Michigan.
Archæan system.[1]
  Keewatin series:
    Soudan formation, Vermilion district, Minnesota.
    Helen formation, Michipicoten district, Ontario.
    Unnamed formation of Atikokan district, Ontario.
    Several non-productive formations in Ontario.

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[1] The Lower Huronian and Laurentian, although present in the series of formations found in this region, do not carry any ore bodies.

The ore-bearing districts have been studied in considerable detail, but the intervening parts are less well known, and it is therefore difficult to correlate the major geological units of the several districts.

Character of Formations.—The Archæan includes a complex series of acid and basic igneous rocks, and two or more sedimentary formations, including the iron formations and slate of the Keewatin. The Algonkian includes four unconformable sedimentary series, all associated with igneous rocks, the entire succession being separated by an unconformity from the Archæan below and the Potsdam above.

The iron ores occur as concentrations in the so-called iron formations, which range in thickness from a few hundred to a thousand feet.

In their present form these iron formations represent alterations of chemically deposited sediments, such as cherty iron carbonates, which are usually interbedded with normal clastic sediments such as slate and quartzite.

In general terms the iron formations may be described as consisting mainly of chert or quartz and ferric oxide, usually segregated into bands, but sometimes irregularly mixed. Jasper is a banded rock of highly crystalline character with the quartz layers colored red. Ferruginous chert differs from it in being less crystalline, and with the quartz either banded or irregularly mingled. This latter type is known as *taconite* in the Mesabi district. Other phases of the iron formation are clay slates, paint rocks (alterations of preceding), amphibole-magnetite schists, cherty iron carbonate, hydrous ferrous silicate (greenalite), and iron ores.

The original iron rocks were cherty iron carbonate, ferrous silicate, and pyritic iron carbonate, and unaltered remnants of these are still found.

The average iron content of all the original phases of the iron-bearing formations for the region, excluding interbedded slates, is 24.8 per cent, and the iron ores, though of great commercial importance, form but a small percentage of the rocks of the iron-bearing formations. This percentage varies from 0.062 to 2.00 per cent.

The iron ores are the result of subsurface alterations of richer layers of the iron-bearing rocks, and are localized both where these alterations have been most effective, and structural features have served to collect the underground waters.

The existence of ore, then, depends largely on secondary concentration. Of great importance in determining the distribution of the ores are impervious basements and fractures, the former often shaped like pitching troughs.

The ore bodies vary widely in their form, although steeply dipping deposits are the rule, with the horizontally tabular ones of the Mesabi range forming a marked exception.

The ores of the Lake Superior region vary from hard blue ores to soft earthy ones. They are mostly hematite with small quantities of limonite, but some magnetite is known in the Marquette district.

The following tables, taken from Van Hise and Leith, show the average composition and range of Lake Superior ores. Many additional ones can be found in the reports on Mineral Resources issued annually by the United States Geological Survey.

Average Composition of Total Yearly Production of Lake Superior Iron Ore for 1906 and 1909

	1906	1909
Moisture	——	11.28
Analysis of ore dried at 212° F.:		
Iron	59.80	58.45
Phosphorus	0.081	0.091
Silica	6.83	7.67
Alumina	1.60	2.23
Manganese	2.70	0.71
Lime		0.54
Magnesia		0.55
Sulphur		0.06
Loss by ignition	3.92	4.12

The range in percentages shown by the analyses from which the foregoing averages are derived is as follows:

Range of Each Constituent of Ores Yielding the Above Averages

	1906	1909
Moisture at 212° F.	——	.50 to 17.40
Range of ore dried at 212° F.		
Iron	38.15 to 66.07	35.74 to 65.34
Phosphorus	0.008 to 0.85	0.008 to 1.28
Silica	3.21 to 40.97	2.50 to 40.77
Manganese	——	0.00 to 7.20
Alumina	0.20 to 3.59	0.16 to 5.67
Lime	——	0.00 to 4.96
Magnesia	——	0.00 to 3.98
Sulphur	——	0.003 to 1.87
Loss on ignition	0.00 to 10.0	0.40 to 11.40

In addition there are given below two other tables compiled by Birkenbine.

TYPICAL ANALYSES OF LAKE SUPERIOR IRON ORES

CONTENT	MARQUETTE RANGE	MENOMINEE RANGE	GOGEBIC RANGE	VERMILION RANGE	MESABI RANGE
Iron	56.5	55.2423	56.308	61.36	56.0996
Phosphorus	0.0353	0.0594	0.0338	0.0373	0.0365
Silica	4.584	6.7693	3.3961	4.2545	3.4867
Sulphur	0.0089	—	—	—	—
Moisture	11.85	6.525	10.828	4.5649	12.3158

ANALYSES OF SILICEOUS ORES

CONTENT	MARQUETTE RANGE	MENOMINEE RANGE	VERMILION RANGE
Iron	42.27	42.129	51.1938
Phosphorus	0.0316	0.0244	0.0498
Silica	35.834	34.141	22.3642
Sulphur	0.0099	—	—
Moisture	1.23	2.2	3.21

The Lake Superior region includes the following districts:

DISTRICTS	STATE	AREA SQ. MI.
Marquette	Mich.	330
Menominee	Mich.	112
Crystal Falls	Mich.	540
Iron River	Mich.	210
Florence	Wis.	75
Calumet and Felch Mtn.	Mich.	200
Penokee-Gogebic	Mich.-Wis.	450
Vermilion	Minn.	1400
Mesabi		
Cuyuna	Minn.	300
Michipicoten	Can.	140

The general mode of occurrence of the ore in several of these is shown in Figs. 140 to 142, and the more important ones are referred to individually below.

Marquette Range (66).—This occupies a rather large area west and southwest of Marquette, Mich., and carries iron formations in both the Upper and Middle Huronian, the latter being the more important. That of the Upper Huronian is underlain by quartzite and covered by slate, while the Middle Huronian iron formation is underlain by slate which in turn rests on quartzites. Igneous intrusions of Keweenawan age are common. The structure of the range is that of a great east-west synclinal basin containing a number of minor folds, and while the ores occur on both limbs of the basin, they are most abundant on the northern one.

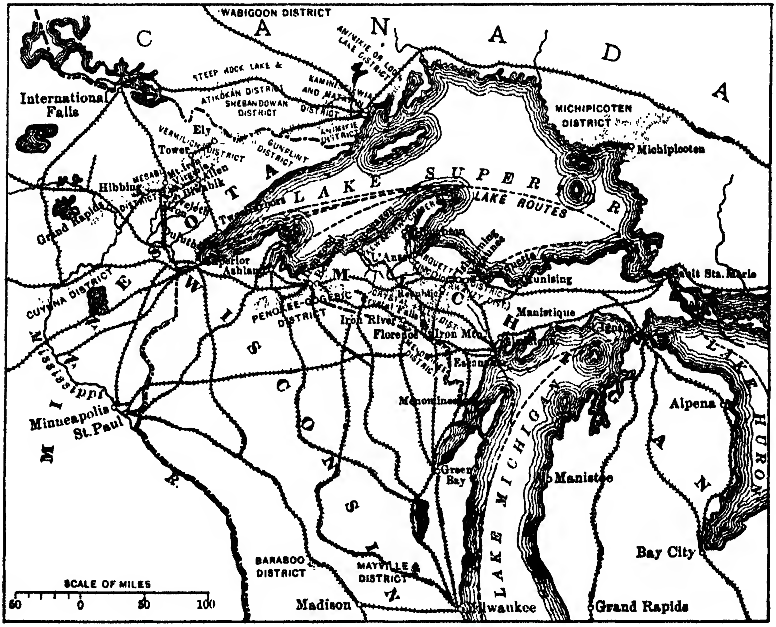

FIG. 139.—Map of Lake Superior iron regions, shipping ports, and transportation lines. (*After Van Hise and Leith, U. S. Geol. Surv., Mon. LII.*)

The ores may be divided into three classes, namely, (1) ores at the base of the iron-bearing Negaunee (Middle Huronian) formation; (2) the ores within the Negaunee formation; (3) detrital ores at the base of the Goodrich (Upper Huronian) quartzite. Ores of the first and second class are mostly soft hydrated hematite; those of the third class are hard specular ones with some magnetite from metamorphism due to greater movements along the contact of the Middle and Upper Huronian during the faulting within these rocks themselves.

Menominee Range (51).—While this carries iron formations in both the Middle and Upper Huronian, only the former are commercially important and are confined to the southern part of the district. The iron ores are mainly gray, finely banded hematite with lesser amounts of a flinty hematite which shows local banding.

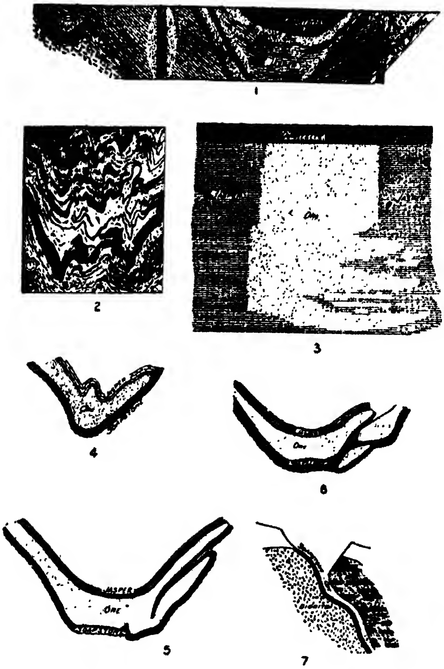

Fig. 140.—Sections of iron-ore deposits in Marquette range. (*After Van Hise.*)

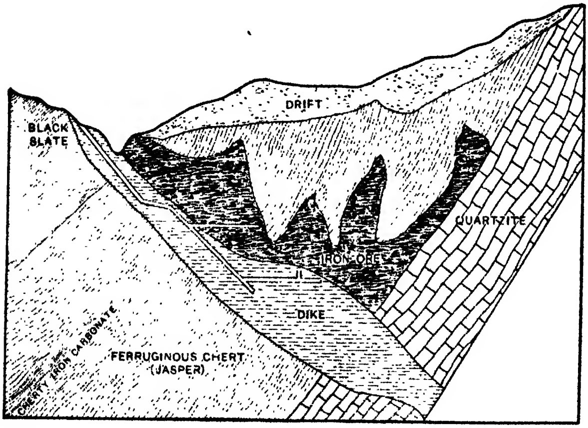

Fig. 141.—Generalized vertical section through Penokee-Gogebic ore deposit and adjacent rocks; Colby mine, Bessemer, Mich. (*After Leith.*)

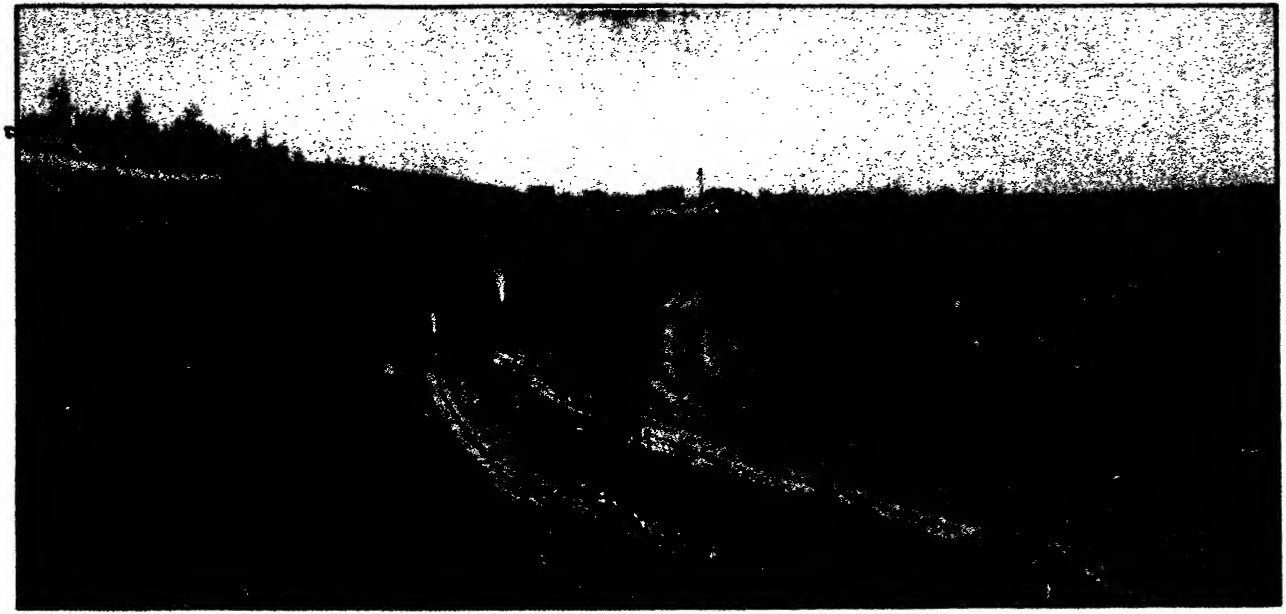

Plate XL.—General view of Mountain Iron mine, Mesabi Range, Minn., shows mining of ore with steam shovels, and covering of (*a*) glacial drift. (*Crandall and Maher photo.*)

Penokee-Gogebic Range (60).—The ores occur in Upper Huronian, the iron formation being overlain by slate and underlain by quartzite and black slate. The former is covered by a gabbro of Keweenawan age, which is found in contact with the iron formation in places and has altered it to jasper and amphibole-magnetite rock. Most of the iron formation, however, is ferruginous chert. The steeply dipping sedimentary rocks are cut by dikes of basic igneous rocks, thus forming troughs in which the ores are concentrated. Most of the deposits reached depths of 1000 feet and upwards, but the horizontal extent is small. While soft hydrated hematite is the normal type of ore, still the hard slaty ore is not uncommon. Manganese is found in a few deposits.

Mesabi Range (61).—The rocks of this region are less folded and metamorphosed, and dip slightly to the southeast. The iron formation, which is mainly ferruginous chert, is overlain by a thick slate and underlain by a thin quartzite, which in turn rests on granite, or graywacke and slate of lower Middle Huronian. At the eastern end of the range the iron formation has been metamorphosed to amphibole-magnetite rock by a gabbro intrusion.[1] The iron-ore deposits are very irregular in shape, but their horizontal extent is great as compared with their depth (Fig. 142), most of them being less than 200 feet. The mining is done mainly by open pits (Pl. XL), and the ore is a rather soft hematite of high grade. It preserves the stratification of the original iron formation and in places is found grading into the latter.

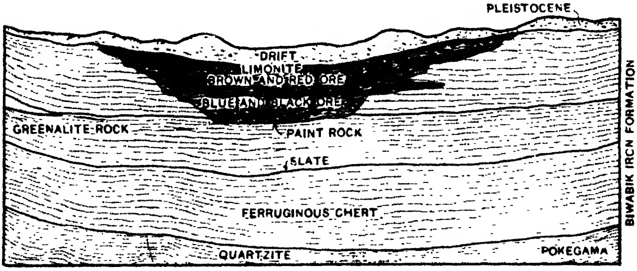

Fig. 142.—Generalized vertical section through Mesabi ore deposit and adjacent rocks. (*After Leith.*)

Vermilion Range (53).—The chief ore deposits occur in the highly folded and metamorphosed Keewatin rocks, and the iron formation is largely altered to jasper. The country rock is mostly greenstones in which the jasper occurs in lenses or troughs. The ores associated with the jasper in these troughs usually have a greenstone footwall and consist of dense hard red or blue hematite, which is sometimes brecciated but rarely specular.

Cuyuna Range (66).—This range lies to the southwest of the Mesabi range and shows a series of small northeast-southwest anticlines in a broad synclinal basin on whose northern limb the Mesabi range is situated, while on the southern limb we find the Penokee. Owing to the limited number of outcrops and lack of development at the present time, the geology is not yet perfectly known,

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[1] Grout and Broderick, Minn. Geol. Surv., Bull. 17; also Gruner, Minn. Geol. Surv.' Bull. 19, 1924.

but the formations seem to include quartzite and its altered equivalents, iron formations, slate, and intrusive granite and diorite. The ores form the altered and concentrated upper parts of the steeply dipping iron-formation strata, which are exposed by the erosion of the anticlines. The hanging wall is commonly chloritic slate and iron carbonate in varying proportions and degrees of alterations, while the footwall is either a quartz schist or amphibole-magnetite schist. The ore bodies thus far found seem to be in the form of lenses 100 to 250 feet thick, with their longer dimensions parallel to the highly tilted bedding of the series. Some of the ore is highly manganiferous.

Canada (112, 113, 114).—On the Canadian side of the boundary there are a number of iron-bearing areas (Fig. 139), only one of which is of importance, viz., the Michipicoten district. Here the iron-bearing formation lies in the Keewatin, the geology and structure being similar to the Vermilion district of Minnesota. The iron formation includes sideritic and pyritic cherts, jaspers, siderite, schists and iron ore, and the Helen ore body lies in an amphitheatre with iron carbonate on the east, ferruginous chert on the north, and tuffs on the south, while a diabase dike crosses the basin.

The ore, which chemically resembles the hydrous Mesabi ores, dips eastward, apparently under the carbonate, but exploration below the latter has developed a very large body of pyrite.

Origin.—The origin of these ores has for years been a puzzling problem to geologists. Foster and Whitney considered them eruptive, while Brooks and Pumpelly looked upon them as altered limonite beds.

The work of Van Hise and Leith has shown us that the Lake Superior ores were concentrated in certain sedimentary iron formations, and it was at first believed that these sediments were derived from the weathering of land areas containing much igneous rock.

Further study has led them to conclude, however, that the iron formations have not only been derived in this way, but that the iron has actually been contributed by greenstone magmas directly to the water in magmatic solutions and that there are all intermediate stages between the two processes (54).

The iron ore as first deposited consisted essentially of chemically precipitated iron carbonate or ferrous silicate (greenalite) with some ferric oxide, all finely interlayered with chert.[1]

Later on, when these sediments were uplifted to form the land surface and exposed to weathering, the ferrous compounds, the siderite and greenalite, were oxidized to hematite and limonite. While this occurred mainly in place, some of the iron was carried off and redeposited elsewhere. This resulted in a ferruginous chert carrying less than 30 per cent of iron.

Further concentration of the iron to 50 per cent or over was accom-

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[1] Algæ may in places have been a precipitating agent. (*Grout.*)

PLATE XLI

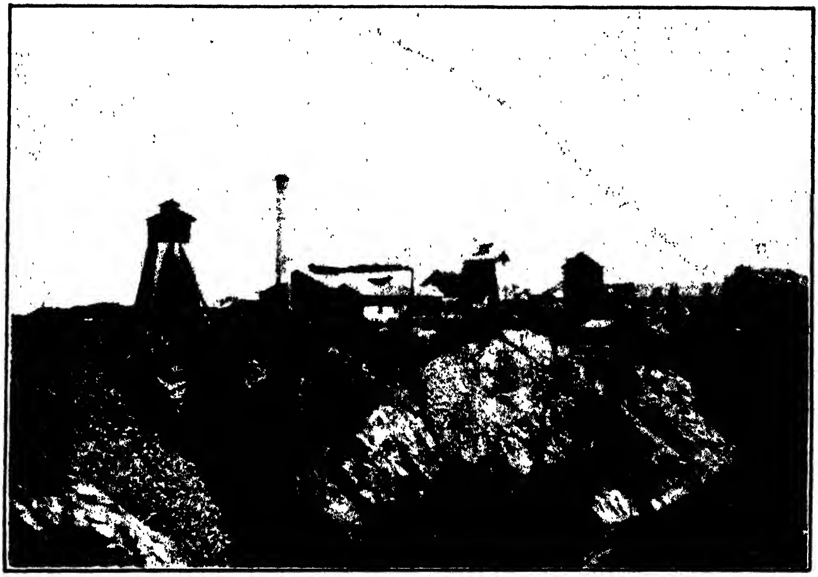

FIG. 1.—Iron mine, Soudan, Minn. Shows old open pit with jasper horse in middle.

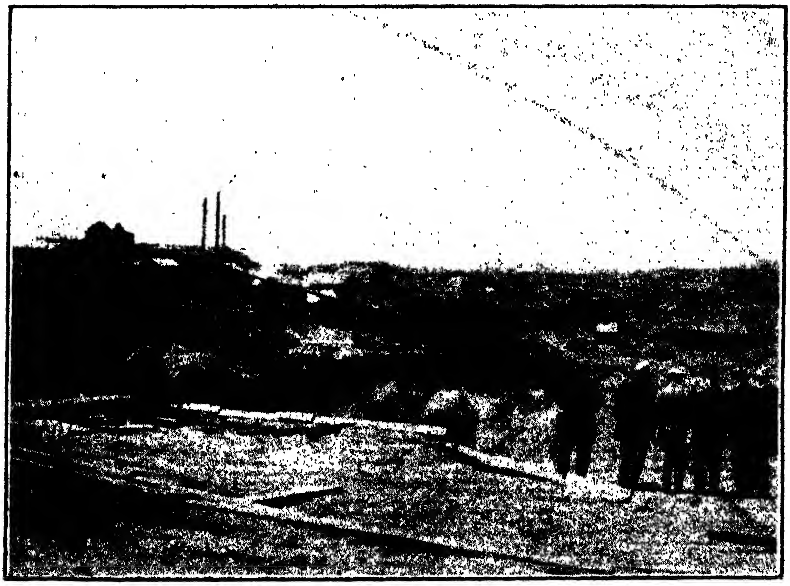

FIG. 2.—View of limonite pit near Ironton, Pa. (*H. Ries, photo.*)

plished mainly by the silica being leached from the bands of ferruginous chert.

Where the concentration of the ore has occurred in troughs, the chemistry of the process is thought to be as follows:

> Part of the ferric oxide was deposited as an original sediment containing silica and other impurities, or in some cases as sulphides or carbonates. This was later enriched by the addition of iron carbonate. These were originally contained in the rocks near the surface, and became oxidized by percolating waters, which took up the carbon dioxide liberated, and were thus able to dissolve iron carbonates or silicates, which they came in contact with in their downward course toward the troughs in which the ore is found.
>
> The precipitation of the ore was then caused by these solutions meeting with others which had filtered in by a more open and direct path from the surface, and hence contained some free oxygen, which converted the dissolved iron compounds into oxides.
>
> The same solutions, carrying carbon dioxide, dissolved the alkalies out of the basic igneous rocks, and these waters were then able to dissolve silica. In some cases the solution of silica proceeded faster than the deposition of the iron ore, and made the rock quite porous. The general result was therefore a concentration of the iron and removal of silica.

The weathering processes have yielded mainly soft ores and ferruginous cherts, while metamorphism has formed hard red and blue specular ores and brilliant jaspers, as well as changed the iron formation into amphibole-magnetic schists.

Most of the rich ores are found below the 1000-foot level, except in the Mesabi district, where the deposits are shallow, as compared with their horizontal extent, some, however, being over 400 feet deep.

In the early period of mining many of the Lake Superior bodies were worked as open cuts, but with depth underground working has been resorted to. There are many deposits in the Mesabi district which are worked as open pits from which the granular ore is dug with a steam shovel and loaded directly on to the ore cars, which are run along the working face (Pl. XL).

The market value of the ores is based on the iron contents, percentage of water, and amount of phosphorus, and at times the manganese content is taken into consideration. Some objection was at first raised to the fine character of the Mesabi ore and its tendency to clog the blast furnace, therefore requiring the admixture of lump ore from the other ranges; but this objection has disappeared, and some furnaces now use over 75 per cent of Mesabi ore in their charge.

The Lake Superior iron ore region is not only the most important in the world, but the production of some of the individual mines is startling. (See production of individual mines at end of this chapter.) The Marquette range was developed as early as 1849, the Mesabi as late as 1892, and the Cuyuna some years after this. The total yield of the Lake Superior region from 1854 to the end of 1927 has been 1,340,343,701 gross tons. While the output has been phenomenal, and the supply large, high-grade ore is no longer abundant, and much ore running high in silica is now shipped.

Wyoming (80).—Important deposits of hematite are found in the pre-Cambrian schists at several localities in Wyoming, viz., in the Hartville District, Laramie County, and near Rawlins, in Carbon County.

The Hartville deposits form a portion of the Hartville uplift, which is a broad, low dome similar to that formed by the Black Hills, and while the iron range extends from Guernsey to Frederick, a distance of 8 miles, the productive area extends only from a point 2 miles northeast and 1 mile southeast of Sunrise.

The pre-Cambrian sediments have been folded into a complex synclinorium, and faulting has been a common phenomenon, while the brecciation which accompanied both the folding and faulting was an important structural factor in the ore formation.

The most important ore bodies are lenses occurring in the schist along a limestone footwall, the ore either replacing the schist or to a lesser extent filling the joint, fault, and breccia cavities. These lenses range up to 1000 feet in length, and conform to the foliation of the schists. Detrital ores derived from the foregoing are also found.

The ores are high-grade hematites (chiefly hydrated), averaging over 60 per cent iron. Sulphur is absent, silica may be high, and much of the ore is non-Bessemer. Two grades of ore are recognized, viz., a hard gray hematite, and a soft greasy one of brown-red color.

Siderite and limonite are of subordinate importance, while the associated minerals are calcite, quartz, gypsum, chalcedony, barite, chrysocolla, etc. The copper minerals occur in the fractures in the hematite. Both types of hematite grade into the schist, but much of the soft ore has been derived from the hard by percolating waters.

Ball assigns an epigenetic origin to the ore, believing that it was deposited by descending water, because (1) the ore is along zones of maximum downward circulation, (2) lenses and veins are found along joints at a distance from the main body, and (3) the associated minerals, quartz, calcite, and limonite, are all water-formed ones. The magnetite and iron pyrite of the schist lying above the limestone footwall are regarded as the source of the iron. During pre-Cambrian times there was extensive erosion of this schist, and a downward transferal of this iron by carbonated surface waters flowing along the impervious limestone footwall, where it was precipitated by oxygen-bearing waters coming by a more direct path.

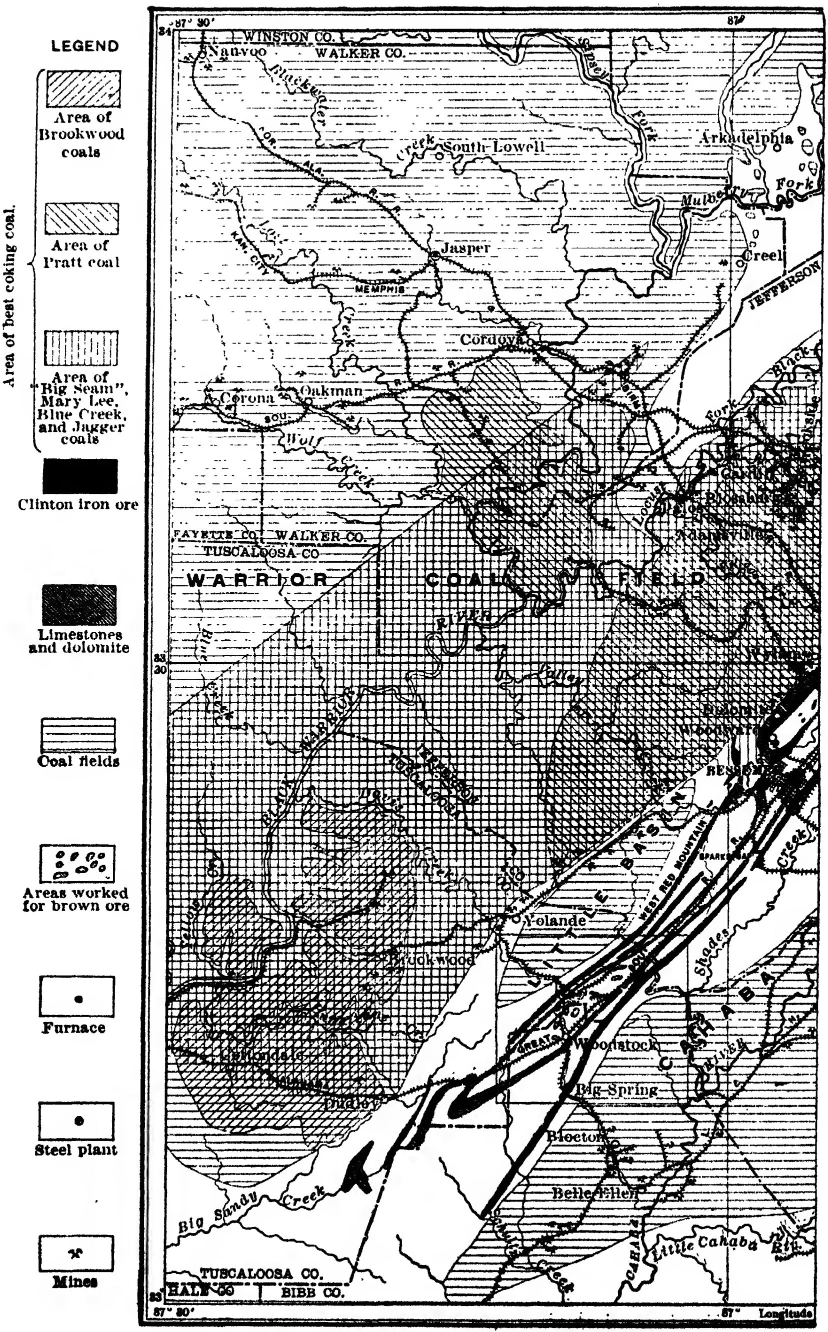

PLATE XLII.—Geologic map of western half of Birmingham, Ala., district. (*After Burchard, Amer. Inst. Min. Engrs., Bull.* 24, 1908.)

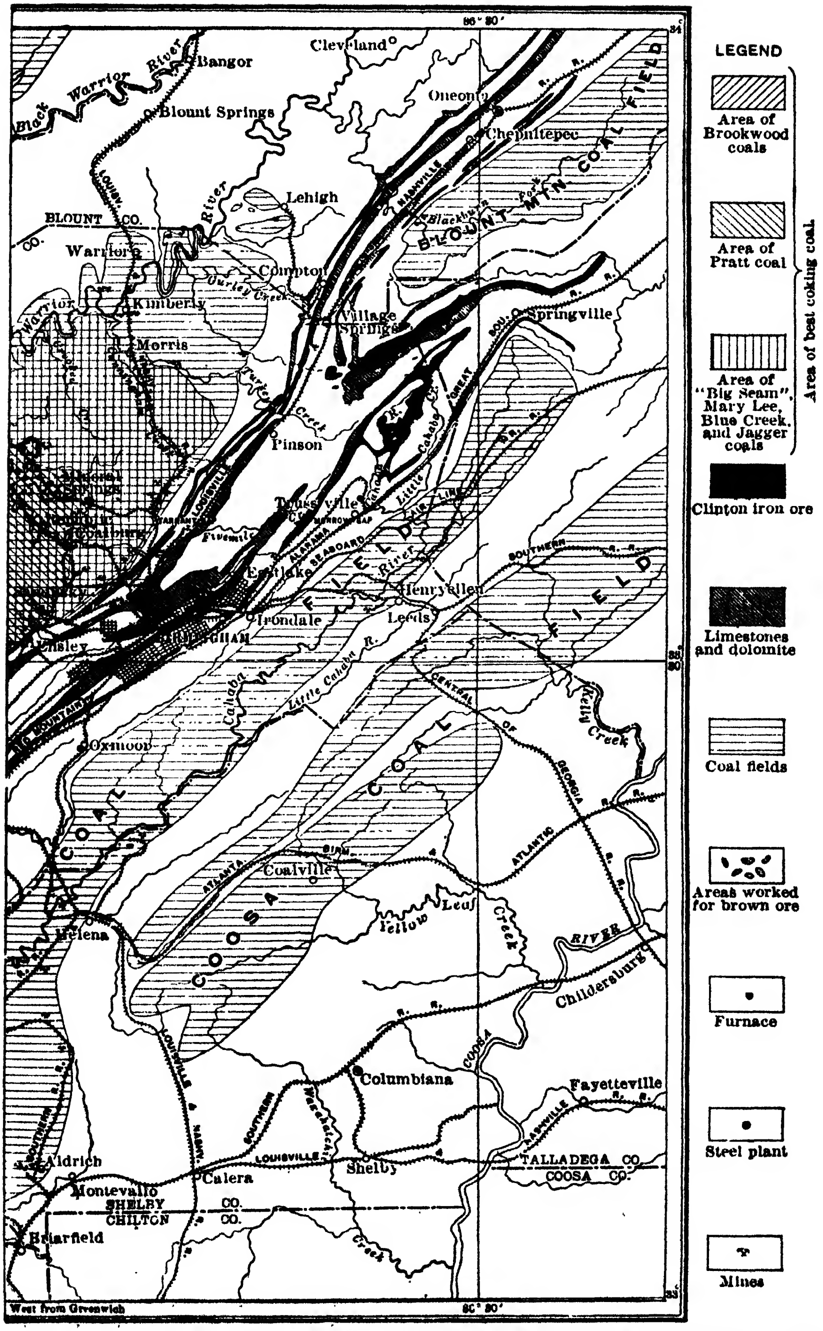

Plate XLIII.—Geologic map of eastern half of Birmingham, Ala., district. (*After Burchard, Amer. Inst. Min. Engrs., Bull.* 24, 1908.)

Missouri (10, 83).—In the St. Francis Mountains of Missouri deposits of specular hematite occur in porphyry. Two prominent hills are known as Iron Mountain and Pilot Knob. The former has produced nearly 4,500,000 tons of ore, and the latter about 1,500,000 tons.

In Iron Mountain the feldspar porphyry contains streaks and veinlets, as well as replacements of specular hematite, with garnet, sphene, amphibole, epidote, and apatite as significant associates. In Pilot Knob the hematite replaces beds of pyroclastic material and to some extent also an overlying porphyry breccia. The associated minerals include tourmaline, apatite, and sphene. This deposit is no longer worked for ore.

Singewald points out that the ore is undoubtedly a hypothermal replacement deposit, although others have earlier expressed somewhat different views. Spurr called the Iron Mountain deposit vein dikes (83), and those of Pilot Knob beach sand deposits.

Clinton Ore (69–79).—This ore, which is also called fossil, pea, or dyestone ore, was given the first name on account of the ore bed having been originally discovered at Clinton, N. Y. It is one of the most persistent iron-ore deposits that is known (Fig. 143), for it occurs at most points where rocks belonging to the Clinton stage of the Silurian are found.

The following districts may be enumerated as showing the location of the more important deposits: (1) west central New York; (2) several narrow belts in central Pennsylvania; (3) Alleghany County, Virginia; (4) a belt through Lee and Wise counties, Virginia, extending southwestward into the La Follette district of Tennessee; (5) narrow belts in the region of Chattanooga, Tenn.; (6) Birmingham, Ala.; (7) Bath County, Kentucky; and (8) Dodge County, Wisconsin.[1] Other known occurrences of minor importance are indicated on the map, Fig. 143, and in addition the ore has been discovered by drilling in Missouri.

Of all these districts, the Birmingham, Ala., one is the most important one, with Chattanooga, Tenn., and central New York ranking respectively second and third, when working.

The Clinton ore deposits occur as beds, or lenses, interstratified with shales and sandstones at different horizons in the Clinton, and as many as three or four beds may be present at any one locality. They show extremes of thickness, ranging from a few inches to 40 feet, but

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[1] It has been shown that this area is not of Clinton age, but is older and represents deposition in local, but connected basins of Maquoketa (Richmond) time (77).

rarely exceeding 10 feet. The thicker beds often contain sandstone and shale partings, and a single bed is sometimes traceable for miles along the outcrop.

The dip of the beds depends on the intensity of folding that has occurred in any given area. Thus the ore beds in New York State are nearly horizontal, while those found in the Appalachian region show a variable and sometimes steep dip.

Fig. 143.—Map of Eastern United States, showing areas of outcrop of Clinton iron ore. (*After McCallie, Ga. Geol. Surv., Bull.* 17.)

Two textural varieties of Clinton ore are recognized, viz., (1) fossil ore, and (2) oölitic ore.

The former is made up almost entirely of a mass of fossil fragments, while the latter consists of small, rounded grains of concretionary character. These two varieties may occur in the same or separate beds.

A second classification, based on grade, includes (1) soft ore, and (2) hard ore. The former is found in the outcropping portion of the seam and may extend to variable depths, sometimes as much as 400 feet, while the latter, which is usually sharply separated from the former, occurs lower down. The soft ore runs high in iron and silica, but low in lime, because this has been removed by weathering. The hard ore runs high in lime, but low in silica and iron. Both varieties are high in phosphorus and hence of non-Bessemer grade.

Birmingham, Ala. (70).—The great development of the Birmingham district is due to peculiar local conditions, for we find the iron ores, flux, and fuel all in close proximity to each other (Pls. XLII, XLIII).

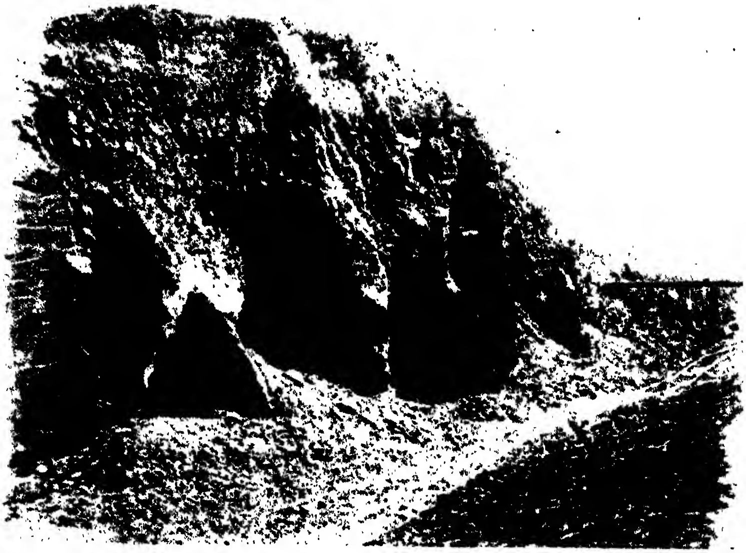

FIG. 144.—Outcrop of Clinton iron ore, Red Mountain, near Birmingham, Ala. (*Photo. from Tennessee Coal and Iron Company.*)

The Clinton ore beds are found in Red Mountain (Fig. 144) on the east side of the valley in which the city of Birmingham lies. There the Clinton formation, which is 200 to 500 feet thick and dips southeastward from 20° to 50°, is composed of beds of shale and sandstone and includes four well-marked iron-ore horizons, generally in the middle third of the formation.

These beds are known as the Hickory, Ida, Big, and Irondale seams, but there is difficulty in correlating them in different parts of the field.

Of these four beds the Big and Irondale are the most important. The thickness of the former is estimated at from 16 to 30 feet, but the good ore is rarely more than 10–12 feet thick, and at most places only 7 to 10 feet are mined. In the middle of the district, the bed is separated into two benches by a parting along the bedding plane, or by a shale bed. Either bench, though producing in one part of the district, may grade into shaly low-grade ore in another part.

The following analyses are given by Harder (Min. Res. 1908), to show the gradation from hard ore to soft ore.

Analyses of Clinton Iron Ore from Alabama

	1	2	3	4
Fe	37.00	45.70	50.44	54.70
SiO_2	7.14	12.76	12.10	13.70
Al_2O_3	3.81	4.74	6.06	5.66
CaO	19.20	8.70	4.65	0.50
Mn	0.23	0.19	0.21	0.23
S	0.08	0.08	0.07	0.08
P	0.30	0.49	0.46	0.10

The unweathered ore is said by Burchard to range from a richly ferruginous sandstone to a ferruginous-siliceous limestone.

New York (75).—In this state the outcrop of the ore extends across the central and western part of the state (Fig. 145). The whole for-

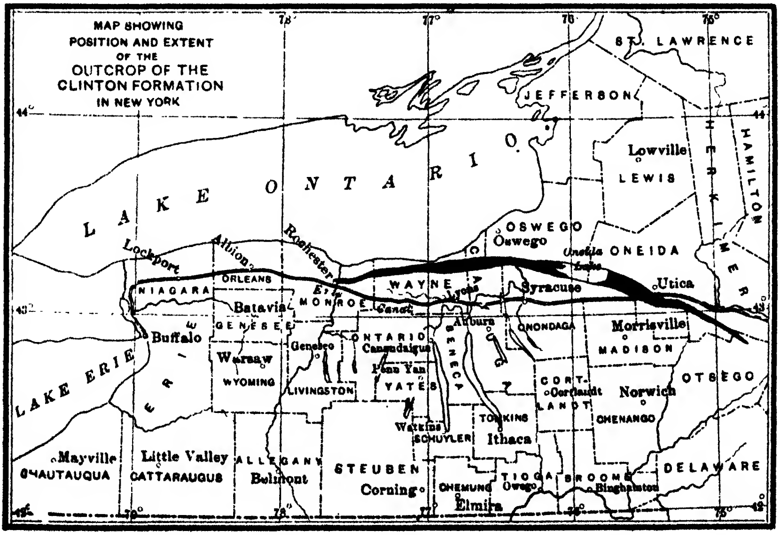

Fig. 145.—Map showing outcrop of Clinton ore formation in New York State. (*After Newland.*)

mation dips gently southward, with a gentle north-south synclinal trough in Cayuga and Wayne counties. Both oölitic and fossiliferous ore are found, and at least two beds, and sometimes four, may be present at any given locality. The ore varies in its richness, and while the deposits are very extensive, they have been but little developed.

Analyses of Clinton Ore.—The following are analyses of the Clinton ore from several localities, which serve more to show its variation in character, than as types. Others are given above under Alabama.

	I	II	III	IV	V
Fe	31.3	31.07	54.3	33.341	57.00
P	0.24	0.69	0.462	1.202[3]	0.678
SiO_2	23.98	8.56	15.64	1.143	7.12
TiO_2	0.225	—	—	—	—
Al_2O_3	7.26	5.04	0.89	5.468	—
MnO	—	Tr.	0.28	—	0.15[4]
CaO	9.15	13.71	1.09	16.56[1]	1.46
MgO	2.92	7.37	0.13	9.974[2]	—
SO_3	0.987	0.072	—	—	—
CO_2	9.6	18.8	None	—	—
H_2O	0.26	Undet.	3.07	10.865	—
S	—	—	0.03	—	–

I, II, N. Y. State Mus., Bull. 123 : 33, 1908. III. Ga. Geol. Surv., Bull. 17 : 130. IV. U. S Geol. Surv., Bull. 385. V. U. S. Geol. Surv., Bull. 285 : 188, Alleghany Co., Va.

[1] $CaCO_3$. [2] $MgCO_3$. [3] P_2O_5. [4] Mn.

Origin of Clinton Ore.—The origin of this ore has created considerable discussion, and whatever theory is advanced, it must explain the following features: (1) the fossiliferous character of some beds, (2) the oölitic character of others, (3) the bedded structure, (4) the soft non-calcareous ore at the surface, and the hard or more calcareous ore at lower levels.

The three theories which have been advanced are the following: (1) original deposition, (2) residual enrichment, (3) replacement. As can be easily seen, the correct solution of the problem is of practical value, since it indicates the possible extent of the ore body.

Residual Enrichment.—This theory supposes that the ore beds represent the weathered outcrops of ferruginous limestones. That is to say, the lime carbonate was leached out by surface waters down to the water level, leaving the insoluble portion carrying the iron, in a more concentrated form. If this theory is correct, then the ore should pass into limestone below the water level.

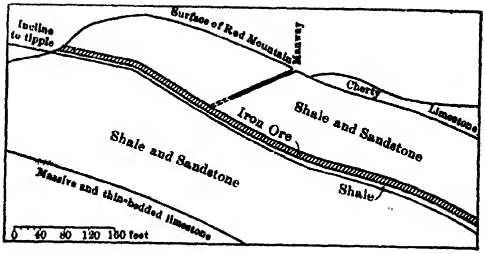

Fig. 146.—Typical profile of slope on Red Mountain, starting on the iron-ore out-crop. Shows bedded character of ore. (*After Burchard, Amer. Inst. Min. Engrs., Bull.* 24, 1908.)

Russell, who was an earnest advocate of this theory, noted that at Attalla, Ala., the Clinton limestone at a depth of 250 feet from the surface carried only 7.75 per cent of iron, while at the outcrop it had 57 per cent of iron. These figures would seem to bear out this theory, but Eckel (70) has recently claimed that they must be incorrect, as the hard ore at the depth mentioned above carries 38 to 42 per cent of iron. Moreover, in none of the many fairly deep mines in Clinton ore has any change to limestone been noted.

Sedimentary Origin.—This supposes that the ores are of contemporaneous origin with the inclosing rocks, having been deposited on the sea bottom as chemical precipitates.

This view was advocated at an early date by James Hall, who believed that the iron came from the old crystalline rocks, which were leached of their iron content, the oölitic ore being a chemical precipitate on the ocean floor.

Smyth (78) in amplifying this theory agrees with Hall as to the source of the ore. He points out that during Clinton times the drainage from the crystalline area was carried into a shallow sea or basin. When the iron was carried into these inclosed basins, it was slowly oxidized and precipitated, gathering layer upon layer about the sand grains, thus forming oölitic ore.

Where the ferruginous waters came in contact with shell fragments the iron was precipitated around these, either due to a reaction with the carbonate of lime, in the shells, or more often by oxidation. Later both types of deposit became covered by ordinary sediments such as shales, sandstones, or even limestones.

Additional evidence favoring a sedimentary origin is the continuation of the ore with depth, some mines in Alabama being 2000 feet from the outcrop. Moreover some borings in Alabama have struck the ore ½ to 1 mile from the outcrop and 400 to 800 feet below the surface. The occurrence of fragments of ore in the overlying limestone also points to the ore being laid down before the lime rock.

McCallie (74), after studying the Georgia ores, while admitting their sedimentary origin, believed that the original iron mineral was greenalite or glauconite. Stose suggests an original deposition as iron carbonate (79).

Replacement Theory.—This theory assumes that the ores were of much later origin than the inclosing rock, and were formed by the replacement of the lime carbonate by iron, brought in by percolating waters, which had leached the ferruginous constituents from the overlying strata.

The structure of the formations, the comparative absence of iron in the limestone overlying the ore, and restricted vertical range of the ores have been advanced as arguments against this theory.

Rutledge (76), however, as a result of his studies of the Clinton ores of Stone Valley, Pennsylvania, concludes that they represent replacement deposits, and that the only part of the iron content which is of sedimentary character is that contained in the siliceous concretions, most of the iron having come from the shale overlying the ore beds; the hematite deposits have thus been formed by replacement of limestone and concentration of the ore. The evidence presented in favor of this view is: (1) the invariable association of the soft, rich ore with the leached decolorized shales, and of the hard, lean ores with unweathered bright shales; (2) the relations of the ores to the shattered sandstones and to the topographic situation of the ores; (3) the fact that analogous replacements are now taking place in the Medina; (4) the observed progressive steps in the transformation of the limestone to an ore, which may be followed in the field, in thin sections, and in chemical analyses, and (5) the absence of conditions, such as a local crumpling, including a shrinking of the strata, pointing to a relative rather than an absolute enrichment of the ores.

In view of the fact that the advocates of the several theories often bring apparently good evidence to support their case, one may perhaps question whether several different methods of concentration have not been operative. To the author, it seems that the sedimentary mode of accumulation has probably been the dominant one in most cases.[1]

Canada.—*Wabana, Newfoundland* (123).—The ores found here are of a distinctly bedded character, being part of a series of northwesterly dipping Ordovician sediments exposed for about three miles along the north shore of Bell Island in Conception Bay. The whole series extending from Lower Cambrian to Lower Ordovician is several thousand feet thick, and consists of unmetamorphosed sandstones and shales, but in the upper thousand feet there has been a concentration of ferruginous minerals.

Within the Lower Ordovician series, considered as equivalent to the British beds of Arenig to Llandeilo age, there are six zones, containing beds of shale and sandstone alternating with oölitic iron ore, and in one zone oölitic pyrite. The iron ore is red brown, massive, and breaks up readily into parallelopiped-shaped blocks, the breaks being marked by minute veinlets of calcite and quartz. Texturally the ore shows a number of concretions from 1/10 to 1/2 inch diameter. These spherules are composed of alternating concentric layers of hematite and chamosite, which were pierced by living boring algæ. Siderite is locally abundant and may replace hematite, chamosite, or even quartz.

The ore, which is of shallow-water origin, and shows ripple-marked surfaces, is thought to represent a chemical precipitate.

Iron, brought into the sea from crystalline rocks on the land, was precipitated, by the oxidizing action of the algæ, as ferric oxide, some

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[1] For ores similar to Clinton compare Geol. Surv., China, Mem. A 2, Pt. I.

of which may have reacted with aluminous sediment to form chamosite. The siderite was possibly formed by ammonium carbonate given off as a decomposition product, below the sediment surface.

The oölitic pyrite represents a deeper water formation, formed presumably in the same way as the pyrite nodules now originating in the Black Sea, viz., by the action of hydrogen sulphide liberated by bacterial action, reacting with iron salts. The Wabana deposits are of great economic importance, the underground workings extending out under the sea.

Analyses of Canadian Iron Ores

	I	II	III	IV	V	VI	VII	VIII
Fe	52.58	47.5	36.70	55.77	31.35	53.89	40.36	59.37
SiO_2 . . .	12.59	22.7[2]	45.20	12.78	46.70[2]	12.52	12.12	8.33
Al_2O_3 . . .	5.71	——	0.25	1.58	0.92	3.17	4.33	1.71
P	1.63[1]	0.65	0.057	0.107	0.81	1.032	1.19	0.057
S	——	0.05	0.019	0.074	0.006	0.091	——	0.137
CaO . . .	1.49	——	1.06	3.77	2.11	2.07	15.26	3.82
MgO . . .	0.42	——	1.59	3.52	0.31	0.41	——	1.05
MnO . . .	0.06	1.2[3]	0.04[3]	0.09[3]	——	1.9	——	——
TiO_2 . . .	0.27	——	——	——	——	——	——	——
Cu	——	——	——	——	——	——	——	0.08
Ignition loss	2.17	——	——	——	——	——	——	——

[1] As P_2O_5. [2] Insoluble. [3] Mn.

I. Hematite, Dominion Bed, Wabana, N. F. II. Bathurst, N. B., magnetite. III. Crude magnetite, Moose Mountain, Ont. IV. Concentrates, same place. V. Magnetite Nictaux-Torbrook basin, N. S. VI. Hematite, Leckie vein, same district. VII. Hematite, shell vein, same district. VIII. Magnetite, Texada Island, B. C.

Nictaux-Torbrook Basin, Nova Scotia (122).—An interesting series of bedded Silurian ores is found in this belt lying between the Devonian granites and the Triassic area, of southwestern Nova Scotia. The ore, which is interbedded with shales and sandstones, dips steeply, and while it is chiefly hematite, it may be locally changed to magnetite, in which the fossils of the original rock are still recognizable.

Other Foreign Deposits.—The hematite deposits of the Minas Geraes district of Brazil,[1] located some 300 miles from the coast, are among the largest known iron deposits of the world. The iron series includes clay slates, subordinate limestone beds, and most important, quartzites (itabirite), the last ranging from a nearly pure quartz rock with scattered flakes of hematite, to massive quartz-free hematite. The ore forms lenses, often of tremendous size, inter-

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[1] Leith and Harder, Econ. Geol., VI: 670, 1911; Derby, Iron Ore Resources of World, Stockholm, 1910: 817; Harder, Econ. Geol., IX: 101, 1914.

bedded with the quartzite. The following analyses show the composition of: (I), hard blue massive ore, and (II) thin-bedded ore.

	Fe	P	Si	Mn	Al	CaO	MgO	S	Ign
I	69.35	0.010	0.13	0.15	0.33	tr	0.03	0.01	0.31
II	63.01	0.184	1.79	0.16	1.53	0.08	0.01	0.03	6.00

The iron-bearing formation is supposed to represent a sedimentary series, the iron having been deposited originally as ferric hydrate or possibly ferrous carbonate. Subsequent metamorphism changed the iron to crystalline hematite, while later surface weathering gave some detrital deposits.

Other interesting and to some extent important hematite deposits are the replacements of hematite in limestone of Bilbao, Spain,[1] the contact metamorphic deposits on the island of Elba,[2] the replacement deposits of Erzberg in Styria,[3] and similarly formed hematites in Carboniferous and Silurian limestones of Cumberland and Lancashire, England.[4]

LIMONITE[5]

Limonite (21, 22, 86–106), or brown hematite, is, like magnetite, of little importance in the United States as compared with hematite, having yielded but 0.9 per cent of the total domestic iron-ore production in 1935, but in other countries of the world it may sometimes be of great commercial importance.

Limonites are rarely of high purity, mainly because of the fact that they are frequently associated with clayey or siliceous matter, but this can sometimes be separated to a large extent by washing.

Types of Deposits (22, 90, 93).—Limonite ores may occur under a variety of conditions, and associated with different kinds of rocks, the more important types being as follows:

1. Residual deposits, consisting of residual clay derived from different kinds of rocks by weathering processes, through which the limonite is scattered in pieces ranging from small grains to large masses. The deposits are usually siliceous, except in those of a lateritic character (Cuba).
2. Gossan deposits, derived usually from the weathering of sulphide ore bodies. These may cap pyrite masses, or sulphides of other metals (many western ones).
3. Replacement deposits.
4. Bedded deposits, usually of oölitic character, and marine origin (Luxembourg). Here the limonite may have been precipitated as such on the ocean bottom, or it was possibly precipitated as siderite or glauconite and later changed to the ferric hydroxide.

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[1] Vogt, Krusch u. Beyschlag, Lagerstätten II: 319, 1912.

[2] Vogt, Krusch u. Beyschlag, Ore Deposits, Translation I: 369, 1914.

[3] Vogt, Krusch u. Beyschlag, II: 311, 1912.

[4] *Ibid.*, p. 317.

[5] The name limonite is used here in a broad sense to include the different hydrous iron oxides.

5. Bog-iron ores, representing deposits of ferric hydroxide precipitated in bogs or ponds, the iron having been brought to the pond in solution. Ferrous compounds are more easily soluble than ferric ones, and the iron may go into solution as sulphate, as bicarbonate in presence of an excess of CO_2, or as soluble salts of organic acids.

The precipitation may be caused: (1) by certain bacteria, which deposit ferric hydroxide in their cells; (2) by oxidation of ferrous carbonate; (3) by precipitation of ferrous carbonate first as such due to loss of CO_2, and presence of organic matter, the carbonate sometimes changing over later to the hydroxide; (4) by change of ferrous sulphate to ferric hydroxide in presence of oxygen, but the former might react with calcium carbonate, and yield siderite with gypsum; or the sulphide may be derived from sulphate in presence of decaying vegetable matter.

The ferric hydroxide is possibly precipitated first in colloidal form, and changes later to a crystalline condition. Its precipitation in some localities has been sufficiently rapid to permit gathering a supply from the pond bottom every few years.

Distribution of Limonite in the United States (20, 22, 86–106).—Although deposits of limonite are widely scattered over the United States (Fig. 147), in 1933, 88 per cent of the production came from Alabama and 10½ per cent from Tennessee.

Residual Limonites.—The residual limonites supply a large percentage of the domestic production, and have been formed (1) by the weathering of pyritiferous sulphide bodies (see gossan), or (2) more often by the weathering of ferruginous rocks.

FIG. 147.—Map showing distribution of limonite and siderite in the United States. (*After Harder.*)

Gossan Deposits (22, 102).—Limonite gossan ores derived from the oxidation of pyrite, chalcopyrite, and pyrrhotite deposits are found at a number of localities in the crystalline belt of New England and the southern Atlantic states, but they are of limited importance at the present time. One belt of historic and former commercial importance is the "Great Gossan Lead" found mainly in southwestern Virginia (22), and traceable for over 20 miles, its contents averaging 40 to 41 per cent metallic iron. (See also Ducktown, Tenn., and Copper in Virginia.)

Limonite gossan ores are not uncommon in many of the western sulphide deposits, and many of them carry more or less manganese oxide, some, as those at Leadville, having sufficient to be used in the manufacture of spiegeleisen. Their main use, however, is as a flux in copper and silver smelting in the western states. The best known deposits are in the Black Hills, South Dakota; Leadville, Colo.; Neihart, Monarch, and Elkhorn, Mont.; the Tintic district, Utah; Tombstone, Ariz.; and Pioche and Eureka, Nev.

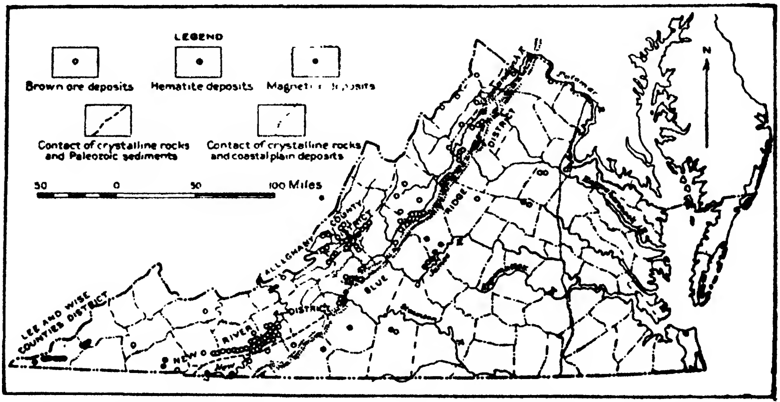

FIG. 148.—Map showing location of iron-ore deposits in Virginia. (*After Harder, U. S. Geol. Surv., Bull.* 380.)

Limonites in Residual Clays.—The other class of residual limonites has many scattered representatives, but the best known ones form a belt extending from Vermont to Alabama (70, 101) and divisible into two groups, viz., the mountain and the valley ores. In these the iron occurs as grains, lumps, or masses scattered through residual clays, associated with Cambro-Silurian limestones, shales, and quartzites.

The mountain ores are located in the eastern part of the Appalachian limonite belt, generally in the Blue Ridge or Appalachian Mountains, or at least near their western edge.

PLATE XLIV

FIG. 1.—Pit of residual limonite, Shelby, Ala. (*After McCalley, Ala. Geol. Surv., Rept. on Valley Regions, Pt. II.*)

FIG. 2.—Old limonite pit, Ivanhoe, Va., showing pinnacled surface of limestone which underlies the ore-bearing clay. The level of surface before mining began is seen on either side of excavation. (*H. Ries, photo.*)

The valley ores are closely associated with them on the west, and there is no sharp line of separation between the two. The two types, however, present certain important differences.

Thus the mountain ores usually form relatively small, disconnected pockets in the residual material over the Lower Cambrian quartzite, at or near its contact with the overlying formation, usually a limestone, while other types of less common occurrence are known. The valley ores, on the other hand, form more extensive though shallower deposits in residual clay overlying limestones (Fig. 150) above the quartzite.

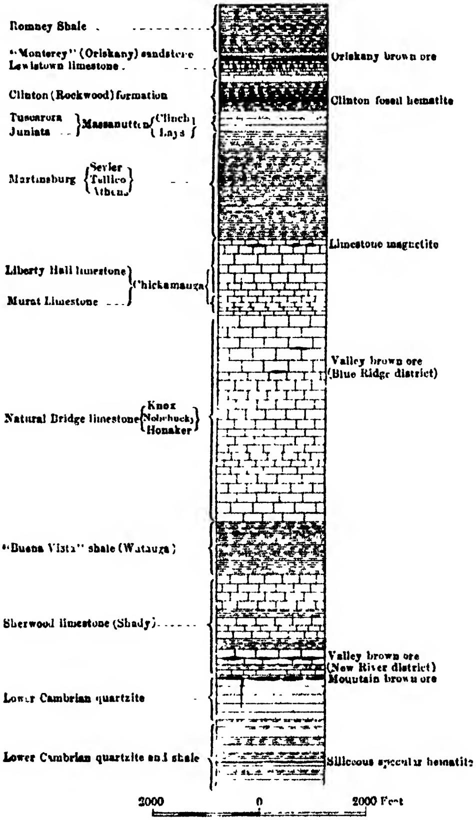

FIG. 149.—Geologic section showing position of iron-ore deposits in Virginia. (*After Watson, Min. Res. Va.*, 1907.)

In either case, however, the ore is not uniformly distributed through the clay, so that individual pockets soon become worked out, necessitating the finding of a new one.

Mountain ores may extend to a depth of several hundred feet, but the valley ores rarely exceed 50 feet in depth, and in neither case do the deposits as a rule exceed 500,000 tons, the average being 100,000 to 200,000. The ore may form from 5 to 20 per cent of the clay and sand in different deposits or different parts of the same deposit. Limonite and göthite are the two iron-ore minerals, the higher grades

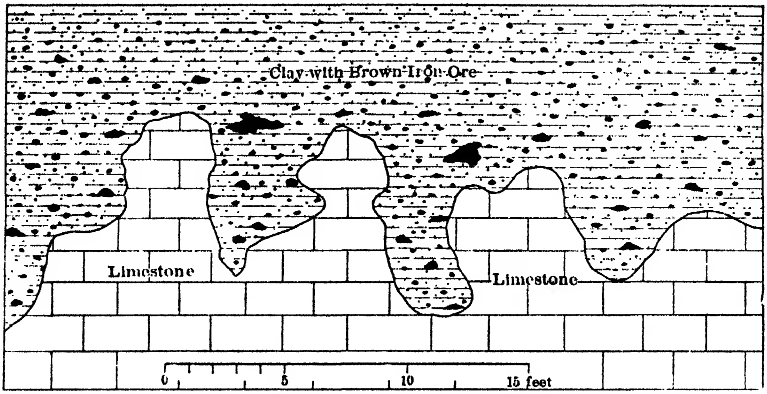

FIG. 150.—Vertical section showing the structure of the valley brown ore deposits at the Rich Hill mine, near Reed Island, Va. (*After Harder, U. S. Geol. Surv., Bull.* 380.)

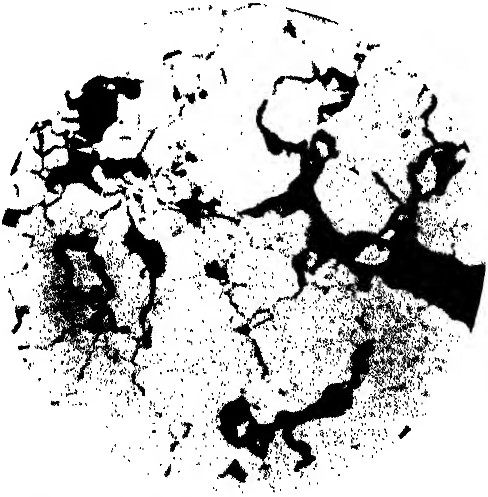

FIG. 151.—Section of fractured quartzite from residual limonite deposit, Pittsville, Va. Iron oxide deposited in part between grains and in part by replacement

carrying as much as 55 per cent metallic iron, but the average shipments run about 45 per cent. The mountain ores are usually poorer than the valley ones, and phosphorus is generally high enough to make the ore non-Bessemer.

The following table shows the percentage range of the chief constituents (Harder) of I, mountain ore, and II, valley ore:

	I Per Cent	II Per Cent
Fe	35.00-50.00	40.00-56.00
SiO_2	10.00-30.00	5.00-20.00
P	0.10-2.20	0.05-0.50
Mn	0.50-10.00	0.30-2.00

While Alabama is the main producer of residual limonites (97, 102), a moderate amount is also obtained from Tennessee and Missouri.

Origin of the Cambro-Silurian Limonites.—Both the valley and mountain ores are believed to have been formed by the action of weathering.

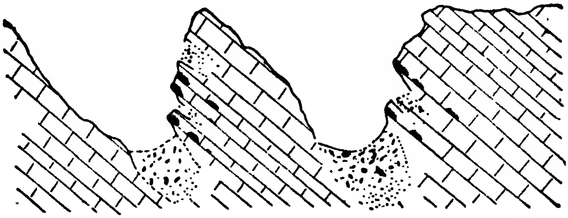

Fig. 152.—Section illustrating formation of residual limonite in limestone. (*After Hopkins, Geol. Soc. Amer., Bull. XI.*)

As the shale and limestones overlying the Cambrian quartzite weathered, the iron oxide was set free, either by the decomposition of ferruginous silicates, or of pyrite or siderite in the limestones. This was then carried downward and concentrated first in the residual clays of the limestone, forming the valley ores. If weathering continued still deeper, the downward percolating iron solutions reached the impervious quartzite, the ores (mountain type) becoming concentrated in the clay overlying this, although some was deposited in crevices in the quartzite.

Oriskany Limonites (22).—These are so called because of their association with the Oriskany sandstone. To be more exact, they are found in the Lewistown (Silurian) limestone, under the Monterey (Oriskany) sandstone, or the Romney (Devonian) shale. The main producing districts were in Alleghany County, Virginia, and central Pennsylvania, but local deposits are found at the same horizon in West Virginia, Kentucky, and Ohio.

The deposits (Fig. 153) form replacements in the upper portion of the Lewistown limestone, and may extend along the strike for a distance of several miles. The thickness and depth are variable, but in some cases may reach 75 feet and 600 feet respectively. The formations in which the ore occurs have been folded and the Oriskany removed from the crests of the folds by erosion, so that the ore is found along the outcrops on the flanks of the ridges.

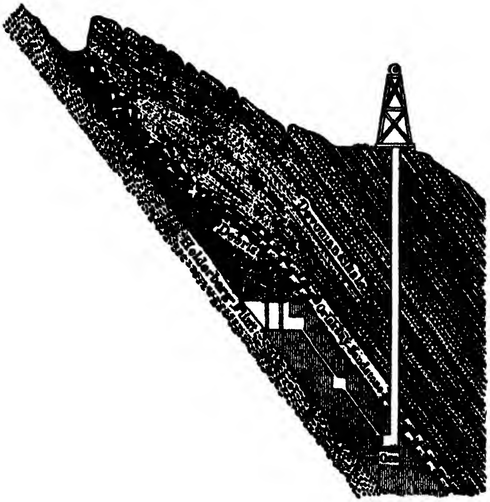

Fig. 153.—Section of Oriskany limonite deposit. (*After Holden, Min. Res. Va.*, 1907.)

The Oriskany ore resembles the mountain ore in texture, grade, and impurities, but differs from it in forming larger and more continuous deposits. It grades into limestone with depth.

Other Limonite Deposits.—In northwestern Alabama, western Kentucky, and Tennessee, limonite occurs in residual and sedimentary clays overlying the Mississippian limestone.[1] Brown ore also occurs in the Claiborne (Tertiary) formation of northeastern Texas (90), and adjoining parts of Louisiana (89) and Arkansas. The ore forms horizontal beds of slight thickness but some extent. It is of little value.

In the Ozark region of Missouri and Arkansas, limonites are found in residual clays over Cambrian limestone, but are of little economic value.

Small deposits are known in Iowa (91), Wisconsin (86), Minnesota, and Oregon.[2]

The brown ores of the Appalachian belt have been much used by pig-iron manufacturers because, owing to their siliceous character, they can be mixed with

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[1] Burchard, U. S. Geol. Surv., Bull. 315: 154, 1907; and Hayes and Ulrich, Geol. Atlas Folio, 95, 1903.

[2] Whittier, Univ. Wash., Bur. Indus. Res., Bull. 2.

high-grade Lake Superior ores, which are deficient in silica. They are also cheaper.

The analyses on p. 470 gives the composition of limonites from a number of different localities.

Canada (4, 90).—Bog iron ore has been obtained from deposits in the Three Rivers District of Quebec, but its importance is decreasing. Some of the ore obtained at the Helen Mine, Ontario, is quite strongly hydrated, but otherwise comparatively little limonite is mined in Canada.

Other Foreign Deposits.—Limonite is obtained at a number of localities in other countries (1), but only a few need mentioning.

The so-called *minettes* of Lorraine, Luxembourg, and Belgium (now exhausted) are of great importance to the European iron industry, especially those of France and Germany, although their development hinges on the coal supply. These minettes underlie about 3500 square miles in Lorraine and Luxembourg.

The ores occur as beds in the Middle Jurassic (Dogger), associated with shales, sandstones, and marls, being found in a vertical range of 75 to 150 feet. The ore beds themselves are usually lenticular, and the deposits lie in synclinal basins which pitch southwest, but are broken by N.E.-S.W., and N.W.-S.E. faults of mostly slight displacement.

In texture the ores are chiefly oölitic, with a matrix of lime, clay or sandy clay. The chief ore mineral is limonite, with occasional hematite, iron silicate, or carbonate.

All of the ores are low grade, containing from 30–40 per cent iron, and 1.5 to 2 per cent phosphorus.

Cayeux believes that the iron has replaced oölites of calcite.

Other Jurassic bedded ores are found on the continent of Europe in Switzerland, Germany, Poland, and the Haute-Marne district of France.[1]

In Great Britain, the sedimentary ores of the Jurassic form the most important source of supply in that country, and while they are composed only in part of limonite, they may be mentioned here.

The ore beds occur in the Lower Inferior Oölite, upper part of Middle Lias, and middle of Lower Lias, the most important producing area being the Cleveland district of Yorkshire.

A generalized section of the series in the Cleveland district is:[2]

	Thickness feet
Upper Lias Shales.	
Middle Lias shales.	
Shale or dogger	0–6
Main seam of ironstone	6–11
Shale and Black Hard	2½–5
Pecten seam	1½–6

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[1] Cayeux, Minerais de fer oolitique de France, Paris, 1909; Roesler, U. S. Geol. Surv. Bull., 706, 1920; Brooks and LaCroix, U. S. Geol. Surv., Bull. 703, 1920. Iron Ore Resources of World, Internat. Geol. Cong., Stockholm, 1910.

[2] Special Reports Min. Res., Gr. Brit., XXIX: 43, 1925. Also vols. XII and XIII.

Ironstone series.	Thickness feet
Shale	3–6
Two-foot seam	1½–2½
Shale	20–30
Avicula seam	0–3
Sandy series.	
Sandy shales and flaggy calcareous sandstones	20–90
Lower Lias shales and calcareous beds.	

Ore is also obtained from the Inferior Oölite above the Upper Lias.

According to Hallimond,[1] the ores are chamosite mudstones, chamosite-siderite mudstones, ferric chamosite oölites, and limonite oölites. Thuringite is not present in the English ores.

All of the ores are low grade, averaging about 30 per cent metallic iron, about 1.0 per cent P_2O_5, and 2.5 per cent SiO_2. Hallimond regards them as aqueous, principally marine, precipitates.[2]

It is interesting to note that the Jurassic supplies about 46 per cent of the iron ores mined in Europe.[3]

Residual ores, of a lateritic type occur in Surigao province, Mindanao, Philippines. The deposits are said to bear a striking resemblance to those of the Mayari district, Cuba. They have an average iron content of 54.00 per cent, with traces of S and P, but no Ni. The blanket of residual clay is up to 60 feet in thickness. Pratt estimates the quantity at 430,000,000 metric tons.[4]

FIG. 154.—Section of oölitic iron ore (*minette*) from Luxembourg. × 33.

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[1] *Ibid.*, p. 7.

[2] *Ibid.*, p. 90

[3] Roesler, U. S. Geol. Surv., Bull. 706.

[4] Amer. Inst. Min. Engrs., Bull. 110: 247, 1916.

