GEOLOGY IN THE SERVICE OF MAN

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INTRODUCTION

GEOLOGY is the Science of the Earth. More particularly it is the study of the nature, structure and history of that thin crustal veneer of our planet which is accessible to man; but narrowed even to this extent, it remains the broadest in scope of all the natural sciences, with nearly all of which it has close contacts, that have often developed from fields of pure scientific speculation into subjects of considerable economic importance.

It is the aim of the geologist to determine what the earth's crust is made of, in terms of rocks and minerals, and to discover how and when they severally were formed. Bound up with this are the problems of geometric structure and arrangement of rock masses, and causes that could produce such structures. Successive earth spasms have not been without profound effect on the distribution of seas and continents, and it is the geologist's business to unravel the complicated story of changing geographies and climates. Finally it is for the geologist to interpret the records left in the fossil remains of animals and plants and show how they are related to those of to-day. In all this, his contacts with the chemist, the physicist, the geographer and the biologist are readily apparent.

Summing up all this knowledge, the geologist is trying to compile a history of the earth, as complete and accurate as the imperfect but ever-growing body of evidence permits. And so he comes to a better understanding of the present state of the natural world, and finds in it the inevitable consequence of a vast succession of changes. It is to him the last 'still' so far developed of a cosmic cinematograph film, many reels of which are forgotten or partially destroyed and others as yet unexposed. The high peaks of the Himalayas or the Alps are largely composed of rocks which were originally the sands and muds of an old sea floor. We think we know how, if not as yet why, they rose to these prodigious heights; and we are certain that in time they will crumble to eroded vestiges no more awe-inspiring than Snowdonia or Lakeland, which in their day have had an alpine grandeur. And from their waste will be built up in another sea thick sheets of sediment destined to make yet another land-mass, and perhaps again a mountain chain. The rhythm of the inanimate world has its counterpart in the organic world too; group after group of plants and animals has struggled to supremacy, only to give way before some other competitor in the onward march. In this we see not merely change, but the something we are encouraged to call progress. The Alps are not better mountains than were those of Wales in their prime; nor is Australia better as a continent than was 'Gondwanaland' in the Permian Period. But the Bushman of Australia was an undeniable advance upon the reptilian inhabitants of Gondwanaland.

This piecing together of the chronicle of the earth we may call the purely scientific and cultural aspect of geology. Its philosophy appeals to many, and its development has given us not only our greatest academic geologists, but all the host of amateurs whose infectious enthusiasm bears witness to the living interest of our science. Indeed, there is no other science, except perhaps astronomy, to which the amateur observer has contributed so much.

But there is another aspect which has sprung from our partnership with the arts. Exploitation of mineral raw materials for modern industry rests upon the partnership of geology with mining and oil technology; siting of dams and tunnels, drainage, road construction, and building materials are as much within the province of the geologist as of the civil engineer; and similar examples could easily be multiplied.

It would have been unnecessary to add to the many books that have been written on the cultural aspect of geology. But little has been done to introduce the economic aspects of our science to the layman, the industrialist and the schoolmaster; and it is the purpose of this little book, after furnishing a necessary but brief account of general principles, to review as simply as possible some of the important but often neglected aspects of Geology in the Service of Man.

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PART ONE

The Nature of the Evidence: An Introduction to the Principles of Geology

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> *The historical student knows that his first business should be to inquire into the validity of his evidence, and the nature of the record in which the evidence is contained, that he may be able to form a proper estimate of the correctness of the conclusions which may be drawn from that evidence.* T. H. HUXLEY

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CHAPTER I

The Crust of the Earth

Geophysical conclusions regarding the earth's interior and the nature of the crust – The temperature gradient – The materials of the earth's crust – High-temperature rocks, low-temperature rocks and metamorphic rocks.

GEOPHYSICISTS tell us that the earth consists of a relatively light solid crust, resting upon a heavy, molten interior. Study of the transmission of vibrations set up by earthquake shocks has revealed great discontinuity in the properties of the earth about half-way to the centre. Below this level the material, though it will transmit longitudinal or compressional waves, is incapable of transmitting transverse or distortional waves; it must therefore be accounted liquid, despite the enormous pressure. Above this level, both push and shear waves are transmitted, and in spite of the high temperatures, it is thus a solid. The liquid core has a density of 12 (it is twelve times as heavy as water), and the shell above it has an average density of 4·3. These high values, however, are partly the result of terrific compression, under weight of overlying material, and it is calculated that if this pressure were eliminated, the density of the core material would be about 8 (matching that of the iron meteorites), and that of the shell 3·4 (comparable with that of the stony meteorites). It is concluded that as a whole the earth behaves as would a stony shell some 2,000 miles thick, resting on a core of molten iron 4,000 miles in diameter.

The shell is not uniform throughout, but consists of layers different in composition and properties. It is because shock-waves, both compressional and distortional, bend as they pass from one layer to another, as a ray of light is refracted on passing from air to water, that we have come to know about them. The outermost shell of all is a siliceous, 'granitic' layer some ten miles thick, with an intermediate layer below, itself composite, but mainly 'basaltic', and some twenty-five or thirty miles thick. Under these skins, the great bulk of the material, extending half-way to the centre of the earth, is mainly composed of the ferromagnesian mineral olivine, with a density of 3·3–3·4.

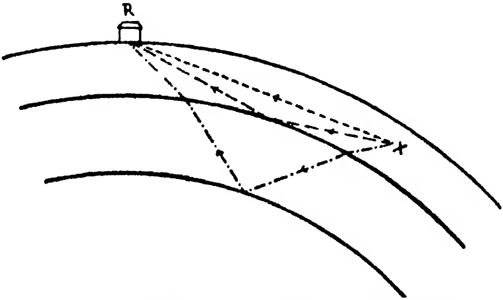

FIG. 1. – Diagram showing the Paths taken by the principal Waves that would be received at a Recording Station *R*, from a Shallow-focus Earthquake at *X*.

The time taken depends on the distance which the waves have to travel, and on certain physical properties of the material through which they pass, so that a succession of tremors is recorded at *R*.

Apart from such measurements of physical properties, we have no means of ascertaining the composition of material lying below the superficial crust. But in accepting the inference that the intermediate and lower stony layers are basaltic and olivine-bearing, we agree that, to the bottom of the solid shell, metallic elements are mostly combined with silica and oxygen as silicates. Statistical summation of analyses of all known rocks has shown that the average proportion of oxygen exceeds 47%, and that eight elements so far preponderate over all others as to compose nearly 99% of the whole. These elements are:

Oxygen	47	75% of the earth's crust
Silicon	28	
Aluminium	8	24% of the earth's crust
Iron	5	
Calcium	3·5	
Sodium	2·75	
Potassium	2·5	
Magnesium	2·25	

The remaining eighty or more elements, including almost all those concerned in the make-up of living bodies and most of the substances useful in the arts, compose no more than 1% of crustal layers.

Fortunately the crustal layers are not all uniform and homogeneous, and natural processes have provided local accumulations of useful substances as mineral deposits which are rich enough to be classified as ores. How variable is the intensity of this segregation may be illustrated by reference to the useful metals gold, copper and iron. Gold, which is reported to average 1 part in 100,000,000 of all rocks, becomes worthy of the miner's attention if its local concentration exceeds 1 in 100,000. Copper, not more abundant on the average than 1 in 10,000, may be recoverable at profit if it forms 0·75% of any great mass or bed of rock, and a rich ore may yield 3% or 4% metallic copper. By contrast, iron, which is, next to aluminium, the most abundant of all metals, is nowhere smelted, even from the most extensive bedded formations of lean ores, if the yield is less than 18–20% of metal. Almost any naturally-occurring mineral has realizable commercial value in the modern world if it contains less than 10% of oxygen and/or 2% of silicon, and is accessible for transport.

As a working hypothesis, then, we may assume that the earth, soon after its separation from the sun, consisted of two immiscible fluids, the lighter of which floated to the outside and in time solidified around the central core of denser metal which has remained fluid to this day. It also remains intensely hot. The high temperature of the earth's interior is not entirely due to residual heat, however, but in some degree to the spontaneous breakdown of radioactive elements such as thorium and uranium. Cooling from the surface and conduction of heat through the solid shell have established a temperature gradient which is a matter of experience in the development of any deep mine. Indeed, it is one of several factors limiting the depth to which a mine can be extended. In British and most European mines, the average rise in temperature is 1 degree Centigrade for every 100 feet of depth, but the gradient varies in different parts of the world. In coal-mines near Manchester, for example, the temperature at a depth of 4,000 feet has risen to 113° F., which is already too hot for comfortable working. But in South Africa a temperature not higher than 100° F. is usual in the 8,000-foot-deep gold-mines near Johannesburg. At such a depth in Britain the temperature would be 176° F. or 80° C. The temperature gradient in South Africa is therefore only about half that of Europe, and extension of mining development to 12,000 feet is contemplated. In North America the temperature gradient is about three-quarters that of Europe. This variation may be due to slight differences in thermal conductivity of the upper layers of the shell; temperature is certainly higher under layers of unconsolidated sediment than in compact siliceous crystalline rocks. The distribution of radioactive minerals may also be important. Temperature is also further disturbed locally in areas of volcanic activity, where molten magma from lower levels has lately come near the surface. In such regions hot springs and geysers are frequent, and in some places, especially along the west coast of North America, north of San Francisco, and in Peninsular Italy and Japan, this source of energy is providing power for cities and great industrial undertakings. Drilled oil-wells near the mountains of California and in India are delivering fluid at surface near the boiling-point of water, and in Iceland hot springs are piped and used for central heating. It is calculated that at the base of the intermediate layer of the stony crust, however, the temperature is everywhere about 650° C.

THE MATERIALS OF THE EARTH'S CRUST

The phrase 'hard as a rock' loses something of its expressiveness when by 'rock' the geologist is indicating a plastic clay or an unconsolidated sand. Yet as 'aggregates of mineral particles', these are rocks just as truly as is a piece of granite or a block of limestone. A mineral is a single substance, and has a precise constitution which in the chemist's shorthand may be expressed by a definite chemical formula; quartz, for example, is a crystalline form of silicon dioxide, SiO_2. A rock, on the other hand, though it may be a mass of associated grains or crystals all of one single mineral species, generally consists of two, three or half a dozen or more kinds of minerals assembled by a series of natural processes. Salt, crystallized from brine, is rock; so, too, is the lava poured out liquid from a volcano and solidified to a mixture of diverse minerals as it cooled. So, too, is a heap of fragments broken from a cliff, pounded and heaped together as pebbles on a beach; or the clay composed of mud particles and microscopic organisms which has settled in the stiller, offshore water of the sea.

High-temperature Rocks

It is well known that certain rocks have formed by crystallization, or at least by solidification, of molten magma; the lava-flows of Vesuvius long ago attracted human attention of no very favourable kind. Greater than lava-flows, other rock-masses represent crystallized magma which never reached the surface, but cooled more slowly at various levels within the crust of the earth. Whatever the conditions under which these *igneous* rocks have cooled, they are portions of the sub-crust shell which, for reasons not at present fully understood, have re-melted and made their way upwards towards the surface.

Sixty per cent of the earth's crust is silicon dioxide, silica, SiO_2; and this as acid-radicle forms silicates of aluminium, iron, calcium, magnesium, potash and soda. Igneous rocks are aggregates of such silicate minerals, but the amount of silica present varies between 80% and 30%, and in chemical classification the proportion determines whether a rock is 'acid' or 'basic'. With variations of silica go variations in other components also, but the silica content is the most convenient index. In an acid rock, the silica is in excess of chemical base requirements, and some may be left over to crystallize as free quartz; orthoclase felspar and mica are also characteristic minerals in the more acid rocks. An acid rock is generally light-coloured and light in weight, with a specific gravity about 2·7. In a basic rock there is deficiency of silica, and 'unsaturated' minerals occur; some kinds of basic plagioclase felspar and dark-coloured ferromagnesian silicates may be dominant, but olivine (a basic magnesian silicate) and the unsaturated felspar-like minerals called felspathoids are distinctive. If, in addition, the basic magma is rich in iron, the excess may separate out as the oxides magnetite and ilmenite. A basic rock is dark-coloured and heavy, with a specific gravity exceeding 3. In the intermediate rocks there is typically neither quartz nor olivine nor felspathoids, but the rocks are composed mainly of various kinds of plagioclase and such ferromagnesian silicates as hornblende and augite.

The type of rock depends not entirely on the composition of the magma, however, but also to a large extent on the physical conditions under which it cooled.

It has been shown experimentally that if a solution or a molten mass of a single substance is cooled, crystals do not begin to form immediately the temperature falls below the freezing point. At first their growth is extremely slow and only about a few scattered centres; at this stage the liquid–solid equilibrium is metastable. As temperature falls further the number of centres rapidly increases; the liquid is now in what is termed the labile state and a precipitate of crystals falls out. Still further below freezing point, if solidification is not complete, the rate of crystallization again falls off. This is represented graphically in Fig. 2.

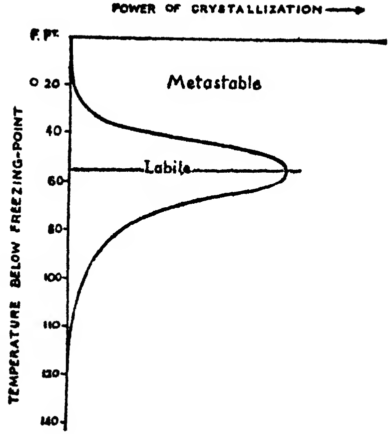

FIG. 2. – Curve representing the Super-cooling of Augite (a Ferro-magnesian Silicate). (After Harker.)

When a magma cools slowly it takes a long time to pass through the metastable condition, and each constituent gathers to so few centres that the resulting solid is coarse-grained. A quickly cooled magma passes rapidly through the metastable region and, solidifying principally in the labile region, a fine-grained texture must result. Or, if the chill be especially rapid, it may pass through both metastable and labile ranges and solidify as a glass without any crystallization at all.

High viscosity impedes molecular movement and favours the production of numerous small crystals instead of fewer bigger ones. In the case of silicate melts, viscosity is considerably affected by the presence or absence of fluxes – water and various gases in the magma. An acid magma, poured out at the surface, loses its volatiles and cools rapidly; under such conditions a glass will probably result. Pumice-stone is nothing more than a natural glass sponge; the sudden expansion and escape of its steam have produced the spongy texture, and the viscous silicate melt has solidified without crystallization. But the same magma intruded at depth cools within the blanket of surrounding rocks, which at depth are themselves quite hot and under great pressure. Volatiles escape but gradually and the magma crystallizes slowly in the metastable range; the rock thus formed will be coarse-grained and wholly crystalline, like granite. The very obvious differences between granite and pumice are almost entirely due to the environment under which the rock solidified.

Crystallization of every substance is conditioned by the presence of others. The freezing temperature of each is lowered and the equilibrium conditions of composition and temperature are related according to the phase-rule laws. Synthetic melts of two or three selected substances have helped to elucidate the succession of crystallization within such mineral families as the felspars and some ferromagnesian minerals. But magmas are mutual solutions of silicates with some half-dozen basic radicles combined singly or in groups, and with each additional constituent the process of crystallization becomes correspondingly more complex; in no case has the full story of complete consolidation been told for any natural igneous rock.

First-formed crystals are free to develop their limiting crystal faces, and the form of mineral grains as they abut upon one another (recognizable in thin slices) early brought to notice an undisputed empirical rule, that the order of crystallization of the mineral constituents of igneous rocks follows closely that of the proportion of silica in their molecules. Accessory minerals with little or no silica come first, followed by basic and later by intermediate ferromagnesian silicates; members of the felspar family also appear in order of increasing acidity, and quartz (i.e., uncombined residual silica) is generally more or less interstitial.

Silicate melts within the temperature range of their crystallization are very viscous, and true equilibrium is attained but slowly. As the early crystals separate, they may sink or float under gravity through the cooling liquid which produced them, and thus the bulk of quite large volumes of the magma differentiates – i.e., is subject to progressive change in composition. It is in general the basic minerals – the iron ores and ferromagnesian minerals with the lowest proportion of silica – which have separated at the highest temperatures and are dense enough to sink long distances through the magma, leaving a liquid from which the more siliceous minerals crystallize later; in other circumstances, the first-formed felspathic minerals may float. Much attention is being given to these complex physico-chemical reactions to-day, but an account of such work is outside the scope of this book. It is a subject as important to those who have to make or maintain high-temperature furnace linings or study the behaviour of slags, or to manufacturers of cements, as it is to petrologists.

We turn now to the classification of igneous rocks on the dual basis of chemical composition and mode of origin.

Those which occur in large masses, slow-cooled at depth and continuous through several cubic miles, have certain physical characteristics in common, regardless of their chemical composition. They are completely crystalline, coarse, with well-grown crystals, generally several millimetres or even centimetres in diameter, and are usually of even grain. These are the *plutonic* or *abyssal* rocks.

Those which result from the chilling of magmas poured out at surface – the eruptive or *volcanic* rocks – often contain some natural glass in which a mass of minute crystals may be embedded. Steam cavities or vesicles and a banded flow-structure are characteristic of volcanic rocks. A few large crystals, brought up with the liquid from below, may give the rock the appearance of the porphyries, so prized as ornamental stone by the ancients, and this structure is named porphyritic. Crystallization had begun in the metastable region before extrusion, and was completed at surface as the lava set.

There is a third class, the *hypabyssal* rocks, intermediate in character, as in origin, between the other two. Intrusions often branch into dykes or walls of igneous rock, forced up along cracks and planes of weakness in the overlying rocks – and here the cooling will be more rapid than in the parent mass, for the volume of magma at hand is smaller, and what there is, is chilled by contact with the colder 'country rock'. How quickly it cools depends on many factors, but mainly on the quantity of hot magma which has flowed through, and on the thickness of the dyke. Dykes are of all thicknesses from a few inches to many hundreds of yards, and the texture of dyke-rocks is correspondingly variable, showing all gradations from a glassy pitchstone to a completely crystalline rock hardly finer in grain than those which are plutonic. Again, the lava from a volcano has originated deep down in the earth's crust, and reaches the surface only via a pipe or fissure; the magma remaining in the pipe after the eruption cools more slowly than the extruded lava, and, like that which has spread laterally to form sheets or sills or laccolites between the bedding-planes, has the variable texture and other characteristics of a hypabyssal rock.

Note

Plutonic, volcanic and hypabyssal or dyke-rocks, thus distinguished by their mode of origin and texture, may be acid, intermediate or basic in composition. A tabular classification is given in Appendix I, p. 207.

Low-temperature Rocks

Minerals of a plutonic rock have crystallized at temperatures between 1,400° and 400° C., and under pressures of some 5–10 tons to the square inch, where they were intruded under a high alpine range which might give 20,000 feet of overburden. They are therefore only in real equilibrium under such conditions deep within the ground. But when, by subsequent erosion, the rock is exposed at the surface to water and to atmosphere, its minerals are no longer stable; and so to a greater or lesser extent all igneous rocks at surface are breaking down. The changes which set in are called weathering, distinguished as a twofold process of mechanical disintegration and chemical decay.

Mechanical weathering is in the main due to the development or release of very local stress, resulting in strains and cracks not only in the rock-masses as a whole, but in the several mineral grains. It is brought about by release of constraint, variation of temperature as between night and day, sun and shade, dampness and drought; and in such a climate as our own, by frost riving. Chemical weathering includes all those reactions which are set up when silicate minerals meet liquid water or atmospheric moisture, particularly when, with the addition of organic decomposition products and carbon dioxide, the water is converted into a weak acid. Under these conditions the felspars and the ferromagnesian silicates (biotite-mica, hornblende, augite and olivine) all decompose. Always something goes into solution and is removed, and what remains is hydrated, oxidized or carbonated, and invariably swells. Only quartz and muscovite, constituents of comparatively acid rocks, are immune.

The felspars, alumino-silicates of potash, soda or lime, and the ferromagnesian silicates, are converted into 'clay-minerals', but the chemistry of the process is very imperfectly understood. Pure china-clay, kaolin, is a simple aluminium hydro-silicate, and the formation of this from felspar must involve the loss of all alkalies which, in contact with water, should pass into solution as carbonates. But the percentage of dissolved alkalies in river-waters is so low that such an explanation is unacceptable; and it seems probable that the alkalies of felspars remain in the mud as secondary hydro-micas, which retain a considerable amount of alkali. We cannot at present say more than that the felspars (and ferromagnesian silicates too) break down into diverse members of the large group of 'clay-minerals' – complex in composition but closely allied to the micas – in an extremely fine state of division. Their breakdown loosens and sets free the less alterable mineral grains such as quartz or muscovite-mica, and the products either accumulate as soil or are carried away in river-water. Chemical disintegration of the igneous rocks, conditioned by this low-temperature instability of high-temperature minerals, is not only the ultimate source of all sedimentary rocks, but also of the soil, without which land plants as we know them could not exist nor, without land plants, land animals.

Sedimentary rocks, which form the greater part of the visible portion of the earth's crust, are more difficult to classify than igneous rocks, having more varied origins and in a sense a wider range of composition. Among their more important characteristics, we may note that they have been spread over wide surfaces, mostly under water, in quasi-horizontal sheets, and that in consequence the majority of them show 'bedding' or stratification and occur in regular layers one upon another. Their succession is the basis of our interpretation of earth history (see Chapter IV). Three principal types are recognized: fragmental or clastic, organic and chemical.

Fragmental or clastic rocks consist of fragments of pre-existing rocks, igneous or sedimentary, together with primary grains of their more resistant minerals, such as quartz, and the secondary products of chemical weathering, such as clay particles. They are thoroughly familiar, both in their uncompacted forms as gravels, sands and muds, and when compacted or cemented into the solid rocks known as conglomerates (and breccias), sandstones and clays or shales. The geologist's classification is the same as the popular one, being similarly based upon grain size. At present this seems the only practicable method, but it has the disadvantage that it groups together rocks of very diverse composition and origin, particularly in the coarse-grained categories. Such rocks may have accumulated under fresh or salt water, or on land; and the material may have been transported by water, wind or ice, or may simply have come to rest on a slope, as in scree or run-of-hill accumulations.

Organic deposits are equally varied. The term is used for all rocks which are predominantly composed of the remains of animals or plants. Those of vegetable origin are generally carbonaceous, like coal and peat, though some simple microscopic plants have 'skeletons' of silica or calcium carbonate. An example of the siliceous type, diatomaceous earth, is of some importance for insulating material, or as a fine abrasive. Organic deposits of animal origin are occasionally siliceous (Barbados earth), but more usually they are calcareous or phosphatic. Animals and simple siliceous or calcareous plants take the necessary chemicals for their shells or skeletons from solution in water, and are thus utilizing the extract products of chemical weathering from older rocks. Shell limestones are the most familiar organic deposits of animal origin; and are frequently used as ornamental stones. The coral limestones so commonly used for marble mantelpieces may be cited as examples, or the encrinite limestones of Derbyshire, chiefly composed of the stems of 'sea-lilies'.

Chemical deposits in the main result from the precipitation of substances in solution. All rivers, clear or muddy, carry dissolved substances to the sea; water evaporating from the surface of the sea is carried back in the atmosphere over the land, where, condensed as cloud, it falls as rain, the run-off extracting and again carrying further minute quantities of chemicals in solution to the sea. There has thus been a gradual concentration of salts in the sea since the beginning of earth history. It is estimated that at the present time over 2,000 million tons of saline matter are carried by rivers into the sea each year, but even so the concentration there is very small – rarely more than 35 parts per 1,000. A strangely uniform proportion of common salt (sodium chloride) is the principal item, and this forms 78% of the total solids in the ocean. The percentage of calcium carbonate is exceedingly small (only 0·34), this proportion contrasting strongly with the high percentage among the salts of river-waters; the reason for this is that calcium carbonate is constantly withdrawn from solution in the sea by lime-secreting animals and plants. Under certain conditions, substances carried in solution in sea-water are precipitated, chiefly in shallow water and in some enclosed seas, by evaporation or by chemical interaction with substances developed by decaying animal matter. Among examples of the former we may cite beds of rock-salt, anhydrite and gypsum (alabaster); among the latter, calcium carbonate and dolomite – i.e., limestones of inorganic origin. But the term chemical deposit also covers the exceptional but economically important potash and magnesia salts, nitrates, iodates and borates, and some, such as guano (phosphate), that are of organic origin.

For completeness, reference may be made here to two other less common types of surface rock. Residual deposits consist of the untransported products of weathering – that is to say, weathered mineral debris left *in situ.* The clay-with-flint capping of the Chalk Downs is an example from this country; other examples include the laterites of monsoon countries, and the commercially important deposits of bauxite, the most desirable aluminium ore. Lastly, the name pyroclastic rock is given to deposits which are clastic or fragmental in character, but are composed of fragments of lava blown out of a volcanic vent, not fragments produced by weathering. They are strictly speaking not low-temperature rocks at all, but their structure is more allied to that of sediments than to igneous rocks.

All these low-temperature rocks, except the residual deposits, so grade into one another that it is impossible to draw any hard-and-fast lines between the different types. Fragmental rocks have usually entombed abundant *fossils*, but only rarely does the concentration of shells entitle them to be classed as organic. Chemical deposits may be organic, sedimentary or volcanic in origin, or the result of chemical precipitation. Limestones, again, which are usually partly chemical and partly organic, often contain so much admixed sediment or clastic material that if the lime be dissolved out with acid, a coherent though friable mass of rotten-stone (shaly or sandy) remains behind.

In certain circumstances these low-temperature rocks, which directly or indirectly are the weathered derivatives of igneous rocks, may again be deeply buried, compressed and subjected to high temperatures. When this occurs it is the turn of the low-temperature minerals to become unstable, and new minerals characteristic of the higher temperatures and pressures form or re-form as the result of a new series of physico-chemical reactions. In general, the process is not a simple reversal of the weathering process, because mechanical sorting inevitable during transport and deposition of sediments has segregated certain products, and the various constituent elements come thus to be associated in altogether different proportions. The clay minerals lose water and are converted into chlorite and mica, and excess of alumina appears as chiastolite, sillimanite or kyanite, according to the temperature. A pure limestone can only recrystallize to marble, a pure sandstone to quartzite; but a sandstone with a calcareous cement or a limestone with scattered silt or sand grains produces lime silicate minerals (wollastonite, tremolite and garnet) practically unknown in primary igneous rocks. The more unsorted the sediment, the nearer the approach to a normal igneous rock, but complete correspondence in mineral constitution can occur only when an igneous rock itself is metamorphosed – that is, recrystallized under higher stress and temperature.

Metamorphism, as the processes just described are called, may be produced in two ways. A large plutonic mass may be intruded, and around it the nearby rocks are modified by heat; recrystallization and other changes are often helped by emanations from the magma itself. This is thermal metamorphism. In the other type, regional or dynamic metamorphism, shearing under enormous pressure as well as high temperatures has operated. This type is not confined, as is the other, to the margins of igneous intrusions. As the name 'regional' implies, it affects vast areas, generally those involved in mountain-building. The greater part of north Scotland is an area of regional metamorphism, and is, indeed, no more than a remnant of a far larger area.

Northern Canada and the Baltic Shield (Finland and Scandinavia) are other examples.

Metamorphic rock types are not familiar in England, and they have no popular names. Thermal metamorphism produces the compact, granular, speckled rocks, known as hornfels, various types of which are distinguished according to the minerals present; dynamic metamorphism gives us the 'foliated rocks', by flow under enormous pressure – gneisses when they are coarse-grained, and schists when they are fine-grained. In all metamorphic rocks, but particularly in regions of intense dynamic metamorphism, high-density minerals such as garnet are characteristic; this represents molecular adjustment, with consequent accommodation of material to smaller volume, under high pressures.

We see thus in the materials of the earth's crust the evidence of a continual process of destruction and regeneration of rocks. The process is far from simple, and it is not truly cyclic, for though some have maintained the contrary, there is still no certain evidence that any large mass of igneous rock has ever been regenerated from low-temperature aggregates, even when these have been returned to plutonic stress-temperature conditions. The sediments have been so sorted and sifted in their making that the chemical elements are never redistributed in the right proportions for re-making igneous magma on a scale comparable with that of a large plutonic mass. There have been, instead, recurrent additions to the bulk of the superficial crust, always by intrusions of magma remelted in the deeper-seated regions of the stony shell.

CHAPTER II

The Building of Continents

Transport, deposition and compaction of sediments – Folding and faulting – Earth movements and unconformity – The geosyncline in relation to mountain-building.