ANALYSES OF LIMONITE

	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	XIV
Fe_2O_3	——	——	62.11	——	——	——	52.86	——	——	——	——	——	——	——
Fe	57.088	29.323	——	49.18	32.59	53.75	——	53.75	36.15	47.00	48.54	47.19	44.68	43.6
MnO_2	——	——	2.85	——	——	——	0.61	——	——	——	——	——	——	——
Mn	0.504	0.33	——	0.32	0.12	0.57	——	0.57	1.40	2.70	——	0.72	——	0.80
SiO_2	5.145	41.575	18.97	13.73	45.24	10.31	33.26	10.31	16.36	12.25	11.22	12.50	18.90	24.00
P_2O_5	——	——	1.10	——	——	——	1.325	——	——	——	——	——	——	——
P	0.122	0.055	——	0.376	0.068	0.191	——	0.191	0.12	0.85	0.38	——	0.09	0.14
S	0.023	0.105	0.06	——	——	——	0.014	——	——	——	0.09	——	0.20	0.018
Al_2O_3	1.471	3.995	2.39	——	6.30	——	5.26	——	——	——	3.61	2.44	5.76	2.3
CaO	0.137	1.85	0.48	——	——	——	0.28	——	——	——	0.84	——	0.18	0.58
MgO	tr.	0.776	0.42	——	——	——	——	——	——	——	——	——	tr.	0.30
P	——	——	——	——	——	——	——	——	——	——	——	0.26	——	——
H_2O	11.01	9.67	11.62	10.33	——	10.48	1.90	10.48	——	——	moist. 13.00	7.10	11.03	——

I. Best ore, Old Hill mine, Salisbury district, Conn., Econ. Geol., II : 171, 1907. II. Poor ore, same mine. *Ibid.* III. Average of 29 commercial analyses of Pennsylvania limonite, Bull. Geol. Soc. Amer., XI : 481. IV. Earthy mountain brown ore, Greenville, Augusta County, Va., U. S. Geol. Surv., Bull. 380 : 222. V. Red shaly mountain brown ore, Buena Vista, Rockbridge County, Va., *Ibid.* VI. Oriskany brown ore, near Low Moor, Alleghany County, Va., *Ibid.* VII. Oriskany brown ore, Covington, Va., U. S. Geol. Surv., Bull. 285 : 187. VIII. Valley brown ore, U. S. Geol. Surv., Min. Res. 1908. IX. Gossan ore, Betty Baker, Carroll County, Va., Min. Res. Va., 1907 : 265. X. Limonite ore, Pittsville, Pittsylvania County, Va., *Ibid.* XI. Average composition, Alabama limonites. XII. Average of Champion area, Birmingham district, Ala., U. S. Geol. Surv., Bull. 400 : 169. XIII. Rusk, Cherokee County, Tex. XIV. Average composition of rock and wash ore, Spring Valley, Wis., Mich. Acad. Sci., 11th Ann. Rept.

Eastern Cuba[1] contains three important districts of residual iron ore, two of these—Moa and Mayari in Oriente province, and a third, San Felipe in Camaguey province. The ore is in residual clay derived from serpentine, and shows a dark red, earthy, surface zone occasionally containing shots and lumps of solid brown ore and hematite, below which is yellowish or yellowish brown ore changing rather suddenly to serpentine. The average depth at Mayari is 15 feet. The analyses indicate appreciable hematite and bauxite in the upper zone, while farther down hydrous iron oxides predominate. We have here then a case of lateritic alteration.

Analyses of the surface ore I, and bottom layer II indicate the high grade of these ores.

	SiO_2	Al_2O_3	Fe_2O_3	Cr_2O_3	FeO	NiO	MgO	H_2O comb.
I	2.26	14.90	68.75	1.89	0.77	0.74	——	11.15
II	7.54	4.97	64.81	3.66	1.49	2.75	1.50	12.75

SIDERITE

United States.—Siderite (74-76) is of little importance in the United States, both on account of the small extent of the deposits (Fig. 147) and its low iron content. When of concretionary structure with clayey impurities, it is termed *clay ironstone,* and these concretions are common in many shales and clays. In some districts siderite forms beds, often several feet in thickness, but containing much carbonaceous and argillaceous matter, and is known as *black band ore.* This is found in many Carboniferous shales.

Iron carbonate in bedded deposits is found in the Carboniferous rocks of western Pennsylvania, northern West Virginia, eastern Ohio, and northeastern Kentucky. These ores were formerly the bases of an important iron-mining industry, but little is obtained now except in southeastern Ohio (109).

Concretions and layers of iron carbonate occur in the Cretaceous clays of Maryland (20) and were formerly mined somewhat extensively in the vicinity of Baltimore and Washington. Small deposits are also known in the Chickamauga (Ordovician) limestone of southwestern Virginia (22). In the western states iron carbonate nodules are found associated with the Laramie (Cretaceous) formation in Colorado and northern New Mexico, but they possess no commercial value.

Foreign Deposits.—The Carboniferous ironstones have been worked in Great Britain since an early date, and those in North Staffordshire were of considerable importance, while those of North Wales were less so. The ores are not infrequently associated with coal and fireclays.[2] The average clay ironstone shows: Fe, 30–35 per cent; SiO_2, 6–15 per cent; Al_2O_3 1–10; Ca, P, and S low. In some localities several beds of ore are present. Jurassic bedded ores which are only in part carbonate are referred to under limonite.

Considerable siderite has been obtained from the Cretaceous limestones of the Bilbao district of Spain, where it forms replacement deposits associated with faults. Associated with it are large masses of limonite and hematite.[3]

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[1] Kemp, Amer. Inst. Min. Engrs., Trans. LI: 4, 1915. (Has bibliography.) Leith and Mead, *Ibid.*, LIII: 75, 1915; and *Ibid.*, Trans., XLII: 90, 1911.

[2] Spec. Repts., Min. Res., Gr. Brit., XIII: 101, 1920.

[3] Adams, Can. Min. Inst., Trans., 1901; John, Zeitschr. prak. Geol., XIX: 208, 1911; Van der Veen, Econ. Geol., XVII: 602, 1922.

PYRITE

Pyrite is primarily used for sulphuric acid, but after driving off the sulphur, the residue is sometimes sold under the name of "blue billy" and used for iron manufacture, being mixed with a natural ore in the desired proportions.

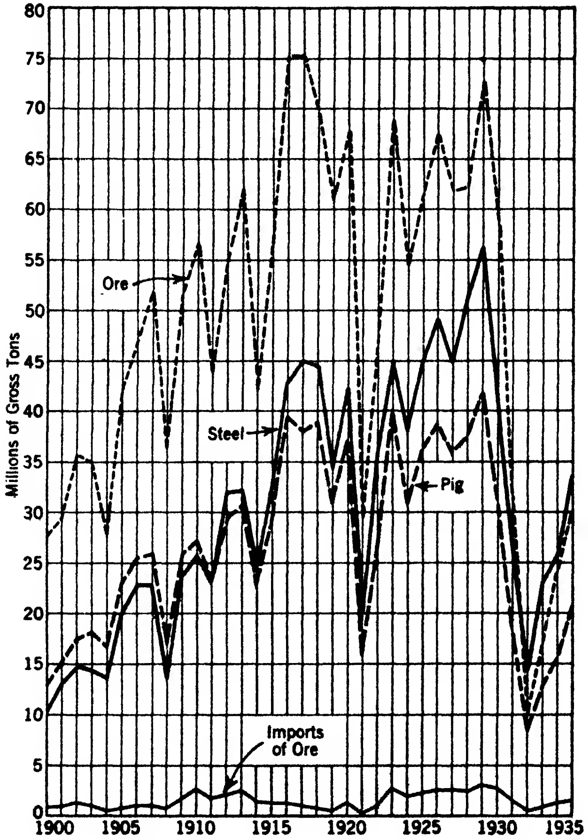

FIG. 155.—Diagram showing the production of iron ore, pig iron, and steel in the United States, 1900 to 1935. (*Minerals Yearbook*, 1936.)

Production of Iron Ore.—The Lake Superior region is now producing about 83 per cent of all the iron ore mined in the United States, and it has large reserves of ore, although the high-grade ones are becoming rapidly exhausted. The low-grade ores of this region and others will, however, be available for a much longer time.

While there is no danger of the present supply of ore soon becoming exhausted, still, with the present consumption, it is well to consider possible sources of the future.

In the United States the Utah and some other western deposits will no doubt be drawn upon, and many ores now looked upon as too low grade to work will also be considered. Aside from domestic sources of supply there are foreign ones which may perhaps be eventually turned to, such as those from Newfoundland and Brazil on this side of the Atlantic, or those of Scandinavia, North Africa, and Russia on the other side. Cuba and Chile are even now sending considerable ore to the United States.

The production of iron and steel over a period of years is shown in Fig. 155.

The production of iron ores in the United States in 1940 was as follows: hematite, 68,869,837 gross tons; brown ore, 934,635 gross tons; magnetite, 3,890,924 gross tons; and carbonate, 513 gross tons. This total of 73,695,899 is 42 per cent greater than the 1939 production. The average value of the ore f.o.b. was $2.51. The four leading states and their percentages of the total production were: Minnesota, 64 per cent; Michigan, 17 per cent; Alabama, 9.9 per cent; and Pennsylvania, 2.0 per cent.

The domestic production of pig iron was 41,253,542 gross tons, and of steel 59,805,970 gross tons.

The imports of iron ore in 1940 were 2,479,326 gross tons, valued at $6,204,641, over half of this coming from Chile. The exports were 1,386,304 gross tons valued at $4,624,555, and most of it went to Canada.

Newfoundland in 1939 produced 1,572,840 short tons of ore. Canada produced 755,731 long tons of pig iron, and 1,384,870 long tons of steel.

The world's production of iron ore in 1938 was 162,000,000 metric tons of which France produced 20.4 per cent, United States 18 per cent, Russia 16.0 per cent, and Great Britain 8.0 per cent.

Iron-ore Reserves (1).—In 1913 the International Geological Congress published a detailed report of the iron-ore resources of the world, which showed that the world's reserves of iron were enormous. Detailed estimates were not always possible, and so for certain areas like Canada, Newfoundland, Mexico, and Africa the term "Very great" was used. For the United States the figure expressed in equivalent of metallic iron was 37,222 million tons, most of this being in the Lake Superior region. Europe was credited with 12,084.6 million tons. Even at that time two tendencies were noted, viz., the use of ores of lower average iron content, and decentralization of the iron industry.

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CHAPTER XV

COPPER

Ore Minerals of Copper.—Copper-bearing minerals are not only numerous, but widely though irregularly distributed. More than this, copper is found associated with many different metals and under varied conditions.

Nevertheless but few copper-bearing minerals are important in the ores of this metal, and the number of important producing districts is comparatively small.

The ore minerals of copper together with their theoretic composition and percentage of copper are as follows:

Ore Mineral	Composition	Per Cent Cu
Chalcopyrite	$CuFeS_2$	34.5
Chalcocite	Cu_2S	79.8
Bornite	Cu_5FeS_4	63.3
Enargite	Cu_3AsS_4	48
Covellite	CuS	66.5
Tetrahedrite	$Cu_8Sb_2S_7$	52.06
Tennantite	$Cu_8As_2S_7$	57
Native copper	Cu	100
Azurite	$2\ CuCO_3, Cu(OH)_2$	55.10
Malachite	$CuCO_3, Cu(OH)_2$	57.27
Chrysocolla	$CuSiO_3, 2\ H_2O$	36.06
Cuprite	Cu_2O	88.8
Melaconite	CuO	79.84
Brochantite	$CuSO_2, 3\ Cu(OH_2)$	62.42
Atacamite	$Cu(OH)Cl, Cu(OH)_2$	59.45
Chalcanthite	$CuSO_4, 5\ H_2O$	25.4

Very few ores approach the theoretic percentages given above. Thus, in Michigan, where native copper is the ore mineral, this as now mined rarely averages above 1 per cent metallic copper, and may fall as low as 0.6 per cent. At Butte, Mont., the important copper-bearing minerals are chalcocite, enargite, and bornite, but the ore in 1923 averaged 3.48 per cent metallic copper. Disseminated ore at Bingham, Utah, averages under 1½ per cent.

Most of the copper ores now worked are of low grade, but can be profitably treated because of the extent of the operations and possibility of concentration. Occasionally low-grade ores are found which are self-fluxing. Sulphuric acid as a by-product from roasting, as at Ducktown, Tenn., may be an asset. Pyrite smelting has permitted the profitable treatment of low-grade pyrite-copper ores, even if they carry no gold or silver. Complex ores of copper, lead, and zinc sulphides are more costly to treat, but this expense may be more than made up for by their gold and silver contents. In the unaltered portion of the ore body the copper compounds are mainly sulphides, but arsenides and antimonides are also known. In the gossan the copper occurs as carbonates, sulphates, silicates, oxides, native, and more rarely as phosphates, arsenates, antimonates, and vanadates.

Gangue Minerals.—Quartz is the commonest gangue mineral, but calcite and siderite are abundant in a few; barite, rhodochrosite, and fluorite are also known. Sericite is found in some veins, and so is tourmaline in certain tin-copper and gold-copper ones.

Metallic impurities may be present which cause trouble in the reduction of the ores. Of these zinc is the most objectionable, but bismuth, though rare, is also very undesirable, but can be eliminated by electrolytic refining. Arsenic, antimony, tellurium, and selenium are partially eliminated in smelting, but must be competely removed by electrolytic methods to make the copper pure enough for electrical work.

Tellurium is not uncommon in some districts, and renders the metal red-short even in small amounts. Silver, even if present in as small amounts as 0.5 per cent, lowers the electric conductivity, and above 3 per cent affects the toughness and malleability of the copper. Sulphur up to 0.25 per cent lowers the malleability, and 0.5 per cent renders the metal cold-short, while 0.4 or more per cent phosphorus makes it red-short.

A high percentage of silica is detrimental, as it requires too much basic flux.

Occurrence and Origin.—Copper ores are found in many formations ranging from the pre-Cambrian to the Tertiary, and the deposits have been formed in many different ways. Indeed in some cases more than one mode of origin may be represented by the deposits of one locality (Clifton, Ariz.; Bingham, Utah), which makes it a little difficult to separate the different occurrences sharply on genetic grounds. Then too, a difference of opinion sometimes exists regarding the origin of some one deposit (Rio Tinto, Spain).

A rough grouping might therefore be made as follows:

1. Magmatic segregations.
2. Contact-metamorphic deposits, in crystalline, usually garnetifer-

ous limestone, along igneous rock contacts. (Clifton-Morenci, Ariz., Bingham, Utah, etc.)

3. Deposits formed by circulating waters, and deposited in fissures, pores, or other cavities, or by replacement.

A. By ascending thermal waters.

B. By waters, probably of meteoric character, and unassociated with igneous rocks.

4. Lens-shaped deposits of variable origin in crystalline schists.

All of these except the first have important representatives in the United States, but in many cases their commercial value depends on secondary enrichment and not the mode of primary deposition.

Superficial Alteration (5, 14, 15, 18, 20, 21).—This may produce results of great economic importance, and excellent examples of it are seen in some of the Arizona ores, where the upper portions of the copper deposits are brown or black ferruginous porous masses, brightly colored with oxidized copper minerals such as cuprite, malachite, azurite, and chrysocolla, while below this at a variable depth they pass into sulphides.

In weathering, the copper minerals, such as chalcopyrite or other sulphides, are usually oxidized first to sulphates, and subsequently changed to oxides, carbonates, or silicates, and occasionally even to chlorides. A concentration of the ore deposit may take place partly by segregation and partly by leaching, and pockets of the ore form, which are surrounded by oxidized iron minerals forming part of the gangue.

While the oxidation will not increase the total copper content of the ore body, still it may change it into a more concentrated form, for the carbonates and other oxidized copper minerals contain more copper than the original sulphide. The ore in the gossan may therefore run from 8 to 30 per cent or more, while below it may show only 5 per cent of copper (see ref. 7 under ore deposit references). These altered ores cannot, however, be more cheaply treated. If leaching follows oxidation, the gossan may be freed of its ore, as at Butte, Mont., where the upper part of the ore-bearing fissures is poor siliceous gangue.

Below the zone of oxidation, there often lies a zone of secondary sulphide enrichment (Chap. XIII), of variable depth, followed still lower down by the primary ore.

But even with secondary enrichment, the deposit may not carry more than 2 per cent of copper, and yet because of its concentrating possibilities and size be worth working.

The processes of secondary enrichment have been referred to in Chap. XIII, and it was shown there that the work of Graton and Murdock has demonstrated that the change is not as simple or direct as was formerly thought.

Importance of United States as a Copper Producer.—The map, Fig. 156, sets forth clearly the distribution of copper ores in the United States, and statistics show the leading position of this country as a world's producer. The following table compiled by Butler some years ago shows in an interesting way the production of copper according to the geologic age of the deposits. These ratios have changed since then.

	PERCENTAGE IN 1913
Pre-Cambrian. Michigan; Jerome, Ariz.; Encampment, Wyo. . .	15.60
Paleozoic. Ducktown, Tenn., and other Appalachian deposits . . .	1.60
Mesozoic. Shasta County, Calif.; Foothills belt, Calif.; Ely, Nev.; Yerington, Nev.; Alaska; Bisbee, Globe, and Ray, Ariz.; others. .	36.71
Tertiary. Butte, Mont.; Morenci, Ariz.; Santa Rita, N. Mex.; Bingham, Frisco, and Tintic, Utah; others	45.98

About 92 per cent of the copper produced in the United States in 1935 was obtained from five states, viz., Arizona, Montana, Utah, Nevada, and Michigan, named in the order of their output, nearly all of the rest coming from the Appalachians and Cordilleran region; the ores of the latter are often worked chiefly for their gold contents, with copper as a secondary product.

Magmatic Segregations

While it is known that copper sulphides may crystallize from a magma, chalcopyrite being the best known example, still few cases of copper ores formed by magmatic segregation are known. Moreover, it is sometimes difficult to prove definitely that the deposit has originated in this manner, in other words whether the copper sulphide has crystallized from fusion, or has been deposited from solution. The criteria that may be used include: (1) primary intergrowths of sulphides and silicates, (2) inclusions of sulphides in silicates, (3) corrosion of silicates by sulphides, if the latter crystallized later, and (4) absence of hydrothermal effects. Metamorphism may sometimes obscure the original characters of the ore body.

Copper ores of this class fall into the two following groups: 1. Those representing crystallizations from the magma, with sulphides and silicates closely associated, but whether the two are contemporaneous, or the sulphides formed later under pneumotectic conditions is sometimes a matter of dispute. 2. Bodies of comparatively pure sulphides, which are believed by some to represent injections.

While Sudbury, Ont. (See Nickel) was formerly placed in this group, many regard the deposits as in part, at least, epigenetic.

Of the injected pyritic deposits, the best known cases perhaps are those of Röros and Sulitjelma, Norway, where great flat lenses, carrying pyrite, chalcopyrite, and pyrrhotite are found in metamorphic schists, closely associated with metamorphosed gabbro, and sometimes in it.[1] Their intrusive nature has been doubted by some. Others placed in this group by some are Bodenmais, Bavaria [2] and Falun, Sweden.[3]

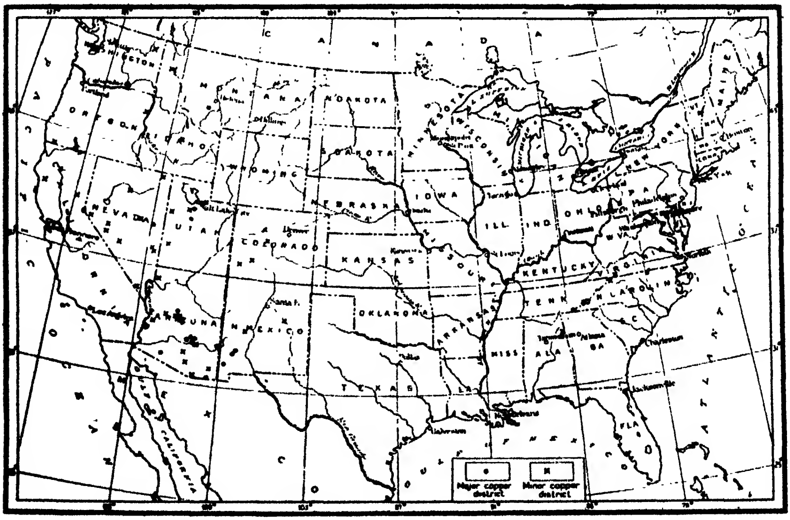

FIG. 156.—Map showing distribution of copper ores in United States. (*U. S. Geol. Surv.*)

Pyrometasomatic Deposits

Some of the most important copper deposits of the world belong not only to this type, but are located in the United States. It should be pointed out, however, that the ores of some of these districts are not exclusively of this type, but include several others which are closely associated genetically. Moreover, while in some cases it was

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[1] Ries and Somers, Amer. Inst. Min. Engrs., Bull. 128, 1917.

[2] Weinschenk, Zeitschr. prak. Geol., 1900: 65.

[3] Sjögren, Internat. Geol. Cong., Stockholm, 1910, Guidebook.

the true contact-metamorphic ores that were first worked at some of these localities, the other types are now the important sources of production. Some deposits, which have the proper mineralogic characters, show no closely associated intrusive.

FIG. 157.—Map of Arizona, showing location of more important mining districts. (*After Lindgren.*)

United States.—*Bisbee, Ariz.* (36, 33, 42).—This district, which contains the famous Copper Queen mine, is located (Fig. 183) in the Mule Mountains but a short distance from the Mexican boundary. The ore outcrops were discovered in 1877, and exploitation began two years later.

The basement rock of the district is the Pinal schist of pre-Cambrian age, on whose peneplaned surface there was deposited about 5000 feet of Paleozoic sediments (Fig. 159). Following a period during which the earlier sediments were very unevenly eroded, there oc-

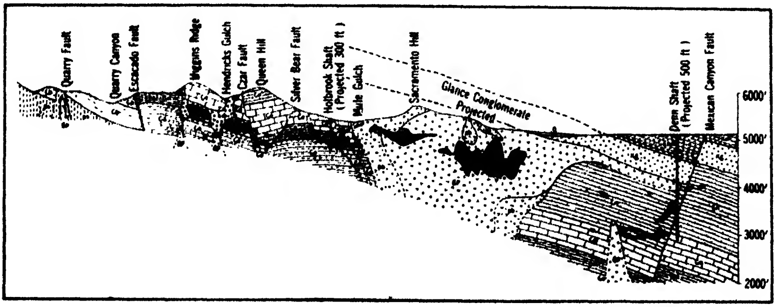
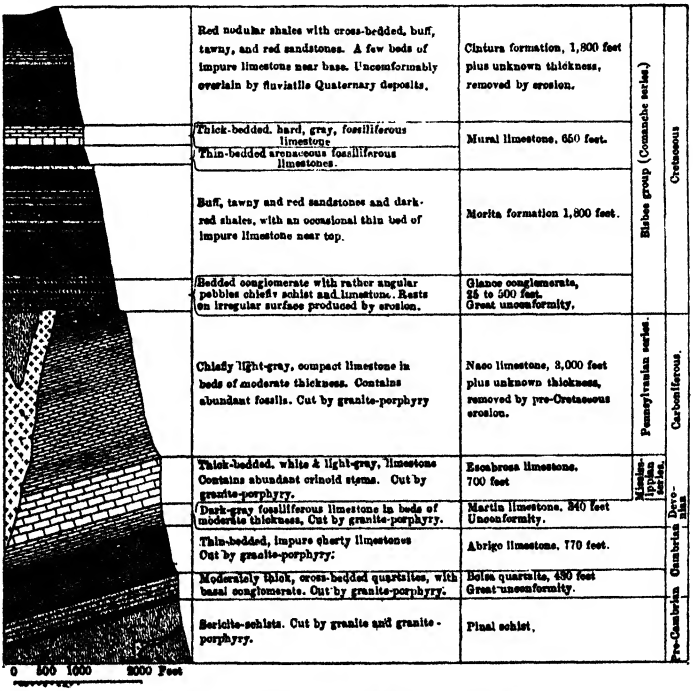


FIG. 158.—Geologic section of Bisbee, Ariz., district. (*After Tenney, Copper Resources of the World* 1935.)

Q, Quaternary; Kn, Kg, Cretaceous; Cn, Ce, Carboniferous; Dm, Devonian; Ꞓa, Ꞓb, Cambrian ps, Archean; gp, porphyry; pb, contact breccia; sib, silica breccia; black, ore bodies.



Red nodular shales with cross-bedded, buff, tawny, and red sandstones. A few beds of impure limestone near base. Uncomformably overlain by fluviatile Quaternary deposits.	Cintura formation, 1,800 feet plus unknown thickness, removed by erosion.	Bisbee group (Comanche series.)	Cretaceous
Thick-bedded, hard, gray, fossiliferous limestone Thin-bedded arenaceous fossiliferous limestones.	Mural limestone, 650 feet.		
Buff, tawny and red sandstones and dark-red shales, with an occasional thin bed of impure limestone near top.	Morita formation 1,800 feet.		
Bedded conglomerate with rather angular pebbles chiefly schist and limestone. Rests on irregular surface produced by erosion.	Glance conglomerate, 25 to 500 feet. Great unconformity.		
Chiefly light-gray, compact limestone in beds of moderate thickness. Contains abundant fossils. Cut by granite-porphyry	Naco limestone, 3,000 feet plus unknown thickness, removed by pre-Cretaceous erosion.	Pennsylvanian series.	Carboniferous.
Thick-bedded, white & light-gray, limestone Contains abundant crinoid stems. Cut by granite-porphyry.	Escabrosa limestone, 700 feet	Mississippian series.	
Dark-gray fossiliferous limestone in beds of moderate thickness, Cut by granite-porphyry.	Martin limestone, 340 feet Unconformity.		Devonian
Thin-bedded, impure cherty limestones Cut by granite-porphyry.	Abrigo limestone, 770 feet.		Cambrian
Moderately thick, cross-bedded quartzites, with basal conglomerate. Cut by granite-porphyry.	Bolsa quartzite, 430 feet Great unconformity.		
Sericite-schists. Cut by granite and granite-porphyry.	Pinal schist,		Pre-Cambrian

FIG. 159.—Geological section at Bisbee, Ariz. (*After Ransome, U. S. Geol. Surv., Prof. Pap.* 21.)

curred a later deposition of Cretaceous sediments whose thickness ranged from 4200 to 5200 feet. The sedimentary series is domed and faulted. On the southwestern flank of the fold, where shattering has been pronounced, the fault zones were invaded by a stockwork of porphyry dikes, and at the southeastern end is the Sacramento Hill porphyry, one of the largest outcropping masses of igneous rock, whose form resembles a laccolith. This is closely associated with the ore bodies.

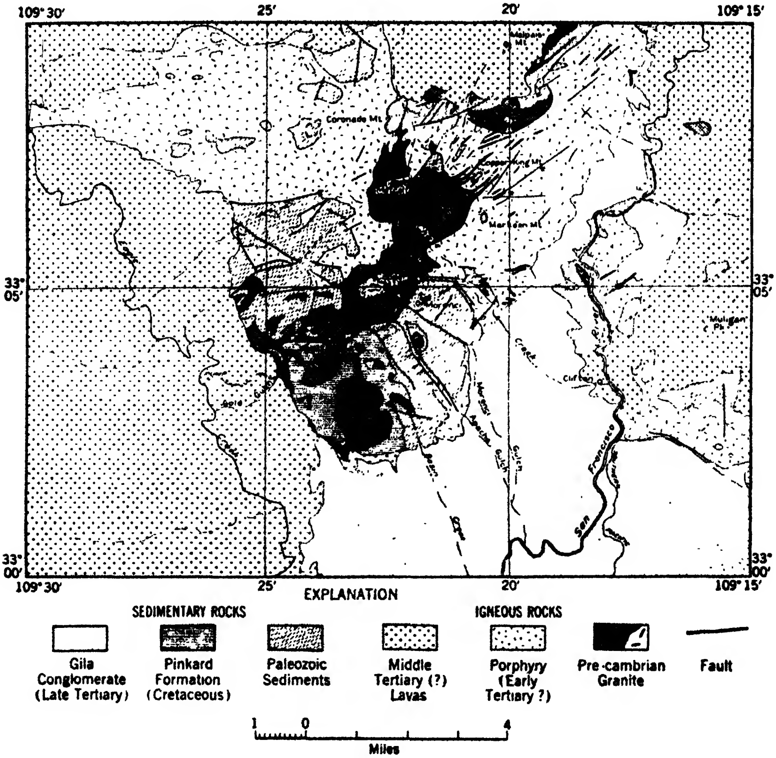


FIG. 160.—Geologic map of vicinity of Morenci, Ariz. (*Copper Resources, World.*)

The ore deposits (Fig. 158) are grouped around more or less independent centers of mineralization associated with separated intrusions, but mineral deposition is confined to one large fault block northeast of the main axis of folding of the range, and this is cut by the pre-Cretaceous Dividend fault, which seems to mark the northern boundary of the ore district.

The ores are found in Paleozoic limestones, associated with the porphyry stocks, the former showing replacement by silica, pyrite, chalcopyrite, and bornite. Much of this ore was enriched and oxidized sulphides.

The bottom of the oxidized zone is very irregular, and in places is said to have reached a depth of 2200 feet.

In the porphyry ore which was discovered later, the ores have been deposited in shattered porphyry, the fractures having been filled by quartz, pyrite, chalcopyrite, and bornite. The rock between carries much pyrite.

The ore which is classed as mesothermal is presumably of about the same age as the porphyry intrusion, and that may be late Cretaceous or early Tertiary.

Clifton-Morenci District (34).—The copper deposits of this district are located at Morenci (Fig. 157) and Metcalf in eastern Graham County. The ores were discovered in 1872, but remained undeveloped for a long time because they were of too low grade and too far from the railroads.

At the present time, however, these large bodies of low-grade ore are utilized, most of the work being done by three large companies.

The geologic section involves the following:

Quaternary (Gila) conglomerate.

Tertiary flows of basalt, rhyolites, and some andesites.

Cretaceous shales and sandstones. Several hundred feet thick.

Lower Carboniferous heavy-bedded pure limestones, 180 feet.

Devonian (?) shale and argillaceous limestone, 100 feet.

Ordovician limestone, 200 to 400 feet.

Cambrian (?) quartzitic sandstone, 200 feet.

Pre-Cambrian granite and quartzitic schists.

Intrusions of granitic and dioritic porphyries of post-Cretaceous age pierce all the older rocks, forming stocks, dikes, laccoliths, and sheets.

All of these rocks have been bowed up and subsequently faulted by late Cretaceous or early Tertiary movements.

Briefly stated, the distribution of the deposits of copper (Fig. 161)

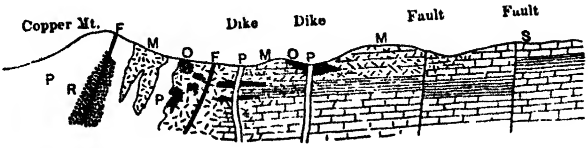


FIG. 161.—Section in Morenci, Ariz., district. *P.*, porphyry; *S*, unaltered sediments; *F*, fissure veins; *M*, metamorphosed limestone and shale; *O*, contact-metamorphic ores; *R*, disseminated chalcocite. (*After Lindgren, Eng. and Min. Jour., LXXVIII.*)

ore is practically coextensive with a great porphyry stock and its dike systems, the deposits occurring either in the porphyry or close to its contact, as well as along dikes of porphyry in some other rock.

The original ores were pyrite and chalcopyrite, of too low grade to be workable, but they have since become so by a process of secondary enrichment. No ores were formed before the porphyry intrusion.

Where the latter is in contact with the granite and quartzite, but little change is produced, but where the porphyry is found adjoining the limestones or shales, extensive contact metamorphism developed, resulting in the formation of large masses of garnet and epidote, especially in the Lower Carboniferous limestones.

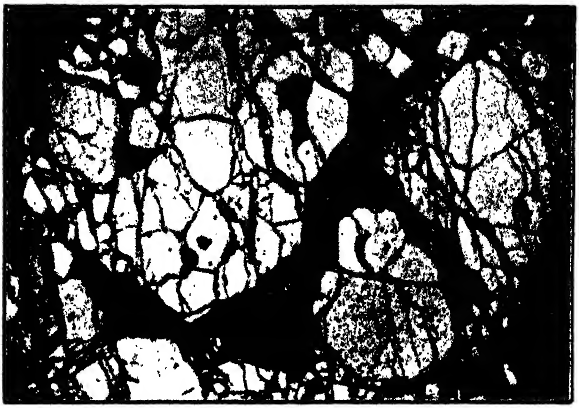


FIG. 162.—Photomicrograph showing replacement in Clifton-Morenci ores. Dark gray chalcocite, developing by replacement of pyrite (light gray). The chalcocite is accompanied by small amounts of microcrystalline quartz, sericite shreds, and kaolin. Black areas represent open field. (*After Lindgren, U S. Geol. Surv., Prof. Pap.* 43.)

Where alteration has not masked the phenomena, magnetite, pyrite, chalcopyrite, and zinc blende accompany the contact minerals.

The ore bodies in the limestone are often irregular, but more frequently roughly tabular, because of the accumulation of the minerals along the stratification planes, or walls of dikes.

In many parts of the district the copper occurs in fissure veins which cut porphyry, granite, and sedimentary rocks, and were probably formed shortly after the consolidation of the porphyry. These in the lower levels carry pyrite, chalcopyrite, and sphalerite, but no magnetite. Surface leaching of these veins has often left limonite-stained, silicified porphyry outcrops.

Accompanying these veins, and of more importance commercially, are often extensive impregnations of the country rock. These disseminated deposits in the highly altered porphyry are leached out above, but lower down show a zone of pyrite and chalcocite, which does not usually extend below 400 feet.

Most of the copper in the district is obtained from concentrating ores containing chalcocite in altered porphyry. In 1923 the yield of copper from the concentrating ores was 2.19 per cent, but the yield of the smelting ores is not reported.

The precious-metal content is so low that much of the output of this district is not refined electrolytically unless the copper is not pure enough to put on the market.

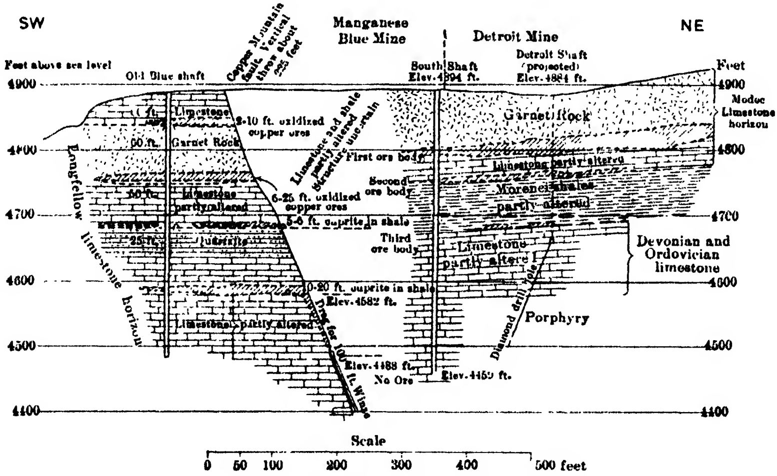


FIG. 163.—Vertical section of ore body in Clifton-Morenci district, showing contact metamorphosed limestone. (*After Lindgren, U. S. Geol. Surv., Prof. Pap.* 43.)

The intrusions of porphyry produced strong contact metamorphism in the shales and limestones of Paleozoic age, resulting in the contemporaneous and metasomatic development of various contact silicates and sulphides,[1] the contact zone thus receiving large additions of iron, silica, sulphur, copper, and zinc, substances unknown in the sedimentary series away from the porphyry.

Subsequent to the solidification of the porphyry, extensive fissuring occurred in both it and the sediments, resulting in the deposition of quartz, pyrite, chalcopyrite, and zinc blende in the fissures and by replacement of the wall rock. These are low in copper, but there is a

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[1] Garnet, epidote, diopside, etc., pyrite, magnetite, chalcopyrite, and sphalerite.

close relation between the veins and contact deposits because of the similarity of their metallic contents, and of the similar development of tremolite and diopside where limestone forms the wall. The extensive impregnation of the porphyry also occurred at this time. Subsequent exposure of the deposits by erosion permitted the entrance of

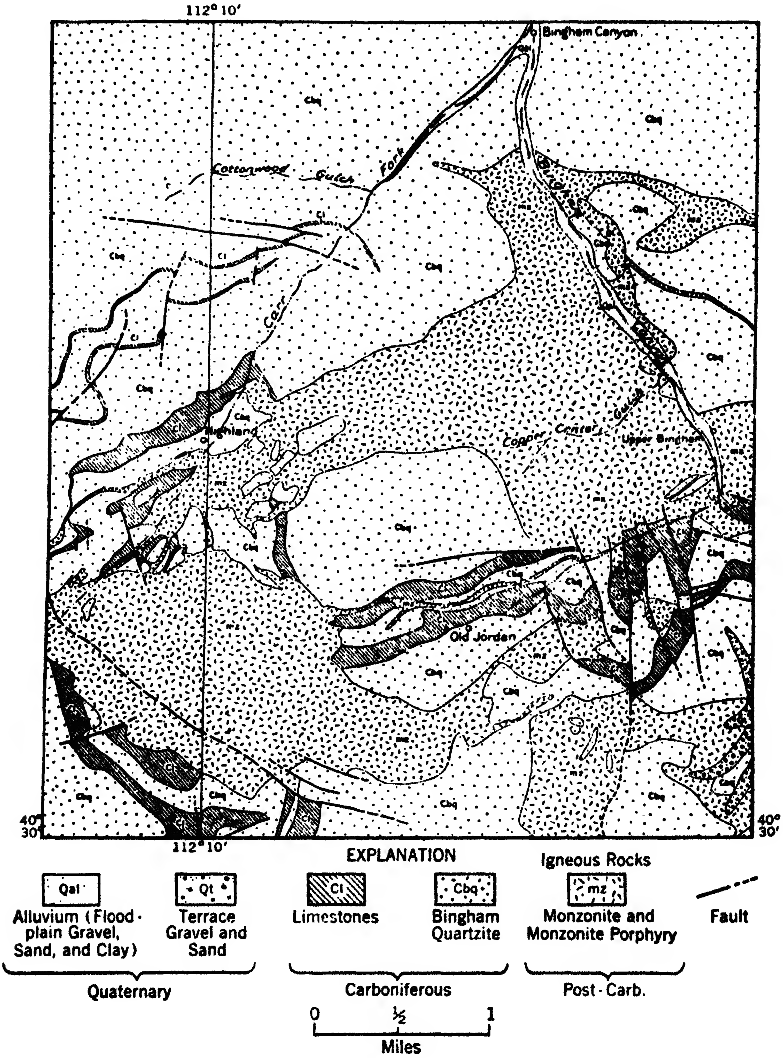

FIG. 164.—Geologic map of Bingham, Utah, district. (*After Boutwell, Copper Resources of the World*, 1935.)

surface waters which was followed by weathering and secondary enrichment.

Bingham Cañon, Utah (118–120, 123, 124, 126).—This camp, which is the leading copper-producing locality of Utah, is situated in the north-central part of the state, on the eastern slope of the Oquirrh Mountains, 30 miles southwest of Salt Lake City.

The rocks of the area include about 10,000 feet of Upper Carboniferous quartzite, within which in stratified sequence there are about 2000 feet with numerous beds of limestone, some being locally 300 to 400 feet thick. These are folded into an open syncline, plunging northwestward. The limestones, which are an integral part of the Bingham quartzite formation, are important because on account of their easier replacement, they have been a dominant factor in controlling the distribution of the non-porphyry ores.

FIG. 165.—Thin section of altered porphyry, from Clifton-Morenci district, containing grains of pyrite surrounded by chalcocite (both black). ×18.

The sediments have been intruded by a great irregular mass of monzonite, which sends out apophyses into the surrounding rocks. A few small sills of basaltic rock and dikes of rhyolite are present in some of the mines, while on the eastern slopes of the ranges a flow of latite covers the sediments.

Faults of varying age, and both post and pre-mineral date are present, but their displacement is usually less than 200 feet.

Plate XLV.—Utah copper mine, Bingham, Utah. Showing great body of monzonite porphyry which is being worked for its copper contents.
(Cut loaned by Amer. Inst. Min. Engrs.)

The limestones, originally black, have not only been changed to white marble by the monzonite intrusion, but have also been replaced by metallic and non-metallic minerals. Indeed in some cases the rock may be a solid mass of garnet, wollastonite, and diopside, with tremolite and specularite less common. The lime silicates may extend to a distance of 2000 to 3000 feet from the porphyry, and farther in fact than the ore minerals.

The ore bodies are of the following types: (1) Irregular masses in limestone, rarely exceeding 3 per cent copper, with chalcopyrite as the chief ore mineral, and abundant associated pyrite. They are low in gold and silver. (2) Vein-like bodies of copper ore, along fissures, bedding planes, and intrusive contacts, sometimes massive sulphides, and made up largely of pyrite with a little quartz, chalcopyrite, gold, and silver. They are probably replacements. (3) Disseminated ores in the fractured portions of the porphyry, and to some extent the quartzite, which in section show an oxidized and leached zone 50 to 150 feet thick, below which there is a secondary enrichment zone of low-grade ore consisting of specks and coatings of chalcocite deposited

FIG. 166.—Section showing replacement of limestone by pyrite (*P*) and chalcocite (*Ch.*) Quartz (*Q*). (*After Boutwell, U. S. Geol. Surv., Prof. Pap.* 38.)

on earlier pyrite, chalcopyrite, or bornite. This is the chief contributor to the output of the district. (4) Lead ores, consisting of galena and pyrite, with varying proportions of sphalerite, as well as minor quantities of copper and silver. These ores lie in a zone outside the copper, but may grade into it.

During the past 20 years, one mine of this district, the Utah Copper (Pl. XLV) has become the greatest one on the continent. In this period it has produced 90,000,000 tons of copper ore, and has removed 54,500,000 yards of capping. It has 564,000,000 tons of 1.1 per cent ore reserves.

The theory of origin advanced by Boutwell is that the quartzites and limestones were intruded by the monzonite in Mesozoic or early Tertiary times, producing contact metamorphism of the limestone and replacing it with sulphides.

After the upper portion of the monzonite intrusion was partly cooled, the inclosing rocks were fractured by northwest-southeast fissures, along which there ascended heated aqueous solutions from the deeper, uncooled portions of the magma. These solutions not only altered the fissures, walls, but deposited additional metallic sulphides, thus enriching the limestones as well as altering the monzonite by the addition of copper, gold, silver, pyrite, and molybdenite.

In the limestones the copper ores were deposited nearer to the intrusive and grade outward into lead zinc deposits. There is also a progressive change in gangue minerals in the same direction, from a garnet-tremolite-pyrite-specularite mixture, to a diopside-wollastonite one.

In 1933 the ore treated at the mills of the Utah Copper Company had an average copper content of 1.03 per cent, with an average recovery of 92.83 per cent.

Ely, Nevada (96, 98, 99).—Ely, which is located in the Robinson district of White Pine County, and was first developed as a gold-silver-lead proposition, is now one of the important copper-mining districts of the country. It is also one of the earliest "porphyry coppers" to be worked. Up to 1932 it had yielded 1,800,000,000 pounds of copper.

The geology involves a great thickness of limestones, and shales with some quartzite ranging from Ordovician to Pennsylvanian in age, which have been folded and faulted. The igneous rocks include an older and a younger intrusive monzonite, with later tuffs, rhyolite, and obsidian.

PLATE XLVI

FIG. 1.—Smelter of Arizona Copper Company, Clifton, Ariz. (*After Church, Min. Mag., X.*)

FIG. 2.—View of Bingham Cañon, Utah. (*After Keith, U. S. Geol. Surv., Prof. Pap.* 38.)

Three kinds of metamorphism have affected the rocks as follows: 1. Contact metamorphism, which changed the shales to pyritiferous hornstone, and recrystallized the limestone with the formation of silicates, magnetite, and copper sulphides; as well as the development of much jasperoid caused by silicification of the limestone. 2. Hydrothermal alteration of the porphyry which involved sericitization and deposition of sulphides. 3. Surface silicification, oxidation, and some supergene enrichment.

Most of the ore is found in the porphyry, and ranges from 1.40 to 1.73 per cent copper, while the contact metamorphic deposits in the limestone yield from 6 to 15 per cent.

The metallic minerals in the porphyry are pyrite, chalcopyrite, bornite, chalcocite, and a little covellite; also small amounts of sphalerite, molybdenite, and magnetite. Although the upper parts of the deposits are oxidized and leached of their copper content, the supergene enrichment is very shallow, and in this respect the deposits are exceptional. Most of the porphyry ore worked, therefore, is of hypogene character.

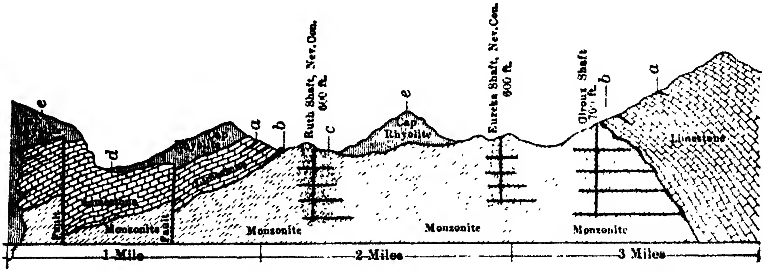

FIG. 167.—Section of Ely, Nev., district. (*From Weed.*)

The ore and porphyry are believed to have emanated from the same source.

Ajo, Ariz. (32, 33).—The ores of this district, which is situated in Pima County, have been known for some time, but large-scale operations did not begin until 1915. Between 1917 and 1930 inclusive the production was 16,340,000 tons of carbonate ore averaging 1.36 copper, and 15,645,000 tons of sulphide ore averaging 1.41 per cent copper. The reserves are said to be large.

The rocks consist of a series of Tertiary rhyolites and andesites, which have been intruded by a lopolith of quartz-monzonite, and the ore consists chiefly of chalcopyrite and bornite with a very little pyrite,

FIG. 1.—View from open cut of Old Dominion mine, Globe, Ariz., looking towards Miami. Rocky surface beyond tank, weathered dacite: low ridges beyond creek, Gila conglomerate. (*H. Ries, photo.*)

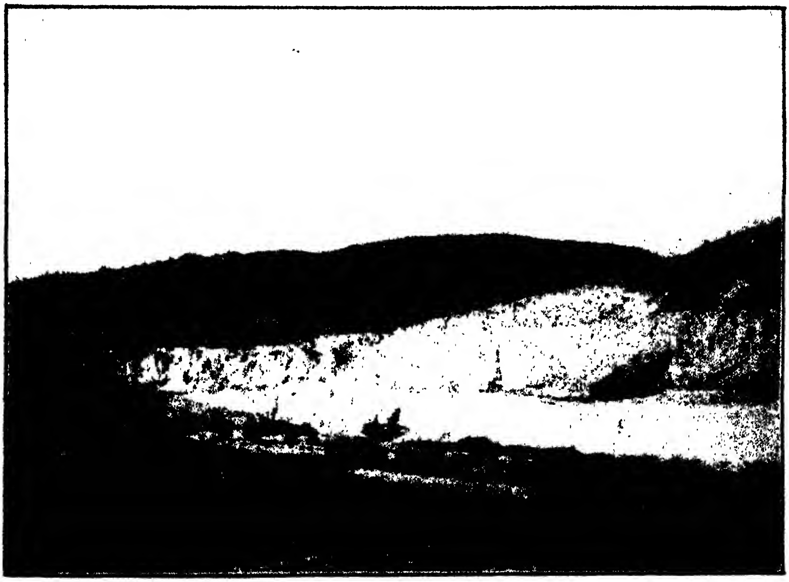

FIG. 2.—South end of the Eureka ore pit, Ruth, Nev. The hills in the background are limestone at the top and porphyry at the base. (*D. Steel, photo.*)

the sulphides occurring as veinlets or disseminated grains. The gangue is quartz and orthoclase. Small amounts of tennantite, a little sphalerite and molybdenite, together with much magnetite and specularite, are present. The monzonite is highly pegmatized, and the richest ore is found in the most intensely altered rock. Oxidized ore, chiefly carbonate, averaged about 55 feet in depth, but this has all been worked out. The negligible amount of secondary enrichment is thought to be due to the small amount of pyrite.

Other Deposits.—Among the other deposits, yielding copper ores in part or wholly of the contact metamorphic type, may be mentioned those of the following districts: Santa Rita, N. M. (102, 103); Yerington, Nev. (97); and Silver Bell, Ariz. (44).

Alaska. *Ketchikan District* (31).—The most important ore bodies are contact-metamorphic ones occurring in irregular masses from 10

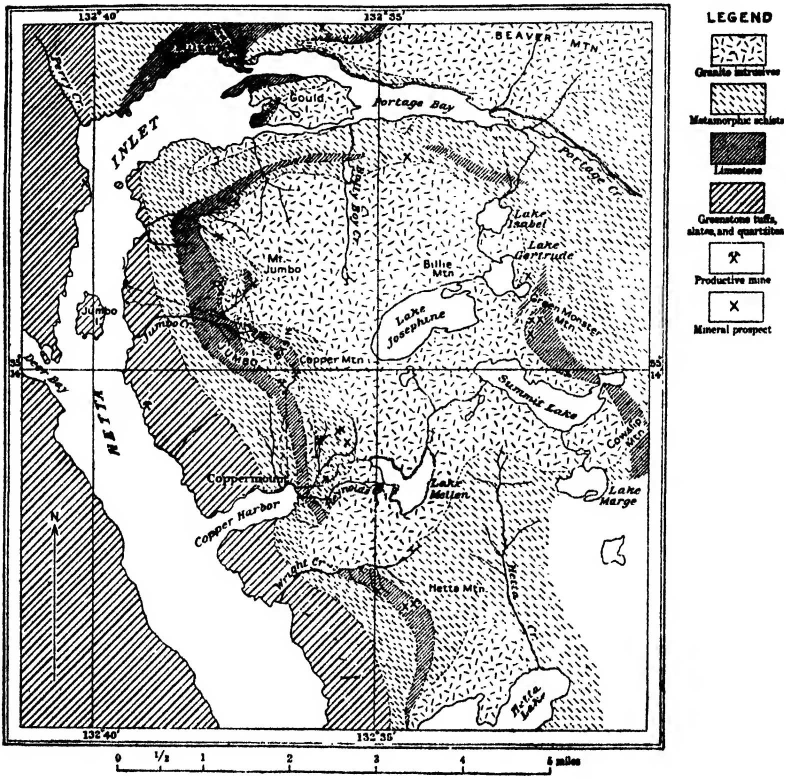

FIG. 168.—Geologic map of Copper Mountain Region, Prince of Wales Island, Alas. (*After Wright, U. S. Geol. Surv., Bull.* 379.)

to 250 feet in dimensions, along the contacts of the intrusive rocks, usually with limestones, the ore composed mainly of chalcopyrite, magnetite, pyrrhotite, and pyrite in a gangue of amphibole, orthoclase, epidote, garnet, and calcite. In addition to these there are lode deposits in shear zones, vein deposits in fissures, and disseminated ores.

The ores mined were somewhat low in grade, with a little gold and silver, but high in iron and lime, and formerly were sold as a flux for smelters of Tacoma and British Columbia.

At Copper Mountain in the Hetta Inlet district (Fig. 168) the ores are (1) contact deposits occurring between granite and limestone or schist, and (2) vein or shear zone deposits, occurring along the bedding planes of the greenstone schist and quartzites. The contact zone is of variable width and is broadest in the limestone.

Canada.—Copper ores of the contact-metamorphic type were formerly worked at Phoenix and Deadwood (145, 147). Another interesting but not large deposit was that at Whitehorse, Yukon Territory (139).

Mexico.—The copper deposits of Cananea,[1] which are in part of the contact metamorphic type, are well known. They have been developed in Paleozoic limestones, by the intrusion of diorite porphyry and granodiorite, and carry chalcopyrite, sphalerite, bornite, magnetite, hematite, and galena, in a gangue of contact silicates. Of greater importance, however, are the lodes and disseminations in sericitized and silicified diorite porphyry. Other interesting deposits occur at San Jose,[2] Matehuala,[3] and Velardena.[4]

Deposits Formed by Circulating Waters

This grouping includes deposits of the fissure vein or related types which have been formed by cavity filling or replacement, and is further subdivided into: (*A*) those deposited by ascending thermal solutions, evidently of magmatic origin; and (*B*) those deposited by waters, probably of meteoric character, and unassociated with igneous rocks.

A. Deposits Formed by Ascending Thermal Waters

This group includes copper ore bodies formed in the lower vein zone, and those deposited at intermediate depths.

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[1] Perry, Copper Resources of World, p. 413, 1935.

[2] Kemp, Amer. Inst. Min. Engrs., Trans. XXXVI: 178, 1905.

[3] Spurr, Garrey and Fenner, Econ. Geol., VII: 444, 1912.

[4] Spurr and Garrey, *Ibid.*, III: 688, 1908.

Hypothermal Deposits

United States.—Copper veins or lodes carrying tourmaline as a high temperature index mineral have been described from a number of localities. In the United States a very interesting deposit is that found in the Cactus mine of southern Utah. This is a low-grade chalcopyrite-pyrite ore containing tourmaline and occurring in a brecciated area of sericitized and tourmalinized post-Paleozoic monzonite.

Arizona, Jerome District (35).—Two large copper mines at Jerome have produced heavily with a considerable quantity of gold and silver as by-products. The United Verde, whose ore body outcrops have been designated by Lindgren as the largest pyritic copper deposit in the United States, and one of the largest in the world. The other, the United Verde Extension, is located on the opposite or down throw side of the Jerome fault, and the ore body is buried under younger rocks. The formations at Jerome involve a series of peneplaned pre-Cambrian metamorphosed rocks, covered unconformably by a series of Paleozoic sediments, which in turn are capped by a flow of Tertiary basalt.

The copper ores occur as replacements of rhyolite and other schists of pre-Cambrian age, and were introduced following the intrusion of the pre-Cambrian Bradshaw granite, but the solutions are thought to have come from a deeper source than it. The chief ore bodies are pyritic copper deposits of replacement origin, and carry pyrite, sphalerite, arsenopyrite, tetrahedrite, and tennatite, with quartz, dolomite, ankerite, and sericite. There has been pre-Cambrian secondary enrichment, resulting in the formation of chalcocite, and some of these bodies are found under the Paleozoic covering.

The ore body of the United Verde mine is a steeply dipping cylindrical mass, 700–800 feet in diameter, and extending to over 3000 feet in depth. Most of the ores run 3 to 5 per cent in copper. The deposits are classed by Lindgren as hypothermal.

California (48–51).—The Plumas County copper belt is not important at present as a producer, but has provoked considerable discussion as to its origin. The ore bodies are found at the contact of gabbro and diorite, occurring in both rocks and in roof pendant material. The ore minerals are chalcopyrite, bornite, ilmenite, and magnetite. After actinolization of the wall rocks the ores were deposited, and there then followed lower temperature hydrothermal alteration with the formation of stilbite. Tolman and Rogers claimed that the ores were late magmatic, while Knopf and Graton consider them hypothermal.

Canada. *Rouyn, Quebec* (135, 141, 144).—This district in western Quebec was discovered in 1922 and has become a producer of some importance. The geologic section is as follows (135):

Quaternary		Glacial and post-glacial deposits
Keweenaw (?)	Nipissing	Diabase
Huronian	Cobalt series	Conglomerate, graywacke, arkose, and argillite
Great unconformity.		
	Intrusives	Basalt, gabbro, peridotite, granites, quartz, diorite Post Timiskaming folding Diorite porphyry Amphibolite
Pre-Huronian	Timiskaming series	Conglomerate, graywacke, lavas
	Probable unconformity	
	Keewatin series	Basalts, andesites, dacites, rhyolites, tuffs, and metamorphosed sediments

The copper sulphides, which also carry gold, are chiefly replacement deposits, and the sulphide ore bodies are known only in the Keewatin rocks. They vary in size and show all degrees of replacement. Some may be 10 to 22 feet long and 1 or 2 feet wide, while others are several hundred feet long and 200 feet wide. Of the sulphides, pyrite and pyrrhotite predominate, while with these are chalcopyrite, sphalerite, and often magnetite. The paragenesis is pyrite, magnetite, pyrrhotite and blende, or blende and chalcopyrite.

Of the country rocks, the fragmental ones seem to be the most extensively replaced; large masses of them have been silicified and later chloritized, and this is believed to have occurred at the same time as the deposition of the blende and chalcopyrite.

The exact source of the copper-bearing solutions appears to be in doubt.

In 1935 the Noranda Mines produced 74,478,436 pounds of fine copper, 268,333 ounces of gold, and 544,559 ounces of silver.

Another example of this type occurs at Rossland, British Columbia (143). Here the Carboniferous sediments have been cut by a series of extrusives and intrusives ranging from Triassic to Tertiary in age, with several periods of deformation and two of mineralization. The ores occur as replacements along fissures and sheeted zones, chiefly in the augite-porphyrite and monzonite, with pyrrhotite and chalcopyrite as the ore minerals in a gangue of altered country rock. Hydrothermal alteration of the wall rock is marked, the high temperature conditions being indicated by the development of biotite, and also some tourmaline, garnet, wollastonite, and epidote. The ore carries gold as well as copper.

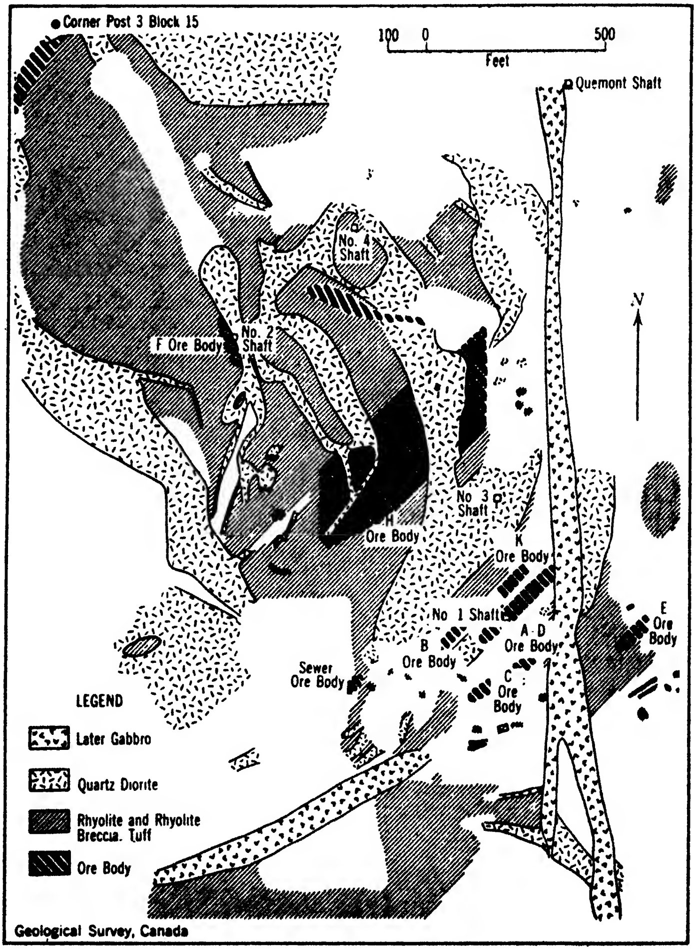

FIG. 169.—Geologic map of Rouyn district. (*After Alcock, Copper Resources of the World,* 1935.)

Mesothermal Deposits

These consist usually of deposits of the fissure vein type, but sometimes form disseminations, etc. They include many important ones.

United States. *Montana* (81–84, 86, 87, 89–94).—The mining camp of Butte, in Silver Bow County, on account of the size and depth of its deposits, has become the greatest copper-producing camp of the world.

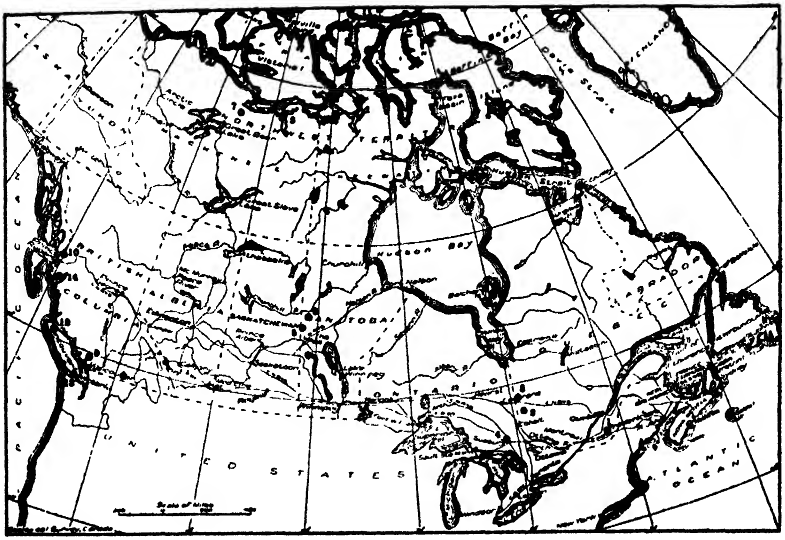

FIG. 170.—Map showing location of copper deposits in Canada. (*After Alcock, Copper Resources of the World*, 1935.)

1. Eastern townships; 2. Rouyn, Que.; 3. Normetal; 4. Sudbury; 5. Flin Flon, Mandy; 6. Sherritt-Gordon; 7. Coppermine River; 8. Bathurst Inlet; 9. Britannia; 10. Hidden Creek, Bonanza, Marble Bay; 11. Copper Mountain; 12. Coast Copper; 13. Sunloch; 14. Drum Lummon.

Through 1932 the county had yielded approximately 10,371,983,748 pounds copper; 1,784,000 ounces gold; 461,279,292 ounces silver; 312,634,454 pounds lead; and 2,565,833,005 pounds zinc.

Butte lies on the western border of the Boulder batholith,[1] the latter having a width of 75 miles and a length of over 100 miles.

Lying between the main range and the Rocky Mountains on the east, and the Bitter Root Mountains on the west, the batholith seems

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[1] Amer. Inst. Min. Engrs., LI: 31 and Bull. 124: 641.

to have been intruded in the Eocene (?) after a period of folding and thrust faulting, and without causing any doming.

Associated with the batholith are a number of fissure veins, those in the Butte district being especially important. The rocks of the Butte district include: (1) Granite or quartz monzonite, the Butte granite, much jointed, and hence permeable to solutions; the host rock of the district. (2) Aplite, locally called the Bluebird granite,

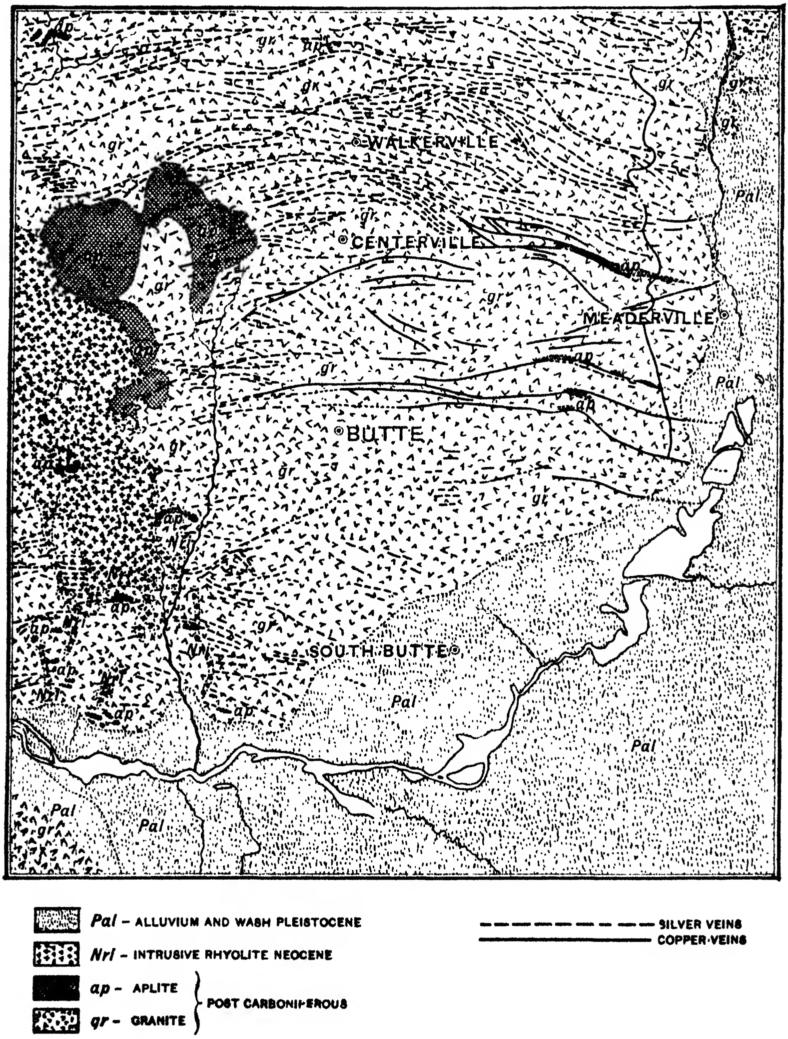

FIG. 171.—Map of eastern part of Butte, Mont., district, showing distribution of veins, and geology. (*U. S. Geol. Surv.*)

in irregular bodies, especially in the northwestern portion of the district. It may be a segregation of the Butte granite. (3) Quartz porphyry dikes, roughly parallel in an east-west direction, and older than the earliest vein system. (4) Rhyolite, of intrusive and extrusive character, especially in the west and northwest part of district, its offshoots cutting both the copper and silver veins. (5) Andesite, of pre-Tertiary age and bearing no relation to the ores.

The granite is cut by many faults, which are hard to detect, and which are often mineralized. Fissures are common in the batholith, and there are several important fracture systems, but only two, the east-west and northwest-southeast ones, are extensively mineralized.

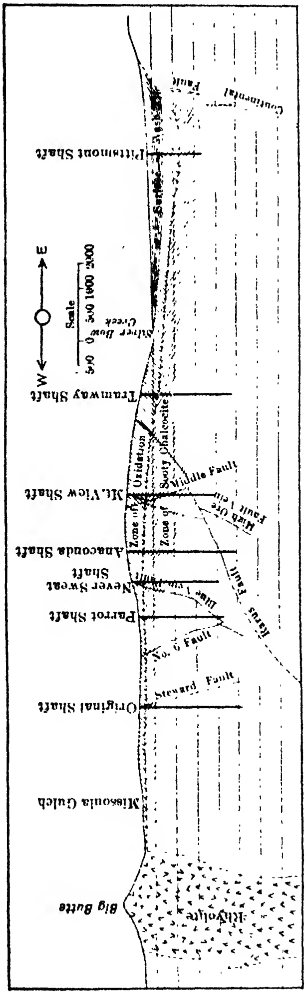

FIG. 172.—Generalized cross section of Butte district. Montana. (*After Sales, Amer. Inst. Min. Engrs., XLVI.*)

There have been identified six distinct fissure systems, which cut the granite, aplite, and quartz-porphyry, but not always the rhyolite, and displacement is found along some. These systems are: (1) Anaconda or oldest, striking east-west, the most strongly and continuously mineralized. (2) Blue, earliest fault fissure, striking in general N. 55° W., and carrying ores of great value. (3) Mountain view breccia fault, striking N. 75° E. and carrying ore. (4) Steward, striking northeast-southwest. and not usually ore bearing. (5) Rarus fault, a complex fissure of variable northeast strike, and dipping about 45° northwest, with fragmental ore dragged in from other veins (Figs. 172, 175). (6) Middle faults, non-orebearing. (7) Continental fault, striking north-south on eastern edge of district, of recent age, with 1500 feet vertical displacement, and Butte on down-throw side (Fig. 172).

The granite is much altered by hydrothermal metamorphism, especially in the Anaconda Hill area, so that it is now a mass of pyrite, sericite and quartz near the veins.

The ore deposits are fissure veins, formed by the filling of fissures and replacement of the country rock, the oldest fissures having been continuously mineralized.

Within the Butte district there are: (1) a main or central copper zone, free from zinc and manganese; (2) an indeterminate intermediate zone, with copper predominant, and with some sphalerite, rhodochrosite, and rhodonite; (3) an outer peripheral zone, which is without copper, but filled chiefly with quartz, rhodonite, rhodochrosite, sphalerite, and pyrite, and which is silver bearing.

In the central or copper zone, the order of relative abundance of the copper sulphides is (92): chalcocite, enargite, bornite, chalcopyrite, tetrahedrite, tennantite, and covellite. Quartz and pyrite form the gangue.

Sales (92) gives the following details regarding the sulphides: Chalcocite has supplied 60 per cent of the Butte copper to date, occurring in veins of all ages, and at all levels down to below 3000 feet. Once regarded entirely as a downward secondary enrichment product, it is now divisible into: (*a*) sooty secondary chalcocite, forming a dull black coating on pyrite and other sulphides or replacing pyrite, sphalerite, enargite and chalcopyrite; (*b*) massive chalcocite, considered as primary because: (1) it is abundant in the deepest levels (over 3000 feet); (2) its intimate association with bornite, enargite, and

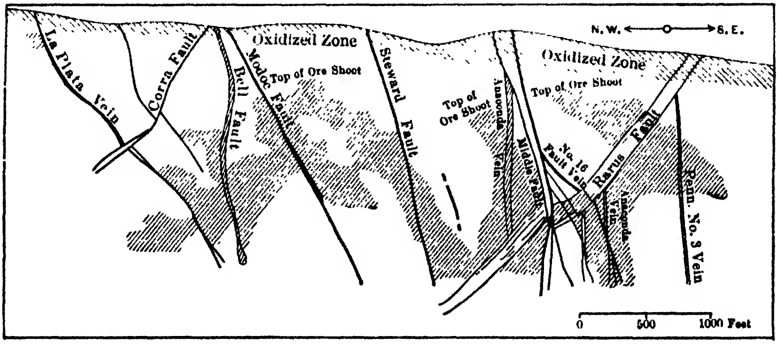

Fig. 173.—Longitudinal vertical projection of the High Ore Vein, a member of the Blue Vein system, distribution of the ore shoots. (*After Sales, Amer. Inst. Min. Engrs., XLVI.*)

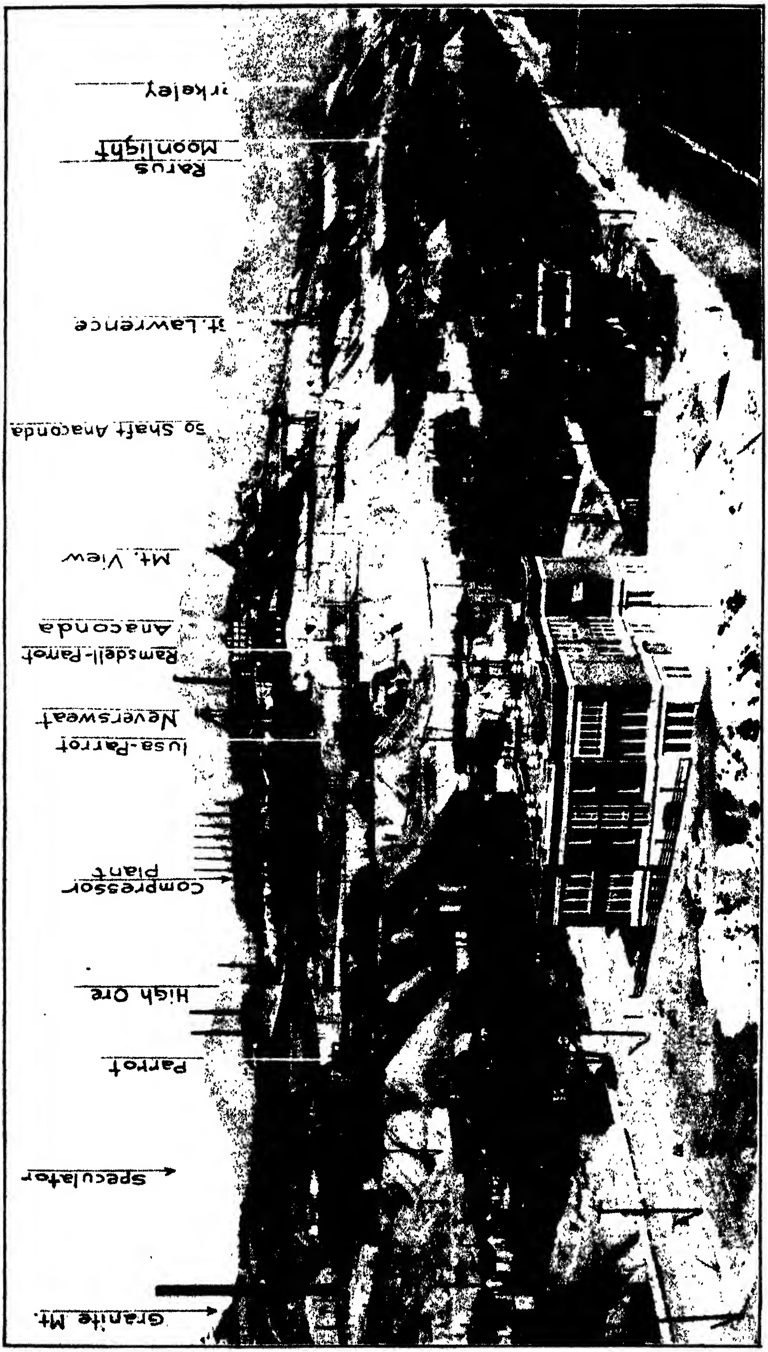

Plate XLVIII. View of hill at Butte, Mont., in which the mines are located. Continental divide in distance. *(Al's photo shop.)*

pyrite show it to be contemporaneous; (3) it occurs at all depths without relation to topography; (4) it is found in dry veins, at deep levels; and (5) there is no evidence of present replacement except in the sooty material.

Enargite is of wide vertical and lateral distribution, of comparatively old mineralization, and usually primary but sometimes secondary.

Bornite is primary, of all ages, and at all levels. Chalcopyrite is chiefly primary; so also is covellite.

The vein outcrops are usually barren of copper, and while the oxidation depth is variable, it averages 250 feet.

In the silver zone, quartz and manganese are the common gangue materials, the veins showing on the surface as ledges of manganese-stained quartz.

The Butte ores have been derived primarily from igneous rocks, the quartz porphyry having perhaps opened up the way for the ore-bearing solutions, the elements carried by the latter having included SiO_2, S, Fe, Cu, Zn, Mn, As, Pb, Ca, W, Sb, Ag, Au, Te, Bi and K.

In the central part of the area, the more highly heated and acid solutions deposited the copper ores, while the zinc, manganese, and lead were precipitated toward the periphery where the temperature was lower, and the solutions more alkaline from reactions with the granite.

The history of this mining camp is full of interest. In 1864 Butte was a gold camp, but difficulties in working the gravels directed attention to the mineral-vein outcrops, and unsuccessful attempts were made to work their copper and silver contents, so that it was not until 1875, after a period of quiescence, that the discovery of rich silver ore in the Travona lode revived the mining industry of Butte. In 1877 several silver mines were opened, followed by others; but this did not last many years, for with the drop in the price of silver many mines closed, although one, the Bluebird, had produced 2,000,000 ounces of silver from 1885 to 1892.

The copper mines were worked to only a limited extent at first, and the industry did not assume permanence until 1879–1880, when matte smelting was introduced. In 1881 the Anaconda mine, which was first worked for silver, began to show rich bodies of copper ore, and since then the output of copper has steadily increased, there being a number of large smelting plants located at Anaconda and Great Falls.

Globe-Miami, Arizona District (38, 40, 43).—This district became well known through the Old Dominion mine at Globe, long before the now more important ores at Miami were developed.

The formations include a pre-Cambrian crystalline complex, the Pinal schist cut by granite intrusives. Overlying these unconform-

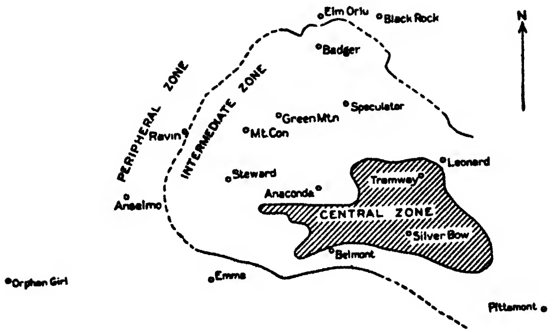

FIG. 174.—Plan showing zonal arrangement of ore minerals at Butte, Mont. (*After Hart, Copper Resources of the World*, 1935.)

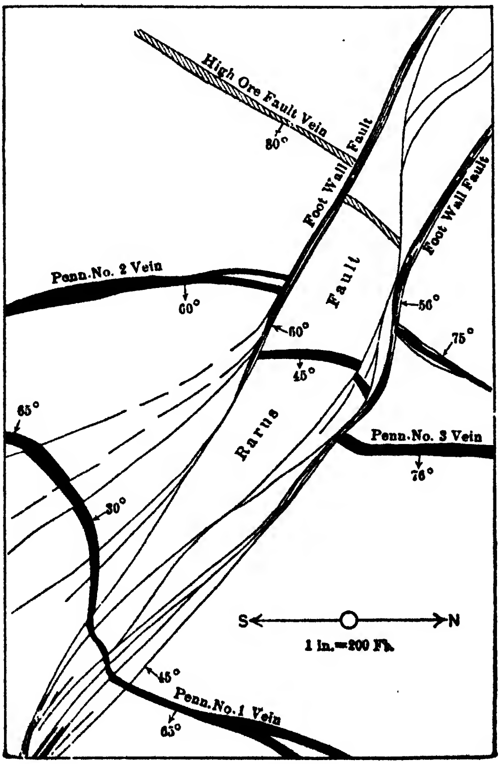

FIG. 175.—Plan of 500-ft. Level of Pennsylvania Mine, showing effect of Rarus fault on different veins. (*After Sales, Amer. Inst. Min. Engrs., XLVI.*)

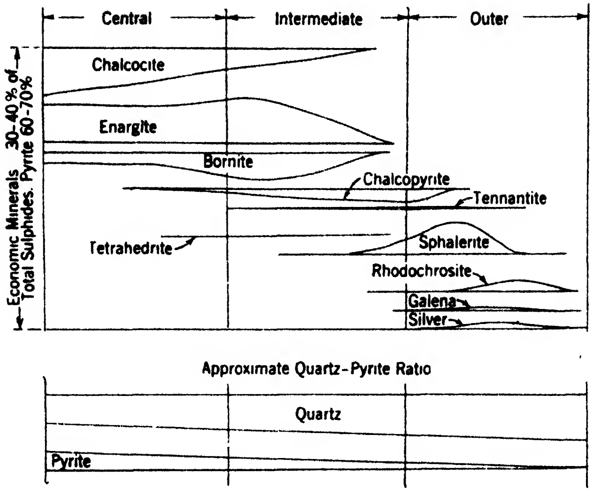

FIG. 176.—Diagram showing paragenesis of ore minerals at Butte, Mont. (*After Hart, Copper Resources of the World*, 1935.)

ably is a thick series of Paleozoic sediments including conglomerates, quartzites, shales, and limestones. In Mesozoic times probably there followed an intrusion of diabase and granitic rocks, and then after an erosion interval Tertiary volcanics and sediments, the Gila conglomerate being prominent among the latter. Faulting of both pre- and post-Tertiary age is known.

Around Miami the great disseminations of chalcocite, in the Pinal schist near the Schultze (Mesozoic) granite are of importance. The original ore was a sulphide of iron and copper, which in its upper part has undergone leaching and oxidation, accompanied by secondary enrichment of the ore below. The section therefore shows a leached capping, followed by an irregular zone of oxidized ore, and this in turn by a secondary enrichment zone, showing grains and stringers of pyrite and chalcopyrite replaced by chalcocite. The ore-bearing solutions came from the Schultze granite, and caused not only deposition of ore, but also extensive silification of the schist.

These disseminated ores represent such an important type in the West today that a few figures showing their low grade, extent, etc., as explanatory of their working at a profit, may be given.

The original ore reserves of the Miami district (Ransome) were estimated at 150,000,000 tons of 2 per cent enriched chalcocite ore, in part oxidized, but in recent years chalcopyritic material, containing under 1 per cent copper, and formerly classed as protore, has been mined and concentrated. The reserves of this in 1930 were over 108,000,000 tons. These mines have produced over 2,000,000,000 pounds of copper.

In the Globe section of the district the ore bodies occur as lenticular replacements in limestone, and as fault lodes, or fissure zones in diabase.

Much of the limestone ore extracted was oxidized, but that in the diabase was enriched material. Some bodies of primary ore of commercial value were also developed. In 1923 the average copper yield of the ore was 1.24 per cent; the gold and silver ran low, but were saved.

Mineral Creek or Ray district, Arizona (38).—The geology here is similar to that at Miami. The deposits (Figs. 177 and 178) are found in sedimentary rocks associated with faults and fissures, or as disseminations in the Pinal schist and granite, this second type being the more important. The production at Ray began in 1911, and the ore bodies at that time were estimated to contain about 115,000,000 tons of ore, running mostly from 1 to 2 per cent copper, and including about 500,000 tons between 5 and 6 per cent.

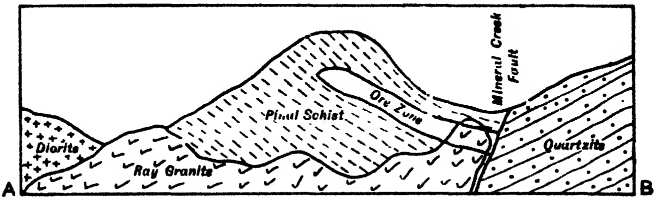

FIG. 177.—Vertical section (A B, Fig. 203) showing ore body in schist, Mineral Creek district, Arizona. (*After Tolman, Min. and Sci. Press, XCIV.*)

Another interesting district of the disseminated type is that of the Burro Mountains in New Mexico (104).

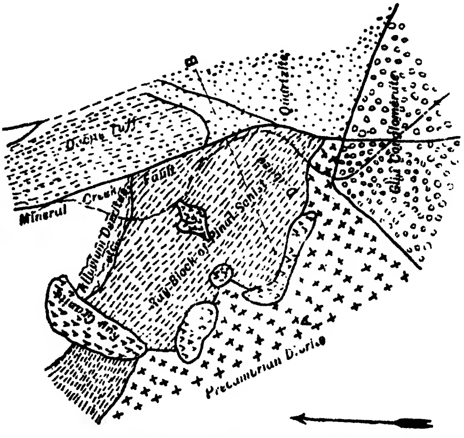

FIG. 178.—Geologic map of a portion of the Mineral Creek, Ariz. copper district. (*After Tolman, XCIX.*)

Alaska. *Copper River District* (26, 28).—This region, which is situated some distance from the coast, and hence difficult of access, has been but little developed, although transportation facilities have now been provided.

At the Kennecott mines (23), which contain some remarkably interesting ore bodies, the section (Fig. 179) shows Triassic or Carboniferous greenstone flows, overlain by 2000 feet of Triassic dolomitic limestones, and these by Jurassic sediments.

The ore bodies, which consist chiefly of chalcocite, with lesser amounts of bornite, covellite, enargite, and tennantite, as well as pyrite, galena and blende, are found in dolomitic limestone, extending upward from the greenstone contact.

In addition great quantities of almost solid chalcocite were found in the talus below the cliffs where the ore body occurs. There is no alteration of the limestone adjoining the ore body, and its origin affords a puzzling problem.

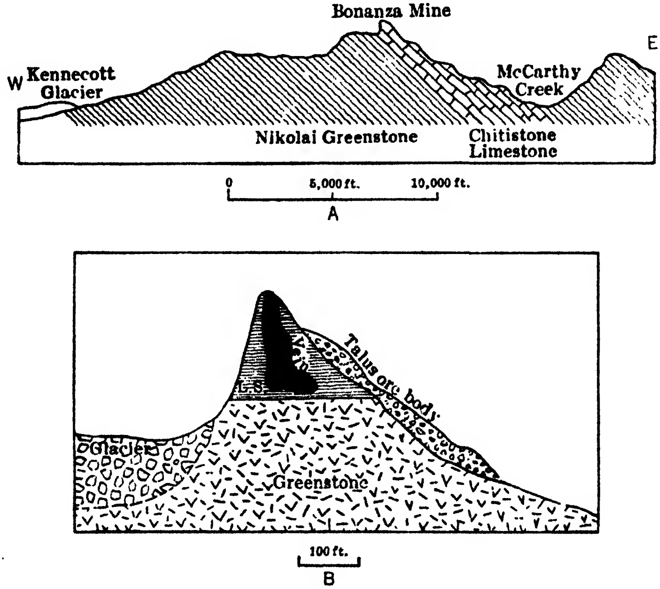

Fig. 179.—A. Vertical cross-section at Bonanza Mine. B. Section at Bonanza Mine to show glacier, ore body and talus slope ore. (*Bateman and McLaughlin, Econ. Geol. XV.*)

Bateman and McLaughlin believe that the ores were deposited by warm meteoric waters which leached the copper from the greenstones and carried it up into the limestone, where it was deposited as chalcocite together with small amounts of other minerals. The ore is therefore a low-temperature deposit, and if the chalcocite is of the isometric variety as claimed, this is probably true.

Foreign Deposits.—Probably the greatest single copper area thus far known is that of Northern Rhodesia[1] with the adjacent portion of Katanga,[2] which has enormous reserves. The important mines in Northern Rhodesia include the Roan Antelope, N'Kana, N'Changa, Mufulira, and others.

The formations include an old pre-mineral basement complex, on which there rests unconformably the ore-bearing Roan series of late pre-Cambrian sediments, 3000–4000 feet thick, while covering these are 14,000 to 15,000 feet of similar sediments also of pre-Cambrian age. The sediments are folded into simple pitching folds.

The ore occurs in one or more beds of the Roan series, which are rather uniformly metallized with minute specks of copper sulphides. These ore-bearing beds may range from 25 to 100 feet in thickness.

Chalcocite is the most important ore mineral, followed by bornite and chalcopyrite. Associates are pyrite, and small amounts of linnæite. The chalcocite may be both hypogene and supergene.

The ores are commonly regarded as being of epigenetic origin, the solutions coming from an underlying granite magma. With such uniform distribution in sediments, some might be inclined to suggest also a syngenetic origin.

Among those which deserve mention here is the Rammelsberg deposit of the northern Hartz district of Germany, interesting not only historically, but also because of its disputed origin. The ore body lies more or less conformably in strongly folded Devonian slates, and has a variable thickness. The ore minerals are chalcopyrite, pyrite, arsenopyrite, and sphalerite in a gangue chiefly of barite. Banding is present, and the ore minerals excepting pyrite are drawn out into streaks. Bergeat[3] and Klockmann[4] thought it a sedimentary deposit, while Vogt[5] and others believed it to have been deposited from solutions of magmatic origin. Lindgren and Irving[6] called it a bedded vein, in part conformable to the surrounding slates, and exhibiting the structure of a dynamometamorphic rock. They agreed with Vogt as to the source.

At the Braden mines in the Chilean Andes, the ore minerals are chalcopyrite, bornite, magnetite, and sphalerite, with tourmaline, quartz, sericite, epidote, etc., occurring as lodes in andesite, at its contact with a tuff. The volcanics surround an ancient crater.

Chuquicamata, Chile, remarkable for its great masses of brochantite underlain by sulphides, should also be mentioned.[7]

Native Copper Deposits.—Deposits of native copper occurring in basic volcanic rocks, especially those of basaltic character, form a widespread type. Their unique character has attracted considerable attention, and their origin has caused much discussion. A noteworthy fact is the constant association of the copper with zeolites, calcite,

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[1] Bateman, Econ. Geol., XXV: 365, 1930.

[2] Robert and Trieu de Terdonck, Copper Resources World, p. 703, 1935.

[3] Erzlagerstätten, p. 329, 1904.

[4] Berg und Hüttenwesen des Oberharzes, 1895, p. 57.

[5] Zeitschr. prak. Geol., 1894: 173.

[6] Econ. Geol., VI: 303, 1911.

[7] Min. Sci. Pr., CXXII: 779.

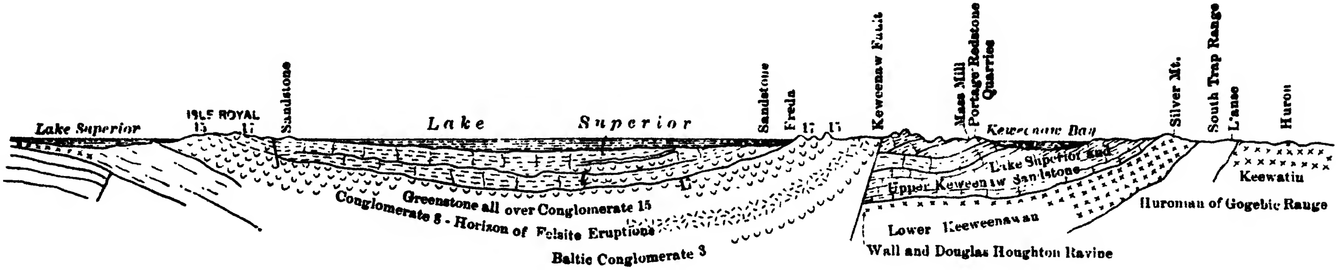

FIG. 180.—Generalized northwest-southwest section including Isle Royal and Keweenaw Point. (*After Lane, Mich. Geol. Surv., Pub. 6, Vol. I, 1911.*)

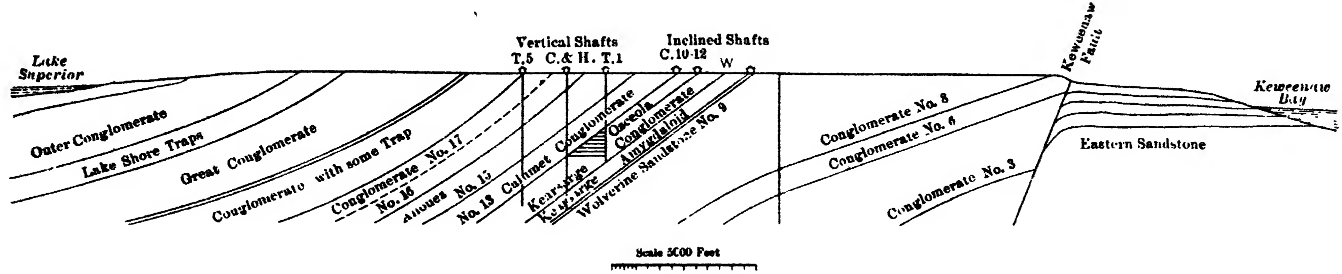

FIG. 181.—Section across the Michigan copper belt. (*After Lane, same as Fig. 180.*)

quartz, epidote, etc., the ore and gangue minerals either filling the gas cavities or replacing the rock.

The igneous rocks are regarded by many as the source of the copper, analysis often showing a small percentage of this metal, and its concentration seems to be associated with the development of the zeolites, so that a theory proving the origin of one must include the other. It is therefore believed by some that the magmas erupted either on the ocean floor, or in bodies of fresh water, absorbed the water of these on cooling, and that this on mixing with magmatic exhalations broke up the copper silicate present, changing it to copper chloride. Iron silicates were similarly affected. These chlorides were

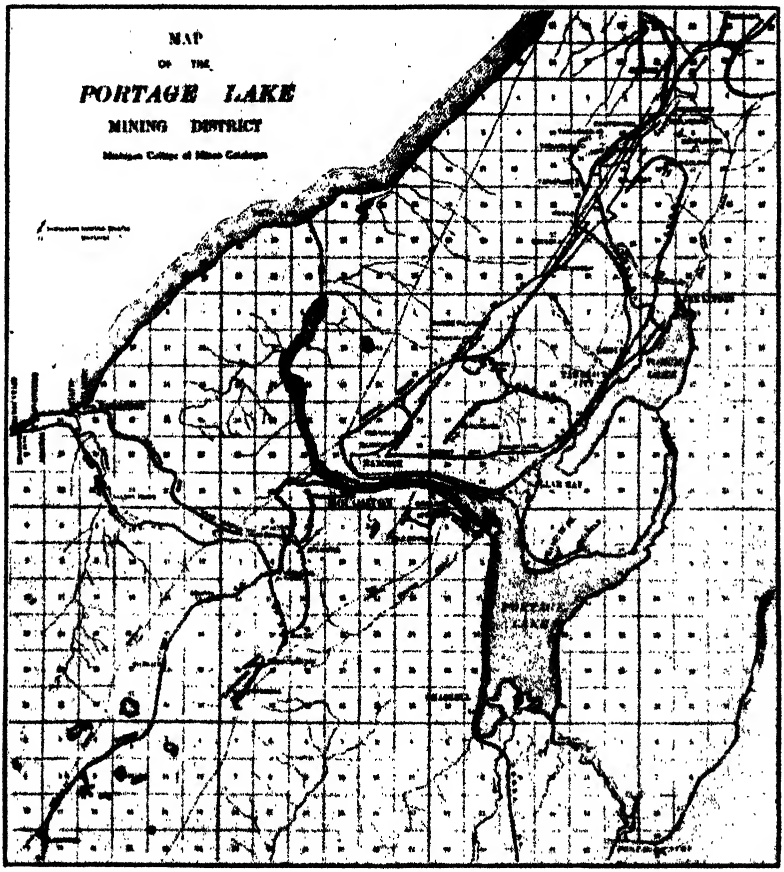

FIG. 182.—Map of a portion of the Michigan copper district, showing strike of lodes.

then decomposed by silicates or even carbonates of lime, yielding native copper, ferric oxide, and calcium chloride. Others believe that the copper was deposited in the rocks by rising magmatic solutions.

Widespread as native copper deposits of this type are, they are not all of economic importance. In North America, the Michigan ones outrank all others. Some production has also been obtained from the Triassic traps of New Jersey (100), and from those on the Bay of Fundy, in Nova Scotia. Other occurrences are known in Oregon (109), the White River region of Alaska (133), and in Arctic Canada (148). In other countries they are known in New Guinea,[1] Brazil,[2] the Transbaikal,[3] Norway,[4] Germany, etc., but not all are productive.

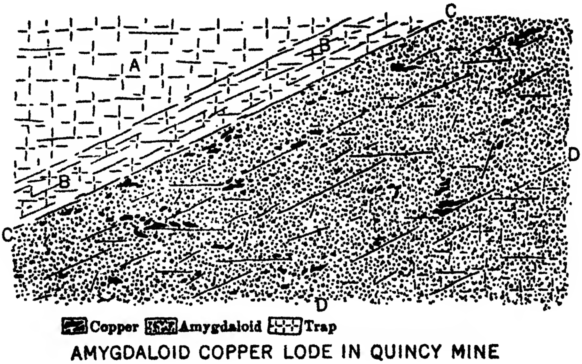

FIG. 183.—Section showing occurrence of amygdaloidal copper, Quincy Mine, Mich. (*After Rickard, Eng. and Min. Jour., LXXVIII.*)

Michigan (67–77).—The copper deposits in this region were worked in prehistoric times. Interest in the possibilities of these deposits was aroused by the Michigan state geologist in 1841, and the first paying deposit was discovered in 1845. Up to the end of 1930 the district had produced 8,403,640,000 pounds of copper.

The Michigan copper belt is 2 to 4 miles wide and over 100 miles long. Most of the copper has come from the central portion of the belt in Houghton County (Pl. XLIX).

The rocks of the region, known as the Keweenaw series, consist of several thousand feet of basalt flows, with felsite conglomerates

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[1] Beck, Lehre v. d. Erzlagerstätten, I: 345, 1909.
[2] Hussak, Centrbl. f. Min., 1906: 333.
[3] Beck, Zeitschr. prak. Geol., 1901: 391.
[4] *Ibid.*, VII: 12, 1899.

PLATE XLIX.—View from Houghton, Mich., looking toward Hancock, and showing a portion of the ridge under which the copper deposits lie.

common in the upper and lower part of the series. There are also felsite and quartz porphyry flows, as well as some sediments consisting chiefly of felsitic debris.

This series of flows and sandstones dip northwest forming the south limb of the Lake Superior syncline (Figs. 180, 181). On the southeast the series is cut off by the Keweenaw thrust fault, and abuts on the southeast against the Cambrian sandstone.

The lava flows have a cellular top, and occasionally this vesicular crust has been broken. The amygdaloidal tops are also red owing to hematite. More than 90 per cent of the copper has come from six ore bodies, one of them being in the conglomerate and the others in the amygdaloid.

The ore mineral is native copper, with native silver present in minor amounts. Copper sulphides and arsenides are occasionally found.

Over most of the area the bed which corresponds to the Calumet conglomerate is a thin shale in sandstone, but where the felsitic conglomerate occurs it thickens to 5 to 20 feet, and extends to depth on the dip. The copper in it is associated with adularia, epidote, calcite, and quartz, as a replacement of finer material between pebbles. There are no zeolites, and the rock in the vicinity of the copper is bleached owing to removal of the hematite.

The cellular lavas do not contain copper in commercial amounts, but the filled amygdaloids (Fig. 183) carry quartz, epidote, chlorite, calcite, adularia, sericite, ankerite, and zeolites. These were permeable to solutions because of their fragmental character. There may, however, be large areas of unmineralized amygdaloids, which owe this to their lower permeability. The average copper recovery of the amygdaloid lodes is said to have been about 1 per cent.

All the deposits contain a little arsenic and sulphur, but those with high arsenic content are highest in sulphur, and show sericite and ankerite gangue, while those containing the least arsenic are sulphur free and show increasing zeolites.

Some of the mines are 10,000 feet on the dip and still in ore.

Two general theories have been suggested to explain the origin of these ores. One, which has been strongly urged by Lane, is that cold, oxidizing surface waters penetrated the hot lavas to great depths, collecting disseminated copper from the volcanics, and distributing it laterally into amygdaloids and conglomerates (75, 76). Here the solutions were supposed to react with ferrous silicates, forming native copper and ferric compounds. Broderick claims that if this theory were correct the deposits should be found on the upper side of impermeable barriers.

A second theory assumes that the intrusives underlying the Lake Superior Keweenawan (70, 71) gave off solutions rich in copper, arsenic, and sulphur. These are supposed to have followed permeable amygdaloid and conglomerate channels upward. They then reacted with the wall rock which was highly oxidizing, their arsenic and sulphur being oxidized by ferric iron of the rocks, and the copper deposited in its native form. According to this theory the lavas were not needed to supply the copper. If it is correct the deposits should be found below impermeable barriers.

According to Graton these ores belong in his leptothermal zone.

Some copper is found in fissure veins, but it is unimportant.

The district is classed as a high-cost producer, owing to its low copper content, and the great depth from which the ore must be raised. This makes it difficult to compete with other districts where the copper is not only found at shallower depths, but also carries other metals, such as gold, or even nickel and platinum.

There has been a steady decrease in the copper production of this district since 1929. In that year it amounted to 186,402,218 pounds, the yield of rock being 1.23 per cent copper, while in 1935 it was 64,108,689 pounds, with ore averaging 2.33 per cent. This increase in tenor was due to richer portions of the ore bodies being worked.

Foreign Deposits.—The Corocoro copper deposits of Bolivia may be placed here. They consist of primary native copper or primary chalcocite in sandstone. Weathering has produced secondary enrichment.[1]

B. Deposits from Meteoric Waters

In many parts of the world there are low-grade disseminated ores of copper (chiefly chalcocite) in sandstones and shales, ranging from Carboniferous to Triassic in age. They are not as a rule sufficiently rich to work, although the carbonates on the surface may make them attractive propositions to some. That they seem to have been concentrated from the surrounding rock by meteoric waters is a commonly accepted view (7).

This type of copper occurrence is widespread in the Red Beds (Permian) of the southwest, but is of no economic importance.

Reference may be made in this connection to the famous Mansfeld copper deposits of Germany, which are possibly of syngenetic nature. These occur as minutely disseminated sulphides in Permian Shale.[2]

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[1] Berton, A.I.M.M.E., Tech. Pub. 698, 1936.

[2] Trask, Econ. Geol., XX: 746, 1925; Schneiderhöhn, Neues Jahrb. Geol., B. B. 47: 1, 1923; Gregory, Inst. Min. Met. (London), 1930.

Deposits, Usually Lens-Shaped, in Crystalline Schists

Scattered over the world are a number of copper sulphide deposits,[1] often more or less lenticular in character, and occurring in schistose rocks, which may be either igneous or sedimentary metamorphics. Some criticism may be urged against grouping them together, because their mode of origin is admittedly somewhat variable, but otherwise they show greater or less mineralogical and structural resemblances.

In general it may be said that they represent deposits formed at deep or intermediate levels, by replacement or in cavities. Zones of shearing have often afforded channel ways for the solutions. While the host rock is often a schist, in other cases it may have been a limestone, of which little or nothing now remains, so complete has been the replacement.

United States.—Copper deposits in schist are most prominent in the Appalachian belt of the east, and in California. The more important ones are reviewed below.

Appalachian States (129, 114).—The Appalachian states contain a number of copper deposits in schist distributed from Maine to Alabama, but few of them are of commercial importance.

Ducktown, Tenn. (112–115).—This district lies in the southeast corner of Tennessee, and within the Blue Ridge division of the Appalachian Mountains. The ore bodies are found in schistose rocks of Lower Cambrian age. No igneous rocks are recognizable in the district except some gabbro dikes, supposedly of late Paleozoic age. The ore bodies (Fig. 184) are tabular and in places somewhat folded. The primary ore consists chiefly of pyrrhotite, pyrite, chalcopyrite, sphalerite, bornite, specularite, and magnetite in a gangue of actinolite, calcite, pyroxene, tremolite, quartz, and garnet.

The gossan of the different ore bodies, now worked out, had a maximum thickness of 100 feet, and between it and the dense sulphides were found shallow zones of rich chalcocite.

The origin of the ores has been variously interpreted. Emmons and Laney (112) believed that they were formed by the replacement of lenticular bodies of limestone, after these had been folded and faulted, together with the enclosing schists.

The interpretation of Ross (115) is quite different, and is based on a study of the Ducktown type of deposit in the eastern United States.

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[1] For discussion of origin see Ries and Somers, Amer. Inst. Min. Engrs., Trans., LVIII: 244, 1918.

According to him there was first introduced rock of aplitic or pegmatitic habit, not very clearly developed at Ducktown. Then followed quartz chiefly as a filling in fractures, but sometimes replacing schist. After this came the ferromagnesian minerals which replaced the schists and even quartz. Introduction of carbonates came next, and this includes all the so-called limestone found at Ducktown. The last stage of mineralization was the deposition of sulphides, the sequence in general being pyrite, pyrrhotite, sphalerite, chalcopyrite, and galena.

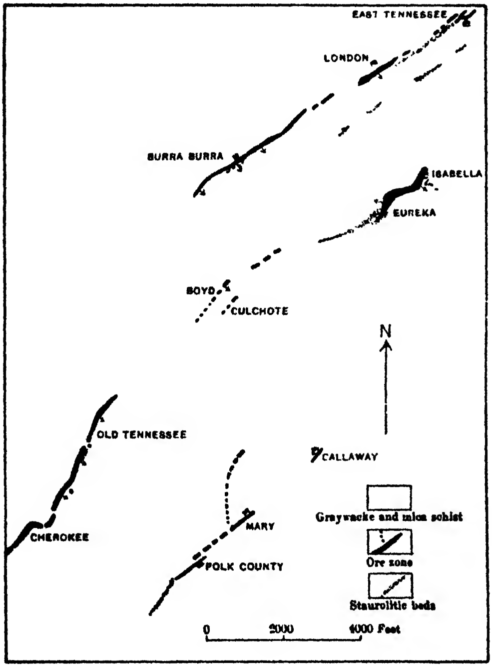

FIG. 184.—Plan of ore bodies at Ducktown, Tenn. (*After W. H. Emmons, U. S. Geol. Surv., Bull.* 470.)

The ore reserves of the district are said to be large. The copper content is low (1 per cent or less), but the production of sulphuric acid is an important asset. A zinc content nearly equal to the copper is separated from the latter by flotation, and the sinter is sold for iron ore.

One ore body, the Burra Burra, has a width of 35 to 75 feet, and a length of more than 3000 feet. The vein has been followed down the dip for 1800 feet, and may extend considerably deeper. Another, the Isabella-Eureka, is probably larger, with a length of 1500 feet and width of 100 to 250 feet. The ore runs less than 1 per cent copper but is high in sulphur.

Virginia-North Carolina.—The Gossan Lead of southwestern Virginia (129) (Fig. 185) and the copper deposits of Ore Knob, North Carolina, also belong to this type. At the former the ore is a mixture of pyrrhotite with subordinate chalcopyrite, and admixed quartz and schists. The vein fills a fault fracture between sericite schists, which contains mica, calcite, quartz and actinolite, replaced by the later pyrrhotite and chalcopyrite (Fig. 186). The copper content is low, viz., 0.75 per cent, and hence the ore is used for acid making, but the residue is available for copper.

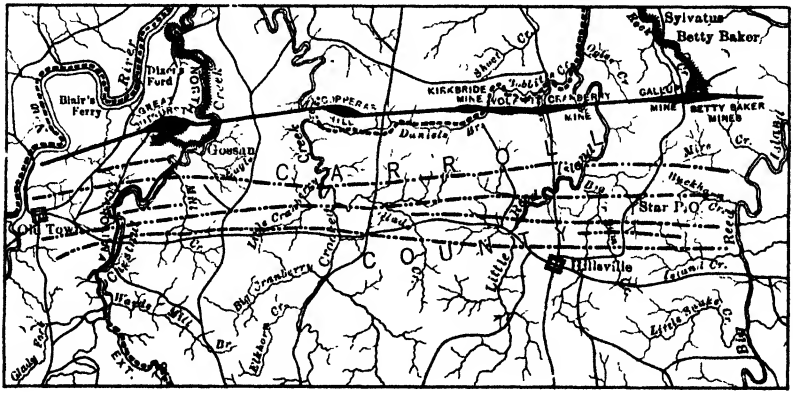

FIG. 185.—Map of Carroll County, Virginia, pyrrhotite area, showing position of the "Great Gossan Lead" in heavy black band, and principal copper mines located on it. Broken lines are other probable leads. (*After Watson and Weed, Min. Res. Va.*)

Not all of these lenses contain sufficient copper to be worked for that metal. Thus at Chestnut Yard, Va., the ore is chiefly pyrrhotite, and is used for acid.

It represents a hypothermal replacement of schist.

California (45–51).—In the Klamath Mountains of Shasta County, there are important replacement deposits of pyritic ore occurring mainly along fissures and shear zones of a Mesozoic alaskite porphyry of Cretaceous age, which has been intruded into folded Devonian and Carboniferous slates. There are also intrusions of quartz diorite of slightly later age than the porphyry; these carry no copper ores, but do contain auriferous quartz veins.

The ore bodies are flat-lying pyritic masses which have replaced the alaskite porphyry. They were capped by a gossan of limonite. The ore minerals are pyrite, chalcopyrite, sphalerite, and small amounts of galena, bornite, and chalcocite. The ore from Iron Mountain runs 3 or 3½ per cent copper, and $1.50–$2.00 per ton gold.

Recent production has come from small chalcopyrite-bearing quartz veins, which are found under the pyritic bodies.

The ore can be treated by flotation, and in the future most of the production will probably come from siliceous ores.

FIG. 186.—Section of ore from Chestnut Yard, Va., showing pyrrhotite (white) and chalcopyrite (black) replacements in hornblende (parallel lines). (*After Weed and Watson, Econ. Geol., I.*)

Canada.—The Pas Mineral Belt (Fig. 170) of northern Manitoba (134, 137, 152) contains several interesting ore bodies, the Flin Flon being especially important (137). Others are the Mandy (135) and Sherritt-Gordon (135). The rocks in which the ores occur are all pre-Cambrian. At the Flin Flon the rocks are of both volcanic and intrusive character, but the ore lies in the former. The ore body is a fairly regular lens, tapering to the northeast and blunt to the southwest. It is 2593 feet long on the surface, but shortens with depth, as does its thickness. The chief minerals are pyrite, blende, and chalcopyrite, with some gold and silver. Arsenopyrite, galena, and magnetite are also noted. The ore is in part massive sulphides and in part disseminated, the latter occurring chiefly near the footwall. It is supposed to be due to replacement along a shear zone in greenstone. There seems to be a difference of opinion as to whether the ore-bearing solutions came from basic or granitic intrusions. The ore body as a whole runs 1.71 per cent copper, but the disseminated type may carry 3 to 5 per cent. The average zinc content is 3.45 per cent, gold 0.074 ounce, and silver 1.06 ounces, per ton. The reserves are in excess of 18,000,000 tons of ore.

In eastern Quebec (136, 150) chalcopyrite-pyrite lenses form replacement bodies in schistose rocks derived from porphyry, and a carbonate rock due to hydrothermal alteration of the schist. At the Eustis mine the ore bodies extend down dip for at least 6500 feet.

At Britannia, British Columbia, ores consisting of pyrite, chalcopyrite, cupriferous pyrite, and a little sphalerite with quartz gangue, are found along a broad shear zone replacing porphyry now metamorphosed to a quartz mica schist (149).

Other Foreign Deposits.—Of the many foreign occurrences, the two best known perhaps are those of Rio Tinto, Spain, and Mount Lyell, Tasmania. The former occur as lenses, often of large size, in sheared and schistose porphyries and slates. The massive pyritic ore carries pyrite, chalcopyrite, sphalerite, and galena. The hematite gossan caps sulphides which, due to enrichment, carry from 3 to 12 per cent copper. The wall rocks, according to Finlayson, show hydrothermal alteration. Klockman argued for a sedimentary origin;[1] DeLaunay regarded them as veins or lodes formed by cavity filling;[2] Vogt assigned a pneumatolytic origin, following the porphyry intrusion;[3] while Finlayson believes them to have been the result of metasomatism by magmatic solutions along shear zones.[4]

At Mount Lyell we have great lenses of pyrite, with quartz and barite gangue, occurring chiefly in sericite schists, which have been intruded by porphyrites. The ore carries from 2 to 3 per cent copper, due to a chalcopyrite content. Large deposits are also worked in Russia.[5]

Uses of Copper.—Since prehistoric times copper alloyed with tin has been used in various parts of the world for the manufacture of bronze. Thus it was used for this purpose in Homeric times, and it is found in the lake dwellings of Switzerland. The bronze found in Troy contains a very little tin, and since this metal is not found in the excavations in the West, it seems probable that the bronze was made in Asia, perhaps in China or India, by some secret process, and imported to the western countries.

By an alloy of copper and tin, although both metals are soft, a

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[1] Zeitschr. prak. Geol., 1897: 113.

[2] Ann. des Mines., ser. 7, XVI: 407.

[3] Zeitschr. prak. Geol., 1894: 241.

[4] Econ. Geol., V: 357, 1910.

[5] Stickney, Kyshtim deposits, Min. Mag., XIV: 77, 1916; also Econ. Geol., X, 1915.

comparatively hard metal is produced. The properties of this alloy, bronze, vary greatly according to the proportions of the two metallic constituents, and these vary with the use for which the alloy is intended. United States ordnance is 90 per cent copper and 10 per cent tin, while ordinary bell metal is about 80 per cent copper, though the percentage varies with the tone required. Statuary bronze is generally an alloy of copper, tin, and zinc; and, in these various bronzes, the color varies from copper-red to tin-white, passing through an orange-yellow.

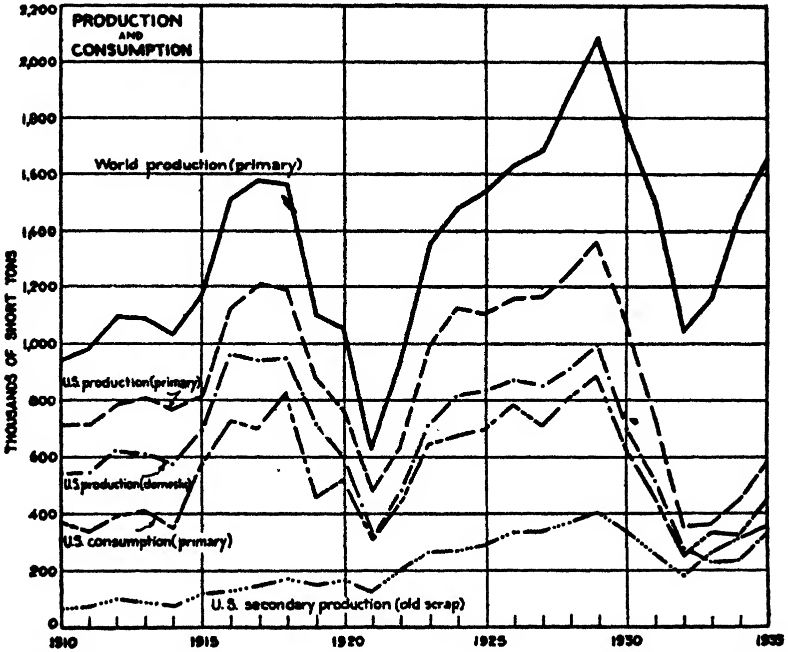

FIG. 187.—Graph showing salient features of the copper industry in the United States, 1910-1935. (*Minerals Yearbook*, 1936.)

An alloy of copper and zinc produces brass, which is found of so much value for small articles used in building and for ornamental purposes in machinery. Copper is also used in roofing and plumbing.

A large supply of this metal is made into copper wire, and the most important present use of copper is in electricity, for which its high conductivity especially fits it for the transmission of electric currents.

Production of Copper.—In Fig. 187 is given the production of copper in the United States and the world. In 1940 the United States produced 65,000,000 short tons of ore, which is an increase from the average of about 59,000,000 from 1925 to 1929.

The production of new copper in 1940 from domestic sources was 1,836,323 pounds; and of secondary copper, 333,890 short tons.

The imports of unmanufactured copper for 1940 were 491,342 short tons, and of refined copper, 68,337 short tons. The exports of metallic and refined copper in 1940 were 804,758 short tons.

The average yield of copper in the ore for 1939 was 1.25 per cent. The five leading states, and their percentage of the total domestic production of copper in 1940, were: Arizona, 36.0; Utah, 23.5; Montana, 13.4; Nevada, 9.1; and New Mexico, 6.3.

The Canadian production for 1939 was 304,412 short tons valued at $60,934,859, of which 54 per cent came from Ontario.

The imports of manufactured copper were valued at $1,171,475, and similar exports at $53,227,919.

Of the world's producers in 1938, Chile supplied 17.0 per cent; United States, 24.5 per cent; Canada, 12.5 per cent; Northern Rhodesia, 12.3 per cent; and Japan, 5.0 per cent.

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CHAPTER XVI

LEAD AND ZINC

It is usually customary to treat these two ores together for the reason that they are so frequently associated with each other, but it must not be understood from this that they are found free from association with other metals, as in the Rocky Mountain region, for example, gold, silver, or copper may often occur with them, forming ores of somewhat complex character.

The silver-lead ores form a somewhat distinct class but are treated in part in this chapter, and in part under gold and silver.

Ore Minerals of Zinc.—The zinc-ore minerals, together with the percentage of zinc which they contain, are:

Sphalerite (Isometric)	ZnS	67
Wurtzite (Hexagonal)	ZnS	67
Smithsonite	$ZnCO_3$	51.96
Hemimorphite (calamine) . .	$2\ ZnO,SiO_2,H_2O$	54.2
Hydrozincite	$ZnCO_3,2Zn(OH)_2$	60
Zincite	ZnO	80.3
Willemite	$2ZnO,SiO_2$	58.5
Franklinite	$(FeMnZn)O, (FeMn)_2O_3$	variable

Of these ores, sphalerite (also known as blende, jack, rosin jack, or black jack) is by far the most important, except in northern New Jersey, where it is practically lacking and franklinite and willemite abound.

Sphalerite may be either a primary or secondary ore mineral. Wurzite has been noted in some of the Missouri ores and also foreign ones, indeed, some massive blendes may be a mixture of sphalerite and wurtzite.[1]

Blende is often associated with other sulphides,[2] especially galena, pyrite, and marcasite, but more rarely chalcopyrite.

Smithsonite, found in the oxidized zone, is a comparatively rare ore mineral in the United States, although it is an important one in Europe. Calamine, also an oxidized ore mineral, is far more abundant, and found in many deposits. Both smithsonite and calamine may occur in a pure and crystalline form, but

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[1] J. Noelting, Zeit. Kryst. u. Min., XVII: 220, 1890.

[2] Teas, Relation of Sphalerite to other Sulphides, Amer. Inst. Min. Engrs., Bull. 131, 1917.

more often they are quite impure, of crusted or earthy character, and are usually intimately associated. Hydrozincite is not uncommon in some districts.

Ore Minerals of Lead.—The lead-ore minerals, together with their composition and the percentage of lead which they contain, are:

Galena	PbS	86.4
Cerussite	$PbCO_3$	77.5
Anglesite	$PbSO_4$	68.3
Pyromorphite	$Pb_3P_2O_8 + \frac{1}{3} PbCl_2$	76.36

There are a vast number of lead minerals in addition to the above, but they have little or no commercial value on account of their rarity.

Of the above-named ore minerals galena is the commonest, and is usually of primary character, secondary enrichment not being definitely known. It frequently, especially in the complex ores, carries variable amounts of silver. The other three lead-ore minerals are usually found in the oxidized zone, and the cerussite is not uncommon, but the sulphate when formed usually changes to the carbonate.

The lead and zinc ores may be divided into three groups as follows: (1) lead and zinc ores, practically free from copper and the precious metals; (2) lead and zinc ores, carrying more or less gold and silver, as well as some iron and copper; and (3) lead-silver ores.

In the first group iron and manganese are not uncommon impurities, and those of southwestern Missouri contain small amounts of cadmium; but this is not injurious, as it is more volatile than the zinc and easily driven off. Calcite, dolomite, and pyrite or marcasite are common gangue minerals, and barite or fluorite may occur at certain localities.

In the United States the ores of the second group are found chiefly in the Rocky Mountain region, and are not only of complex character, but differ in their form and origin from most of the eastern ones. Quartz is probably the commonest gangue mineral, but there may be other less important ones. Antimony, arsenic, and iron may be among the impurities.

The silver-lead ores, found in many of the western states, carry silver and lead as their chief metals, but may contain smaller amounts of zinc, gold, or iron. The silver contents, though sometimes high, are not necessarily visible, and may be contained within the galena as argentite[1] or other sulphides.

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[1] Nissen and Hoyt, Econ. Geol., X: 172, 1915.

Mode of Occurrence.—Zinc and lead ores may occur under a variety of conditions, viz.: (1) as true metalliferous veins; (2) as irregular masses in metamorphic rocks; (3) as irregular masses or disseminations, formed by replacement or impregnation in limestones or quartzites; (4) in cavities not of the fissure-vein type; and (5) in residual clays.

Mode of Origin.—While both lead and zinc may form under a variety of conditions, they are not found in commercial quantities in igneous rocks including pegmatites. Occurrences of workable character of one or the other are found in: (1) contact metamorphic deposits; (2) hypothermal zone veins; (3) mesothermal veins; and (4) in sedimentary rocks, apparently unassociated with igneous ones and of disputed origin. The third and fourth are the most important, and veins of the third often contain gold, silver, and copper. Hewett[1] has called attention to the fact that the limestone adjoining many lead and zinc deposits has been dolomitized.

Neither lead nor zinc ores are restricted to any one formation, but the majority of economically valuable deposits of these metals, without silver, gold, or copper, are found in the Paleozoic formations, although a few are known in pre-Cambrian and Triassic (Silesia, and Raibl, Italy) rocks.

While the metallic content of the ore as mined is often low, still, owing to the great difference in gravity between ore and gangue minerals (excepting pyrite or marcasite and blende), it is often possible to separate them by mechanical concentration; and for the zinc ores magnetic separation has been successfully tried. Flotation is also used.

Superficial Alteration of Lead and Zinc Ores.—Galena is often altered near the surface to anglesite or cerussite. The former, however, is unstable in the presence of carbonated waters and changes readily to the carbonate. Phosphates are developed in rare instances.

Sphalerite, the common ore of zinc, is often changed superficially to smithsonite, hydrozincite, and hemimorphite.

The chemical changes involved in the weathering of lead ores are probably simple, but those of zinc are more complex than was formerly thought (5). They are given in Chapter XIII under Secondary Enrichment.

Galena is more resistant to weathering and solution than sphalerite, hence when associated in the same deposit, galena is often found in the oxidized zone while sphalerite is removed.

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[1] Econ. Geol., XXIII: 821, 1928.

The soluble compounds produced by weathering may be carried down below the water level and reprecipitated as sulphides (see reactions, Chap. XIII), but authentic cases of secondary zinc and lead sulphides are rare and disputed by many (63).

Distribution of Lead and Zinc Ores in the United States.—The general distribution of lead and zinc ores is shown on the map, Fig. 188. Important deposits of lead alone are found in southeastern Missouri. There are also a number of small veins in metamorphic rocks from Maine to Georgia, but they are of little importance. Zinc ores, sometimes almost free from lead, occur in New Jersey, the Virginia Tennessee belt, the Saucon Valley, Pennsylvania, and southwestern Missouri. Lead and zinc together, free from gold, silver, or copper are prominent in the Upper Mississippi Valley. The mixed ores are very important in the Cordilleran region.

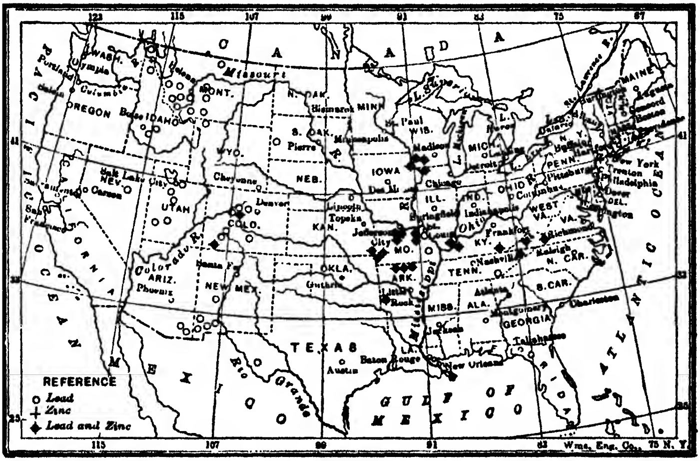

FIG. 188.—Map showing distribution of lead and zinc ores in the United States. (*Adapted from Ransome, Min. Mag., X.*)

Of the localities supplying argentiferous lead ore[1] Idaho is the most important, most of the ore coming from the Cœur d'Alene district. In Utah much is obtained from the Park City district of Summit County, the Bingham Cañon and Cottonwood districts of Salt Lake County, and the Tintic district of Juab County. Colorado's main supply of lead in 1935 came from Lake County.

Idaho and Utah together yield about 43 per cent of the lead pro-

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[1] This term is applied to those occurrences of lead associated with silver. In the smelting of the ore, the two metals are separated.

duced in the United States. The important lead ores of the western region are closely associated with both igneous and sedimentary rocks.

Most of the zinc obtained in the Rocky Mountain states is from complex ores. Leadville and Red Cliff are the most important producers. The former is described below together with some others of minor importance.

Pyrometasomatic Deposits

United States.—Few undoubted deposits of this type are known. *Magdalena, N. Mex.* (60).—At this locality faulted blocks of Paleozoic limestone have been cut by granite-porphyry dikes, the former containing roughly lenticular ore bodies, which in their oxidized zone yield lead, silver, and zinc, while in the sulphide zone the ore carries much sphalerite with a little galena and chalcopyrite. Magnetite and specularite are present, while the gangue has abundant epidote, pyroxene and tremolite, but little garnet.[1]

At Hanover, N. Mex., deposits of zinc ore occur in Paleozoic limestone near the contact with a quartz monzonite porphyry (61).

Hypothermal Deposits

United States.—*Sussex County, New Jersey* (57, 60).[2]—This district (Fig. 189) includes two areas, viz., Mine Mill, at Franklin, and Sterling Hill, at Ogdensburg, two miles farther south.

The ore deposits are in white crystalline limestone, which is bounded on the northwest by gneiss, and on the southeast by blue Cambrian limestone along a fault line.

At Mine Hill (Fig. 190) the northerly pitching ore body which lies adjacent to the limestone gneiss contact, has the shape of a trough, whose eastern side some think is folded over. Magnetite deposits outcrop locally along the limestone-gneiss contact.

The Sterling Hill (Fig. 191) deposit at Ogdensburg lies away from the limestone-gneiss contact. The ore body is also a trough, which pitches towards the east, and has a hook-like outcrop. Both sides of the trough dip southeast. A branch of the west limb crosses the trough.

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[1] U. S. G. S., Prof. Pap. 68. See also Ref. 76 for others.

[2] Some classify this as a contact metamorphic deposit.

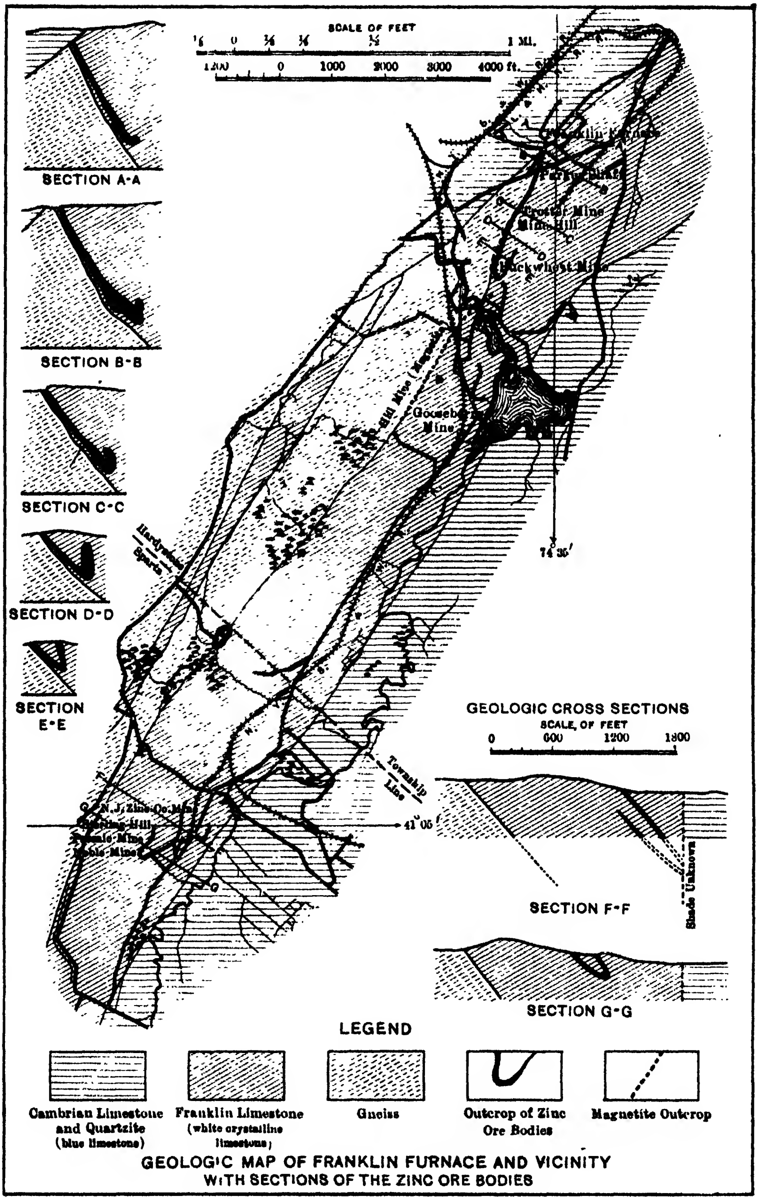

Fig. 189.—Geologic map of Franklin Furnace and vicinity, with sections of the zinc-ore bodies. (*After Spencer, N. J. Geol. Surv.*)

The ore minerals are principally franklinite, willemite (often somewhat manganiferous), and zincite. These, together with tephroite, are practically the only metallic minerals at Sterling Hill; but in the Mine Hill deposits, several other zinc- and manganese-bearing minerals, mainly silicates, are not uncommon. Sphalerite occurs sparingly.

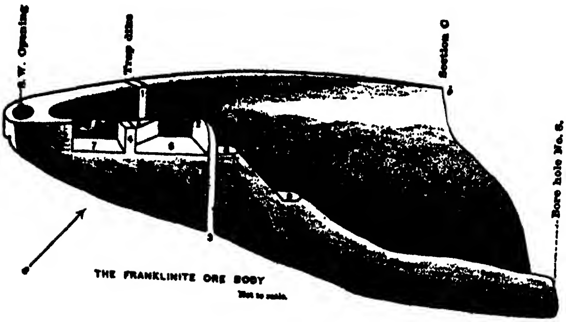

FIG. 190.—Model of Franklin zinc-ore body. (*After Nason, Amer. Inst. Min. Engrs., Trans. XXIV.*)

The gangue minerals are calcite, rhodonite, garnet, pyroxene, and hornblende. The ore is granular, and some of it shows a marked banding, which to some may be the result of metamorphism, but which is due largely to the different ore minerals having been deposited in separate streaks. There is usually a gradation from ore into country rock.

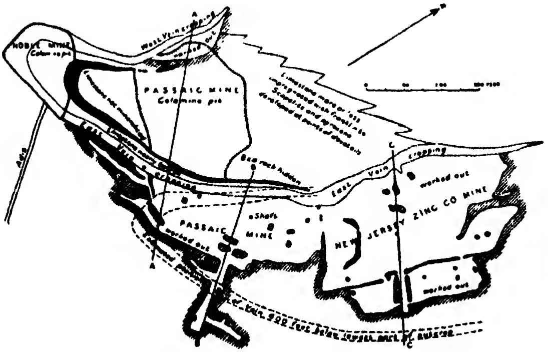

FIG. 191.—Plan of outcrop and workings of the Sterling Hill ore body. (*After Spencer, N. J. Geol. Surv., Ann. Rept.,* 1908.)

At Sterling Hill the limestone lying between the outcropping ends of the sides of the trough is mineralized, while inside the trough of ore there is a curved dike of hornblendic pegmatite, and on the convex side of the dike, towards the ore, there are occasional developments of garnet, zinciferous pyroxene, and biotite.

We have here then two zinc deposits, quite different from other known ones of this metal, because the oxides, franklinite and zincite, and the silicate willemite, occur in great abundance, although very rare elsewhere.

The origin of these deposits is of unusual interest, for they not only contain in abundance a number of zinc minerals, rare or unknown elsewhere, but many other mineral species as well.

Kemp[1] considered that the ore was probably deposited by solutions stimulated by intrusions of granite, and subsequently metamorphosed, but Wolff[2] suggested that they were contemporaneous in form and structure with the inclosing limestones and hence older than the granites.

Spencer[3] argued that the present characters of the ore masses and wall rocks originated contemporaneously because the two are not sharply separated; so that the deposits must have been introduced either before or during the metamorphism of the containing rocks and the igneous rocks which are now gneisses. Ries and Bowen (58) after field and petrographic studies of the ore bodies concluded that the ore minerals were deposited by replacement subsequent to the metamorphism of the limestone, the order of deposition being tephroite and willemite, franklinite, and zincite. Then followed intrusion of the Sterling Hill syenite, and folding of the ore bodies. After this the pegmatites were injected, the juices from which entering the ore bodies developed zinc and manganese-bearing silicates.

Post ore fracturing was accompanied by the introduction of sphalerite and pyrite, with some galena and chalcopyrite. Numerous basic dikes were intruded in post-Ordovician times.

The origin of these deposits has undoubtedly been a puzzling problem, and while Vogt, Lindgren, and others may consider them as contact metamorphic, they are not typically such, and might in the author's opinion be reasonably considered as hypothermal.

Palache has recently suggested that deposits of hydrated oxides and silicates of iron, manganese, and zinc replaced the white limestone and that these ore bodies were changed to their present composition at the time of the recrystalization of the enclosing limestone (57).

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[1] N. Y. Acad. Sci., Trans., XIII: 76, 1894.

[2] U. S. Geol. Surv., Bull. 213: 214, 1903.

[3] N. J. Geol. Surv., Ann. Rept., 1908: 23, 1909.

Tarr (59) believes the ore minerals were originally deposited in the limestone as sulphides and carbonates, then weathered to oxides and hydroxides, and then later metamorphosed to the present ones. A similar theory has been advanced by Rastall.[1]

Aside from its peculiar ore deposits this district is also of interest because of the large number of minerals which it has yielded, over 140 having been found to date.

Other hypothermal veins occur in the Boulder batholith and its contact zones in Montana, the Alta vein southwest of Helena being one. Here the ore was chiefly argentiferous galena with sphalerite and pyrite, as well as some tourmaline.

New York (63–67). Zinc ores occur in the Grenville limestones of St. Lawrence County, N. Y., one important deposit being at Edwards, where the ore body is an irregular, somewhat folded, steeply dipping lens which has been worked to a depth of 1500 feet. Sphalerite is the ore mineral, and with it there are varying amounts of pyrite and occasionally galena. The gangue minerals include pyroxene, serpentine, and tremolite, but these may also occur in the limestone outside of the ore zones. The deposit is evidently a hypothermal replacement, the solutions having come from the pre-Cambrian granite of the area. Another deposit at Balmat, a few miles southwest of Edwards, is similar so far as the primary ore is concerned but has a unique feature described by Brown (63), viz., the development of a body of supergene ore which carries sphalerite, willemite, ilvaite, chlorite, hematite, and magnetite.

Canada. *Kimberley, B. C.* (92, 96).—The Sullivan mine at this locality is probably the greatest producer of lead and zinc in North America. The ore body which is a replacement deposit forms a great lenticular mass in the Aldridge formation of the Purcell series (pre-Cambrian), and grades into the country rock. The rocks are argillites and quartzites of varying purity. The ore minerals are galena and sphalerite with some jamesonite. Associated with these is pyrite, pyrrhotite, some cassiterite (which is saved), garnet, diopside, and some others.

Schwartz suggests that the pyrite may be the earliest mineral, followed by contemporaneous pyrrhotite and sphalerite, and still later by galena. The gangue minerals are said to be earlier than the sulphides. Some of the ore exhibits wonderful banding, which is thought to be due to differential sulphide replacement along the beds. The ore averages 10 to 11 per cent lead and 12 to 13 per cent zinc.

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[1] The Geology of the Metalliferous Deposits.

At Moyie, British Columbia (93, 94), the St. Eugene mine, now inactive, contains argentiferous galena, with subordinate blende, pyrite, pyrrhotite, magnetite, and a little chalcopyrite, the gangue minerals being garnet, actinolite, quartz, and calcite The ore body, which is associated with a zone of fissuring, represents a hypothermal replacement in quartzite, but the source of the solutions is not certain as there is no nearby intrusive.

Other Foreign Deposits.—The best-known example perhaps of this group is the Broken Hill Lode in western New South Wales.[1]

This great lode, discovered in 1883, was first worked for silver, then silver lead, and in recent years, also zinc. The rocks of the region include: (1) pre-Cambrian sediments, chiefly arkoses and sandstones near the lode, all altered to gneisses and schists; (2) amphibolites derived from eruptives; and (3) granite gneisses and pegmatites. Regional metamorphism was accompanied by shearing along the line of the lode, and later injection of pegmatite along the ore zone. There was also developed in the country rock, garnet, gahnite ($ZnAl_2O_4$), sillimanite, and rhodonite.

The ore bodies, which are associated with the shear zone, often form peculiar saddle-shaped masses. A gossan rich in manganese and iron passes downwards into oxidized ores of lead, silver, and some copper, while below this is a coarse-grained mixture of sphalerite and galena, carrying silver, and intergrown with quartz, garnet, feldspar, and rhodonite. Oxidation extends to depths of 500 to 600 feet, and secondary enrichment is well marked. The primary ores average 3 to 14 oz. silver, 14 to 16 per cent lead, and 8 to 18 per cent zinc.

The theories advanced to explain these saddle deposits include lateral secretion (Pittman and Jacquet); bedded deposits (Krusch, Stelzner and Bergeat); epigenetic origin (Beck), and contact metamorphism (Vogt). Moore[2] suggests replacement in the hanging wall of the tabular shear zone, the beds being replaced in such a way as to give the saddle form.

In this same group may also be mentioned the lead-silver-zinc ores of Sala, Sweden, which occur in dolomitized limestone. One series of steeply dipping ore bodies carries silver and lead, with some blende, pyrite, arsenopyrite, and stibnite; the other series of lesser dip predominates in zinc. The ore minerals are intergrown with salite, tremolite, actinolite, epidote, biotite, and a little tourmaline. They are regarded as replacements, but show no direct connection with any instrusive.[3]

Mesothermal Deposits

United States.—Most of the deposits of this type found in the United States carrying lead or zinc may contain appreciable silver or gold. A prominent example is that of Leadville, Colo., but in recent years large quantities of blende have been obtained from Butte, Mont.

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[1] Vogt, Krusch, and Beyschlag, Ore Deposits, Translation, I: 399, 1914. Andrews, Mem. Geol. Surv., N. S. W., No. 8 Geology, 1922; Mawson, Mem. Roy. Soc. S. Austral., 1912, Inst. Min. Engrs., VI, No. 2, 17, 1910.

[2] Moore, Econ. Geol. XI: 327, 1916.

[3] Vogt, Krusch, and Beyschlag, Lagerstätten, II: 264, 1912; also Sjögren, Internat Geol. Cong., Stockholm, 1910, Guidebook, No. 28.

(see under Copper), and considerable zinc also comes from the Cœur d'Alene District, Idaho.

Leadville District, Colorado (12, 13, 17.) —This district, which lies on the western slope of the Mosquito range in Lake County, was formerly one of the important mining areas of the United States. Up to the end of 1930 it had produced $446,167,000 worth of metals, of which gold formed 12 per cent, silver 43 per cent, zinc 21 per cent, lead 21 per cent, and copper 3 per cent. It has also yielded pyrite for sulphuric acid, manganese, iron, and small amounts of bismuth.

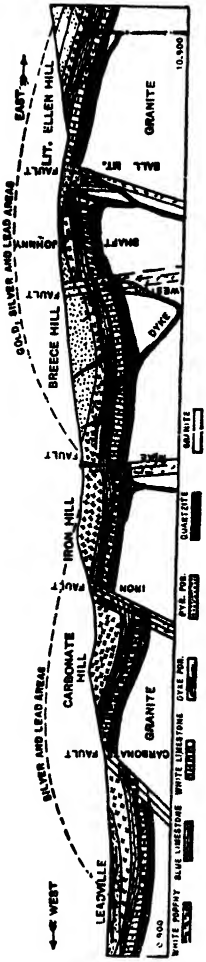

FIG. 192.—Ideal section of Leadville, Colo., district. (*After Warwick, Min. Mag., XI.*)

Gold placers were first worked in the bottom of California gulch, then later the rich oxidized silver ore attracted attention, while still later came the development of the sulphide bodies.

The western slope of the Mosquito range has a number of spurs which by faulting have been broken up into a series of hills that owe their rounding to later erosion. Among these hills Breece, Carbonate, Fryer, Iron, etc., are important as sources of ore supply, an additional quantity having been obtained from what is known as the downtown district in the city limits of Leadville (Fig. 192).

The bedrocks of the region range from pre-Cambrian to Pennsylvanian, but there is little of the oldest rock exposed. A covering of glacial drift and lake deposits is also present.

The geologic section (17) is as follows:

		Feet
Pennsylvanian	**Weber grits and shales**	**1200±**
Mississippian	**Leadville limestone restricted**	**120**
Devonian	**Chaffee dolomite**	**80**
	Parting quartzite	**27**
Ordovician	**Manitou white limestone**	**95**
Cambrian	**Sawatch quartzite**	**135**
Pre-Cambrian	**Granite, gneiss, schist**	

Exposures of the oldest rocks are not abundant in the vicinity of the mines but they are encountered underground.

The sediments were invaded in late Cretaceous or early Tertiary by: 1. An earlier or "white" porphyry, which is of granitic character and occurs mainly as great intrusive sheets between the Weber shales and blue limestone, with some thinner ones at lower horizons. 2. Later gray porphyry of quartz-monzonitic composition, which forms intrusive sheets, some of which have dike-like offsets. 3. Eruptions of rhyolitic agglomerate of post-ore age.

The sequence of events was somewhat as follows: 1. Intrusion of the later porphyry which broke the sediments and caused some faulting. 2. Folding of the sediments and the development of reverse faults. 3. The stock-like intrusion of Breece Hill. 4. Minor normal faults radially arranged around the stock. 5. Ore deposition. 6. Large-scale normal faults of late Tertiary (Fig. 192).

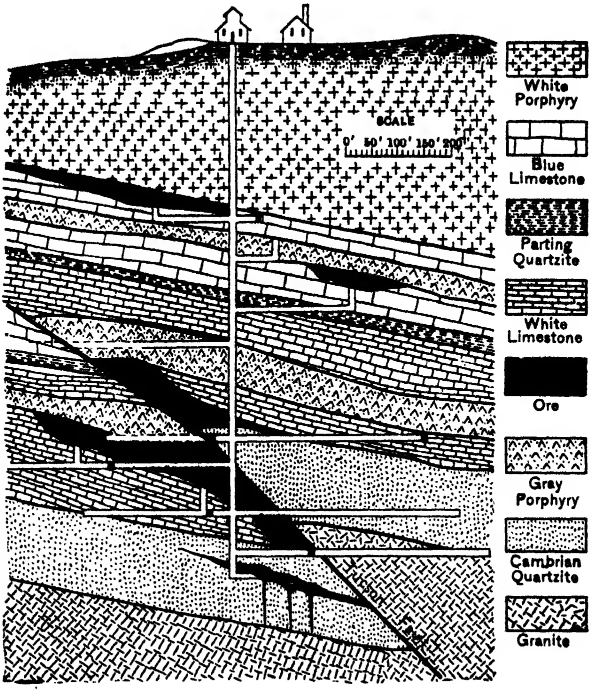

FIG. 193.—Vertical section along line *AB*, Fig. 194. Tucson shaft, Leadville, Colo. (*After Argall, Eng. and Min. Jour., LXXXIX.*)

The distribution and size of the ore bodies are governed mainly by structural conditions, the form, and in part mineral composition depending on the country rock. Three groups are of commercial importance as follows: 1. Hypothermal magnetite-hematite deposits in limestone adjoining the Breece Hill stock. 2. Veins of mixed sulphides found in eastern part of district, both in and outside of the stock.