LAND surfaces are, and have always been, for the most part areas of weathering and decay. Such deposits as are formed upon them – river gravels and lake deposits, sheets and mounds of morainic debris left behind on the retreat of glaciers, accumulations of wind-blown sand and dust, and screes – all these are only temporary, for they will themselves be weathered away if the levelling-down of the continent proceeds to its final stage. Land deposits of past ages are therefore comparatively rare, and the bulk of the sediments throughout the geological record are marine. As we must confine ourselves here to the broad outlines of the subject, only incidental reference will be made to deposits other than those accumulated in a marine environment.

Transport

The kinetic energy of running water enables it to move already-broken and disintegrated material. In the United States of America alone, at least 800 million tons of solid matter are carried annually to the sea by rivers. The competency of a river to transport material will depend on, among other things, the grain-size of the material and on its own velocity. This latter varies not only with the slope of the ground, but also with the shape of the channel in cross-section, the regularity of its course, and the volume of water. Experimental data have suggested that the size of the largest particles which a current can carry varies as the sixth power of the velocity; that is to say, if the velocity be doubled, the stream can move particles not twice but 2^6 or sixty-four times as large! In conditions of natural streams and rivers, the figure may be more nearly the fourth or fifth power, but even so the increase is sufficiently remarkable. Finely divided material of the mud grade is kept in suspension by the eddies; coarser material is rolled along the river-bed, progressing intermittently by a succession of short or longer leaps as locally the current strength increases and exceeds the critical velocity of turbulence. Larger pebbles and boulders remain stationary except during flood periods, when the carrying power is so vastly increased that even these can be rolled along the bed and smaller grades will be carried in suspension.

Deposition and Sorting

Conversely, when a stream enters a lake or runs out to sea and the velocity is checked, its carrying power is in like manner reduced and its load is dropped. This reduction in carrying power should ideally lead to a grading of the resulting deposit, for the check is gradual and progressive. We should expect to find that the material is thrown down in order of size and weight; first the pebbles and coarse sand, then the finer sand, and farther out in the sea or lake the silt and mud. To a large extent this is so, especially in the coarser grades, and even in the finer grades of fresh-water lake deposits. Exceptions are due to the trapping of finer material in the interstices of coarser-grade material, and to the flocculation of clayey matter carried in suspension by rivers when they meet the salt sea-water. When finely divided clay material comes in contact with an electrolyte (such as sea-water), the minute electric charges carried by each particle are discharged, and the clay particles are able to come together and form clots, often large enough to enmesh tiny quartz grains, and heavy enough to settle along with the sand grade. This is the explanation of the muddy tidal estuaries and muddy sand-flats at the mouths of rivers, as contrasted with the clean sandy deltas of lakes. But such unsorted material is generally worked over by tidal and current action of the sea itself, which often winnows out the finer grades and carries them in suspension till they can settle in the deeper, more tranquil portions of the sea. Once deposited, the clay-grade material is very stable, and more difficult to rewash than is sand.

On the shallow shelves fringing the continents, deposits are not as a rule zonally arranged in grade size, coarser to finer traced outwards; they may show exceedingly good sorting, but it will be in patches rather than in regular zones. Only the finer grades of sediment reach the continental slopes, however; and the deeps of the oceans are beyond the reach of land-derived (or terrigenous) sediment altogether. Oceanic muds, as distinct from the organic oozes, which also accumulate far out from shore – and accumulate incredibly slowly – have their origin in volcanic and meteoric dust which settles from the atmosphere.

Accumulation and Compaction

The sediments in an area of deposition accumulate layer upon layer, often changing slightly or even sharply in composition through changes in the character of the material supplied by rivers, or in the direction or strength of marine currents, or even in the depth of the sea as a result of warping movements of the earth's crust. A bed of mud may be succeeded by one of sand, or of calcareous material, and often there is a regular alternation of rock types in quite a small thickness of deposit. Even when the same type of material accumulates without a break, there will usually be a horizontal layering or grain in the rock, due in part to the deposition of all irregularly-shaped fragments with their longer axes horizontal. Sedimentary rocks accumulate like autumn leaves, and even if they are all the same kind of material, each sheet represents a former surface of the sea-floor, and may lack cohesion with the sheets above and below it. The bedding-planes, as they are called, which separate individual sheets, may be far apart (Fig. 3), as in what the quarryman calls a freestone; in such cases, slabs 10 or 14 feet thick may be obtained. Or they may be so close together, as in a paper shale, that fifty to a hundred

FIG. 3. – Nearly Horizontal Sediments in Central New York, showing Bedding-planes and Vertical Joints in Two Directions at Right Angles. (Drawn from a photograph in C. M. Nevin, *Structural Geology*.)

of them can be counted in the space of an inch. The freestone bed exemplifies stratification; the paper shale, lamination; but there is no hard-and-fast line to be drawn between them. Each successive parting marks a temporary check in delivery of material supplied, and represents a lapse of time which is often far longer than that occupied in the deposition of the bed.

As the thickness of sediment increases, the pressure on the first-formed layers increases and they become more compact. The first and most important stage in the process of compaction is the squeezing-out of water, particularly in shaly rocks. Surprising though it may seem at first sight, a mud comprises only 10–20% of solid matter, and the remaining 80–90% is water. Under pressure of increasing load, some of this water is expelled, the flaky particles felt together, and the mud becomes a plastic clay. But it still carries some 30–35% of water. On deeper burial, most of this remaining water is squeezed out, and the rock becomes a shale or mudstone. This final compacting brings with it chemical changes and recrystallization too, and the later stages of the process, as also the compaction of a sandy rock, are aided by rise in temperature due to the blanketing effect of the overlying sediment. The accumulated sediment is

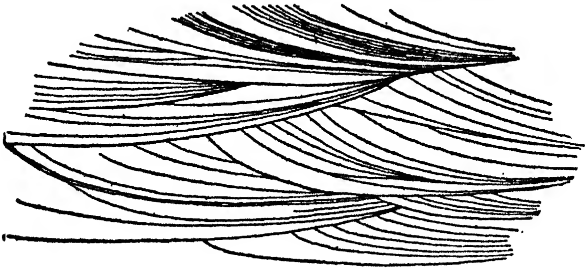

FIG. 4. – Small-scale current bedding in a thin band of fine silt from the Trias (Keuper marls) of Notts. (Magnified about five times.)

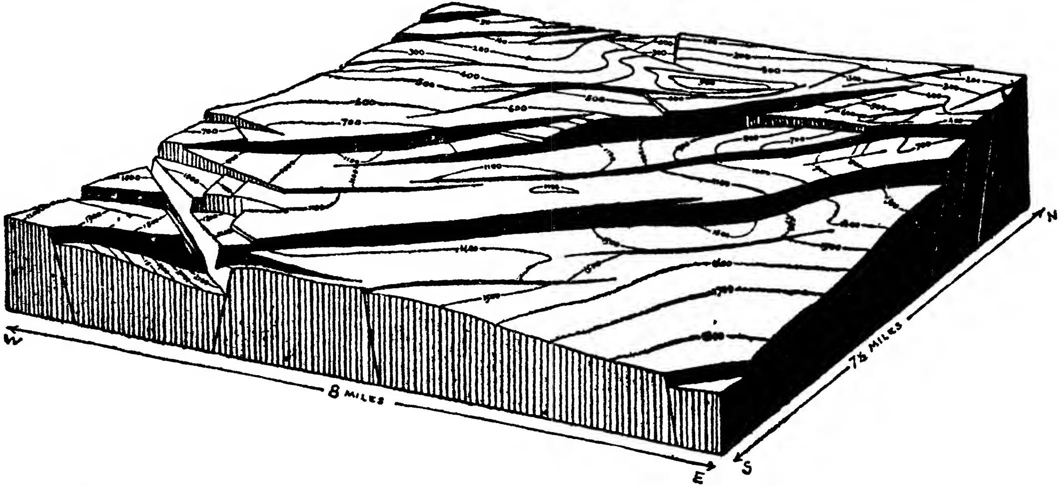

FIG. 5. – Block Diagram showing the surface of the Top Beeston Coal-seam, as it would appear if the overlying strata were stripped away, over an area of sixty square miles in the neighbourhood of Wakefield.

Contours are drawn at intervals of 100 feet below sea-level. Notice the varying displacement of the faults, dying away laterally to nothing. Only major faults are represented; minor faults are too numerous and have too small a 'throw'. The area, like the majority of coalfield districts, is known in detail as a result of mining operations, but there is no reason to suppose that the fracturing of this minute portion of the earth's crust is in any way exceptional. (Simplified and reduced from the Geological Survey Memoir on Wakefield.)

becoming a part of the earth's crust, and the temperature gradient of the earth's crust is being established through it. Compaction of a porous rock may also be accompanied by cementation, as substances like silica, calcium carbonate and iron oxides are dissolved and elsewhere redeposited from solution as they squeeze through the pore spaces between component particles of the rock.

Drying and compaction of a sediment accentuate the bedding-planes and contribute to the development of cracks or joints through the rock in directions more or less at right-angles to the bedding-planes (Fig. 3). Shrinkage due to drying, shrinkage of igneous rocks due to cooling, and shearing stresses developed by movement within the earth's crust or alterations in the overlying load, all lead to the production of joints. At great depths, under a heavy overburden, joint-planes and bedding-planes are kept 'closed'; but as the overburden is removed by subsequent erosion, they become open fissures and are accentuated by weathering. If it were not for the presence of bedding-planes and regularly developed 'sets' of joints, quarrying operations would be vastly more difficult; but the develop-

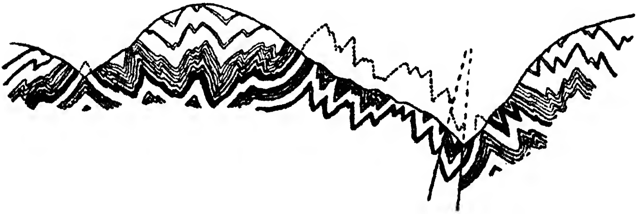

FIG. 6.—Section through highly-folded strata in the Compressed Lower Palæozoic Shale-belt of the Southern Uplands of Scotland.

Length of section about 1½ miles. (Simplified and reduced from the Geological Survey Memoir on the Silurian Rocks of Scotland.) This intense folding should be contrasted with the gently-folded strata of the London syncline (Fig. 27, p. 100).

ment of frequent and irregular joints, through the operation of intense stresses, renders a rock useless except perhaps for road-metal.

Folding and Faulting

Time and again in the earth's history, land has sunk below the sea, or the sea-floor has been elevated to form dry land; evidence of this is to be found, for instance, in the raised beaches and submerged forests around our own coasts. Where a region of accumulating sediment is uplifted to form a new land-mass, it may be by a gentle crustal warping which results in little or no deformation of the originally horizontal bedding-planes. But it is, on the other hand, sometimes accompanied by contortion and fracture. Folding is the term applied to deformation of the layers of rock to forms similar to the ripples and waves on the surface of a sheet of water, or the rucking-up of a carelessly laid carpet when a door is opened. An arched fold, in which the bedding-planes of the two sides are inclined away from the centre or axis of the fold, is called an anticline (*anti*, against), while a trough fold, where the sides slope towards one another, is a syncline (*syn*, together). Faults are dislocations or fractures of the crust, where strains have found relief in an actual break, accompanied by relative displacement of rock-masses on the two sides of the fracture (Fig. 5, p. 33).

Unconformity

So long as sedimentation is proceeding uninterruptedly a succession of bedded rocks is being built up layer upon layer, all the bedding-planes being parallel to one another – i.e., conformable. If the area is uplifted to form dry land the rocks may be thrown into a series of folds, they may be dislocated or faulted, or they may simply be gently tilted; but the bedding-planes maintain conformity one with another whatever form the whole group assumes. As soon as the area is raised above sea-level, however, erosion will begin, and, given sufficient time, the irregularities and folds will be planned off to level ground only slightly above sea-level. Should the region now sink and again become an area of deposition, a new series of strata will be laid down upon the eroded edges of older series. This newer series will rest with discordance upon the older formations, from which it is separated by a surface of unconformity (Fig. 7). Whatever deformation subsequently affects the newer series is bound also to affect the older; but the bedding-planes of the newer series can never become conformable to those of the older, for the earlier series has been tilted, folded or faulted before the newer beds were in existence. The unconformity represents a physical break in the regular geological succession of that area – it is the record of a major time-gap unrepresented by sediments in our column of strata in this particular region. How big the time interval not represented we cannot tell until we have in some way correlated the upper and lower series with their equivalents in some other area where there was a steady deposition of sediment producing a continuous rock succession. Fortunately it is rarely impossible to find such an area, for there have always been oceanic regions, and continuous deposition has been going on somewhere; but the correlation may be difficult.

The Geosyncline

We have already pointed to the necessity for a local sinking of the sea-floor to accommodate the supply of detritus if sediment is to accumulate to great thickness over any given area. If the sinking is too rapid, there will be a resultant deepening of the sea and the character of the sediment delivered will change to finer-grained and muddier types; but the sedimentation will be continuous.

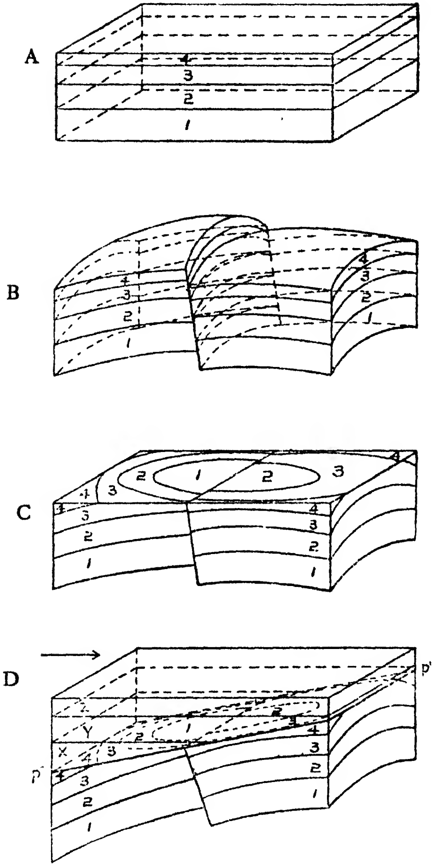

FIG. 7. – Stages in the making of an Unconformity.

From above downwards: (A) Conformable series of strata (1–4) undisturbed. (B) The same series, folded into a dome, faulted, and raised above sea-level. (C) The same, after erosion to a level plain. (D) Deposition of newer series (*X*, *Y*, *Z*) unconformable to the older; *p*-*p*′, plane of unconformity. The newer series was deposited in a sea transgressing in the direction of the arrow, so that each member of the newer series successively thins out and is overlapped by the conformable bed above it; the region around *p*′ was dry land while *p* was receiving deposits of sediment.

If, however, there is no movement, the sea will silt up, and then the material will be carried forward to some other area, and a break in the sedimentary succession must result. Because this necessary adjustment between rate of sinking and deposition is never perfectly balanced, the succession of sedimentary rocks is full of innumerable small non-sequences, which do not as a rule indicate large time-gaps. In certain regions approximate adjustment has been sufficiently prolonged to permit the accumulation, in continuous sequence, of as much as 40,000 or 50,000 feet of relatively shallow-water sediment; that is to say, has allowed the deposition as essentially one unit of a thickness approximating to nine miles of sediment. This seems to be about the limit to which sinking and sedimentation can proceed. It will be recognized that this is nearly as thick as the granitic layer of the earth's crust, and it must be accompanied if not actually caused by large-scale adjustments in that crust itself.

A trough of deposition of this vast type is termed a geosyncline, and such features have a very important relation to the main subject of this chapter, the building of continents, because so far as we know they inevitably become the site of revolutionary crustal movements. For as much as perhaps 100 million years, the tranquil deposition of sediment in such a sinking area may continue with accumulating stress at lower levels in the crust. Then come instability and readjustment, and development of extreme types of folding and faulting, with growth of important mountain chains like the Alps, the Carpathians, the Caucasus and the Himalayas. All these are localized in what not so very long before were geosynclinal areas.

The types of structure that we associate with the term 'mountain-building movement' are illustrated by the vertical sections shown in Figs. 8 and 9. Low-angle faults, known as thrusts, occur, along which surfaces masses of

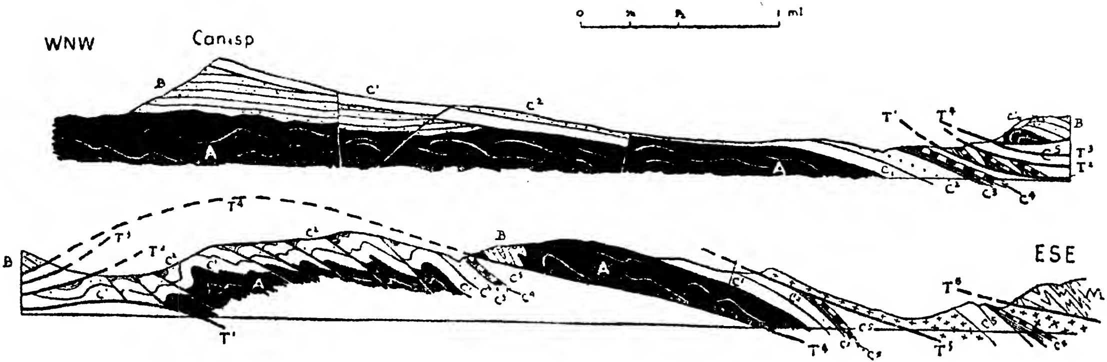

FIG. 8. – W.N.W.–E.S.E. Section through Canisp in the North-west Highlands of Scotland, showing the effects of Thrusting.

A, Pre-Cambrian gneisses. *B*, Torridon Sandstone (Pre-Cambrian) resting unconformably upon *A*. *C*1–*C*5, various members of the Lower Cambrian resting unconformably upon *B* or *A*. *M*, Moine Schists, thrust on top of the Cambrian from the east.

*T*1–*T*6, thrust-planes. *T*1, called the 'sole', carries Pre-Cambrian gneisses and overlying Cambrian rocks over the undisturbed succession to the west. *T*4, the Ben More Thrust, carries Pre-Cambrian gneisses, Torridon Sandstone and Cambrian westwards over *T*1 and the minor thrusts *T*2 and *T*3. *T*6 is the great Moine Thrust.

Section schematized and simplified from Geological Survey of Great Britain; the igneous intrusions of Canisp have been omitted, but the intrusive syenite towards the east end of the section is indicated by crosses.

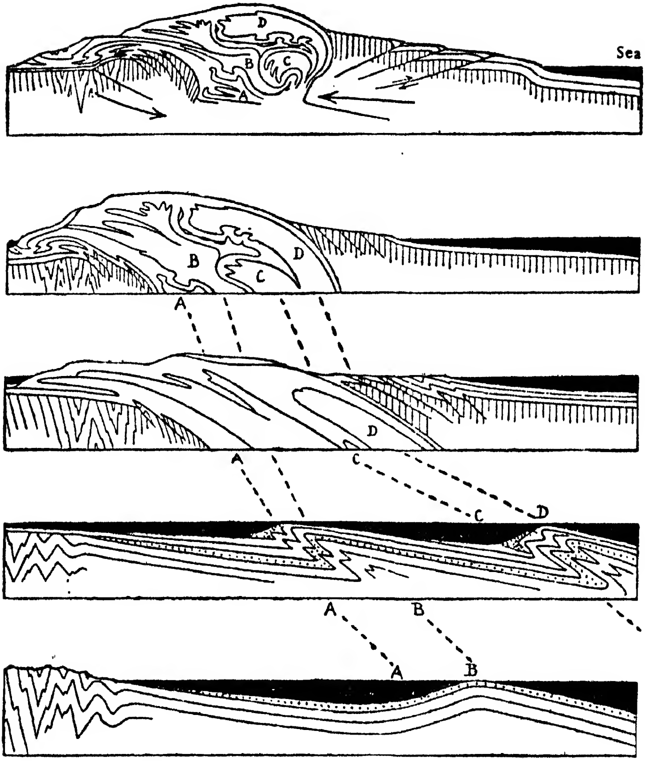

FIG. 9. – Hypothetical stages, from Carboniferous to Late Tertiary, in the Formation of the Western Alps.

Simplified and adapted from sections by Professor E. Argand.

Below, Carboniferous sea with geanticline (*B*) and geosyncline (*A*).

Liassic sea with erosion of geanticlinal crests (*B* and *D*) and deposition in geosynclinal areas (*A* and *C*).

Above, three successive stages in the Tertiary folding, showing the development of the geanticlinal and geosynclinal areas into great complex overfolds or nappes (*A*, *B*, *C* and *D*) and the 'pinching-out' of the roots of these folds.

The Alps of to-day are the eroded remnants of the structures represented in the last stage.

rock have been driven laterally, almost horizontally, for distances of twenty miles or more. And enormous overfolds, called nappes, in which the core of the fold lies horizontal, likewise represent even more striking evidence of vast lateral displacement (Fig. 9 and Plate 2).

The cause of the formation of geosynclines is not known, but there must be liquefaction and lateral flow of material, probably of the basaltic layer of the shell, out from underneath these steadily deepening basins. A long phase of local accumulation of this type is almost invariably associated in its end stages with igneous activity; with outpouring of lava-flows on a regional scale; and later, following the folding, with plutonic intrusions and great swarms of dykes. And the substitution of some 40,000 feet of newly deposited sediments for the same thickness of basaltic or granitic material, or thoroughly consolidated sedimentary rock, undoubtedly results in a weakening of the crust in the region where it has occurred.

The development of earth stresses is in some way consequent upon contraction of the earth's interior with loss of heat, which compels a corresponding crustal shortening if the crust is not to be left unsupported; and it will be noted that the dominant movement indicated by thrusts and nappes is a lateral movement, with a lesser vertical component. The common simile of the wrinkled skin of a dried apple is not inapt; but here the shrinkage of the interior leads to a general wrinkling of the skin over the entire surface instead of a localized wrinkling.

Geophysicists have calculated that crustal shortening should be of the order of 50–100 miles for each major readjustment, and that this should have occurred six times during the last 1,500 million years. That is to say, that there should have been six separated epochs of mountain-building movement during the time which we estimate has elapsed since the earliest rocks were formed. Geologists have recognized at least four such epochs in the British record; traces of the earlier ones are more difficult to unravel, and the earliest of all may well be so obscure that sufficient evidence is not available. Correspondence between geophysical theory and geological observation is sufficiently close to make the theory acceptable. The geologist's estimate of the amount of shortening is, however, considerably in excess of that of the geophysicist – at least 100–200 miles in different instances – and there is as yet no satisfactory explanation of this discrepancy.

We may now sum up very briefly the processes involved in the building of a new landmass. Sedimentation is going on all the time, the weathering of land surfaces providing the debris and the oceanic areas constituting the collecting-dish and semi-permanent resting-places for the products. Because of certain little-understood processes deep down in the earth's crust, the accumulation of sediment may in an elongate trough-like area proceed to an enormous thickness. Such a sedimentary episode may continue for 100 million years or more, and deposition is not for long uninterrupted during all that period. Local crustal disturbance may produce folding and faulting, often quite intense, but not of the regional 'mountain-building' kind; and the intervals of elevation are represented by physical breaks or unconformities, sometimes small, sometimes relatively large. The story of the formation of sedimentary groups is complicated, but each can be accepted as a chapter of geological history. This is followed by a spasm of yielding, which is localized in the areas of thickest sedimentation because the maximum crustal weakening is just there. Mountain chains rise, phœnix-like, to a height of many thousand feet, and what had been an area of submergence and deposition becomes a region of dry land and high ground, which will be subjected in its turn to degradation by weathering and erosion.

CHAPTER III

The Development of Scenery

The erosion of a river valley – Youth, maturity and old age – Peneplanation; effects of submergence and emergence – Modification of topography by ice action – Glacial diversion of drainage – Wind erosion and deposition, sand-dunes and loess – Marine erosion and the form of the coastline – Effects of submergence and emergence.

We have already referred briefly to the effects of mechanical and chemical weathering in describing the origin of low-temperature rocks, and these processes will be further discussed when we consider in more detail the origin of soils. Here it is only necessary to bear in mind that the surface rocks of every land-mass are breaking down into a mantle of decomposed and partly decomposed fragments and particles. The agents responsible for this decay can act only to a limited depth, so that if the products were allowed to accumulate where they formed, the process would slow down and eventually cease. Sub-aerial weathering by itself cannot reduce the general level of a land-mass to any appreciable extent. Where, however, the products are carried away by such agents of transport as rivers, wind or ice, or moved by gravity, fresh surfaces are reached and the process continues. The forms which a land-mass assumes as it undergoes denudation are therefore the result of the dual processes, weathering and transport, working in such close co-operation that it is often difficult to separate them.

Erosion of a River Valley

No one has seen the initiation of a river system on a newly uplifted continent, but it is obvious that since no land surface can be perfectly smooth, the run-off water after heavy rain must find its way to any slight hollows and, following the steepest course to lower levels, will begin to establish its runnels as definite stream-courses or gullies. From this the youthful river system is soon developed.

A river, as we have seen, carries material in suspension and rolls it along the river-bed; in either case it not merely removes the products of sub-aerial erosion, but uses the fragments as its own tools for erosion. Collision between fragments moving at different velocities abrades the fragments and reduces their size; friction between moving sand and boulders and the stream-bed erodes the valley. The large circular pot-holes seen in a rocky stream-bed are a familiar manifestation of this frictional erosion.

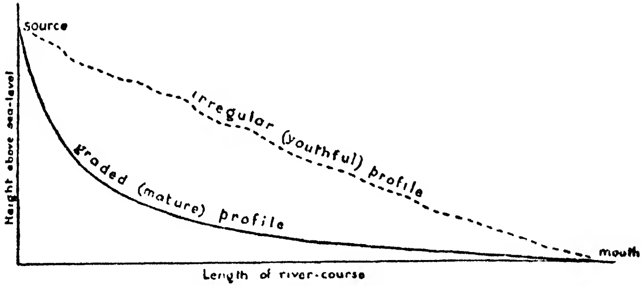

FIG. 10. – Diagrammatic representation of the longitudinal profiles of youthful and mature stages in the erosion of a river valley. (Vertical Scale greatly exaggerated.)

Now the load, which is the quantity of abrasive the stream carries at any moment, depends both on velocity and volume, and varies continuously along its course. Where slopes are steep, active erosion will occur, for there turbulence is in excess of that required to transport the load. Where the course flattens out and the velocity is checked, the stream may be unable to carry all its load, and temporary deposition then occurs. On the other hand, where a tributary joins the main stream, the increase of velocity resulting from increased volume will generally be more than sufficient to carry the combined load, and increased erosion will occur.

For the moment, we may regard the stream-source and its base-level, i.e., where it enters the sea, as two fixed points. To begin with, the downward course may be quite irregular; but at all points where velocity and volume are more than sufficient to carry the load erosion will be active until inevitably the longitudinal profile is flattened out to one along which load, velocity and volume are everywhere in equilibrium and no further erosion can occur. This is a concave logarithmic curve known as the graded profile. 'At grade', as the stream now is, it can do no further down-cutting.

In fact, however, gradually but progressively the load is carried forward, and wherever the stream-floor is uncovered down-cutting is continued. High ground is always subject to attack by sub-aerial erosion and the level of the source is slowly lowered. Therefore the graded profile continues to approach, though ever more slowly, the horizontal base-level of erosion, which is sea-level.

Concurrently with these changes in longitudinal profile, the transverse profile or cross-section of the valley is undergoing change. To begin with, when the stream is actively eroding, the down-cutting is more rapid than sub-aerial erosion of its banks, and the sides of the valley consequently meet to form a steep V. But as the rate of down-cutting slackens, the valley begins to open out. Sub-aerial erosion pushes material down from the wings of the V, while with debris keeping the stream-bed covered, the waters swing from side to side, under-cutting laterally at the base. And because the current always centrifuges to the outside of a bend, curves are accentuated and the valley is widened. The section changes to a wide-open, flat-bottomed V with gently convex sides. This stage of valley section is attained first where the river enters the sea, for here the river is at base-level from the start and there is no possibility of down-cutting. Temporary base-levels may be established at various points along a river's course at weirs or barriers of resistant rock or owing to some other cause, but in general both the graded profile and the mature valley section extend gradually upwards from mouth to source. Even when a graded profile is established throughout, the valley section will generally be found to change from a broad open V in the lower reaches near the mouth to a narrow, steep-sided V at high levels.