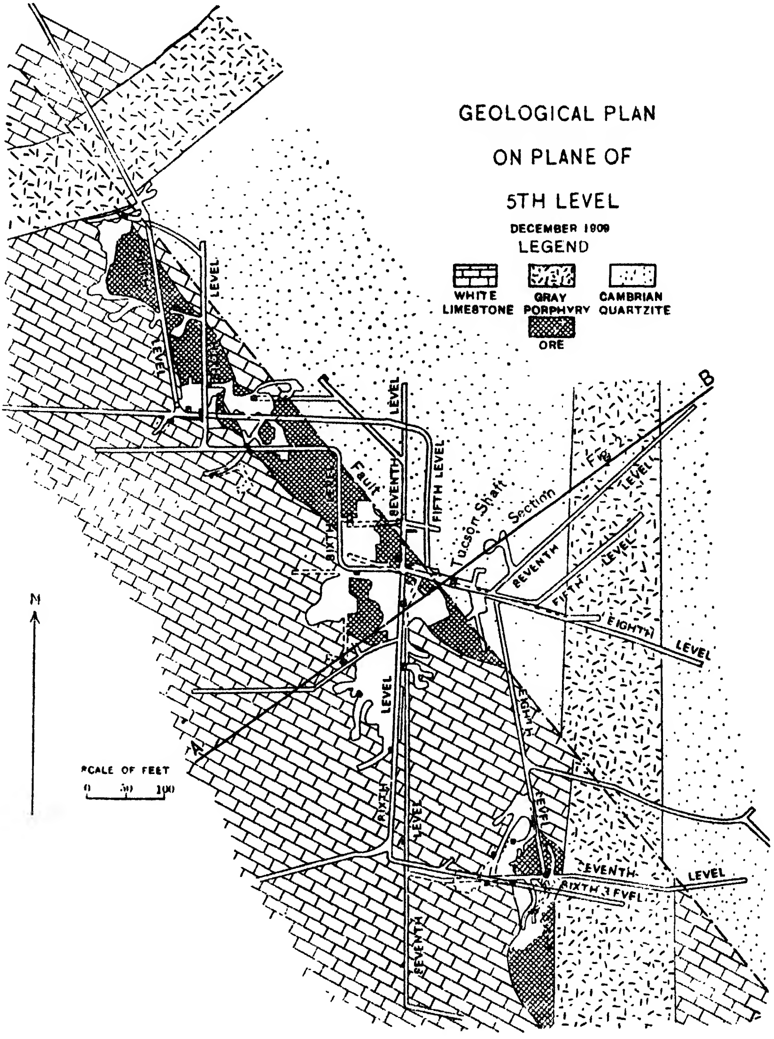

FIG. 194.—Geologic plan of fifth level and workings, Tucson shaft, Leadville, Colo. (*After Argall, Eng. and Min. Jour., LXXXIX.*)

Where these cut limestone they expand into replacement deposits. These deposits, which are mesothermal, have been of value chiefly for gold, but they may carry silver and occasionally copper, and in the

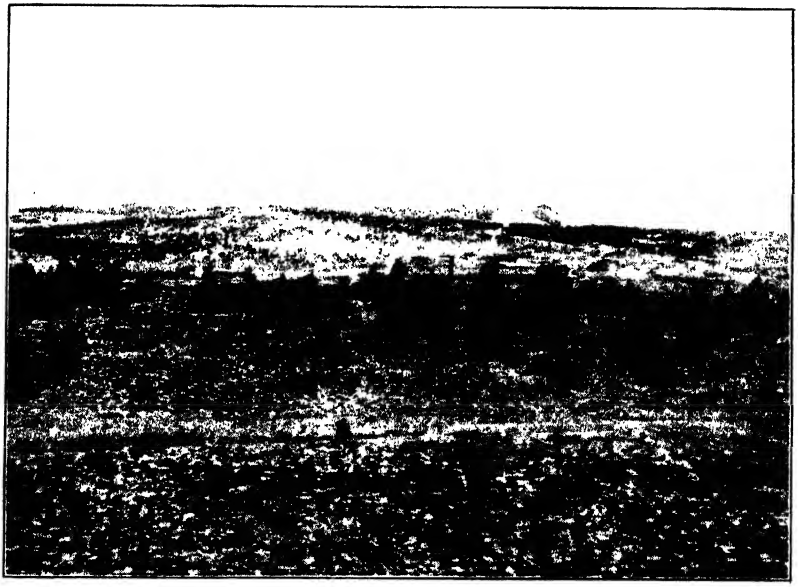

Fig. 1.—From Carbonate Hill, Leadville, Colo., looking towards Mosquito Range. (*H. Ries, photo.*)

Fig. 2.—View from south end of Carbonate Hill, Leadville, Colo., overlooking California Gulch in foreground, and town of Leadville in the valley. Sawatch Range in distance. (*H. Ries, photo.*)

outer part of the replacement bodies are blende and galena. 3. In the western part of the area veins are relatively scarce, but there are large sulphide replacements in limestone which have supplied most of the production. The ore bodies lie along fractures or sheeted zones under impervious covers, and their most favorable location is at the top of the Leadville limestone. Their dimensions may be as great as 2000 feet long, 800 feet wide, and 200 feet thick. Veins may be associated with them, and these in siliceous rock are narrow and carry gold, but in limestone expand and carry silver-zinc or lead-zinc ore.

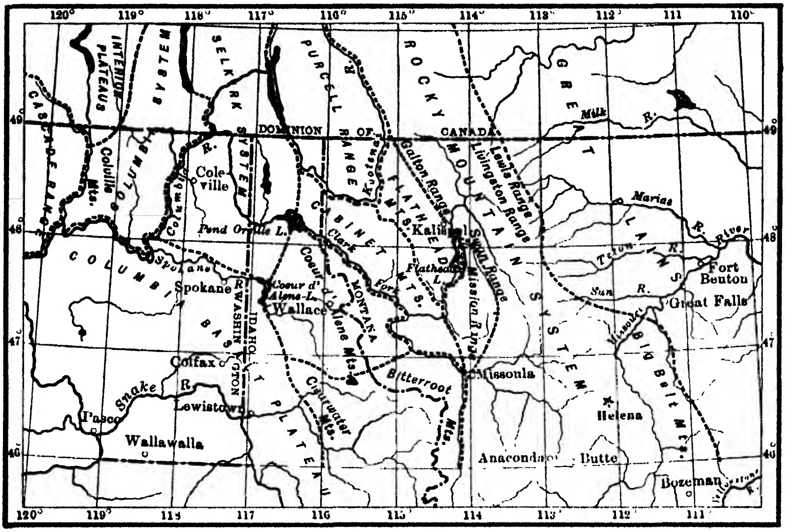

Fig. 195.—Map showing location of Cœur d'Alene, Idaho, district. (*After Ransome, U. S. Geol. Surv., Prof. Pap.* 62.)

The ore-bearing solutions are supposed to have risen along the fault fractures.

Oxidation and enrichment have extended to considerable depths. Weathering of pyrite in the white porphyry has supplied sulphuric acid and ferric sulphate to waters percolating downward. This attacked the sulphides in the underlying limestone, resulting in cerussite forming in place from galena. Sphalerite was dissolved and reprecipitated as smithsonite and calamine which replaced limestone, dolomite, and manganosiderite in favorable places beneath the original sulphide ore body. Pyrite oxidized to limonite bodies, while the manganiferous siderite on weathering gave manganese iron ore. Much copper has

FIG. 1.—View in Wisconsin zinc district. (*H. Ries, photo.*)

FIG. 2.—View looking north over the Cœur d'Alene Mountains from the Stemwinder tunnel above Wardner. Shows mature dissection of plateau-like uplift. Town of Wardner in foreground. (*After Ransome, U. S. Geol. Surv., Prof. Pap.* 62.)

also been reprecipitated at lower levels as chalcocite. Gold is said to have been precipitated by blende. There is also secondary silver.

Cœur d'Alene, Idaho (24–27).—The Cœur d'Alene district (which is really made up of several local mining districts) lies in Shoshone County, mostly on the western slope of the Cœur d'Alene Mountains. Wallace is the principal town, but there are several smaller ones, as Wardner, Mullan, Burke, Mace, Gem, and Murray.

The prevailing rocks here are a thick (10,000 feet), apparently conformable series of shales, sandstones, and some limestones of Algonkian age, which on the west are faulted down against granitic and gneissic rocks, but extend some distance to the eastward.

The condensed section is as follows:

	FEET
Striped Peak shales and sandstones	1,000+
Wallace sandstones, shales, and limestones	4,000
St. Regis shales, and sandstones	1,000+
Revett white quartzite	1,200
Burke shales and sandstones	2,000
Prichard shales and sandstones	8,000
	17,200+

The igneous rocks include some small intrusive stocks of monzonite, and a few dikes of diabase and lamprophyre-like rocks, but the age of all is uncertain.

The rocks show a series of complex, sometimes overturned, folds as well as extensive faults, and slaty cleavage has been developed in all except the quartzite.

The ore deposits are composite veins, formed largely by replacement along vertical shear zones of northwest strike.

The ore consists of galena, with pyrite and sphalerite present in small amounts; tetrahedrite is unimportant. Siderite and quartz are the chief gangue minerals. The siderite was deposited first, replacing the quartzite; the galena was deposited later, replacing either of the two gangue minerals.

It is thought that the solutions came from the monzonite, and adjoining the latter there are found some contact metamorphic deposits carrying galena, sphalerite, pyrite, pyrrhotite, chalcopyrite, and magnetite. Siderite is not found in the contact metamorphic zone.

The Bunker Hill is the largest mine in the district, the lode having been traced 7000 feet. The Morning mine has been worked to a depth of over 5000 feet.

The Cœur d'Alene region in 1934 yielded 140,300,000 pounds of lead, 50,000,000 pounds of zinc, 7,050,000 ounces of silver, 2,800 ounces of gold, and 1,475,000 pounds of copper.

Park City, Utah (78), which is located on the eastern slope of the Wasatch Range, about 25 miles southeast of Salt Lake City (Fig. 219), has made Summit County famous as one of the important mining centers of this country, as there are here large bodies of rich silver-lead ores carrying minor values of gold and copper. The success of this camp, therefore, depends more or less on the condition of the silver and copper industry.

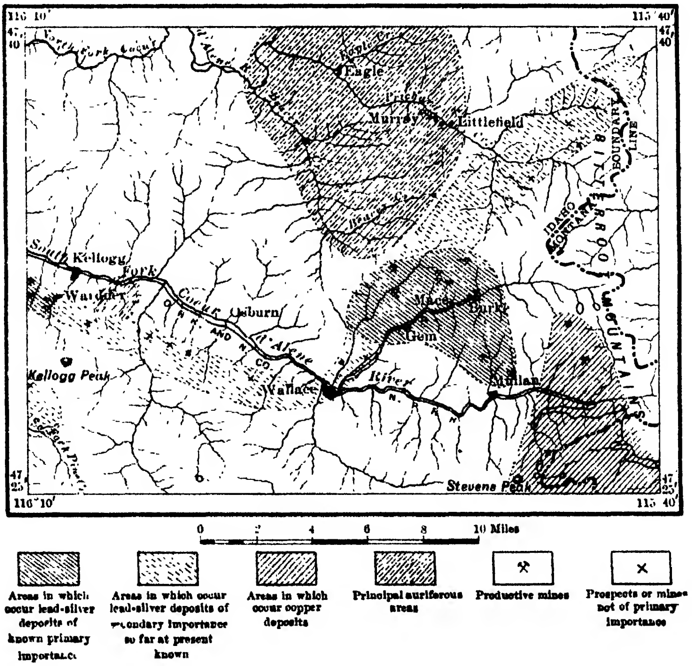

FIG. 196.—Geologic map of Cœur d'Alene, Idaho, district. (*After Ransome, U. S. Geol. Surv., Prof. Pap.* 62.)

The geological section involves a series of limestones, quartzites, and shales, of Carboniferous to Triassic age, the series being folded into an anticline, which has been intruded by diorite rocks of late-Cretaceous age. Numerous fault fractures cross the district. The ores, which in the oxidized zone are cerussite, anglesite, azurite, malachite, etc., and in the sulphide zone are galena, sphalerite, tetrahedrite, and chalcopyrite, occur either as lodes or fissures, or as bedded deposits in limestones. The latter, which supply most of the ore, form replacements in certain strata of both the Upper Carboniferous and Permocarboniferous, and lie between siliceous members as walls. Both types of ore deposit are frequently associated with porphyry.

The fissures carry either silver or lead with or without zinc, and copper or gold with some silver. The replacement ores of the limestones hold silver and lead chiefly. The contact ores contain copper and gold with or without silver, and form irregular bodies in metamorphic limestone adjacent to the igneous rock. They were probably deposited earlier than those replacement ores in limestones which are associated with the lode deposits.

In 1935 the Park City district produced: lead, 26,360,250 pounds; silver, 2,500,256 ounces; copper, 697,530 pounds; zinc, 26,360,250 pounds; and gold, 8,006.20 ounces.

Tintic District, Utah (78–80).—This district lies in the Tintic Mountains, about 65 miles southwest of Salt Lake City (Fig. 219).

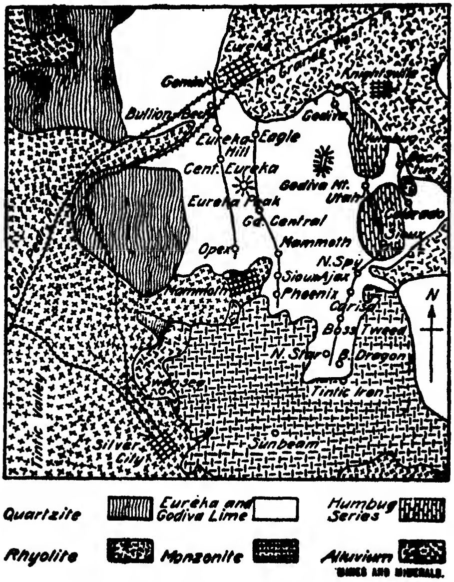

FIG. 197.—Geologic map of Tintic district, Utah. (*Adapted from Tower and Smith.*)

The rocks of the district include over 12,000 feet Paleozoic sediments, folded into an anticline and syncline, and broken by faulting, fissuring, and sheeting. Following a period of erosion there was a period of igneous activity in the Tertiary, yielding rhyolite tuffs and breccias, and a later monzonitic intrusion. The ore deposits include: (1) thin iron-manganese deposits on the limestone-igneous rock contacts; (2) veins of silver-lead ores in monzonite, mostly abandoned; and (3) limestone replacement and fissure deposits. The last, or most important, occur in four parallel zones, the lead-silver ores predominating at the north end of the belts, and gold-copper ores at the south end, while zinc is found in both. The ores are oxidized to depths of over 2300 feet, but sulphides are now being worked. The ore-bearing solutions are thought to have come from the monzonite.

The Tintic is one of the oldest camps in the state, the ore having been discovered in 1869, and it was at first shipped as far as Baltimore and Wales.

The same type of ore occurs in Big and Little Cottonwood cañons and Bingham Cañon (Fig. 219), the latter having been worked longer than those of the Tintic district. The camps lie southeast and southwest of Salt Lake City, and the ores are oxidized silver-lead ones, parallel tc the bedding of Carboniferous limestones and the underlying quartzite. Galena and pyrite occur in the lower workings below water level.

San Francisco District, Utah (77).—This is an area producing essentially silver-lead ores, as well as copper and zinc, and lies in Beaver County, Utah. There is a sedimentary series of Paleozoic limestones, shales, and quartzites, covered by a thick flow of lava, and intruded by quartz monzonite and related rocks. The ore deposits consist of: (1) replacements along fissures in quartz monzonite, as in the Cactus ore zone, referred to under Copper; (2) replacements in limestone, consisting chiefly of lead-silver with smaller amounts of gold and copper, and also some contact deposits; (3) replacement fissure deposits in the lava, the primary ore containing chiefly pyrite, galena, and sphalerite in a gangue of quartz, sericite and altered lava. Interesting replacements of one sulphide by another occur.

Aspen, Colorado (16, 20).—The ores are oxidized and occur in highly folded and faulted Carboniferous limestone, although the section involves rocks ranging in age from Archæan to Mesozoic. Two quartz porphyries, one at the base of the Devonian, the other in the Carboniferous, are present, but bear no special relation to the ore.

At the close of the Cretaceous the rocks were folded into a great anticline, with a syncline on its eastern limit, which passed into a great fault along Castle Creek west of the mines. Contemporaneous with the folding there were also produced two faults parallel to the bedding of the Carboniferous dolomite, while at the same time much cross faulting occurred. The ore is found chiefly at the intersection of these two sets of fault planes, and Spurr believes that the ores were deposited by magmatic waters ascending vertically along faults, and were precipitated by a reaction between the solutions and certain wall rocks, chiefly shale. Mingling of solutions at the intersection of fissures also played an important rôle in the formation of the ore. This stronger deposition of the ore at the intersection of fault planes was thought by Weed to be due to secondary enrichment, but Spurr finds little evidence of secondary sulphide formation.

On account of the intimate association of the dolomite, quartz, and barite with the ore their origin is considered as similar.

The ores are peculiarly free from other metals except lead, and the rich polybasite (Ag_9SbS_6) ores of Smuggler Mountain do not contain even this.

The mining camp of Aspen started in 1879, but its development for a time was much retarded by lawsuits. The richer ore bodies were not discovered until 1884, and then by underground exploration, for owing to the heavy mantle of glacial gravels their outcrops were hidden. Since also the ore carries no iron or manganese, as do the Leadville ores, its outcrop may be inconspicuous.

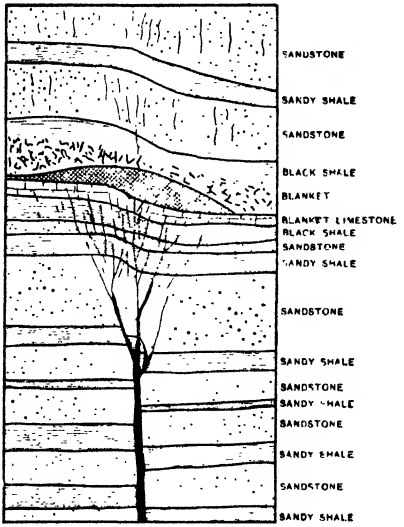

FIG. 198.—Diagrammatic section across a northeasterly lode at Rico, Colo., showing "blanket" of ore. (*After Ransome, U. S. Geol. Surv., 22d Ann. Rept.*)

Rico, Dolores County, Colorado (18, 19).—In this region the mountains, which are the remains of the structural dome rising above the Dolores plateau lying in the San Juan region, contain a series of sedimentary beds ranging from Algonkian to Jurassic in age, which have been uplifted partly by the intrusion of igneous rocks, as stocks, sills, and dikes, and partly by upthrows due to faulting.

The ore occurs as lodes, replacements in limestones, stocks, and blankets, the last consisting usually of deposits lying parallel to the planes of bedding or to the sheets of igneous rock, and known locally as "contacts," although not such in the true sense.

The four types of deposit mentioned may pass into each other. Most of the ore in the district has, however, come from the blankets, and the bulk of this has been found in the Carboniferous, especially in the Hermosa formation, a striking feature of the deposits being their limited vertical range.

The ores are primarily galena, often highly argentiferous and associated with rich silver-bearing minerals. In many deposits the more or less complete oxidation of the silver ores has resulted in powdery masses, often very rich in silver. Below the zone of oxidation, the veins have not been successfully worked.

The bulk of the ores can be roughly divided into pyritic ores, usually low grade, and silver-bearing galena ores, sometimes containing rich silver minerals. Quartz is the commonest gangue mineral, but the beautiful pink rhodochrosite is also conspicuous.

The ore deposition is believed to be closely associated with the igneous intrusions of the district, especially with the later ones.

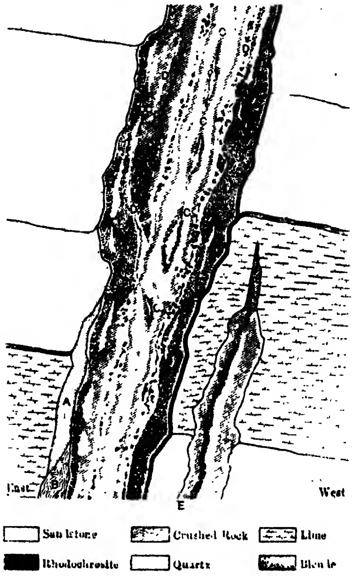

FIG. 199.—Vein filling a fault fissure, enterprise mine, Rico, Colo. (*After Richard. Amer. Inst. Min. Engrs., Trans. XXVI.*)

Other Occurrences.—Argentiferous lead ores also occur in the Ten Mile district, in Chaffee County, and along the Eagle River, both in Colorado.

The Eureka district[1] of eastern Nevada (Fig. 211), discovered in 1868, is chiefly of historic importance. The ores are oxidized lead-silver ores, carrying some gold. They occur in Cambrian limestone which is much faulted and crushed, and is part of a Paleozoic section 30.000 feet thick.

The ore is associated with a great fault, and is oxidized to a depth of 1000 feet. There are two mining districts, Prospect Hill and Ruby Hill. Near the mines are great prophyry masses which are supposed to have afforded the ores. Up to 1882 the output was not far from $60.000,000 of precious metals and 225.000 tons of lead, but the production now is insignificant.

Montana contains several lead-silver ore localities. Those of Neihart (54) occur as veins in gneiss and igneous rocks. The ores being galena, silver sulphides, and some blende. The veins are best defined in the

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[1] Curtis, U. S. Geol. Surv., Mon. VII, 1884; and Emmons, *Ibid.*, Mon. XX, 1892.

gneiss, and are mostly replacement deposits, which have been subsequently fractured and secondarily enriched. Lead-silver ores also occur at Glendale and in Jefferson County. Some are also known in South Dakota, and at Lake Valley, New Mexico (61).

Canada. British Columbia.—The Slocan (91) district, which lies between the Kootenay and Arrow Lakes of the Selkirk province of southern British Columbia, contains a number of silver-lead and zinc deposits. The country rock includes a series of interbedded argillaceous quartzites, limestones and slates of the Slocan series (Carboniferous?), which have been invaded by the granitic rocks of the Nelson (Jurassic?) batholith. Folding, faulting, and lithologic similarity of the sediments have interfered with an accurate determination of the structural details. There is also an extensive system of quartz pophyry and lamprophyre dikes which seem to antedate the vein fissures. The ores occur in veins, in part breccia filled, whose length varies from a few hundred to over 4000 feet, and a thickness of from a few inches to over 50 feet. Ore shoots of varying size and sometimes following cross-fractures are common. The chief ore minerals are galena, sphalerite, and freibergite, as well as ruby silver, native silver, and argentite. Chalcopyrite and pyrite are common but unimportant. Siderite, calcite, and quartz form the gangue. Weathering effects are shallow, and the ore seems to be primary, derived probably from the Nelson batholith.

Other Foreign Deposits.—At Buchans, Newfoundland, ores are worked which consist of a mixture of barite, sphalerite, galena, and chalcopyrite, forming replacement bodies in Paleozoic tuffs.[1]

Przibram, Czechoslovakia, is a classic locality, yielding silver-lead ores.[2] The steeply dipping veins occur in graywackes and clay slates, which have been folded, faulted, and intruded by a diorite stock. There are also a number of diabase dikes, which follow the veins more or less closely. The veins, some of which have been followed to a depth of over 3500 feet, show a variable thickness, some being 25 feet. The common ore minerals are galena and blende, with some pyrite and chalcopyrite, in a gangue chiefly of calcite, siderite, and quartz. Silver sulphides are found especially in the oxidized zone. Where the veins pass from the graywacke into the diorite, they may lose their galena and silver, and take up stibnite (Pl. XXXVI, Fig. 1). The origin is not perfectly clear, but was possibly connected with the associated intrusives.

The Freiberg, Saxony, district, now practically closed, possesses an historic interest, because it was here that Werner in 1791 developed his theories regarding fissure veins. The veins, of which over 1100 are known, occur in an arch of biotite gneiss, and are separable into an older and a younger group. The former

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[1] Newhouse, Econ. Geol., XXVI: 399, 1931.

[2] Vogt, Krusch, und Beyschlag, Lagerstätten, II: 197, 1912.

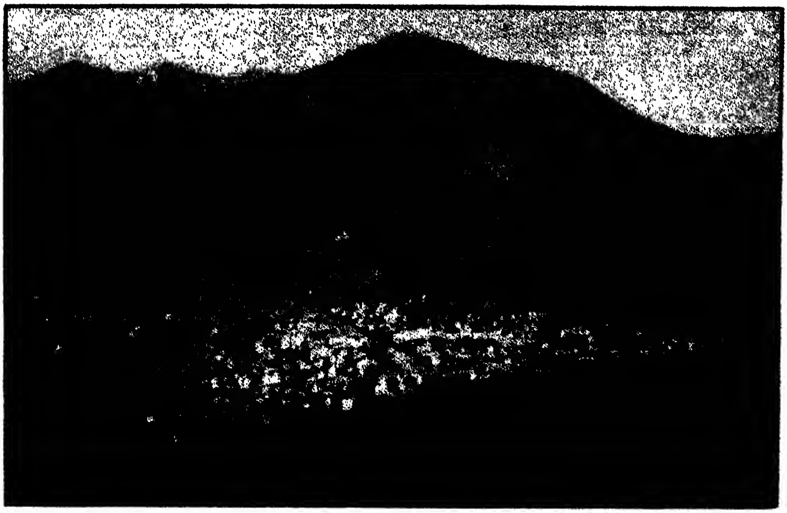

FIG. 1.—General view of Rico, Colo., and Enterprise group of mines.

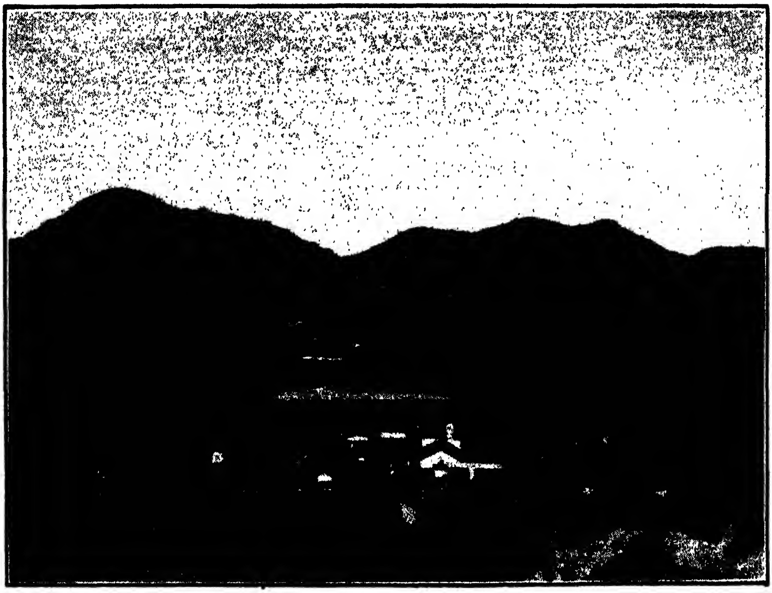

FIG. 2.—View of Tintic district. (*H. Ries, photo.*)

contains the argentiferous quartz, pyritic lead, and argentiferous ("noble") lead formation. The latter, the barytic-lead formation.[1]

Clausthal, Germany,[2] is also well known on account of its series of veins carrying argentiferous galena, blende, and subordinate chalcopyrite, pyrite, or marcasite, in a gangue of calcite-quartz (Pl. XXXV), or barite-siderite. The enclosing formations consist of Devonian and Carboniferous clay slates and graywackes. The ores are found filling fissures or breccia zones, and while unassociated with igneous rocks, may be genetically connected with the granite of the Brocken Mountains of the Harz.

Laurium, Greece,[3] is another locality deserving mention, its replacement deposits of ores carrying argentiferous galena and sphalerite in crystalline limestone. In Burma the Bawdwin mines have been steady producers of lead zinc and silver for many years. They represent replacements of ancient volcanic rocks.[4]

Among the Mexican silver-lead deposits those of the Sierra Mojada [5] forming replacement deposits in Cretaceous limestone and similar ones of the Santa Eulalia district [6] are worthy of note.

Epithermal Deposits

United States.—In the Creede district of Colorado (121), lead-silver zinc veins occur in rhyolite, and rhyolite breccias, the ore carrying sphalerite, galena, pyrite, etc.. in a gangue of manganiferous quartz, barite, chlorite, and adularia.

At Lake City, Colo. (15), the ores fill fissures in Tertiary flows and tuffs of the Silverton volcanic series. The primary minerals at lower levels are chiefly quartz, galena, blende, and pyrite, while at shallower depths there are also tetrahedrite, rhodochrosite, barite, and jasperoid. Secondary minerals are chiefly pyrargyrite and galena, as well as some chalcocite and possibly proustite. Native gold occurs in the upper part of the sulphide enrichment zone. The mineralizing solutions came probably from a quartz-monzonite intrusion.

Others carrying a stronger content of gold and silver are referred to under those metals.

Deposits in Sedimentary Rocks, Unrelated (?) to Igneous Ones

Deposits of lead and zinc in sedimentary rocks, and showing no close relationship to igneous rocks form a widely distributed type, whose association with calcareous rocks, as limestones, dolomites, and calcareous shales is most pronounced.

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[1] Vogt, Krush, und Beyschlag, Lagerstätten, II: 163, 1912. Müller, Geol. spec. Karte,Kgr. Sachsen, 1901.

[2] *Ibid.*, II: 177, 1912.

[3] Beyschlag, Vogt und Krusch, Lagerstätten, II: 163, 1912.

[4] Loveman, A.I.M.E., Trans., LVI: 170, 1917.

[5] Shaw, A.I.M.E., Trans., LXVIII: 556, 1923.

[6] Prescott, A.I.M.E., LI: 57, 1916.

PLATE LIII

FIG. 1.—View of valley at Austinville, Va. Zinc ores in hill at left, white heap of mill tailings on right. (*H. Ries, photo.*)

FIG. 2.—Old oxidized ore workings at Austinville, Va. The ore was in residual clay which formerly covered these limestone pinnacles. Sulphides underlie these. (*H. Ries, photo.*)

The primary ore minerals are galena and blende, while above them in the weathered zone are the usual oxidation products. Iron sulphide may often be present, and is undesirable, but gold and antimony are rare, and the deposits are with few exceptions non-argentiferous. The blende may contain small quantities of cadmium, or the latter as the sulphide, greenockite may be present as a secondary mineral. Nickel and cobalt are found in small amounts in some southeastern Missouri ores. Dolomite is a common gangue mineral, and chert is often present.

The deposits, which are not of great depth, may fill solution cavities, fault fissures, or form disseminations.

The origin of these ores has in the past been credited to meteoric waters, but now opinion seems to be changing.

United States.—In the United States this type of ore deposit is especially important in the Mississippi Valley region, and also in southwestern Virginia and east Tennessee.

Virginia-Tennessee Belt (73–75, 81–83).—The zinc deposits of the southern Appalachian region form a belt located chiefly between Roanoke, Va., and Knoxville, Tenn.; the ores being mined at present are at Austinville, Va., Mascot, Tenn., and Jefferson City, Tenn.

The rock formations, which consist of beds of Cambrian and Ordovician limestone with some shales and a little sandstone, have been folded and faulted, the faults being both thrust and cross ones.

The ores are associated with breccias formed by overthrusting and associated phenomena, and the ore bodies occupy definite and narrowly limited stratigraphic positions, but they are not confined to any particular horizon. Thus in southwest Virginia they are in the shady dolomite (Lower Cambrian), while at Mascot and Jefferson City, Tenn., they occur in the Knox dolomite (Lower Ordovician), and at still another district in the Rome (Middle Cambrian).

The ore minerals include sphalerite, galena (not always present), pyrite, cherty silica, fluorite, and barite, the last two not abundant or always present.

The ore is commonly composed of brecciated dolomite (which may have been recrystallized), cemented by a coarse white secondary dolomite. Sphalerite often forms bands around the fragments of wall rock, replacing it and, to some extent, the secondary dolomite. Pyrite may be of two periods with respect to sphalerite.

In the early days of mining, oxidized ores (Fig. 200) carrying smithsonite and calamine were worked, but the present output from the region is all sulphides.

The early theories of origin considered the ore to have been deposited by meteoric waters (83). One was that the minerals had been gathered by downward percolation from a disseminated state in the limestones. A modification of this theory assumed that artesian circulation (83) had gathered the metallic minerals from the limestones, and then risen along the fracture zones where they were deposited. There seem to be objections to both of these views (73).

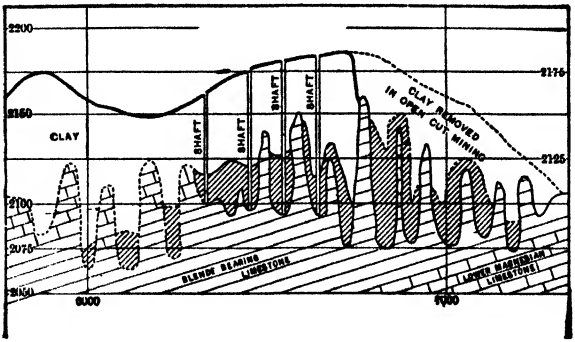

Fig. 200.—Section of Bertha zinc mines, Wythe Co., Va., showing irregular surface of limestone covered by residual clay-bearing ore. (*After Case, Amer. Inst. Min. Engrs., Trans. XXII.*) Compared with Plate LIII, Fig. 2.

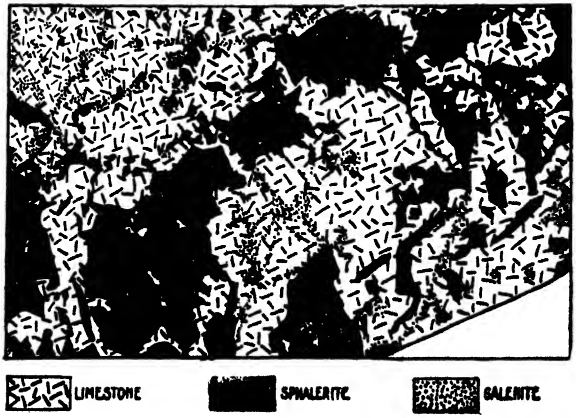

Fig. 201.—Section showing replacement of limestone by sphalerite and galena, Austinville, Va. (*After Watson, Va. Geol. Surv., Bull. I,* 1905.)

Currier (73) and others have more recently suggested that the ores were deposited by hypogene solutions rising from considerable depth along deep cross fracture zones—another case perhaps of telethermal deposits.

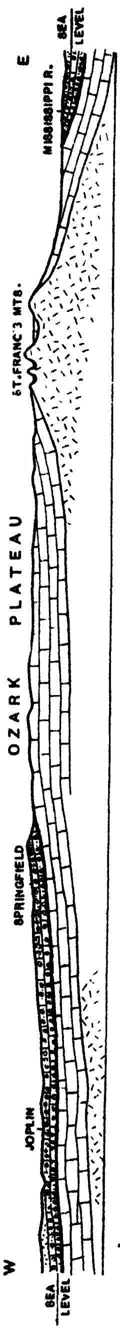

FIG. 202.—General west-east section through Joplin and the St. Francis Mountains. Shows the flat-topped dome of Cambrian and Ordovician limestones and pre-Cambrian rocks overlain by thin Devonian shale and Carboniferous sediments. (*U. S. Geol. Surv., Atl. Fol.* 148.)

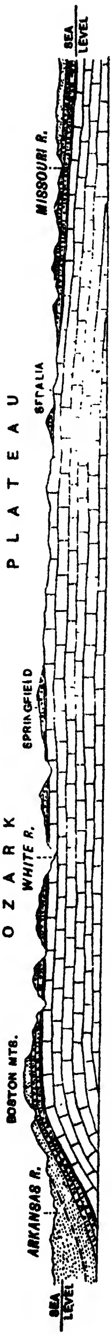

FIG. 203.—General south-north section through Springfield and Sedalia. Shows the flat-topped dome of Cambrian and Ordovician limestones overlain by thin Devonian and Carboniferous sediments. (*U. S. Geol. Surv., Atl. Fol.*, 148.)

Pennsylvania (72).—The Saucon Valley deposits promised at one time to become prominent producers, but have not, owing more to geological conditions than actual scarcity of ore.

Mississippi Valley Lead and Zinc Region.—This region contains two important areas: (1) the upper Mississippi Valley area of southwestern Wisconsin including a small portion of northern Illinois and southeastern Iowa, and (2) the Ozark region, which includes (*a*) northern Arkansas (6, 7), now of little importance; (*b*) central Missouri, with small lead-zinc ore bodies (33); (*c*) the Tri-States area of southwest Missouri, with adjoining portions of Oklahoma and Kansas; and (*d*) southeast Missouri, important as a source of lead.

Ozark Region (7, 33, 38, 51).—The Ozark uplift or plateau is a low, rudely elliptical dome (Figs. 202, 203) lying mostly in southern Missouri and northern Arkansas. The Boston Mountains form the southern boundary, while it merges into prairie on the west and north, and the Gulf Plains on the east and southeast.

The rocks are mostly of sedimentary origin, but pre-Cambrian granite and porphyry form some of the peaks of the St. Francis Mountains. The Cambrian and Cambro-Ordovician dolomites, and limestones and sandstones underlying the central Ozark area, surround these mountains concentrically, and are in turn flanked successively by Devonian and Pennsylvanian rocks.

Tri-States District (38, 39, 42–50, 70, 71).—This district includes an area in southwestern Missouri, southeastern Kansas, and northeastern Oklahoma. It extends roughly from Springfield, Mo., to Miami, Okla., a distance of about 100 miles, and with a width varying from a few miles to 30 miles. The term Joplin district is still sometimes used for that portion of the area in Missouri and near Galena, Kans., while the Miami-Picher district includes portions of Oklahoma and Kansas around the towns whose names it bears.

The area is important as a zinc producer, and also one of appreciable lead output. Zinc forms about 85 per cent of the output of the region and lead 15 per cent. In 50 years prior to 1932 the region yielded 50 to 80 per cent of the zinc mined in the United States, and 20 to 30 per cent of the world output of this metal.

The first mining began near Joplin in 1848, and in Oklahoma in 1891, but since 1918 the chief activity has been in the Miami-Picher district.

The general geological section given by Fowler and Lyden is as follows:

		Feet
Pennsylvanian	Cherokee. Shale and sandstone	0–350
Mississippian	Carterville (Mayes)	0–50
	Boone Limestone, dolomite, and chert. Some oölite beds. Contains ore deposits	200–400
Devonian	Chattanooga shale. Absent in most of area.	0–60
Ordovician	Largely dolomite	700–1000
Cambrian	Dolomite and sandstone	0–800
Pre-Cambrian	Igneous rock	

The Boone chert is the surface rock in the Joplin area, but covered by Pennsylvanian shale to the west.

The Mayes limestone, called the Carterville in the Joplin district, is apparently absent in places, and this appears to have led to the idea of sinkholes being present in it. Its thickness is irregular.

The Boone is a limestone which carries large amounts of chert, indeed the latter rock sometimes forms the entire portion of certain beds. It occurs (44) as (1) nodules; (2) cherty layers 2 to 5 inches thick, and (3) massive beds up to 30 feet thick. The possible origin of this chert is mentioned below.

There is an unconformity between the Boone and the Mayes, and also between the latter and the Cherokee shale. Pebbles of the chert are found in the Mayes.

The granitic rocks have been encountered in drill holes at depths of 1200 to 2000 feet below the surface.

The formations of the area are but slightly disturbed except in the Picher district where the Miami syncline accompanied by normal faults occurs. The faults in the area have displacements of 30 to 40 feet or more. Fractures are particularly abundant in the Boone and according to Weidman are respectively pre- or post-Mayes and Cherokee in age.

The brecciation in the Boone chert is thought to be due to compressive movements (71) and confined mainly to the vicinity of the ore deposits.

The ore bodies occur in a zone 50 to 150 feet thick in the upper half of the Boone chert, and the richest mines in the district are found around the Miami syncline.

The ore bodies are more or less irregular in shape, and are described as: (1) flat runs, 100–1000 feet wide, 5–30 feet high, and roughly parallel to the stratification; (2) vertical runs, 10–20 feet wide, 100–150 feet high, and following nearly vertical fracture zones; (3) pockets, small bodies of ore-bearing rock, somewhat circular in shape.

The ore bodies are said to be larger and richer beneath the shale in the Picher district.

The ore minerals are blende and galena, and these together with jasperoid, cement the Boone chert breccia, but in addition the ore occurs as vein fillings in fractured chert, and as replacements in the fracture walls. Accessory sulphides are pyrite, marcasite, and chalcopyrite, while the gangue minerals are commonly chert, dolomite, and calcite.

Fowler and Lyden (44) give the sequence of the minerals in the ore deposits as follows: dolomitization of limestone, chertification, deposition of jasperoid, then galena and sphalerite, pink dolomite, calcite, quartz, marcasite, pyrite, and chalcopyrite. There is also some later sphalerite which may have come from solution and redeposition of the earlier zinc sulphide. Enargite crystals have also been found locally on the surface of chalcopyrite.

In those areas where the shale is absent, and the Boone formation rises above the water table, there are smithsonite and calamine, as well as some cerussite.

In the Oklahoma-Kansas part of the area the ore averages 5.5 per cent zinc and 1 per cent lead. Since 1927 the old tailings have been retreated and yielded 1.5 per cent zinc with a little lead.

Two problems, viz., the origin of the chert and that of the ore, have been productive of much discussion.

Fowler and Lyden claim that the Boone was originally a slightly siliceous limestone which was replaced by chert, the latter having been introduced as silicic acid, which they believe to have come from magmatic sources, and in support of this view they state that little chert has been found in the areas of least disturbance. This chert is supposed to have replaced the Boone limestone as nodules, layers, and massive beds. They also distinguish between an older and a younger chert, the latter cementing fragments of the former.

Tarr has argued most strongly (70) for the primary origin of the chert, claiming that the brecciation is due to the solution of the limestone and collapse of the remaining chert. He also disputes the idea that there is less chertification away from the disturbed zones than close to them.

The origin of the ores has been explained as due to meteoric or magmatic waters. If their accumulation and deposition are due to meteoric waters, this is thought to have been accomplished by one of two ways: 1. It may have been done by descending ground water, which leached the metallic compounds from the formations above and redeposited them below, a theory advanced by Winslow, Buckley, and also Buehler. 2. Artesian circulation is believed to have leached the metallic compounds from the sedimentary formations and to have carried them into the Tri-States area, where the rising solutions deposited them in the Boone formation. This view was supported by Van Hise, Bain, W. S. T. Smith, and Siebenthal (48), who worked out the details of the process.

According to the magmatic theory thermal waters are supposed to have risen from some underlying mass of igneous rock causing the chertification of the limestone, and later deposition of the jasperoid and sulphides. The advocates of this view include Spurr, Pirsson, W. H. Emmons, Weidman, Fowler, and Lyden.

The evidence which these writers advance in support of the magmatic origin is: 1. That the ore bodies show a relation to structure, being localized where the Boone formation is sheared and shattered due to deformation, and furthermore that in such areas the beds are brecciated and chertified. 2. That, although there is an absence of igneous rocks in close association with the ores, nevertheless, they are encountered at depths as already mentioned, and Weidman has pointed out that granitic intrusions have arched the beds adjacent to the Miami syncline, and have also silicified adjacent rocks. 3. Graton and Harcourt have shown that spectroscopic tests of the sphalerite indicate the presence of cadmium, germanium, gallium, and indium which may be of magmatic derivation.

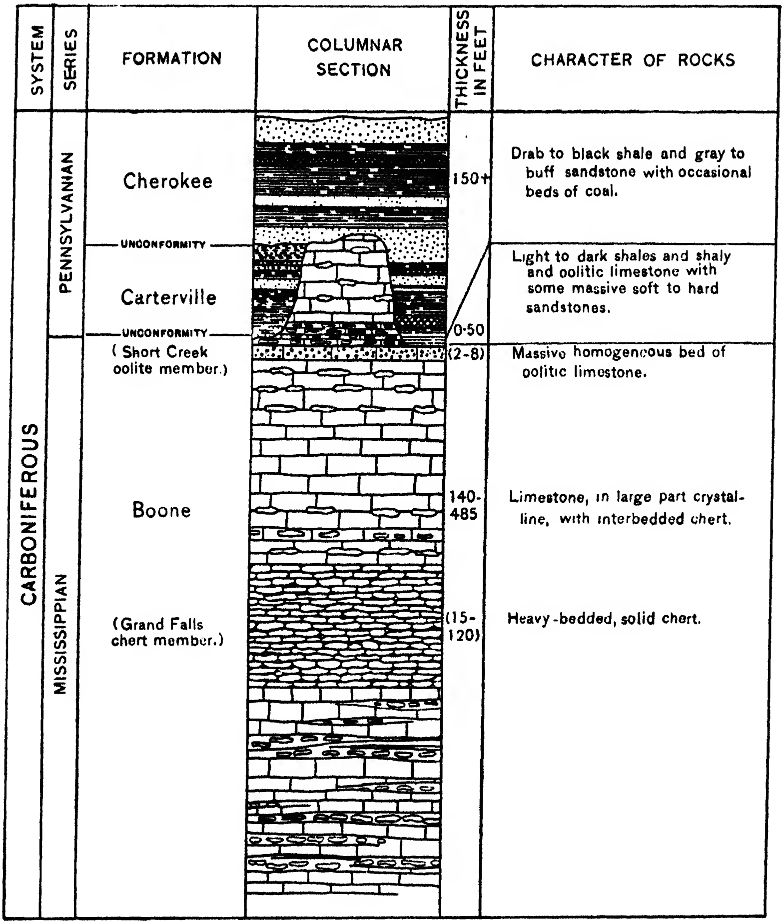

FIG. 204.—Generalized geologic section of Joplin district. (*U. S. Geol. Surv., Atl. Fol.* 148).

It can probably be said that the theory of magmatic origin for the Tri-States ores is gaining ground, and if true it would place them in what Graton has called the Telethermal zone.

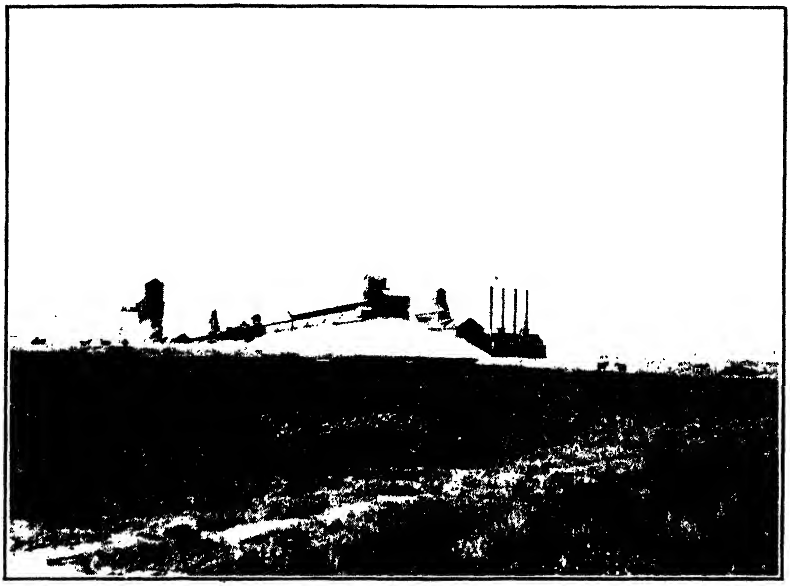

FIG. 1.—Mills and tailing piles near Picher, Okla. (*H. Ries, photo.*)

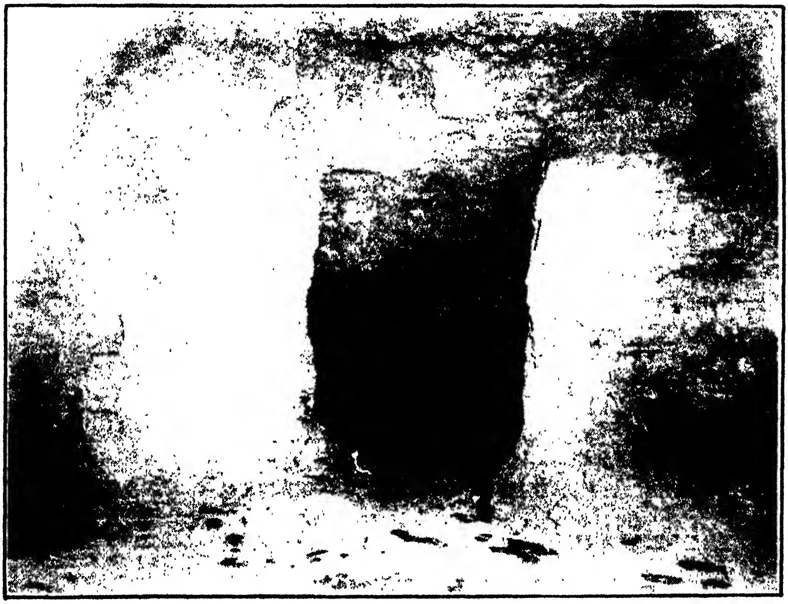

FIG. 2.—Chambers in Disbrow Mine, near Webb City, Mo. These include both sheet ground and the "broken ground" above. (*Photo. from F. C. Wallower.*)

Southeast Missouri (5, 40, 51).—This district, which is located in St. Francis, Madison, and Washington counties, 60 miles south of St. Louis, is the largest lead-producing area of the United States. The geologic section (Fig. 206) is:

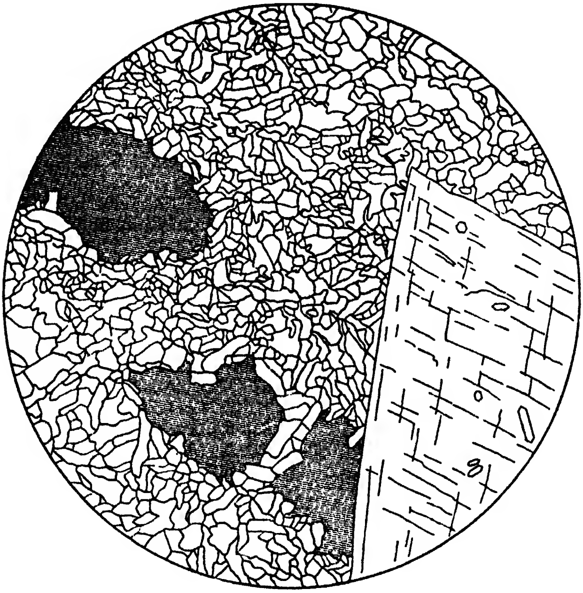

Fig. 205.—Photo-micrograph of jasperoid, showing fine granular aggregate of quartz, with sphalerite (shaded) and dolomite, the latter including minute quartz crystals. ×53. (*After Smith and Siebenthal.*)

		Feet
Upper Cambrian	Potosi dolomite	400
	Derby and Doe Run dolomites	150
	Davis shale	160
	Bonneterre dolomite, upper part light gray dolomite, lower part more shaly	300–400
	Lamotte sandstone	365
	Unconformity	
Pre-Cambrian	Granite	

The rocks are essentially flat, and basic dikes intrude the Bonneterre dolomite.

The ore bodies occur mainly in the Bonneterre dolomite and to a lesser extent in the underlying Lamotte sandstone. In the former they are confined to the lower beds of the formation which contain more organic material, and are not found in the upper beds of light-colored rock.

Their general form is flat and tabular, and some of them are of considerable size, being as much as 1000 feet wide and over a mile long. Their thickness varies, being often not more than 6 feet, but in some cases as much as 125 feet.

Galena is the ore mineral and occurs chiefly as disseminations, but it may also form horizontal sheets along the bedding planes, or filling small fractures and lining the walls of fractures and joints. In some shale beds replacement is almost complete. Associated with the galena there may be pyrite, but sphalerite and chalcopyrite are unimportant. The average lead content of the ore is 3 to 4 per cent, but the concentrates carry over 70 per cent. The ore is practically non-argentiferous.

In the Fredericktown area the mineralization is quite different, for there the replacement is mainly of pyrite, associated with which are sulphides of lead, copper, nickel, and cobalt.

There has been a difference of opinion as to whether the Bonneterre ores have been deposited by meteoric or magmatic waters.

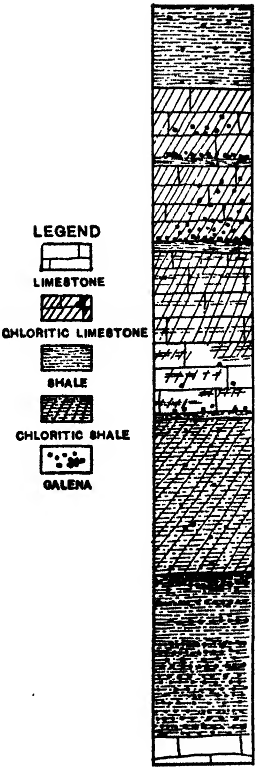

Fig. 206.—Four and one half foot section showing occurrence of ore in Bonneterre limestone, Doe Run, Mo. (*After Buckley, Mo. Bur. Geol. Min., IX.*)

Upper Mississippi Valley.—This area embraces southwestern Wisconsin (86), eastern Iowa (31, 32), and northwestern Illinois (24), but the first-named state contains the most productive territory. The section in the Wisconsin area (86), which may be taken as typical, involves the following formations, beginning at the top:

		Feet
Pleistocene	Loess, alluvium, and soil	7
Silurian	Niagara limestone	50
Ordovician	Maquoketa shale	160
	Galena limestone	230
	Platteville limestone (Trenton)	55
	St. Peter sandstone	70
	Lower Magnesian limestone	200
Cambrian	Potsdam sandstone	700
Pre-Cambrian	Crystalline rocks	

A bituminous shaly layer, known as the *oil rock,* occurs at the base of the galena, and below it, or at the top of the Platteville, is a fine-grained limestone called the *glass rock.* The formations show a series of elliptical basins with anticlinal structures between them.

There are also faults of different types of small displacement.

The ore occurs as: (1) Disseminations in the oil rock, (2) in vertical joint-like cracks or crevices, (3) in inclined fractures called *pitches,* (4) as a cement of breccia in fracture zones, and (5) parallel to the beds in the so-called *flats* (Fig. 207). All except (1) are fissure fillings and replacement is rare.

The ore is localized in or near the basins, and frequently shows crustification.

The chief ore bodies lie in the Galena limestone, but others have been found in the oil rock as well as below it, in the Niagara limestone and the Maquoketa shale.

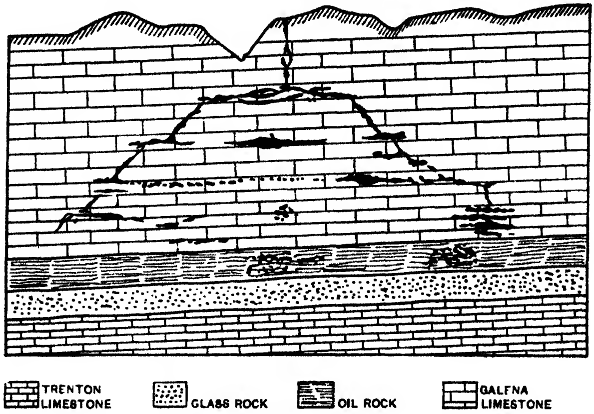

FIG. 207.—Section showing occurrence of lead and zinc ore in Wisconsin; fissure ore in flats and pitches, and disseminated ore in wall rock. (*After Chamberlin.*)

The important primary minerals are marcasite,[1] pyrite, sphalerite, galena and calcite. The pyrite occurs at the margins of the fissures, and also as botryoidal masses which may have originally been marcasite. Much of the sphalerite is thought to have originally been wurtzite. Galena mostly postdates the sphalerite.

Secondary minerals are those derived from the weathering of the primary ones.

In explaining the origin of the ore bodies some have claimed (86) that the metallic minerals were gathered by circulating meteoric waters

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[1] Behre, Scott and Banfield, Econ. Geol., XXXII: 783, 1937.

from the Galena limestone; these waters entered the limestone probably from the northeast, where the overlying shales had been eroded, and moved to the southwest. The ore was precipitated in crevices as sulphides, either because of a reducing action exerted by bituminous matter present in the rocks or by hydrogen sulphide.

Surface waters descending crevices have produced a secondary concentration, which has resulted in a separation of the zinc and galena accompanied by a transferal of much of the former to lower levels.

More recently Behre has expressed the view that the ores are due to rising solution of ultimate magmatic origin.

Lead was discovered in the Upper Mississippi area as early as 1692 and the first mining was done in Dubuque in 1788. The early work was restricted to lead mining entirely, the zinc ores being disregarded. The increased price of zinc in later years led to the opening of deposits below water level and a continued production of zinc. Mechanical concentration methods have been introduced, and while the galena can be separated quite thoroughly from the sphalerite and marcasite, the last two are parted with difficulty. On account of the presence of marcasite in most of the mines, the zinc ores of this district command a lower price than those from other areas.

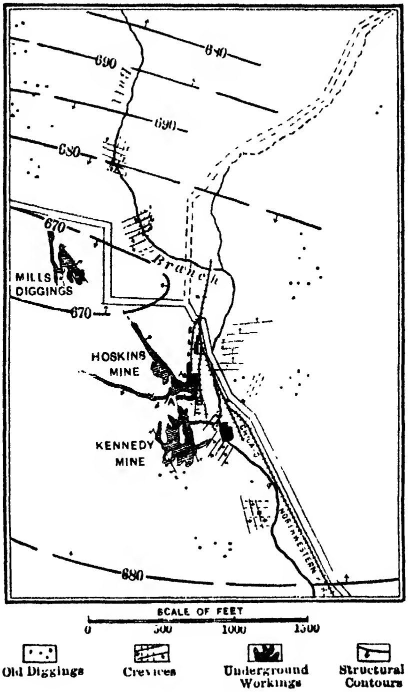

FIG. 208.—Map of a portion of Wisconsin lead and zinc district, showing strike of crevices, underground contours of Galena limestone, and underground workings. (*After Bain, U. S. Geol. Surv., Bull.* 294.)

Both electrostatic and electromagnetic separation have been used on these ores with good results. Thus working on a material that assays 30 per cent zinc and 20 per cent iron, the zinc product assays 56 per cent zinc and 4 per cent iron, while the iron product gave 39 per cent iron and 5 per cent zinc.

The crude ore yields from 5 to over 20 per cent concentrates, and these in 1927 averaged about 31.6 per cent zinc.

Foreign Deposits.[1]—Europe contains two important lead-zinc districts, somewhat analogous to the Mississippi Valley type. In the Moresnet district of Belgium the ores occur in Devonian and Carboniferous limestones, which are

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[1] Beyschlag, Vogt und Krusch, Lagerstätten; U. S. Bur. Mines, Min. Invest. No. 18.

folded and faulted. The ore deposition has been in part by replacement and in part by cavity filling, ores from the latter often showing magnificent banding (Pl. XXXIV, Fig. 1), due to alternating layers of iron sulphides and sphalerite and wurtzite. Galena is also present. Near the surface the ores have been weathered to calamine, etc.

The second of these located in Silesia and Poland, is among the world's leading producers. Here the Triassic limestones and shales form a shallow syncline some 20 miles long, with Beuthen, Germany, near the western end, and the eastern part in Poland. There are a number of small faults in the western part of the basin, some of them of pre-mineral age. The ore appears to form replacements, and is also deposited around breccia fragments in dolomitized limestone, the sulphide minerals consisting of blende, wurtzite, galena, and marcasite. The combined lead and zinc values are about 16 per cent, and the galena is slightly argentiferous. There is a difference of opinion as to whether the ores have been deposited by descending or ascending solutions, some writers holding for the latter, because some of the ore-bearing fissures extend downward into the Carboniferous.[1] At Raibl and Bleiberg, Italy, the ores are found in Triassic dolomite under two structural conditions, viz., (1) along several northward trending faults, and (2) as roughly tabular masses lying nearly parallel to the bedding. The wall rock has been dolomitized. Kraus and Posepny thought that the ore had been deposited in solution cavities, but Hewett believes that it was deposited in open breccias, and that these were later brecciated and the cavities filled with dolomite. The minerals are sphalerite, some wurtzite, galena, and a little marcasite and chalcopyrite.[2]

Other European occurrences in limestone are those of Santander, Spain, Sardinia, England,[3] etc.

Uses of Lead and Zinc.—Both of these are important base metals; although in value of production they rank below gold, silver, copper, and iron, neither do they come into competition with these, for they lack the high tenacity of iron and steel, the conductivity of copper, and the value resulting from scarcity possessed by gold and silver. They are of value, however, on account of their high malleability and the application of their compounds for pigments.

Uses of Lead.—Lead finds numerous uses in the arts, the most important being for white lead. Litharge, the oxide of lead, is used not only for paint, but also somewhat in the manufacture of glass, although red lead is more frequently employed instead.

A further use of lead is for making pipe for water supply, sheet lead for acid chambers, and shot.

Among the alloys formed by lead are type metal (lead, antimony,

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[1] Beyschlag and Michael, Zeitschr. prakt. Geol., 1902: 143; Hewett, Econ. Geol., XXIII: 841, 1928; Stappenbeck, Arch. f. Lagerstättenf., Hft. 41, Berlin, 1928.

[2] Posepny, Jahrb. k. k. geol. Reichsanstalt, XXIII: 313, 1873; Kraus, Lead Zinc Deposits of Raibl, Vienna, 1913; Hewett, Econ. Geol., XXIII: 841, 1928.

[3] Louis, Min. Mag. XVI: 15, 1917.

and bismuth, with copper, or iron), white metal, organ-pipe composition, and fusible alloys used in electric lighting.

In addition to these, the acetate, carbonate, and other compounds are used in medicine. In smelting, lead is used to collect the gold and silver, and the bulk of the lead of commerce is obtained as a by-product in the smelting of the precious metals.

Uses of Zinc.—Metallic zinc is used for a variety of purposes, partly owing to its slight alteration in air, and secondly, because it can be rolled into thin sheets. In this condition it is used extensively for roofing and also for plumbing, and as a coating to iron this metal is extensively called for in galvanizing. It is also used for cyaniding gold.

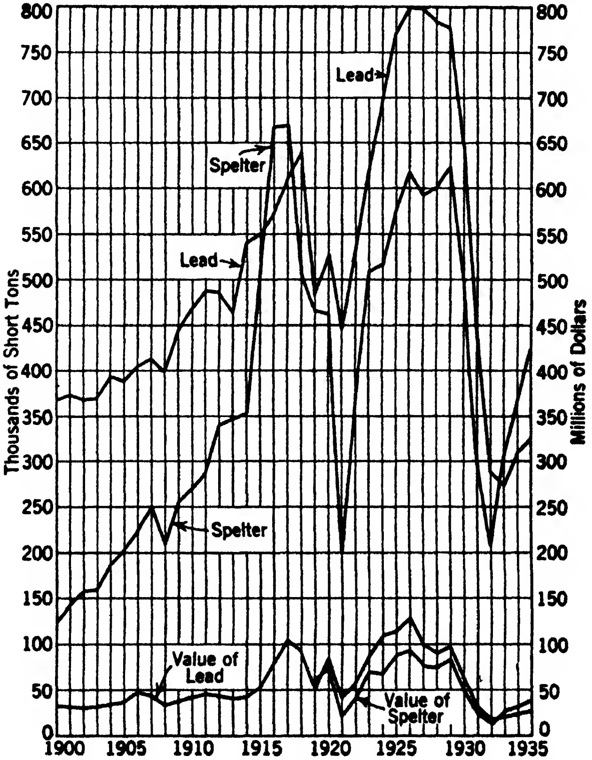

FIG. 209.—Graph of lead and zinc production in United States from 1900-1935. (*Minerals Yearbook*, 1936.)

One of the most important applications is for making brass, which is ordinarily composed of 66 to 83 parts of copper and 27 to 34 parts of zinc. The composition varies, entirely depending on the use to which it is to be put, and, with the variation in proportion, the color becomes more golden, or whiter, according as the percentage of copper is increased or decreased. With an increase in the amount of zinc, the alloy becomes more fusible, harder, and more brittle.

White metal is an alloy of zinc and copper in which zinc predominates, and which is often employed for making buttons. Imitation gold is also made by alloying zinc with a predominance of copper, varying from 77 to 85 per cent of the mass, and this is in common use as "gold foil" for gilding. Zinc is also made use of in the construction of electric batteries.

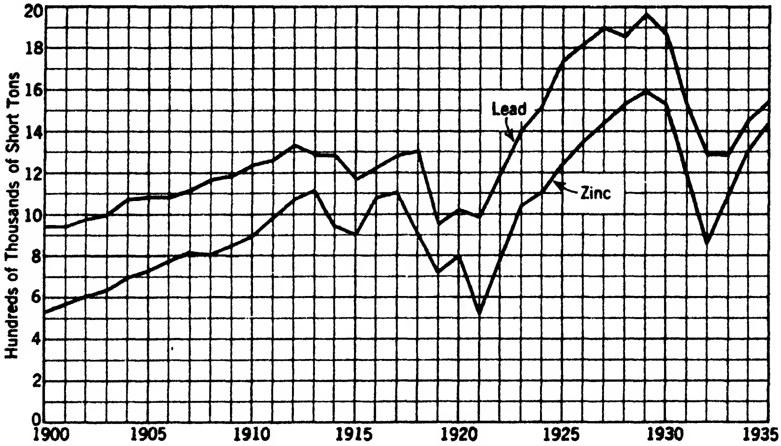

FIG. 210.—Graph of world's lead and zinc production from 1900-1935. (*Minerals Yearbook*, 1936.)

German silver has 60 parts copper, 20 zinc, and 20 nickel. Its use is for mathematical and scientific instruments.

Zinc is used wholly or in part as the base of four pigments, viz., zinc oxide, leaded zinc oxide, zinc-lead oxide, and lithopone. All of these can be made directly from the ore, and the first three usually are. Zinc oxide is the most important of the four. Lithopone is an intimate mixture by chemical precipitation of zinc sulphide and barium sulphate.

Production of Lead and Zinc.—The production of distilled and electrolytic zinc (including primary and secondary) in the United States in 1940 was 724,192 short tons valued at $85,084,650, while that of refined lead also from domestic and foreign sources was 533,179 short tons, the value of both being $53,318,000.

The order of the four leading states for 1940 was as below:

Zinc (recoverable)	Per Cent	Lead (recoverable)	Per Cent
Oklahoma	24.3	Missouri	37.6
New Jersey	13.7	Idaho	23.0
Idaho	10.5	Utah	15.6
Kansas	8.6	Montana	5.0

The imports of zinc ore (zinc content) in 1940 were 180,320 short tons and came chiefly from Mexico. Those of lead ore (lead content), base bullion, and refined lead amounted to 282,490 short tons. The exports of zinc ores and manufactures in 1940 were 90,073 short tons valued at $11,302,228, while pig lead was 23,755 short tons.

Canada in 1939 produced 194,284 short tons of lead valued at $12,313,768. About 97 per cent of it came from British Columbia. The zinc production for the same year was 197,266 short tons, valued at $12,108,244, and British Columbia was the largest producer.

The Canadian imports of manufactured lead in 1939 were valued at $3,367,822, while similar exports had a value of $9,871,007. The manufactured zinc imports were valued at $2,229,458 and the exports (which included some ore) at $9,922,232.

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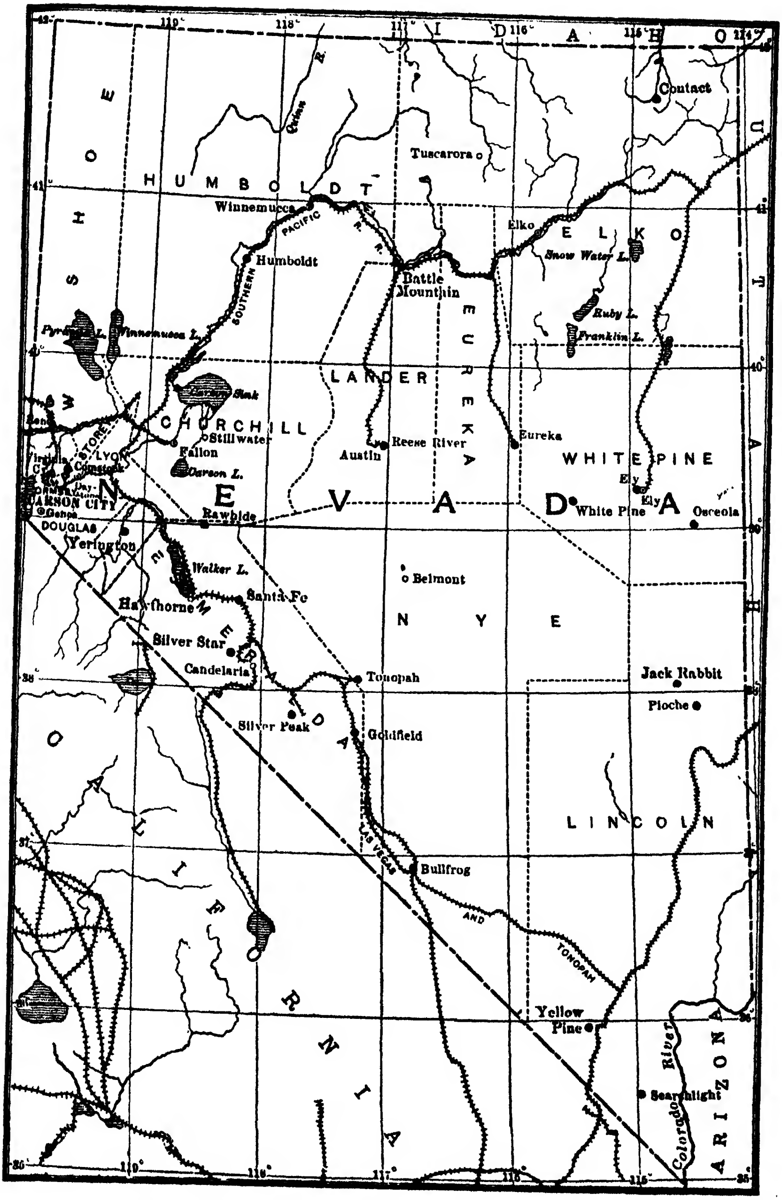

Fig. 211.—Map of Nevada, showing location of more important mining districts.

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CHAPTER XVII

GOLD AND SILVER

Gold and silver are obtained from a variety of ores, in some of which the gold predominates, in others silver, while in still a third class these two metals may be mixed with the baser metals, lead, copper, zinc and iron. Few gold ores are absolutely free from silver, and *vice versa*, so that a separate treatment of the two is more or less difficult; however, some lead-silver ores, although they may carry some gold, are discussed in the lead and zinc chapter.

Ore Minerals of Gold.—Gold occurs in nature chiefly as native gold, mechanically mixed with pyrite, or as telluride such as calaverite ($AuTe_2$; Au, 39.5 per cent; Ag, 3.1 per cent; Te, 57.4 per cent).[1]

Gold is also found at times in chalcopyrite, arsenopyrite, and stibnite, but not as a rule in such large amounts as may be shown by pyrite. Sphalerite and pyrrhotite sometimes carry it.

The gold-bearing sulphides, as well as the tellurides, are of primary character, although auriferous chalcopyrite might be formed by secondary enrichment.

Native gold may occur in the primary, secondary enrichment, or oxidized zones. The tellurides, which are usually associated with pyrite, are widely distributed, though not so abundant, but not always recognized; indeed by some they are mistaken for sulphides.

Ore Minerals of Silver.—The minerals which may serve as ores of silver, together with the percentage of silver they contain, are shown in the table on the following page.

Galena, sphalerite, pyrite, chalcopyrite, and chalcocite may all be and frequently are argentiferous, but in most ore deposits the silver usually favors the first named.

Of the ore minerals above mentioned, the most common primary ones are argentiferous galena, sphalerite, and pyrite, while native silver and the sulphides and arsenides are less common.

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[1] Other tellurides are sylvanite, krennerite, and petzite.

MINERAL†	COMPOSITION	Ag
Native silver	Ag	100.
Argentite, silver glance	Ag_2S	87.1
Pyrargyrite, ruby silver	$3Ag_2S, Sb_2S_3$	59.9
Proustite, light ruby silver	$3Ag_2S, As_2S_3$	65.5
Stephanite, brittle silver, black silver	$5Ag_2S, Sb_2S_3$	68.5
Polybasite	Ag_9SbS_6	75.6
Cerargyrite, horn silver	AgCl	75.3
Bromyrite	AgBr	57.4
Embolite	Ag(ClBr)	64.5
Iodyrite	AgI	46.0
Tetrahedrite (freibergite)	$4(Cu_2Ag_2FeZn)S,Sb_2S_3$	Variable; usually present; may be high

† Other less common ones are polyargyrite, pearcite, miargyrite, etc.

In the oxidized zone, silver chloride is the most abundant and native silver less so, while the iodides and bromides are quite rare and formed only under certain conditions.

The secondary enrichment ores include native silver, argentite, stephanite, tetrahedrite, pyrargyrite, and proustite.

Mode of Occurrence.—Most of the gold and silver mined in the United States is obtained from fissure veins, or closely related deposits of irregular shape (166), in which the gold and silver ores have been deposited from solution, either in fissures or other cavities, or by replacement. Considerable gold and a little silver are obtained from gravel deposits, and some true contact-metamorphic deposits are known. Gold has been found to occur in rare instances as an original constituent of igneous rocks (3, 28) and also metamorphic ones, but there are no known deposits of commercial value belonging to this type.

The gold- and silver-bearing fissure veins include two prominent types (166), viz.: (1) the quartz veins, and (2) the propylitic type, in which the metasomatic alteration of the wall rock is often propylitic. In the quartz-vein type silver is present usually in but small quantities, while in the propylitic type the silver often is an important constituent. Veins of intermediate character may also occur.

While the mode of occurrence of gold and silver is quite variable, the character of the wall rock is equally so, gold and silver ores being found in either sedimentary or igneous rocks, and along the contact between the two, showing that the kind of rock exerts little influence, except perhaps where replacement has been active. On the other hand the influence of locality is much stronger, for it has been found that many gold- and silver-bearing deposits are closely associated with masses of igneous rock, the most common of these being diorite, monzonite, quartz-monzonite, granodiorite, while true granites are rare as associates. A second large class of vein systems shows a close association with lavas of recent age, and the telluride ores rather favor these.

Weathering and Secondary Enrichment.—The superficial alteration of gold ores differs somewhat from that of deposits containing ores of the other metals. In quartz veins with auriferous pyrite, the change of the latter to limonite leaves a rusty quartz with nuggets or threads of free gold, and leaching may remove most of the iron.

The conditions under which gold is removed by the influence of manganese are discussed under Secondary Enrichment, Chapter XIII.

Telluride ores weather in a somewhat characteristic manner, the product being free gold. This may be of earthy appearance and faint brownish color, or consists of aggregates of extremely small crystals of gold which form a spongy mass, or a thin film on the surface of the rock.

Silver sulphides are changed to chlorides, and native silver may also be formed. In the weathered portion of some silver-bearing deposits, silver bromides and iodides are also found.

Penrose has suggested [1] that such ore bodies were in the vicinity of saline deposits, where haloid compounds were dissolved by the soil waters that penetrate the ores. Keyes, however, believes that the prevailing source of saline materials is the wind-blown dust produced by disintegrative processes so predominant in arid regions.

Downward secondary enrichment has evidently occurred in a number of silver and silver-gold deposits. According to W. H. Emmons (10), all deposits in which gold appears to have migrated include manganiferous ores. In deposits carrying both metals, especially where chlorides form, secondary silver minerals are likely to be precipitated as bonanzas near the surface, while gold is carried deeper, but if chlorides are not formed in manganiferous deposits, silver may be carried deeper than gold. Abundant pyrrhotite is said to halt rapidly the downward migration of both gold and silver. In copper deposits where silver and gold migrate downward, these are deposited chiefly in the upper part of the secondary sulphide zone. Some de-

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[1] Jour. Geol. II: 1894.

posits of rich silver ore and some of rich gold ore terminate downward in low-grade sphalerite ores.

Geological Distribution.—Gold and silver ores have been deposited at a number of different periods in the geological history of the continent, notably in the pre-Cambrian, Cambrian, Cretaceous, and Tertiary ages.

Some of the Appalachian veins are probably early Paleozoic, and those of Nova Scotia are post-Cambrian. Silver ores show much the same geological range.

The geological distribution is referred to in more detail under Metallogenetic Epochs in Chapter XIII.

Classification.—A classification of gold and silver ores is in any event attended with more or less difficulty. Divisions based on geological and structural characters would for many purposes be more satisfactory, while for commercial or metallurgical work a grouping according to metallic contents is perhaps more desirable.

The following classification according to the associations of the ores is sometimes used in the United States.

1. *Placers or Gravel Deposits.*—These serve chiefly as a source of native gold, but may, and often do, contain a little silver, much of which is never separated from the ore in which it occurs. These gravels are derived chiefly from quartz veins of Mesozoic age in the Pacific coast region, and to a less extent from pre-Cambrian veins of the Appalachian region and Black Hills of South Dakota. Some are also derived from veins in Tertiary lavas, but these usually contain the metals in such a finely divided condition, or in such combination, that they do not readily accumulate in stream channels.

Large quantities of placer gold are obtained from Alaska and California.

Taking all sources, we see that placer gold is obtained by dredging, drift-mining,[1] hydraulicking, and sluicing, as well as in small amounts from dry placers in the southwest and beach gravels of California and Oregon.

Dredging, which was started in New Zealand about 1882, and first profitably tried in the Bannock district of Montana in 1893, is now of great importance, the modern bucket elevator dredge (often electrically driven) being capable of excavating a large yardage daily. The total value of gold in millions of dollars produced in this manner by several states up to 1923 is: Idaho, 4½; Alaska, 24¾; California, over 130; all others, 21½.

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[1] In decreasing quantity from frozen ground in Alaska, but still in considerable amounts from buried channels in California.

2. *Dry or Siliceous Ores.*—These include: (*a*) the gold and silver ores proper; (*b*) fluxing ores carrying considerable quantities of iron and manganese oxides with small gold and silver contents; and (*c*) precious-metal bearing ores with copper, lead, and zinc in small amounts. Colorado, California, Nevada, South Dakota, and Alaska have been the largest gold producers of this type.

The siliceous gold ores are in part free milling (amalgamating) as Alaska, California, and Oregon; in part both amalgamating and concentrating; in part simply concentrating, as parts of Colorado and Arizona; in increasing part all-sliming and cyaniding; and in part smelting.

A great deal of the silver from the gold-silver siliceous ores is obtained with the gold by amalgamation and cyanidation, the silver being recovered by refining the mill bullion. The remainder is obtained by smelting rich ores and refining copper or lead bullion produced.

The siliceous ores are of varying age. Those of California, Oregon, and Alaska are Mesozoic and associated chiefly with quartz—monzonite, granodiorite, and diorite. Another great class of post-Miocene age, found chiefly in Colorado, Nevada, and Montana, is associated with Tertiary lavas. Some formerly very productive ones carry fluorite and normally also tellurides. In some, gold may predominate; in others, silver. A third class, of pre-Cambrian age, is found in the Atlantic states, Wyoming, and South Dakota, the last mentioned including the famous Homestake mine.

3. *Copper ores*, with variable, and sometimes very small amounts of copper.

The largest gold producers are those of Utah, Arizona, Nevada, and Montana. The silver production comes from the electrolytic refining of Michigan copper, and blister copper produced by smelting. The great disseminated deposits of Utah, Arizona, Nevada, and New Mexico are yielding increasing quantities, while the vein deposits of Butte, Mont., are also important.

The gold- and silver-bearing copper ores exhibit great differences in form and age; neither do all the occurrences yield much gold or silver, and, moreover, they are of more importance as gold producers, silver being less often associated with the copper.

4. *Gold- and silver-bearing lead ores*, containing 4½ per cent or more of lead. The gold is obtained chiefly from Utah and Colorado. The silver comes mainly from the lead-silver ores of Cœur d'Alene, Idaho, Utah (chiefly Park City and Tintic), Colorado (San Miguel

and San Juan counties). Most of the output is obtained by the desilverization of lead bullion.

5. *Copper-lead or Copper-lead-zinc Ores.*—These are unimportant as compared with the others. The gold supply is small, and the main silver supply is from Idaho and Montana.

6. *Zinc ores*, containing at least 25 per cent zinc. These yield little gold, and the silver which is mainly a by-product from the smelting of zinc concentrates is obtained chiefly from Montana and New Mexico.

Extraction.—Since gold and silver ores vary so in their mineralogical associations and richness, the metallurgical processes involved in their extraction are varied and often complex.

Those ores whose precious metal contents can be readily extracted after crushing, by amalgamation with quicksilver, are termed *free-milling ores.* This includes the ores which carry native gold or silver, and often represent the oxidized portions of ore bodies. Others containing the gold as telluride, or containing sulphides of the metals, are known as *refractory ores* and require more complex treatment. These, after mining, are sent direct to the smelter if sufficiently rich, but if not they are often crushed and concentrated mechanically or in addition by flotation. The smelting process is also used for mixed ores, the latter being often smelted primarily for their lead or copper contents, from which the gold or silver are then separated. While in some cases there are smelters at the mines, still there is a growing tendency towards the centralization of the industry, and large smelters are now located at Denver, Salt Lake City, etc., which draw their ore supply from many mining districts.

Low-grade ores may first be roasted, and the gold then extracted by leaching with cyanide solutions. The introduction of the cyanide process, which is applied chiefly to gold ores, has permitted the working of many deposits formerly looked upon as worthless, and in some regions even the mine dumps have been worked over for their gold contents.

The most important gold-milling centers of the United States are the Mother Lode district of California; the Black Hills, South Dakota, Alaska, and Colorado.

Distribution of Gold and Silver Ores in the United States (Fig. 212).—Gold ores are widely distributed in the Cordilleran and Appalachian regions, while the silver ores are found chiefly between the Great Plains and Pacific coast ranges, exclusive of the Colorado plateau region. This occurrence in two widely separated areas is brought out in an interesting manner in Fig. 212.

About one-half of the United States production of gold comes from four states—California, Colorado, South Dakota, and Arizona. In these, however, the ores vary widely in their mineralogical associations, the gold occurring mostly in combination with silver, lead, copper, and zinc ores, but also at times free, or, in what was formerly the most productive district, as a telluride.

The Pacific belt, excluding Alaska, supplies about 26 per cent of the total amount of gold produced, the famous Mother Lode region, mentioned later, being the most important producer. Alaska yields about 13 per cent, and the Basin Range province about 16 per cent, collected from widely separated deposits in Utah, Nevada, Arizona, and New Mexico, in which the gold is associated with copper, silver, or lead.

About 50 per cent of the silver obtained in the United States comes from the Rocky Mountain region. The Basin Range province furnishes something under one-half, about one-half of this coming from Utah.

FIG. 212.—Map showing distribution of gold and silver ores in the United States. (*Adapted from Ransome, Min. Mag., X.*)

The gold and silver occurrences of the United States can be grouped under three regions as follows:

1. *Cordilleran Region.*—This includes several types geologically arranged as follows: (*a*) Belt of Pacific coast Cretaceous gold quartz ores, characterized by ores with free gold, and auriferous sulphides, extending along the Pacific coast from Lower California up to the British Columbia boundary. The deposits belonging to this are especially important in California, but farther north, in Oregon and Idaho, the veins in many cases have been covered up by the lava flows of the Cascade Range, and those known in that region differ somewhat

from the California deposits in containing many mixed silver-gold ores and also veins carrying auriferous sulphides without free gold. The ores of this belt are all of undoubted Mesozoic age, and are accompanied by many extensive placer deposits, which have been derived by the weathering down of the upper parts of the quartz veins, the portions now remaining in the ground representing probably but the stumps of originally extensive fissure veins (166).

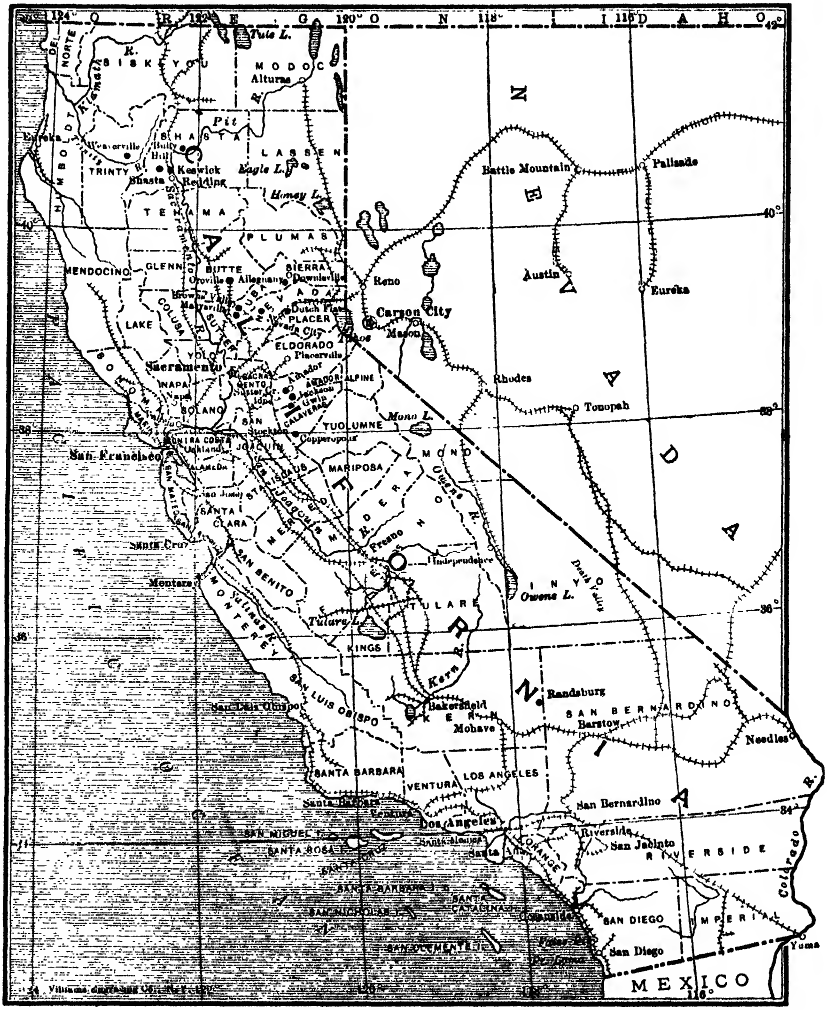

FIG. 213.—Map of California, showing location of more important mining districts.

Among the deposits of this belt two groups stand out in some prominence, namely, those of the so-called Mother Lode district and of Nevada County.

(*b*) Late Cretaceous or Early Tertiary deposits, occupying a broad zone in the central and eastern part of the Cordilleran region, and yielding gold ores of varying character. While they differ in age and characters from the Pacific coast ores, and those of the belt next to be mentioned, nevertheless they are not absolutely separated from them geographically.

The Mercur, Utah (Fig. 219), and Leadville, Colo. (Fig. 221), deposits, the latter referred to under lead and zinc, are included under this type.

The northward continuation of this belt of gold-bearing veins in Idaho and Montana presents somewhat different types of deposits, for there the veins are causally connected with great batholiths of Mesozoic granite; and while the veins resemble those of the Pacific coast in the quartz filling and free gold contents, they differ from the latter in containing more silver, and often large quantities of sulphides with little free gold. In fact, in their geologic relations they are intermediate between the quartz vein and propylitic type. Of special prominence are those of Marysville, Mont. (109), and Idaho Basin, Florence, etc., in Idaho. This difference is more marked in the Montana occurrences, in which the gold becomes subordinate and is obtained as a by-product in silver mining.

(*c*) Eastern belt of Tertiary gold-silver veins, formerly more important than the preceding class and characteristic of regions of intense volcanic activity. The veins cut across andesite flows, or more rarely rhyolite and basalt. They may be entirely within the volcanic rocks, or the fissures may continue downward into the underlying rocks, which have been covered by the volcanic masses. Many of these Tertiary deposits belong to the propylitic class, showing characteristic alterations of the wall rock. The ores are commonly quartzose, and though either gold or silver may predominate, the quantities of the two metals are apt to be equal. Bonanzas are of common occurrence, and on this account the mines may be very rich but short-lived; still, the workable ore in many extends to great depths, but is less rich than nearer the surface. Extensive and rich placers are rarely found in the Tertiary belt of veins, for the reason that the fine distribution of the gold is not favorable to its concentration and retention in stream channels. Deposits of this type have been worked in a number of states, including Colorado, Nevada, Arizona, New Mexico, and Idaho.

Colorado formerly led in the production of gold ores, for in no state were the Tertiary deposits of the propylitic type developed on such a scale.

2. *Black Hills Region.*—The ores which are found chiefly in the northern Black Hills, include: (*a*) auriferous schists in pre-Cambrian rocks; (*b*) Cambrian conglomerates; (*c*) refractory siliceous ores; (*d*) high-grade siliceous ores; and (*e*) placers. Of these, the first is now the most important.

The surface placers, being the most easily discovered, were developed first, followed by the conglomerates at the base of the Cambrian.[1] These are found near Lead, occupying depressions in the old schist surface, and the material is thought to have been derived from the reef formed by the Homestake ledge in the Cambrian sea. These deposits are of interest as being probably the oldest gold placers known in the United States. The fact, however, that the matrix of the gold-bearing portion of the conglomerate is pyrite rather than quartz, and the occurrence of the gold along fractures stained by iron has led some to believe that the gold has been precipitated chemically by the action of iron sulphide and is not a detrital product.

3. *Eastern Crystalline Belt* (167).—Gold, with some silver, has been found in the rocks of this belt from Vermont to Alabama, but the deposits are of little importance except in North Carolina (144), South Carolina (155), Georgia (91–94), and Alabama (32), in other words, in the southern Appalachian and Piedmont region; but even in this part of the area the deposits are not found everywhere, but are restricted to three belts (Becker), viz.: (1) the Georgia belt, extending from Montgomery, Ala., across northern Georgia to North Carolina; (2) the South Mountains region of North Carolina; (3) the Carolina belt, lying to the eastward of the others, and extending from South Carolina northeastward through Charlotte, N. C., and continued in Virginia; at least the Virginia deposits lie in part in the line of strike of this zone. This belt is now unimportant.

Geologic Comparisons (18).—It will be seen from the preceding pages that the ores of South Dakota and the Appalachians belong to an older group whose age ranges from pre-Cambrian to Paleozoic, and to which belong also the gold ores of Nova Scotia, Ontario, and Quebec. Here too belong many of the deposits of Brazil and other eastern and northern South American countries. Representatives of this group are known also in other countries, notably Australia.

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[1] These are referred to as cement mines, owing to their partly cemented character.

The other North American occurrences belong to a younger group of late Mesozoic to Quaternary age. Few representatives of this class are found in Canada, but they yield the enormous silver supply of Mexico, and many are known and worked in the Andean region of South America.

Other important occurrences are worked in Hungary, New Zealand, etc.

Pyrometasomatic Deposits

Gold and silver may be present in small amounts in copper deposits of this class, but ore bodies of this type containing the two metals as important constituents are rare.

Such a case has, however, been recorded in the Cable mine in the Philipsburg quadrangle of Montana (102), where the ore body occurs in limestone surrounded by quartz-monzonite. The chief non-metallic minerals are calcite, quartz, barite, and dolomite, with pyrite, chalcopyrite, pyrrhotite, arsenopyrite, magnetite, specularite, and gold as the primary metallic ones. Contact silicates also occur.

Another interesting deposit is that at Spring Hill, Mont.[1]

Of considerably greater importance is the ore deposit of the Nickel Plate Mine at Hedley, British Columbia (94), which is of a rare type. The ore deposits occur at the contact of dikes and sheets of gabbro in Carboniferous limestones which are interbedded with quartzite, shale, and volcanic tuffs. The ore bodies, which are of irregular outline, contain arsenopyrite, with chalcopyrite, pyrrhotite, blende, pyrite, native gold, and tetradymite (Bi_2Te_3). The gangue includes garnet, epidote, diopside, amphibole, quartz, calcite, and axinite. The gold averaged $11.00 per ton.

Other deposits of this group are auriferous tellurides at Elkhorn, Mont., and deposits of argentiferous and auriferous bornite at Chiapas, Mexico.[2]

Hypothermal Deposits

These include deposits, chiefly in the form of fissure veins, precipitated under high-temperature conditions, either in cavities or by replacement. In most of the deposits belonging to this class, gold is more abundant than silver.

United States.—Gold and silver ores of this class are not very abundant in the United States, but include some well-known deposits.

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[1] Jones, Econ. Geol., XXIX: 544, 1934

[2] McCarthy, Inst., Min. and Met., London, Trans. IV: 169, 1895.

Silver Peak, Nev. (139).—The deposits at this locality are so closely associated with igneous rocks that Spurr has classed them as magmatic segregations (Chap. XIII), but some may feel that they might be better put in the deep-vein zone class. The ore occurs in lenticular masses and fissure veins of quartz, which grade into alaskite and this in turn into granite, so that the quartz represents the end-phase of the intrusion. The gold occurs chiefly in the quartz. Paleozoic limestone is the main country rock.

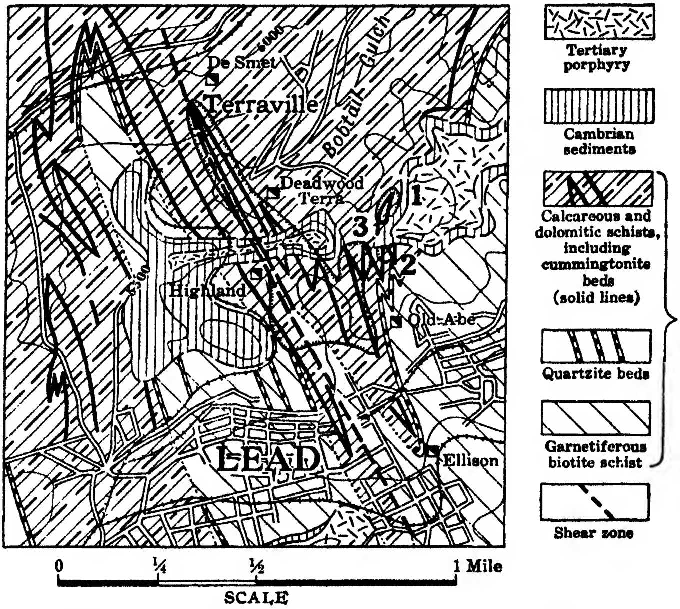

FIG. 214.—Geologic map of vicinity of Lead, S. Dak. (*After Paige, U. S. Geol. Surv., Bull. 765.*)

South Dakota (156–161).—Of the gold mines in the Black Hills area, the Homestake is not only the most important, but is also the greatest one in the United States, having paid $97,062,202 in dividends between 1876 and 1936.

The geology involves a series of pre-Cambrian sediments about 9500 feet thick, which have been intensely metamorphosed and much folded. Their age is given as Algonkian by most writers, although Hosted and Wright (157) class them as Keewatin. Cambrian sediments rest on the upturned and eroded edges of the older rocks. Intruded into both series are dikes and sills of Tertiary (Eocene) rhyolite and phonolite (Fig. 214).

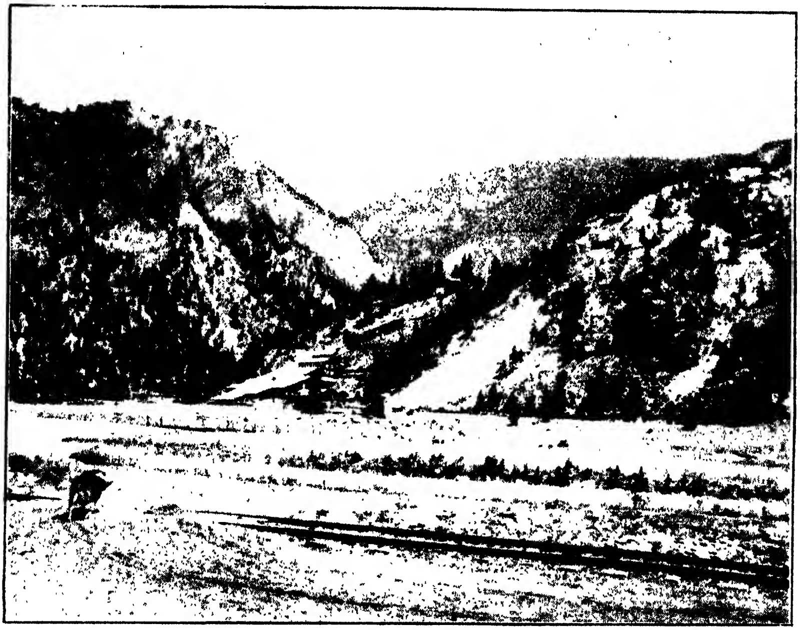

FIG. 1.—Mill of Nickel Plate mine, Hedley, B. C. Mines on ridge in background. (*H. Ries, photo.*)

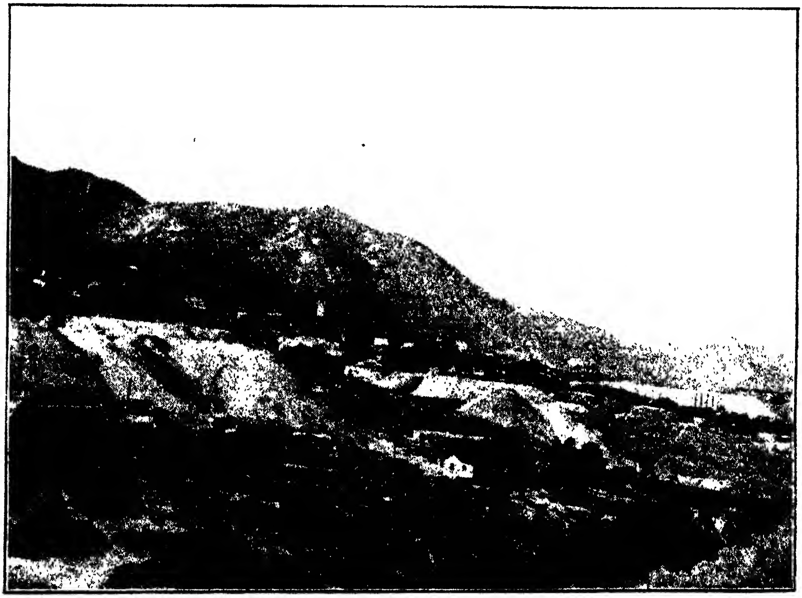

FIG. 2.—Virginia City, Nev., Mt. Davidson in rear, on whose lower slope the Comstock Lode outcrops. (*H. Ries, photo.*)

The ore bodies are the result of replacement of a bed of carbonate rock rich in iron and magnesia, but poor in lime, which bed has been squeezed and thickened as a result of folding. The metallic minerals are native gold with low silver values, arsenopyrite, pyrite, pyrrhotite, magnetite, specularite, chalcopyrite, and blende. The gold seems to favor the pyritic minerals. Non-metallic minerals include cummingtonite, biotite, chlorite, quartz, and calcite, with a little garnet and fluorite.

There seems no doubt that the deposits are of hypothermal origin, and that they may be of pre-Cambrian age, although some claim them to be Tertiary (157). Of interest in this connection is the free gold found in Cambrian conglomerates overlying the pre-Cambrian rocks. Some claim this to be a fossil placer (156), while others assert (157) that it is of Tertiary age, and of hypogene character. The true solution of its origin would have an important bearing on the age of the Homestake mineralization.

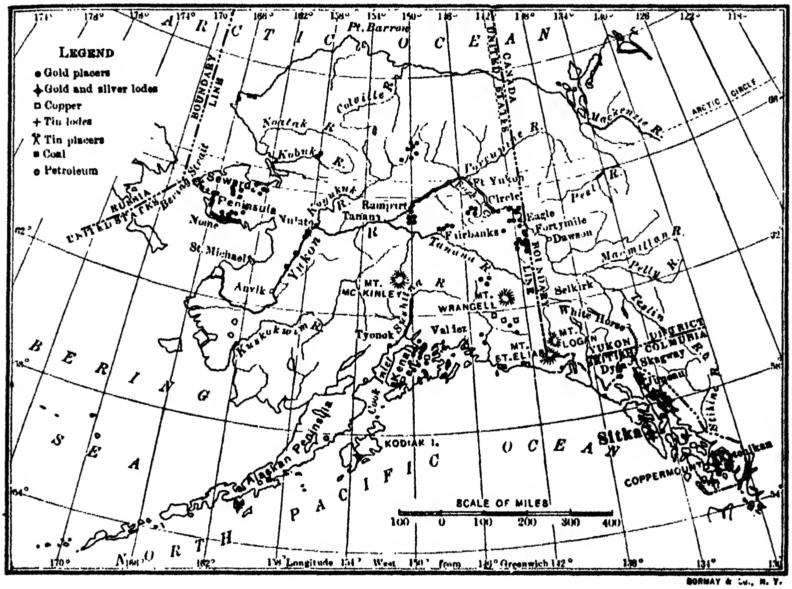

FIG. 215.—Map showing mineral deposits of Alaska. (*After Brooks, U. S. Geol. Surv., Bull.* 250.)

In 1935 the output of this mine was 1,379,163 short tons of ore milled, with $19,191,013 of bullion recovered, the ore value per ton being $13.91. The 1936 output was slightly larger.

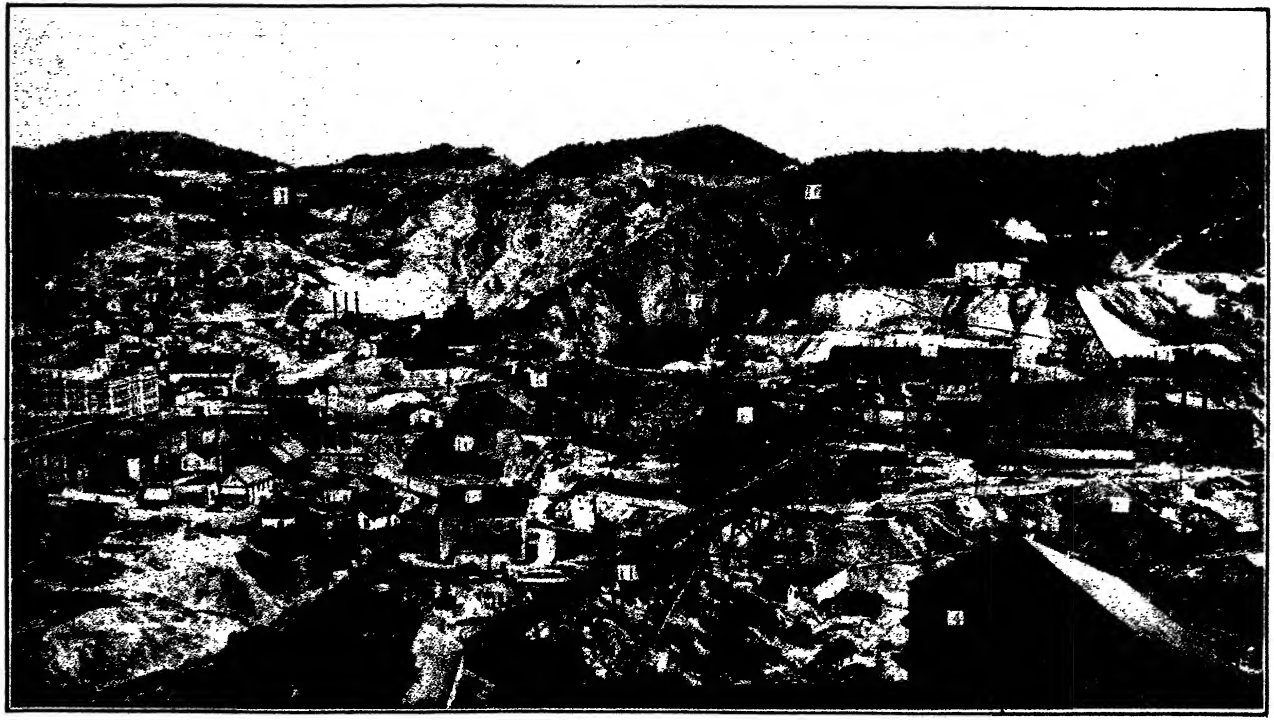

Plate LVI.—Homestake mills, hoists, and open cuts at Lead, S. Dak. (*After O'Hara, S. Dak. Sch. of Mines, Bull.* 6.)

1. Highland hoist and sawmill.
2. Golden Star hoist.
3 Old Abe hoist.
4. Ellison hoist.
5. Homestake mill.
6. Golden Star mill.
7. Amicus mill.
8, 9, 10. Plate houses.
11. Steel bridge.
12. Superintendent's residence.
13. Coal chute.
14. Hotel Smead.
15. Office, Hearst free library, and company store.
16. Old experimental cyanide plant.
17, 18. Open cuts.
19. Wood chute.
20. Shop.
21. Miners' bath and dressing rooms.

Appalachian Belt (167).—The crystalline belt of the southern Appalachians contains numerous quartz veins, some of which are of lenticular character. There may also be replacement deposits in silicified schist. The placers derived from these quartzose ores have yielded considerable gold in the past, notably in Georgia, Virginia, and North Carolina, but the vein mining has been less productive. It is doubtful whether all the veins belong to the deeper-vein zone, some probably having been formed at intermediate depths.

Canada.—A number of gold or gold and silver deposits are known in Canada, but the most important producers are in Ontario.

Porcupine (208, 212, 215).—This is the most important gold-producing district in Canada, having yielded $209,133,079 worth from 1910 to 1927 inclusive, and in 1936 $21,054,860[1] in gold and $80,375 in silver.

The formations of the Porcupine area are all pre-Cambrian. Beginning at the bottom they include: (1) Keewatin dacite and basalt flows; (2) Upper Keewatin (?) rhyolite flows and pyroclastics; (3) Timiskaming conglomerate, graywacke, and slate. These are all extensively folded and in the Porcupine area form a northeast-pitching syncline. Quartz porphyry followed along lines of structural weakness (215). The vein filling followed these, and while most writers have stressed replacement, Hurst believes that cavity filling was most important, and that widening or multiplication of cavities to recurrent stresses accounts for the spread of the veins. Gold was deposited with pyrite in the wall rock, but most of it is in the quartz veins. Among the associated minerals in addition to the above are pyrrhotite, scheelite, galena, tellurides, tourmaline, albite, ankerite, calcite, and chlorite.

Some of the shafts have reached a depth of 4000 feet.

Kirkland Lake (210, 220).—This is the second largest gold producer in Canada, having produced $19,933,074[2] worth of gold in 1936, and nearly $90,782 worth of silver. The initial production dates back to 1913.

The bed rocks are all of pre-Cambrian age, and include the following formations:

Algoman, consisting of diabase and lamprophyre dikes, syenite, porphyry, red syenite, and basic syenite.

Timiskamian, conglomerate, greywacke, volcanic tuffs and flows.

Keewatin, with pillow lava, diabase, green schists, rusty carbonate, iron formation, and tuff.

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[1] Calculated at $20 per ounce.

[2] Gold figured at $20 per ounce.

Only the first two of these are of importance in connection with the ore.

The ores occur in fracture zones, due to faulting, especially in porphyry and syenite, and also in conglomerates. There are three principal zones of mineralization, of which the central one, which has been traced over 2 miles, has a width of half a mile. The veins consist of sheared and brecciated rocks cemented by quartz, and partially replaced by it together with carbonates, sericite, and chlorite. Native gold accompanied by tellurides and sulphides occurs in streaks and small fractures.

The ore solutions are supposed to have come from a deep-seated Algoman intrusive, represented on the surface by small syenite masses. It is probable that the ore is mesothermal, but some place it rather deep in that zone.

Other gold quartz veins are known in the Lake of the Woods (18) and Rainy Lake district (211), Lakes Abitibi (210) and Larder Lake (213).

The deposits at Rossland, B. C., described under copper, have also yielded considerable gold.[1]

Other Foreign Deposits.—*West Australia*[2] contains several gold mining districts, that of Kalgoorlie being the most important, the others including Pilbarra, Murchison, and Mount Margaret. The rocks are chiefly crystalline schists derived from igneous rocks and granites together with altered sedimentaries, but the gold deposits are found chiefly in the schists. Two types are recognized, viz.: (1) quartz veins in amphibolite, or at its contact with granite, and (2) lodes, formed by ore deposition along shear zones. The first class carries native gold, galena, blende, pyrrhotite, chalcopyrite, arsenopyrite, stibnite, bismuthinite, pyrite, scheelite, chlorite, calcite, sericite, and sometimes tourmaline; the latter has native gold, tellurides, pyrite, chalcopyrite, blende, galena, pyrargyrite, magnetite, siderite, ankerite, sericite, tourmaline, albite, etc. The wall rock bordering the lodes has been noticeably altered.

Brazil contains several deep gold mines in the province of Minas Geraes, of which the Morro Velho is not only the most important, but also the deepest in the world, having reached a vertical depth of 8000 feet.[3] The ore deposits are quartz veins in Archaean schists, gneisses, and granites, or in sedimentary schists and quartzites.

India.—The pre-Cambrian veins in crystalline schists of the Kolar gold fields in Mysore, India, also belong in this group.[4]

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[1] For other Canadian localities see references at end of chapter.

[2] Bulletin of West Austral. Geol. Surv., especially Nos. 6, 14, 15, 20, 22, 23, 45, 46, 51, 56, also Lindgren, Econ. Geol., I: 530, 1905; Maclaren and Thomson, Min. and Sci. Pr., CVII: 45, 1913; Larcombe, *Ibid.*, CXI: 238, 1915.

[3] Harder and Leith, Jour. Geol., XXIII: 341 and 385, 1915; also Lindgren, Amer. Inst. Min. Engrs., Bull. 112: 721, 1916.

[4] Hatch, Geol. Surv., Ind., Mem. 33, 1901.

Mesothermal Deposits

This group includes a number of auriferous quartz veins, carrying free gold, pyrite, and even other sulphides, but lacking the silicates characteristic of the deep-vein zone. The quartz veins do not, as a rule, show a high silver content. Alteration of the wall rocks sometimes occurs, resulting in the development of sericite, carbonates, and pyrite.

United States.—*California. Mother Lode Belt* (57, 65).—This includes a great series of quartz veins, beginning in Mariposa County and extending northward for a distance of 112 miles. The veins of this system break through black, steeply dipping slates and altered volcanic rocks of Carboniferous and Jurassic age (Fig. 216), and since they are often found at a considerable distance from the granitic rocks of the Sierra Nevada, they have apparently no genetic relation with them. The veins, which occur either in the slate itself or at its contact

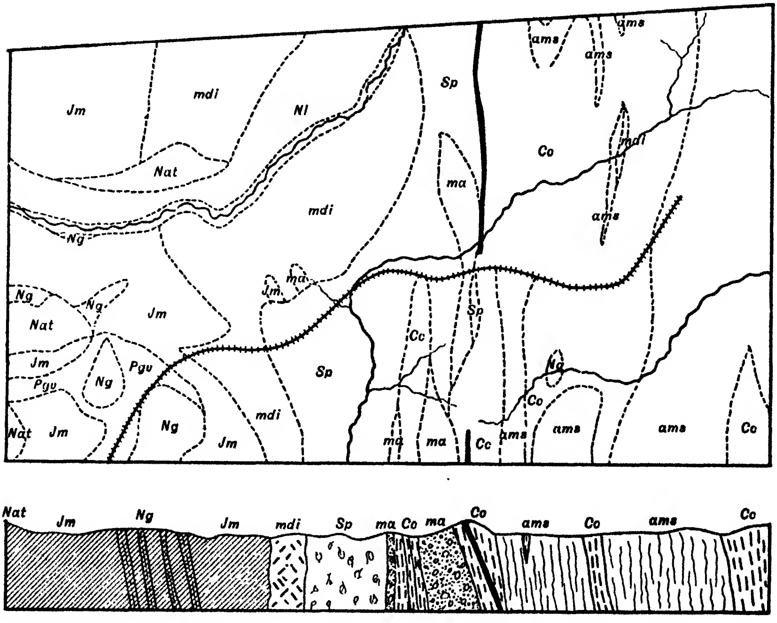

FIG. 216.—Map and section of portion of Mother Lode district, Calif. *Pgv*, river gravels, usually auriferous; *Ng*, auriferous river gravels. Sedimentary rocks: *Jm*, mariposa formation (clay, slate, sandstone, and conglomerate); *Cc*, calaveras formation (slaty mica schists). Igneous rocks: *Nl*, latite; *Nat*, andesite tuffs, breccia, and conglomerate; *mdi*, meta-diorite; *Sp*, serpentine; *ma*, meta-andesite; *ams*, amphibole schist. (*From U. S. Geol. Surv., Atlas Folio, Mother Lode sheet.*)

PLATE LVII

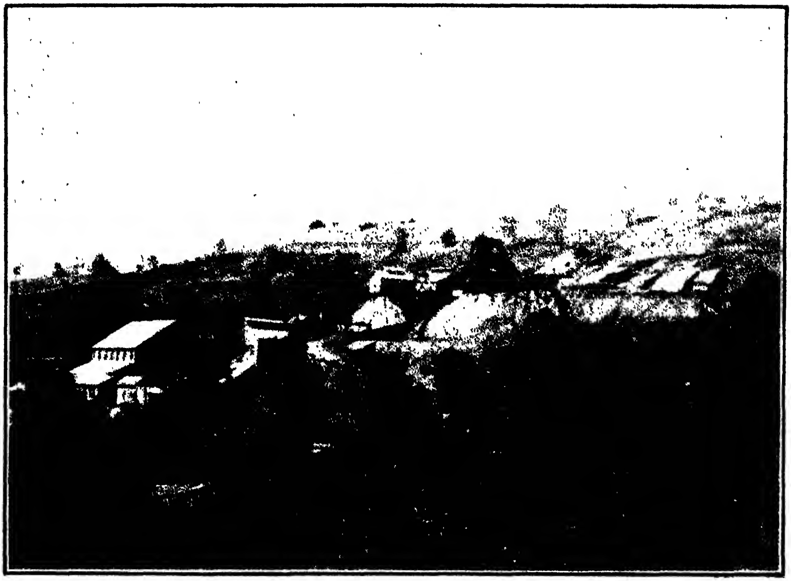

FIG. 1.—Kennedy mine on the Mother Lode, near Jackson, Calif.

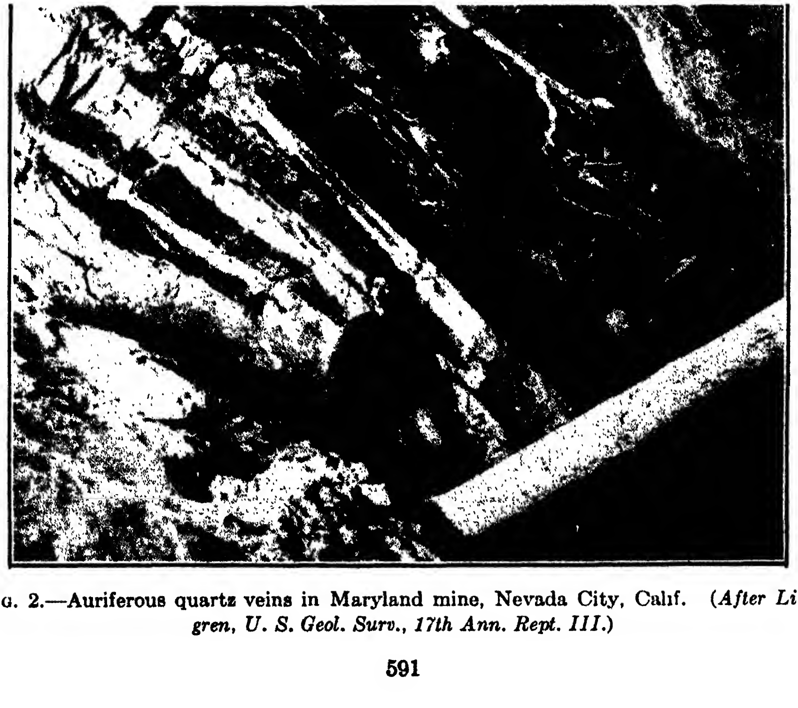

FIG. 2.—Auriferous quartz veins in Maryland mine, Nevada City, Calif. (*After Lindgren, U. S. Geol. Surv., 17th Ann. Rept. III.*)

with diabase dikes, show a remarkable extent and uniformity, due to the fact that in the tilted layers of the slates there were planes of weakness for the mineral-bearing solution to follow. The ore is native gold or auriferous pyrite in a gangue of quartz, and the average value may be said to vary from $3 to $4 up to $10 per ton. The veins often split and some of the mines have reached a depth of several thousand feet. At the southern end of the belt the gold occurs more frequently in the wall rock adjoining the quartz veins.

Nevada County (62).—In Nevada County the mines of Grass Valley and Nevada City are likewise quartz veins (Pl. LVII, Fig. 2) but they occur along the contact between a granodiorite and diabase porphyry, as well as cutting across the igneous rock (Fig. 217). Two systems of fault fissures occur, and in these the ore is found either in native form or associated with metallic sulphides. The width of the vein averages from 2 to 3 feet, and the lode ore generally occurs in well-defined bodies or pay shoots. The vein filling was deposited by hot solutions, and while the wall rocks contain the rare metals in a disseminated condition, Lindgren (62) believes that the ores have been leached out of the rocks at a considerable depth. Later studies by Howe indicate that the veins were formed by replacement of the wall rock by quartz, calcite, and metallic sulphides, and that after later fracturing of the vein filling, solutions entered depositing gold (59).

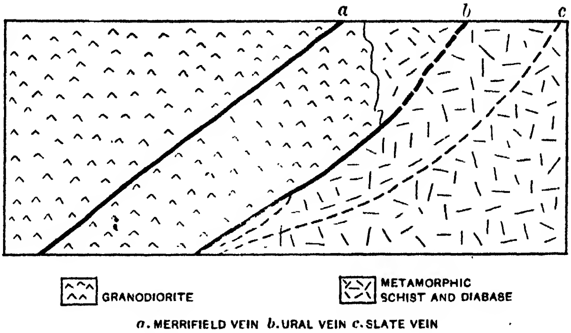

FIG. 217.—Section illustrating relations of auriferous quartz veins at Nevada City, Calif. (*After Lindgren, U. S. Geol. Surv., 17th Ann. Rept., II.*)

In Oregon, the quartz veins are worked in Baker County, which is the most important gold-producing region of the state (152, 153). Gold ores with sulphides in quartz gangue are worked in the Monte Cristo district of Washington (180).

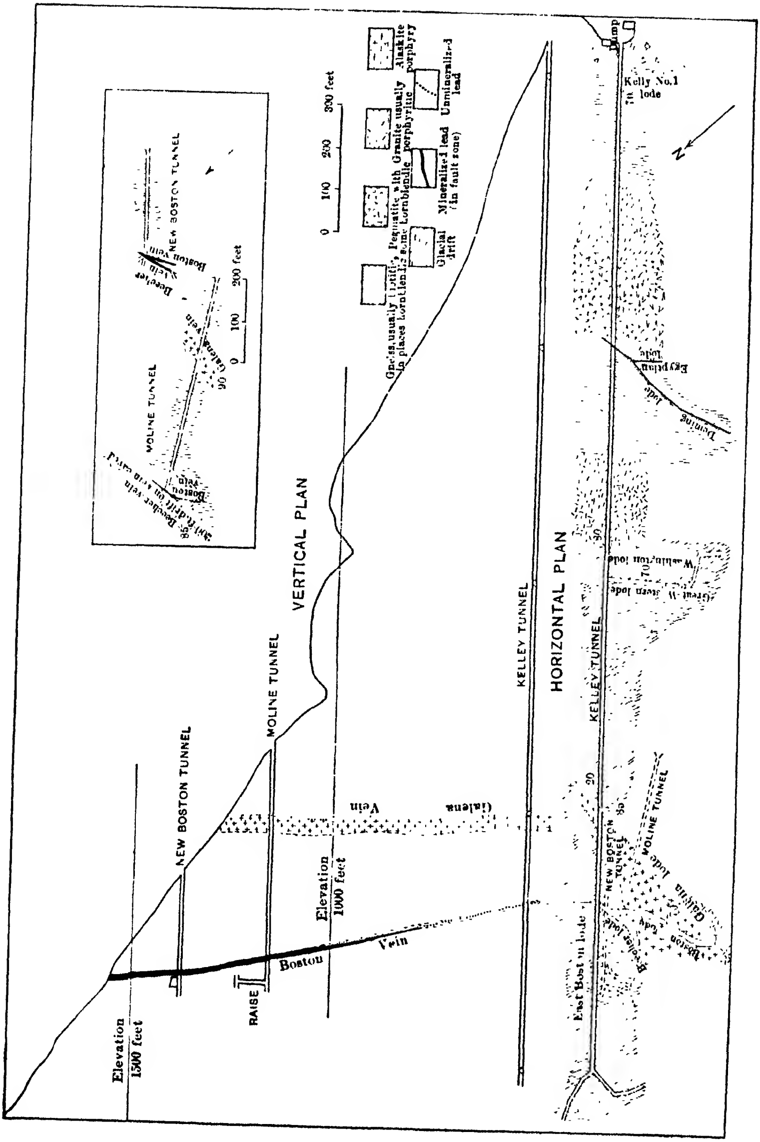

FIG. 218.—Vertical and horizontal plan of Kelly tunnel and associated mine workings, Georgetown, Colo., district. (*After Spurr, U. S. Geol. Surv., Prof. Pap.* 63.)

South Dakota. Siliceous Cambrian Ores (156, 158).—The refractory siliceous Cambrian ore is found in the region between Yellow Creek and Squaw Creek, and formerly yielded about two-thirds as much gold as the Homestake. The deposits, which occur as replacements in a siliceous dolomite (Fig. 220), are found at two horizons, one immediately overlying the basal Cambrian quartzite, and the other near the top of the Cambrian series. The ore forms flat banded masses known as shoots, and varying in width from a few inches to

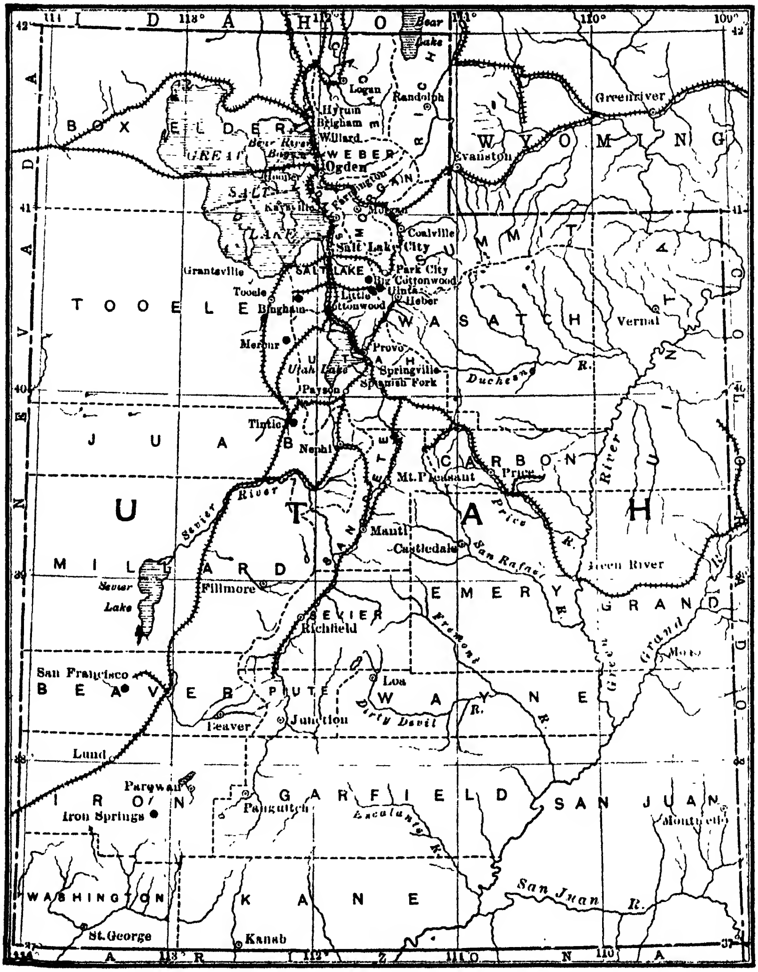

FIG. 219.—Map of Utah, showing location of more important mining districts.

300 feet. It is overlain by shale or eruptive rock, and associated with a series of vertical fractures, made prominent by a slight silicification of the wall rock. These fractures, which are termed *verticals*, are supposed to have conducted the ore-bearing solutions.

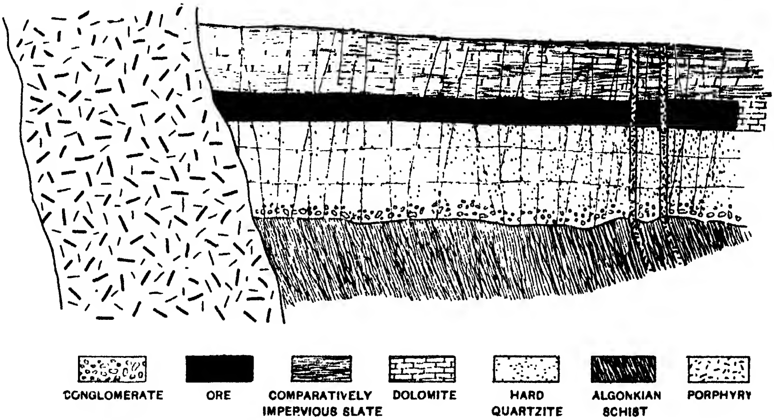

FIG. 220.—Typical section of siliceous gold ores, Black Hills, S. Dak. (*After Irving, U. S. Geol. Surv., Prof. Pap.* 26.)

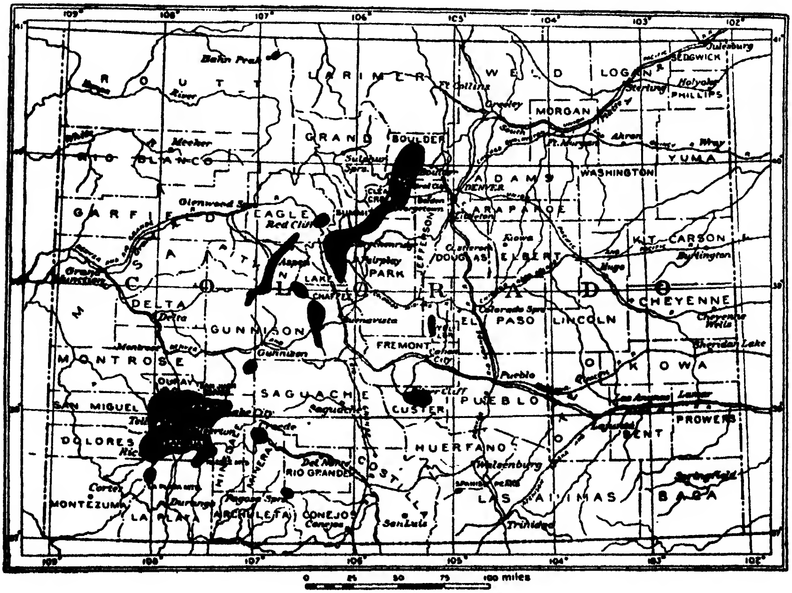

FIG. 221.—Map showing approximate distribution of the principal silver, lead and gold regions of Colorado. (*After Spurr.*)

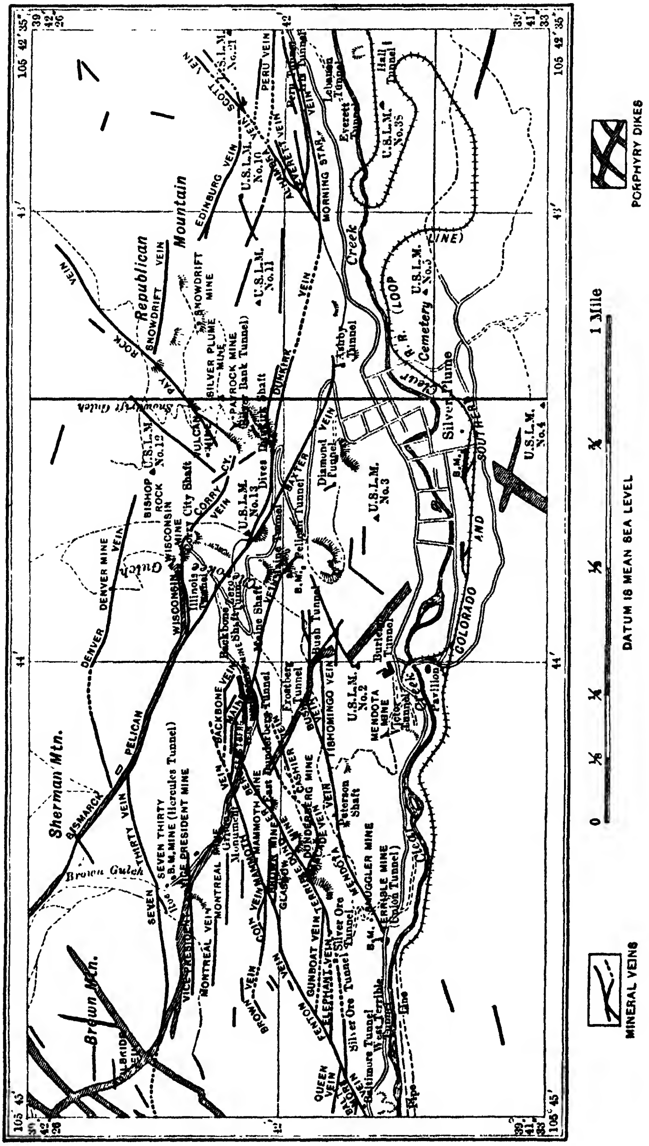

FIG. 222.—Map showing veins and porphyry dikes in the Silver Plume, Colo., region. (*After Spurr, U. S. Geol. Surv. Prof. Pap.* 63.)

The ore is a hard, brittle rock, composed of secondary silica, with pyrite and fluorite, and at times barite, wolframite, stibnite, and jarosite.

Georgetown, Colo. (89).—Clear Creek County (Fig. 221), in which

Georgetown lies, is, next to Gilpin County, the oldest mining district in Colorado, if not the entire Rocky Mountain region.

There are a number of mining camps in this area, including Georgetown, Idaho Springs, Silver Plume, Central City, etc., but the only area which has been described in detail is that included in the Georgetown quadrangle. The conditions here, however, are in a general way similar to those existing in other parts of the district.

The earliest rocks of the district consist of a series of pre-Cambrian schists, the oldest ones (Idaho Springs formation) being probably of sedimentary origin, but the later ones metamorphosed igneous rocks.

This series has been successively injected by about eight types of plutonic rocks ranging from granites to diorites.

Following these, in late Cretaceous or early Tertiary, came the intrusion of a series of porphyry dikes which are as varied in their composition as the plutonics. These porphyries are of more than local interest because they form part of a wide irregular zone that extends in a general northeast-southwest direction from Boulder to Leadville and then on to the San Juan region (Fig. 221). It will thus be seen that many important mining districts lie within it.

The ore-bearing fissure veins (Fig. 218), which may occur in any of the older schistose rocks of the district, are divisible into two groups, viz., argentiferous blende-galena ones with little gold, and auriferous pyrite veins with or without silver. The former predominate in the Georgetown region, the latter southwest of Idaho Springs, but the two types of ore are occasionally known to occur in the same vein. Both types of veins are seen to show a general agreement in trend and distribution with the porphyry dikes (Fig. 222), and the vein formation is thought by Spurr not only to have followed the porphyry intrusions, but to show characteristic petrographic associations. That is, the silver-galena-blende veins are related to dikes of alaskite porphyry, granite porphyry, quartz-monzonite porphyry, and dacite; the auriferous pyrite veins with bostonite, alaskite, quartz monzonite, biotite latite, and alkali syenite.

The two classes of veins show the same primary minerals (galena, blende, and pyrite), but the proportions of them in each differ, and they have the same bonanzas, wall rocks, and gangue minerals (mainly quartz).

It is suggested by Spurr that the alteration of the wall rocks was caused by descending atmospheric waters, changing them to mixtures of quartz, sericite, carbonates, and kaolin, and the gangue minerals have, moreover, come from the walls; but while the source of the metals in the silver veins is in doubt, Spurr considers that the metalliferous minerals of the gold veins were contributed by magmatic waters.

Crosby has questioned whether the gold and silver veins represent distinct classes, and points out that since the former outcrop at low levels, they may simply represent the basal portions of silver veins, these being known to outcrop only at the higher points in the district.

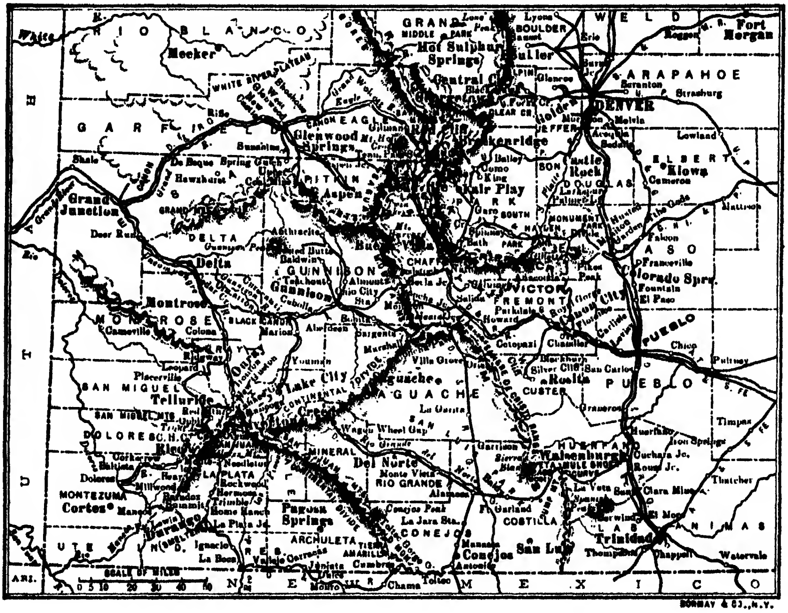

FIG. 223.—Map of Colorado, showing location of mining regions. (*After Rickard, Amer. Inst. Min. Engrs. Trans.*, 1904.)

Gilpin County (66).—The rock formations are somewhat similar to those of the Georgetown quadrangle, as are also the gold-silver ore veins, which are grouped by Bastin and Hill as: (1) pyritic ores; (2) galena-sphalerite ores; and (3) composite ores, carrying the minerals of both the other classes, and being the result of dual mineralization. Most of the veins occupy zones of minor faulting, the ore deposition having been partly by filling and partly by replacement.

Alaska.—Gold was first discovered in 1849 on Kenai Peninsula by the Russians at the time they were in possession of the Territory. The estimated value of the production was $20,000 in 1880; since that time it has increased many times over until it reached a maximum of $22,036,794 in 1906, dropped to $5,927,000 in 1927, but in 1936 had reached $18,433,000.[1] In 1936 38½ per cent of the gold production in Alaska came from lodes, and 61½ per cent from placers. The total gold production of Alaska, up to 1935, has been $450,681,000, many times the $7,200,000 purchase price of the territory from Russia.

Silver having a total value of $12,423,937[2] has been produced up to 1935. At present none of the Alaskan mines are worked exclusively for the silver content of their ores. Of the total silver production, $8,865,260 has come from copper lodes, $2,242,676 from gold lodes, and $1,316,001 from gold placers.

Auriferous Lodes.—Gold-quartz veins were first discovered near Sitka in 1879, but the first important production came from the Treadwell mine on Douglas Island southwest of Juneau in 1882. In 1934, $4,877,000 or 70 per cent of the lode gold production of Alaska came from this district in southeastern Alaska, and by far the greater part of this came from the Alaska Juneau mine at Juneau, which has been called the lowest-grade gold mine in the world. In 1934, an average of 11,790 tons of ore was mined daily, having an average gold content of 83 cents a ton. The geology of this district bears a strong resemblance to the Mother Lode district of California. At the Alaska Juneau mine, the gold-quartz bodies occur in broad zones, as irregular and disconnected groups of small veins in steeply dipping slate, schist, and greenstone. Wernecke[3] believes that the quartz is from a magmatic source, and that the veins were formed by repeated openings of the wall rock. Gold and sulfides, also from a magmatic source, were deposited near the close of the period of quartz deposition. The veins are mesothermal, and a vertical range of over 2000 feet has been proved.

The Willow Creek district in south-central Alaska produced $1,301,000 of gold in 1934. The gold-quartz veins are similar to those of the Grass Valley district in California, as they are of mesothermal origin and occur in granodiorite.

Lode gold is produced from a number of other districts. In most of these the gold occurs with quartz in fissure veins and is of mesothermal origin. Secondary enrichment is found in only a few places in the unglaciated area of the Yukon River basin.

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[1] Gold at $35 per ounce since and including 1934.

[2] Production figures from U. S. Geol. Surv., Bull. 880, 1936.

[3] Engineering and Mining Journal, Vol. 133, No. 9, Sept. 1932.

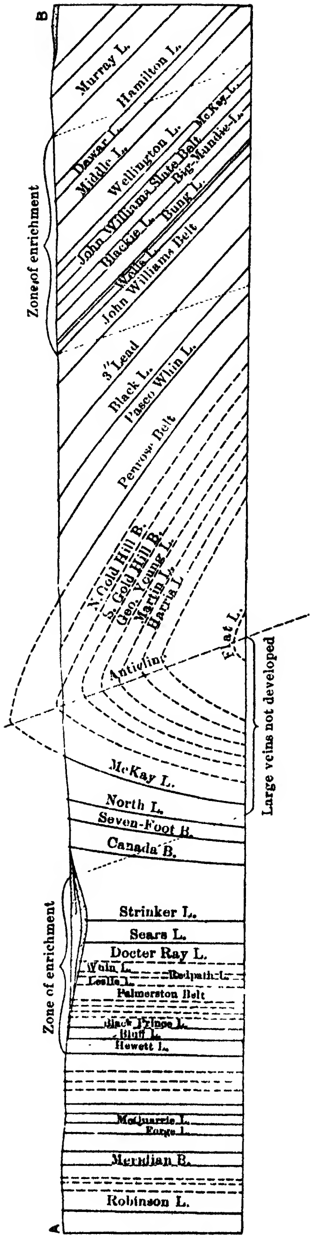

FIG. 224.—Section across the Goldenville district, Nova Scotia. (*After Malcolm, Can. Geol. Surv., Mem. 20-E.*)

Canada. *Nova Scotia* (201, 202).—The gold veins of this province, which form a belt along the south coast, occur in folded Cambrian (?) slates and quartzites which have been intruded by Silurian (?) granites. The veins, which are often saddle-shaped, are usually found along the axes of plunging anticlines, and most of them are paralled to the stratification. Some show a strong crenulation supposed to be of post-mineral character, and small veins often pass outward from the main ones. The ore mineral is native gold, in quartz gangue, and associated with pyrite, chalcopyrite, galena, blende, and arsenopyrite. While the ore is supposed to be due to cavity filling, Faribault believes that the veins are older than the granite, but Rickard holds that they are later.

Cobalt.—This famous silver district is described under Cobalt.

Great Bear Lake.—On the east shore of Great Bear Lake[1] there is a series of veins carrying uraninite, cobalt and nickel arsenides, chalcopyrite, native silver, and bismuth in a gangue of quartz and rhodochrosite. The country rock is pre-Cambrian sediments. The ores are refined at Port Hope, Ontario. During 1934, twenty-six tons of ore were treated with the recovery of radium, uranium, silver, and lead valued at $210,000.

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[1] Kidd, Econ. Geol. XXVII: 145, 1932; Thomson, Univ. Toronto Stud., Geol. Serv., No. 32, 1932.

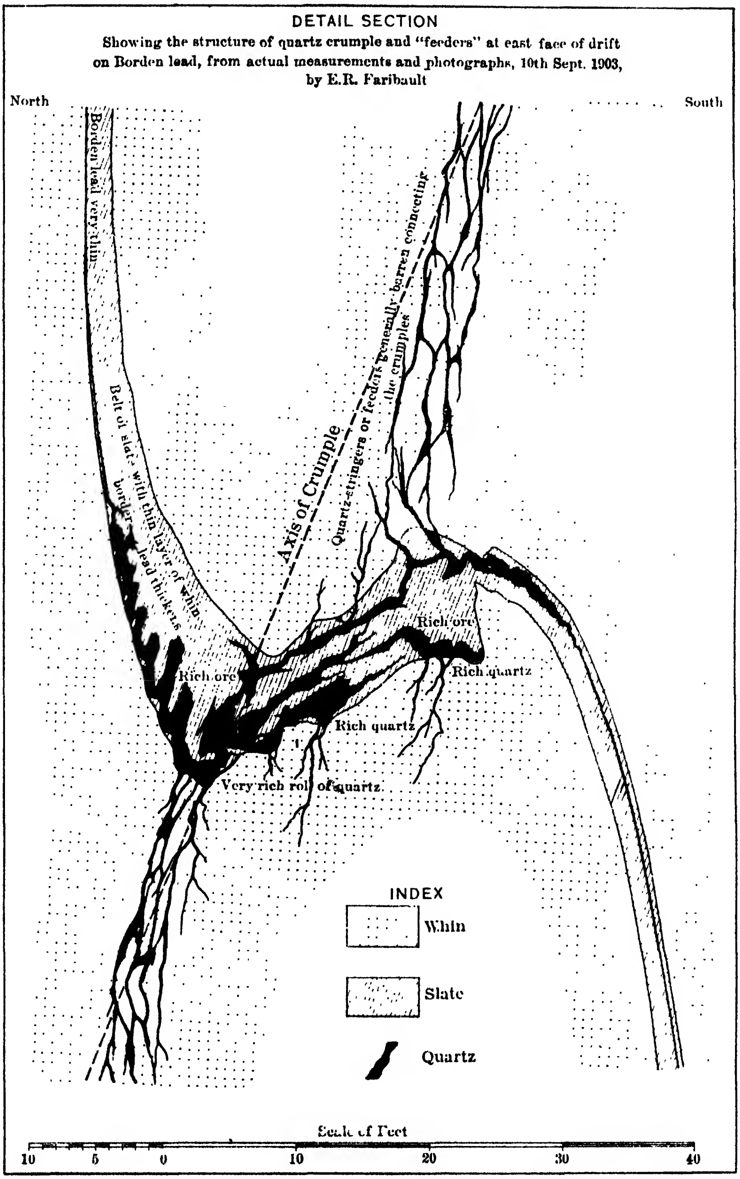

Fig. 225.—Transverse section of a part of West Lake Mine, Mount Uniake, N. S. (*After Malcolm, Can. Geol. Surv., Mem.* 20-E.)

Other Foreign Deposits.—*Victoria.*[1] This colony contains two well-known gold districts, viz., those of Bendigo and Ballarat. In both we find strongly folded Ordovician slates and sandstones cut by a batholith of granite or quartz monzonite. At Bendigo especially the ore bodies show saddles along the axes of anticlines, there being not only several lines of these saddles, but in each line a number, one below the other. Other irregular veins occur. The ore is gold-bearing quartz, with associated pyrite and arsenopyrite, and some albite. These reefs, as they are called, have been worked to a depth of 4500 feet, but are much richer in the first 2500 feet.

At Ballarat, the gold-quartz veins show more irregularity of form, and the rich ore often appears to be at the contact of flat bodies of quartz with thin veins of pyrite, or carbonaceous seams in the slate, both known as "indicators."

Other important Australian districts are those of Charter Towers, Queensland, and Hill End, New South Wales.

Queensland.—The ore body at Mount Morgan, Queensland,[2] is to be classed as one of the interesting occurrences of the world. Worked for many years as a gold deposit, it later showed signs of changing to copper. Below a rich gossan of limonite and manganese carrying free gold, there is a mass of porous, crumbly, siliceous rock, carrying gold and some silver, which is in the oxidized zone. This at depths of 200 to 300 feet grades into a mixture of pyrite and chalcopyrite, carrying gold. While several theories of origin have been advanced, it can probably be regarded as a replacement, and is provisionally placed in the intermediate group.

Epithermal Deposits

These include a great number of gold and silver deposits, in which the two metals mentioned are present in varying proportions, and always associated with Tertiary volcanics. The group corresponds to the young gold-silver group of Vogt, Krusch, and Beyschlag.[3]

The wall rocks may show propylitization, silicification, or, in rarer cases, alunitization. Sericitization is also noted. Quartz is the commonest gangue mineral, but carbonates of lime, iron, or manganese, as well as adularia, are noticed. The gold may be native or combined with tellurium; the silver is usually present as sulphides, sulpharsenides, or sulphantimonides.

United States.—As stated before, the ores of this group were formerly of great importance in the western United States.