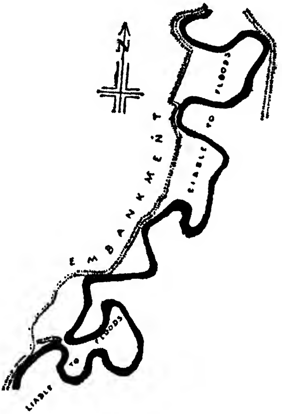

FIG. 11. – Meanders in the River Severn at the edge of the Great Shropshire Plain north-west of the Breidden Hills.

From 6-inch Ordnance Survey maps, reduced to 2 inches to the mile, with the sanction of the Controller of H.M. Stationery Office.

As the valley opens and the flat valley-floor develops, characteristic meanders appear. This term is applied to the exaggerated swinging of a stream-course wandering among its own debris, no longer held in by rocky valley-sides. Any slight irregularity in the course – caused in the first place, it may be, by a fall of bank – is accentuated because of the greater velocity of the stream on the outside of the bend. Inside each bend the progress of the water is delayed and deposition of sand and larger pebbles occurs, shifting the stream-course into a wider and more pronounced arc (Fig. 11). Gradually the neck of land between neighbouring loops becomes so narrow that the main stream, generally at flood, cuts through, and taking the direct course, abandons its meander as an ox-bow lake.

From the earliest stages development of a river system is by competition among tributaries. The effective base-level for each tributary is controlled by the level at which it joins another to constitute a major stream; so that the grading of smaller valleys waits upon the new grading of the main stream as this works headwards past successive points of confluence.

An open, old-age river valley when it is near base-level actually becomes an area of deposition instead of erosion. In periods of flood, the turbid river-water overflows among the vegetation of the flood-plain, producing a sheet of almost stagnant water. Silt and mud are no longer held in suspension, but are deposited on the plain, the coarser material near the banks of the river just outside the main current, and the finer material farther away from the stream. In this way alluvial plains are formed with natural levees or banks of slightly higher ground bordering the riverside.

As the river system passes through the stages of maturity and old age, the whole of its drainage-area is gradually reduced to a land surface of very low relief, across which the sluggish waters meander. This is the peneplain, the end stage of river erosion. Of what, at the mature stage, was a well-developed system of fingering divides separating stream from stream, only a few odd isolated hills called monadnocks remain, ultimately to be levelled off mainly by wind action and chemical weathering.

We have spoken of the base-level or sea-level as though this were a final datum, but of course all this will be altered if the landmass undergoes elevation or submergence, and the river systems must be consequentially affected. Following submergence, the base-level is moved up-stream and deltas and river mouths are converted into open estuaries; aggradation follows, and the lower reaches of the valleys become filled with sediment. Emergence has the effect of lowering the base-level, and the rivers become rejuvenated. Vigorous down-cutting, starting from the mouth of the stream, works its way up-stream as a new graded profile develops in relation to the new base-level. During readjustment, a head of rejuvenation or 'knick-point' works backwards up the valley. It marks the limit where the old grade intersects the new; it progresses most rapidly where there is most water and affects each tributary successively as it passes their junction with the main stream until the re-adjustment is complete. If the down-cutting keeps pace with uplift where the river previously meandered, rejuvenation may result in incised meanders, like those of the Wear at Durham and the lower Wye at Chepstow. Incised meanders are always evidence of uplift.

Modifications due to Ice

During the Great Ice Age much of north-west Europe was occupied by glaciers and ice-sheets, which in places have modified the river-made topography most effectively. In the milder climate which has followed, rivers and sub-aerial erosion are steadily re-developing water-worn forms, but much evidence of glacier work remains.

The movement of ice in glaciers and ice-sheets is very slow, as Mark Twain discovered when attempting his descent by means of the Gorner Glacier, but their power of erosion depends on factors other than velocity. Rock fragments frozen into the bottom of the ice are dragged over the ground like a gigantic file. In Britain the most conspicuous erosional effects are those due to valley glaciers in mountain regions, while the work of ice-sheets is characterized more especially by what they have deposited.

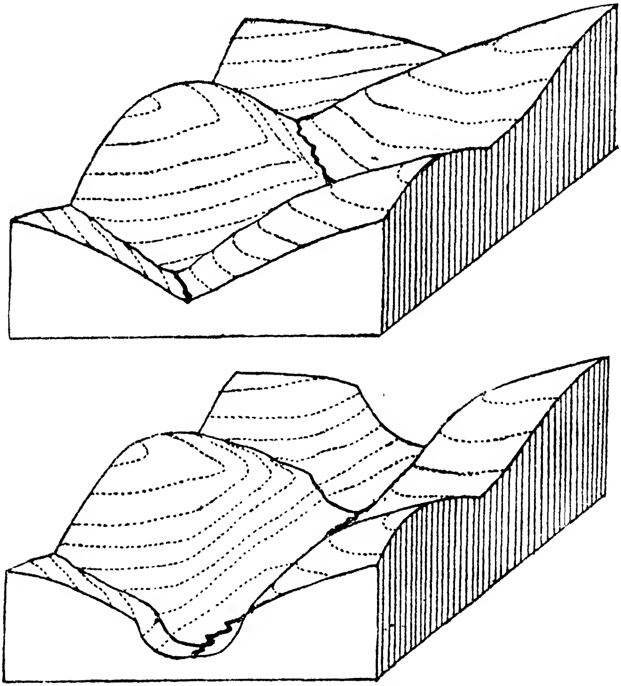

FIG. 12. – Block diagrams illustrating glacial modification of topography. The V-shaped cross-section and interlocking spurs characteristic of river erosion are replaced by a straightened valley with U-shaped section, truncated spurs, and 'hanging' tributaries.

Ice action in mountainous regions results in modification of pre-existing topography which owed its character to earlier river action. The modifications arise because in so many ways ice acts in a manner precisely contrary to that of running water. A glacier 'flows', not so much as an exceedingly viscous fluid like pitch or sealing-wax in hot weather, but by the growth and recrystallization of ice crystals, by adjustments along glide-planes in the solid substance of the crystals and by development of thrust planes between masses of clean and dirty ice. Because ice is essentially a rigid substance, one of the most characteristic features of a valley which has been glaciated is a general straightening of the valley sides and the cutting off of projecting overlapping spurs such as are typical of river erosion. This is accompanied by a scooping-out of rock from the bottom of the valley, converting it from a V- to a U-shaped section. Where smaller tributaries come in, these are no longer graded to the floor of the main valley, but are left as the 'hanging valleys' so characteristic of glaciated mountain regions, as illustrated in Fig. 12. A straight U-shaped valley with truncated spurs and hanging lateral valleys is typical of glacial erosion. The heads of the valleys may also be deeply excavated by 'plucking' at the bergschrund – the line where the glacier ice begins to move away from its parent snow-slope – leaving the steep-walled, semi-circular amphitheatres known as cirques (the Welsh cwm and the Scottish corrie). Other characteristic features of glacial erosion are the well-known *roches moutonnées*, masses of rock projecting from the valley floor or sides, which have been scored, striated, and it may be polished by overriding ice except on the side from which the ice moved away, where also plucking action has left a steep, irregular face.

Unlike a river, a glacier can excavate a rock-basin deep below its normal grade, and is indeed the only natural agent capable of so doing. In the past this was thought to be an essential feature of glacial erosion, but one by one many British lakes once cited as rock-basins have been shown to be held up by mounds of morainic material.

Glaslyn and Llydaw, under Snowdon, and Loch Coruisk, in Skye, are among those that remain as well-authenticated rock-bound lakes, and one can walk right across the downstream end of these on solid rock; many of the smaller tarns of Lakeland and North Wales are also true rock-basins.

Characteristic deposits left behind by valley glaciers retain the form of lateral or terminal moraines – mounds of relatively unsorted sand and gravel, with some ice-scratched boulders, accumulated at the sides and lower end of the glacier as the ice thawed. Their material has not been rolled and dragged along as in a river, but frozen in the ice, and it is therefore generally angular. Some moraines have a big effect upon scenery, for they may block the lower part of the valley completely and, acting as natural dams, hold up large bodies of water. But it is the vast ice-sheets which overspread and melted on lowland areas that have left behind the most important of glacial deposits – namely, boulder clay. This is an entirely unsorted deposit, generally consisting of a stiff clay composed partly of crumbled soil and rock, and partly of undecomposed rock-flour, ground by the ice as it moved, in which are embedded boulders and pebbles of all sizes. Some of the boulders are scratched and striated, and, having travelled great distances, are often quite foreign to the district where they are now found. Such a deposit could never have been laid down by water, for no current capable of moving the boulders could have allowed the clay to settle. Boulder clay forms a mantle deposit varying in thickness from a few feet to some hundreds of feet, obscuring the solid geology of most of East Anglia and Lowland Scotland, and much of central and northern England. Along its southern margin there are fan-like mounds of outwash gravels – fluvio-glacial deposits laid down by melt-waters as they flowed away from the edges of the ice-sheet.

We have only touched upon the more important modifications of land surface introduced by ice action, but, before leaving the subject, reference must be made to one other important effect – diversion of drainage. Sometimes glacial deposits blocking a valley have compelled the stream to seek a new course, and sometimes the ice itself caused blockage and temporary or permanent diversion, especially on the lower ground when in later stages of glaciation the climate had so far improved that surface rivers reappeared. One example of the latter must suffice for illustration.

The River Severn rises on Plynlimon, in central Wales, and flows north-eastward as far as Welshpool, as if to join the Irish Sea by the valley of the Dee. The story is complicated, but, in brief, ice from the Irish Sea in glacial times drove southwards up the Dee valley and ponded back the waters of the Severn in a great lake over all the Shropshire plain. This lake found outlet over Wenlock Edge at Ironbridge, and the ice-front remained stationary long enough for the overflow to cut down the Ironbridge gorge to such a level that the river was permanently diverted. Ironbridge gorge to-day constitutes a temporary base-level to which the upper Severn has been upgraded. The middle Severn across Shropshire has all the characters of an old-age river; below the gorge for some miles it continues vigorous and youthful, but in its lower reaches meanders again by Tewkesbury and Gloucester.

Wind Erosion and Deposition

In moist climates such as our own, wind is not a very important agent either of transport or erosion; but there are indications that at several periods in the past even this country has had wind play a role similar to that which it plays to-day in treeless regions like the Libyan Desert or the Sahara. Its erosive action is that of a natural sand-blast, and it produces characteristic differential erosion, fretting out the softer beds in remarkable detail. Another characteristic is the high polish imparted to wind-cut surfaces of compact rocks.

As an agent of transport, wind, like ice, can carry sand and dust uphill; like water, it collects well-sorted and graded deposits. The best graded of all are wind-blown sands. In this connection it will be realized that whereas under water the effective density of a quartz grain is reduced by the buoyancy of the water from 2·6 to 1·6, in air the density has its full value when velocity suffers the slightest check; and the viscosity of air is negligible. These factors are mainly responsible for the rounding by bruising of far-travelled quartz grains which is so typical of wind-blown desert sands.

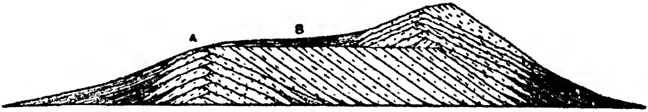

FIG. 13. – Diagrammatic cross-section to show the probable structure of a Whaleback Dune in the Egyptian Sand Sea. (After Bagnold, *Physics of Blown Sand and Desert Dunes.*)

One type of deposit – sand-dunes – will be thoroughly familiar to seaside visitors where salt spray prevents the growth of plants. They are current-bedded (see Fig. 4), and the probable structure of a large desert dune is shown in Fig. 13. In true desert regions, sand-dunes are equilibrium forms, and therefore more or less stable, their position being determined by some local configuration of the land which controls the wind-currents. But most dunes are migrating down-wind, and in many coastal districts shore sand is encroaching on the inland country. The only method of fixation is to cover the dunes with growing plants, the commonest being marram grass, which is hardy enough to tolerate the blast and aridity.

In desert areas the fine, dusty material which is whirled high above the ground is blown away completely to neighbouring steppe areas, where, entangled in the grass, it builds great deposits of the material called loess. This is exceedingly fine and very even-grained. It is composed largely of quartz and mica with some fresh unaltered felspar, and is the waste from rocks reduced to powder by mechanical, not chemical, weathering. It is, in fact, the rock-flour of wind erosion, accumulated through the ages as an unstratified blanket deposit often as much as 100 feet or more thick, which by alternate wetting and drying develops characteristic vertical jointing. An enormous area of north China is covered with loess, the subsequent washings from which impart the colour to the Yellow River (Hwang Ho); the source of this deposit is the Gobi Desert of Outer Mongolia. Nearer home, loess occurs across middle Europe and Russia; mixed with organic matter, it forms the famous Black Earth of the Ukraine. Much of this European loess, however, is not dust from hot deserts, but glacial material which the wind of the period swept away before the vegetation destroyed by the cold had returned to cover and protect it. The prairie soils of North America are similar.

Marine Erosion and the Form of the Coastline

The active agent of marine erosion is, of course, the dash of waves breaking against the shore, armed with shingle and gravel picked up from the beach. To some extent also, disruption of rocks in sea-cliffs may result from the compression of air in open joints and bedding-planes when at high tides large waves are flung against them.

Abstract discussion of the form of a coast is difficult, because so many factors are involved which can hardly be treated separately. At the outset, however, we may say that if marine erosion is more rapid than local sub-aerial weathering, cliffs are certain to result. The sea cuts away at the base to a height determined by tide and wave activity, undermining the upper portion, and falls of cliff not merely keep the seaward face steep, but provide fresh ammunition for the waves to use in further scouring. The presence of cliffs is therefore an indication of active marine erosion; it is not, as might be thought, an indication that the rocks of that coastal district are hard. So far as one can generalize, the reverse is more often the case, and unclimbable cliffs are more commonly found composed of soft rocks such as the Lias and Boulder Clay along the coast of Yorkshire, or the relatively soft Chalk of Kent and Sussex, than of hard granitic or metamorphic rocks which, as in South Cornwall, give a jagged, steeply-sloping coast.

Where rocks of different hardness alternate, however, erosion operates differentially, the soft rocks being cut back into bays and inlets, while the harder rocks stand out as capes and headlands. Relative hardness in this way exerts its influence on the outline of a coast. So too in detail do the joint-planes, for marine erosion finds and widens cracks. Bedding-planes are similarly important, both as planes of weakness ready for attack and as planes bounding sheets of rock of varying hardness. Geological structure likewise is involved, because the inclination of the rocks determines the lie of both bedding-planes and joints; and the strike or 'run' of the rocks, in relation to the direction of coastline, controls the number of different kinds of rock in contact with the waves. Where the coastline cuts across the strike of the rocks – i.e., across the grain of the country – there is a maximum probability that rocks of different hardness will be subjected to wave-action and an irregular coast will result; so far as a coastline is parallel to the strike, only one kind of rock is exposed to wave-action, at least in the initial stages of erosion.

Perhaps the most impressive case is the erosion of a high plateau composed of thick-bedded, slabby rock, lying horizontally, with occasional well-developed joints which are mostly nearly vertical. The Old Red Sandstone of Caithness and the Orkneys illustrates marine erosion under these conditions. In the absence of differential hardness, wave-action mainly exploits the joint-planes, leaving upstanding masses known as sea-stacks. Caves and arches may occur as intermediate stages in the process, but as erosion proceeds the roofs and arches give way. The sea encroaches steadily on the land, cutting back the main cliff face, but leaving for a time the outlying pillars or stacks; in due course, these too are undercut, and must collapse (Plate 4).

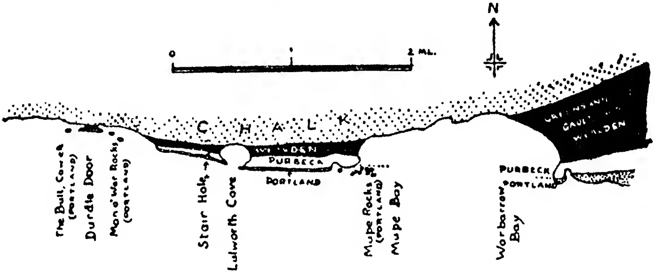

FIG. 14. – Geological map of the Coastal Region near Lulworth Cove, Dorset, showing progressive erosion features.

Simplified and adapted from Geological Survey (1-inch) Sheet 342 New Series, with the sanction of the Director of the Geological Survey and the Controller of H.M. Stationery Office.

Stacks are also formed where bedding-planes are not horizontal, but vertical, and the sea exploits bedding-planes as elsewhere joint-planes. The Needles, off the Isle of Wight, are outlying stacks of vertical Chalk, and similar features are to be seen near Swanage.

West of Swanage, in the neighbourhood of Lulworth Cove, the coastal erosion is of particular interest. The coastal region is here formed of a series of strata of varying hardness, striking east-west and steeply inclined landwards. The coast itself, which has likewise a general east-west trend, is formed by a rampart of hard Portland Stone and Lower Purbeck Limestone; behind this lies a belt of soft Weald Clay, and behind this again the relatively resistant Chalk. This natural rampart has been breached by the sea at several places, and shows progressive stages of marine erosion. Thus, at Stair Hole the sea has cut a hole or archway through the wall of harder rock and, with the assistance of sub-aerial erosion, has produced a small conical hole some 200 yards in diameter in the soft rocks behind. Lulworth Cove is a next stage of the process; there the arch has collapsed and the breach in the hard rocks has been widened. The soft Wealden rocks have been scoured out to form a beautifully oval bay, backed by the Chalk, with a narrow outlet to the sea formed by walls of nearly vertical, hard limestone. In Worbarrow and Mupe Bays the process of lateral widening has been carried still farther; as also to the west, where Durdle Door, the Bull, the Blind Cow and other remnants of the hard Portland and Purbeck Limestones still remain as stacks.

As in all forms of erosion, active marine erosion must be accompanied by transport and removal of the debris which would otherwise clutter up and protect the coast from further action. Usually it is removed by tidal action and undertow, and by the process of alongshore drift. Material carried by this latter means, often for considerable distances, may come to rest for a time in spits, usually where the current encounters that of an outflowing river. Hence the form of a coastline is not all due to erosion, but may show features resulting from deposition. One of the best-known of these coastal accumulations is the Chesil Beach, near Weymouth. This runs N.W.–S.E. for some ten miles, connecting the Isle of Portland with the mainland near Abbotsbury, and ponding back a narrow lagoon of water known as the Fleet. Again, in Suffolk, the prevailing southward drift of material along the coast has produced a spit partly composed of alongshore-drifted shingle with some material contributed by the River Alde, the mouth of which has been 'diverted' from Aldeburgh to below Orford some ten miles to the south.

Finally, in this very brief survey, we must refer to the pronounced effects of uplift and submergence. Most striking are the effects of submergence, particularly if this occurs when glaciated valleys still in a stage of youth or early maturity have been drowned, for then their topography gives rise to an exceedingly irregular coastline with long inlets extending up what were once narrow, steep-sided river valleys or glacial troughs. The fjord coast of Norway and the west coast of Scotland and New Zealand are examples of the kind of irregularity which results. Two reasons may be noted why these sea-lochs and inlets could not have resulted from straightforward marine erosion.

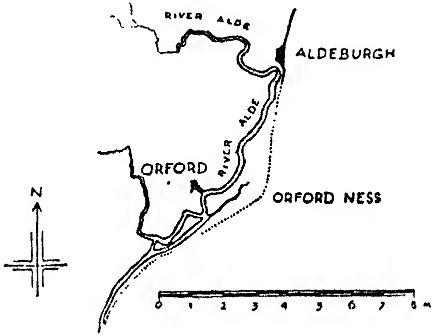

FIG. 15. – Map of the Suffolk coastline near Orford Ness, showing the formation of a shingle spit at the mouth of the River Alde.

Adapted from Geological Survey (¼-inch) Sheet 16 (2nd ed.), with the sanction of the Director of the Geological Survey and the Controller of H.M. Stationery Office.

Firstly, there is a limit to the backward cutting of a bay by wave-action, and when this limit has been reached, the rate of retreat of the coast is determined by the rate of erosion of the more resistant headlands. Sea-lochs, on the other hand, extend inland for miles (the Sogne Fjord is over 100 miles long), yet they are not more than three or four miles wide at most; and the bordering hills slope down without a break into relatively deep water. The submarine and the land topography are continuous – a condition utterly unlike that of shallow, wave-cut platforms of marine erosion. Secondly, the contours of these lochs, since they are of terrestrial origin, do not show that simple relation to geological structure which is characteristic of all coastlines due to marine erosion.

Emergence, on the other hand, provides coastlines almost as simple as the others are complicated. The nearly level sea-floor, with its sheet of new-made sediment, appears as a gently-sloping land surface, its coastline almost straight and everywhere formed of the same kind of relatively unconsolidated rock. There is hardly any factor to introduce variety or relief into such a coastline until erosion has bitten quite deeply. The harbourless coasts of West Africa and the south-east United States are characteristic examples.

Summarizing, we see that fundamentally all land forms and scenery are controlled by the character and disposition of the subsoil rocks – i.e., by underground geology. But what is apparent in any kind of country is the fretted surface etched by agents of denudation. Hard and compact rocks resist, and, enduring, stand as hills; cracked rocks and shaly aggregates swell and open up wherever their lateral support is moved. With weakened foundations even the most massive rocks give way, and towering escarpments crumble and are reduced to scree.

Along our coasts the dash of breakers undercuts the cliffs, and with rapid weathering of newly-exposed raw rock, gravity does the rest. Wave-battering comminutes the fallen blocks, and under-tow removes the debris. On land, wherever there is rainfall, water in finding its level helps soil and shattered material down the slopes. Gathering from runnels to streams and from streams to rivers, running water uses the rock waste to scour and corrode its bed. Surface waters never flow uphill, but pond to overflow their barriers. This law of drainage and the behaviour of water-borne rock-waste stirred up by the current, rolled along, and from time to time dropped to blanket the stream-floor, compel the grading of all river valleys. The niceties of the complex adjustments are marvellous – a science in itself – but dwellers among them take the resultant 'normal' forms for granted. Only where natural drainage goes underground to caves, or is held up in lakes, or 'abnormal' carvings left by glaciers or by sandblast, or products from volcanic vents meet the eye, is the imagination so startled that there is popular demand for explanation and analysis of scenery.

CHAPTER IV

Epitome of the Geological History of Britain

James Hutton and William Smith – Principles of correlation and progressive evolution – Geological time – The Pre-Cambrian ; the Lower Palæozoic: Cambrian, Ordovician and Silurian systems; and the Caledonian Alps – the Old Red Sandstone, the Carboniferous system and the Hercynian folding – The New Red Sandstone – Jurassic and Cretaceous – The Tertiary and the Alpine movements – Quaternary: Pleistocene and Recent.

AMONG the great figures of the past whose labours helped to establish geology as a science, there are none more justly revered than James Hutton and William Smith.

Hutton (1726–97), after practising medicine and later agriculture, returned to his native city of Edinburgh and there published in 1795 his masterly *Theory of the Earth.* Many previous writers of the eighteenth century, both in this country and abroad, had revealed occasional flashes of truth in the exposition of naïve dogma, but from the very method of approach it can hardly have been other than accidental; such flashes seem to have passed unnoticed at the time and were unproductive of any permanent light. Hutton's work was truly scientific in its approach and outlook, though not unnaturally many errors of interpretation were incorporated. Among his outstanding contributions, Hutton first clearly recognized that sedimentary rocks were derived from the waste of former land surfaces; he interpreted the significance of unconformities, and appreciated that uplift of the land and the birth of mountains were accompanied by folding and contortion of strata. For the first time, the geological record was rightly read as the record of continual change, new continents rising from the destruction of the old by processes of which 'we find no sign of a beginning, no prospect of an end'.

Unlike Hutton, William Smith (1769–1839) had no university education, and indeed even the limited instruction of his village school at Churchill, in Oxfordshire, was interrupted by his roving habits and his love of collecting fossils. As assistant to a surveyor, he taught himself the rudiments of geometry and surveying, and later built up an extensive practice of his own. This was a time, before the building of the railways, when England's canal system was being developed, and Smith travelled extensively while engaged on these and similar professional duties. His interest in geology became a passion, and found a ready application in the engineering and agricultural problems of his work. It has been said of him: 'No single man made so great an individual advance, or placed it upon such an enduring foundation, or did so much on which the future of his science was to depend, as William Smith'; and though he wrote but little, he began and completed the first geological map of England and Wales, an achievement viewed to this day with admiration and amazement.

Smith's knowledge of geological structure applied and incorporated in this map was based upon the application of two laws. The first, called the law of superposition, may be stated: *Of any two strata or formations, that which was originally below is the older.* As soon as it was recognized that sedimentary rocks were deposits, it followed that their relative position indicated their relative age. This was even deduced in a remarkable paper by John Strachey published in the Royal Society's *Philosophical Transactions* in 1719; and was recognized by others, such as Michell and Whitehurst, around the middle of that century; but it was in its resolute and practical applications that Smith's genius appeared. For the second principle, that of correlation by means of fossils, the credit is entirely due to Smith; he discovered that *each bed or group of beds is characterized by its own particular set of organic remains*, and by these can be recognized in different parts of its outcrop. Fossils thus acquire a new importance, as a means of determining the age of the strata in which they occur, when once their relative age has been determined by superposition.

In these two simple principles we have the means of building up a complete geological column, arranged in chronological order. The major units are the geological *systems*, which have been divided into *formations* and other rather less well-defined sub-units, which are in turn parted into *zones* and even *sub-zones*, the smallest division recognized. These finer divisions give us proportionately more accurate correlation over wide areas and more accurate knowledge of what parts of the succession may be lacking in any given district; in fact, a more detailed knowledge of geological history. To this end, geological research has always tended towards more and more minute sub-division; but until recently the chronology thus established has been entirely relative. It was as though we knew, say, the dynasties of Chinese history and within them the succession of emperors, and could even recognize with considerable exactitude their historical equivalents in other parts of the world, without being able to give, for example, to the Ming Dynasty the precision A.D. 1368–1644.

Numerous attempts have been made to establish an absolute time-scale. Thus if we could estimate the average rate of accumulation of sediment and could calculate the maximum thickness of every geological system, it would be a matter of simple arithmetic to determine the actual time in years represented by the full thickness of the geological column. But the rate of accumulation of sediment, depending as it does upon so many factors, is far too variable and complex to admit of a reliable average, nor can we make a proper allowance for the innumerable small breaks in the succession. Another suggested method is by calculation of the time necessary for the accumulation of the present percentage of salt in sea-water (27·213 parts per 1,000, average) from the averages of what is carried annually in solution by rivers. But when it is mentioned that such corrections as we already know to be necessary increase the estimated time by at least 300%, it will be realized that this method also is unreliable.

The most promising line of investigation – and one which may be expected in due course to yield fairly accurate results – is radioactivity. Many rocks contain minute quantities of radioactive minerals, which are constantly suffering atomic disintegration involving the generation of helium and, as an end product, the formation of lead. Knowing the rate of disintegration, we can calculate the age of the rock by determining the amount of helium and lead present. The helium ratio, as it is called, gives us a minimum figure; for, being a gas, some helium is likely to have escaped; the lead ratio furnishes a maximum, for some lead may have been present originally. The chief difficulty in the application of this method arises from the fact that these radioactive minerals start life in igneous rocks, which are often themselves difficult to place accurately in the sedimentary series. An igneous rock is newer than the newest sediment into which it is intruded, and older than the oldest sediment containing fragments of it; some can be dated with considerable precision, whilst for others there is a big time interval between the possible extremes. With patience, however, and a great deal of laborious laboratory analysis, radioactivity has provided fairly consistent, and hence we think accurate, figures for the age, in years, to put alongside the established geological column. These figures are given in Appendix II, which shows the main subdivisions of the stratigraphical succession of Great Britain.

The Pre-Cambrian

The Pre-Cambrian rocks are so named because they underlie the oldest fossiliferous rocks, to which Sedgwick gave the name Cambrian, from their typical development in North Wales. They represent a vast interval of time – far greater than all that has elapsed since – but they are difficult to interpret and wellnigh impossible to correlate. Many of them have been intensely altered and converted into schists and gneisses; and even where they are unaltered, they are devoid of recognizable fossils.

They form the present land surface of the Highlands of Scotland, north of a line drawn from Stonehaven to Helensburgh, and small isolated patches occur in Wales, the Midlands and Cornwall. The gneisses are undoubtedly the oldest of our Pre-Cambrian rocks, but despite their antiquity there is no sign of anything we can recognize as the original crust formed when the earth solidified. Some gneisses are sheared igneous rocks, which must have been intrusive into a crust of which we have no knowledge; and some are altered sediments representing the decay of pre-existing rock. The unaltered volcanic rocks are mostly acid lavas (the Wrekin and the Stretton Hills of Shropshire furnish examples), clearly newer since they are not metamorphosed. Youngest-looking of all is the Torridon Sandstone formation of Scotland, massive reddish-brown sandstones and interbedded mudstones which suggest deposition on a continent under semi-arid conditions. All these, and others less well known, such as the Dalradian and Moine Schists of Scotland and the Longmyndian and the Charnian rocks of the English Midlands, present but a very imperfect record of a period of more than 1,000 million years.

Vast areas of Scandinavia and northern Canada are formed of Pre-Cambrian rocks, and these give us longer and more complete successions, but even here the unconformities are of enormous magnitude and at present there is no method of establishing a reliable correlation with the fragmentary representatives in Britain.

The Lower Palæozoic: Cambrian, Ordovician and Silurian Systems

With the Cambrian system the record of the rocks begins to reveal a satisfactory and more or less consecutive story. In this country these rocks are entirely marine and rest with pronounced unconformity on a land surface of Pre-Cambrian rocks. This unconformity, and the Cambrian rocks upon it, record a great marine transgression, the initiation of a period of marine deposition in what is called the Lower Palæozoic geosyncline. Throughout the Cambrian, Ordovician and Silurian periods – i.e., for something like 150 million years – a belt of sea 200–300 miles wide extended across the British Isles in a direction approximately N.E.–S.W. In Cambrian times it was apparently separated by a strip of land from another sea which overlapped the north-west coast of Scotland, but by Middle Ordovician times the shore-line of the latter appears to have shifted away to the north-west, for we have no evidence of it in Upper Ordovician or in Silurian times. By the beginning of the Ordovician, too, the main trough seems to have widened considerably towards the north; but thereafter the fluctuations of its shore-lines were relatively small.

This trough is our most typical British geosyncline, and in some parts of it sediments accumulated to a total thickness of 45,000 feet or about nine miles. Sedimentation was not uninterrupted, and there are numerous unconformities indicating crustal warping, accompanied by local folding and faulting; and during the Ordovician period volcanic activity was sporadic and widespread. Volcanic ashes and lava-flows, both mostly submarine, constitute a large part of the Ordovician succession in North Wales and the Lake District. Some of our finest scenery has been carved out of these great sheets of andesitic or rhyolitic rocks, but individual mountains such as Snowdon and Scawfell are not, and never have been, themselves volcanoes.

The distribution of sediments along and across the geosyncline is most regular in the lower part of the Silurian. In the Southern Uplands of Scotland, Ordovician and Silurian sediments form a broad belt extending N.E.–S.W. from the Berwick coast to Wigtown and south Ayrshire. They are intensely folded, but bands in them are highly fossiliferous, so that it has been possible to subdivide them minutely and to correlate them with precision. Any horizon traced N.E.–S.W. maintains its lithological characters with little change, but in the direction at right angles to this, coarser rocks give place to finer-grained types south-eastwards, until at Moffat, 40 feet of fine, sooty-black shales are the exact and full representative of nearly 1,000 feet of coarse grits and sandstones around Girvan to the north-west. There can be little question that in the former direction (N.E.–S.W.) we are following along the length of the geosyncline, but that in the latter direction (S.E.–N.W.) we approach the coastline from the open sea. If we plot the thickness and character of equivalent lower Silurian sediments across this postulated geosyncline, we note the following measurements:

N.W.					S.E.
Girvan	*Moffat*	*Lake District*	*Conway*	*Welsh Borderland*	*Shropshire*
Conglomerates, sandstones, shales, etc.	Black shales	Grey and black shales	Grey and black shales	Sandstones and shales	Absent
700 feet	40 feet	30 feet	300 feet	2,400 feet	

Considerable thicknesses of shallow-water sediments were thus accumulating in two strips, the one following the north of the Southern Uplands and the other through South and Central Wales and the Welsh borderland. Between them lay more open sea, which only very fine

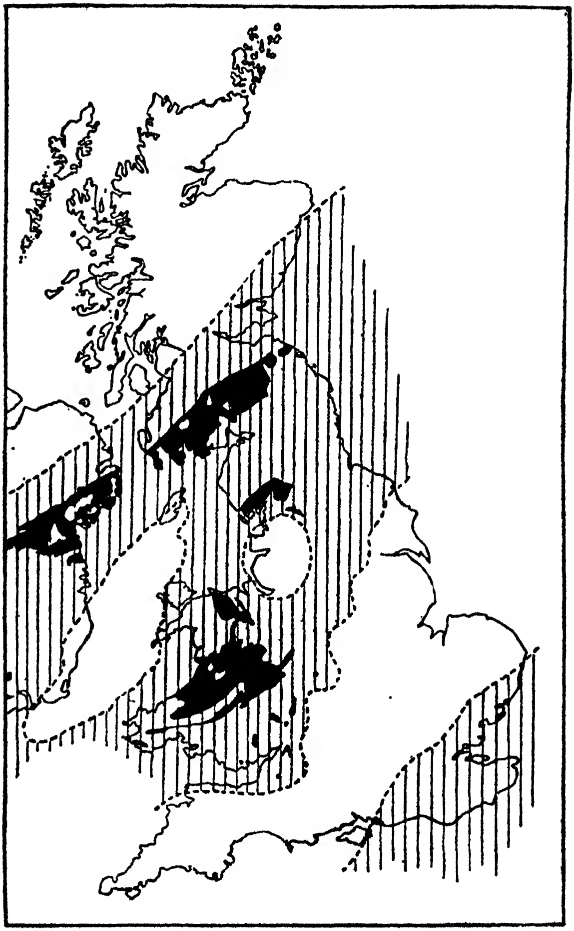

FIG. 16. – Sketch-map showing probable distribution of Sea (shaded) and Land at the end of the Lower Silurian.

Present outcrops of Silurian rocks shown solid black.

mud could reach, and the few feet of black shale at Moffat, the Lakes and North Wales represent roughly the axis of the geosyncline. Shropshire at this time lay just landward of the S.E. coastline, but it was submerged towards the end of Lower Silurian times when the sea transgressed towards the S.E.; later, in Middle Silurian times, in front of a shallow lagoon which extended south-eastwards across the Midlands, coral reefs flourished, and are preserved to us in the well-known Wenlock Limestone. Sandbanks in the Girvan district record the nearest recognizable approach to the other coastline, which followed the Highland border a little farther N.W., but is now covered by Old Red Sandstone and so down-faulted that it is inaccessible to us.

Throughout Silurian times the scene of maximum sedimentation was shifting towards the middle of the trough; thousands of feet of coarser 'grits' and sandstones covered the thin shales of the Lower Silurian of Moffat, the Lake District and North Wales towards the end of the period as the geosyncline was 'silting up', and the latest Silurian beds carry brackish-water fossils.

Then followed the intense crustal movements of the *Caledonian* mountain-building period, which, starting in Scotland in post-Ordovician times, culminated about the middle of the succeeding Devonian or Old Red Sandstone period; readjustments and after-effects continued even as late as Carboniferous. The rocks of the geosyncline were folded, faulted and thrust, and the width of the trough must have been very considerably reduced as the strata were crushed together and piled up ready for denudation into mountains. Despite the depths to which the earliest sediments were buried and the intensity of the movements to which they were subjected, no regional high-temperature metamorphism has been observed; but we can attribute to these pressures the particulate rearrangement and partial recrystallization that converted Cambrian shales into the wonderfully cleaved slates exploited at Penrhyn, Llanberis and Nantlle in North Wales. Similar though in general less perfect cleavage was imparted to Ordovician and Silurian rocks elsewhere in Wales and the Lake District.

The Old Red Sandstone

As an indication of age, the terms *Old Red Sandstone* and *Devonian* are synonymous, the former being applied to terrestrial deposits and the latter to their marine equivalents.

During the Caledonian upheaval most of Britain north of London and the Bristol Channel became land, the shoreline trending approximately east–west. Conditions seem to have been semi-arid, occasional torrential rains scouring the rock-waste from the weathered hills and mountains, and spreading out vast fans of debris over the flatter lowlands. In the intermontane basins there were transient lakes where lived the primitive fishes first made known about 100 years ago in the classic works of Hugh Miller and Agassiz. It is now recognized that some of these fishes were air-breathing as well as gill-breathing, and, like the present-day lung-fish of Australia, could probably survive short periods of complete drought. Farther north, in the Orkneys and Shetlands, the flagstones and shales of the Middle Old Red Sandstone are clearly water-laid, and indicate the existence here of a large sheet of fresh water. Terrestrial rocks are also encountered in the Baltic provinces, in Spitsbergen and in Greenland, and there can be litttle doubt that Britain was but a piece of the huge northern continent of Old Red Sandstone times.

There was important igneous activity in Scotland and the north of England; the lavas of Ben Nevis and Glencoe, the Sidlaws, the Cheviots and the Ochil Hills, represent the volcanic phase, and many of the larger granite masses of Scotland and the Lake District the plutonic phase which followed.

Lavas are also interbedded with the marine limestones, shales and grits of the Devonian of Devon and Cornwall; and though covered by newer rocks under the London District, marine Devonian rocks are almost certainly continuous, and outcrop still farther east in the Ardennes and the Rhine valley. In North Devon three or four intercalations of Old Red Sandstone type in the marine succession mark temporary extension of torrential deltas associated with oscillations of the shore-line.

The Carboniferous System

In the Bristol area and along the South Wales coast the Old Red Sandstone passes up without a break into the marine beds of the Lower Carboniferous, representing but a slight northward advance of the marine conditions which had existed throughout the Devonian in the south. Elsewhere in England and Wales there is pronounced unconformity as the sea gradually transgressed and laid higher beds of the Lower Carboniferous on various older rocks. In Scotland, as in the south, there is no break; but here the early Lower Carboniferous rocks are either volcanic or shallow-water deposits of lacustrine type, with oil-shales and coal-seams alternating with bands of marine limestones in their upper part. A rugged island belt named St George's Land, lying over mid-Wales and the Midlands, was never completely submerged, and North-west Scotland likewise remained a land area throughout the Carboniferous.

The most familiar *Lower Carboniferous* rocks of England consist of shallow-water limestone of the St George's Land and Pennine area, shell reefs and lagoon deposits, some chemically precipitated and some organic, the latter including both coral and brachiopod limestones. Very little clastic material, and that only in the form of fine mud, reached the sea in which the Lower Carboniferous of South Wales

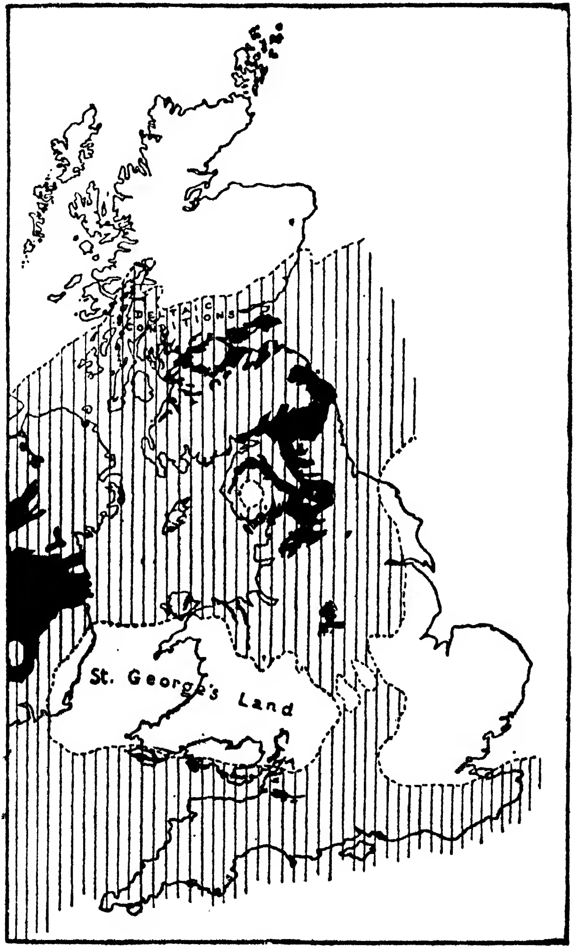

FIG. 17. – Sketch-map showing probable distribution of Sea (shaded) and Land towards the close of Lower Carboniferous Times.

Present outcrops of Lower Carboniferous rocks are shown solid black.

and the centre of England was laid down; a striking contrast to Scotland and Northumberland, where deltaic shales and sandstones with coal-seams fringed the northern landmass, and in rhythmic series alternate with beds of limestone through Durham into Yorkshire. Towards the close of Lower Carboniferous times conditions changed rather abruptly and the calcareous deposits are succeeded by shaly and sandy beds.

The *Millstone Grit* formation (Middle Carboniferous) which follows these shales at the top of the 'Mountain Limestone' of the Pennines, consists of coarse, thick-bedded, massive grit-banks interbedded with much shale. It is essentially a vast delta deposit, related probably to a large river draining the northern landmass which provided the clastic material. But it is far from a simple delta; repeated submergence gave it a complicated composite character, and only its thin marine bands are widespread. Occasional thin coal-seams occur in the north of England.

The *Coal Measures* which form the upper division of the Carboniferous consist for the most part of shales and silty sandstones known as 'bind', with nodular bands of ironstone, beds of marly 'clunch' and fireclay; seams of coal make up less than 5% of the total thickness. The characters of these coal-seams will be more fully described in Chapter X. It is difficult to find a present-day analogy to the forested swamp conditions under which the coal formed. 'The vast area covered by some of these coal-seams has been compared with that of the forests on some of our modern tropical or sub-tropical swamps and deltas; but it must be confessed that no exact present-day representative of the growth and preservation of carbonaceous matter on the scale of the Coal Measures has yet been found' (Watts).

Great thicknesses of sediment had accumulated during the Old Red Sandstone and Carboniferous periods, and the close of the Carboniferous saw the renewal of mountain-building movement – the growth of the *Armorican* or *Hercynian* folds which compressed the rocks of Devon and the south of England as had the Caledonian those of Scotland and North Wales. The direction of these Permo-Carboniferous folds is mainly E.–W., as compared with the N.E.–S.W. trend of the Caledonian, and in front of them the Coal Measures were bent down and escaped denudation in the coalfield 'basins' in which they now occur; the South Wales Coalfield, the Yorkshire Coalfield and the Durham Coalfield are relatively clear examples, being uncovered or only partially covered by newer rocks.

New Red Sandstone: The Permian and Trias Systems

The second marine phase had ended with the Carboniferous, and Britain was again elevated to dry land. The full effect of the Hercynian mountain-building was felt farther to the south; while here the resulting land surface seems to have been of relatively low relief. As Old Red Sandstone followed the Caledonian movements, so in North Europe the Hercynian was followed by a widespread arid period, this time with salt lakes and true desert; and this second land period bridges the interval between Upper Palæozoic and Mesozoic, for it includes the two systems, Permian and Trias, conveniently taken together as New Red Sandstone.

Red sandstones, which are dominant in both New and Old Red Sandstone systems and even in the upper Pre-Cambrian, owe their colour to dehydrated iron oxides derived from rock-weathering. Normally this iron is carried away in solution, but in the absence of organic acids such as humic acid from decaying plant matter, it is oxidized and remains to colour the rock debris. A red colour is therefore an indication of lack of plant life. In the Pre-Cambrian there were no land plants, and they were not abundant in the Old Red Sandstone, so that the red colour of these early beds is not conclusive proof of desert conditions; but the Carboniferous land and marshes supported a luxuriant vegetation, and the red colour of the overlying Permian and Trias is accepted as evidence of desert conditions. Interstratified with the red beds, too, we find wind-blown millet-seed sand-dunes and deposits of rock-salt and gypsum.

The *Permian* rocks of this country are of two main types. In the north-east the Magnesian Limestone rests with a sandy base upon the folded, faulted and eroded Carboniferous rocks of Durham, Yorkshire and Nottingham. This is a concretionary dolomite deposited in a landlocked sea which extended eastwards over Germany. Some of its beds are calcareous and quite fossiliferous, but relatively few species could tolerate the strongly saline conditions when dolomite was precipitated. In Cumberland, in the Midlands and in south-west England shales, marls and red sandstones occur with bands of scree-breccia ('brockram') and conglomerate. These are unfossiliferous and very difficult to correlate with the development to the north-east. They appear to be mainly Permian in age, but follow conformably upon thick beds of red Upper Coal Measures. Similar red beds in Texas, Russia and South Africa have yielded remains of our earliest land vertebrates; alongside these ungainly reptiles, amphibia flourished in pools and watercourses as they had in the Carboniferous swamps. The granites of Cornwall and Devon and their associated dykes and mineral veins are younger than the Coal Measures but older than the New Red Sandstone of Exeter.

Triassic deposits form a more or less continuous blanket over patches of Carboniferous and Permian on which they rest unconformably. Their outcrop extends along the Ouse and Trent valleys in Yorkshire and Nottinghamshire, spreading out as a winding sheet over the west Midlands, Cheshire and the Severn valley below Bridgnorth, and continuing as a strip across Somerset and Devon to Exeter in the south. In this country, reptilian footprints, and abroad, remains of the higher types of reptile such as mammal-like reptiles and early dinosaurs, herald the beginning of the Mesozoic era, and marine equivalents in other parts of the world carry fishes, aquatic reptiles and early ammonites. Towards the top the red colour gives place to anæmic green or grey, and the Rhætic Marls mark the beginning of the next marine transgression.

Jurassic and Cretaceous

Though the Mesozoic begins with the Trias, it is the marine Jurassic and Cretaceous that typify this era of British history. Land extended far to the north and west of Britain – indeed, a north-west landmass persisted and sediment was derived from it, almost continuously from Cambrian till well into Tertiary times. Land, which had been a region of weathering during the Trias, also lay over what is now East Anglia, and was not submerged until the Upper Cretaceous. Between this eastern peninsula (or island?) and the north-west mainland was the gulf of relatively shallow seas in which were deposited the variable clays, shelly limestones, ironstones and sands of the mid-Mesozoic succession. At certain periods in the *Jurassic*, coral-reefs flourished along the shores, while deltaic deposits reminiscent of the Coal Measures accumulated in the north. Towards the close of Jurassic times, slight uplift made land connection between the eastern and western landmasses, restricting the sea to a small area of Yorkshire and Lincolnshire (continuous with a north European sea to the eastwards), while in the southern basin fresh-water conditions developed under which the Purbeck limestones and Wealden lake rocks accumulated. These contain remains of some of our earliest mammals and great reptiles such as *Iguanodon.* Thereafter a marine transgression,

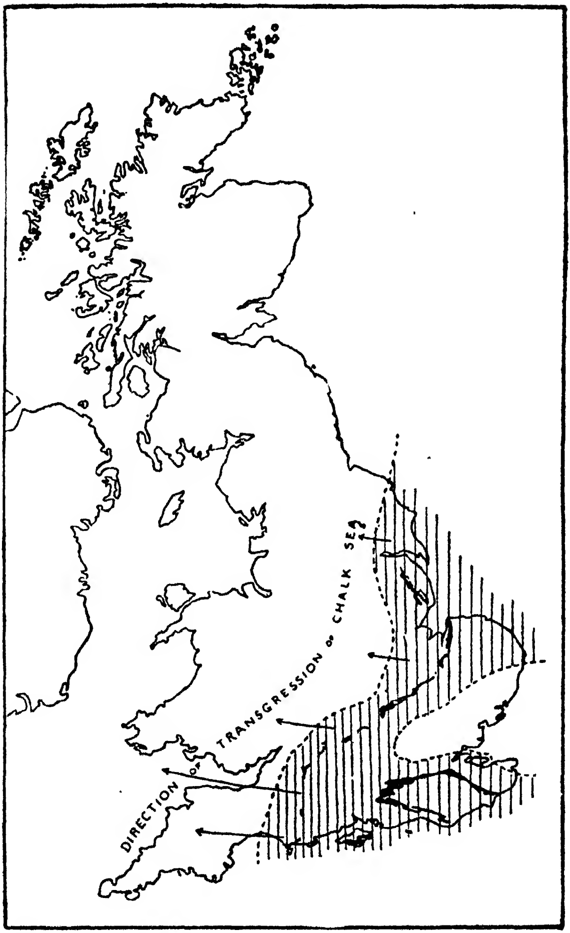

FIG. 18. – Sketch-map showing probable distribution of the Sea (shaded) and Land towards the end of Lower Cretaceous (Lower Greensand) Times.

Present outcrops of L. Greensand beds shown solid black. During Gault times the eastern landmass was submerged and the sea transgressed farther westwards, while the Chalk sea transgressed still farther.

beginning with a break-through of the midland isthmus, soon carried the shore-line even farther west than it had been in the Jurassic.

The relation between our Cretaceous and Jurassic systems illustrates admirably the effect of marine regression followed by transgression, and hence a completed story such as should be associated with every unconformity. In South Lincolnshire and in Sussex the Jurassic passes up into the *Cretaceous* with perfect conformity, though in the southern basin the transition beds are fresh-water. Elsewhere there is unconformity, with overlap, the break becoming greater and greater as traced towards the west and north-west. Lower Cretaceous rocks successively thin out and disappear, so that progressively newer Cretaceous beds come to rest upon progressively older beds to the west. North-west also the marine transgression continued until in Co. Antrim Chalk rests upon Carboniferous Limestone, and in Ardnamurchan upon Pre-Cambrian.

The Chalk is the best-known and certainly the most distinctive of the Cretaceous deposits. At one time compared with the Globigerina Ooze of the Atlantic deeps, it is now realized that although *Globigerina* and other foraminifera occur, the bulk of the chalk is composed of finely comminuted shell fragments, together with microscopic calcareous algæ; and analysis of the fauna indicates that the depth of the sea was never very great – certainly not more than 600 fathoms, and at times no more than 100 fathoms. A century ago the Chalk was the principal source-rock of London's well-water, furnishing an artesian supply, and it still is the reservoir rock for many towns and villages along its outcrop in the Chilterns and the Downs. Almost the whole of England and Wales, and much of Scotland, was covered by the Chalk sea, which at its maximum spread westward to Ireland and the Scottish Isles.

The Tertiary

The end of the Cretaceous witnessed yet another marine regression, and beds equivalent to the uppermost Chalk as known in Denmark either were never deposited here or had been removed by erosion before the deposition of the Tertiary, which lies unconformably upon an eroded Chalk surface. Many of the molluscs and other fossils of the Tertiary era belong to living genera – in fact, the original definition of the Tertiary systems was based upon the increasing percentage of living genera – and it is possible to draw conclusions regarding climate with progressive certainty through the Tertiary era.

The *Eocene* was laid down in a shallow basin of deposition which extended from Belgium and France to south and eastern England. In the Lower Eocene, when the sea had spread to Kent, equivalent fresh-water beds occur about Reading, while the area farther west and to the north was dry land, at this time probably a peneplain.

Eocene deposits began with relatively cold-water conditions, becoming progressively warmer, and in the London Clay have been found remains of crocodiles, turtles, Nautilus shells and fragments of drifted palm trees like those of Burma or Malaya. This is succeeded by barren sands of Bagshot and Aldershot in the London area, and very fossiliferous clays in Hampshire and the Isle of Wight, still carrying a sub-tropical fauna.

Immense volumes of basaltic lava were poured out on this Eocene land surface, and massive remnants of these form the Giant's Causeway area of Antrim, the Western Isles, and Iceland. It was only subsequent to the outpouring of these lava-flows (which have included between them a few plant-beds, enough to prove their age) that the northern landmass (the lost continent of Atlantis ?) finally foundered and sank.

The overlying *Oligocene* is but poorly represented by a small thickness of mainly fresh-water deposits in the Isle of Wight, and there are no English deposits of undoubted *Miocene* age. The whole of Britain was raised to dry land by the most recent or *Alpine* mountain-building movements during the Miocene. Again, Britain, lying far to the north, escaped the full severity of the compressive movements which built the Alps, the Carpathians and the Himalayas. Their effect here was a sharp fold along the south coast and across the Isle of Wight, and several gentle folds which include the London and Hampshire basins and the Weald anticline of south-east England. Erosion had exposed the surface of the Chalk over the central Weald by *Pliocene* times, and when there was again a temporary submergence, pockets of ferruginous sand and marine gravels were deposited on the Chalk at the top of the Downs. The present radial drainage of the Weald is probably due to post-Pliocene uplift renewed along the line of the Miocene axis, and from this time on Britain has been mainly a land area.

Apart from these patches of relatively unfossiliferous Pliocene gravel over the Downs, more considerable areas of shallow-water or coastal shell-banks of newer Pliocene age occur in East Anglia, the fossils revealing a steady deterioration in climate as the Great Ice Age of the Pleistocene draws nearer.

Quaternary: Pleistocene and Recent

Spreading out from centres of distribution in the high ground of several areas in Scotland, the Lake District and North Wales, the ice-sheet gradually grew until it covered most of Britain north of a line from the Bristol Channel to the Thames Estuary. Along the east coast it contended with the Scandinavian ice-sheet, which contributed boulders and pebbles of Norwegian origin.

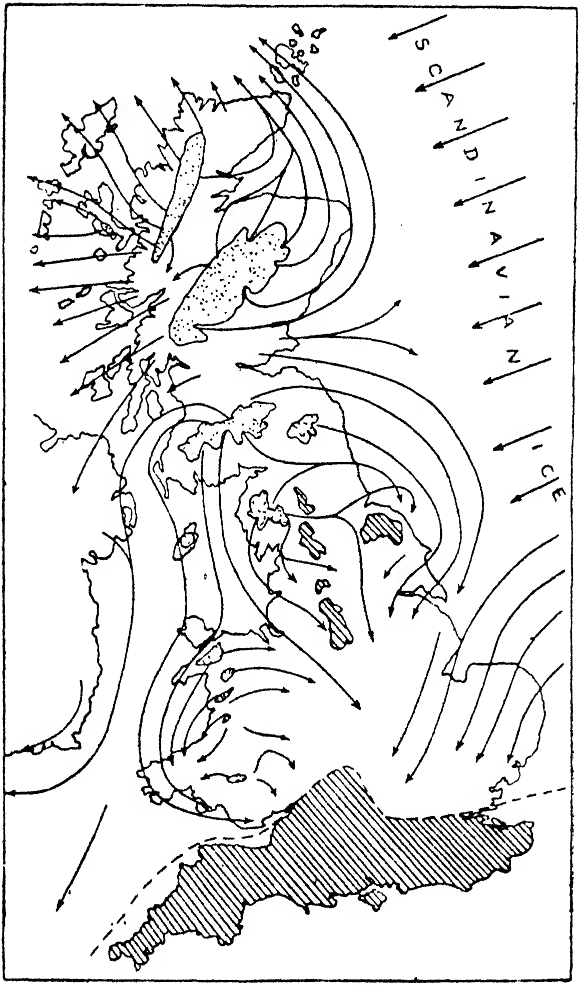

FIG. 19. – Sketch-map showing approximate extent and directions of flow of the ice-sheet during period of maximum glaciation.

Snowfield areas which were never overridden by extraneous ice are shown stippled, and unglaciated areas shaded.

The exact sequence of events is still in dispute, but there is accepted evidence for more than one interglacial period to which are referred fluvial gravels containing relatively warm-water shells and the bones of hippopotamus and rhinoceros, associated with the flint implements of primitive man. The whole period was of such short duration, geologically speaking (it may have covered about half a million years), that little evolution occurred in the fauna, and the correlation of glacial deposits, with or without fossils, is hazardous. But man was developing more rapidly, and where his implements are available the stages of human culture provide approximate indices of Pleistocene time.

Lowering of sea-level during the Ice Age and slight oscillations following subsequent recovery are indicated by submerged forests and peat-beds and by the raised beaches around the coasts of Britain. Some of this oscillation may have been a direct result of the loading of land surfaces with great thicknesses of ice; and there must have been regional lowering of the surface of the sea due to abstraction of water to form the ice. The mountain areas suffered distinctive modifications, which present-day erosion is slowly eliminating; diversion of drainage occurred in many parts; and much of the pre-existing topography of the lowlands was buried under the thick mantle of drift left behind when the ice-sheet finally melted.

CHAPTER V

The Construction and Use of Geological Maps

Geometry: topographic contours, structure-planes defined by contours, and the line of intersection or outcrop – The making of a geological map – Types and scales of maps issued by the Geological Survey – Use of geological maps.