Goldfield, Nev. (133, 134).—Goldfield lies near the eastern border of Esmeralda County (Fig. 211), on the southern rim of one of the

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[1] Rickard, A. I. M. E., Trans., XX: 463; Lindgren, E. and M. J., Mar. 9, 1905; Vogt. Krusch und Beyschlag, Lagerstätten, II: 107; Stillwell, Econ. Geol., XIII: 100.

[2] Rickard, Amer. Inst. Min. Engrs., XX: 133, 1891; Vogt, Krusch und Beyschlag, Lagerstätten, II: 134, 1912.

[3] Lagerstätten, II: 12, 1912.

typical desert basins of the region which connects, through a low pass on the north, with a still larger basin west of Tonopah.

The geologic structure (Fig. 226) of the district is quite simple, consisting essentially of a low dome-like uplift of Tertiary lavas and lake sediments, resting on a foundation of ancient granitic and metamorphic rocks.

The kind of rocks in this district, their age, and relationships are shown in the map and section given by Ransome (Figs. 227, 228). The oldest or Cambrian beds were intruded by alaskite at about the close of Jurassic time, and there then followed a long interval of erosion before the eruption of the Tertiary lavas. It will be seen from the section that the same type of rock was in some cases erupted more than once.

The ores of this district, which are of somewhat complex character, consist of native gold and pyrite accompanied by minerals containing copper, silver, antimony, arsenic, bismuth, tellurium, and other elements.

The free gold occurs in some of the ores, in fine particles closely crowded together and forming bands or blotches in the flinty gangue, and is not likely to be recognized as such until examined with a lens. The common associated minerals are pyrite, marcasite, bismuthinite, and famatinite (?). At times the rich ore shows a curious concentric crustification, consisting of fragments of silicified, alunitized, and pyritized rock, covered with shells of gold and sulphides.

The ore bodies, which were noted for their remarkable richness and irregularity (Fig. 229), are closely related to fissures, usually of irregular trend, but not representing fault planes.

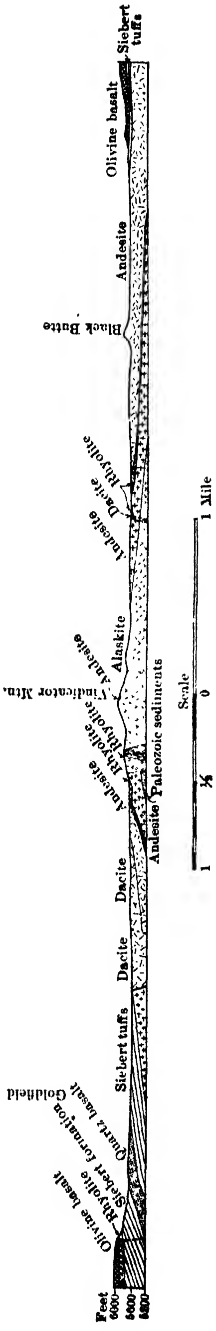

Fig. 226.—Geologic section across the Goldfield district. (*After Ransome.*)

The deposits (Fig. 229) are defined as irregular masses of altered and mineralized rock, traversed by multitudes of small irregular, intersecting fractures, such fracturing passing in many places into brecciation.

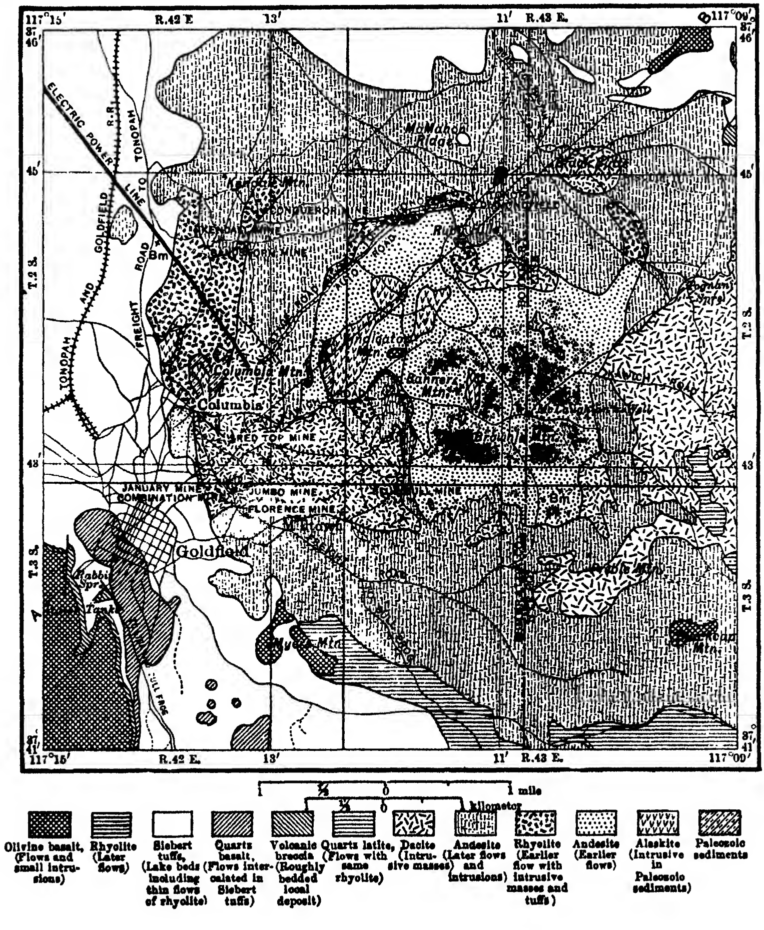

FIG. 227.—Geologic, Map of Goldfield, Nev., district. (*After Ransome, Econ. Geol.*)

These irregular masses are termed ledges (Fig. 230), and within them occur the actual ore bodies or pay shoots. Capping these ledges of soft rock are craggy outcrops (Pl. LVIII, Fig. 2) of silicified and alunitic material which stand out in relief on the surface because more resistant than the surrounding rocks. The ores are almost invariably associated with these, but every siliceous knob is not underlain by ore.

The most important ore bodies are found in dacite, but some small although rich ones are known in the Milltown andesite (Fig. 228).

The alteration of the rock adjoining the fissures is of three types. Where it is most intense the rock has been changed to porous, fine-grained aggregates consisting essentially of quartz. A second type is the change to a soft, light-colored mass of quartz; while a third, which is of propylitic character, consists in the development of calcite, quartz, chlorite, epidote, and gypsum.

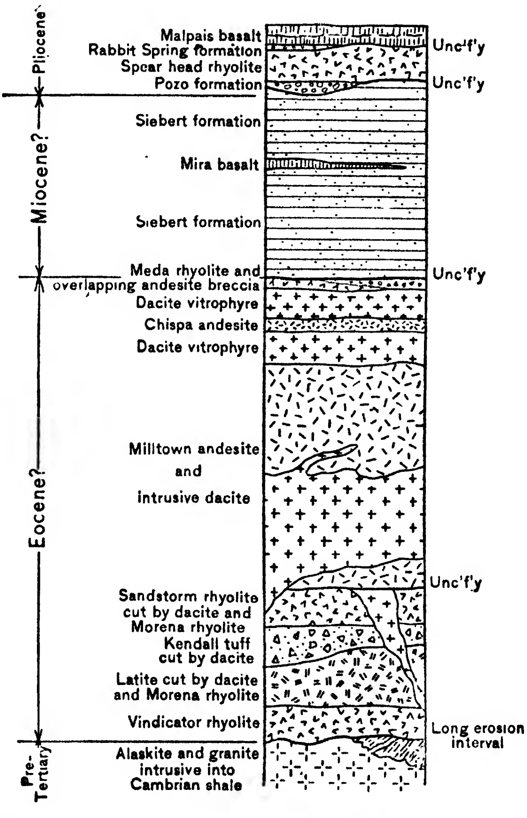

FIG. 228.—Generalized columnar section of geological formations at Goldfield, Nev. (*After Ransome, U. S. Geol. Surv., Prof. Pap.* 66.)

Most of the ore produced during the first two or three years of the camp was oxidized in character, but later some of the mines were working in sulphides.

Origin.—Ransome's theory is that after the dacite had solidified,

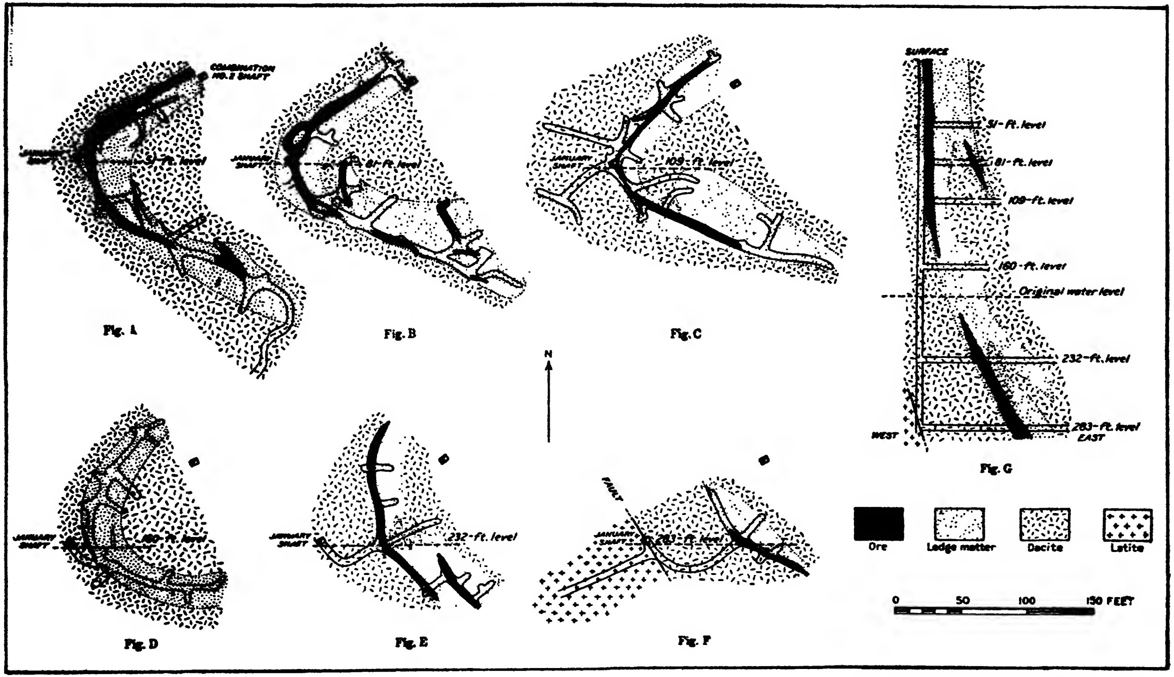

FIG. 229.—Plans of the principal levels of the January mine, Goldfield, Nev., with a diagrammatic section, showing relation of ore, ledge matter, and country rock. (*After Ransome, U. S. Geol., Prof. Surv., Pap.* 66.)

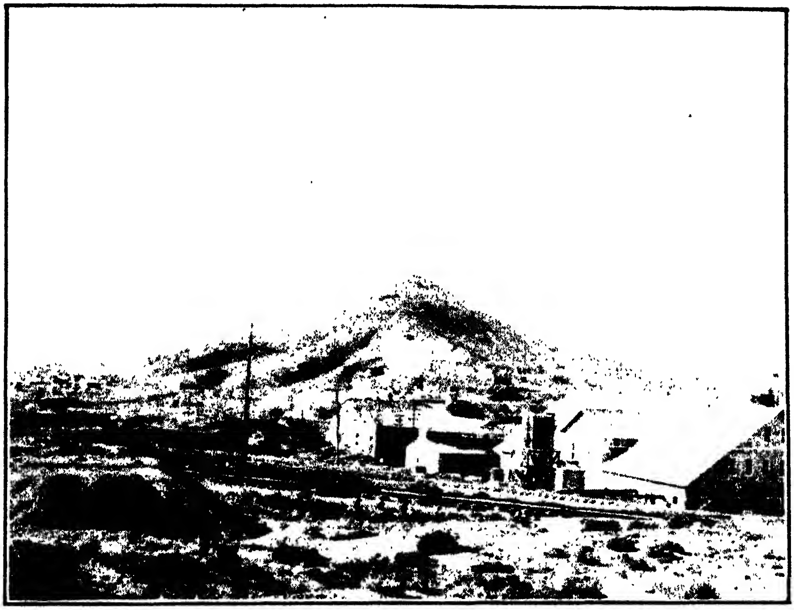

FIG. 1.—Columbia Mountain, Goldfield, Nev., from the south. (*H. Ries, photo.*)

FIG. 2.—Ledge outcrop in dacite between the Blue Bell and Commonwealth mines, Goldfield, Nev. The conspicuous white dump is alunitic material. The rough knob on sky line near right side of view is Barner Mountain. (*After Ransome, U. S. Geol. Surv., Prof. Pap.* 66.)

but not perhaps entirely cooled, the subjection of the rocks to stresses of unknown origin developed a complicated system of fractures.

Hot waters carrying hydrogen sulphide with some carbon dioxide and the metallic constituents of the ores rose along these fissures; oxidation of a part of the hydrogen sulphide to sulphuric acid occurred in the upper parts of the fissure zones or at the surface.

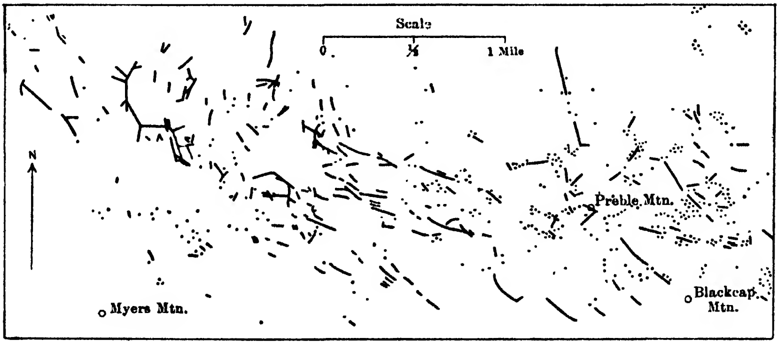

FIG 230.—Map showing outcrops of siliceous ledges east of Goldfield, Nev. (*After Ransome, U. S. Geol. Surv., Prof. Pap.* 66.)

These acid solutions then percolated downward through the shattered rocks, changing their feldspars to alunite, mingled with the rising solutions, and precipitated most of their metallic load as ore, but the original solutions were not everywhere rich in metals.

Following this the ledges were fractured, and a second stage of mineralization occurred, during which further deposition of ore and in some cases repeated precipitation followed more fracturing.

The ledges are thought to have been formed during the first stage of deposition, and the softening and alunitization of the rock, as well as the propylitization, are believed to have occurred at the same time. Some good ore was also deposited then.

From the year 1904 to the end of 1922 the Goldfield district produced $82,771,626 in gold, 1,350,782 ounces of silver, and 1,558,245 pounds of copper. The maximum total production of about $11,000,000 was reached in 1910, since which time it has dropped off very considerably. The bulk of the ore is cyanided.

Tonopah, Nev. (114, 116, 137).—This district, which was opened up in 1900, grew steadily in production so that its maximum yield in 1913 was about $9,500,000.[1] Tonopah (Pl. LIX, Fig. 2) lies in the

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[1] In 1926 it was $454,076.

arid desert region of Nevada, and the rocks consist according to Spurr of a somewhat complex series of flows and intrusives as follows:

8. Basalts and rhyolites.
7. Siebert tuffs.
6. Rhyolitic flows.
5. Midway andesite flow.
4. West end rhyolite, intrusive just above 3.

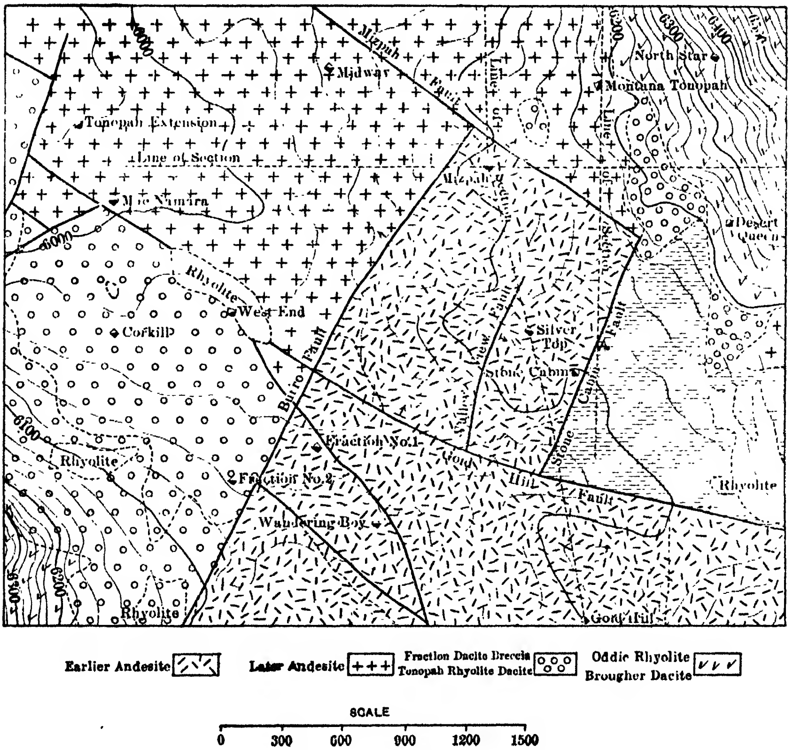

Fig. 231.—Geologic surface map of the producing area of Tonopah. (*After Burgess, Econ. Geol., IV*: 683, 1909.)

3. Montana breccia, a trachy-alaskite intrusion, just above 2.
2. Andesite intrusion between 1*a* and 1*b*.
1. Trachyte consisting of: *a*, an upper part, and *b*, a lower flow-banded glassy part.

Burgess (117) differs with Spurr in considering that they are all surface flows.

The veins belong to three sets or periods as follows: (1) the chief

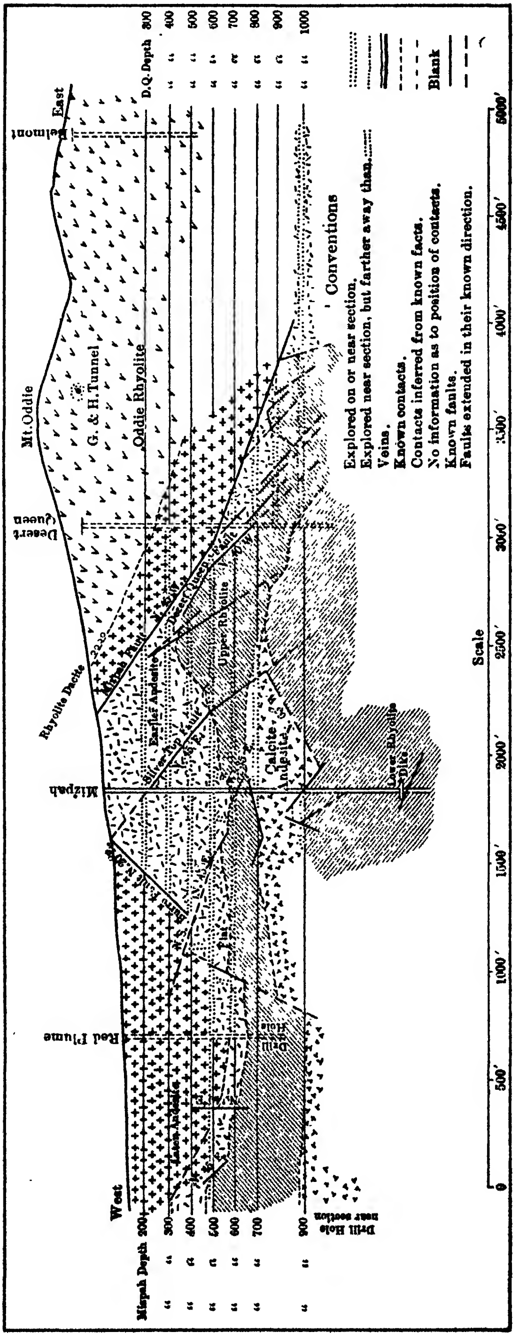

FIG. 232.—East-west section through Mizpah shaft, Tonopah. (*After Burgess, Econ. Geol. IV*: 684, 1909.)

set, formed after the lower trachyte, and before the andesite intrusion, carrying quartz, gold and silver; (2) formed after the West end rhyolite and before the Midway andesite, and including four subgroups, viz., *a*, large typically barren quartz veins; *b*, tungsten-bearing veins; *c*, barren, mixed quartz and adularia veins; *d*, productive veins like those of set 1; (3) formed after the Tonopah rhyolite, and carrying quartz with occasional lead, zinc and copper sulphides.

The rocks are complexly faulted, and the movement has occurred at different periods. The primary ore consists of finely divided native gold, argentite, and polybasite in a gangue of quartz and adularia. In the oxidized ore, which may extend to over 700 feet, cerargyrite, embolite, and iodyrite are found.

The district is now being worked by leasers, and in 1935 owing to increased price of gold the number increased, resulting in an output of about $451,000 gold and silver.

Comstock Lode, Nevada (115).—This lode, of historic interest, is located near Virginia City, in southwestern Nevada (Pl. LV, Fig. 2), and is a great fissure vein (Fig. 233), about 4 miles long, several hundred feet broad, and branching above, following approximately the contact between eruptive rocks, and dipping at an angle of 35 to 45 degrees. There is abundant evidence of faulting, which in the middle portion of the vein has amounted to 3000 feet. The lode is of Tertiary age, and contains silver and gold minerals in a quartzose gangue.

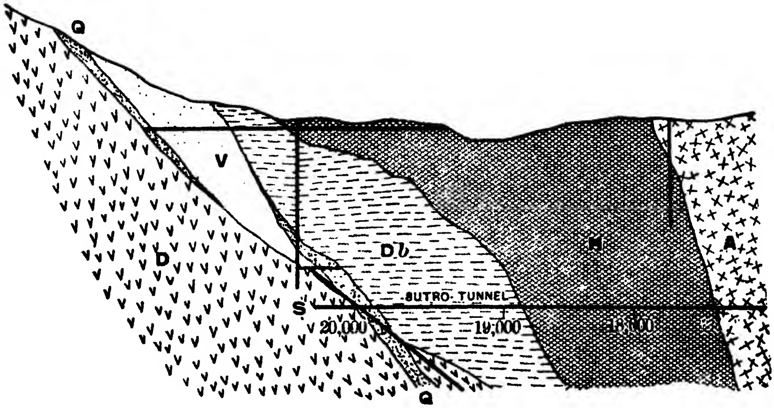

FIG. 233.—Section of Comstock lode. *D*, diorite; *V*, vein matter in earlier diabase (*Db*); *H*, earlier hornblende andesite; *A*, augite andesite. (*After Becker.*)

One of the peculiar features of the deposit is the extreme irregularity of the ore, which occurs in great "bonanzas," some of which carried several thousand dollars to the ton. The faulting is considered to have been quite recent, and the high temperatures encountered in the lower levels of the mine indicate that there is probably a partially cooled mass of igneous rock at no great depth.

In former years the enormous output of this mine caused Nevada to be one of the foremost silver producers. It was discovered as early as 1858, and increased until 1877, after which it declined. Many serious obstacles were met with in the development of the mine, such that it has never become a source of much profit in spite of its enormous output. In 1863, at a depth of 3000 feet, the mine was flooded by water of a temperature of 170° F., as the result of a break in the clay wall; and to drain it $2,900,0000 was spent in the construction of the Sutro tunnel, which was nearly four miles long, but by the time it was finished the workings were below its depth. A second difficulty was the encountering of high temperatures in lower workings, those in the drainage tunnel mentioned being 110° to 114° F. The lode is credited with a total production of over $378,000,000. In 1926 its $1,181,277 production of gold was the largest in the state.

Cripple Creek, Colorado (79).—This district, which is a most important one of this type, is a producer of ores containing gold almost exclusively. The region lies about ten miles west of Pike's Peak proper, but in the foothills of this mountain mass.

The rocks of the district include (1) a series of pre-Cambrian metamorphic rocks and igneous basement complex, and (2) the products of the Tertiary Cripple Creek volcano (Fig. 234).

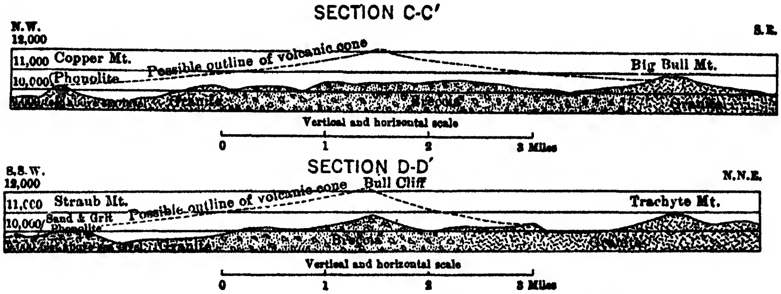

FIG. 234.—Sections showing possible outline of the Cripple Creek volcanic cone at the close of the volcanic epoch. (*After Lindgren and Ransome, U. S. Geol. Surv., Prof. Pap.* 54.)

The metamorphic rocks include a quartz-muscovite-fibrolite schist, and a biotite gneiss; the old igneous rocks include (1) three varieties of granite, viz., the Pike's Peak (quartz-biotite-microline), Cripple Creek (finer-grained but similar), Spring Creek (quartz-orthoclase mainly, and of medium grain); and (2) differentiation products of an olivine-syenite magma.

The Tertiary volcanic rocks represent a series of chemically related products, from a single eruptive center. Commonest of these are tuffs and breccias, which are cut by a series of dikes of phonolite, next a latite-phonolite, followed by a syenite, trachydolerite, and several dark basic dike rocks.

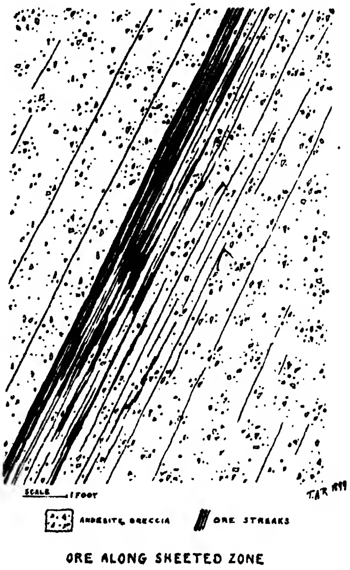

Fig. 235.—Section of vein at Cripple Creek, Colo. (*After Rickard.*)

The ore bodies, which in nearly all cases are associated with fissures, are of two types, viz., (1) lodes or veins (Figs. 235, 236), and (2) irregular replacement bodies, occurring usually in granite. The two are not sharply separated.

The ore bodies are found filling small fissures and sheeted zones (Fig. 235) in the breccias or granite, and as irregular replacement bodies adjacent to the fissures.

The veins, which are characterized by narrowness of the fissures and incomplete filling, have a roughly radial pattern. They are usually steep, but there may be flat ones.

Three stages of deposition are recognized as follows: (1) Dense masses of quartz, adularia, and dark purple fluorite. (2) The same minerals, deposited in cavities and often showing crystal outlines. Associated with them are dolomite, celestite, gold tellurides (calaverite or sylvanite), and locally blende, galena and molybdenite. (3) Smoky to colorless quartz in druses, as well as chalcedony and pyrite.

The Cripple Creek district has shown a rapid rise and decline. Gold mining began in 1890 and increased to 1900 when the production exceeded $18,000,000. It declined from then to 1917 but remained above $10,000,000. In 1930 it was about $2,500,000, and in 1936 about $1,000,000. Up to the end of 1930 the total gold recovery was given as $349,371,000 gold and 1,905,000 ounces silver.

Water has been a serious obstacle to mining, and the Roosevelt drainage tunnel over four miles long was driven at an altitude of 8000 feet. Only three mines have been extended below this level.

San Juan Region, Colorado (74, 78, 87, 88).—This region covers a large tract of mountainous country, in southwestern Colorado, and includes the counties of San Juan, Dolores, La Plata, Hinsdale, and Ouray. The continental divide crosses it, but the main portion consists of a deeply cut volcanic plateau. The area is an important one

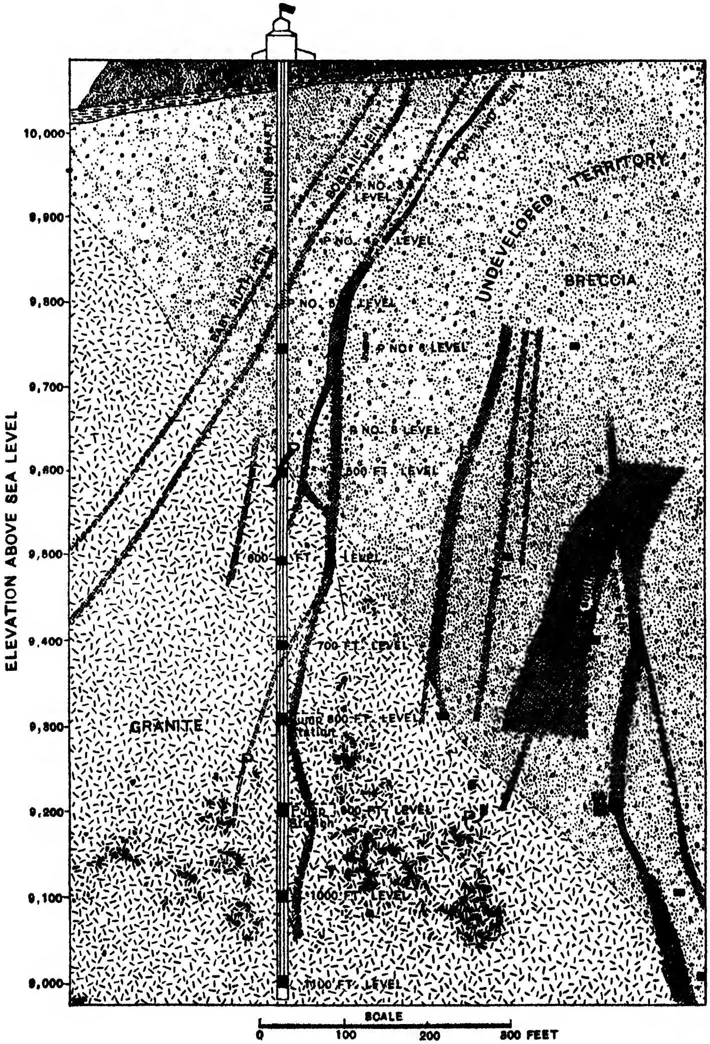

FIG. 236.—Vertical section through the Burns shaft, Portland Mine, Cripple Creek, Colorado. Shows breccia, contact veins, and dikes. *V*, veins; *P*, phonolite. (*After Lindgren and Ransome, U. S. Geol. Surv., Prof. Pap. 54.*)

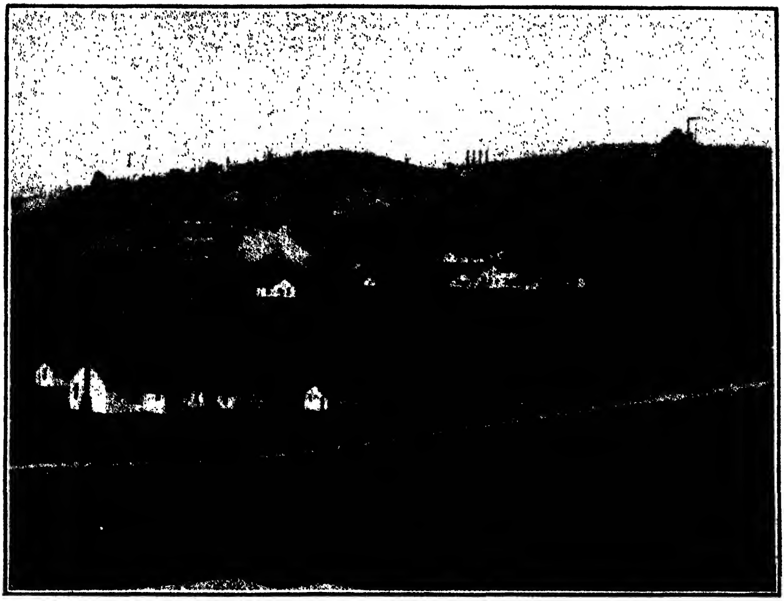

FIG. 1.—View of Independence Mine and Battle Mountain, Cripple Creek, Colorado (*A. J. Harlan, photo.*)

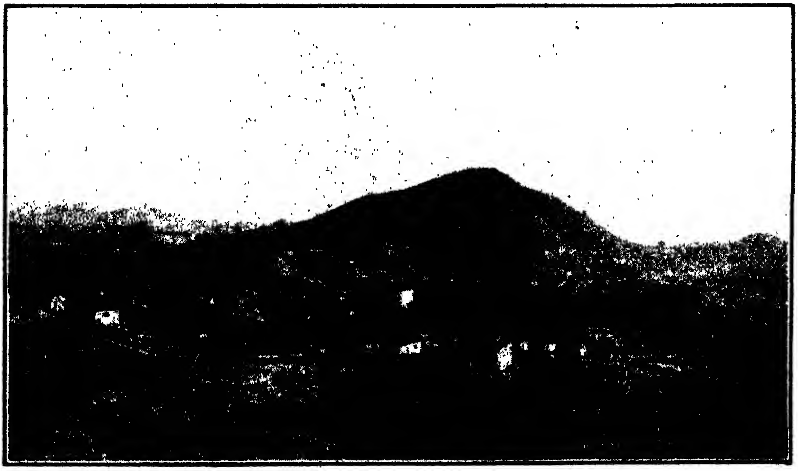

FIG. 2.—View of Tonopah, Nev., with Mt. Oddie in background. (*H. Ries, photo.*)

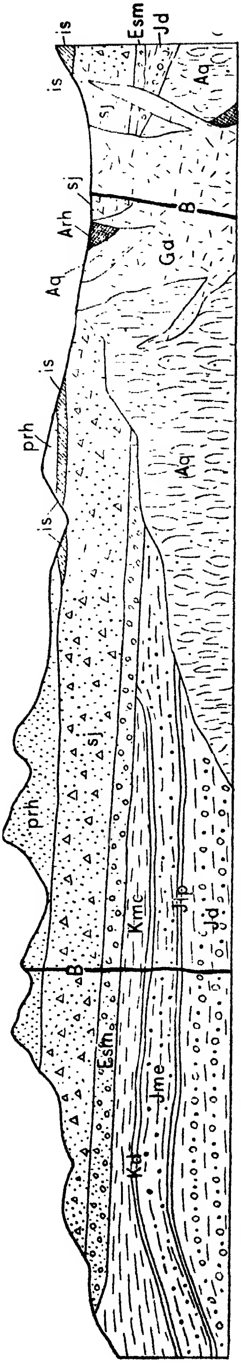

FIG. 237.—Geologic section across the northwest portion of the Telluride Quadrangle. (*U. S. Geol. Surv.*) *Arh*, older rhyolite; *Sj*, San Juan series; *is*, Intermediate series; *prh*, Potosi rhyolite; *B*, basic dikes; *Gd*, gabbro diorite; *Aq*, quartzite; *Jd*, Dolores formation; *Jlp*, La Plata sandstone; *Jme*, McElmo formation; *Kd*, Dakota formation; *Kmc*, Mancos formation; *Esm*, San Miguel formation.

noted for its veins carrying gold, silver, and lead ores in varying proportions, but, owing to the precipitous slopes, high ridges, and great altitude at which the veins outcrop, mining is sometimes attended with difficulty. Important towns in the area are Telluride, Silverton, Ouray, Creede, etc.

The geological history of the San Juan region is exceedingly complex, the pre-Tertiary surface being deeply buried under volcanic beds which still cover the main area, but the older rocks have been exposed by erosion in the surrounding districts. The most complete section is seen in the Animas Valley, between Silverton and Durango, but the two generalized columnar sections of the Telluride and Ouray quadrangles will serve to give a somewhat clear idea of the age and succession of the formations.

The entire region has not been studied in detail geologically, but several quadrangles are known with some intimacy and may be referred to.

Telluride Quadrangle.[1] — In this quadrangle, whose geologic section is shown (Fig. 237), the ores occur in veins which are filled fissures that penetrate all rocks exposed in the area, and were later even than the rhyolite or the intrusions of the diorite stocks. Four general directions of fissuring are noted.

The lodes are narrow zones of closely spaced fissures filled with ore, little of which is found outside of the zone. The veins vary in width, averaging about 3 feet, but the ore usually forms a narrow strip following one side or the other, and rarely filling the entire zone.

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[1] Purington, U. S. Geol. Surv., 18th Ann. Rept., III, p. 751, 1898.

The veins also vary somewhat in their regularity, according to the kind of rock through which they pass, being best developed in the andesite. Faulting is rare.

The ore minerals are galena, freibergite (argentiferous gray copper), polybasite, proustite, stephanite, and perhaps other silver sulphides, with more or less gold, which may be in pyrite and chalcopyrite. There are also a number of metallic and nonmetallic gangue minerals, including sphalerite, zinc blende, mispickel, magnetite, native copper, quartz, calcite, siderite, rhodochrosite, dolomite, fluorite, barite, sericite, biotite, chlorite, amphibole, apatite, garnet, orthoclase, picotite, and kaolinite.

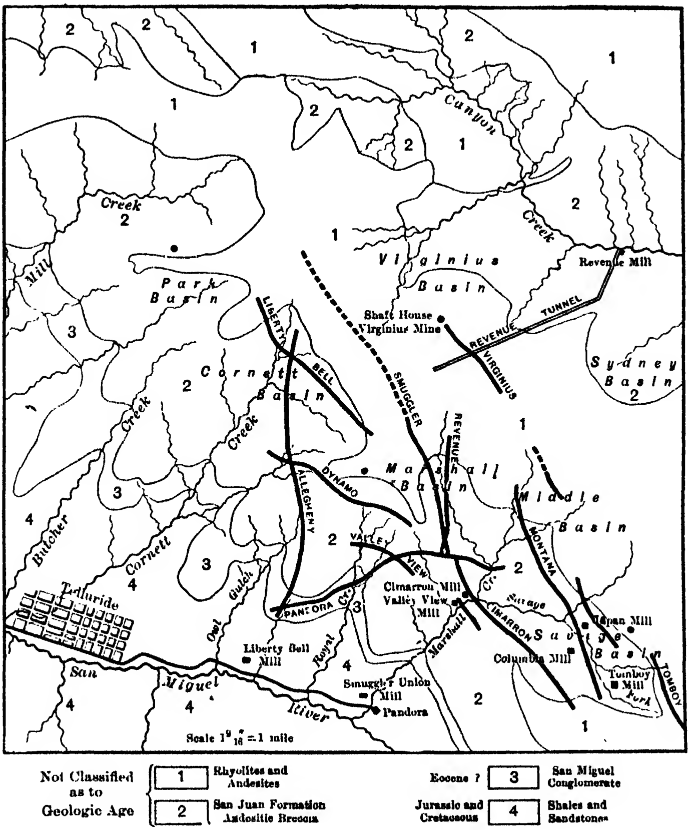

FIG. 238.—Geologic map of Telluride district, Colo., showing outcrop of more important veins. (*After Winslow, Amer. Inst. Min. Engrs., Trans. XXIX.*)

The greater number of veins have been found in the granular rocks of the stocks along the central, east, and west portions of the area, and in the heavy andesitic breccia, tuff, and agglomerate of the San Juan formation, best developed in the northern half of the area. This last horizon has been the most productive.

The ore appears to have been deposited from ascending hot-water solutions which penetrated all open spaces in the fissured zones.

Ransome explains it as follows: Surface waters percolating downward dissolve alkalies from the igneous rocks as sulphides. These alkalies as they become hotter on approaching the magma become charged with sulphidic and carbonic acids derived from volcanic sources, thus becoming solvents for the metals, and silica, lime, etc., which they gathered from the more basic portions of the magma. These solutions then brought metals and silicates and deposited them higher up.

The metals were deposited in the fissures, while the penetration of the wall rocks by the alkaline solutions containing sulphuric acid changed the iron in the ferromagnesian silicates, and the potash went toward the formation of sericite. Carbonates were deposited on the walls, due to the action of water on lime feldspars. Silica was set free and removed mostly from the walls. Gold was carried into the walls to some extent.

Silverton Quadrangle (88).—This quadrangle lies east of the Telluride. The oldest formations are the Archæan schists and gneisses, overlain by Algonkian quartzites, and these in turn by Cambrian, Devonian, and Carboniferous sediments, the whole being capped by a thick series of Tertiary volcanics similar to those of the Telluride quadrangle, but separated from the top of the Carboniferous by a conglomerate. A number of unconformities are present in different parts of the series.

The ore deposits are of three types, viz.: (1) lodes, which include most of the now productive deposits; (2) stocks or masses, which include most of the ore bodies formerly worked on Red Mountain; (3) metasomatic replacements, including a few deposits found in limestones or rhyolite.

The lodes, which are widely distributed and vary in size and degree of mineralization, may occur in all the rocks from the pre-Cambrian schists to the latest monzonitic intrusions, cutting the Tertiary volcanics, but the greater number are found in the San Juan tuff and Silverton volcanic series. Moreover, the gold and silver are not uniformly distributed in the quadrangle.

The most conspicuous fissuring is northeast-southwest, with dips usually of about 75°, and faulting noticeable in but a few lodes. The fissures were formed substantially at the same time, and probably in late Tertiary.

Most of the lodes are simple fissure veins, showing bands of gangue and ore confined between definite walls, while the width of the workable vein varies from a few inches up to 10 or 12 feet.

The wall rock is not usually much altered except in the rhyolite replacement deposits.

The ore minerals are tetrahedrite, very common, may carry both As and Sb; enargite, common in Red Mountain range; chalcopyrite, common and sometimes auriferous; galena, very important and widespread; sphalerite, common and accompanies galena, and several silver sulphides, not very abundant. Both native gold and silver also occur.

The gangue minerals are quartz, barite, calcite, dolomite, rhodochrosite, kaolinite, pyrite, etc.

The ores were probably deposited by ascending waters, but their exact source or depth of origin is not known.

Metasomatism of wall rocks differs in different parts of the quadrangle. Thus, for example, in the Silver Lake Basin, feldspar is altered to sericite, calcite, and quartz; augite, to calcite and chlorite; and biotite, to sericite and rutile. Sericite and quartz are common close to the vein.

Ouray Quadrangle (78).—The ore deposits, which may be regarded as an extension of those of the Silverton quadrangle area, are all located near the town of Ouray, and while the district contains but few productive mines, they are of great scientific interest. A few are found in disturbed rocks near dikes or sheets of porphyry, but most of them occur in but slightly disturbed formations. All owe their existence to the presence of fissures, the form of the ore body depending, however, on the openness of the fissure and kind of wall rock. The three following types are recognized: (1) fissure veins of great vertical extent; (2) replacements in quartzite; (3) replacements in limestone. Where the fissures followed by the ore-bearing solutions were open, a simple, banded, filled vein was formed; but where narrow, the solutions spread out laterally in the wall rock, replacing the same, and the process reached a maximum in the more soluble beds.

The fissures show great vertical extent, and the characters of the several types are as follows:

Fissure Veins.—(*a*) This type, which is the most important, includes silver-bearing veins in fissures of slight displacement, distributed from the Mancos shale, to the sandstone underlying the McElmo. Ore more abundant and of higher grade in quartzite walls, but may be absent or of low grade in shales. Tetrahedrite and argentiferous galena, with quartz and barite gangue as common vein minerals. (*b*) Gold-bearing veins representing a group of mineralized, highly inclined, sheeted zones in dikes of quartz-bearing monzonite porphyry. The chief minerals are auriferous pyrite, and chalcopyrite in a gangue of country rock and clay.

Quartzite Replacements.—Irregular bodies in the Dakota sandstones, with gold and subordinate silver.

Limestone Replacements.—Broad flat ore bodies, adjoining fissure veins, or associated with numerous small vertical fissures. Silver predominates in some, with a barite, silica gangue, and gold with a magnetite gangue in others. The former are associated with the fissure veins which penetrate limestone.

All the deposits of the Ouray district appear to belong to a single period of mineralization, and are of recent formation, being later than the latest igneous intrusions.

Other Occurrences.—Among the other occurrences of this group may be mentioned the gold-quartz veins in rhyolite of the De Lamar mine in Idaho (95); the Bullfrog district of Nevada (131), and the National mining district in the same state (128). At the last named, the fissures in Tertiary lavas carry gold and some silver in a quartz gangue, together with pyrite, blende, and always more or less stibnite, while one contains cinnabar. One vein had a remarkable shoot of pale gold which in four years yielded nearly $4,000,000.

Another interesting occurrence is in the Republic district of Washington whose beautifully crustified quartz veins carry both gold and selenium (177), the only other deposit of this type being the Redjang Lebong of Sumatra.[1]

Foreign Deposits.—*Hungary.*—In eastern Hungary,[2] including Transylvania, there are a number of gold and silver deposits, associated with Tertiary eruptives chiefly andesites and dacites. Those in Hungary include Nagybanya, Felsöbanya, and Kapnik, and in Transylvania, Brad (the most important), Nagyag, etc. At Nagyag the gold occurs as tellurides; in the other Transylvanian districts it is native. Accompanying it are silver-ore minerals, as well as some pyrite, galena, blende, antimony, and tetrahedrite, in a gangue chiefly of quartz, but often containing as well manganese carbonate and silicate. The veins, which

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[1] Beck, Erzlagerstätten, I: 488; Truscott, Min. Mag., VI: 355, 1912.

[2] Vogt, Krusch und Beyschlag, Lagerstätten, II: 31, 1912.

may be a meter thick, are usually fissure fillings, and the lodes may be 30 to 60 feet across. Propylitic alteration of the wall rocks is common.

New Zealand.—The veins of the Hauraki region known in later years for the output of the famous Waihi mine, contain small veins of massive or comb quartz with rich pockets of gold in propylitized Tertiary andesites and dacites in the northern part of the district, while in the southern part the veins are of great width, with the ore shoots uniform and continuous.[1]

Mexico[2] contains a number of well-known representatives of this group, located especially in the eastern Sierra Madre, which, though usually occurring in Tertiary eruptives, sometimes cut sediments. Among these localities should be mentioned Parral, Guanajuato, Real del Monte, Zacatecas, and Pachuca. Silver predominates, the ore minerals, including pyrargyrite, argentite, stephanite, and polybasite, accompanied by tetrahedrite, galena, and blende in a gangue chiefly of quartz. The greater part of the Mexican gold production comes from the mines of El Oro.

Gold Placers

These form an important source of supply of gold, together with a little silver, and, although widely distributed, become prominent chiefly in those areas in which auriferous quartz veins are abundant. So, while in North America they are found in many parts of the Cordilleran region, the Black Hills, and southern Appalachian region of the United States, their greatest development is in the Pacific Coast belt from California to Alaska,[3] and in the Yukon district of Canada.

Most of the gold placers are of Tertiary or Quaternary age, but older ones are also known.

Types of Placers.—Placer deposits may be formed in different ways, as follows:

Eluvial Placers.—These originate in those regions where gold-bearing rocks are subjected to deep weathering, during which the gold may undergo more or less concentration, and also migrate down slope to some extent. The gold grains are usually angular, as they have not been exposed to the wearing action of streams. In the United States, this type is known in the southern Appalachians, but it has also been found in Brazil, the Guianas, etc.

Dry or Eolian Placers (45).—In regions of aridity, where the rocks are disintegrated, the lighter particles may be blown away while the heavier ones, including gold, remain behind.

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[1] Finlayson, Min. Mag., II: 281, 1910; also Econ. Geol., IV: 632, 1909.

[2] Vogt, Krusch und Beyschlag, Lagerstätten, II: 66, 1912. Aguilera, Amer. Inst. Min. Engrs., Trans. XXXII: 497, 1902; Winchell, *Ibid.*, LXVI: 27. (Pachuca); Blake, *Ibid.*, p. 216, 1902. (Guanajuato); Bordeaux, A. F. J., *Ibid.*, XXXIX: 357, 1909. (Silver mines.)

[3] Pardee, Ore Deposits of Western States, p. 419, 1933.

Stream Placers (61).—These represent the most important and widespread type. As the products of rock decay are washed down the slopes into streams, the fine clayey material is carried a long distance, but the heavier particles, including gold, settle rapidly, the gold, on account of its higher gravity, usually collecting in the lower part of the deposit, or even in crevices of the bed rock. Even if it does not do so at once, agitation of the sediment may cause it to settle deeper, or even slowly migrate down stream as the sediment shifts. Coarse gold carried down by streams from higher levels, will settle with coarse sediment in the upper part of a stream's course, but very fine flake gold may be transported some distance farther down stream.

In some regions thick gold-bearing gravel deposits have by downward cutting of the streams due to elevation of the land, been deeply trenched, leaving the uneroded remnants as benches along the valley slopes. Cases of this sort are found on the western slope of the Sierra Nevada in California, on Anvil Creek in the Nome district of Alaska, and in the Klondike district of the Yukon.

In some instances stream placers may have become buried under other barren gravels, or lava flows. (Victoria and some California deposits.) The gold in such instances has to be recovered by underground methods. Such buried placers are sometimes located by geophysical prospecting.

Marine Placers.—These are formed by the sorting action of the waves along coasts where auriferous gravels or sands are exposed. They are known in Oregon, but the best examples were those of Cape Nome, Alaska.

Size of the Placer Gold.—Gold occurs in placers in the form of nuggets, flakes, or dust-like grains. The nuggets represent the largest pieces, and the finding of some very large ones has been recorded from time to time in different parts of the world. Two large nuggets are recorded from Victoria; one, the "Welcome Stranger," weighing 2280 ounces; and the other, the "Welcome Nugget," weighing 2166 ounces. Most of the placer gold obtained is in small grains, and some may be very fine. Lindgren states that a piece of gold worth one cent is without trouble divisible into 2000 parts, each of which can be readily recognized in a pan.

Associated Minerals.—Placer deposits may contain a number of heavy minerals, which settle out with the gold in the sluice boxes. These include magnetite, ilmenite (black sand), garnet, zircon (white sand), monazite (yellow sand), cassiterite, and platinum. Pyrite or marcasite may form in the gravels.

California (61).—These have been derived from the wearing down of the Sierras, and are found in those valleys leading off the drainage from the mountains. Many were formed during the Tertiary period, when the Sierras were subjected to a long-continued denudation, while violent volcanic outbursts at the close of the Tertiary have often covered the gravels and protected them from subsequent erosion. These lava cappings are at times 150 to 200 feet thick, as in Table Mountain, Tuolumne County.

Many of the gravel deposits are on lines of former drainage, while others lie in channels still occupied by streams. Some show but one streak of gold, while in others there may be several, some of which are on rock benches of the valley bottom (Fig. 239).

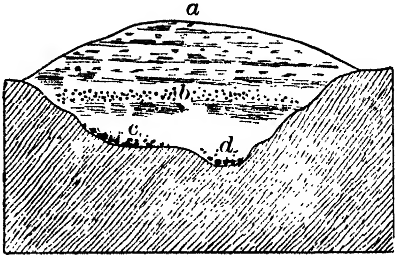

Fig. 239.—Generalized section of old placer, with technical terms. *a*, volcanic cap; *b*, upper lead; *c*, bench gravel; *d*, channel gravel. (*After R. E. Browne.*)

During the early days of gold mining in California the gravels at lower levels and in the valley bottoms were worked, but as these became exhausted, those farther up the slopes or hills were sought.

In the earlier operations the gravels were washed entirely by hand, either with a pan or rocker, and this plan is even now followed by small miners and prospectors; but mining on a larger scale is carried on by one of three methods, viz., drift mining, hydraulic mining, and dredging.

Drift mining is employed in the case of gravel deposits covered by a lava cap, a tunnel being run in to the paying portion of the bed and the auriferous gravel carried out and washed.

In hydraulic mining (Pl. LX, Fig. 1), a stream is directed against the bank of gravel and the whole washed down into a rock ditch lined with tree sections, or into a wooden trough with crosspieces or riffles on the bottom. The gold, being heavy, settles quickly and is caught in the troughs or ditches, while the other materials are carried off and discharged into some neighboring stream. Mercury is sometimes put behind the riffles to aid in catching the gold.

Owing to the amount of debris which was swept down into the lowlands, a protest was raised by the farmers dwelling there, who claimed that their farms were being ruined; and it soon became a question which should survive, the farmer or the miner, for in places the gravels and sand from the washings choked up streams and accumulated to a depth of 70 or 80 feet. The question was settled in 1884 in favor of the farmer by an injunction, issued by the United States Circuit Court, which caused many of the hydraulic mines to suspend operations; and at a later date this was extended by state legislation, adverse to the hydraulic mining industry. Owing to this setback, hydraulic mining fell to a comparatively unimportant place in the gold-producing industry of California, while at the same time quartz mining increased.

The passage of the Caminetti law now permits hydraulic mining, but requires that a dam shall be constructed across the stream to catch the tailings. This resulted in a revival of the industry, but even so, the placer mining industry is seriously hindered by the present laws governing it.

Dredging consists in taking the gravel from the river with some form of dredge. The method, which was first practiced in New Zealand, has been introduced with great success into California, and it is also used in Alaska. The gravel when taken from the river is discharged onto a screen, which separates the coarse stones, and the finer particles pass over amalgamated plates, tables with riffles, and then over felt, or may be caught by other means.

Placer gold is also worked in Idaho, Montana, Oregon, New Mexico, and Colorado, all of the deposits except those of the last two states having been derived mostly from Mesozoic veins.

Gold also occurs in beach sand of certain portions of the Pacific coast of Washington, Oregon, and Alaska (176).

In arid regions, where the gold-bearing sands are largely the product of disintegration, and water for washing out the metal is wanting, a system known as dry blowing is sometimes resorted to.

Alaska.—Placer gold deposits have been found in many parts of Alaska, and up to 1935 they produced $293,136,000 or approximately two-thirds of the entire gold production of the territory. In 1935, placer gold having a value of $9,703,000 was produced.

Workable deposits of placer gold were first discovered in the Forty Mile district of the Yukon Basin in 1886 and caused a stampede into this region. Other large stampedes resulted from the discovery of gold on the beaches at Nome in 1899, at Fairbanks in 1904, and in the Kuskokwim region in 1909.

In recent years, placer gold mining has been greatly stimulated by the increase in the price of gold, and by improved mechanical means of mining, so that interest in many of the old camps has been revived, and deposits that were once of too low a grade can now be worked at a profit. At the present time gold is taken from the gravel by all known

PLATE LX

FIG. 1.—Hydraulic mining of auriferous gravel. The sluice box in foreground is for catching the gold.

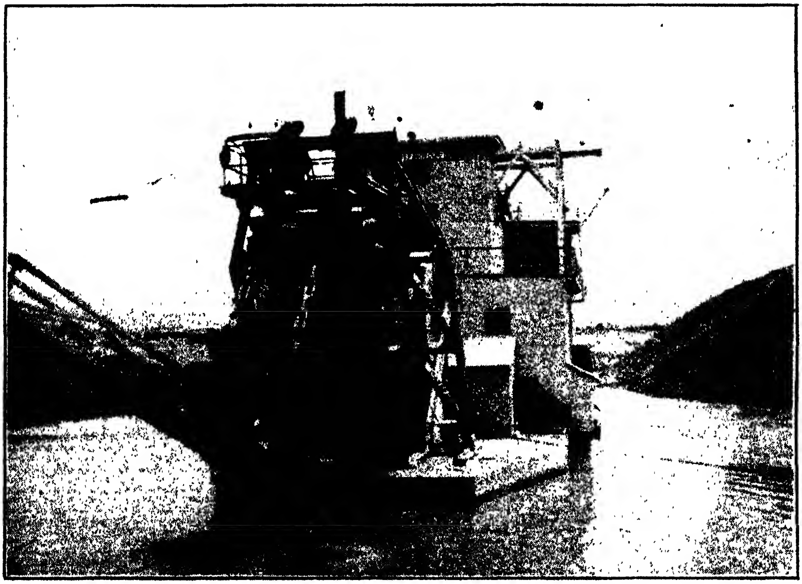

FIG. 2.—Gold dredge near Helena, Mont. (*H. Ries, photo.*)

means, from primitive hand methods, hydraulicking, power shovels, and draglines, to dredges that dig to a depth of over 100 feet. More than 65 per cent of all the placer gold produced in Alaska in 1940 was mined by dredges; the average value per cubic yard of gravel dredged was about 54 cents.

The Fairbanks district in the Yukon Basin is still the largest placer camp in Alaska, and, in 1939, gold having a value of $6,041,000 was mined. By far the greater part was mined by dredges. The area has never been glaciated, and an interesting feature of these deposits is their great thickness, sometimes 300 feet, and most of them are permanently frozen. Practically all of the gold lies on the bed rock or in the lower few feet of gravel. The productive zone is overlain by barren gravel, which in turn is overlain by muck containing mastodon remains.

Seward Peninsula, the second largest district, produced $2,922,000 in gold in 1939, and 81 per cent of it was recovered by dredges. The greater part of the production is around Nome, which is of geologic interest as most of the gold comes from the old beach lines where the gold has been reconcentrated from the coastal plain gravel.

The Kuskokwin district, which produced $1,283,000 of gold in 1939, is the third largest producer. The gold occurs in creek and bench gravel, and in a few instances as residual placers.

Yukon Territory (142).—The discovery of placer gold in the Klondike in 1896 caused a stampede to that region, and in the next ten years the value of gold produced is reported to have been $107,000,000. Placers are still being worked in the territory, but the production is not as great as formerly, being reported as about $1,693,000 in 1934, most of which came from the Dawson district.

Victoria.[1]—This colony contains a remarkable series of buried channels, called "deep leads." The gold occurs in gravels of Tertiary streams, which, following a depression, became covered by thick beds of sand and clay, and these in turn by basalt flows of several hundred feet thickness. The gold was first discovered in the upper part of the former stream courses and then followed down under the basalt.

Russia.—Gold gravels, which Purington claims belong to one of the greatest placer fields of the world, have been developed on the Lena River, in Siberia.[2]

South Africa.[3]—The auriferous conglomerates of the Johannesburg district of the Transvaal, South Africa, are among the most remarkable known. They

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[1] Lindgren, Min. Mag. XI: 33, 1905, and Eng. and Min. Jour., Feb. 16, 1905.

[2] Min. Mag. XII: 341, 1915.

[3] Hatch, Types of Ore Deposits, San Francisco, 1911; Gregory, Econ. Geol., IV: 118, 1909; Hatch, Min. and Sci. Pr., CIII: 98 and 132, 1911; Horwood, Min. and Sci. Pr., CVII: 563, etc., 1913; Schwarz, Min. Mag., XIII: 223, 1915.

are of apparently simple structure, yet very puzzling as to origin. The section involves a basal series of crystalline schists intruded by granites, on whose eroded surface rests the Upper and Lower Witwatersrand system of slates, quartzites, and conglomerates, aggregating 19,000 feet in thickness, and overlain in turn by the Ventersdorp system of volcanics.

The Witwatersrand, which is probably of Cambrian or pre-Cambrian age, forms a syncline with Johannesburg on its north side. The series has been faulted and also cut by diabase dikes, and while auriferous conglomerates are found at several different horizons, the most productive ones are in the upper part.

The ore consists of pebbles mostly of quartz, in a sandy matrix, with abundant pyrite in the cement. The gold, which occurs in the cement but not in the pebbles, is closely connected with the pyrite. Some of the gold has migrated and recrystallized. It is not yet definitely settled whether the auriferous conglomerate represents an ancient placer, or whether the gold and pyrite are epigenetic[1] and introduced after the dikes, and for the detailed arguments the articles referred to should be consulted. It is provisionally placed with the placer deposits.

Uses of Gold.—Gold is chiefly used for coinage, ornaments, and ornamental utensils. It is employed to a considerable extent in dentistry and in an alloy for the better class of gilding.

Its value for use in the arts depends on its brightness, freedom from tarnish, and its ductility and malleability, which permit it to be easily worked. As pure 24-carat gold is too soft for use, it is alloyed with a small amount of some other metal, such as copper, to gain hardness.

Uses of Silver.—This metal was formerly of much importance for coinage, but is much less so now. It is, however, widely employed in the arts for making jewelry and utensils such as tableware. Its salts are of more or less value in medicine and in photography. Its brightness and white color are valuable properties when the metal is used, but, unlike gold, it tarnishes somewhat readily when exposed to sulphurous gases. There are a number of alloys of silver, those with gold and copper, respectively, being of importance.

Production of Gold and Silver.—The mine production of gold in the United States (including Philippines and Puerto Rico) in 1940 was 5,984,163 fine ounces, valued at $209,445,705. This price is figured at $35 per ounce. It should be remembered that for 1933 it was $25.56, and in earlier years about $20 per ounce. This increase in the market value naturally stimulated the mining of gold.

Of the total 1940 production, California contributed 24.3 per cent, Philippines 18.6 per cent, Alaska 12.6 per cent, South Dakota 9.8 per cent, Nevada 6.7 per cent.

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[1] Graton, Econ. Geol., XXV, Supplement to No. 3, 1930. (Hydrothermal origin.)

The mine production of silver in the United States and Territories in 1940 was 71,824,746 fine ounces, valued at $51,075,375, with silver calculated at a little under 71 cents an ounce, as compared with 64½ cents in 1934.

The percentage of gold in fine ounces obtained from different types of ore in the United States in 1940 was as follows: placers, 31.00; siliceous, 57; copper, 11; lead, 0.35; copper-lead, and zinc, 1.7. Similar figures for silver were: placers, 0.2, siliceous, 41.1; copper, 29.4; lead, 4.4; zinc, 0.03; copper-lead, .3, lead-zinc, 24.0.

Canada in 1939 produced 5,094,379 fine ounces of gold valued at $184,115,951 figured at $35.03 per fine ounce. The value of the Canadian gold is 38 per cent of all the minerals produced in the Dominion and 53 per cent of all the metals. The output came not only from gold-quartz ores, but also in a substantial amount from complex ones. Ontario is the chief producer.

The silver output of the Dominion in the same year was 23,163,629 fine ounces valued at $9,378,490, British Columbia supplying 46 per cent of the total value. The Sullivan Mine in that province was the largest single source. The output of the Northwest Territories is from the silver-radium ores of Great Bear Lake, and that from Manitoba is from the Flin Flon ore body. The output from the

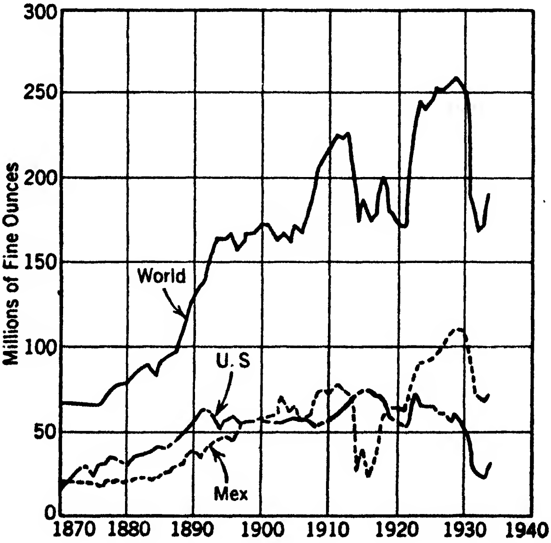

Fig. 240.—Mine production of silver from 1870 to 1934.

nickel-copper deposits is greater than that from the formerly famous Cobalt, Gowganda, and Lorrain areas of Ontario.

An estimate of the world production of gold in fine ounces for 1940 is 41,560,000 fine ounces, of which the amount contributed by the following countries is approximately: Africa, 40 per cent; Europe, 13.2 per cent; United States and Philippines, 11.7 per cent; Canada, 12.8 per cent; and Oceania, 5.4 per cent.

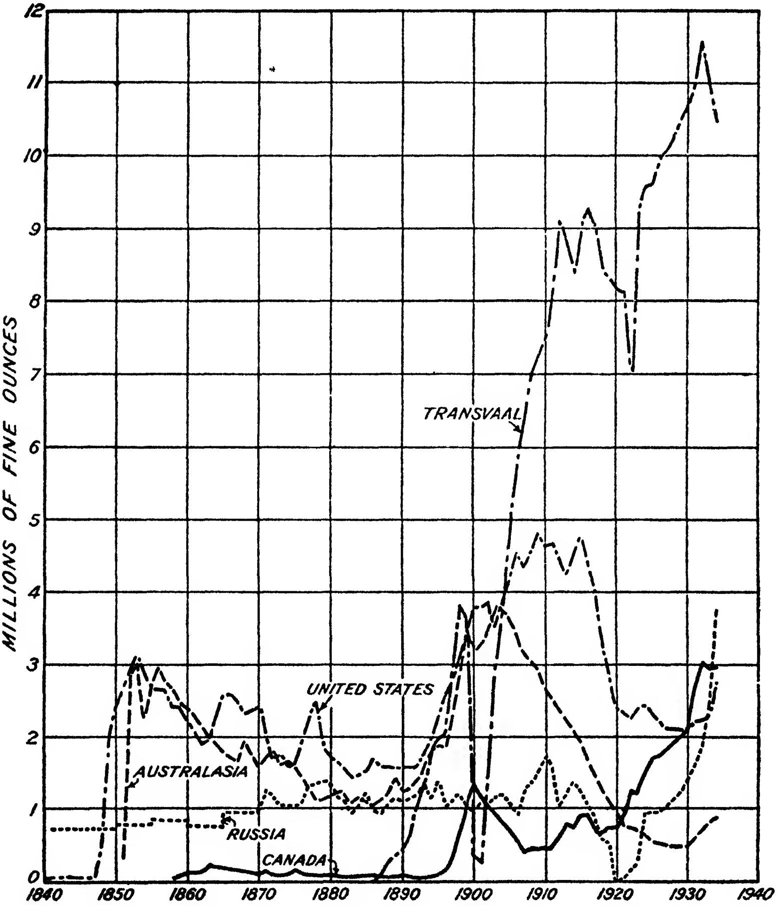

FIG. 241.—Production of gold in the main producing countries, 1840 to 1934. (*After Robinson, Mines Br. Can.*, No. 769.)

An estimate of the world production of silver for 1940 is 275,644,000 fine ounces. The estimated proportion of this contributed by several countries is as follows: Mexico, 30 per cent; United States and Philippines, 24.4 per cent; South America, 10.6 per cent; Europe and Asia each about 8 per cent.

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CHAPTER XVIII

MINOR METALS

ALUMINUM—MANGANESE—MERCURY

ALUMINUM

Ores.—This is one of the few metals whose ores do not present a metallic appearance. Many different minerals contain aluminum, but it can be profitably extracted from only a few. Common clay, for example, presents an inexhaustible supply, but the chemical combination of the aluminum in it is such that its extraction up to the present time has not been found commercially practicable, although a number of processes with this end in view have been patented.

The minerals which might serve as sources of aluminum together with the percentage of metal they contain are: *corundum,* Al_2O_3 (53.3 per cent); *cryolite,* $3NaF \cdot AlF_3$ (12.8 per cent); *diaspore,* Al_2O_3, H_2O (45.1 per cent); *bauxite,* $Al_2O_32H_2O$ (39.13 per cent); *gibbsite,* $Al_2O_33H_2O$ (34.6 per cent).

Of these, corundum is too valuable as an abrasive, and is not found in sufficient quantity to permit its use as an ore of aluminum. Until the discovery of bauxite, cryolite (q. v.) was the chief source of the metal, all of it being obtained from Greenland.

Aluminum ore is usually called bauxite, but some question the validity of this mineral. Of the other aluminum hydrates gibbsite is known in the Arkansas deposits. Watson believes it present in the Georgia ones, and diaspore occurs in Missouri flint clays.

Bauxite[1] derives its name from Baux in southern France, where it was first discovered, but in later years large deposits have been found in the United States. It is usually pisolitic in structure, but may sometimes resemble clay in appearance. The common impurities are silica, iron oxide, and titanic acid; and the variation in the amount of these ingredients can be seen from the following analyses of both domestic and foreign occurrences.

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[1] The term bauxite is here used broadly to include both bauxite and gibbsite.

Analyses of Bauxite

	1	2	3	4	5	6	7	8
Alumina (Al_2O_3)	57.60	61.89	63.16	59.22	61.00	62.05	62.46	39.92
Ferric oxide (Fe_2O_3) . .	25.30	1.96	23.55	3.16	2.20	1.66	0.81	16.84
Silica (SiO_2)	2.80	6.01	4.15	3.30	2 10	2.00	4.72	20.00
Lime carbonate ($CaCO_3$)	0.40	——	——	——	——	——	——	——
Titanic acid (TiO_2) . .	3.10	——	——	3.62	——	——	0.23	1.47
Water (H_2O)	10.80	27.82	8.34	28.80	31.58	30.31	31.03	19.52
Moisture	——	——	——	1.90	3.12	3.50	——	1.25
Alkalies (Na_2O, K_2O) .	——	——	0.79	——	——	——	——	——

1. Baux, France. 2. Glenravel, Ireland. 3. Wochein, Germany. 4. Georgia. 5. Rock Run, Alabama. 6. Arkansas. 7 and 8. Wilkinson County, Georgia.

It should be stated that all of these, except Nos. 3 and 8, represent good grades of ore, but that within any one district, or even in the same deposit, there may be considerable variation in composition.

It is indeed probable that some highly aluminous fire clays and kaolins may contain aluminum hydroxides, and Galpin (9), has identified gibbsite (hydrargillite) in those from Olive Hill, Kentucky, etc. Diaspore occurs in certain Missouri fire clays. Aluminum hydroxides also occur abundantly in laterites, but these are too impure to be used as ores of aluminum.

Distribution of Bauxite in the United States.—Bauxite in commercial quantity has been found in only a few districts in the United States. These are the Georgia-Alabama district, the Arkansas district, Wilkinson County, Georgia, near Chattanooga and Keenburg, Tenn., a small area in southwestern New Mexico, and limited deposits in Alabama and Mississippi.

Georgia-Alabama (15).—The bauxite deposits of these two states, except those of Wilkinson County, Georgia, noted below, form a belt about 60 miles long, extending from Jacksonville, Alabama, to Cartersville, Ga. (Fig. 242). The ore, which is either pisolitic or clay-like in its character, forms pockets or lenses of variable diameter and depth, in the residual clay derived from the Knox dolomite (Fig. 243 and Pl. LXII). A pronounced feature is their occurrence close to 900 feet above sea level, few being found above 950 feet or below 850.