A GEOLOGICAL map is essentially a plan showing the outcrop of the various geological formations in the area represented. The geological *lines* are the outcrops of the bedding-planes, faults, or other planes separating the formations, the areas occupied by the formations themselves being distinctively coloured or shaded. Standard symbols are used to indicate dip, axes of folding, the downthrow side of faults, metalliferous veins, and other geological information.

The outcrop of any bedding-plane – that is to say, the line of demarcation which follows the upper or lower boundary of a given formation – depends on two variables: the shape or form of the formation, and the topography or shape of the land surface. For this reason topographic contours defining the shape of the land surface are inserted upon all but small-scale geological maps. Given the topography and the shape of the bedding-plane, it is a matter of simple geometry to draw on the map the line of intersection or outcrop. Equally (and this is more usually the problem), it is possible to determine, from the shape of the outcrop and the topography, the form of the bedding-plane – i.e., to deduce the underground geological structure implied by the particular form of outcrop. This is the process of geological map-reading.

The best method of defining graphically in plan the

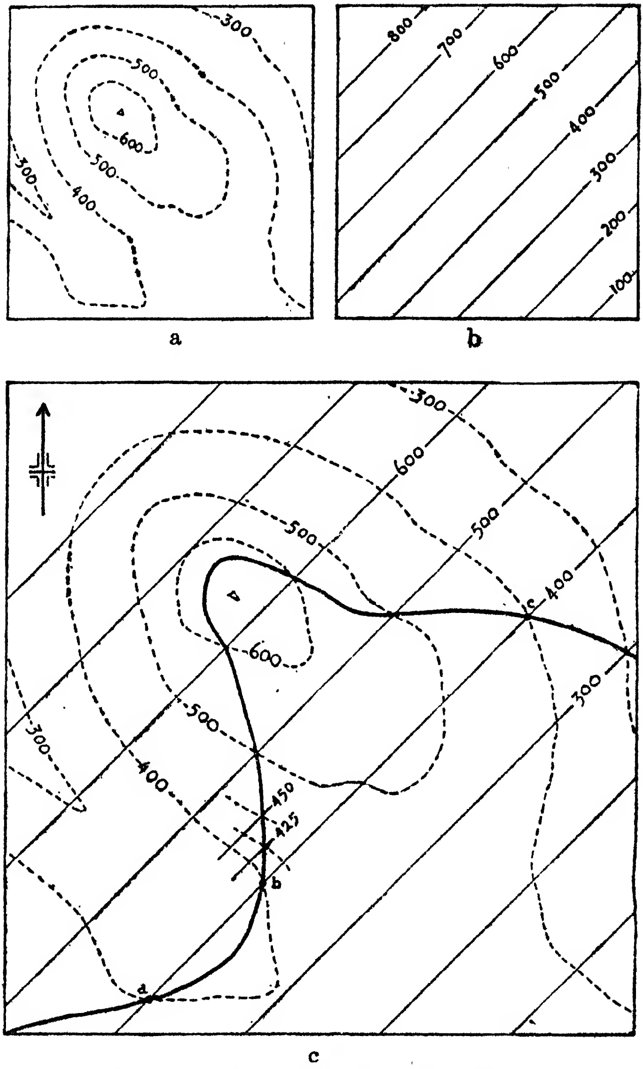

FIG. 20. – Topographic Contours, Stratum Contours and Outcrop. (For explanation, see text opposite.)

form of any surface is by the use of selected contours* projected on to the plan. Most people are familiar with the use of topographic contours for defining a land surface. On the ordinary 1-inch-to-the-mile Ordnance Survey maps these contours are drawn at 100-foot intervals up to 1,000 feet, and at 250-foot intervals above this level, but the selection of the intervals is, of course, arbitrary, and the larger interval over the less-used and less-useful parts of the countryside is a matter of official economy.

The principle can be applied to the definition of any surface. The contours of any uniformly inclined plane are a series of parallel straight lines evenly spaced, and the distance between the contours records the steepness of inclination; the contours of an inverted bowl or dome would be concentric circles.

The superposition of two sets of contours on the same map need not present much confusion. In Fig. 20*a* is shown an area of simple relief rising to a height of slightly more than 600 feet, and in Fig. 20*b* the stratum-contours of a uniformly-inclined, even bedding-plane dipping to the south-east; the two are superimposed in Fig. 20*c*. The outcrop of the bedding-plane (i.e., its line of intersection with the surface of the ground) is the locus of all points where these two surfaces are at the same height. Precise localities where the two are at the same height are fixed by the intersections of stratum- and topographic-contours; additional points of less accuracy can be obtained where desired by the intercalation of intermediate contours, both stratum and topographic. Such an outcrop is shown in Fig. 20*c* by the heavy black line.

But had we been given only the outcrop and the topo-

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* If we imagine a land surface progressively flooded by 100-foot rises of sea-level, the successive shore-lines are contours; the projection of these on to a horizontal plane surface would give 100-foot contours ready for reduction to the scale of the map.

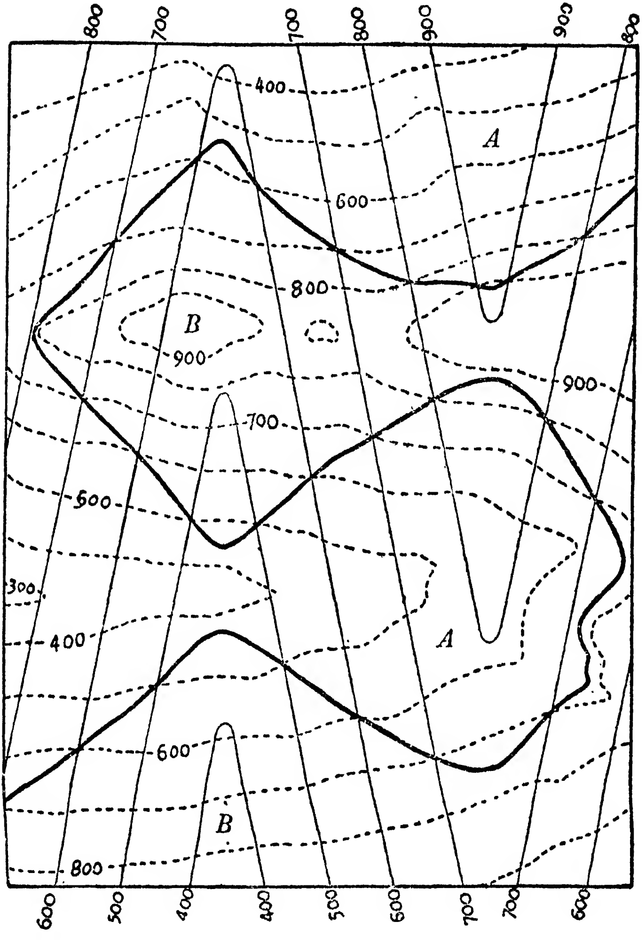

FIG. 21. – Geological map showing the outcrop of a bedding-plane separating the two formations *A* and *B*, folded into symmetrical pitching folds.

graphy, it would have been possible to draw in the stratum-contours, and thus to determine the shape of the bedding-plane that would produce such an outcrop. At each locality where the outcrop cuts a topographic contour of a given denomination, the plane is obviously at that height; and since the stratum contour must pass through all points in the plane at the same height, its line can be drawn by joining such points together (e.g., *a*, *b*, and *c* for the 400-foot contour in Fig. 20*c*). When, as in this instance, all possible stratum-contours thus drawn are straight, parallel and evenly spaced, it follows that the bedding-plane is a uniformly dipping even plane. The geological structure must then be that of evenly dipping series of beds or sheets.

Except for horizontal beds, whose outcrops follow the contours of the ground, and vertical beds, whose outcrops coincide with the strike and are independent of topography, this is the simplest conceivable structure. It is not possible to go farther into the application of geometry to map-reading here, but two other diagrams (Figs. 21, 22) are included to show the relations of outcrop, stratum-contours, and topography for a symmetrical pitching fold and for an unconformity (where more than one series of dips has to be considered). Those with the faculty of 'seeing solid' will probably experience little difficulty in interpreting these figures, which will be improved if the different formations are lightly coloured in crayon.

Construction of Geological Maps

In the construction of geological maps the problem is not the theoretical one of inserting the outcrop of a given structure across a particular area; it is to plot so far as we can and as accurately as we can the actual outcrops of geological formations in a particular area. During the process we formulate our ideas concerning geological structure, and the finished map represents a personal interpretation of the evidence available. The difficulties are almost entirely due to the mantle of vegetation, soil and

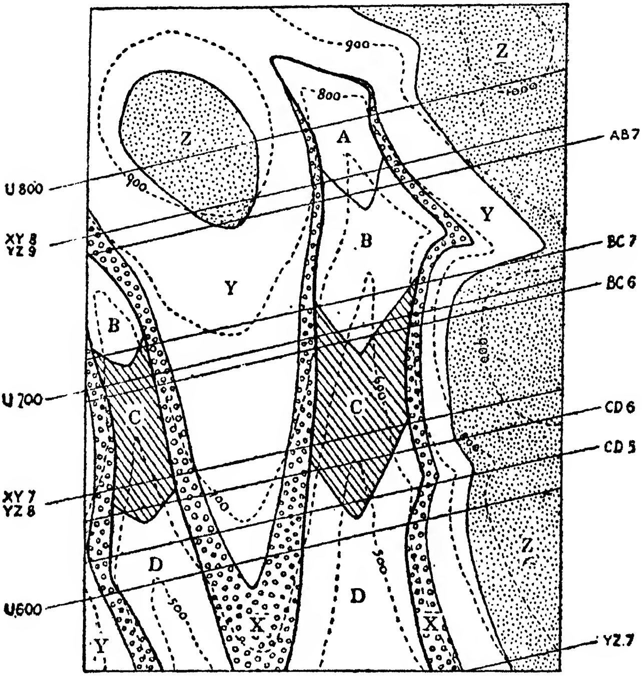

FIG. 22. – Geological Map illustrating Unconformity (pp. 35, 36 and 87).

An older series of beds, *A*, *B*, *C*, *D*, has been tilted towards the south and eroded to a peneplain; on this surface has been deposited the newer series of beds *X*, *Y*, *Z*, which has been subsequently tilted in the same direction as the older series. The strike lines (stratum-contours) for the older series, the plane of unconformity (*U*), and the newer series are here all parallel, but differently spaced because of their different dip angles.

superficial deposits obscuring what is called the 'solid geology' of the region. Only a fraction of this solid geology is visible in the few natural exposures which occur in an area; the natural ones are upstanding crags or bare patches of rock on hillsides or along stream-beds; others are man-made, such as mines and quarries or cuttings for roads, rail, or drainage. Yet from this limited evidence we have to deduce the distribution of solid rock under all its coatings of drift and vegetation. To a certain extent we can extrapolate. Having measured dip and strike of a bed in some exposure, we can construct stratum-contours and predict how its outcrop should run across country; but in Nature dip and strike are seldom constant over large areas, and even small faults may produce important discontinuities of outcrop lines. Hence geometric constructions have but a limited use; they must only be applied locally, and inferences drawn from them must be checked by every kind of field observation. The evidence of 'topographic features' and relief due to differential weathering and of lines of springs is most important, and may reveal the run of some particular horizon across country.

Where the drift is thin or absent, the colour of the soil or the nature of the vegetation may be immediately significant. Where there is a mantle of glacial drift, river alluvium, or transported soil, we have somehow to get evidence of what lies below; the material thrown out from rabbit-burrows is not to be despised, or we may use an auger-drill, operated by hand, if the material is unconsolidated and free from pebbles. Such a drill under favourable conditions can get samples from a depth of 10 feet or more. As a last resort, trenches may be dug to locate a contact or prove the geological horizon quite precisely. Mechanical drilling is a method too costly to be employed unless there is the prospect of an economic return.

The information gained from all such sources is plotted accurately on a topographic map. In this country we are more than fortunate in our Ordnance Survey sheets, and the scale of 6 inches to the mile is that now generally adopted by investigators. The evidence has then to be pieced together like a jig-saw puzzle, checked and tested in every way possible; and the solution is rarely if ever complete. No finished geological map is to be regarded as more absolute than a reasonable interpretation of the available field evidence. New cuttings, fresh information from well-borings, etc., even the general advance of geological knowledge, will surely lead to adjustments and corrections. The work of the Geological Survey was barely begun when it had at length finished the 1-inch geological maps of Britain; the first sheets of the 'old series' were out of date before the 'new series' was started, and many of the latter already stand in need of revision.

Types and Scale of Maps Issued by the Geological Survey

The standard map issued by the Geological Survey ot Great Britain is the '1-inch' map, in which the geology is represented on the basis of a 1-inch-to-the-mile Ordnance Survey map. The whole country has been mapped on this scale once, giving us the beautiful hand-coloured sheets of the Old Series maps. Revision now in progress provides us with the New Series, colour-printed maps for most of Britain, which are generally issued in two forms, the Solid and the Drift Editions. In the former all but a few of the superficial deposits, like river alluvium, are omitted, and the geology is shown as it would appear if the mantle of soil, drift and vegetation were swept away. In the Drift Edition the various types of superficial deposit – river-gravels and terraces, glacial drifts, residual deposits, etc. – are all distinguished, and naturally in some areas this obscures much of the solid geology. The issue of New Series maps now covers most of the country, precedence being given during the re-survey to areas where rocks and minerals are of recognized economic importance.

In the preparation of the Old Series maps, which began little more than a century ago, the geological surveyors had only the 1-inch Ordnance maps for the basis of their work; by the time the New Series maps were being prepared, 6-inch and in some cases 25-inch-to-the-mile Ordnance Survey maps had become available. This 6-inch map is the most usual basis for the geological surveyor to-day, the 25-inch (where available) being used in areas of exceptional complexity; and the New Series 1-inch maps are a reduction from 6-inch field maps. It is not usually practicable to publish 6-inch geological maps, but in most coalfield areas there is a sufficient demand, and printed copies of such large-scale maps are issued.

For regional purposes, excellent colour-printed ¼-inch-to-the-mile maps are available, showing in less detail the geology of a much larger area; and a new edition of the first-rate 25-mile-to-the-inch geological map of the whole of the British Isles has recently been issued (1940) at the price of 2*s*. (colour-printed). More recently still, an admirable two-sheet map (Scotland, and England and Wales) has been issued on the scale of ten miles to the inch.

Use of Geological Maps

Ability to read a geological map is so important that the training forms a vital part in the curriculum of the student, and the ability is essential to the qualified geologist. For a geological map is at once the most precise and the most concise method of expressing what is known of the geology of any region. It gives us a first approximation for the selection and exclusion of sites where particular kinds of rock, such as brick-clay, limestone, building-stone, or road-metal, may be exploited. It helps us to expect possible water-bearing horizons and to estimate the depth at which they may be encountered. It enables us to deduce the underground geometry of a persistent horizon, such as a coal-seam or a bedded iron-ore, though naturally our knowledge is progressively corrected and becomes far more exact and useful for further predictions as the exploitation of the mineral deposit proceeds.

In fact, wherever it is desired to locate particular kinds of rock, to predict the behaviour of a given rock at depth, or to deduce the geological structure of a region for any purpose, the geological map is the first source of information to which we turn. Additional field-work is almost always necessary before a recommendation for action can be given, but the scope of the necessary investigation can be considerably narrowed down beforehand by making full use of the information presented on modern geological maps.

PART TWO

Some Applications of Geology

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Not only are the sciences involved with each other, but they are all inextricably interwoven with the complex web of the arts, and are only conventionally independent of it. HERBERT SPENCER

CHAPTER VI

The Geology of Water Supply

Rainfall, evaporation and run-off – Porous and permeable rocks – The water-table – Springs and bournes – Artesian wells – Pumped wells and the cone of exhaustion – Contamination.

THE rainfall on any land area is dispersed partly by run-off from the surface, and partly by percolation into the ground. The run-off contributes directly to streams and rivers, and suffers continuous loss by evaporation. The underground water may re-issue at a lower level, as springs which feed the superficial water-system, and much of it is absorbed by vegetation and lost through transpiration; but some is stored within the rocks. As a first approximation, applicable to a moist and temperate lowland, it is estimated that one-third of the rainfall constitutes the run-off, one-third sinks into the ground, and one-third is lost by evaporation. The problems of water supply involve the conservation of superficial sources in reservoirs, and the geologist may be of assistance to the water engineer in the siting of reservoir dams on stable foundations; but it is more often in connection with underground sources of supply that he is called upon, and only these will be considered in this chapter; his function in regard to overground supplies will be considered in Chapter IX.

That any water sinks into the ground at all is due to the permeability of certain kinds of rock, and permeability is accordingly the first factor to be considered in the question of underground water supply. A permeable rock may be porous, or pervious, or both.

The term 'porous' is commonly applied to such rocks as sandstones which hold water or allow it to pass through their substance, and the principal factors affecting porosity are grain-size and shape, grading or sorting, and the amount and distribution of cementing material. A moderately coarse-grained rock composed of rounded grains, well-sorted and without much cement, carries most water. Angular grains pack together more closely, and the relative amount of pore-space is less; an ill-sorted rock has much potential pore-space already filled with fine sediment; and a fully cemented rock has obviously lost most of its original pore-space. Grain-size bears on the question in a rather different way. A fine-grained rock may be highly porous, but the water it holds is in capillary tubes and will be difficult to extract. Furthermore, the component minerals of most fine-grained rocks put them in the category of what we may call 'wettable rocks', like clay. Dried clay has considerable, though exceedingly fine, porosity; but as soon as it is wetted, the water fills the pores and is held in a loose chemical bondage with the clay colloid so that the rock becomes impermeable.

A pervious rock is one which is traversed by open cracks and fissures which can contain water even though the rock itself (as for example a typical igneous rock or a thoroughly cemented sediment) may be so compact as to be impervious. Joint- and bedding-planes, faults, and shatter-belts may all contribute to the fissuring of such a rock and render it pervious.

It has already been suggested (Chapter II) that joint-planes are closed at depth and only appear as open cracks nearer the surface when erosion of the overburden has allowed release from pressure. The same is true of porosity; at very great depth, the weaker mineral grains crush into the pore-space, and a muddy sandstone for example which has perhaps 20–30% pore-space at surface may have none at a depth of ten to fifteen miles. Water cannot therefore percolate downwards indefinitely, for a lower limit is imposed by this closure of pores and fissures at depth.

Downward percolation of rain-water is not the only source of underground water, though it is probably the principal one. In addition to such water, known as *meteoric*, geologists have recognized two other categories, *connate* and *magmatic*. Connate water represents water originally present in the pore-spaces of a rock as its particles were deposited, which has never subsequently been expelled; it is, in fact, water of the original sea in which the sediment accumulated. The saline character of some underground waters is due to this cause, but, of course, sea-water may in certain circumstances at the present day find its way through a permeable rock and maintain the salinity, and there are other possible causes. The other source, magmatic water, represents water expelled from cooling igneous magmas, which has therefore never been at surface or in contact with the atmosphere at all. Most mineral veins have been precipitated from solution in ascending magmatic waters.

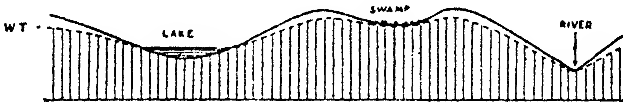

FIG. 23. – Diagram showing the relation between Topography and Water-table in a Homogeneous, Permeable Rock.

We see, then, that wettable rocks like clay are rendered impermeable and permeable rocks are saturated to the lower limit of porosity and fissuring by the ingress of surface water from above. The upper level of saturation is not, however, the ground surface, owing to evaporation and underground flow; but is a somewhat flatter edition of the surface topography known as the *water-table* (Fig. 23). This surface rises under hills and falls away towards the stream courses, the slope being determined by the rate and quantity of water flowing. The rate of flow is dependent on pressure and frictional resistance, which is a measure of permeability and is largely determined by the dimensions of the open pores and joints. In some fine-grained rocks a gradient as steep as one in twenty may be maintained; more usually the ground-water gradient is of the order of one in forty or fifty, and in massive limestone country one in 200 would be steep. Moreover, the height of the water-table fluctuates, being built up after heavy rainfall in the winter and sinking in summer, especially during prolonged drought, until restored in the next wet period. Wherever and whenever the water-table intersects the surface of the ground, water seeps out, and there is a nicety of balance between the topography of the water-table and the surface topography of the land. In wet and temperate climates the water-table coincides with ground-level along the bottom of valleys, and some underground water is added to that contributed by run-off along the whole length of the river course. Should a valley-floor be above the summer level of the water-table, drainage goes underground until seasonal rains and winter cessation of evaporation again saturate the ground and raise the water-table. Then intermittent streams – the 'bournes' of the Chalk Downs – resume their surface flow.

Conditions over large areas are usually more complicated than this, owing to the alternation of permeable and impermeable layers and to folding and lines of faulting. Impermeable layers interrupt the flow of underground water and isolate the water-bearing horizons, so that each permeable group has its own independent water-table (Fig. 24). Impervious beds are the containers; they hold up water coming down from overlying beds, and if the feed is lateral they afford a roof or seal to water pressing upwards from below. Outcrops of such layers are commonly responsible for lines of intermittent springs along a hillside, water being thrown out in the wet season at the contact of permeable and impervious beds.

Faults generally affect the water-table by blocking or diverting flow, sometimes providing an outlet to underground water that would not otherwise be available. They are therefore a common cause for the location of springs of useful volume and permanent flow, unlikely to be affected by seasonal fluctuations of the water-table (Fig. 25).

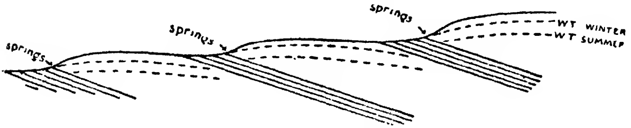

FIG. 24. – Diagram showing the effect of impervious layers (shaded) upon the water-table and the production of intermittent springs.

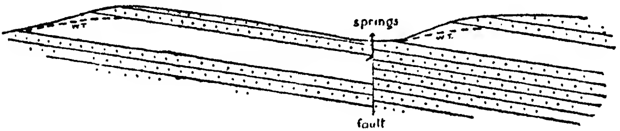

FIG. 25. – Diagram showing the effect of Faulting in tapping an underground supply. Owing to the head of water, the springs will be permanent.

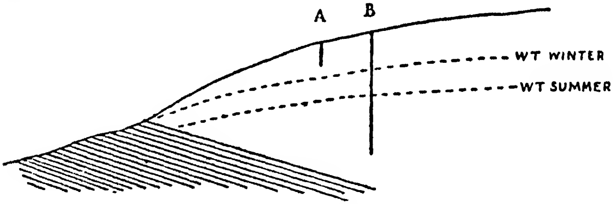

FIG. 26. – The well *A* lies above even the winter level of the water-table, and although a limited supply may be obtained from a well-jointed rock, it will be uncertain and liable to contamination. Well *B*, which has been sunk below the summer level of the water-table, will provide a permanent supply.

Wells are controlled outlets where underground water has been made available for human needs. Some small

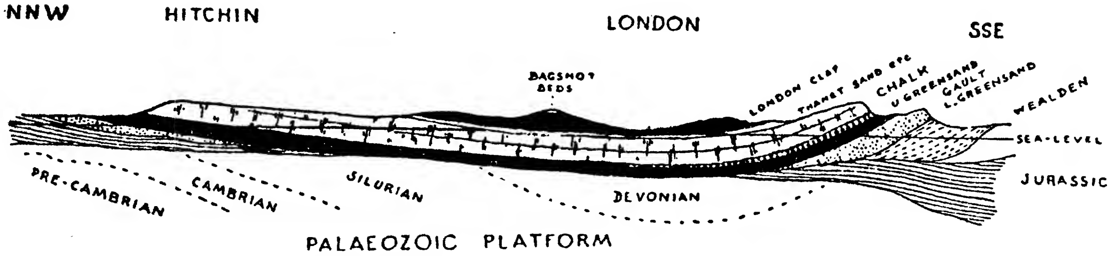

FIG. 27. – Generalized Section across the London Basin, adapted and simplified from Geological Survey Memoir *Water Supply of the County of London.*

The impervious clays (the London Clay and the Gault) forming respectively the upper and lower seals of the originally artesian system are shown in solid black. Length of section, about seventy miles; vertical scale exaggerated seventeen times and dips correspondingly distorted.

cottage wells may have been dug only a few feet deep to intercept a limited supply of surface water before it reaches the water-table. This is usually travelling in joints and fissures and is unfiltered, and therefore suspect. There is less risk of contamination and a continuous supply is assured if the well is sunk to a depth below the surface level of the water-table (Fig. 26). The most favourable of all sites for a well, however, is provided by a synclinal trough of alternating permeable and impermeable rocks (Fig. 27). When, as often happens, the impermeable cover is a soft shale or clay, and the water-bearing rock is a sandstone or limestone more resistant to weathering, it is likely that the level of the water-table at the rim of the basin will be sufficiently above ground surface near the centre to give a head of water, and the well flows without pumping. Such a well is an artesian well. Conditions in the London Basin, where the chalk and the sandy beds of the Lower Eocene are sandwiched between the overlying London Clay and the underlying Gault Clay, are typically artesian; and large supplies have been obtained in many places since this underground source was first successfully tapped nearly a century ago to supplement London's superficial sources. But so much water has been extracted to supply the needs of the metropolis that in the central area the water-table head has fallen some hundreds of feet below ground-level, and the 900 wells catalogued in 1937 were supplying less than one-eighth of the water used in London. (Between thirty and forty gallons per head is supplied daily by the Metropolitan Water Board to an eight million population.)

When water is pumped continuously from a well, the rate of flow through the rocks is usually insufficient to maintain the original head and level of water in and near the well, and the water-table is lowered around it until there is enough pressure behind the exaggerated slope to restore equilibrium and maintain the necessary flow. Thus there is produced a more or less conical depression of the water-table around the well (Fig. 28), known as the *cone of exhaustion.* A deep well from which a large yield is being pumped may bring neighbouring smaller wells within its cone of exhaustion, and these, being drained, dry up and must either be abandoned or sunk deeper.

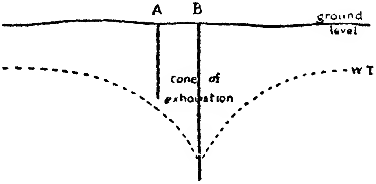

FIG. 28. – Cone of Exhaustion around a deep well, *B*, which is taking a large output.

The adjacent well *A*, originally sunk below the level of the water-table in this region, is now completely deprived of its supply.

The essentials for a good underground supply are therefore a suitable water-bearing rock or aquifer; a suitable geological structure; and a sufficient area of outcrop of the selected aquifer in a satisfactory catchment area. By suitable water-bearing rock, we mean one which is sufficiently permeable to allow the required quantity of water to flow

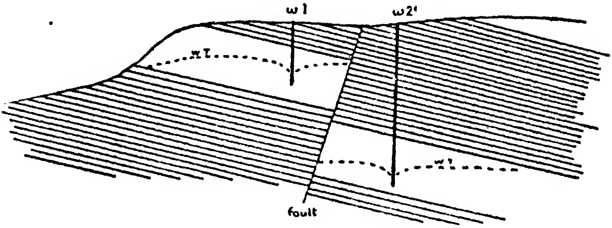

FIG. 29. – Examples of Unsuitable Well-sites.

At *w1*, the catchment is small and the reservoir insufficient; at *w2*, the well will enter water when first sunk, but as the horizon has no open catchment, and the fault, bringing clay against clay, makes a sealed joint, no supply can be maintained.

through it; if, in addition to its porosity, the rock is well-fissured, this will greatly facilitate the yield and allow a wider area to be drawn upon. By suitable geological structure, we mean one that provides an adequate volume of porous rock between an upper and a lower seal. The structure shown in Fig. 29 is unsatisfactory, however porous the rock may be, because the reservoir at *w*1 is insufficient for more than a small supply. Lastly, with reference to catchment areas, it may be noted that many rocks in other respects suitable carry little or no water because an impervious superficial layer (such as boulder clay) covers most of their outcrop and the rain-water runs off without entering the ground.

Contamination of water supply is most likely to occur when the level of the water-table has been so lowered that all the water that goes underground within a catchment area drains quickly and directly to the wells. Where the natural balance has not been artificially disturbed in any area, there is usually a perceptible seaward flow of fresh water along the bottoms of valleys and estuaries – a seepage of ground water into the superficial water system. Should the water-table be lowered by pumping, this flow will to some extent be interfered with and river or estuarine water may percolate or run back into the rocks. Now, it is along such valleys that human settlements are concentrated and where consequently industrial refuse and decaying organic matter are most likely to accumulate. In such low-lying regions the streams and surface waters become contaminated, and if instead of running off superficially they percolate into the ground, the danger of contaminated water supply becomes serious. Heavy pumping by some particular consumer may, by lowering the water-table over a wide area, have consequences far-reaching for others as well as upon his own supply. It is desirable to have wells cased with cemented brickwork or with steel tubing down to and a little below the apex of the cone of exhaustion to exclude nearby superficial drainage and ensure that the water pumped is drawn from below the water-table, ready filtered by passing through the rock. By such precautions the risk of contamination is minimized.

As a result of the general lowering of the water-table of the London Basin, the possibility now exists that polluted drainage and estuarine water are drawn into the underground Chalk fissures from areas where river-gravel and alluvium rest directly upon the pervious Eocene and Cretaceous rocks. At all these places the flow originally was from the hills towards the sea, and such a contingency could not arise until the water-table had been considerably lowered. Abandoned or disused wells, often filled with refuse, are another source of anxiety to the authorities around London and elsewhere.

CHAPTER VII

Geology and Soils

The origin of soils – Weathering control by climate – Soils of humid regions – Soils of semi-arid regions – Soils of arid regions.

WE have already mentioned the weathering and decay of rocks at surface under temperate conditions in considering the origin of sediments, and again in connection with the sculpturing of land forms. There is a third aspect of the process, neglected by many geologists, and that is the influence of weathering on soil formation.

Soil is a complex mixture of the products of rock waste with varying amounts of organic matter, both living and dead. It forms the outermost layer or shell of the earth's crust, where the most superficial rocks, whatever their nature, are continuously in contact with the atmosphere, and where in consequence the processes of chemical decay and mechanical disintegration complete their reactions, or at least exert their maximum effect. Soil is likewise in a sense the meeting-place of the organic and the inorganic worlds, for mingled with the rock waste and mineral debris are decaying remains of plants and animals, and a wealth of living organisms – earthworms and insects, the roots of living plants, and millions upon millions of bacteria. The chemical secretions of living organisms and the chemical products of organic decay influence the processes of rock decomposition to an extent not yet fully appreciated, and it is clear that the character of a soil is dependent on a very large number of factors – chemical, geological and biological – largely controlled by climate.

The processes of denudation of extensive land surfaces fall into two categories, soil-making and soil-removing; either group may be dominant or the two may be in equilibrium. Gravity, hill-creep, and running water or wind may carry away the products of rock wastage as fast as these are detached, and the surfaces of immature topography or wind-swept plateaux are almost bare raw rock, unless and until the climate allows the growth of sufficient vegetation to bind the soil layer. Removal of the established vegetation without change of climate, as, for example, by deforestation, may result in the rapid loss of much soil; or an ice-cap, such as that which spread over the northern hemisphere during the Great Ice Age, may completely strip a region of all its soil. In most regions, however, thanks largely to the protective cover of vegetation, there is equilibrium between the processes of soil formation and soil removal, so that as it creeps downhill the slowly moving mantle of soil is continuous.

Processes of rock decay involve a breakdown of the complex high-temperature silicate minerals of igneous rocks. During this hydrolysis and carbonation of the felspar and ferromagnesian constituents, something is invariably taken into solution and is carried away; and what remains usually contains plant food and is the raw material of the soil. What is taken and what remains varies with the temperature and quantity of ground-water moving, and this in turn depends very largely on climate. In the early stages of weathering and in temperate climates the nature of the parent rock almost controls the character of the resulting soil, but under extreme climatic conditions the reactions may be carried so far that the nature of the parent rock exerts relatively little influence.

Soils of Humid Regions

Where rainfall is greater than evaporation throughout the year, the soluble products of rock decay are carried away with the excess of water and the soils are left with less of certain chemical constituents than the rocks from which they were formed. The following are some of the more important types of soil produced under such conditions.

Podsols

Podsols are white or light-grey soils consisting mainly of silica, with some aluminium silicate. They occur in cold or cool temperate climates where the rate of bacteriological decay is not sufficient to destroy the peaty humus, and thus acids are present to neutralize the alkaline carbonates set free by hydrolysis of the silicate minerals. In addition, leaching has been so intense that little but the original stable quartz remains in the top soil layer. All the hydrolysed products of mineral weathering have been carried downwards into the subjacent soil layer, where colloidal clay minerals, ferric hydroxide and humus tend to be concentrated. Often the ferric hydroxide, kept soluble in the presence of humus, is reprecipitated between the soil and the subsoil to form a hard 'iron pan'. Such soils, which cover enormous areas of Russia, Northern Europe, Canada, and North-east United States, are almost entirely deficient in nutrient salts, and can therefore support little in the way of vegetation. Coniferous forest, birch-scrub, and heath, which require a minimum of mineral salts, are principal among the few types of vegetation which can colonize such regions.

Brown Earths

The greater part of North-west Europe and the Eastern United States has a brown loamy soil containing much clay and owing its colour to ferric oxide and humus. This is associated with deciduous forest and mixed farming. Mature soils of this type are devoid of calcium carbonates and to some extent deficient in alkali, but are not otherwise strongly leached. Where cultivated, the calcium deficiency requires to be made good by periodic liming; and manuring adds other salts and organic matter necessary to improve the crop yield.

Laterite

Laterite is the name given to a red or brown clay formed by weathering under a monsoon climate in the sub-tropics. It was originally described from India, where it was used for road-surfacing and 'brick'-making, and the name is derived from *later*, the Latin for brick. When wet and freshly dug, it may be quite soft and can be cut into blocks or bricks which on exposure harden sufficiently to be used for building.

Under hot, moist climatic conditions, rapid bacteriological decay removes humus, and there is no accumulation of organic acids to neutralize the alkaline salts which result from silicate hydrolysis. Hence carbonate solutions bring about almost complete dissolution of the quartz grains and the silicates. According to some authorities, direct bacterial action is an important contributory factor. Be this as it may, the residual material (the 'soil') consists predominantly of the hydrated peroxides of iron and more rarely aluminium and manganese. Such deposits are formed by the decomposition of many kinds of rock, igneous, metamorphic, and even sedimentary. The hydrated oxides produced are rarely pure, and most laterites carry a considerable amount of combined silica, suggesting that an appreciable proportion of clay mineral allied to kaolin or serpentine has survived as well. The alkalies, however, are almost completely leached away.

Where the proportion of iron oxide is high, the material has been used as an ore of iron; and the corresponding aluminous varieties, known as bauxite, are of great economic importance as a natural concentrate of aluminium.

Soils of Semi-arid Regions

In semi-arid regions rainfall is balanced by evaporation. During the dry season the normal downward flow of the soil-water is reversed and it is drawn again to the surface, where it evaporates and deposits those salts it had taken into solution. Hence the leaching processes so characteristic of humid regions cannot take place; instead, all the soluble products of weathering remain in the soil. Calcium carbonate and gypsum (calcium sulphate) are the commonest of such substances, but there are others as well, and they tend to affect the type of clay-mineral and produce varieties which are base-saturated (usually with calcium) and mildly alkaline.

The *Black earth* of the main grain-producing areas of Russia is of this character, and similar soils occur in North America and Africa. The parent rock of the black earth is usually the wind-borne loess, but sediments of various kinds (including limestones) and granite can form an almost identical soil under these conditions. The dark colour is due to the high proportion of organic matter, which may amount to 10%.

The *Chestnut earths* of Russia and North America occur where the climate is somewhat drier. Calcium carbonate concretions occur nearer to the surface than in the black earths and the proportion of organic matter is less. Passing to regions of still greater aridity, the percentage of organic matter falls still lower (1% or less) and the soils assume a paler colour, light-brown or grey. Sodium salts are usually abundant in such soils, along with calcium carbonate and gypsum, which accumulate quite near to the surface.

Soils of Arid Regions

In desert climates there is no regular rainfall and the [illegible] decay of rocks hardly occurs at all; the 'soil' is a mechanically disintegrated sand consisting of shattered mineral grains and undecomposed particles from the parent rock. Often the surface rocks are soaked with dew, and sometimes the water-table, fed by occasional rains, is near enough to the surface for extract saline solutions to be drawn up by capillarity. As the water evaporates, the dissolved salts crystallize out, giving upstanding stones their 'desert varnish', caking and cementing the sands (desert sands are commonly cemented with gypsum), and sometimes forming nodular masses and efflorescent incrustations of alkaline salts on the surface. There is, of course, insufficient plant life to contribute any substantial proportion of humus to the soil.

CHAPTER VIII

The Geology of Petroleum

Theories of origin – The source rock – The reservoir rock and structural traps – Geological exploration for oil – Geophysical prospecting.

CRUDE petroleum is a mixture or mutual solution of solid, liquid, and gaseous hydrocarbons, mostly of the paraffin series (C_nH_{2n+2}). Small quantities of diverse other chemical substances associated with these in variable proportions have to be separated at the refinery, and the properties and value of the crude oil of different oil-fields may therefore vary. Unlike coal, oil retains no vestige of its original components, and instead of remaining in the rocks where it was formed, it migrates under gravity, in general floating upon ground-water. Accordingly, though much attention has been given to the problem of its origin, we have scarcely passed beyond the stage of guesswork.

Few if any geologists now subscribe to the inorganic theories of origin so popular with the chemists of last century, who thought that water percolating downward through the earth's crust became converted into steam and by interaction with carbide of iron and other metals produced hydrocarbons. But while authorities to-day regard an organic origin as virtually certain, the nature of the organisms remains in doubt. Probably many kinds of organism have contributed, and the claims of both plants and animals have been pressed. Microscopic plants, such as the single-celled algæ and diatoms, or plant remains like spores, and, among animals, the single-celled foraminifera, all constitute possible and perhaps probable sources of some oil. Each has been widely distributed from early geological times and is often present in enormous quantity.

Possibly, higher types of marine animals may have contributed, but in spite of the experimental laboratory making of paraffins from fish-waste by Engler and others, this is not considered so likely a supply of natural oil as the lower forms of life. Accumulation of such finely disseminated organic matter in the slowly deposited muds of regions where sea-bottom conditions are stagnant and so anaerobic that complete decomposition before burial is prevented, appears to be the most probable first step in the formation of petroleum.

Nor is there much direct evidence of the chemical and biochemical changes which must have occurred in the conversion of this organic matter into oil. The early stages were probably associated with bacterial action. That anaerobic bacteria are capable of producing quantities of methane (marsh gas) is evident from many a recent mud, but we know nothing of the production of any of the higher members of the paraffin series. These bacteria break down albumen and cellulose, eliminating most of the oxygen and nitrogen, and perhaps as a result of their action fatty acids ($C_nH_{2n}O_2$) may be produced. The final stages in the generation of petroleum are likely to have been entirely inorganic processes, to which heat and pressure due to subsequent loading of accumulating sediments have doubtless contributed.

As the source rock becomes compacted, the water and oil are squeezed from the interstices and the oil begins its migration. In the later phases, physical factors other than compaction come into play; more especially surface tension (much less for oil than water), gravity (oil is lighter than water and very much lighter than salt water), and vapour-pressure of any undissolved gases. The oil passes from the source rock, the characters of which are mostly conjectural, into the more open spaces of a reservoir rock, where it can accumulate.

A good oil-reservoir rock has much the same characters as a good water-bearing rock. Sands or sandstone, with pore-space sufficiently large, and limestones or dolomites which are cavernous or fissured enough to allow the oil free movement, are the most suitable types for exploitation.

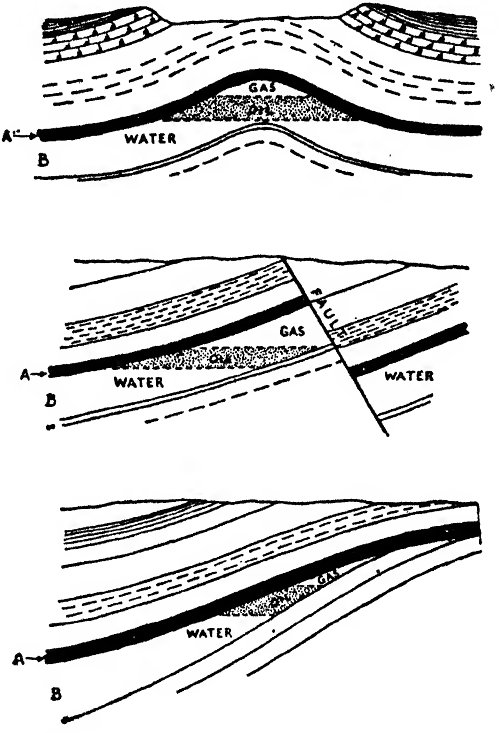

FIG. 30. – Diagrammatic sections showing the accumulation of oil and gas in three common types of trap structure.

A, the impervious cap rock; *B*, the reservoir rock. (Based on Nettleton, *Geophysical Prospecting for Oil.*)

Lastly – for without it the oil would seep out to surface and be lost – a suitable geological structure is necessary to contain the accumulating oil and a cap rock to seal it. The simplest oil-pool structure is a dome or anticlinal fold, and the most usual cap rock is impervious shale or clay. Because of the low specific gravity of oil and its ability to float on water, the effective geological structure for accumulation and retention of oil is the inverse of that furnishing a good water reservoir.

Each one of these four requirements is essential to the formation of an exploitable oil-field. The oil must have been generated in the source rock and expressed from it largely by compaction under increasing load; it will have migrated laterally and upwards as a result of gravity until retained in the structural trap where it accumulated. Here it is often under considerable pressure, sealed or maintained by hydrostatic head. The pressure when a well is first drilled may be sufficient to deliver a powerful flow; but this soon drops, and through most of the life of an oil-field the crude oil has to be pumped to the surface. In the final stages, when a field is approaching exhaustion, the oil has to be coaxed out by reducing frictional and capillary resistance in various ways, and the last of it can never be completely extracted. Under present conditions, the oil film which clings to grains and lines pore-spaces of the reservoir rock is inaccessible, and indeed it is admitted that not more than half of the oil originally present can be recovered by existing methods of production.

The geologist's first function in exploration for oil is to locate suitable reservoir structures among rocks accepted as potentially oil-bearing.

Surface seepages are often found, gaseous, liquid, or solid; but less reliance is placed on these now than heretofore. Natural gas (methane), hydrogen sulphide (H_2S), and carbon dioxide are the commonest gases. At Heathfield, Sussex, natural gas was used to light the railway station for many years. Oil shows vary considerably in appearance,

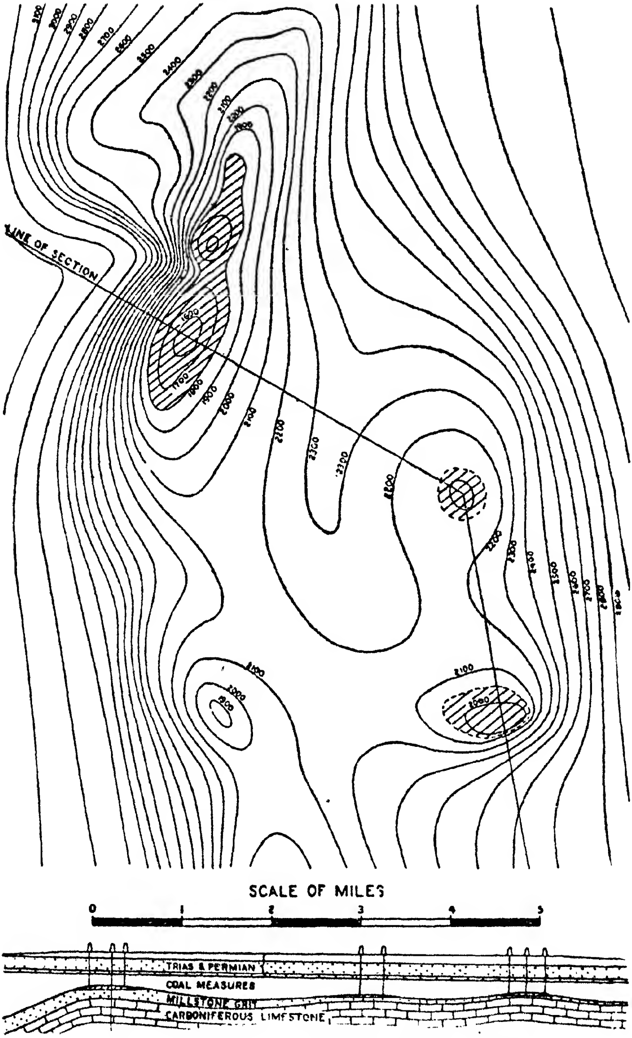

FIG. 31. – An English Oil-field Area (Eakring, Notts.).

Diagrammatic cross-section and structural contour map showing underground contours on principal producing horizon at 100-foot intervals, in feet below sea-level. The shaded areas indicate extent of oil accumulation.

some being quite light-coloured water-oil emulsions, but most are dark, viscous, or almost solid. Asphaltic oils usually leave heavy residues, but many filtered oils evaporate quickly and completely, so that their shows are very difficult to see. The absence of surface indications is no evidence of the absence of oil, whilst a large spread may sometimes prove to be the only oil that is left. Solid residues in the form of pitch lakes are generally asphaltic. Even without surface indications, it is usual to adventure the very considerable cost of 'wild-cat' trial wells wherever there is evidence of apparently suitable sedimentary succession and structure.

It is always the task of the geologist to prepare a detailed structure-map of the selected area. Every change of dip, in direction and particularly in amount, is of significance; for from these and other surface indications must be produced contour-maps (the working equivalent of true-scale models) to show that the dome structure as it affects the possible oil reservoir has 'closure' * and to locate a high point for the test drill. Changes in dip of no more than a few degrees may make a difference of scores or hundreds of feet of closure in a large-scale dome. Describing the Chalk of the London Basin, a geologist made the classic remark: 'The dip here steepens abruptly to three degrees'; the oil geologist in many areas has to deal with similarly gentle folds.

In the delineation of such slight structures as may be of vital importance to the oil geologist, the most exact correlation of strata is necessary. Sometimes this is accomplished by the specialist palæontologist working with microscopic fossils such as foraminifera, many thousands of which may lie entombed in a few inches of quite narrow core; or sometimes it is obtained by the application of physical

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* By 'closure' is meant the height of the central part of the inverted basin, above the escape-point on its lip.

methods: for example, the Schlumberger or electrical surveys of boreholes, registering the position of clays, sands, and limestones in the borehole by measurements of resistivity and other electric properties.

Surface indications, even of structures, are not everywhere available, however. Oil-bearing strata may be overlain unconformably by beds which are newer than the movement which produced the oil-traps; and such blanketing deposits (even if they be only alluvium) completely hide the structures it is so necessary to locate. Here is the province of the geophysicist.

Geophysical prospecting does not look for oil, but, by measurements at surface, the geophysicist may in favourable circumstances be able to locate unseen bounding surfaces between different rock formations and so to interpret underground structure. There are three main geophysical methods, based upon seismic, gravitational, and electrical measurements.

The seismic methods, which have in recent years been most successful, have been likened to echo-sounding through rocks instead of water. A charge is fired in a shot-hole 10 to 100 or more feet deep, and the shock-waves, reflected back from various hard-rock horizons below ground, are picked up by groups of suitably distributed detectors, amplified, and recorded photographically on a moving film which also registers the precise instant of explosion. The depths of the reflecting surfaces are calculated from the travel times, and after correlation of the results from a series of such measurements, contoured maps can be drawn showing the depths and form of the reflecting horizons.

In the gravitational methods an extremely sensitive torsion balance (called after one of its inventors the Eötvös balance) or some type of gravimeter is used to measure minute variations in the force of gravity over a given area.

These variations are interpreted in terms of probable rock-mass distribution underground; thus a large anticline, the core of which is denser than its flanks, has at the surface above it an area of slightly increased gravity. As an indication of the delicacy of the instruments and the care and manipulative skill required in their use, it may be mentioned that the variation measured is no more than a few milligals per mile, and a milligal is approximately one millionth of *g*, the normal force of gravity at the earth's surface.

Several electrical methods have been developed, depending in principle on comparative measurements of electrical resistivity and inductance of the rocks; but whilst extensively used in mineral prospecting, they are rarely used in oil-field exploration, largely because they cannot penetrate to a sufficient depth. Reference has already been made to the use of such methods in correlation of holes already drilled.

It is perhaps appropriate to conclude this very brief account of geological mapping and geophysical prospecting in search of oil with the following quotation from one of our foremost oil geologists:

> The hazards of oil exploration are well known to the investing public, but the reasons for them are probably less well appreciated. After as complete a survey of a potential oil region as is possible, using all geological and geophysical assistance, the average chance of success of an exploration boring cannot ever be rated, on the basis of past experience, as better than perhaps one in ten; but past experience has also shown that if financial resources can stand the strain of the nine unsuccessful efforts, the reward from the fortunate tenth may be expected to give sufficient compensation.

CHAPTER IX

Engineering Geology

Foundations, creep, and landslips – Reservoirs – Tunnels: the Mersey Tunnel – Building-stone, bricks, cement, roofing-slate, and road metal.

ONE of the first points of contact between the geologist and the engineer brings us back again to the distribution of sub-surface water, for such water plays an important role in mass movement of the ground by reducing friction between particles or between adjacent layers of incompletely consolidated strata. Thus, lubricating the soil particles on a sloping surface, artificial or natural, it facilitates hill-creep and enables the wetted mass under gravity to make its way imperceptibly or by sudden lurch downhill. Or again, percolating through a previous layer, it may wet a sloping clay layer, making it so unstable that the mass above and behind it begins to slide.

Rigidity of Foundations

Choice of the ideal site for heavy buildings is rarely practicable, for other considerations generally predominate, but it is often possible to guard against the worst conditions.

Unconsolidated rock may require pile-driving or raft construction. There may be difficulties in recognizing when 'solid rock' is entered, and thin clay bands within glacial drift have been mistaken for solid Gault, Lias, or other Mesozoic clay. Stratified rocks themselves vary greatly in reliability. Igneous and metamorphic rocks, sandstones, and limestones – in short, rocks which do not swell when soaked in water – provide stable foundations; while clays, shales, above all boulder clay, are to be avoided wherever possible. Under a thick mantle of superficial deposit and where permanently water-logged, clays and shales may give satisfactory frictional support for piles, but near the surface they are liable to seasonal wetting and drying and afford no real stability.

In mining areas, even where foundations are of the best, settlement may result from collapse of underground workings. Where the workings are deep and systematic, and their advance is regular, the wave of settlement lags a year or two behind the mining, and little damage may be done. But in shallow mines, temporary timbering soon rots, and unless the roof-rocks are strong enough permanently to bridge the galleries, these stope their way upwards until surface rocks and the buildings founded upon them may also collapse. The customary method of working rock-salt by solution and pumping up the brine leads to local subsidence above the channels of solution, and this also is unavoidable. The settlement of St Paul's some years ago was from a more unusual cause; flow of underground water had washed away some of the finer material from among the sand and gravel on which the building rests, and this had to be, and was, successfully replaced and the foundation strengthened by extensive grouting with cement.

Surface Creep and Landslides

Cuttings and embankments rarely escape the effects of creep and slip unless the strata are completely drained in course of their construction.

Piles of loose material at the surface assume an equilibrium slope at the 'angle of repose', which varies with the size and shape of grains, the character of the material, and the proportion of water present. For stability, the side of an embankment or cutting must be appreciably less steep than this. This angle is greater for drained moist material than when it is either completely wet or dry. Saturation may therefore lead to slumping and slipping, which is largely countered by construction of herring-bone stone drains or 'conduits' filled with blocks of limestone or furnace slag to facilitate drainage and keep the water-table low. Similarly, where buttresses and revetments are necessary, these can be made safe by driving drainage tunnels at their foot. Planting of trees and shrubs is recommended for open slopes; beech and birch, with shallow rooting systems, are reported unreliable; but where they will grow, poplar, ash, and rowan are generally effective. Grass and tree-roots generally not only bind the soil and subsoil as a mat, but by preserving a more constant moisture content reduce the volume changes associated with alternate wetting and drying of the surface soil.

The walls of cuttings through compact and solid rock have less tendency to slip, friction between adjacent joint-blocks being usually sufficient to hold them even where the dip is outwards towards the cut face. Much, however, depends on the scale of the excavation and the nature of the minor partings and the condition of the rocks. In general, given the geological conditions of a slight dip and pervious strata resting upon a clay rock, landslides are liable to occur wherever the slope of the ground leaves the 'toe' of drained rock unsupported. Such over-steepness of slope is a characteristic of youthful stages of river erosion, where there has been glacial modification of river valleys, or along cliffs cut by active marine erosion. Sliding is recurrent until with loss of relief in a mature topography stability has been regained. Unstable conditions may be re-introduced by engineering construction, and overloading by earth-banks; the erection of heavy surface buildings may also be mentioned as a likely contributory cause. Prevention is proverbially better than cure, and indeed for land-slips there is no sure cure. In small cuttings it may be possible to cut back and remove the moving overburden, or to drain and hold it with strong revetments. Prevention requires a study of structural relations (in the geological sense) and the avoidance of impossible sites.

Water-supply Reservoirs

Selection of surface reservoir sites is governed by a variety of factors, and the number of possible large sites remaining unscheduled in this country is now very limited. Three kinds of survey – topographic, rainfall, and geological – are a necessary preliminary to the final decision. The question of distance from the consumer will have been considered at an early stage.

The large-scale contoured topographic plan will indicate surface form and extent of the area to be flooded, and show the possible positions for the dam, and hence the volume of water to be retained. What is retained must suffice for the promoters of the scheme, supply accommodation water to smaller towns along the route of the pipe-line, and maintain the statutory proportion of 'compensation water' to riparian and water-mill owners along the river course below the dam. It should also be remembered that the surface area of the reservoir determines the amount of water lost by evaporation. Rainfall records will show the total fall over the catchment area, but only by stream-gauging and by analogy with neighbouring similar sites can an approximate estimate be made of the expected run-off. Investigation through several decades of past records is required, as it is necessary to allow for a possible succession of three dry years. The geological survey will provide information concerning the texture, porosity, and general conformation of the floor rocks, which should obviously not favour leakage. The disposition of bedding, jointing, faulting, or other surfaces of weakness in proximity to the dam site are also matters of importance.

The ideal catchment area is high moorland or mountain country composed of hard compact rocks, as little fissured as may be. Rainfall on such country is generally above the average, and the run-off from it may exceed one-third the annual fall. Such country is too bleak for cultivation and, being sparsely inhabited, the site value is minimal and the necessary disturbance of population small. Valleys in such regions are commonly immature, and in certain areas of the north and west, glaciated; being deep and comparatively narrow, their dams are shorter than those required in more widely-open valleys of mature topography to the south and east. In Britain, the western uplands are almost entirely formed of Lower Palæozoic, Pre-Cambrian, or igneous rocks, which, whilst fulfilling the run-off requirements better than most, also provide good foundations for the dams and local building material for their construction. Numerous valleys in the Millstone Grit, Lower Carboniferous, and Old Red Sandstone moorland country, because of their proximity to coalfield centres of population, are convenient, and are now largely devoted to water catchment. Their argillaceous rocks are less completely compacted and are liable to swell and lose strength when wetted. In choosing dam sites in the steeper valleys it is therefore necessary to make sure that the sides of the valley are undisturbed by landslides and that the site of the water cut-off trench has not been seriously affected by heaving under lateral side pressure across the valley-floor.

Tunnels

In illustration of the application of geological principles to tunnelling, the special case of the new Mersey Tunnel as recorded by the consulting geologist will be considered.

When construction along the selected line was proposed, more than usual geological information was already available. The formations outcropping on either side of the Mersey had been mapped, and there were good records of borings in the neighbourhood. Moreover, there was experience of the same formations in the earlier Mersey Railway Tunnel, only 400 feet to the south of the new site.

Both east and west banks of the Mersey are of Middle Bunter Sandstone (Lower Trias), which could properly be assumed also to underlie the river-bed. These rocks are hard, reddish sandstones, massively jointed and bedded, well cemented by silica and iron oxide, and with considerable crushing strength. Their porosity, however, is about 15%, and they form an important water-bearing horizon in the district, so that much water was to be expected. In the railway tunnel, built without a water-tight lining, pumping at the rate of about 5,000 gallons a minute has been continuous ever since its construction.