The bauxite is believed by Hayes to be a hot-spring deposit. It is underlain by the Knox dolomite, and this in turn by the Conasauga shales, which are several thousand feet in thickness, and contain from 15 to 20 per cent of alumina and also pyrite. The region is one of marked faulting. Alteration of the pyrite by percolating meteoric waters has yielded sulphuric acid, which attacked the alumina of the

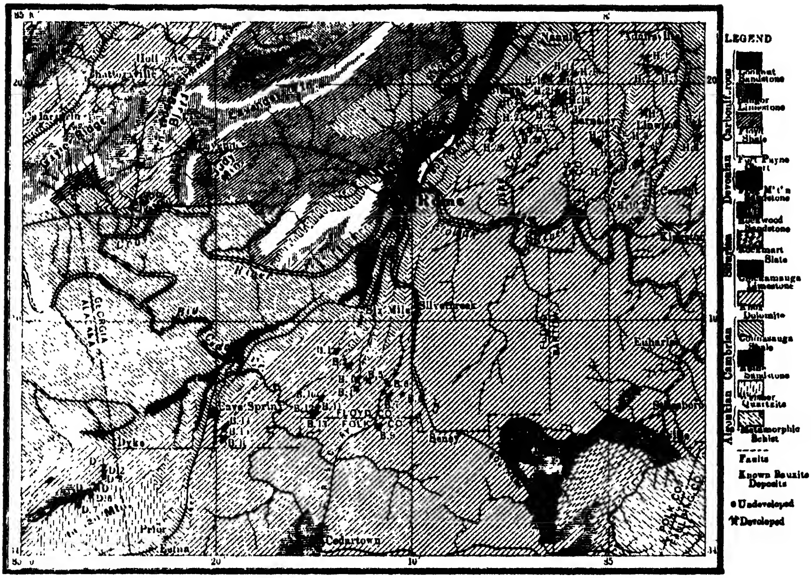

Fig. 242.—Geologic map of Alabama-Georgia bauxite region. (*After Hayes, U. S. Geol. Surv., 16th Ann. Rept., III.*)

shale, with the formation of alum and also ferrous sulphate. Both of these have been carried toward the surface by spring waters, but since they had to pass through the higher-lying limestones, the lime carbonate acted on the dissolved allum according to the following equation:[1]

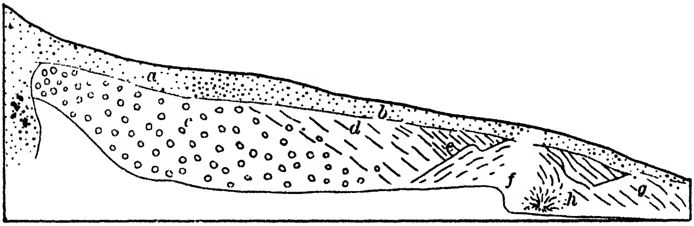

Fig. 243.—Section of bauxite deposit. (*a*) residual mantle; (*b*) red sandy clay soil; (*c*) pisolitic ore; (*d*) bauxite with clay; (*e*) clay with bauxite; (*f*) talus; (*g*) mottled clay; (*h*) drainage ditch. (*After Hayes.*)

$$Al_2(SO_4)_3 + 3\,CaCO_3 = Al_2O_3 + 3\,CaSO_4 + 3\,CO_2$$

It is more likely, however, that the bauxite is the result of lateritic weathering, as is the case in other regions (15). The exact nature of the process has not been clearly demonstrated.

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[1] For clearness, the water combined with alumina is left out.

The Georgia-Alabama deposits, which represent a unique type of occurrence, were discovered in 1887, and have been worked steadily since that time.

Coastal Plain Belt (13, 16).—Bauxite deposits associated with Lower Cretaceous clays are known to occur from Georgia to Mississippi.

Those in Georgia lie near the margin of the Coastal Plain, about 30 miles east of Macon. The bauxite deposits, which occur apparently near the contact of the Tuscaloosa (Lower Cretaceous) and Claiborne (Tertiary) formations, form beds up to 10 feet in thickness, and the ore is generally either pisolitic or concretionary, but some forms exhibit an amorphous character and even flinty appearance. The color varies from white or cream to bright red. Analyses are given above.

The origin of the bauxite is a somewhat obscure problem, and as the field is but little developed, evidence is difficult to secure. Veatch points out, however, that all stages of transition from the clay to the bauxite can be observed, and suggests that the latter has been formed by a desilication of the kaolinite in the clay by circulating meteoric waters carrying some chemical that was capable of abstracting the silica from the hydrous aluminum silicate.

Tennessee Field.—Deposits of bauxite are known on the southeast slope of the Missionary Ridge, near Chattanooga (2), and were worked for the first time in 1907. They are of the same character as those found in the Georgia-Alabama field, and may be regarded as a northward extension of that region. A large quantity of ore has been taken out but there has been no production since 1928. At Keenburg, Carter County, bauxite is found at an elevation of 2200 feet in residual clays derived from the Watauga shale (Cambrian).

ANALYSES OF BAUXITE FROM MISSIONARY RIDGE, TENN.

	1	2	3	4	5	6
Insoluble	12.13	11.15	11.33	11.07	13.12	12.65
Loss on ignition .	28.97	30.04	30.20	30.00	30.39	30.31
Alumina (Al_2O_3) .	57.56	57.63	57.37	57.83	55.11	55.50
Iron oxide (Fe_2O_3)	1.34	1.18	1.10	1.10	1.38	1.34

Arkansas (12).—The occurrence of bauxite in Arkansas has been known since 1891, but owing to a more accessible eastern supply, there was little development in the region until 1900. The deposits, which are much more extensive than the Georgia-Alabama ones, are found in two areas, one the Bryant district, lying 18 miles southwest of Little Rock, and the other the Fourche Mountain district, just south of Little Rock (12).

The ore consists of (1) horizontal, tabular, bodies of irregular outline, which grade downward into kaolin and this in turn into syenite; and (2) detrital deposits in Tertiary sediments.

The former is the more important type, and may be either pisolitic or granitic in texture. Some of the ore is amorphous or clay-like.

The ore bodies average about 11 feet in thickness with a maximum of 35 feet. Gibbsite occurs chiefly in the granitic ore and bauxite in the pisolitic.

Several theories have been advanced to explain the origin of these deposits. According to Mead (12), the syenite was first weathered to kaolin, and the upper and more porous portions of this changed to bauxite by circulating surface waters. Contemporaneous with this, there occurred more or less erosion, which carried much of the bauxite into the Tertiary sea, where it was deposited with other sediments. Later the entire area became covered by these Tertiary deposits, after which another period of erosion occurred (Fig. 244).

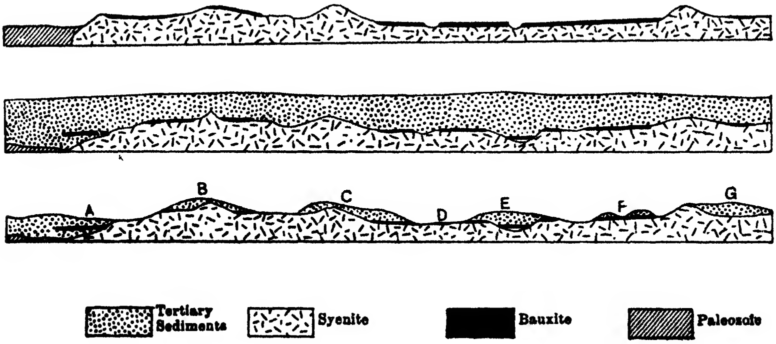

FIG. 244.—Generalized cross sections illustrating the geologic history of the Arkansas bauxite occurrences. *A*, lens of bauxite interstratified with the Tertiary sediments; *B*, Tertiary hill with bauxite exposed on both sides, but prevented from extending through the hill by a rise in the syenite surface; *C*, Tertiary hill with bauxite on right, but absent on left; *D*, bauxite capping on syenite; *E*, hill of Tertiary sediments with bauxite on both sides, separated by Tertiary valley between, in which is lens of detrital bauxite; *F*, Tertiary hill, with valley exposing underlying bauxite; *G*, Tertiary hill with concealed bauxite under it. (*After Mead*, *Econ. Geol.*, *X*, 1915.)

Hayes suggested that the bauxite was formed by the action of hot alkaline solutions on the syenite.

Other Occurrences.—Bauxite is known to occur in Botetourt County, Virginia, in residual clays with iron and manganese ores, but the deposits have not yet proved to be of commercial value. Deposits are also known near Silver City, N. M. (3), and appear to have been derived from a basic volcanic rock by decomposition and alteration in place. Owing to their remoteness from the railroad, they are of little commercial importance.

Small deposits of bauxite are known to occur in Alabama (15) and Mississippi[1] (13). The deposits appear to be associated with the Wilcox formation, and seem to be the result of lateritic weathering.

Foreign Deposits.[2]—British Guiana yields large supplies of bauxite. According to Emory (7) the most important deposits are lenses of massive bauxite in the coastal plain. Dutch Guiana also has extensive deposits,[3] from which large shipments have been made. France is also a large producer. That at Baux, from which it is named, occurs in beds associated with Cretaceous limestones and clays. Bauxite deposits are known at a number of localities in different parts of the world (8), but the individual production is not large. In Germany and Ireland it occurs as a weathering product of basalt. Other deposits, associated with limestones, are found in Austro-Hungary, Italy, and Yugoslavia.

Uses of Bauxite.—The chief use of bauxite is for the manufacture of aluminum, much of the ore for this purpose being imported, but about 48 per cent of the domestic production in 1935 was used for this purpose. Aluminum salts represent a second use, and consumed 28 per cent of the domestic production, while 23 per cent was consumed in the manufacture of artificial abrasives.

High-alumina cement, and refractories, consume about 1 per cent of the domestic production. Alundum, an artificial abrasive, is made in large quantities at Niagara Falls, by fusing calcined bauxite in the electric furnace. A new use is in oil and sugar refining.

Uses of Aluminum.—The chief use of this metal is for making wire for the transmission of electric currents, but a large quantity of it is also used in the manufacture of articles for domestic or culinary use, instruments, boats, and other articles where lightness is wanted. It is also employed in the manufacture of special alloys, among which may be mentioned magnalium, an alloy of aluminum and magnesium; and wolframinium, a tungsten-aluminum alloy. Aluminum silver is an alloy of copper, nickel, zinc, and aluminum;

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[1] Adams, Econ. Geol. xx: 615, 1927.

[2] Dammer und Tietze, Nutzbaren Mineralien, I: 262, 1913.

[3] Kilinski, Min. and Met., ix: 59, 1928.

aluminum zinc includes a series of alloys containing various proportions of these two metals.

Production of Bauxite.—The shipments of bauxite (dried) in the United States in 1940 was 438,913 long tons, valued at $2,578,968, or $3.44 per long ton. About 97 per cent of the domestic production came from Arkansas, and the balance from Georgia, Alabama and Virginia. The production since 1913 is shown in Fig. 245.

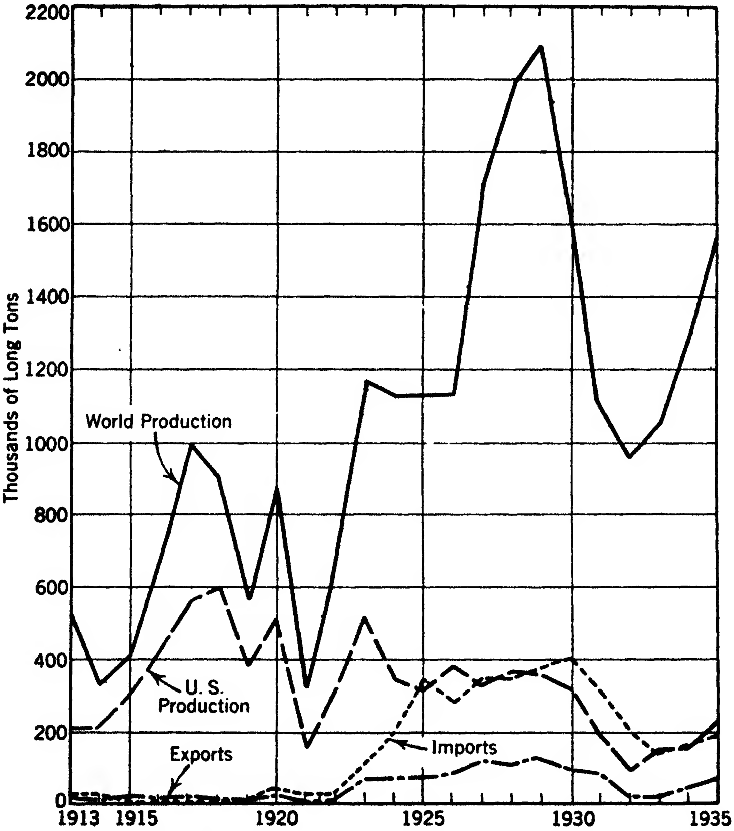

FIG. 245.—Trends in bauxite production in the United States and in the world compared with shipments into the United States and domestic exports, 1913–1935. (*Minerals Yearbook*, 1936.)

The imports in 1940 were 629,552 tons, valued at $4,298,969, while the exports were 81,913 long tons, valued at $1,542,703.

The world production of bauxite in 1940 was 4,627,000 metric tons, with British Guiana, France and Hungary each 15 per cent; Surinam, 13 per cent; and United States, 9 per cent.

The value of primary aluminum produced in the United States in 1940 was $75,292,000, and aluminum salts shipped, $12,882,578.

The world's aluminum production in 1940 was estimated at 803,000 metric tons, of which the United States produced 23 per cent, Germany and Austria, 30 per cent, and Canada, 13 per cent.

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MANGANESE

Ore Minerals and Ores.—While many different minerals contain this metal, practically the only ones of commercial value are the oxides and carbonates, and in this country mostly the former. The silicate is not used as a source of manganese, owing to its high silica percentage.

The important ore minerals of manganese are the following: *pyrolusite*,[1] the black oxide (MnO_2, 63.2 per cent Mn); *psilomelane* (chiefly MnO_2, H_2O; K and Ba variable, 45 to 60 per cent Mn); *braunite* ($3Mn_2O_3$, $MnSiO_3$, 69.69 per cent Mn); *wad*, a low-grade earthy brown or black ore in which the percentage of manganese varies from 15 to 40); *manganite* (Mn_2O_3, H_2O; 62.4 per cent Mn); *rhodochrosite* ($MnCO_3$ 61.7 per cent MnO). To these should be added *franklinite* $(FeZnMn)O \cdot (FeMn)_2O_3$.

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[1] *Polianite*, also MnO_2, is tetragonal.

The manganese ores proper consist usually of a mixture of oxides, and indeed these compounds are really the only ones of importance in the United States. Pyrolusite and psilomelane are by far the most important, and are often intimately associated, the pyrolusite generally assuming a crystalline and the psilomelane a massive structure. They may locally have some admixtures of iron oxide, and then they are of use in the steel industry, but when free from iron they are, in addition, of value for oxidizing and coloring purposes. Wad is often of too low grade, owing to impurities, to be used as an ore of manganese, but it is sometimes employed for paint. Rhodochrosite, found as a common gangue mineral in some western mines (Rico, Colo.; Butte, Mont., silver mines), has been mined at Butte. It has, also, been mined in some quantity in the Huelva district of Spain,[1] and in Merionethshire, Wales (6).

Manganese ores, in addition to being associated with iron, are sometimes mixed with zinc and silver. They may therefore be classified as follows:

1. Manganese ore, with 35 per cent Mn. If the manganese is present as oxide, other substances can make 45 per cent of the total. If present as carbonate, only 27 per cent of the others may be present. The iron content in most domestic manganese ores is low.
2. Ferruginous manganese ore, with 15-35 per cent Mn. This may run 14-25 per cent Mn, 25-35 per cent Fe, 8-20 per cent SiO_2. The supply comes mostly from Minnesota, Michigan, Nevada and Colorado. It is used in spiegeleisen.
3. Manganiferous iron ore, with 5-10 per cent Mn.
4. Manganiferous silver ore, referring to oxides or carbonates with over 5 per cent Mn, and enough silver to make the ore more valuable as a source of the latter metal. The ores may contain appreciable iron. The manganese forms a more fluid slag.
5. Manganiferous zinc residuum. This has 12-15 per cent Mn and up to 40 per cent Fe. It is used for iron-manganese alloys, and comes from treatment of New Jersey zinc ores.

Origin (20).—Manganese oxide deposits are usually of secondary origin, having been formed by weathering processes, which caused the decay of the parent rock containing manganiferous silicates, and the change of these latter to oxides. By circulating ground water they have often been concentrated in residual clays, the manganese having been transported probably as bicarbonate, or perhaps as sulphate. Although iron also may have been present in the parent rock, and the two are sometimes deposited together, still they have in many in-

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[1] Hayer, Zeitschr. prakt. Geol., 1911: 407.

stances been separated from each other, because conditions favorable for precipitation are not the same for both, or because the soluble compounds of manganese formed by weathering are sometimes more stable than corresponding iron compounds, and hence may be carried farther by circulating waters before they are deposited. Manganese oxides may be precipitated from sea water, as nodules of it have been obtained by dredging from the sea bottom.

Few bedded deposits of manganese ore are known, but those of the Georgian Republic undoubtedly belong to this class. Bedded deposits of Cambrian age have been described by Dale from Newfoundland.[1] Manganese bog ore is also occasionally found.[2]

The most extensive and important deposits of manganese ore known, are with one exception, those occurring in residual clay, in which the manganese occurs as concretionary masses, and may have been deposited in colloidal form.

The oxides are also found as replacements of various rocks, and in veins. Rhodochrosite occurs as a gangue mineral, and at Butte, Mont., is present in commercial quantity.

Distribution of Manganese-bearing Ores in the United States (10).—Although the manganese-bearing ores are widely distributed in the United States, only a few localities are of commercial importance, and the manganese-mining industry has been shrinking for several years.

The reason for this is that the domestic ores are of much lower grade than the imported ones, and often require washing and sorting to render them marketable. Moreover, they occur in small, scattered pockets, often remote from lines of transportation, and may carry a high percentage of phosphorus and silica.

The demand is therefore supplied largely by high-grade ores from India, Brazil, and Russia, but the closing off of many of these sources during the European war temporarily stimulated manganese mining in the United States.

The occurrence of the four classes of domestic ores may be referred to separately.

Manganese Ores.—The best known occurrences of this somewhat widely scattered type of ore have been in the Appalachian and Piedmont regions, southern Mississippi Valley, and Pacific coast. The

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[1] Proc. Am. Phil. Soc., LIV: 371, 1913.

[2] Hewett, U. S. Geol. Surv., Bull. 795, 1927: Bancroft, Can. Geol. Surv., Sum. Rept., 1917, Pt. B: 28, 1918. Hewett, Ore Deposits of Western States, p. 488. (Sedimentary manganese in U. S.)

chief producing districts have been the James River Valley and Blue Ridge regions in Virginia; Cave Springs and Cartersville districts in Georgia; Batesville district, Arkansas; the Livermore-Tesla district in California, and Phillipsburg and Butte, Mont.

Eastern Area.—Manganese deposits are found in the Atlantic states from Vermont to Alabama, and two states in this belt, Georgia and Virginia (28, 32, 33), were formerly the leading domestic producers. In the crystalline rocks of the Piedmont province, deposits of commercial value have been proved only in Virginia. In this state the manganese area lies chiefly northeast and southwest of Lynchburg. The ore minerals are mostly granular pyrolusite and psilomelane, commonly occurring as nodules in residual clays from mica schists, quartzite and limestones of Cambrian age. Umber is sometimes present. In several mines where the workings have extended into hard rock, the ore occurs near the contact of quartzite, at times replacing the latter. Crystalline limestone is found closely associated with the ore deposits, but its relations to the ore are not definitely known.[1]

The Appalachian Valley deposits occur in two districts, viz., the Blue Ridge and New River.

The ores of the first district, which are the most important of the two, occur in a series of irregularly distributed deposits along the west foot of the Blue Ridge from Front Royal to Roanoke, a distance of about 150 miles. This same belt includes the Blue Ridge iron-ore deposits, which may sometimes contain an appreciable amount of manganese. So, too, iron may be found in the manganese deposits.

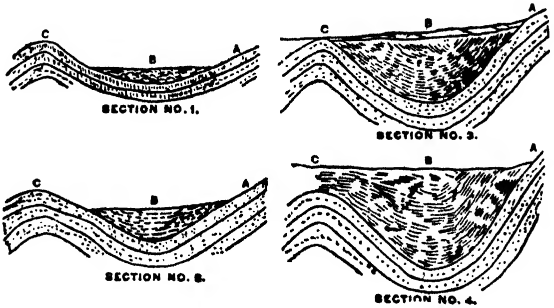

FIG. 246.—Sections of manganese deposit. Crimora, Va. (*After Hall.*)

The manganese ore occurs as pockets in clays of residual or sedimentary character, along the contact of the Lower Cambrian quartzite

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[1] Supplied by T. L. Watson.

with the overlying formation, and more rarely in fissures penetrating the quartzite.

The mine at Crimora (Fig. 246 and Pl. LXI) was one of the largest known. The ore formed pockets in residual clay, but it is no longer being worked.

In the New River district, the ore, which is mainly psilomelane, occurs as large masses mixed with iron ores in residual clay, but is of little commercial importance.

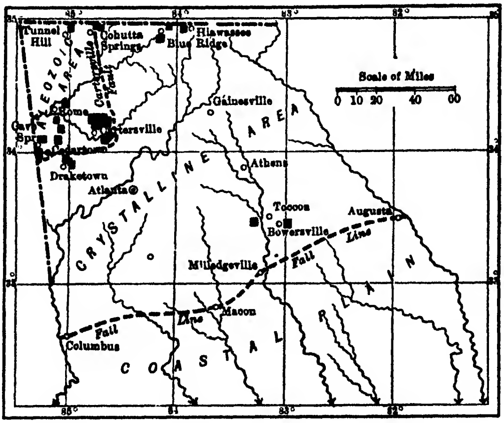

FIG. 247.—Map showing Georgia manganese areas. (*After Watson, Amer. Inst. Min. Engrs., Trans. XXXIV.*)

The Virginia areas mentioned extend southward into Tennessee, and some ore is mined there (10, 27).

Georgia.—In northern Georgia (4, 10, 33) the ore results from the decay of limestones and shales, Cave Spring and Cartersville being important localities (Fig. 247). The deposits are found in the areas underlain by both the crystalline and Palæozoic rocks, but only those associated with the latter have proved to be of importance. In this region the rocks consist of Cambro-Silurian limestones and quartzites, which have been much folded and faulted, and have been weathered down to a residual clay, which is often not less than 100 feet thick. The ore occurs as pockets, lenticular masses, stringers, grains, or lumps, irregularly scattered through the clay, and rarely forming distinct beds. None of the deposits are large, though some 30 feet in length have been worked. More or less limonite, barite, ocher, and

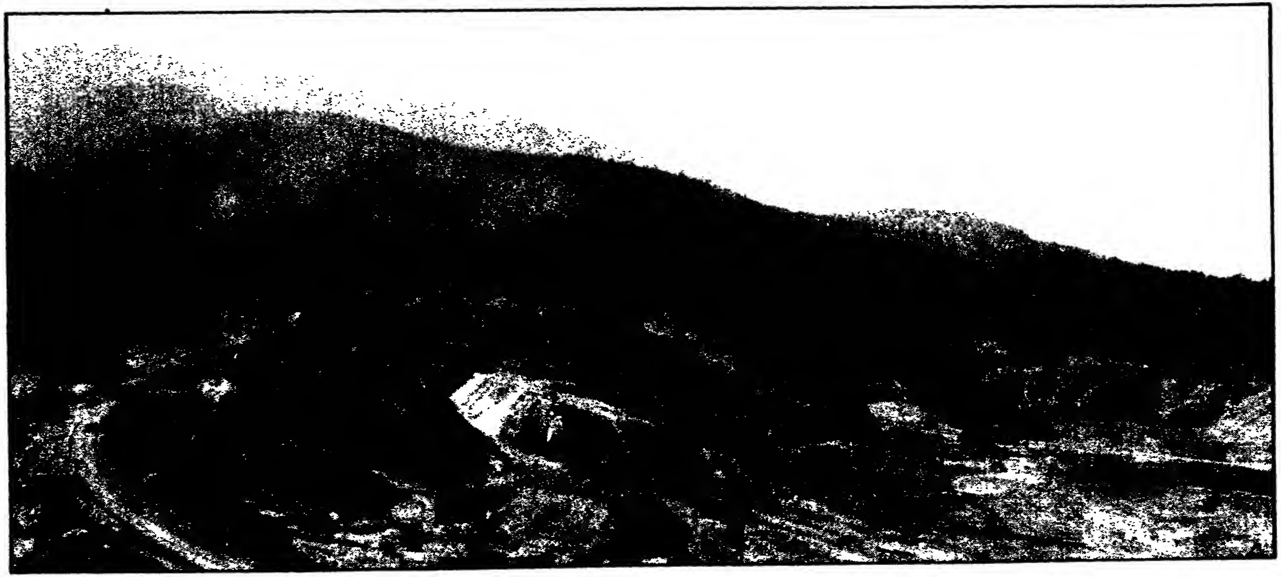

Plate LXI.—Panoramic view of Crimora Manganese Mine, Virginia. Ridges in background are quartzite of Blue Ridge. (*H. Ries, photo.*)

bauxite may be associated with the ore (Fig. 248), and, indeed, complete gradations from manganese to iron are found, as shown by the following analyses:

Mn	60.61	54.94	41.98	15.26	2.30
Fe	1.45	3.62	16.22	39.25	52.02
P	0.052	0.034	0.227	0.193	0.24

The better-grade ores are usually low in silica, iron, and phosphorus. In the Cartersville district, which is the more important, the ore is found in residual clays derived from the Beaver limestone and Weisner quartzite, while in the Cave Spring area it occurs only in the clays overlying the Knox dolomite.

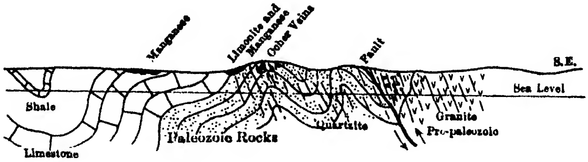

Fig. 248.—Section in Georgia manganese area, showing geologic relations of manganese limonite, and ocher. (*After Watson, Amer. Inst. Min. Engrs. Trans. XXXIV.*)

Penrose thought that the manganese was derived from the underlying Cambro-Silurian sediments, while Watson, on the contrary, believed that the crystalline rocks to the east and south had furnished the ore, as none is found in the parent rock from which the clays were derived. The manganese was probably taken into solution as a sulphate, and concentrated by circulating waters of meteoric origin in the residual clays where now found.

The Georgia deposits have been worked for a number of years. The ore, which has to be purified by washing and crushing, is used in part for paint and in part for steel manufacture.

Other Eastern Occurrences.—Deposits are known at several localities in Vermont, North Carolina, South Carolina, and Pennsylvania, but are unimportant commercially.

Lower Mississippi Valley and Gulf Region.—The Arkansas deposits are the only important ones in this region.

Arkansas.—Manganese ore is found in the region around Batesville (17), associated with horizontally stratified limestones and shales, ranging from Ordovician to Carboniferous Age (Fig. 249). The Cason

FIG. 1.—View of bauxite mine in Bryant district, Ark.

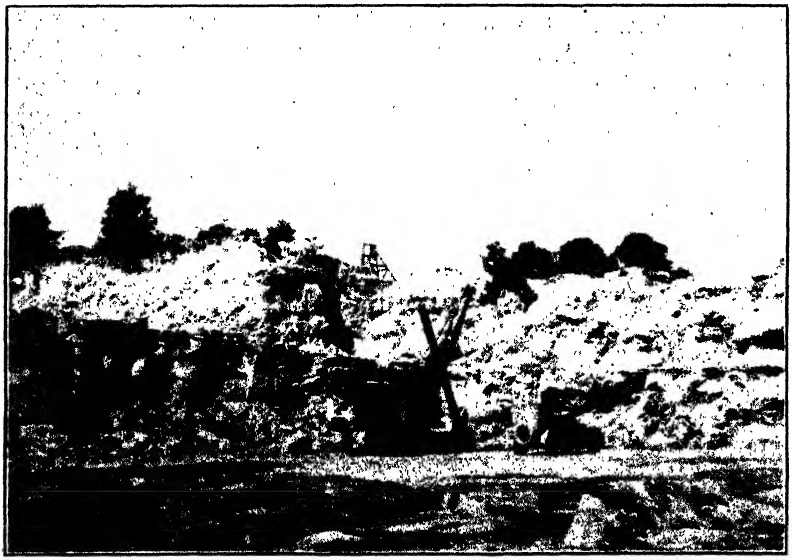

FIG. 2.—Sulphur Bank, California, mercury deposits. (*H. Ries, photo.*)

shale, of Silurian Age, occurring near the middle of the section (Fig. 249, *b*), carries manganiferous nodules, the rock being quarried and sold as low-grade ore. The best marketable ore (Fig. 249, *c*) occurs as nodules in residual clays occupying depressions in the Fernvale limestone. Some have suggested that the manganese found here has been derived by leaching from the shale horizon. The residual clays (Fig. 249, *a*), formed at a higher level than the Cason shale, are barren of manganese. Arkansas ranks next to Georgia in importance.

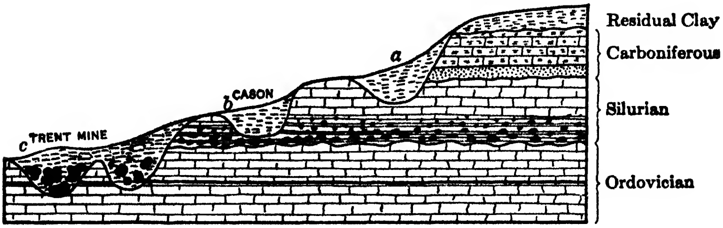

FIG. 249.—Section in Batesville, Ark., manganese region, illustrating geological structure and relation of different formations to marketable and non-marketable ore. (*After Van Ingen, Sch. of M. Quart., XXII.*)

Western States.—Montana has been a producer of carbonate ore from Butte. High-grade ore suitable for chemical purposes occurs in the Philipsburg district, where it forms tabular bodies or pockets in Cambrian limestone, associated with silver-bearing quartz veins and related to Tertiary granodiorite intrusions. The ore is a mixture of manganite and pyrolusite, but passes into rhodochrosite with depth.

At Butte the veins occurring in granite carry manganese oxides above, but pass into rhodochrosite and rhodonite with depth. Silver, zinc are associates. It was the largest producer in 1936.

A number of other deposits are found scattered over the west, especially in Nevada, Utah, California, New Mexico, etc.

Some, such as those at Las Vegas, Nev., and Topock, Ariz., are interesting because they occur as bedded replacement deposits in tuff. Veins, fissure fillings, and breccia deposits of manganese oxides occur in Tertiary lavas at many southwestern localities.

Manganiferous Iron Ores.—Those of the Appalachian Valley have already been referred to in connection with the manganese ores. The most important deposits are in Vermont, Virginia, and Tennessee, and consist chiefly of psilomelane and limonite mixtures. Much iron ore of the Lake Superior district carries from 2 to 10 per cent metallic manganese, and some large bodies are known on the Cuyuna range.[1]

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[1] Harder, Amer. Inst. Min. Engrs., Bull. 129, 1917.

The average manganese content over a 24-year period from the different ranges is given by Zapffe (37) as: Gogebic, 3.87; Menominee, 4.72; Mesabi, 2.86; and Cuyuna, 11.32. The greatest demand is for ores running 8–10 per cent Mn. Beneficiation of the ores is possible. Other occurrences have been noted from Gunnison County, Colorado (10), Juab County, Utah, and Missouri, but they are not of commercial value.

Manganiferous Silver Ores.—The most important deposits are those found at Leadville, Colorado. Manganiferous silver and iron ores are important in the oxidized zone of the Leadville district, forming large masses adjacent to the sulphide deposits. Some have suggested that they represented infiltrations from the porphyry, but P. Argall has shown that manganiferous siderite in irregular masses is abundant as a limestone replacement. He therefore suggests that weathering of the siderite has yielded the manganese. The ores range as follows: manganese, trace 40 per cent; iron, 8–50 per cent; lead, trace 5 per cent; insoluble, 5–34 per cent; silver (in 1914) 2–25 ounces per ton; gold, trace. Ores of similar character are found at Neihart and Castle, Mont. Rhodochrosite occurs in the silver veins at Butte, Mont., and a considerable amount has been shipped. Still other manganiferous silver ores have been noted from scattered localities in New Mexico, Arizona, Utah, and Nevada, but appear to be of little commercial importance. Some found in the Tintic district, Utah, have been used as flux at the local smelters.

Canada (17).—The Canadian production is very small. A number of scattered deposits are known in Nova Scotia, New Brunswick, and Quebec.

Other Foreign Deposits (23).—The Tschiaturi deposits of Georgia in southeastern Russia, represent the largest known manganese deposits of the world, the reserves being not less than 50,000,000 tons. The manganese ore forms beds 5 to 8 feet thick, occurring near the base of the Eocene, and associated with marls, clays, and sandstone. The ore is oölitic pyrolusite in a matrix of earthy manganese ore, and is undoubtedly of sedimentary origin.[1] Other extensive deposits occur in the Ukraine, but they are more siliceous than the Georgian ones (23).

India.—Much manganese ore is mined in the Madras and Bombay Presidencies of Central India.[2] The ores are all oxides and occur: (1) associated with or derived from manganese-bearing silicates, as bands or lenticles, in Archaean gneisses and schists; (2) as superficial formations on the outcrops of

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[1] Sauce, Beiträge z. Kenntniss der Manganerz Lagerstätte von Tschiaturi im Kaukasus, Abh. z. prak. Geol., Bd 8, 1926.

[2] Fermor, Geol. Surv., India, Mem. 37, 1909.

such rocks as quartzites, shales, slates and hematite-schists; and (3) as concretions in laterite.

Brazil,[3] a third important world's producer, has important deposits in Minas Geraes. They are residual ores, which have been formed by the weathering of schists containing spessartite, rhodochrosite and tephroite. Other deposits occur in Bahia.

Cuba.—Manganese ores are found in three districts: Oriente, Santa Clara, and Pinar del Rio, but only the first is of commercial importance. The ores are associated with sedimentary rocks, and occur in residual clay associated with jasper. Replacements of limestone are also known. Pyrolusite, psilomelane, manganite and wad are found (2).

Gold Coast (23).—Here again there are residual manganese ores of great extent, the proven reserves being 10,000,000 tons. The bed rocks are metamorphosed sediments, which contain rhodonite and spessartite, and it is from these that the manganese ores have been derived, the latter being both massive and concretionary.

Uses of Manganese.—The chief use of manganese is in the metallurgical industry, probably 15 pounds of manganese being required for every ton of steel produced. Next in importance comes its use in the battery industry, and in addition there are miscellaneous uses.

Production of Manganese.—The quantity (long tons) of manganiferous raw materials shipped in the United States in 1940 was: manganese ore, 36,429; ferruginous manganese ore (10–35 per cent Mn), 320,000; manganiferous iron ore (5–10 per cent Mn), 816,541, having a total value of $4,424,687. Montana is the leading producer of man-

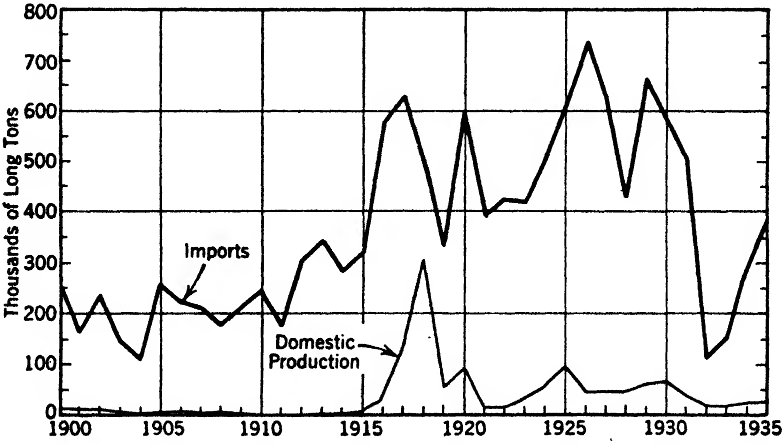

FIG. 250.—Imports and domestic production of manganese ore, 1900–1935. (*Minerals Yearbook.*)

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[3] Harder, Amer. Inst. Min. Engrs., Trans. LVI: 786, 1917; Singewald and Miller, *Ibid.*, LVI: 7, 1917.

ganese ore and Minnesota of both ferruginous manganese ore and manganiferous iron ore.

The imports of manganese ore into the United States in 1940 were 1,282,079 long tons, of which Russia supplied 24 per cent; Gold Coast, 19 per cent; India, 14.7 per cent; Brazil, 13 per cent; and Cuba, 10 per cent. The Canadian production for 1939 was 396 tons, valued at $3688 and came entirely from New Brunswick.

The world's production of manganese ore in 1938 was 5,107,000 metric tons.

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MERCURY

Ore Minerals.—While mercury is sometimes found native in the form of *quicksilver*, the commonest ore mineral is *cinnabar* (HgS), which contains 86.2 per cent mercury. Native amalgam of mercury and silver is known, and *calomel,* the chloride, as well as other compounds, are sometimes found.

Among the less common ones may be mentioned: *montroydite* (HgO); *tiemannite* ($HgSe$); *onofrite* ($Hg(S,Se)$); and *coloradoite* ($(HgTe)_4$). *Schwatzite,* the mercurial tetrahedrite, is not uncommon, being known from a number of localities in Europe and South America. In the United States it is known in the Blue Mountains, Oregon, and may have been the original ore mineral, whose decomposition formed the present mercurial ore minerals at some other localities (Plomosa district, Arizona, and La Plata district, Colorado).

The commercial sources of mercury contain a comparatively small amount of other metallic minerals, although a number of different ones have been found and cinnabar may at times occur in small quantities in veins of the other metals. Thus it is a frequent accompaniment of stibnite, and is also found in some gold and copper deposits. The dyscrasite found in the Cobalt, Ontario, silver veins, also carries mercury.

Mode of Occurrence.—Mercury ores are not confined to any particular formation, but are found in rocks ranging from the Ordovician to Recent age in different parts of the world. Nor are they peculiar to any special type of rock, although igneous rocks are often found in the vicinity of them. They occur as veins, disseminations, or as masses of irregular form. Silica, either crystalline or opaline, and calcite are common gangue minerals, while pyrite or marcasite are rarely wanting, and bitumen is widespread.

Many mercury deposits occur along lines of fissuring, and these may be marked by hot springs.

The commercially valuable occurrences have apparently been deposited at shallow depths, although mercury minerals are sometimes found in small quantities in the intermediate and even deeper vein zone.

Tenor of Ores.—The percentage of mercury in many ores of this metal is very low. Those of Almaden, Spain, are said to average 6 per cent, and are probably the richest worked anywhere. The average tenor for Pacific coast ores given for 1918 was 0.38 per cent, while Texas in the same year averaged 0.87 per cent, Idria, Italy, 0.65 per cent, and Mte. Amiata, Italy, 0.89 per cent.

Origin.—The origin of mercury ores has been studied chiefly by Becker and later by Schrauf (17). The former points out that silica (either crystalline or amorphous) and calcite are common gangue minerals, but pyrite or marcasite are almost equally abundant, as is also bitumen. In addition to these, the ores show an irregular association with other metallic minerals, such as antimony, silver, lead, copper, arsenic, zinc, or even gold. Becker believes that the cinnabar has been precipitated from ascending waters by bituminous matter, having come up in solution as a double sulphide with alkaline sulphides. He further suggests that the deposits represent impregnations and are not replacements.

Hot springs carrying mercury in solution are known at Steamboat Springs, Nev. (Pl. XXXIV, Fig. 2), and Sulphur Bank, Calif.

Distribution in the United States.—California has always been the most important producing state. Deposits are, however, also known in Texas, Oregon, Utah, Nevada, New Mexico, and Arizona.

California (24) (Fig. 251).—The California ores occur chiefly in metamorphosed Cretaceous or Jurassic rocks, with some in the Miocene and even Quaternary. The deposits, which are termed "chambered veins" by Becker, are fissured zones. Eruptive rocks seem in many cases to be involved in the ore formation, and at New Almaden a rhyolite dike runs paralled with the ore body. The ore here occurs along the contact between serpentine and shale, filling in part the interstices of a breccia. These mines, which were the largest in the state, have been worked to a depth of over 2,500 feet, but were closed down in 1926.

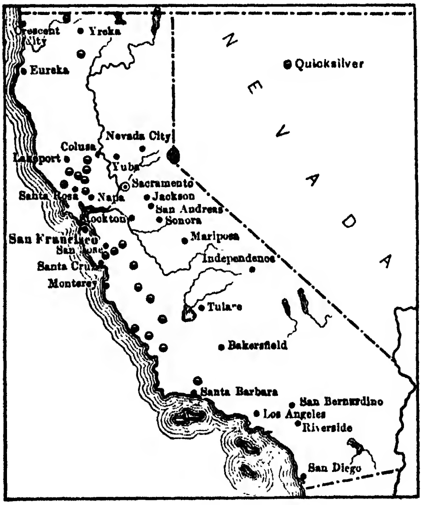

FIG. 251.—Map of California mercury localities.

At the New Idria mine, located in southeastern San Benito County, the ore bodies occurred in metamorphic rocks of Lower Cretaceous age, just south of their contact with the unaltered sediments of the Chico (Lower Cretaceous) formation. The ore, which consists of a mixture of pyrite and cinnabar, with a gangue of silicified and brecciated metamorphic sandstones and shales, may occur as veins, stockworks or impregnations. It is interesting to note that in driving a tunnel to connect with the 1060-foot level considerable natural gas was encountered, and that at another locality, New Almaden, exhalations of carbon dioxide were encountered in some of the lower levels.

At Sulphur Bank (LXII, Fig. 2) the ore is found as disseminations and in fractures in volcanic rocks. Associated with it is native sulphur formed from the H_2S fumes which escape from below.

Other occurrences are in Colusa County, where the cinnabar is found in altered serpentine, and in Napa County, where it occurs along the contact of sandstone and slate. The minerals associated with these are bitumen, free sulphur, stibnite, mispickel, gold and silver, chalcopyrite, pyrite, millerite, quartz, calcite, barite, and borax. The vein is a fissure filled with brecciated fragments, and cuts through sandstone, shale, and augite andesite, the cinnabar cementing the breccia together, but at times also impregnating the walls. Hot waters which circulate through the vein still deposit gelatinous silica.

Mercury has been found in Idaho in the Yellow Pine district, but the production is not important.[1] Another district is east of Lovelock, Pershing County, Nev. (11) and there is appreciable production from Malheur County, Ore.[2]

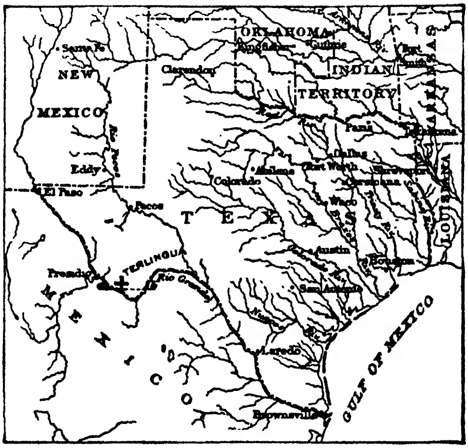

FIG. 252.—Map showing Texas mercury region. (*After Hill, Eng. and Min. Jour., LXXIV.*)

Texas (10, 13, 23).—The Terlingua district in southern Brewster County has been a producer for 30 years. The area is about 84 miles from the Southern Pacific railroad in a very arid region, and contains about 30 mines and prospects.

The rocks are sediments of Cretaceous age cut by igneous rocks, and faulted. In addition the sediments exhibit several anticlinal structures to which the ore bodies seem to be related.

Ore has been mined from the Edwards-Georgetown limestone, Del Rio shale and Buda limestone of the middle Cretaceous, and from the Eagle Ford shale, Austin and Taylor limestones of the upper Cretaceous. At one place ore was also found in a porphyry sheet. The ore occurs most frequently in fissure veins (Figs. 253, 254), but some is found in breccias and lateral enrichment deposits.

The chief ore mineral is cinnabar, but in addition some quick-

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[1] Schrader and Ross, U. S. Geol. Surv., Bull. 780: 137, 1926.

[2] U. S. Min. Res., 1927.

silver and oxychlorides of mercury are found. Ross (17) suggests that the cinnabar is the only hypogene mercury mineral, and that the others have resulted from its oxidation. The gangue minerals are calcite, much of it bituminous, aragonite, gypsum, iron oxides, pyrites, psilomelane, and pyrolusite.

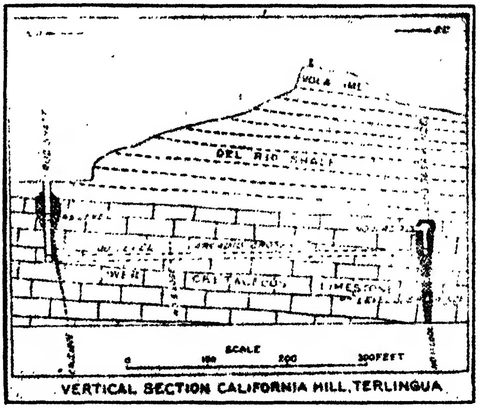

FIG. 253.—Vertical section of California Hill, Terlingua, Tex. (*After Turner, Econ. Geol., I.*)

Arkansas. — Cinnabar occurs in southeastern Arkansas in a district about 30 miles long and under 2 miles wide, in sandstones of Pennsylvanian age, which have been folded into a vertical position and faulted.

The ores occur chiefly as fracture fillings in the sandstone, with cinnabar, quartz, and dickite as the principal minerals. They are considered to be of hydrothermal origin. The maximum depth reached in mining is something over 200 feet. Development began in 1931 (5).

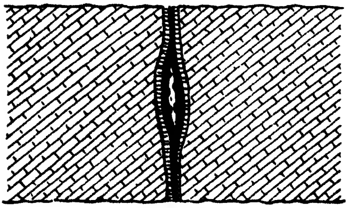

FIG. 254.—Section of cinnabar vein in limestone, Terlingua, Tex. (*After Phillips, Univ. Tex. Min. Surv., Bull. 4.*)

Foreign Deposits.[1]– Spain[2] is the largest producer, with Italy a close second. In the first-named country, the Almaden deposit is the world's greatest producer. Here the ore forms impregnations and replacements of three steeply dipping beds of Silurian quartzite. The principal bed is 8 to 14 meters thick, and the ore averages about 8 per cent mercury. This deposit, unlike most others, extends to a considerable depth. At Monte Amiata in Tuscany the ore occurs as disseminations, chimneys, etc., in Cretaceous and Tertiary limestones, shales, and sandstones associated with trachyte. A third large deposit is that at Idria, Italy, where the ore, chiefly cinnabar, but sometimes native mercury, is found forming impregnations, stockworks, and veins in limestones, shales, marls, and dolomites of Triassic age. There seems to be a connection between the ore deposition and a large overthrust of post-Cretaceous times.

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[1] Beyschlag, Vogt, and Krusch, Translation by Truscott, I: 454, 1914.

[2] DeKalb and Ransome, Econ. Geol., XVI: 301, 1921.

Mexico[1] and Czechoslovakia are also contributors to the world's production. Huancavelica, Peru (4), was formerly an important producer.

Uses of Mercury.—Quicksilver is used chiefly in the manufacture of electric appliances, drugs, scientific apparatus, and fulminate for explosive caps. Mercury fulminate is being replaced by picric acid, trinitrotoluene, etc. Quicksilver is used in decreasing quantity for the recovery of precious metals, especially gold, because of the increased use of the cyanide process, the decrease of free-milling gold ores and placer gravels, and the increased efficiency and economy in stamp milling, resulting in a decreased loss of quicksilver. Mercuric oxide (red oxide of mercury) is the active poison in antifouling paint for ships' bottoms. Quicksilver, though formerly much used for silvering mirrors, is now largely replaced by silver nitrate. A new use of quicksilver vapor is for generating power. In the last few years cinnabar has found an increased use for coloring rubber products, however organic dyes may be used as a substitute for it.

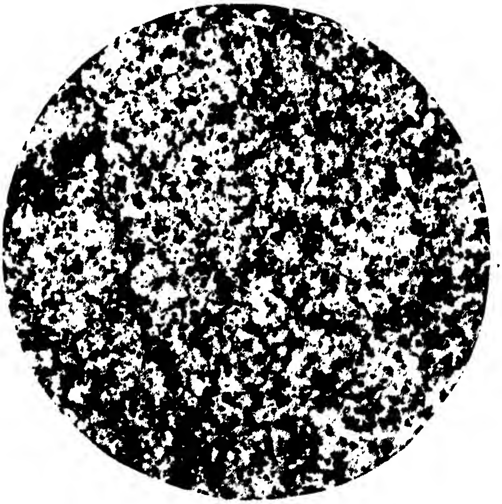

Fig. 255.—Thin section of limestone impregnated and replaced (?) by cinnabar Idria, Italy. ×33.

Extraction.—Cinnabar is easily decomposed by heat, giving off when heated in air, or retorted with quicklime, the mercury vapors and sulphur dioxide in one case, or mercury, calcium sulphide, and calcium sulphate in the other. The mercury is collected by subsequent condensation.

Retorts are adapted only to ores carrying 4 per cent or more of mercury,

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[1] Zeitschr., prak. Geol., VI: 91.

while low grade ores are treated in shaft furnaces, some of the more modern ones being capable of treating an ore running as low as 0.25 per cent metal.

Production of Mercury.—The production of mercury in the United States in 1940 amounted to 37,777 flasks (of 76 pounds each) valued at $6,681,618. The imports for the same period were 171 flasks with a value of $17,961. The value per flask in 1940 was $176.87 in New York. The production for the last few years has varied considerably.

Canada can now meet its own requirements.

The world's production in 1938 was 148,343 flasks or 5113.7 metric tons. Of this amount Spain yielded 27 per cent, United States 11.4 per cent, and Italy 44 per cent.

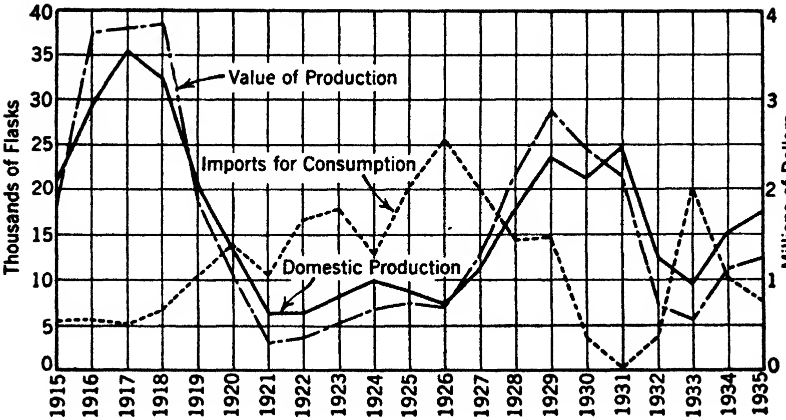

FIG. 256.—Trends in domestic production, value, and imports of mercury, 1915–1935. (*Minerals Yearbook*, 1936.)

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CHAPTER XIX

MINOR METALS (Continued)

ANTIMONY TO VANADIUM

ANTIMONY

Ore Minerals.—*Stibnite* (Sb_2S_3) is the most important ore of antimony, and the metal is rarely obtained from any other mineral, although native antimony has been sparingly found. The oxide *senarmontite* (Sb_2O_3)[1] seldom occurs in any quantity. A small amount of antimony is present in some silver-lead ores. The stibnite, together with a gangue of quartz, and frequently calcite, usually forms veins cutting igneous, sedimentary, or metamorphic rocks, and less often is found in replacement deposits. Other metallic sulphides may be associated with the antimony; some deposits are auriferous, and less often argentiferous.

Stibnite is not necessarily a mineral of the shallow-vein zone, for it may occur in deposits formed at intermediate depths, or even in the deep-vein zone, but commercial deposits occur chiefly in the shallow zone.

Cairnes (3) classifies antimony deposits as follows:

- I. Ores deposited in cavities, chiefly fissure veins.
    - *a*. Of value, chiefly or entirely for antimony.
    - *b*. Auriferous stibnite.
    - *c*. Antimony and silver.
- II. Replacement, chiefly in limestone.

Distribution of Antimony in United States.—Antimony has been found at a number of localities in the Cordilleran region, but the great distance of the deposits from the railroad has helped to make them of little commercial value, and the domestic production is very small and irregular.

It is therefore only the richest and best-located deposits that are worked. Some of the known ore bodies are also said to lack value

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[1] Others are cervantite (SbO_2) and stibiconite ($H_2Sb_2O_5$).

because of their content of arsenic, zinc, or lead minerals, and hence are refused by the buyers so long as they can get purer ores (Hess).

Many gold and silver ores carry some antimony, and in smelting it combines with the lead, giving a product known as antimonial lead, much of which is produced in the United States.

The large amount of antimony now manufactured in the United States is obtained: (1) as by-product from the smelting of foreign and domestic lead-silver ores containing small quantities of antimony; (2) from antimony regulus, or metal from foreign countries; (3) from foreign ore; and (4) from some copper ores.

Very little has been published regarding the occurrence of antimony ores in the United States. Hess has described some deposits in Arkansas (5), where the antimony occurs as bedded veins in sandstones and shales, with a quartz gangue, and associated with a number of different metallic minerals. The deposits are of doubtful value, except possibly when high market prices prevail.

Along Coyote Creek, in Garfield County, Utah (10), there are found flat-lying deposits of stibnite and its oxidation products in Eocene (Tertiary) sandstone and conglomerates. The ore in sight is all low grade, although some rich pockets have been worked out in the past.

Stibnite veins in rhyolites and basalts are known in western Nevada, and have been specially referred to in the National district (8). There, the fissures, which have a quartz gangue, all carry more or less stibnite, together with small amounts of pyrite, blende, etc.

Canada.—The Canadian production of antimony is small and spasmodic.

It occurs at West Gore, Nova Scotia (4) in fissure veins in Cambrian slates. The minerals are stibnite, native antimony, pyrite (auriferous), mispickel, kermesite (Sb_2S_2O) in a gangue of crushed slate, quartz, and calcite. Other veins are found at Prince William, near Fredericton, New Brunswick (13). An interesting series of veins in granite is found in the Wheaton River district, Yukon Territory. The veins, which occur chiefly in granite and vary from a few inches to 5 feet in width, carry stibnite, sphalerite, tetrahedrite, argentiferous galena, and antimony ochre, in a gangue of quartz (3).

Other Foreign Deposits.—China is the largest producer of the world, the deposits of the Hunan Province[1] being of importance. There the ore near Hsinhua is distributed in seams, pockets, and bunches in Carboniferous dolomite, while at the Pan-shi mines it occurs as fissure veins in sediments (6).

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[1] Wheeler, Eng. and Min. Jour., CI: 637, 1916.

France was formerly a large producer, numerous deposits being found in the Central Plateau region. The veins, which cut schists, granite, and also clastics, carry stibnite in a quartz gangue.

The Japanese veins are found chiefly in Mesozoic and Paleozoic sediments, often near quartz porphyry, or even in it.

Replacement deposits are known in Italy,[1] Algeria,[2] and Mexico.

Uses.—Antimony metal is used chiefly in the manufacture of alloys of lead, tin, zinc, etc. Type metal, which is an alloy of lead, antimony, and bismuth, has the property of expanding at the moment of solidification. Britannia metal is tin with 10 to 16 per cent antimony and 3 per cent copper. Babbitt, or antifriction metal, consists of antimony and tin, with small amounts of lead, copper, bismuth, zinc, and nickel. These antimonial lead alloys consume about 7.2 per cent of the total utilized, and most of it is recoverable. Tartar emetic, a potassium-antimony tartrate, antimony fluoride, and ammonium sulphide, and other double salts are used in medicine and as a mordant for dyeing, while antimony persulphide is employed for vulcanizing and coloring rubber. Antimony trioxide is employed as a substitute for white lead, zinc oxide, etc., in pigments. It is also used in a glaze for coating enameled iron ware, as a reducing agent in chemical work, and as a detector of alkaloids and phenols. The trichloride is used in bronzing gun barrels, in coloring zinc black, and as a mordant for patent leather and silver. Antimony is used in storage batteries, and vermilion red for coloring rubber. Antimony trisulphide is used in pyrotechnics for making "Bengal fire." Antimony chromate, or "Naples yellow," is used for coloring.

Production of Antimony.—In 1940 there was produced 1124 short tons of ore and concentrates, containing 494 short tons of antimony. The equivalent of 1915 short tons of antimony was also produced as a by-product from antimonial lead. In addition 162 short tons from foreign ores and 867 short tons from scrap.

The imports in 1940 were 37,966 short tons of antimony ore, with an antimony content of 15,733 short tons of antimony, valued at $2,027,612, and 209 tons of antimony metal valued at $50,048. The exports in 1940 were: foreign antimony (regulus or metal), 711 short tons, valued at $96,836.

The price of antimony in New York was 14.0 cents per pound.

Canada has not produced any antimony from 1917–1938, although small quantities have been obtained in the past. In 1939 there were

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[1] Bergeat, Erzlagerstätten, II: 883.

[2] Fuchs and de Launay, Gites Mineraux, 2: 205.

produced 1,225,585 pounds valued at $151,469, mostly from the Trail smelter in British Columbia.

The world's production of antimony in 1938 was 32,200 metric tons. Of this amount China, Mexico and Bolivia each produced about 23 per cent, and Yugoslavia about 6 per cent.

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ARSENIC

Ore Minerals.—Although arsenic-bearing minerals are widely distributed in many countries, the commercially valuable occurrences are few, and moreover few arsenic-bearing minerals are important as sources of the metal. *Arsenopyrite* (FeAsS with 46.02 As) is the most important and the most widely distributed of the arsenic minerals. It may occur in schists, gneisses, pegmatites, contact-metamorphic deposits, or quartz veins, and usually favors deep-zone conditions. Other sulphides may be associated with it, as well as gold and silver.

Orpiment (As_2S_3, 60.96 As) and *realgar* (As_2S_2, 70.08 As) may be both original and secondary minerals, formed usually at shallow depths, but comparatively unimportant as ores, although considerable quantities of the latter are said to be mined in China (2). The two occur in some quantity also at Mineral Creek, Lewis County, Washington.

Native Arsenic, though occasionally found, is never in commercial quantities, and the oxides *arsenolite* and *claudetite,* of secondary nature, are likewise unimportant.

Arsenic is found combined with a number of metals, or with a metal and sulphur in many primary ore deposits. Among the better known of these compounds occurring in ore deposits of the United States or Canada alone may be mentioned enargite (Cu_3AsS_4), tennantite ($Cu_8As_2S_7$), proustite ($Ag_6As_2S_6$), smaltite ($CoAs_2$), niccolite

(NiAs), chloanthite ($NiAs_2$), cobaltite (CoAsS), and sperrylite ($PtAs_2$). Of these, the enargite is an important ore mineral at Butte, Mont.

Distribution in the United States.—No deposits are worked exclusively for their arsenic contents, but some have been prospected in Utah, Virginia (8), and Washington. The domestic supply is a by-product, produced by the smelters of the American Smelting and Refining Co., the Anaconda Copper Mining Co., the Jardine Mining Co., and the United States Smelting, Refining and Mining Co.

Foreign Deposits.—White arsenic is made as a by-product in Canada, being saved by the smelters at Thorold, Copper Cliff, and Orillia, Ontario, from arsenical silver ores from Cobalt, Ontario.

Arsenic is produced in Mexico as a by-product in smelting lead ores.

Uses of Arsenic.—Of the white arsenic used in the United States, insecticides consume about 70 per cent; weed killers, 16 per cent; glass industry, 2 per cent. A new arsenic-copper combination, AsCu, is gaining in importance as a wood preservative.

A comparatively small amount of arsenic is used in the form of metal, as in the manufacture of shot, in lead base alloys for battery-grids, bearings, electric cable sheathing, medicine, etc. Realgar is used in printing, tanning, and pyrotechnics, and orpiment in textile dyeing.

Production of Arsenic.—The production (sales) of white arsenic in the United States in 1940 was 23,339 short tons, obtained as a by-product in the smelting of other ores. The production has been rising in the last 4 years. The imports of white arsenic for the same year were 9929 short tons, valued at $453,030, while the exports were probably about 3900 tons.

Canada in 1939 recovered from its silver-cobalt ores 870 tons valued at $52,257. The imports of arsenic compounds for that year were valued at $87,650, and the exports $26,389.

In addition to the United States, Mexico and West Australia, other important producers have been France and Germany. Sweden, however, has also been a large producer.

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BISMUTH

Ore Minerals.—The principal ores of this metal, together with percentage of metallic bismuth which they contain, are: *bismuthinite* (Bi_2S_3, 81.2); *bismite* (Bi_2O_3, 96.6); and *bismutite* (Bi_2O_3, CO_2, H_2O, 80.6). Although all of these contain a high percentage of metallic bismuth, the content of the ore as mined does not usually exceed 10 or 15 per cent. Native bismuth is likewise found at a number of localities.

Bismuth ore minerals are almost invariably associated with other metallic minerals, which are the primary object of mining operations, the bismuth being a by-product obtained in the treatment of these.

Distribution of Bismuth in the United States.—Very little bismuth ore is mined as such in the United States, and practically all of that used in this country is obtained as a by-product from lead ore smelting. The bismuth is an impurity which has to be removed from the refined lead. The lead ores contain on the average from 0.15 to 0.25 per cent bismuth. Experiments (2) show that the flue dust of Anaconda, Mont., smelter carried 1.15 per cent bismuth trioxide, and amounted to about 275 tons per year.

Some of the gold ores on Breece Hill, near Leadville, Colo., carry as much as 5 to 8 per cent bismuth,[1] and nearly all of the gold ores at Goldfield, Nev. (*q.v.*), carry this metal, partly in the form of bismuthinite. Other western ores also carry bismuth.

Foreign Deposits.—The deposits of economic value in foreign countries are comparatively few. The mines of Schneeberg, Altenberg, Annaberg, and Johann-Georgenstadt, in Saxony, have contributed considerable bismuth ore in the past. The bismuth here is chiefly native. At Schneeberg the ores are chiefly in cobalt-bearing veins. At Joachimsthal, Czechoslovakia, the metal occurs in argentiferous veins. Bismuth as native metal, ochre, and carbonate, associated with gold, silver, and tin, have been found at Tasna and Choroloque, Bolivia. The former occurrence is in slates, and the latter in porphyry. This country is the world's chief source of supply. At Meymac, France, bismuth ores have been found in veins in granite, together with wolframite and arsenopyrite.

A large amount of bismuth occurs in South America, and the deposits form the world's chief source of supply. Much has also been shipped from China to England and Germany.

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[1] George Argall, private communication.

The Cerro de Pasco Copper Corporation, in Peru, has obtained bismuth by treating the residues from its lead ores.

The smelter at Trail, British Columbia, is said to be producing bismuth at its electrolytic refinery.

The only Australian colony producing bismuth in any quantity is Queensland.

In New South Wales native bismuth, and bismuthinite associated with molybdenite in quartz gangue, forms pipes in granite in the Kingsgate district (3).

Uses of Bismuth.—Bismuth has been used chiefly for medicinal and pharmaceutical purposes, but attempts are being made to increase its industrial uses. With lead, tin, and cadmium it forms an easily fusible alloy whose melting point lies between 64° and 94.5° C. Such alloys can be used in safety fuses, dental amalgams, and automatic sprinklers.

Production of Bismuth.—For some years bismuth has been produced in the United States as a by-product of lead and copper smelting, but statistics of production are not given out.

The imports in 1940 were: bismuth, 123,880 pounds, valued at $118,260; compounds, mixtures, and salts, 4 pounds, valued at $31. Much bismuth comes in lead bullion and hence is not recorded.

Canada in 1939 produced 409,449 pounds of bismuth, valued at $466,362. This came from silver-lead ores treated at Trail, B. C. Metallic bismuth in the amount of 10,252 pounds valued at $10,835 was imported, and also $8671 worth of bismuth salts.

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CADMIUM

The chief ore mineral of cadmium is *greenockite* (CdS), but no deposits of this mineral are known, and it is found chiefly in association with sphalerite. Greenockite occurs in the Joplin, Mo., district as a greenish yellow coating on sphalerite, being a secondary deposit which has been caused by the decomposition of cadmium-bearing blende in the upper part of the ore body, and the precipitation of the sulphide at lower levels. The table on p. 668 gives the analyses of a number of samples of Missouri ore and their cadmium contents.

The calamine ores from Hanover, N. M., also contain cadmium in sufficient quantity to give a yellow tint to the zinc oxide made from them.

Cadmium is produced as a by-product, Canada, Germany, the United States, and Australia being the chief producers in 1936.

It is obtained from: (1) zinc ores treated by fractional distillation; (2) bag-house fumes from lead smelters treating zinciferous ores; and (3) residues from the purification of zinc solutions at electrolytic zinc or lithopone plants.

ANALYSES OF CADMIFEROUS ZINC BLENDES
(W. George Waring, analyst)

ORE	ZINC	IRON	LEAD	COPPER	CADMIUM
Sphinx mine, Neck City, Mo.	65.77	0.55	0.00	0.077	0.135
Ore from Golconda, Ill. . . .	60.55	1.18	0.51	0.046	0.110
Standard mine, Fortuna, Mo.	61.97	0.55	0.815	0.133	0.436
Maude B..mine, Webb City, Mo.	55.70	4.90	Trace	Trace	0.227
Big Six mine, Aurora, Mo. .	56.75	1.88	None	0.004	0.018
McKinley mine, Prosperity, Mo.	57.20	1.25	5.29	None	0.550
Hudson mine, Pleasant Valley, Mo.	62.05	0.61	None	0.030	0.322
Underwriters' mine, Webb City, Mo.	57.95	1.60	1.62	——	0.710
Blende from Kentucky fluorspar mines	53.50	0.77	0.76	None	0.211
Average of 2270 carloads from Webb City, Mo., 1902.	57.08	2.60	0.90	0.050	0.337

The quantity of cadmium present in zinc ores is small. Thus the highest Silesian blende carried 0.259 per cent Cd, the lowest 0.004 per cent, and a calamine had 0.306 per cent. Shipments from the Joplin district in 1903 and 1904 gave 0.304 to 0.388 per cent (3). Some zinc ore from Brazil is credited with 2.4 per cent.

Uses of Cadmium.—A somewhat recent use of cadmium is as a bearing metal in the automobile industry, but prior to that time most of it was used for rust-proofing nuts, bolts, etc. It can also be employed for low-melting alloys. Cadmium and copper are said to have the best combination of electrical and mechanical properties for trolley wires, etc. Cadmium salts can be used as a source of the metal for plating and in pigments. Some are also employed in photography. Cadmium yellow is an important pigment.

Production of Cadmium.—The production of metallic cadmium in the United States in 1940 was 5,921,488 pounds, while the cadmium content of cadmium compounds was 845,000 pounds. In general, the domestic production has been increasing in recent years. The imports of metallic cadmium in 1940 were 27,491 pounds.

The Canadian production of metallic cadmium in 1939 was valued at $662,209, and came mostly from Trail, British Columbia, and Flin Flon, Manitoba.

Those countries which are the heaviest producers of zinc are the largest producers of cadmium.

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CHROMIC IRON ORE

Ore Minerals.—*Chromite* (FeO, Cr_2O_3) is the chief source of the compounds of the metal chromium which are used in the arts. This mineral occurs in basic rocks like peridotites or in the serpentines derived from them.

A number of other chromium bearing minerals are known (5), but they are of no commercial importance. Chromite is rather resistant to weathering, and where chrome silicates are found associated with it, they were probably the latest primary chrome bearing minerals to form (5). These silicates may include the chrome garnet (*ouvarovite*), chrome diopside, chrome mica (*fuchsite*), and chrome chlorides (*kammererite* and *kotschubeite*).

Occurrence and Origin (5).—Chromite may occur as disseminated grains, bunches, stringers, or in lenses, the last named being the type commonly worked. Some ores showed a banded structure. The origin of the ore is usually ascribed to magmatic segregation, but there is

	France	Coleraine, Can., Concentrated Product	Asia Minor	Styria	Calif.	Russia
Cr_2O_3	37.00	53.64	53.00	53.00	42.20	59.00
SiO_2	2.53	2.31	2.15	2.50	5.48	2.20
Al_2O_3	13.15	14.02	7.62	8.00	13.60	10.00
MgO	12.53	15.75	13.31	11.58	14.88	11.62
FeO	34.79	11.47	24.92	24.92	23.84	18.18
CaO	——	2.81	——	——	——	——

some difference of opinion as to whether the chromite crystallized early or late in the consolidation process (8, 19, 20). In most cases the igneous rock is more or less completely serpentinized.

Analyses.—The table on p. 669 gives the composition of several of the types of chromic iron ores.

Distribution of Chromite in the United States (5).—Chromite mining is an industry of very little importance in the United States, because the deposits, though widespread, are rarely of workable size. Deposits are known in Maryland (22), Pennsylvania (4), North Carolina (16), Wyoming, and California (5).

The ore was at one time obtained from Chester and Delaware counties, Pennsylvania, and Baltimore County, Maryland, but these localities are no longer worked. Chromite sand was formerly obtained from stream deposits within the chromiferous serpentine area of Maryland.

California (5) contains a number of chromic iron ore deposits, scattered through the serpentine and closely related intrusive rocks of the Coast Range and the Sierra Nevada, but the production from these is usually small, as the transcontinental transportation problem is a serious one.

The deposits of Shàsta County, which have in recent years attracted the most attention, occur in a mass of serpentine and allied rocks. In one of these an ore body about 45 feet wide and 150 feet long was found.

Alaska (9).—Chromic iron ore is said to occur as a lode deposit near Port Chatham on the Kenai Peninsula, and chromite fragments have also been found in the gold placers of Shungnak in the upper Kobuk basin.

Canada (3).—The Canadian production is generally small. Deposits are known to occur in the serpentine rocks of the Quebec asbestos area (which see), where they form irregular or lens-shaped bodies of workable size, and also nodules and grains disseminated through the serpentine and pyroxenite.

Other Foreign Deposits.[1]—The principal foreign sources of chromite, and of the world are New Caledonia, Rhodesia, Turkey in Asia, and Greece, but during the war most of these were practically closed to the United States.

New Caledonia.—The ore in the southern part of the island occurs as rich, soft, masses in ferruginous clay, and as veins and irregular masses in serpentine. That found in the northern part of the island is more important, and may run 67 per cent Cr_2O_3.

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[1] Beyschlag, Vogt, and Krusch translation by Truscott, I: 244, 1914.

Rhodesia (13).—This country is the greatest world's producer, the Selukwe district being most important. The ore occurs in talc schist and serpentine, either as disseminations or massive lenses, which may range from 150 to 450 feet in length.

South Africa (25).—Chromite occurs in the norite zone of the Bushveld igneous complex in the Rustenburg and Lydenburg districts of the Transvaal. Associated with it are picotite, magnetite and silicates. Very small amounts of platinum metals are also present.

Turkey.—In Turkey in Asia, the chromite ore occurs in serpentine, while that of Greece is associated with both basic rocks and limestone (1).

Interesting but not very important deposits are found in Norway, at Mount Dun in New Zealand, and at Kraubat in Styria (Fig. 109).[1] Some is also found in the Cuban iron ore deposits (2). India is the second largest world's producer. The deposits occur in serpentine.

Uses of Chromite.—Chromite is used chiefly in metallurgical products, such as castings, stainless steels, and ferrochrome alloys. Refractories such as chromite brick form a second important use. Additional amounts are used in the manufacture of chromium salts.

Production of Chromite.—The price of chromic iron ore is based on its percentage of chromic oxide, the standard ore containing from 45

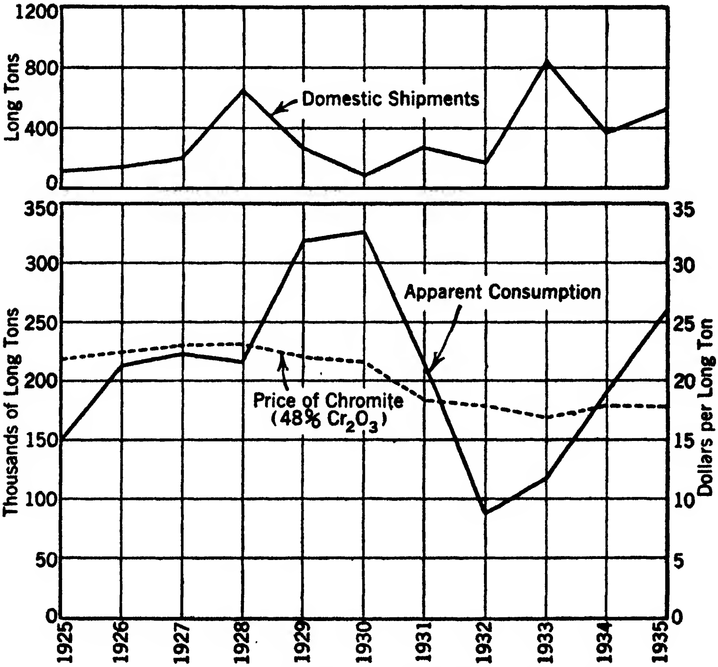

FIG. 257.—Trends in consumption, price, and domestic shipments of chromite in the United States, 1925–1935. (*Minerals Yearbook.*)

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[1] Beyschlag, Vogt, and Krusch translation by Truscott, I: 244, 1914.

to 50 per cent. Low silica is desirable. The silica permissible in 50 per cent ore is 8 per cent.