Since the thickness of these Middle Bunter sandstones exceeds 1,000 feet, the tunnel could not be expected to touch the underlying Lower Bunter, the characters of which are therefore not involved. Similarly, the softer, iron-cemented Upper Bunter sandstones were only likely to be encountered beyond a north-south fault in the eastern approaches to the tunnel. By detailed study of the rocks on either side of the Mersey, G. H. Morton had deduced in 1863 the occurrence of another north-south fault within the Middle Bunter, underneath the Mersey. The 'solid' Trias rocks are blanketed by superficial deposits of Boulder Clay, laid down on a highly irregular pre-Glacial floor. Portions of deep buried channels, often 130 feet or more below sea-level, have been revealed by borings in the vicinity, and T. Mellard Reade had predicted the existence of a buried channel underneath the Mersey.

Both these predictions had been verified during the construction of the railway tunnel. The north-south fault was found as a 10-inch belt of shattered sandstone and clay, and the floor of the buried channel, about 100 feet below sea-level, formed the roof of the tunnel for nearly 100 yards.

Fortunately, loose sands at the bottom of the channel were so sealed by an overlying layer of boulder clay that there was no serious flooding.

Because of its greater size (the excavation was 47 feet in diameter) it was deemed essential that the New Tunnel should be excavated entirely within the solid rock; it should not only avoid the buried channel, but be separated from it by an adequate cover. Moreover, since gradients were limited by specification, depth controlled the length of the approaches and had to be decided before work commenced. Examination of scraps of evidence from all the known buried channels in the district – assumed to be tributaries of the main channel under the Mersey – led to the opinion that the main sub-glacial stream course drained southwards, in the opposite direction to the present Mersey. Therefore it seemed justifiable to conclude that the drift-filled channel would be no deeper than at the railway tunnel to the south, and might even be at a slightly higher level. On this evidence, the initial shafts were sunk and excavation of pilot headings proceeded. Inflow of water was practically stopped by the François cementation process, injecting under hydraulic pressure aluminium sulphate and sodium silicate, followed by cement.

The sandstone proved so hard that it had to be broken up by blasting, except near large buildings and in the vicinity of the buried channel where this was prohibited; but the roof held, and falls of rock were rare. Because of the strong tidal flow, the course of the buried channel could not be investigated by exploratory borings from the tideway, so the ground above and ahead of the pilot workings was probed by advance trial borings. With the lower pilot heading always well in advance of the upper, bores were driven horizontally forwards and obliquely upwards at small angles for 60–100 feet. When at last exploratory borings from the lower heading located the buried channel, the upper heading was provided with a special pressure shield and cased with cast-iron segments, and as each segment was added, exploratory borings were made radiating upwards and outwards, so that the base of the channel was effectively contoured from below. As at the railway tunnel, coarse sand and gravel in the trough of the channel were full of water, but sealed by the boulder clay above. Owing to the quantity of this water, it was impossible to drain and grout these sands, so the trial bores were plugged. The previously estimated depth gave the necessary head of solid rock, and excavation proceeded, leaving the drift-filled channel undisturbed though close overhead.

The approach headings gave little trouble, though in places the occurrence of fault cracks and fissures made it necessary to support the roof with steel and timbering.

It is interesting to note that the cost of all this exploratory work, including 66,000 feet of trial borings, was less than one-fifth of 1% of the total cost of construction of the tunnel.

Building-stone

Every kind of fully- or partly-cemented or consolidated rock, igneous, sedimentary, and metamorphic, has somewhere been used as building-stone; but certain properties render some varieties particularly suitable for the purpose. Apart from considerations of divisional planes, jointing, bedding, or cleavage, the essential properties are those associated with strength and durability. The architect or engineer must be assured not only that the material will bear all the stresses he wishes to put upon it, but also that it will continue to do so after it has been in place many years. Durability means resistance to the point of immunity from the corrosive action of an industrial or city atmosphere, or, it may be, sea-water, etc., as well as from the mechanical effects of temperature changes and frost action.

The highest immunity is asked for, but it may be noted that æsthetically some slight chemical weathering to 'mellow' the surface is desirable.

The hardness of a stone depends not so much on the mineral hardness of its major constituents as on the fit or state of aggregation of the minor particles between them. A loosely cemented sandstone may be so friable that it can be crumbled between the finger and thumb, while a compact limestone may be accounted a hard and durable stone, though the hardness of calcite is far less than that of quartz.

Other things being equal, medium-grained rock is preferred to coarse-grained rock. It dresses more evenly and is usually more resistant to both chemical and mechanical weathering; it suffers less by frost action and the effects of temperature changes, and does not show the same tendency to uneven weathering.

Allied to texture, porosity is a factor of the greatest importance. By way of open pores, water sinks or is drawn into the stone, increasing the opportunities for chemical decay and rendering it liable to frost disintegration. The latter effect is greater in minutely porous than in open-grained rocks of the same percentage pore-space, because water drains out less rapidly, so that the rock is liable to remain saturated. 'Quarry water' is also held in the pores, and when first quarried the 'green' stone is more or less saturated with water containing mineral matter in solution. As this dries out at surface, the stone matures and a seasoned crust is formed. For this reason, it is desirable that dressing and carving should be done while the stone is still green. Again, when exposed to weather, rain and dew soaking into the stone dissolve something of the more soluble constituents, and these solutions choke the surface pores as they evaporate and add their contribution to the 'weather face'.

Jointing in an igneous rock, or jointing and bedding in a sedimentary rock, determine the size and regularity of the natural blocks obtainable, and a rock otherwise suitable may be valueless as building-stone if the joints are too close together. Predisposing the jointing in igneous rocks are the parting directions known as rift and grain. In general these are due to some orientation of those constituent mineral crystals having cleavage, or to microscopic flaws, and may be related to strain suffered by the rock during or after consolidation. The quarryman and stone-dresser locate and use these planes of weakness, though they are invisible to most observers. In sedimentary rocks, joints and bedding-planes are the partings which should control both quarrying and working of the stones. Even the most reliable freestones give good service in buildings only if they are laid on their natural bed – i.e., when placed with the bedding-planes horizontal. If this precaution is ignored, not only is the strength of the rock less than normal, but in weathering the bedding-planes may open up so rapidly that the whole stone will need replacement within a very short time.

Recorded crushing strengths of rocks are empirical measurements of the resistance of test-pieces to compressive force. They vary with the shape and size of the test-piece, the rate of loading, and the nature of the bearing surfaces. Test-laboratory practice is not standard, and figures tabulated are therefore not comparative. For use as wall stone, some soft limestones and sandstones reported as having a crushing strength of about 3,000 lb. to the square inch are as satisfactory as diabase, for which 30,000 lb. is cited. Almost any rock sound and uniform enough to be dressed for use as a building-stone has a crushing strength far in excess of average building requirements; every upstanding natural cliff demonstrates that in large masses its rock is practically uncrushable. The transverse or tensile strength, though usually of much greater importance to the builder, is rarely investigated, and little information is available. It is unrelated to crushing strength. Here, too, laboratory practice is not standardized; the test consists in determining the weight which breaks a test-bar of about 1 square inch cross-section resting upon supports about 6 inches apart. The importance of transverse strength in stones for use as lintels is obvious.

In addition to examination of thin sections under the microscope for determination of texture and mineral composition, and the measurement of crushing and transverse strength, other laboratory methods of testing durability and behaviour during weathering have been devised. In Britain, the Building Research Station, under the Department of Scientific and Industrial Research, was founded in 1920 to provide a State service for the building industry, and the investigation of all kinds of structural materials is one part of the Station's work.

Clays and Brickmaking

A clay is finely divided material containing sufficient colloidal matter and clay-minerals, with their characteristic affinity for water, to form a plastic mass when wet. Most clay contains a large proportion of some hydrated aluminium silicate ($Al_2O_3,mSiO_2,nH_2O$, m and n both variable), though other clay-minerals have a more complex constitution. All are the breakdown products of alteration of igneous rock minerals, mainly the felspars and ferromagnesian silicates, from which they have been derived by chemical weathering. Hence the majority of clay beds occur as water-laid sedimentary deposits.

When a clay dries, it shrinks, the amount of shrinkage depending on the amount of water held between the mineral particles or within the molecular structure of the clay-minerals. Nearly all clays are mixtures of several clay-minerals, with silt and some fine sand, and the amount of bulk contraction varies greatly. Excessive shrinkage (more than 30% by volume) renders a clay unmanageable for brickmaking or for ceramic purposes, and preliminary drying and firing tests are necessary to ensure that in this respect a prospective clay is satisfactory. Excessive shrinkage may be counteracted by admixture with pre-burnt material (known as grog) or with sand.

After the moulded bricks are air-dried, some water still remains, and owing to the extreme closeness of the plastic texture, not all of it is able to escape even during the early stages of firing. What is not driven off enters into more permanent chemical combination with the alumina, silica, iron and alkalies to form a silicate glass. The process of firing a brick consists in the production of sufficient glass to bind the unfused particles together.

The suitability of a clay for brickmaking will therefore depend, not only on the amount of its shrinkage on drying, but also on the proportion of minor chemical constituents. Some soda, lime, and even magnesia, are essential for low-temperature fluxing, and some iron is desirable to import a 'warm' red or brown colour to the brick, but excess of fluxes leads to over-vitrification. Most clays carry a certain amount of organic carbon, and with it, sulphur, generally in the form of ferrous sulphide, which impart a blue or black colour to the unweathered clay. In the oxidizing atmosphere of the kiln, when the steam is gone, the carbon is burnt out and then the sulphides form sulphates of alkalies, magnesia and lime. During service, appreciable quantities of these sulphates are in time leached by rain and drawn to the surface of the brick, forming an unsightly efflorescence. Sodium sulphate is not merely unsightly, it disintegrates the brick, for while at low temperatures its crystals carry 10 molecules of water, warmed in the summer sun these break down to $Na_2SO_4,4H_2O$, ready on cooling to take up again the six molecules of water with a consequent expansion which disintegrates the fabric of the brick more effectively than any frost.

The earliest brickmaking process, still employed in village industries, is a wet process. The clay is puddled, moulded, air-dried for some weeks, and then fired. Contraction during drying is allowed for in the original size of the mould and is kept within limits by admixture with sand or ashes. Brickearth, which is a loess-like, inter-glacial deposit of clay and silt, is a favourite material. Considerable time and heat are wasted in driving off the water, losses to some extent obviated in the semi-wet process. In this process, applying a power-press for moulding, little water is added to the brick clay. In dry-process brickmaking the brick is moulded entirely by packing of crushed rock (shale or slate) under stress sufficient to crush or rotate the particles, and the aggregate is made up with only the minimum of water present in the clay-mineral constituents of the quarried rock.

London stock bricks were made from brickearth such as that of the Lea Valley, mixed with domestic refuse, much of it house cinders and vegetable waste, which provide so much combustible matter that the mixture is practically self-burning. Fragments of unburned cinder are often visible on broken surfaces. The great modern mass-producing brickworks using Oxford Clay have a similar fuel-saving advantage in that a proper proportion of bituminous 'knots' occurring in the clay reduces coal-firing to a minimum. Exact control of the burning process is essential, however, for the water has to be driven off before the carbonaceous matter can be burnt, and not until all the carbon is removed will the iron sulphides oxidize and the brick turn red.

Portland and other Cements

The middle of the eighteenth century saw various experiments in calcining mixtures of clay and lime to make a

Roman cement or hydraulic mortar, but the discovery of Portland cement (named from its resemblance to grey Portland stone) is attributed to Joseph Aspdin early in the nineteenth century. The product from natural mixtures remained in the experimental stage until the middle of last century, when a product with predictable properties was developed.

Portland cement is a mixture of about two-thirds limestone and one-third clay, burned at clinkering temperature and ground to a fine powder. Mixed with sand, it sets not too rapidly under water, forming a cheap binding material stronger than any previously known. The mineralogy of the changes which occur during firing and setting is still not fully understood, but the chemistry has been investigated empirically by long-continued experiment and analysis, and it appears that the solid solution of calcium aluminate in calcium silicates formed at high temperature is capable of taking up water and crystallizing as a mixture of minerals as it sets. The solid solution is obtained by 'fritting' below the temperature of fusion, and its formation is accelerated by intimate mixing of the constituent raw materials before they are fired. As in brickmaking, some 'impurities' of alkali and iron help the fluxing, but excess of these and any admixture of coarse particles of free silica are rigidly avoided. Aggregates containing underburned cements which may carry free lime will crack when the quicklime slakes and expands after other constituents have set.

The raw materials are carbonate of lime, usually in the form of chalk or ground-up limestone, and silicate of alumina as clay. The works are sited where these materials, coal and water can be conveniently assembled near a large consumers' market. Calcareous and argillaceous ingredients may occur naturally mixed in one formation, as in the Chalk Marl (the impure argillaceous base of the Chalk of eastern England) and some Liassic deposits with alternating layers of shale and limestone; but no single deposit in this country yields a material of precisely correct composition. The Chalk Marl of East Anglia is the nearest approach, but even here carefully controlled mixing of the more calcareous upper strata with the more argillaceous lower layers is essential.

Before firing, the ingredients must be finely ground and intimately mixed in the right proportions; and as in brick-making, this may be by wet, semi-wet, or dry process, the drier processes having some advantage of fuel economy. The wet process is used wherever water is abundant and the raw materials are such as disintegrate readily in water; it became standard practice at cement works along the Thames and Medway, where Medway mud is mixed with local Chalk. The semi-wet process, now little used, employs a minimum of water for grinding and mixing. In the dry process, both limestone and clay are dried before being milled to a fine flour; dust from the kilns must be collected before the combustion products are allowed to escape into the air.

Some 'Roman Cement' is still produced locally in Dorset and Somerset by calcining septarian or cement-stone nodules containing a suitable proportion of clay. It sets very rapidly, and only a small amount (not more than 50%) of sand can be used in a mortar made with it.

Plaster of Paris is prepared from gypsum (alabaster) by 'boiling off' three-quarters of the water of crystallization at about 125° C.:

$$2CaSO_4,2H_2O \rightleftharpoons 2CaSO_4,H_2O+3H_2O.$$

The reaction is reversible, and the material sets hard and rapidly as water is again taken up by the sulphate molecule. Most British plaster comes from gypsum deposits associated with the Triassic marls of the Trent Valley and Cumberland or from the Purbeck beds of the Weald.

Roofing-slate

When mudstone or shale is subjected to intense lateral pressure at moderate temperatures, adjustments occur in the orientation of the constituent particles and secondary micaceous minerals crystallize with their flakes all perpendicular to the direction of pressure. The rock thus acquires a definite grain and can be split into thin sheets parallel to the new structural direction; it has, in fact, developed slaty cleavage.

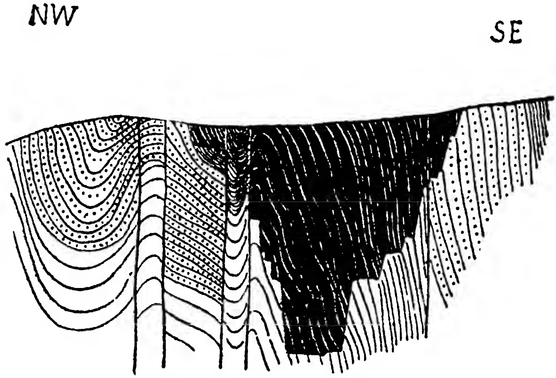

FIG. 32. – Section through a Slate Quarry (Fronheulog) in the Nantlle district of North Wales.

Showing the folding and faulting of grits (stippled) and slates associated with the development of cleavage. The cleavage-lines are omitted from the figure, but depart only a few degrees from the vertical. Scale approximately 1 inch to 200 feet.

Cleavage sufficiently good for roofing-slates can be imparted only to a fine-grained rock containing minute flaky particles which can be re-orientated in a matrix from which secondary micas can be reconstituted at relatively low temperatures. It is thus confined to some argillaceous rocks and a limited variety of volcanic ashes. A silt, composed wholly of exceedingly fine but equidimensional particles of quartz, cannot 'take' cleavage any more than a sandstone or a limestone. It must also be remarked that cleavage surfaces are quite independent of the original bedding-planes of the sediment, which, though completely sealed, are often revealed by stripes of colour or thin layers of interbedded silt or sand. The relation of cleavage planes to bedding will depend on what folding was imparted to the rock in earlier stages of the compression and how those folds are traversed by the cleavage. The latter is a regional feature, and is often remarkably constant over wide areas; by chance in certain places bedding and cleavage may coincide, but commonly the cleavage traverses the original bedding at high angles.

Most productive of all British slate-producing areas – the most famous in the world – is the belt of country between Snowdon and the North Wales coast, including Bethesda, Llanberis, and Nantlle (Fig. 32). With the onset of the Caledonian mountain-building movements, Cambrian rocks here were gripped as in a vice between the rigid block of the crystalline Pre-Cambrian rocks of the Padarn-Tryfan ridge and the massive volcanic pile of Snowdonia. Folding, strike-faulting, and cleavage are all closely interrelated modes in the process of adjustment under the heavy superincumbent load, as the massif of Snowdonia was driven towards the Padarn block.

Perfect cleavage was also impressed upon certain Lower Ordovician sediments south of Snowdon, where about Blaenau Ffestiniog they are extensively mined. A less perfect cleavage is developed in the overlying Upper Ordovician and Silurian rocks throughout North Wales. Slates are also quarried on a large scale from the Devonian at Delabole in Cornwall, and the cleaved Pre-Cambrian volcanic ashes of Charnwood Forest and of the M. Ordovician Borrowdale series in the Lake District have been wrought for use where strength and beauty of colour rather than thinness are required. The attractive Stonesfield and Collyweston 'slates' of Oxford, Gloucester, and Northampton are thinly-bedded sandy limestones, and not true slates at all, and the 'grey slates' of Yorkshire and Lancashire are banded flagstones of Coal Measure age.

Road Metal

Many of the properties required of a good road metal – with greater emphasis on compactness and resistance to abrasion and to weathering – are in common with what is asked for in a building-stone. But rock which is closely and irregularly jointed may also be satisfactory, since in any case the stone must be crushed and screened to size; and on this account many fine-grained igneous and limestone rocks that are unsuitable for building purposes are acceptable as road metal. A quarter of a century ago it was thought that a certain amount of incipient weathering was desirable so that the aggregate might 'bind' with water, and fine-grained basic igneous rocks where they occurred in sufficiently large masses were greatly esteemed. With the increase of motor traffic, however, a new factor in macadamized road construction was introduced. Ability to bind with water ceased to be of importance, but behaviour with tar and oil-residue binders became of prime importance. Diorites and gabbros, where available in large quantity, and particularly dolerites, are among the most reliable rock types under heavy traffic. Acid igneous rocks do not hold tar so well, but their screened chippings make the best non-slip surface dressing. Among sedimentary rocks, some Lower Carboniferous limestones make sufficiently strong aggregates, and compact Cambrian and Ordovician quartzites are in demand for top dressings. Most sedimentary rocks are too crumbly, or break into flaky fragments along their planes of structural weakness such as bedding and lamination.

CHAPTER X

Mineral Supplies for Heavy Industries

Coal: nature, rank and quality of coal – Mode of formation – Exposed and concealed coalfields – Estimation of workable reserves. Iron: sedimentary and replacement ores – Magnetite.

COAL

COAL, more important economically than any other kind of rock, is the principal member of the group of carbonaceous deposits formed from partially decomposed plant matter. In Britain it is associated with the Carboniferous System, to which it gave the name, but in different parts of the world it may be of any age from Upper Devonian to late Tertiary.

Ordinary 'household' or bituminous coal is a *humic coal* – that is to say, it is formed of plant-matter which was mostly wood or bark. It has the kind of banded structure characteristic of sedimentary deposits. The layers along which it generally breaks into slabs are composed of an extremely friable, charcoal-like substance ('fusain') which soils the fingers, and in which the unfilled cell-structure of woody fragments is easily seen. Other distinctive layers, generally lenticular in form, are black, shining, bright coal ('vitrain' or 'anthraxylon'), also composed of woody fragments, but in which the cell-spaces are filled with carbonaceous material. By some authorities, two other kinds of layers are recognized, distinguished respectively the one by the possession of a matt, the other by a satin-like surface. The first of these – dull, hard coal ('durain') – is a mixed aggregate which includes, along with wood and bark, macerated cuticle, spore-cases and little bits of resin. The second is also composite, with fairly large pieces of wood and bark set in a matrix of smaller bits, and variously transformed to vitrain and fusain, and intermingled on a macro- and microscopic scale. For most purposes it is sufficient to distinguish the three components bright coal, dull or hard coal, and mineral charcoal (vitrain, plant detritus, and fusain).

Coals of the other group, the *sapropelic coals*, are less abundant. They comprise the non-woody cannel coal and 'boghead', composed of macerated plant-detritus, including resistant pollen grains and spores, and, in 'torbanite', a large proportion of algæ. Not only are these unbanded, but the characteristic jointing or 'cleat' breaks of the humic coals being far apart and less perfect, the smaller lumps show mostly a conchoidal fracture.

Humic and sapropelic coals differ in origin, but a classification based on this is less convenient than chemical analysis, which records the degree of alteration of the original organic substances. With a steady increase in the percentage of carbon, there is a less regular decrease in the other constituents, oxygen, hydrogen and nitrogen.* This variation in composition is shown in the following analyses of average fuels; for classification, percentages must be on a dry, ash-free basis.

	Carbon	Hydrogen	Oxygen	Nitrogen
Wood	50	6·25	42·75	1
Peat	57	6·5	34·5	2
Lignite	70	5·5	23	1·5
Bituminous coal	86	5·5	6·8	1·7
Anthracite	94	3·5	1·5	1

Ordinary bituminous coals thus occupy an intermediate range between the relatively unaltered peats and lignites, and the highly mineralized anthracite.

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* Sulphur is usually present as well, but less comes from an organic source than by reduction of sulphates in the water under which coal formed.

The degree of alteration determines what is known as the 'rank' of a coal, and might be expressed in the variation of the oxygen content. The equivalent hydrogen variation is slight in lignites and bituminous coals, between about 4% and 6%, which is within the range observable in the different layers of some single specimens. The oxygen variations, on the contrary, from 50% in wood down to zero, cannot be due to differences in the plant constituents, which in all modern plants are wonderfully constant, but must be a result of some post-depositional geological changes.

Almost all Tertiary coals are of low rank, but the existence of American Tertiary anthracites proves that age alone is not the controlling factor. Whilst the full story has yet to be unravelled, two facts are outstanding. Firstly, rank in a single seam may vary progressively across a coalfield, and wherever one seam varies, all others above and below vary sympathetically – i.e. variation in rank is areal. Secondly, in undisturbed vertical section, the deeper seams are of higher rank than those nearer the surface (Hilt's law). Both these observations point to the operation of geological factors, and, among these, temperature and pressure are properly suspected of having played a leading part.

The uses to which a coal is put depend on its behaviour when heated in air or in the absence of air – that is, on its calorific value and the products from its distillation.

The calorific value, expressed as British Thermal Units per pound, or metrically as calories per gramme, varies with the rank, and can be predicted if we know the carbon and hydrogen content of the coal. Non-combustible ash decreases efficiency in more than its direct proportion, and if what fails to burn melts to a clinker in the fire, the value of the coal as fuel is much impaired. Four very different sources provide the mineral matter of coal ash. First, there is the original mineral matter of the vegetation, which was leached as the plants lay rotting in the swamp, and in quantity is of small importance. Then there is the mud or silt which flood-waters brought in to filter among and finally smother the growing plants. This forms the bulk of the incombustible material in most dirty coals; it has generally been leached to fireclay and by itself when burnt forms fluffy dust which does not clinker. Thirdly, swamp waters renewed by floods provided ferruginous solutions bearing sulphates and carbonates which active bacteria have reduced to brassy pyrite (iron sulphide) and ironstone (iron carbonate). Much of this was precipitated as a filling in the empty plant-cells. Lastly, coal-seams as they were deeply buried, consolidated and developed the transverse fractures known as 'cleat'. Such cracks as gaped were filled with mineral vein deposits (mostly mixed carbonates) which alone in the fire calcine to lime, magnesia and iron oxide, but in the presence of muddy sediments combine with silica to form slag and so build up the troublesome clinker.

Coal distillation is a process of decomposition. The volatile products take with them all the oxygen, most of the hydrogen and about half the nitrogen and sulphur, along with some of the carbon, in the form of gas, coal-tar and ammonia, leaving as residue 'fixed carbon' in the familiar domestic or gasworks coke. What is collected varies with the rate of heating, the temperature in the retort, and with the type of coal. Some 10–20 gallons of tar is produced from each ton of coal used, and under chemical treatment and re-distillation this yields benzene, toluene and all the bewildering suite of coal-tar derivatives that are the intermediate raw materials of the dye, drug, and plastics industries. Large-scale distillation of coal in coke-ovens, however, is primarily for the making of the coke required in the blast furnaces, and the gas and coal-tar

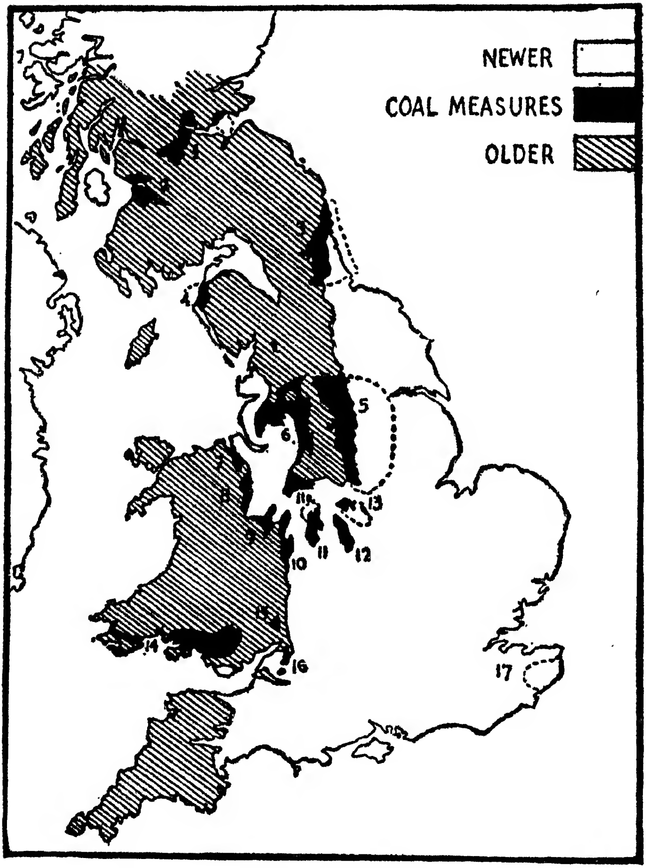


FIG. 33. – Sketch-map of the Coalfields of Great Britain.

Approximate extent of the more important concealed fields shown by broken lines. 1. Central Scotland – 2. Ayrshire – 3. Durham and Northumberland – 4. Whitehaven – 5. Yorkshire, Derby and Notts – 6. Lancashire – 7. Flint – 8. Denbigh – 9. Shrewsbury – 10. Coalbrookdale – 11. South Staffs – 11a. North Staffs – 12. Warwick – 13. Leicester – 14. South Wales – 15. Forest of Dean – 16. Bristol and Radstock – 17. Kent.

are by-products which in former times were largely wasted. Coke is essential for iron-smelting; it is also used for making water-gas, a mixture of carbon monoxide and hydrogen obtained by forcing steam and air alternately through red-hot coke. The best coking coals, which give hard coke by rapid distillation, are those bituminous coals carrying about 25% or 30% volatiles; bituminous coals with more than 30% volatiles are more suitable for town gas-making, or in steelworks for the making of producer gas.

Origin of Coal

As might be expected, the conditions of formation of this extraordinary and valuable type of deposit have been the subject of much attention and not a little controversy. To-day it is generally accepted that most British, European and American coal-seams are not accumulations of drifted vegetation, but plant matter which accumulated and was 'coalified' in the place where it grew. The wide extent of the seams, each with its fire-clay 'seat-earth', their uniformity, their astonishing freedom from admixed detrital sediment, and the rarity of aquatic animal remains, are evidence against the drift theory. The seat-earths (in reality fossil soils) are conspicuously deficient in alkalies, calcium and iron, which we may conclude were extracted by the coal-plant roots whose traces are still recognizable where they pierced the mud.

The Coal Measures, however, consist of much besides the coal-seams and their underlying seat-earths. Shales, silts and sandstones build up the bulk of the succession. Most Coal Measure shales contain drifted bits of land plants, generally including twigs of lycopods and leaves of ferns, some of which are beautifully preserved. In many bands, remains of fresh-water mussels (*Carbonicola*, etc.) are frequent, and at half a dozen separated horizons marine molluscs, including goniatites, have been collected. The sediments are therefore predominantly fresh-water or deltaic deposits, interbedded with a few well-recognized bands of marine sediment formed when the sea spread across the deltas and for a short time flooded the coalfield region as a whole.