Although an important consumer of chromite, the United States has only a small production. This amounted to 2662 long tons shipped in 1940, with a value of $28,784, and came mostly from California. The imports of crude chromite in 1940 were 657,689 long tons (Cr_2O_3 content, 301,672 long tons), valued at $8,754,770. The price per ton at New York was $28.00.

Small quantities of chromite were produced in Canada in 1936 from the Thetford-Black Lake district of Quebec, and Obonga Lake in northwestern Ontario.

The world's production in 1939 was 1,167,000 metric tons, of which Russia produced over 20 per cent, Turkey 16 per cent, Southern Rhodesia 11.9 per cent, and Union South Africa, 13.7 per cent.

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MOLYBDENUM

Ore Minerals and Occurrence.—*Molybdenite* (MoS_2), *wulfenite* ($PbMoO_4$), *molybdite* $[2(FeO_2)\cdot 6MoO_3\cdot 15H_2O]$, and *ilsemannite*

($MoO_2 \cdot 4MoO_3$) may serve as sources of the metal, the first two being the most important.

Molybdenite occurs in quartz veins, pegmatites, granites, metamorphic rocks, and contact-metamorphic deposits, and is usually associated with acid igneous rocks. Molybdite is an oxidation product.

Colorado.—The United States possesses the largest known molybdenite deposits, and the chief output has come from Climax, Colo. Here the ore occurs in a circular stock of granite which spreads downward. The granite has been silicified, the change being most intense in the center and grading off towards the margin, so that three zones can be recognized, namely, a central, intermediate, and outer one. In the outer zone where the silicification is less the biotite of the granite is bleached, the plagioclase sericitized, and there is a development of pyrite and secondary orthoclase. Most of the ore occurs in the intermediate moderately silicified zone. Here veinlets of quartz with molybdenite are abundant, and these are cut by other veinlets containing quartz, pyrite, and topaz. The central core is essentially massive quartz (2).

The ore zone is estimated to have a thickness of 250 to 400 feet, but its depth is not known.

The primary minerals are chalcopyrite, fluorite, hübnerite, molybdenite, orthoclase, pyrite, quartz, sericite, sphalerite, and topaz. The molybdenite occurs exclusively in quartz veins, which vary from under ¼ to ¾ inch in thickness and cut the rock in all directions. Veinlets with the other minerals cut the molybdenite veinlets, but may be abundant in all three zones.

The mineralizing solutions are thought to have come from a Tertiary intrusion not visible in the area. The ores are classed as mesothermal.

There are large estimated reserves, but large tonnages of more than 1 per cent ore do not occur, and 0.8 per cent is regarded as workable material.

Several occurrences have been described from Quebec and Nova Scotia (8), but the production is small and irregular.

Uses of Molybdenum.—Molybdenum is of importance for the manufacture of extra hard high-speed tool steels, and for this purpose has replaced tungsten to some extent. It is added in the form of calcium molybdate or as ferromolybdenum. Molybdenum steels are much used in airplane and automobile construction. Sheet and wire molybdenum are used in the radio industry as a substitute for tungsten. Some molybdenum compounds are used in making dyes and chemicals.

Production of Molybdenum.—In 1940 there were produced 33,128 short tons of molybdenum concentrates with a molybdenum content of 34,313,000 pounds (about 52 per cent). Colorado supplied 66 per cent, and the copper ores of Utah, Arizona and New Mexico, 30 per cent. Molybdenum concentrates carrying 90 per cent MoS_2 were quoted at 45 cents per pound of content of the sulphide.

The United States production has tripled since 1934.

The imports in 1939 consisted of ores, various alloys, and molybdenum compounds, whose total molybdenum content was 26,347 pounds valued at $32,327. The exports in 1940, and which were embargoed to enemy countries, were valued at $4,904,000.

Canada in 1939 produced 2722 pounds of molybdenum concentrates.

The United States produced 93 per cent of the world's supply of molybdenum in 1940.

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NICKEL AND COBALT

Ore Minerals.—These two metals can best be treated together, for nearly all the ores containing the one are likely to carry some of the other, and furthermore, in smelting, the two metals go into the same matte, and are separated later in the refining process.

The ore minerals of nickel and cobalt, of recognized occurrences, together with their composition and the percentage of nickel or cobalt they contain, are shown in the table below. Of these some occur only in small amounts as millerite, pentlandite, genthite, and chloanthite.

The nickeliferous pyrrhotite is the most widely distributed of the economically important nickel ore minerals and may carry small amounts of cobalt. It is also called magnetic pyrites. Nickel ranges from a trace to 6 per cent, but an increase above this brings it into pentlandite. Millerite is sometimes found associated with pyrrhotite ores.

Ore	Composition	Ni	Co
Pyrrhotite (nickeliferous)	FeS	0–6	—
Millerite	NiS	64.6	—
Pentlandite	(FeNi)S	22	—
Genthite	$2NiO_2, 2MgO, 3SiO_2, 6H_2O$	22.46	—
Niccolite	NiAsS	43.9	—
Linnæite	$(CoNi)_3S_4$	30.53	21.34
Chloanthite	$NiAs_2$	28.1	—
Smaltite	$CoAs_2$	—	28.1
Cobaltite	$CoS_2, CoAs_2$	—	35.4
Erythrite (Cobalt bloom)	$Co_3As_2O_8 + 8H_2O$	—	29.45
Annabergite (Nickel bloom)	$Ni_3As_2O_8 + 8H_2O$	29.2	—
Garnierite	$H_2(NiMg)SiO_4$	5–20	—
Gersdorffite	NiAsS	35.4	—
Cobalt-arsenopyrite	(FeCo)AsS	—	6–25
Skutterudite	$CoAs_3$	—	20.7

Distribution in the United States.—The United States is of no importance as a producer of nickel and cobalt from domestic ores, and the known occurrences have not been worked for several years. At Mine la Motte, Missouri, some nickel and cobalt have been obtained as a by-product in lead mining. Nickeliferous pyrrhotites are known in Virginia and Pennsylvania (15, 22), while in Oregon and Idaho (14) some nickel and cobalt ores have been found. In Alaska, nickeliferous pyrrhotite occurs in basic igneous rocks. The only nickel now produced in this country is that saved as nickel salts in the electrolytic refining of blister copper.

The electrolytic refining of copper yields all the nickel now produced in the United States.

Canada.—Canada is the most important source of nickel and cobalt ores in North America, as well as the leading world's producer of the former metal.

Sudbury, Ontario (28–50).—This district (Fig. 258) produces over 90 per cent of the world's supply of nickel and is also one of Canada's largest producers of copper, as well as of a considerable amount of platinum.

The sulphides of nickel and copper were noticed in 1856, and a railroad cut made in 1883 disclosed the chalcopyrite body on the site of Murray mine. At first the ores were exploited for copper alone, but the discovery of nickel-steel in 1889 encouraged the production of nickel also.

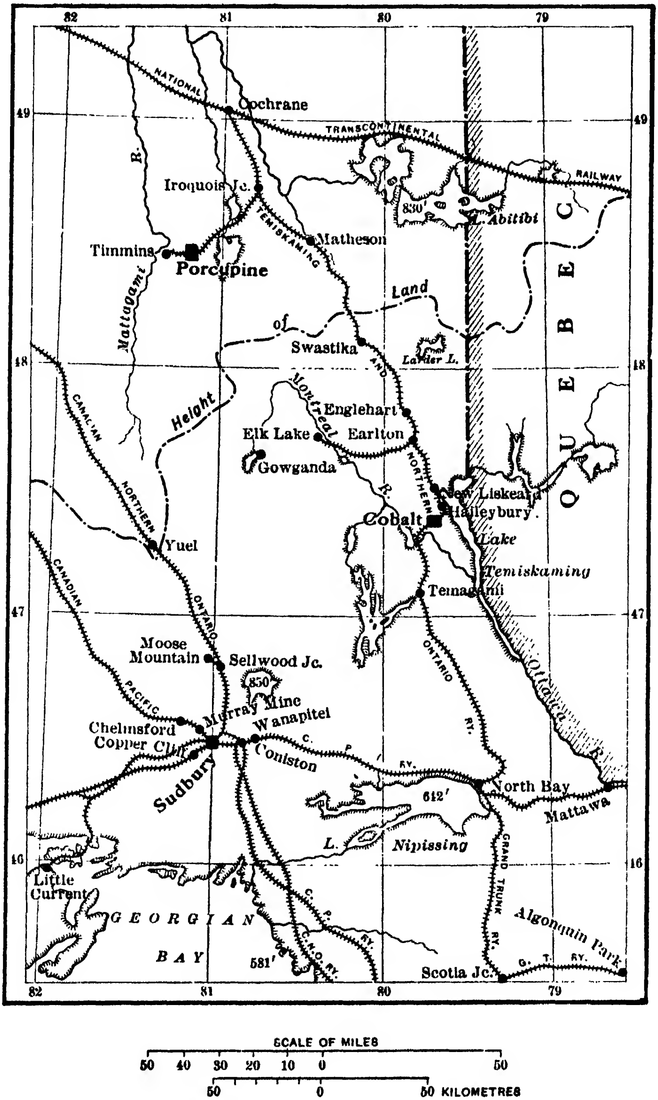

FIG. 258.—Map of Cobalt—Porcupine—Sudbury region. (*Ont. Bur. Mines.*)

The formations of the region which have been described in great detail by Coleman (25) include a spoon-shaped sill of norite-micropegmatite (Figs. 259 and 260) about 35 miles long and 15 miles wide. The outer margin or bottom of the sill is norite, which grades upward into the micropegmatite.

The rocks in the basin, whose total thickness is 9000 feet, form the Whitewater series, and the members in ascending order are the Onaping fragmental volcanics, Onwatin slate, and Chelmsford sandstone. The rocky rim around the basin consists of late pre-Cambrian intrusives injected between the base of the Whitewater series and the earlier complex on which it was deposited. This pre-Whitewater complex consists of pre-Huronian granite and granite gneiss on the north and east of the basin; of Keewatin volcanics and the overlying Sudbury series, as well as pre-Huronian sediments on the south. These are steeply tilted, and also intruded by basic rocks related to the nickel eruptive; also on the south are late pre-Cambrian granites which have invaded the rocks of the old complex as well as the

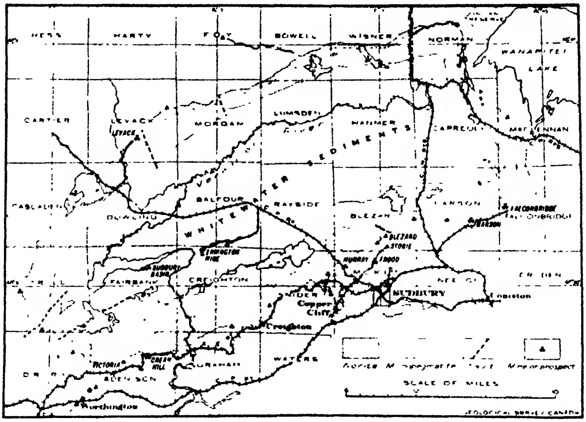

FIG. 259.—Geologic map of Sudbury, Ont., nickel district. (*After Alcock.*)

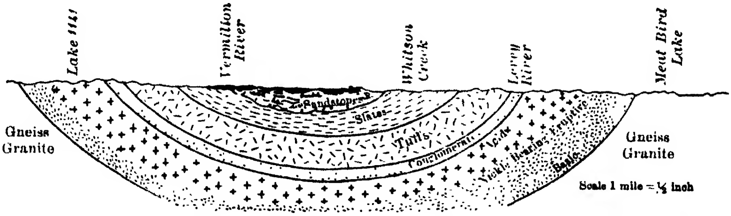

FIG. 260.—Geologic section of Sudbury, Ont., nickel district. (*After Coleman.*)

nickel-bearing norite. The youngest rocks are olivine diabase and traps.

The ore bodies occur: (1) usually along or adjacent to the southern edge of the norite; and (2) as offset deposits which are in irregularly shaped elongated bodies of norite, that cut the rocks of the surrounding complex.

The ore minerals are chiefly chalcopyrite and pyrrhotite, commonly closely associated. Pentlandite is the nickel-bearing mineral, and sperrylite carries the platinum. Other minerals such as ilmenite, pyrite, sphalerite, galena, molybdenite, arsenopyrite, etc., may be present in small amounts.

The origin of these ore bodies has been a subject of discussion for many years, the literature on the subject is voluminous, and the last word has probably not been said.

Bell, Coleman, and Barlow believed that the ore was due to magmatic segregation, having settled out in the lower part of the eruptive, and hence should be found around the outer or norite rim of the basin.

Tolman and Rogers (48) suggested that the ore minerals were late products of crystallization from the magma, or in other words were of pneumotectic character.

At some variance with this was Howe's theory of magmatic differentiation at depth, followed by later injections of the sulphides. This is somewhat similar to a view suggested later by Bateman, except that the latter believed that the ores had undergone later modification by hydrothermal action.

Dickson (38) was one of the first to differ distinctly from the advocates of magmatic segregation, expressing the idea that, since the ore seemed to occur as a cement for brecciated rock fragments, along shearing planes, the ore minerals had been deposited from solutions by a process of replacement. This view was agreed to by Knight (40) and others.

Wandke and Hoffman call the ores high-temperature replacements along belts or zones of shearing or brecciation. They, like previous investigators, have presented a long array of facts to substantiate their views, and point out among other things that quartz-diorite is a common associate of the ore bodies, and that the associated nonmetallic minerals show an unusual type of hydrothermal alteration, consisting of hornblende, biotite, and quartz, which affects all the rocks associated with the ore.

Since some of the so-called contact deposits extend into the rocks underlying the sill, and others may be some distance from the "nickel eruptive," it hardly seems as if magmatic segregation could be appealed to as the sole cause of origin of all the ore bodies.

Finding some ores in the neighboring rocks still leaves a choice of magmatic injection as suggested by some, or deposition from solution as advocated by others. Hydrothermal alteration is commonly associated with the latter view. Quite recently Coleman, Moore, and Walker have gone over the ground again, their views in summary being (37): The eruptive sheet is a unit formed by the segregation of the magma into a more basic portion, norite, grading upwards into a more acid phase, micropegmatite. In the lowest part of the eruptive, sulphides (pyrrhotite, pentlandite, chalcopyrite) occur as blebs scattered through the norite in such a way that they must have been present when the magma cooled. There is no nickel ore where there is no norite or related basic rock. The occurrence of the marginal ores in bays of norite in the older rocks supports the theory of settling sulphides. The very fresh condition of the silicates in contact with the sulphides, and gradation from massive sulphides to pyrrhotite norite spotted with sulphides, support the magmatic segregation theory. Experiments by Newhouse on pyrrhotite-pentlandite melts, show that with one exception the order of separation—pyrrhotite pentlandite, chalcopyrite—is the same at Sudbury and Alexo, Ontario, Lancaster Gap, Pa., and Dalton, Mass. In the offset deposits, whose origin is an interesting problem, the rocks are in many respects similar to those of the basic portion of the main intrusion, but they have been greatly altered, and it is because of this, the authors claim, that these rocks have been given various identifications. There seems no doubt that they are connected with the main intrusion. The offset bodies are therefore supposed to be connected with offset intrusions, but it is admitted that in some cases as in the Frood ore body copper was added to the intrusion from the main magma, as liquid sulphides and by hydrothermal solutions which deposited quartz and carbonates and somewhat modified and rearranged the offset ores.

An analysis of a high-grade matte gave: NiCo, 48.82; Cu, 25.92; Fe, 2.94; S, 22.50; Au, 0.02 ounce; Ag, 3.14 ounces; Pt, 0.13; Ir, 0.02; Os, 0.02; Rh and Pd, trace.

The precious metals are left behind as a residue in the final refining of the copper, and this residue analyzes: Pt, 1.85 per cent; Pd, 1.91 per cent; Au, 0.56 per cent; Ir, Rh, Ru, 0.39 per cent; Ag, 15.42 per cent. This residue is treated for the separation of these metals, and a minimum of 95 per cent recovered.[1]

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[1] Langer and Johnson, Can. Min. Inst., Bull., July, 1927.

The reserves of this ore are very large.

Cobalt, Ontario (17).—The silver-cobalt-nickel veins at Cobalt present one of the most remarkable series of ore deposits known, having their analogue only in certain foreign occurrences. The district lies near the boundary of the provinces of Ontario and Quebec, and was formerly an important producer (Fig. 258).

The geological section at this locality is as follows:
Glacial drift.
Silurian.
  Niagara limestone.
  Great unconformity.
Pre-Cambrian.
Later dikes of aplite, diabase, and basalt.
Nipissing diabase, probably of Keweenawan age.
Cobalt series. Conglomerate, greywacke, and other fragmentals.
  Unconformity.
Lorrain granite.
Lamprophyre dikes. Near some of the mines.
Temiskaming series. Conglomerate and other fragmental rocks.
Keewatin complex. Includes basic volcanics, now altered to schists and greenstones; altered sediments including jaspilyte, slates and greywacke.

The ores occur in mostly well-defined veins which range from less than an inch to as much as a foot or more in thickness, and occupy narrow, almost vertical, fissures or joints, cutting through a series of slightly inclined metamorphosed fragmental rocks (Cobalt series) of Lower Huronian Age. Some are also found in the diabase and Keewatin, although these last two were never so productive.

Most of the ore has come from veins or parts of veins that originally lay beneath the sill (Fig. 261).

The important ore mineral is native silver, but associated with it, in varying quantities, are niccolite, smaltite, chloanthite, cobaltite, millerite, argentite, dyscrasite, pyrargrite, arsenopyrite, etc. The oxidized zone, which is usually but a few feet in depth, shows native silver, erythrite (cobalt bloom), and annabergite (nickel bloom). Calcite is the chief gangue mineral, quartz being much less common.

W. G. Miller (17), who has given more careful study to this region than anyone else, believes that the ore was deposited by highly heated impure waters circulating through cracks and fissures following the post-middle Huronian diabase eruption. The metals may have been brought up by these waters from a great depth, or they may have been leached out of the now folded and disturbed greenstones and other Keewatin rocks. He inclines to the theory, however, that the diabase magma was the source of both the cobalt-nickel minerals and the silver.

The cobalt arsenides were probably the first minerals deposited, and this was followed by a slight disturbance of the veins, resulting in the formation of cracks and openings in which the silver and later minerals were deposited. Some have suggested that the silver was deposited by supergene solutions.[1] Many of the veins are very rich, but all are not so. As an example of the former, an open cut on the Trethewey vein, 80 feet long and 25 feet deep, yielded $200,000 of ore from an 8-inch vein. A shipment of 80 tons of this ore gave approximately: As, 38 per cent; Co, 12 per cent; Ni, 3.5 per cent; and 190,000 ounces silver. Pay was received only for the cobalt and silver.

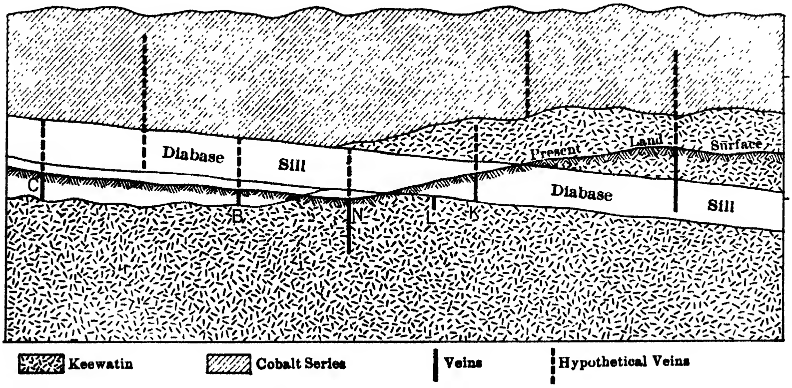

FIG. 261.—Generalized vertical section through the productive part of the Cobalt, Ontario, area.

The Section shows the relations of the Nipissing diabase sill to the Keewatin and the Cobalt series, and to the veins. The eroded surface is restored in the section, and the sill is less regular than the illustration shows. *B* and *C* represent a large number of veins that are in the fragmental rocks, Cobalt series, in the foot wall of the eroded sill; *N* represents a type of vein, in the Keewatin below the eroded sill; *L* a vein in Keewatin footwall, but not extending upward into the sill; *K* a vein in the sill itself; *T* a vein in Keewatin hanging wall and extending downward into the sill. (*After Miller, Ont. Bur. Mines, XIX, Pt. II,* 1913.)

The veins at Cobalt are unique among North American ones, but resemble those of Annaberg, Joachimsthal, and other localities, referred to on p. 682.

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[1] See also Bastin. Econ. Geol. XII, 1917; Whitehead, *Ibid.*, XV, 1920; Bastin, *Ibid.*, XX, 1925; Whitman, Univ. Calif. Pub. XIII, 1922; Knight, Ont. Dept. Mines, XXXI, 1922.

The discovery of these deposits was made in building the Temiskaming and Northern Ontario railroad, and their development made Ontario one of the leading silver producers of the world. It was at one time the chief source of the world's supply of cobalt, but now has important competitors in Belgian Congo and Northern Rhodesia.

Other Foreign Deposits.—Deposits of nickeliferous pyrrhotite in basic eruptive rocks are known at a number of localities in Norway, the ore averaging 1.5 to 2.5 per cent nickel.[1] Deposits of a similar type are known in Italy, Spain, and Russia, but they are of little economic importance.

Next to Sudbury, New Caledonia is the most important source of nickel in the world.[2] The island consists of ancient schists and Mesozoic sediments, pierced by eruptives, especially peridotite. The latter is more or less altered to serpentine. The ore minerals are hydrated silicates, chiefly garnierite. They occur as veinlets and concretionary masses in the serpentine and peridotite. There are also green siliceous masses carrying 9 to 10 per cent nickel. Most of the ore is low grade, averaging 7 per cent nickel after drying at 100° C.

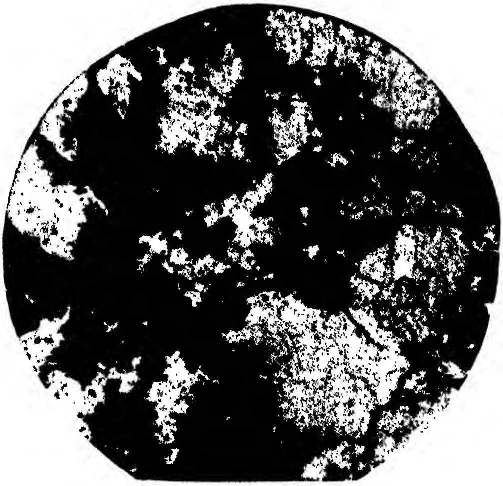

FIG. 262.—Section of calcite, and native silver, the latter in part replacing the former. Cobalt, Ontario. ×30.

Deposits of cobalt-silver ore similar to those of Cobalt, Ontario, are found in Germany and Czechoslovakia, viz., Joachimsthal and Annaberg. The ores of these two districts include compounds of cobalt, nickel, bismuth, and silver, and in addition uranium, which has not been found in the deposits of Cobalt, Ontario.

At Joachimsthal, Czechoslovakia, there is a series of mica schists, talc schists, and limestones cut by dikes of basalt. The veins, which antedate the basalt, but cut the other rocks, are narrow, often brecciated, and contain hornstone, quartz,

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[1] Vogt, Krusch and Beyschlag, Translation, I.

[2] Glasser, Ann. de Mines, 15th ser., Tome IV; 299 and 397, 1903; Miller, Report Royal Ontario Nickel Commission, 1917.

calcite, and dolomite as gangue material. Various silver, nickel, cobalt, bismuth, and arsenic minerals are present, as well as lead, zinc, iron, and copper sulphides, together with uraninite.[1] The cobalt and nickel ores are generally the older and the silver ones younger.

At Annaberg, Saxony, the veins occur in gray gneiss. There are two groups, the younger and most important carrying silver-cobalt ores, with nickel and bismuth in a gangue chiefly of barite, fluorite, quartz, and brown spar. The older veins carry tin and lead.

The veins at Schneeberg, Saxony,[2] occur in contact-metamorphic clay slates, but become poorer on passing into the underlying granite.

The ore minerals are smaltite, chloanthite, niccolite, bismuthinite, and native bismuth in a gangue of quartz, hornstone, calcite, and dolomite. Silver minerals are rare.

New South Wales was formerly the second largest world's producer of cobalt.[3]

The copper ores of both Northern Rhodesia and Katanga carry cobalt, and are important producers of this metal.

Uses of Nickel.—Nickel is now widely used for making nickel, nickel-chromium, and nickel-molybdenum steels. Such steels possess great hardness, strength, toughness, and elasticity. They are consequently widely used for structural purposes, armor plate, motor cars, locomotives, etc.

Stainless and corrosion-resisting steels are of great importance, in the airplane, auto, and railway industries. Monel metal is a nickel-copper alloy (68 per cent nickel, 30.5 copper, and 1.5 iron), widely used because of its corrosion resistance, and the fact that it can be rolled.

Uses of Cobalt.—Cobalt is of importance as an alloy in making high-speed cutting tools and permanent magnets. Stellite is a cobalt-chromium-tungsten alloy of great hardness. Cobalt oxide is a blue pigment of value for coloring glass and pottery.

Production of Nickel.—The production of nickel as a by-product of copper refining in the United States in 1940 amounted to 554 short tons. The imports for the same year were 92,468 short tons valued at $41,743,917, while the exports were 11,994 short tons, with a value of $9,857,334. The average price was 35 cents per pound.

Canada, in 1939, produced 226,105,865 pounds of nickel (exported matte, refined and electrolytic Canadian nickels, oxides and salts),

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[1] Vogt, Krusch und Beyschlag, Lagerstätten, II: 173, 1912. Also Miller, Ont., Bur Mines, XIX, Pt. II: 213, 1913.

[2] Vogt, Krusch und Beyschlag, Lagerstätten, II: 173, 1912; Dalmer, Kogler, and Müller, Section Schneeberg, Geol. Spez. Karte Sachsen, 1883.

[3] Pittman, Mineral Resources, New South Wales, N. S. W. Geol., Surv. 1901.

valued at $50,920,305. The imports of manufactured nickel were valued at $1,581,970, while the exports of metal in all forms were valued at $57,933,511.

The world's production in 1938 was 115,500 metric tons, of which Ontario produced 82 per cent, New Caledonia 10 per cent, and Greece 1.7 per cent.

Production of Cobalt.—There was no production of cobalt in the United States in 1940, but the imports of cobalt ore, metal and oxide amounted to 11,396,267 pounds, valued at $5,000,586.

The Canadian production for 1939 computed as metallic cobalt amounted to 732,561 pounds, valued at $1,213,454, and came entirely from northern Ontario. The imports of cobalt oxide were 542,025 pounds valued at $148,711, and the exports of cobalt and cobalt compounds had a value of $1,260,961.

Canada, for many years the leading producer, had its market nearly halved in 1926 by the development of copper-cobalt deposits in the Belgian Congo, but recently northern Rhodesia has taken the lead. Burma, French Morocco, and China have been producers.

A syndicate representing Belgian Congo, Rhodesia, and Deloro, Canada, controlled more than 80 per cent of the world's output outside of China.

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PLATINUM GROUP OF METALS

Platinum.—The ore minerals of platinum are *native platinum* and *sperrylite* ($PtAs_2$). The former is predominantly an alloy of platinum with other metals of the same group such as palladium, iridium, and rhodium. Other elements that have been detected in nuggets are osmium, ruthenium, iron, copper, and gold (4). Some placer platinum contains much osmiridium. The Russian crude platinum contains 80–83 per cent Pt; the Colombian, 80–86 per cent. Crude platinum from California and Oregon may show 25–45 per cent iridium.

Occurrence.—Platinum may occur in placers or in bed-rock deposits. In the latter it may be an original constituent of igneous rock, or vein material. Until recent years the entire world's supply was obtained from placers, and these are still the most important source.

Placers.—In these, native platinum alloyed with other minerals of the platinum group is the ore mineral. The placers are usually stream and less often beach deposits, the material having been derived from basic igneous rocks, such as peridotite, or its derivative, serpentine, in which the platinum is sometimes found in small quantities as an original constituent of the rock. Other heavy minerals such as chromite, etc., may be associated with it. The black sand of some gold placers contains platinum and associated heavy minerals.

A large, and for many years the most important, placer region, is that of the Ural Mountains in Russia, where platiniferous gravels occur in many of the streams, and have been worked to a maximum depth of 60 feet; but the tenor at present is said to be decreasing. Dredges are now used for working the deposits, but Russia has fallen to second place in the list of producing countries.

In Colombia, gold-platinum placers are scattered over an area of 5000 square miles, being found in the channels of present streams, and in Tertiary conglomerates. The latter contain pebbles of basic igneous rocks. The gravels are worked by dredges.

Some placer platinum is yielded by beach deposits in Oregon, and by river gravels in California. In fact, the bulk of the platinum produced in California is a by-product saved from gold dredging operations along the base of the Sierra Nevada. In Alaska the Goodnews Bay district, south of the mouth of the Kuskokwim River, supplied over 28,000 ounces in 1940. This is a relatively new development. The average composition of the platinum in percentage of the different constituents is: Pt, 69.39; Ir, 12.45; Pd, 0.48; Rh, 1.08; Ru, 0.21; Os, 2.45; Au, 0.96.

Other producing countries are Tasmania (osmiridium) and Ethiopia.

Bed-rock Deposits.—No bed-rock deposits of platinum metals are known in the United States, but an appreciable amount is obtained as a by-product in the smelting of gold and copper ores (15). The Rambler Mine at Laramie, Wyo. (4, 16), and the Yellow Pine district of Nevada (6) at one time attracted attention.

The Sudbury, Ontario, district, noted for its nickel deposits (q. v.), has sperrylite occurring in the pyrrhotite and chalcopyrite. Palladium arsenide is also present, but seems to favor the nickel rich portions of the ore.

Considerable attention was attracted by the discovery, in 1924, about 50 miles west of Lydenburg, South Africa (10, 18), of platinum as a constituent of basic and ultra-basic igneous rocks, which are a portion of the Bushveld igneous complex. The platinum-bearing rock, which in many places is said to be rich enough to work, is found over a belt of country about 60 miles long.

The platinum is associated with the lower norite zone of the Bushveld complex, under several different conditions. Some occurs in masses of a variety of peridotite called hortonolite-dunite, the quantity of platinum being said to range from about 0.1 to 7 ounces per ton. A second occurrence is with the bed-like deposits of chromite, also found in the norite zone. A third type includes platinum and palladium, with associated pyrrhotite, pentlandite, and chalcopyrite.

The platinum mining companies have developed large reserves of ore carrying from 3 to 8 pennyweights per ton, but extraction methods are not yet thoroughly satisfactory.

Another apparently promising discovery has recently been investigated in the Waterberg area, 100 miles north of Pretoria, Transvaal. Here the platinum occurs in lodes, the main one of which is said to be traceable for 2½ miles. The deposits consist of closely spaced quartz stringers separated by strips of felsite, while at other times they exhibit brecciated felsite cemented by quartz. The platinum, which is native, and alloyed with palladium, etc., is rarely visible, except in very rich ore.

Uses of Platinum Metals.—The industries named in the order of their demand for platinum are: jewelry, chemical, dental, and electrical.

Palladium, which is the cheapest of the platinum metals, finds its first use in the dental industry, where it forms a substitute for gold because it is less conspicuous and does not tarnish. The electrical and jewelry industries come next in importance, with chemical and miscellaneous uses third.

Iridium is used for hardening platinum in jewelry and electrical work, and for fountain-pen points.

Rhodium, which is one of the whitest and hardest of metals, and never tarnishes, is used as a finish for jewelry and silverware, as well as surfacing reflectors for searchlights.

Production of Platinum Metals.—The production of crude platinum in the United States and Alaska in 1940 amounted to 36,500 troy ounces, having risen from 885 ounces in 1931. This was due to the Goodnews district of Alaska, the product from which was refined abroad. An additional 7774 ounces was obtained as a by-product of gold and copper refining. Of the latter 3183 ounces were palladium. From foreign crude platinum and nickel-copper refined in this country there were obtained 30,524 ounces platinum, 1360 ounces palladium, and 841 ounces iridium.

There was, however, a considerable importation of platinum metals into the United States in 1940, which totaled 195,645 troy ounces valued at $5,748,005. About 64 per cent of this by weight was platinum, and about 30 per cent palladium.

The price of domestic crude platinum during 1940 varied from $26.92 to $51.03 per ounce, while foreign crude was $26.92 to $51.03 per ounce. Refined platinum and palladium were priced at about $38.00 (max.) and $24.00, respectively.

The Canadian production in 1939 was 148,902 ounces of platinum valued at $5,222,589, and 135,402 ounces of palladium and rhodium, valued at $4,199,622, all of it obtained from the nickel-copper ores of Sudbury. Only 25 ounces were obtained from placers.

The manufactured imports were $234,139, and similar exports, $6,178,227.

The world's production of platinum metals in 1939 was over 531,000 troy ounces. Canada contributed 50 per cent, followed by Russia, Colombia and the United States.

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SELENIUM

This rare and little-known element, which forms not over 0.0002 per cent of the known rocks, is not known to occur in deposits by itself, even though it forms combinations with a number of other metals, which are found in nature. It is found in some gold, silver, and copper ores.

Thus Spurr has called attention to its presence in the gold ores of Tonopah, Nev., where it is found, at least in part, as a silver selenide. It is associated with gold in the Republic district of Washington (4).

The commercial supply of the United States, however, is furnished in part by the electrolytic copper refineries, as nearly all blister copper contains it.

Uses.—Selenium is used as a red colorant of glass, while selenite of soda gives a bright red color to enamels used for covering steel. Owing to its low electrical conductivity in the light, and higher conductivity in the dark, selenium wire is used in automatically lighting and extinguishing gas buoys.

Selenium may be added to steel to increase its machinability. It is used in a rectifier for changing alternating to direct current. Certain soils have a relatively high selenium content, which has a poisonous effect on cattle.

Production of Selenium.—The production of selenium in the United States in 1939 was 227,131 pounds, and for several years the output has been decreasing. The imports of selenium and its salts in 1940 were 134,429 pounds valued at $198,163. The price in New York is about $1.75 per pound.

Selenium is produced in Canada as a by-product in the refining of blister copper, and in 1939 amounted to 150,771 pounds valued at $266,714, said to originate in the ores of the Noranda Copper Mines at Rouyn, and those of Sudbury, Ontario.

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1. Eilers. Amer. Inst. Min. Engrs., Trans., XLVII: 217, 1914. (Selenium, etc., in blister copper.) 2. Gale, U. S. Geol. Surv., Bull. 340: 261, 1908. (In Ur. and Va. ores.) 3. Hess, U. S. Geol. Surv., Min. Res., 1914. (General.) 4. Lindgren and Bancroft, U. S. Geol. Surv., Bull. 550, 148, 1914. (Republic, Wash.) 5. Santmyers, U. S. Bur. Mines, Inf. Circ. 6317, 1930. (General.) 6. Spurr, U. S. Geol. Surv., Prof. Pap., 42: 92, 1905. (Se in Tonopah ores.) 7. Truscott. Inst. Min. and Met., Trans., X: 54, 1901. (Redjang Lebong, Sumatra.)

TANTALUM

Tantalite ($FeTa_2O_6$) and *columbite* [$(Fe, Mn)Nb_2O_2$] are the only minerals found in the United States from which tantalum could be produced. They occur in pegmatite veins, and are said to be found in some abundance in those of the Black Hills of South Dakota; other occurrences are near Canyon City, Colo.; near Spruce Pine, N. Ca.; near Amelia, Va., etc. There were no shipments in 1940.

Production of Tantalum and Columbium.—No shipments of tantalum-bearing ores in the United States have been reported since 1939, when the output was reported as 340 pounds valued at $200.

The total imports of tantalum ores in 1940 were 490,460 pounds compared with only 56,561 in 1939, the previous high record.

These greatly increased imports were due to collapse of European markets for ores from Belgian Congo, Brazil and other African sources. The average value was lower due to their greater columbium content than those from Australia.

There were no shipments from Canada.

electric lamps, but it has been superseded by tungsten. It has been used in radio chargers. Several alloys of tantalum and other metals have been made. Tantalum dishes are quite resistant to cold acids.

REFERENCES ON TANTALUM

1. Hess, U. S. Geol. Surv., Bull. 380, 1909. 2. Watson, Min. Res. Va., 1907: 298, 390. (Va.) 3. Youngman, U. S. Bur. Mines, Inf. Circ. 6328, 1930. (General.)

TELLURIUM

This element has but slight commercial value, as little use has been found for it. The somewhat widely distributed telluride of gold and silver ores form a comparatively common source of it, but owing to the lack of demand, no attempt is made to save the tellurium. Cripple Creek, Colo., yields *sylvanite* $(AuTg)Te_2$ and *calaverite* $(AuTe_2)$. *Tetradymite* (Bi_2Te_3) is found at a number of localities.

All the tellurium of commerce is obtained as a by-product from copper ores.

Uses.—Tellurium is used as a hardening and strengthening agent in lead and its alloys. It is also employed in the manufacture of rubber products, serving to increase their tensile strength and resistance to abrasion.

Production of Tellurium.—The amount sold in the United States in 1939 was 63,431 pounds, quoted in New York at $1.75 a pound. The production has been rising. Some of it is exported to Europe.

Canada, in 1939, produced 2940 pounds valued at $4769.

REFERENCES OF TELLURIUM

1. Santmyers, U. S. Bur. Mines, Inf. Circ. 6317, 1930. (General.)

TIN

Ore Minerals.—*Cassiterite* (SnO_2), with 78.6 per cent metallic tin, is the principal ore mineral of this metal, but owing to the presence of impurities it rarely shows this composition.

Its hardness (6–7), imperfect cleavage, non-magnetic character, high specific gravity (6.8–7.1), and brittleness help to distinguish it from other minerals that are likely to occur with it. Ilmenite and magnetite have sometimes been mistaken for it.

Stream tin is the name applied to cassiterite found in placers. *Wood tin* is a variety of cassiterite having a fibrous structure. *Stannite,* or tin pyrites, a complex sulphide of copper, iron, and tin, rarely serves as an ore mineral.

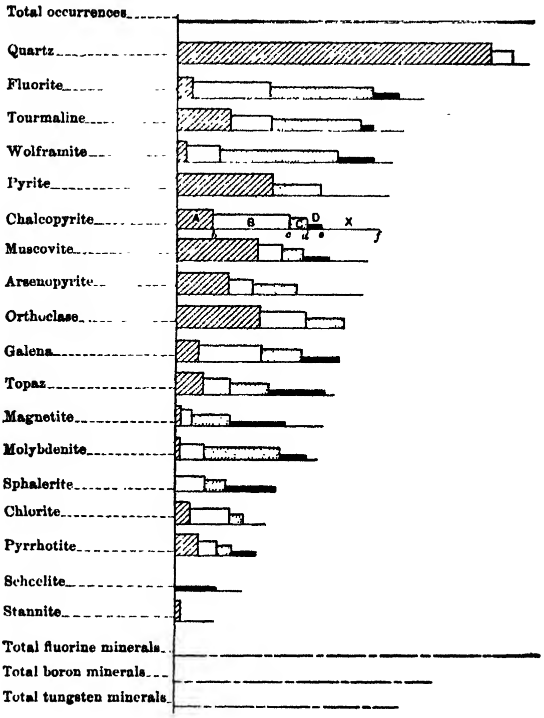

FIG. 263.—Approximate quantitative distribution of the more important minerals associated with cassiterite. Length of line is proportional to the number of occurrences. Height represents relative abundance. *A* = very abundant; *B* = plentiful; *C* = prominent; *D* = rare; *X* = quantity unknown. (*After Ferguson and Bateman, Econ. Geol. VII.*)

Mode of Occurrence.—Cassiterite may occur in the following ways, not all of them being of commercial importance:

(1) As an original constituent of igneous rock; (2) as veins, formed under pneumatolytic or hydrothermal conditions; (3) as contact-metamorphic deposits; (4) as hot-spring deposits; and (5) in placers.

Of these Nos. 2 and 5 are of commercial importance, the others being rarely so.

Cassiterite in Igneous Rocks (9).—Cassiterite is known to occur as an original constituent of granite, but there are no known magmatic segregations of economic importance. It may also occur as a primary constituent of pegmatite dikes, associated with lithium and phosphorus minerals, as near Gaffney, S. Ca. (15), or in the Black Hills, South Dakota (27). These dikes exhibit sharp walls, and there is no replacement of the wall rock by cassiterite.

Contact Metamorphic Deposits (9, 21).—This type is known at a few localities. Those of Pitkäranta, Finland, show cassiterite associated with scheelite, topaz, and fluorite in limestone near its contact with granite.[1]

Another interesting deposit occurs on Lost River, Seward Peninsula, Alaska (14). Here the invasion of limestone by granite has produced a contact zone, carrying pyroxene, tourmaline, axinite, pageite, ludwigite, vesuvianite, fluorite, scapolite, scheelite, cassiterite, magnetite, galena, and sphalerite.

Other cases are known at Schwarzenberg and Berggiesshübel, Saxony, and the Zeehan district, Tasmania (21).

Pegmatites (10, 11, 27).—Cassiterite is sometimes found as a constituent of pegmatite, the deposits formerly mined in South Carolina, and those of the Black Hills, South Dakota, being of this type.

Tin Veins (9, 21).—These form a rather well-marked type in most cases of hypothermal character, which usually occur in or near granites, although occasionally found in other igneous rock. Their close association with pegmatites has at times also been noticed. They commonly show a rather uniform group of minerals (Fig. 263), the metallic ones including cassiterite, wolframite and scheelite, arsenopyrite, bismuth, and others in lesser amounts, while the gangue minerals include quartz (important), lithia mica, topaz, tourmaline, fluorite, etc. Cassiterite is the chief ore mineral, but the tin content is generally low, often under 1 per cent. The cassiterite frequently occurs in the wall rock on either side of the fissures, and where these are abundant a considerable mass of rock may be impregnated with ore.

A characteristic feature of tin veins is the metasomatic alteration of the wall rock, resulting in a coarse-grained mixture of quartz, muscovite, lithia mica, topaz, and tourmaline, called *greisen*. If tin is present in the vein, it usually occurs in the greisen, replacing the feldspar. The tourmaline and topaz are not always equally prominent, and one or the other may be absent.

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[1] Beyschlag, Vogt and Krusch, Ore Deposits, Translation, I: 405.

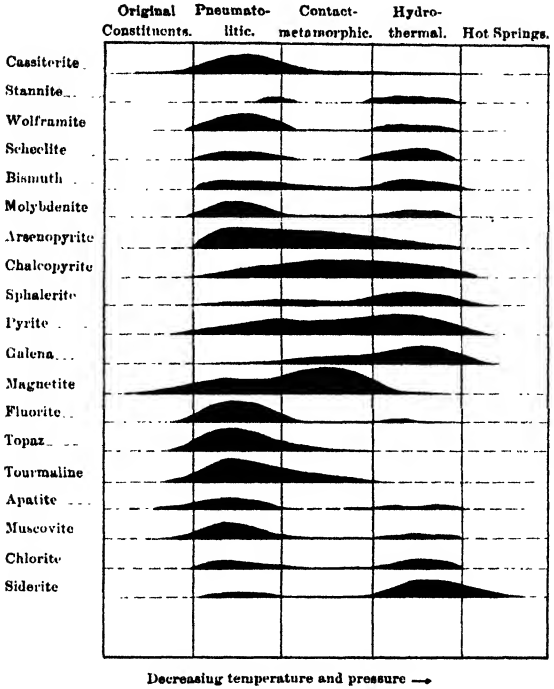

FIG. 264.—Diagram to illustrate the genetic distribution and gradation of some of the more common minerals in their association with cassiterite only. (*After Ferguson and Bateman, Econ. Geol. VII.*)

Greisenization is not confined to granites, but may also be developed in shale, slate, limestone, and diabase.

The two following analyses represent, I, the fresh granite, and II, greisen derived from it.

	I	II		I	II
SiO_2	74.68	[1]70.41	Na O + Li O	1.54	0.98
Al_2O_3	12.73	[1]13.06	K O	4.64	3.01
Fe_2O_3	.....	1.42	H_2O	1.17	0.76
FeO	3.00	5.09	TiO_2	0.71	0.49
MgO	0.35	0.09	SnO	0.09	0.49
CaO	0.09	[2]	AlF_2	.....	[3]3.91
CuO	0.50	....	CaF_2	.....	0.29
				99.50	100.00

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[1] After deduction of part of Al. [2] CaO calculated as CaF_2. [3] Calculated value.

The change in general indicates addition of iron, lithium, tin, fluorine, and boron, with subtraction of lime, potash, and soda.

Vogt, Beaumont, Daubrée, and others believe that the tin veins were formed immediately after or even during granitic eruptions, and that the mineral solutions originated by the action of hydrofluoric or hydrochloric acid on the magma, still entirely or partly in igneous fusion. These extracted fluorides of silicon, tin, boron, and lithium as well as phosphoric acid. The type of alteration of these pneumatolytic emanations varies somewhat, schist being altered somewhat differently from granite.

Tin veins have also been found in volcanic rocks at a number of localities including the Cerro de Potosi district, Bolivia,[1] Guanajuato, Mexico,[2] Lander County, Nevada,[3] and Mount Taylor, New Mexico.[4]

Placer Deposits (8, 9).—These are the most important source of tin ore, and have been formed in the manner described under "gold placers." Accompanying the cassiterite there may be wolframite and other heavy minerals. Tin placers are of little importance in the United States, but they are of great importance in the Malay states and Dutch Indies, as well as in Nigeria. In many localities dredges have been introduced for working the gravels.

Hot Springs Deposits.—Tin appears to be formed in some cases by precipitation at normal pressure from thermal waters, for a stanniferous silicious sinter has been deposited by a hot spring in Malacca. It contains SiO_2, 91.8; SnO_2, 0.5; Fe_2O_3, 0.2; and H_2O, 7.5 (quoted by Lindgren).

Distribution of Tin Ores in the United States (11).—Tin has been found at many localities in both the eastern and western United States as well as in Alaska, but most of the deposits have thus far proved to be of little or no commercial value. They have been described from North and South Carolina (9), South Dakota, Wyoming (27), and Virginia (25).

Alaska (14).—Tin is found in the York region of the Seward Peninsula, where it occurs chiefly in placers and lodes and at a number of other places, but as yet there has been little production. The lode deposits show the following types: (1) quartz veins cutting phyllites or metamorphic slates; (2) disseminations in more or less altered granite rocks; (3) in quartz porphyry dikes cutting limestone, and

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[1] Singewald, Econ. Geol., VII: 272, 1912.

[2] Wittlich, Zeit, prak. Geol., 1910: 121.

[3] Knopf, Econ. Geol., XI: 652, 1916.

[4] Hill, U. S. Geol. Surv., Bull..725, 437, 1922.

PLATE LXIII

FIG. 1.—Old workings of tin mine, Altenberg, Saxony. (*H. Ries, photo.*)

FIG. 2.—Rutile mine, near Roseland, Va. (*H. Ries, photo.*)

accompanied by fluorite, zinnwaldite, etc. The placer deposits are the only ones of importance.

Foreign Deposits.—Cassiterite veins are known in many parts of the world (8). The Cornwall, England, deposits, worked for many years, show tin veins occurring in post-Carboniferous granites, and also in slates (*killas*) intruded by them. An interesting feature is the presence of copper with little tin in the upper parts of the veins, which changes to a straight tin ore where the veins pass from slate to granite. Not a little tungsten is also obtained from some of the workings.[1]

Fig. 265.—Geologic map of Altenberg-Zinnwald tin district, Saxony. 1. Porphyritic granite; 2. Teplitz quartz porphyry; 3. Granite with flat tin lodes; 4. Silicified porphyry; 5. Quartz porphyry impregnated with tin ore; 6. Steep tin lodes; 7. Tin gravel. (*After Vogt, Krusch, und Beyschlag, I.*)

Another classic district is that of the Erzgebirge[2] in Saxony, and neighboring parts of Czechoslovakia. At Altenberg (Fig. 265), the ores form a stockwork of small veins cutting a post-Carboniferous granite (Pl. XXXVI, Fig. 2, and Pl. LXIII, Fig. 1) and an older granite porphyry, the development of greisen being quite extensive. In the neighboring Zinnwald deposits, the flat veins appear to be formed largely by filling.

Interesting and important deposits are those of Mount Bishoff, Tasmania, where the schists have been cut by dikes of granite porphyry, both rocks being replaced by tourmaline and topaz, and the entire mass carrying veins of cassiterite.[3]

Curious because of their mineralogical relations are the Bolivian veins (23). The country rock, which is Devonian slate, intruded by granite porphyry dikes, is extensively tourmalinized. Associated with the cassiterite and stannite are stephanite, ruby silver, tetrahedrite, blende, wolframite, arsenopyrite, etc.

The Mexican ores are unique because of their occurrence in rhyolite, but of little commercial value.

The chief source of the world's production is the Malay Peninsula, and Banka and Billiton Islands off Sumatra. The ore here is obtained chiefly from placers.[4] Tin veins are also known in both districts.

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[1] MacAlister, Econ. Geol., III: 363, 1908; Davison, Min. Mag., XLIII: 143, 1930.

[2] Singewald, Econ. Geol. V: 166 and 265, 1910.

[3] Krusch, Zeitschr. prak. Geol., 1900: 86.

[4] Penrose, Jour. Geol., II: 135, 1903; Min. Mag., XV and XVI; Adams, C. I. M. M., Trans. XXXI: 115, 1929.

Uses of Tin.—The two great consumers of tin are the automobile and the food-packing industries.

Tin plate consists of thin sheet steel coated with pure tin, and standard plate has about 1½ per cent of tin by weight. One pound of tin is required for 220 square feet of tin plate. The production of this in 1935 amounted to 1,700,000 long tons.

Terne plate is sheet steel coated with an alloy of tin and lead. It is used chiefly for roofing and automobile gas tanks, the domestic production of this in 1935 being 191,000 long tons.

Other uses of tin are for soft solder, babbitt (89 per cent Sn, 11 per cent Pb), britannia metal (82–90 parts Sn, with Sb, Cu, and sometimes Zn), type metal, tinning of brass and bronze products, tin chemicals, and tin foil. Aluminum is being tried as a substitute for coating steel, and if it works will seriously affect the demand for tin.

Production of Tin.—Although the United States is the largest consumer of tin, the production is exceedingly small, having amounted to but 44 long tons in 1940 with a value of $48,000. This is a great decrease since 1936. Most of the metal was mined in Alaska. The United States is, however, a large producer of secondary tin, the amount in 1939 having been 26,000 long tons valued at about $29,276,000.

The imports in 1940 of metallic tin were 124,810 long tons, valued at $128,294,410, and of tin concentrates, 3000 long tons (tin content), worth $2,687,154.

The world's production (estimated) of tin in 1940 was 231,700 long tons, of which the Malay States produced 36 per cent, Bolivia 16 per cent, and the Netherlands Indies 19 per cent.

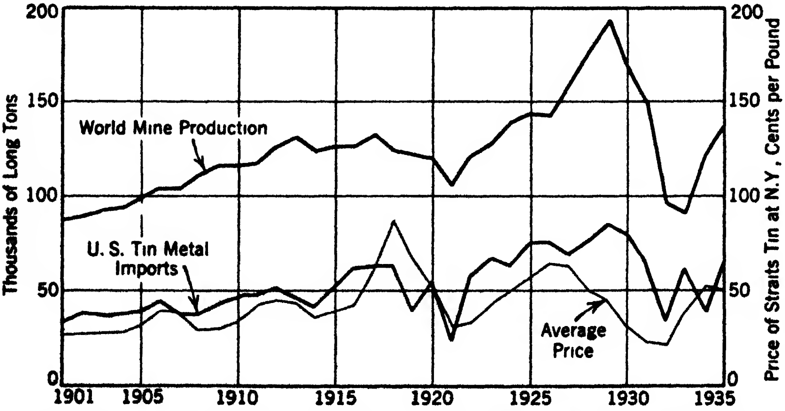

FIG. 266.—Trends in world mine production, imports, and average price of tin, 1901-1935 (*Minerals Yearbook, 1936.*)

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1. Ahlfeld, Econ. Geol., XXXI: 48, 1936. (Bolivia.) 2. Behrend, Zeit. prak. Geol., XXVII: 19, 1919. (Congo.) 3. Brown, Neues Jahrb., B.B. 68, Abt. A., H. 2: 298, 1934. (Cornwall) 4. Chapin, U. S. Geol. Surv., Bull. 592, 385 and 397, 1914. (Seward Penin.) 5. Davies, Imp. Inst. Res. Bur., Mon. 1919. (General.) 6. Derry, Econ. Geol., XXV: 145, 1930. (Manitoba.) 7. Dewey, Proc. Geol. Assoc., London, XXXVI: 107, 1925. (Cornwall.) 8. Fawns, Tin Deposits of the World, London, 1905. 9. Ferguson and Bateman, Econ. Geol., VII: 209, 1912. (Geologic features) 10. Graton, U. S. Geol. Surv., Bull. 293, 1906. (s. Appalachians.) 11. Graton, *Ibid.*, Bull. 260: 188, 1905. (N. Ca. and S. Ca.) 12. Hess and Graton, *Ibid.*, Bull. 260, 161, 1905. (Occurrence and distribution.) 13. Keith, *Ibid.*, Bull. 660-D, 1917. (Kings Mt. S. Ca.) 14. Knopf, *Ibid.*, Bull. 358, 1908. (Alas.) 15. Knopf, *Ibid.*, Bull. 640, 125, 1916. (Nev.) 16. Knopf, Econ. Geol., XI: 652, 1916. (Wood tin, Nev.) 17. Koeberlin, *Ibid.*, XXV: 91, 1930. (Supergene cassiterite.) 18. Lusk, Min. Mag., XXII: 331, 1920. (Nigeria.) 19. Richardson, U. S. Geol. Surv., Bull. 285: 146, 1906. (Franklin Mts., Tex.) 20. Sinclair, Eng. and Min. Jour., CXXIV, No. 2: 55, 1933. (Nigeria.) 21. Singewald, Econ. Geol., VII: 263, 1912. (Genetic relationships.) 22. Smith, U. S. Geol. Surv., Bull. 880-A: 75, 1937. 23. Turneaure, Econ. Geol., XXX: 14, 1935. (Bolivia.) 24. Umpleby, U. S. Geol. Surv., Bull. 528, 1913. (Lemhi Co., Idaho.) 25. Watson, Va. Geol. Surv., Bull. XV-A, 1918. (Va.) 26. Wing-Easton, Econ. Geol., XXXII: 1, 1937. (Malay States.) 27. Ziegler, Min. and Sci. Pr., CVIII, Nos. 15 and 16, 1914. (Harney Peak, S. Dak., pegmatites.)

TITANIUM

Ore Minerals.—While more than sixty mineral species contain titanium, the largest concentrations of the element occur as *ilmenite*[1] ($FeO\ TiO_2$, 31.6 per cent Ti when pure) and *rutile* (TiO_2, 60 per cent Ti when pure). Ilmenite is at present the most important commercially of the two, while rutile is produced in relatively smaller amounts.

Mode of Occurrence (4).—Rutile is found as a constituent of (1) igneous rocks; (2) pegmatite dikes; (3) contact metamorphic deposits; (4) veins; (5) regionally metamorphic rocks; and (6) beach sands; the chief sources of supply are 1, 2, and 6.

Ilmenite may occur as a constituent of (1) titaniferous magnetites; (2) dikes; (3) pegmatites; (4) beach sands; and (5) replacement deposits. Of these 2, 3, and 4 are the most important types worked.

Distribution of Titanium Ores in the United States. *Virginia.*—The most important deposits of titanium ore found in the United States are those of the Amherst-Nelson County area (Fig. 267) in

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[1] See also titaniferous magnetite, p. 432.

Virginia. Smaller ones occur on the northwest edge of the Piedmont Plateau, and in the Goochland and Hanover counties area, near the central-eastern margin of the same province.

In the Nelson County area there is found an interesting group of rocks, which Watson and Taber thought were all igneous, and derived from a common parent magma. The later work of Ross (3) indicates that they may have been affected by hydrothermal action. All are characterized by the prominence of apatite, ilmenite, and rutile. The rock types present are: (1) biotite-quartz-monzonite, the Lovingston granite, which forms the country rock; (2) pegmatite, hydrothermally altered and titanium bearing; (3) nelsonite dikes composed chiefly of apatite, with rutile or ilmenite in varying proportions; (4) gabbro; (5) gabbro-nelsonite, intermediate between 3 and 4; and (6) diabase dikes.

Fig. 267.—Map showing location and relations of rutile deposits in Nelson County, Va. (*After Watson, Min. Res. Va.*, 1907.)

The pegmatite which is worked for its titanium minerals was originally oligoclase (3) with antiperthitic inclusions of microcline. This rock is bluish gray, but is cut by numerous veinlets of nearly white secondary albite. Secondary ferromagnesian silicates have developed near fractures which replacing solutions followed and ilmenite has been deposited in close proximity to them, but the rutile further in. Other minerals developed are sericite, tremolite, and clinozoisite. Blue quartz is a prominent feature of the ore, and appears to have been deposited later. Its color has been found to be due to rutile.

The nelsonite is commonly described as a dike, but the presence of phlogopite, embayed apatite, etc., suggests that it and the gabbro nelsonite may have been subject to hydrothermal alterations. The pegmatite is worked for its ilmenite and rutile contents, and the nelsonite has been worked intermittently.

Some ilmenite is obtained from the basic igneous rock of the Magnet Cove in Arkansas, and the Tahawas, N. Y., ilmenite deposits are now being developed for pigment.

Titanium and other heavy minerals are found in beach sands at Mineral City a short distance south of St. Augustine, Fla., but they have not been worked for several years. The concentrates carried ilmenite, zircon, rutile, and monazite. The source of the sands is the Piedmont area, whence the minerals set free by weathering were carried by streams to the sea, and then southward by shore currents, where along the Florida coast they were concentrated by storm waves (2). Ilmenite beach sands have also been worked at Redondo, Calif.

Canada (1).—The chief known occurrence of titanium ores in Canada is near St. Urbain, north of Bay St. Paul, Quebec. The ilmenite deposits are found in anorthosite in the form of disseminations, lens-shaped bodies, and stringers. While some have regarded them as magmatic segregations, it is more generally believed that the ore is a replacement deposit formed after the consolidation and shearing of the anorthosite. Ilmenite is found intergrown with hematite, and there is considerable rutile in one ore body. The absence of magnetite is unique. Gilson recognizes a definite paragenesis which is oligoclase, phlogopite, rutile, apatite, sapphirine, spinel, ilmenite, quartz, sulphides, serpentine, chlorite, carbonates, and zeolites.

Other Foreign Deposits. An important world source of supply is the beach sands in the state of Travancore, India (7). Originally worked for monazite, they are now worked mainly for ilmenite, which is exported. One of the largest and purest ilmenite-magnetite deposits is that in the Sogndal south of Egersund, Norway. The ore is concentrated and is used for white titanium pigments.

Uses of Titanium.—The chief and growing use of titanium is for making pigments, of which the world's production is now about 200,000 tons, some 35,000 tons of this being credited to the United States. Ilmenite is employed for this purpose. A second application is in ceramics, and the use of rutile for this purpose is increasing. A third use is in metallurgy for making ferrotitanium and other titanium alloys. There is little use for metallic titanium. Rutile is also used for coating welding rods, and in the manufacture of titanium tetrachloride for smoke screens, but ilmenite can also be employed for this purpose.

Production of Titanium.—In 1940 ilmenite and rutile were produced in Nelson County, Virginia, and Hot Springs County, Arkansas, while ilmenite was produced in Amherst County, Virginia, but the statistics are not published. The ilmenite production may equal several thousand tons, and the rutile several hundred. There has been no production from the Florida beach sands for several years.

The imports for 1936 were: ilmenite, 221,641 short tons; and rutile, 312,065.

India and Norway are the largest foreign producers of ilmenite, and Australia and Brazil of rutile. Quebec produces a little.

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TUNGSTEN

Ore Minerals.—Four minerals may serve as important sources of tungsten, viz.: *hübnerite* ($MnWO_4$, 76.6 per cent WO_3); *wolframite* ($(FeMn) WO_4$, 76.4 per cent WO_3); *scheelite* ($CaWO_4$, 80.6 per cent WO_3); *ferberite* ($FeWO_4$, 76.3 per cent WO_3).

Of these the wolframite is the most abundant, while scheelite and ferberite are somewhat rare. The commercially important occurrences include: (1) quartz veins; (2) pegmatite dikes (or veins); (3) placers; (4) contact metamorphic zones; and (5) replacement deposits.

The inclosing rocks may be volcanic or plutonic igneous ones, metamorphic gneisses and schists, or even sedimentaries. The tungsten mineral forms the most prominent mineral in a deposit, or occurs as a subordinate one in veins carrying tin, gold, or silver.

Among the minerals that may be found accompanying tungsten are galena, pyrite, siderite, quartz, chalcopyrite, pyrrhotite, fluorite, tetrahedrite, sphalerite, barite, cassiterite, topaz, arsenopyrite, etc.

The tungsten minerals may occur in the deposits as disseminations, pockets or masses, or in some veins in bands.

Distribution in the United States.—Tungsten minerals are known to occur at a number of localities in the United States, but the quantity available usually exceeds the demand. Abnormal conditions and high prices during the European war exerted a tremendous stimulus on domestic production, but most of the deposits are again idle. Chinese ore at present dominates the world's markets.

A few of the United States deposits are referred to below, partly to give some idea of the mode of occurrence (12).

Colorado (10).—The most important tungsten deposits of Colorado are found in southeastern Boulder County. The ore mineral ferberite occurs in crush zones in pre-Cambrian granite and gneiss. Silica has been deposited with the ferberite.

Arizona (7, 12).—Hübnerite is found irregularly distributed in vertical quartz veins cutting granites and gneissic rocks, near Dragoon, Cochise County.

California (13).—In the Atolia district of San Bernardino County, another domestic source, the ore mineral scheelite occurs in veins with quartz and calcite in granodiorite and schist. The veins occupy a shear zone. Contact metamorphic deposits have been worked near Bishop.

Nevada (17).—Mill City, Nev., is one of the world's important tungsten districts, as well as the chief producer in the United States, supplying probably 75 per cent of the domestic production. The deposits are located in the Eugene range in a fault block involving Triassic sediments.

The ore bodies, which are of vein-like form, have originated by contact metamorphism caused by a granodiorite which has intruded the sediments and altered them to marble, hornfels, slate, and quartzite. The ore occurs in the thin limestone members of this series, the tungsten mineral being scheelite, whose chief associates are garnet, epidote, and quartz as well as abundant pyrite. Folding, faulting, and fracturing have separated the ore bodies, and they form isolated, nearly vertical, segments, arranged *en echelon* along a line that strikes about N. 20 E. Kerr believes that the principal ore formation probably occurred toward the end of intrusive action and prior to the formation of quartz veins, and accompanying end-stage effects which consisted of a quartz-albite invasion and silicification.

The concentrates carry 65–70 per cent WO_3, about 6 ounces of silver and a trace of gold per ton. Until 1932 the normal ore carried 1.10 per cent scheelite, but new discoveries have increased the quality and quantity of the ore reserves.

Second in importance are the tungsten veins at Silver Dyke, Nev. (18), where scheelite occurs in quartz associated with albite. The vein system lies close to the contact between post-Jurassic diorite and intruded Triassic volcanics.

South Dakota (15).—Wolframite is found near Lead City as flat, horizontal, but irregular masses, associated with the oxidized, refractory siliceous gold ores. These ores are replacements of a dolomite deposited by rising thermal solutions.

Canada (6).—Tungsten ores have been reported from a number of localities in Canada, but the production is small and irregular, and comes from the scheelite-quartz veins of Nova Scotia. Other occurrences have been recorded from Beauce County, Quebec, and the Slocan district of British Columbia.

Other Foreign Deposits.—China supplies the greater part of the world's demand for tungsten. According to some the supply comes from veins, but Lindgren gives placers as the source.[1]

Tungsten deposits of some importance are worked in Burma. The ores are reported to occur as veins in granite, schist, and pegmatite.[2]

This country is the third largest producer.

Queensland[3] and New South Wales[4] have wolframite in quartz veins, greisen and placers.

In Portugal, wolframite, associated with scheelite and tungstite (WO_3), as well as cassiterite, pyrite, arsenopyrite, tourmaline, and fluorite, is found in veins and stockworks.

The Malay States also produce tungsten.[5]

Uses of Tungsten.—This metal is of importance in the manufacture of high-speed tool steels, also in complex alloy steels, and in nonferrous alloys of the stellite type. Lamp filaments, radio-tube filaments, and contact points in electrical apparatus represent other important uses. In the chemical industry it may be employed in the production of certain dyes (lakes) and mordants. Sodium tungstate is used for fireproofing curtains.

Production of Tungsten.—The tungsten ore concentrates, figured on a basis of 60 per cent WO_3, shipped in the United States in 1940, amounted to 5319 short tons, valued at $5,062,199, the price per unit of concentrate being $20.61. There has been a great increase in production in the past five years. Nevada is the chief producer.

The imports of tungsten ore and concentrates, with a tungsten content of 5,610,882 pounds, were valued at $4,690,723. In addition there were imports of tungsten metal, tungsten carbide, tungstic acid, etc. Canada in 1939 shipped 8825 pounds valued at $4917. Exports were only in the manufactured form.

The world production in 1935 was 37,840 metric tons of concentrates (60 per cent WO_3). China was the largest producer. Bolivia and Portugal are now also important.

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[1] Mineral Deposits, 3rd ed., 745; King-Lan and Huei-Shing, Geol. Surv. Kwangtung and Kwangsi, Ann. Rep., I: 29, 1928.

[2] Griffiths, Min. Mag., XVII: 211, 1917; Campbell, Econ. Geol. XV: 511, 1920.

[3] Cameron, Queensland Geol. Surv., Rept. 188, 1904.

[4] Carne, N. S. W. Geol. Surv., Min. Res. No. 15, 1912.

[5] Scrivenor, The Geology of the Malayan Ore Deposits, 1928.

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URANIUM AND VANADIUM

Ore Minerals.—The minerals which carry one or the other, or both, of these elements, and which are of commercial importance, are: *carnotite* ($K_2O \cdot 2UO_3 \cdot V_2O_5 + 8H_2O$); *roscoelite* or vanadium mica ($H_8K(MgFe)$ $(AlV)_4(SiO_3)_{12}$); *pitchblende* or *uraninite* (U_3O_8); *uvanite* ($2UO_3 \cdot 3V_2O_5 \cdot 15H_2O$); *descloisite* ($ZnPb(OH)VO_4$); *patronite* ($V_2S_5$); and *vanadinite* ($Pb_5Cl(PO_4)_3$).

Of these carnotite is the most important ore in the United States, not only because of its uranium content, which is in more demand than the vanadium, but also because it carries radium, so much sought after now because of its radioactive properties. Associated with the carnotite is more or less roscoelite.

Distribution of Uranium and Vanadium in the United States (1, 10).—The chief source of uranium and vanadium in the United States is a somewhat extensive area in western Colorado and adjoining portions of Utah (5, 7).

The metals have been obtained chiefly as a by-product in the isolation of radium from the carnotite ores, which occur in loosely cemented Jurassic sandstone. Associated with the carnotite are several other vanadium minerals, chief among which is a micaceous ore not definitely identified, as well as hewettite, uvanite, vanoxite, etc. The ores always carry more vanadium than uranium. The deposits are mostly small and carry from 2 to 4 per cent vanadium oxide.

Another type of ore is a roscoelite-bearing sandstone, formerly extensively worked in San Miguel County, Colorado. The ore bodies were mostly flat lenses, and some of the ore ran 3 per cent vanadium oxide.

The origin of these deposits has been a puzzling problem. Vanadium is known to occur in small quantities in many sedimentary rocks, and the present deposits may represent concentrations by surface waters, although Hess suggests that the dikes found in this region may have some connection with the mineralization of the sandstone.

Vanadium minerals are widespread in the oxidized parts of many lead veins, but they contribute little to the output.

At Cutter, Sierra County, New Mexico (6), vanadinite associated with lead, zinc, and copper has been found in veins cutting Carboniferous limestone.

Pitchblende has been found at a number of localities in the United States, including Central City, Gilpin County, Colo. The mines were originally worked for gold (10).

The United States uranium and vanadium industry has serious competitors at the present time, for the Peruvian deposits dominate the vanadium production, while the newly discovered ores of the Belgian Congo control the uranium-radium market.

Canada (8).—Pitchblende and native silver were discovered at Great Bear Lake, Northwest Territories, Canada, in 1930. They occur in shear zones cutting pre-Cambrian sediments and volcanics near their contact with granite. The pitchblende occurs as colloform masses, and in addition to silver there are a number of other metallic minerals.

Foreign Deposits.—The important European deposits of pitchblende are found at Joachimsthal,[1] Czechoslovakia, and at Johanngeorgenstadt, Marienberg, Freiberg, and Schneeberg in Saxony. The veins are referred to under nickel and cobalt.

Of great importance are the vanadium deposits at Minasraga, 20 miles from Cerro de Pasco, Peru.[2] The ore mineral, patronite (V_2S_5), is found as a lens-shaped mass in red shales, associated with a black hydrocarbon called *quisqueite*.

In Katanga, Belgian Congo, there were developed in 1921 some uranium-bearing veins which have become important producers, and at present dominate the radium market. The ores which are associated with copper deposits form

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[1] Becke, Zeitschr. prak. Geol., 1905: 148.

[2] Hewett, Amer. Inst. Min. Engrs., Trans. XL: 274, 1910.

veins in faulted and crumpled metamorphic rocks, but they are somewhat irregular in distribution and thickness. The uranium minerals are pitchblende and its alteration products, including a number of rare species.

Production of Uranium and Vanadium.—In 1940 the United States produced 796 short tons of carnotite valued at $61,800. This contained 16,909 pounds of uranium and 51,377 pounds of vanadium. There were also produced 95,549 short tons of vanadium ores valued at $968,000. The output came from Arizona, Colorado, New Mexico and Utah.

The imports of uranium oxide and salts in 1940 were 240,199 pounds, valued at $388,353. Those of uranium ores were 2,400,198 pounds valued at $2,110,927. The ores of vanadium had a vanadium content of 2,574,951 pounds, valued at $1,216,705.

The important world producers of vanadium in 1939 were: Southwest Africa, 514 metric tons; northern Rhodesia, 384 metric tons; Peru, 1016 metric tons. Arctic Canada and Belgian Congo have been important sources of radium-uranium ores.

Uses of Uranium.—Uranium salts are used in the glass and ceramic industries as coloring agents, in dyeing, and in photography. Some ferrouranium is used in hardening and toughening steel.

Uses of Vanadium.—The main use of vanadium is as an alloy in steels where great toughness and torsional strength are needed. It is sometimes used in certain tungsten alloys for making high-speed tool steel. Metavanadic acid has been used as a substitute for bronze paint, and vanadium chloride is used as a mordant in printing fabrics, and the trioxide as a mordant in dyeing.

It is also used as a catalyst in the manufacture of sulphuric acid and certain organic chemicals.

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