Coal-seams are thus the product of low-lying forest growths which were continuous over vast areas. There are no such extensive forested swamp areas at the present time, but we may picture something akin to the Great Dismal Swamp of Virginia covering an area as wide as the flood-plain of the Amazon or the delta of the Ganges. Vitrain was formed from bark and woody tissue, as fallen trunks lay water-logged in stagnant peaty water; fusain may be the twigs and branches partly rotted in the air; and the dull layers in the coal the macerated plant debris generally kept wet, but sometimes dried, and so decomposed that only cores and the most resistant spores, cuticles and resin-grains survived. It is thought that not less than 15 feet of such woody 'peat' must have accumulated to produce each foot of coal – 50 or 60 feet of forest debris for a 4-foot seam. Eventually, the whole of this plant deposit was submerged, and thereafter overwhelmed and buried beneath great thicknesses of deltaic sandstones and shales, upon which (when the reception area had been filled and stability was restored) renewed forest growths appeared. Across the deltaic swamps, distributory streams cut their irregular channels, and where these became filled with sandy sediments the lateral continuity of the seam was broken and the 'wash-outs' of the miner were produced.

The cannels and other sapropelic coals are very different. They are lake or pond deposits, limited in extent and lenticular in form; they include notable proportions of detrital matter; they have no seat-earths; and in them remains of fishes and other aquatic animals are not infrequent. They are, in fact, drift-coals; and the sheets of water in which they formed were quite small clearings within the great expanse of swampy forest area.

Coalfields and Coal Reserves

Coal occurs to-day and is exploited in separated areas known as coalfields – tracts occupied by Carboniferous rocks – and they may be concealed or exposed. In England and Wales an exposed coalfield is an outcrop of Coal Measures (of Upper Carboniferous age), and a concealed coalfield is one wherein the Coal Measures are buried beneath an unconformable cover or overburden of Permian or Mesozoic rocks. In England and Wales all our coalfields are basins or broadly synclinal structures, the Coal Measures resting more or less conformably upon the Millstone Grit or unconformably on Lower Carboniferous or older rocks. Some of them, like the South Wales Coalfield, are wholly exposed; others, as the Yorkshire Coalfield (Fig. 34), where the eastern portion of the basin disappears under a progressively thickening wedge of newer strata, are partly exposed and partly concealed; some, again, like the Kent or Dover Coalfield, are entirely concealed.

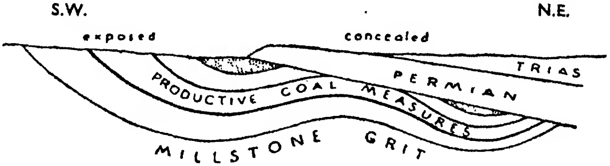


FIG. 34. – Diagrammatic section across the Yorkshire Coal Basin (about the latitude of Barnsley).

Two only of more than a score of workable seams are represented, to emphasize the structure and eastward thinning of the productive measures. Unproductive Upper Coal Measures are shown stippled. The diagram suggests truncation of Coal Measures by the Permian unconformity in the neighbourhood of the River Trent. Further east in Lincolnshire under increasing thickness of unconformable cover, they may come in again at depths too great for predictable exploitation.

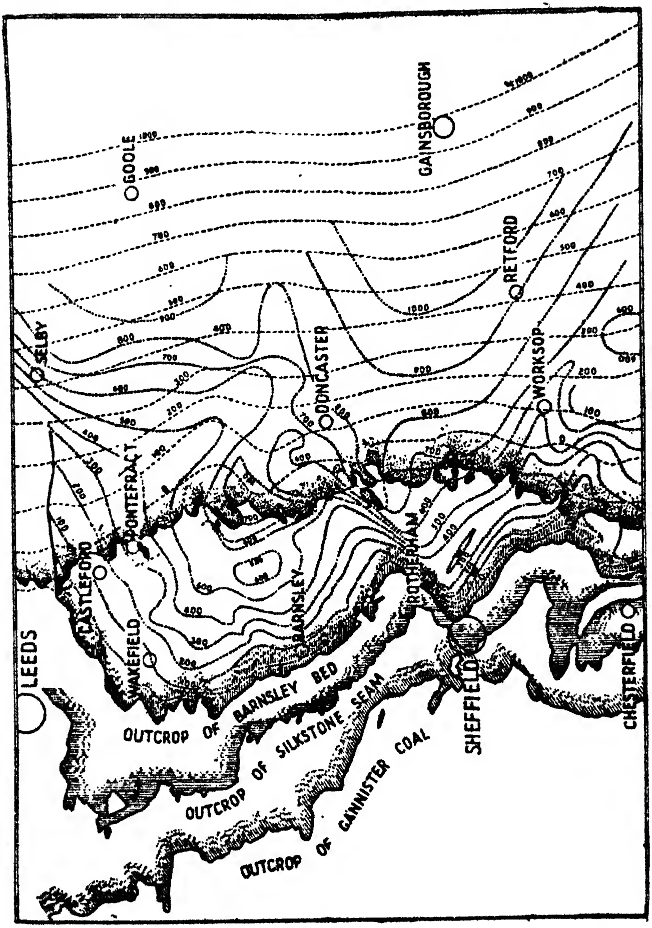


FIG. 35.—Map of the central portion of the Yorkshire-Nottinghamshire Coalfield showing surface outcrops of the major coal-seams, with sub-surface contours of the Barnsley Bed and of the overlying Magnesian Limestone (i.e., the surface of the Carboniferous-Permian unconformity). Depths are given in yards.

In many parts of the world, coal-bearing strata have been involved in mountain-building movements and are highly contorted and, it may be, overthrust; and even in the least disturbed British fields there are few square miles without a major fold or a fault-displacement of 100 feet or more. Thus it is more than ever important to be able to identify seams in order to obtain a three-dimensional picture or true-scale model of the structure of each field, and upon that to plan development. Identification of individual seams by plant remains preserved in roof shales has proved difficult and unreliable. Possibly investigation of microscopic spores now being studied may be more helpful. More reliable as datum lines are the occasional shale-bands with marine fossils and, under the eye of the expert palæontologist, the fresh-water mussels of some coal-roof shales and shales interbedded with bands of ironstone among the Measures are trustworthy and useful. Sandstones are generally recognized by their place in the succession at neighbouring pits, but they are never persistent. Coal-seams are identified by their banding and constitution, especially by the pattern of the succession of their dull and bright layers. Quite thin coal-seams, resting on fire-clay 'seat-earths', are generally persistent over many miles. Thick coal-seams are most safely correlated by their position in relation one to another and to interstratified shell-bearing horizons. The barren character of most of the deltaic lenses of sediment and their rapid lateral variations, both in texture and thickness, make positive identification difficult even for the specialist. In the Upper Coal Measures – red rocks which were deposited as conditions were becoming more and more arid in the North and the Midlands – even the molluscs fail, and accurate correlation over wide areas is at present impossible.

Two attempts have been made (Coal Commissions of 1871 and 1905) to estimate the workable reserves of coal in

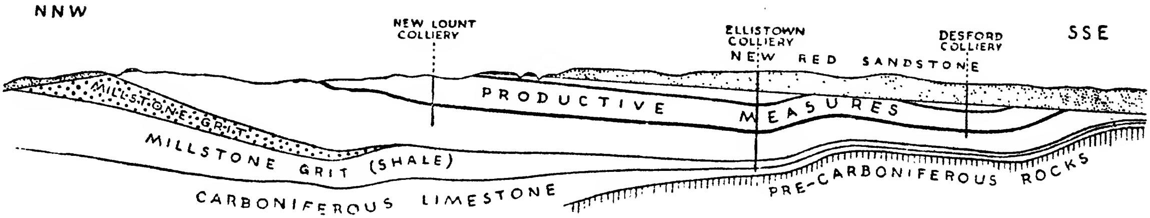


FIG. 36. – Generalized Section across the Leicester and South Derby Coalfield.

Showing the thinning of Carboniferous rocks against the Pre-Carboniferous land-mass to the south. Simplified and adapted from Geological Survey, Wartime Pamphlet No. 22 (Leicester and South Derbyshire Coalfield).

Britain. The area and thickness of each seam in the exposed coalfields can be measured, and it is relatively simple to calculate the volume of coal contained in seams accounted workable. In the concealed coalfields there is greater uncertainty, and estimation of workable reserves is less reliable. Naturally, the more a field becomes explored the greater should be the accuracy, but concerning the concealed area of east Yorkshire, Nottingham and Lincolnshire, for which the 1905 Commission so greatly exceeded the conservative estimates of their predecessors, one could wish that their optimism could still be justified. Some of the factors to be taken into consideration will be appreciated from the accompanying Figs. 34, 35.

In this area the form of the top surface of the Coal Measures, indicated by the contours of the base of the Permian (Fig. 35), is strangely regular. From outcrop along a line through Pontefract, a mile or two west of Doncaster and Mansfield, and on to Nottingham, it slopes down eastward to pass a thousand yards below sea-level near the mouth of the Trent, and thence south-eastward by Lincoln to the Wash. The cover rocks are the heavily watered Magnesian Limestone and Bunter Sandstone (in the east overlain by Keuper Marls), and from under these thirty modern pits are getting at least 20 million tons of the famous Barnsley-Top Hard coal per year. In demonstrating that productive Coal Measures with certain valuable coal-seams carry on a dozen miles and more beyond the exposed coalfield, these great pits have made certain the existence of perhaps a further 1,000 million tons of coal. But they have also demonstrated a progressive eastward thinning of the measures, with reduction of rank and failure of intermediate seams. Other associated features suggest that the margin of the depositional basin of the Middle Coal Measures is to be expected not far beyond the Trent. The evidence of extending colliery workings has also made it clear that folds and faults similar in scale and frequency to those of the exposed field are to be expected in the concealed area. The presence of 'snags' of old rock sticking up in the midst of the marginal area of the coal-swamps had been expected from experience of the relations of Carboniferous to underlying rocks across the Central Midlands, and has lately been demonstrated by borings in south-east Nottingham and Lincolnshire.

Considered as one unit this East Pennine or North Midland coalfield lies within an oval sixty-five miles long between Leeds and Nottingham, and more than forty miles broad from Sheffield to the Humber. It is the largest, perhaps the richest, and certainly now the most prosperous of British coalfields. Within it, more than 200,000 mine workers are employed in supplying some 60–70 million tons per year, one-third of the country's total coal production. Quite half of that large output is from the Barnsley-Top Hard seam, which in course of little more than a century has been followed down dip to a depth of half a mile, twelve to twenty miles from outcrop. The seam has been almost exhausted to a depth of a quarter of a mile, and around existing pits more than half the best is gone. Of the other coal, two-fifths is from the Parkgate-Deep Hard coal, 200 yards deeper in the series, the remainder being obtained from some half-dozen locally important but less persistent seams. The Barnsley Coal and seams above it are of free-burning type. The tough 'hards' are the best in the country for steam-raising and for steel-making, while the associated 'brights' are house coals grading into gas coal and coking coal in the central parts of the Frickley and Maltby sub-basins. Parkgate and other coals below the Barnsley horizon, more especially the Silkstone and Beeston coals in Yorkshire, and the Deep Soft, Tupton and Black Shale in Derbyshire, are of higher rank. They are the country's main present supply and reserve of gas coal and of the kinds of coal required at coke-ovens which feed blast-furnaces. Where modern coke-ovens alongside collieries are near to towns, their gas is conveniently 'gridded' and distributed for domestic and industrial service; where the iron and steel industry is located near the ironfield, the coke is fed to blast-furnaces and the gas applied for the conversion of iron into steel. In either case, tar and other valuable by-products are collected.

Although the Tyne and other valleys which open to the north-east coast have been sending Sea Coal to London since the fourteenth century, the Northern Coalfield continues to mine some 40 million tons of coal per year from a score of different seams. The area is mostly exposed coalfield, and none of the pits is very deep. East of Durham, there is cover of Magnesian Limestone, which is heavily watered near the coast, and under it the seams are rising to outcrop a few miles out to sea. Northumberland coals are free-burning house and steam coals. They grade into Durham gas coals and thence to the fat coals from which in the south and western districts are made the high-class metallurgical coke for which the county is renowned. Towards Berwick and north of Hexham are a number of coals among the limestones near the top of the Lower Carboniferous.

Since the Navy turned from smokeless coal to oil, the relative importance of the South Wales Coalfield has declined and lately its output (less than 26 million tons in 1949) has been down to half what it was during the 1914–8 war. The coalfield is wholly exposed and reserves enough to last for several centuries have been measured up. The coalfield is sixty miles long and its pits are nowhere more than thirty miles from the shipping ports of Newport, Cardiff and Swansea on the Bristol Channel. The produce of the western district, about one-sixth of the whole, is the world-famous low-ash anthracite. The central area has the high-grade 'admiralty' smokeless and many grades of steam coal. Low volatile coking coals and house coals are from a crescent area east of the Taff round the ends of the East Glamorgan and Monmouthshire valleys. Regional advance of rank north-westward is associated with the incoming of bands of sandstone and a great increase in the total thickness of measures among and above the coals.

The half-dozen separated Scottish coalfields taken together now produce almost as much fuel as does South Wales. Coal from the shallow coalfields of the west (Ayrshire) and central (Lanarkshire) area is mainly from Upper Carboniferous coals of similar age to those of England; their coals are far seen into. Towards the east, especially in Fife and the Lothians (connected under the waters of the Firth of Forth) the Edge Coal series of Lower Carboniferous age holds larger reserves of coal, and while the central coalfield is still the most productive area, the large deep pits of Fife and the Lothians are increasing in importance. The bulk of Scottish coal is free-burning, of low and medium rank, good for steam-raising, steel-smelting, manufacturing and domestic purposes. Only where, as in Stirlingshire, large masses of igneous rock have been intruded and the adjoining ground was heated up, are the coals suitable for gas and coke making. Close to the igneous rock, some of the coal is 'burnt' or over a limited space converted into anthracite. Volcanic necks and outpourings of lava interrupted the Scottish Lower Carboniferous coal-swamps in many areas, and since the coal-seams formed the whole region of the Central Valley has been invaded by successive families of whinstone sills and dykes.

The quantity of coal mined in the remaining dozen of minor English coalfields exceeds the production of Scotland, but is less than that of Durham and Northumberland. The output from Lancashire with Cheshire is about 12 million tons; from North Staffordshire six million; and

North Wales two million. These, and the seried row of Midland coalfields – Shrewsbury and Coalbrookdale, Cannock and the Black Country, Warwickshire, South Derbyshire and Leicestershire – are together about as productive as Lancashire; and they are parts of the once continuous depositional sheet which overspread the southern Pennines.

The area sixty miles round Buxton developed as a geosyncline – a great collecting-dish, which at Manchester sank two miles deep as it was filled with Coal Measures. Despite subsequent geological accidents, it still contains half the country's coal reserves, supplies 100 million tons of coal a year, and supports some 20 million of our population. It was never a simple basin, but had for its foundations a wheel-like complex of broken structures which retarded sinking along, and allowed more accumulation between, the spokes, with a noteworthy increase of accumulation towards the hub. Between the stages of progressive downward movement, often four or five times greater near the middle than towards the rim, coal forest spread across the marshes of the delta which it was filling, until each in turn was overwhelmed. Coals in the places of deepest settlement attained the rank of coking coal: the lower Measures of South Lancashire, the central area of North Staffordshire, and the edges of Wales, as in Yorkshire and North Derbyshire; but elsewhere (notably in Shropshire and the Black Country, Warwickshire, South Derbyshire and Leicester) on the margins of the unsettled area, they remain free-burning, grading to sub-bituminous almost lignitic type. Uplift supervened, and movements before and subsequent to the Permian have intensified the wheel structure, bending and faulting the sheets of coal and Coal Measures especially along the flanks of basins where, in the Midlands, Boundary faults developed. Ensuing denudation of the crests stripped all Coal Measures from the Peak District of Derbyshire and from the divergent ribs or spokes which separate the several coalfields of the Midlands. There are similar folds and faults on the east side of the Pennines, but fortunately the destructive denudation of that coalfield had not proceeded so far before it was covered by the Magnesian Limestone.

IRON

Of hardly less importance than coal for heavy industry are supplies of iron-ore. Next to aluminium, iron is the most widely distributed of all metallic elements; few rocks are entirely devoid of it, and those that are, like china-clay, glass-sands and refractories, may be of economic importance in consequence. But in workable ore, the percentage of iron must be high, and what is associated with the iron must be reactive and readily fluxed away in the course of smelting. Most iron-ores carry the metal in the form of oxides, carbonate, or silicate; rich ores carry 50–65% of iron, but leaner ores with as little as 20% may be of economic interest provided that they occur in accessible, large masses. The metallurgist names the ores acid or basic according to the treatment required to convert their iron into steel. Ores with less than one-twentieth of 1% of phosphorus and sulphur have special value for making acid steel, and are classed as 'hæmatite'. Ores with more of these deleterious impurities provide the metal used in iron foundries and forges. If the proportion is so much as half of 1%, additional treatment of the molten metal with lime or soda-ash is necessary, and this is undertaken on a basic hearth; basic slag, rich in phosphates, is a valuable by-product of this refining process.

To the geologist, the usual classification is into sedimentary, crystalline and replacement ores. A sedimentary ore is a deposit of hydrated oxide, carbonate or silicate, formed by chemical precipitation, making up part (or sometimes nearly the whole) of a bed of sediment; in a replacement ore, the iron has been brought in subsequently by solutions, which by chemical interaction have replaced the original rock. There are also high-grade magnetite ores formed at high temperature by crystallization of excess of iron in igneous and metamorphic rocks.

Sedimentary Ores

Sedimentary iron-ores are always to some extent phosphoric and therefore 'basic.' The iron in them was extracted from land waste as ferrous iron in solution. Exceptionally, under fresh-water conditions, it was precipitated as ferric hydrate, ochre or bog-iron by algal growths. More usually, as clay ironstone, it gathered as nodules under anaerobic conditions beneath the surface of the sludge of Coal Measure deltas or under like conditions in Wealden or other estuarine swamps. Most important, however, of all the sedimentary iron-ore deposits are the mixed silicates and carbonates of the chamosite oolites with sideritic matrix which formed where sand, silt and mud were alternately deposited and winnowed over shoals and shell-banks at the bottom of the sea. The conditions of precipitation are not fully understood, but the oolitic grains were built up of successive coatings of ferrous silicate on shell-fragments or sand-grains as currents or breakers rolled them about and washed away the finer particles of mud. From time to time there was oxygen enough to rust their skins, but generally reducing conditions prevailed and ferrous carbonate (siderate) was precipitated in the matrix.

Most sedimentary bedded ores where found at surface carry their iron in the form of limonite, Fe_2O_3,xH_2O, and in rusting have lost their original structure. Wherever the ore is embedded in an impervious shale or is mined near or below the water-table, siderite and chamosite retain the constitution and structure they had when originally deposited. Commonly such ores are wrought by uncovering the outcrop by mechanical diggers and drag-line excavators, and where the dip is slight, stripping of overburden is undertaken on a very extensive scale. At natural outcrop, the oxidation of ferrous salts to limonite is generally complete, and with leaching of shell-fragments and soluble impurities the ore may be considerably enriched. Surface waters also carry oxygen underground, and travelling along joints and percolating between grains convert the grey and blue-green ferrous minerals to porous crusts of brown limonite, working inwards until compact blocks are turned to box-stones. Brown limonite is the mineral most desired; blue-green chamosite may melt before it smelts, and when the proportion of unweathered kernels becomes too great they have to be loaded separately and roasted, like the produce of mines and deeper workings, before being sent to the furnace. Where the ore is regular and fairly rich (over 30% of iron), opencast workings may proceed until the depth of overburden is ten times the thickness of the ore.

The following examples will serve to illustrate this varied class of ore.

The *Northampton Ironstone* is by far the most extensive and accessible British iron-ore. On it, as our main national reserve, our blast-furnaces will have to depend in coming years for home supplies of ore. It consists of a compact group of beds, all ironstone, averaging 8 feet in thickness, but at different places varying from 6 to 15 feet, underlying a 50-mile strip of dissected plateau five to ten miles wide which extends east of the Middle Jurassic (Oolite) escarpment from Grantham in Lincolnshire across Rutland to Northampton. This is estimated to hold 1,000 million tons of ore carrying more than 30% of iron. The scratching of its ramifying outcrop began almost a century ago and the rate of its exploitation had grown continuously to over six million tons a year in the period between the wars. Some 200 million tons have already been removed, and recent developments round Corby have greatly increased the demand.

The ore is a concentrate of chamosite ooliths, passing upwards and downwards into marine Northampton Sands; it is therefore a siliceous ore. A few feet below the ironstone there is everywhere the sticky Upper Lias Clay: above it, the Middle Jurassic formations are a pile of non-sequential lenses. In most favourable circumstances, the immediate overburden is a soft sandstone of the Lower Estuarine Series, up to 30 feet thick; but elsewhere massive Lincolnshire Limestone – sometimes 100 feet of it – has to be quarried or blown up and excavated before the iron is reached. More troublesome because so undependable is the overriding glacial Boulder Clay which fills old hollows and conceals the structure of the upland area.

The *Frodingham Ironstone* (North Lincolnshire Ironstone) was a narrower ore bank in the Lower Lias which, because of its self-fluxing properties and its accessibility, has been and is so intensively worked that two-thirds of its 200 million tons originally available above sea-level is already gone. The ore bed consists of a pack of lenses, 30 feet thick in the central area, falling to 20 feet in about three miles on either side; it was built up of rusty chamosite ooliths, now limonite, set in precipitated siderite and chamosite mud, but with an average of one-third of its substance entangled shells and shell-fragments which reduce the iron percentage to about 20 and make it a calcareous or limy ore.

Since 1860, the seven-mile outcrop which backs the low escarpment crossed by the Doncaster-Grimsby railway east of the Trent has been stripped of its leached and enriched ore over a width of from half to nearly two miles, and present opencast workings are yearly exploiting three to four million tons of unweathered rock from beneath blown sand and shaly Lias Clay to a depth of over 70 feet. Already the floor of most of the workings is below stream-level, and the banks of disturbed clay are difficult to hold. But the ore bed has been proved to extend in good condition as it dips eastward for several miles, and despite difficulties inherent in the weakness of the overlying rocks, a shaft has been sunk and underground workings on a large scale are proceeding.

The *Cleveland Ironstones* form the top of the Middle Lias under most of a 12-by-4-mile belt of moorland along the north-west face of the Cleveland Hills some ten miles east of Middlesbrough, and from the topmost bed (Cleveland Main Seam) some 350 million tons of ore have been taken since 1854. Outcrops along the steep scarp edges of the moor are narrow, and most of the ore has been mined through adits which delivered some five or six million tons per year for the forty years prior to 1914. Between the wars, quarried ore from Northamptonshire has been supplied to Middlesbrough more cheaply than that from the local mines; and with another 100 million tons remaining within the mining area (and more to the south) active developments have ceased and the average yearly output has fallen to less than two million tons.

Cleveland ironstones are typical fine-grained silicate-carbonate mudstones built up of small chamosite ooliths with a few sand-grains and recognizable shell-fragments, and quite a high proportion of minute rhombs of siderite embedded in the mud. It was the study of these structures under the microscope which proved that Jurassic marine ironstones were not altered limestones (secondary iron-ores), but had their iron minerals formed by direct precipitation on the bottom of the Jurassic sea.

Marlstone in the Midlands, contemporaneous with the Cleveland Ironstone, is generally ferruginous, but the distribution of the iron is patchy and nowhere was there enough of it precipitated in the shell banks to make a primary ore body. There are, however, places where the rock was open-textured and so exposed on gentle dip-slopes that much of the calcite has been leached away, and it is there acceptable as a secondary ore. The spur of the escarpment north of Melton Mowbray had many million tons of ore of that kind, and the rolling plateau west of Banbury which culminates in Edge Hill is being extensively exploited. Reserves in Leicestershire are far seen into, but on the borders of Oxfordshire several hundreds of millions of tons remain. The ore is generally limy and carries about 25% of iron.

Clay Ironstone. Bands of nodules of ferrous carbonate, grown as concretions in carbonaceous mud, constitute an appreciable proportion of many fresh-water and estuarine shales, and it has been estimated that British Coal Measures contain an ultimate reserve of 34 billion tons of such ore, carrying more than 30% of iron. The interest of British Coal Measure ironstones is traditional. Individually impersistent, rarely so much as 3 inches thick, neighbours to the coal-roof in many coalpits, these bands provided the only dependable supplies of British iron a century ago and even so late as the 'sixties. At that time, six or seven million tons per year were being exploited and furnaces had been built in those localities where clayband or blackband ironstone was available at nearby outcrops or from roof-shales of hard coals or coking coals in the neighbouring mines. More than half the English and all the Scottish blast-furnaces have continued in operation on these sites.

Clay ironstone nodules, separated from their matrix and roasted, make a rich and readily smelted ore, but their metal being phosphoric could not be converted by Bessemer's original process into steel. The Jurassic ironstones provided cheaper ore for foundry iron, while the demand for puddled iron (for the manufacture of which clay ironstone is especially suited) very rapidly declined. By the eighteen-eighties the output had fallen to less than half, and during the last quarter of a century very little has been worked, though exploitation on a small scale for making special iron continues in the Potteries coalfield.

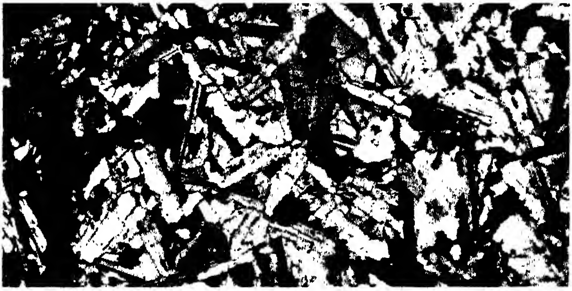
Replacement Ores

The conversion of chamosite and siderite to limonite is one process of chemical replacement, but the term replacement ore is generally reserved for ore bodies to which the wanted metal has been delivered in solution from an outside source. The hæmatite deposits of Cumberland, Lancashire and Glamorgan are characteristic of this group. Here the hæmatite occurs in lodes, flats and veins, and in large irregular masses known as sops which have taken the place of pre-existing rock of another composition and have not disturbed the neighbouring structure. Quite 90% of British hæmatite has replaced Carboniferous limestone, but brown hæmatite has done much the same to Coal Measure sandstones in the Forest of Dean, and in the Lake District there are places where volcanic rocks and granite are similarly affected. Occasionally large shells, corals, oolitic grains and other characteristic textures have been 'pseudomorphed' in hæmatite, and retain their shapes. At an early stage in this ore-formation in limestone, waters travelling along selected joints and bedding-planes widened their courses to sinks and caves, in which later solutions highly charged with iron reacted with and exchanged bases with the walls of country rock, and coated them with crystalline precipitate, until as mineral veins the cavities were more or less completely filled.

There is, however, strong difference of opinion as to whether the iron-bearing solutions were steaming hot, derived from igneous magmas, and cooling as they came up from below, or were descending surface waters charged with the iron they had dissolved from the overlying, iron-rich New Red Sandstones. That the replacement was in the main of post-Triassic date is shown by the relation of ore-bodies to post-Triassic faults, and it is perhaps significant that New Red Sandstone (Triassic) rocks are never far away.

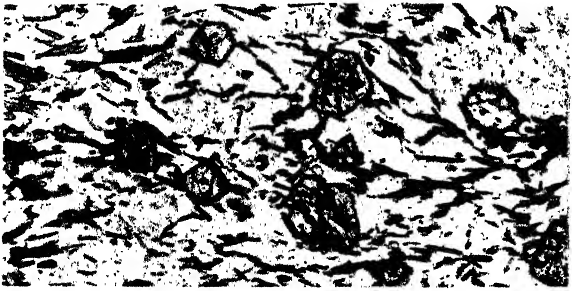
West Coast hæmatite iron made from Lake District ores mined in Cumberland between Cockermouth and Egremont, or on the Lancashire border around Millom and Furness, and smelted with Durham coke, has for a century now deserved its reputation as 'standard best' for the manufacture of highest duty steel. The rich hæmatite as mined is almost free from phosphorus and sulphur, and its 'kidneys' and 'pencil ore' carry over 60% of iron. A hundred million tons of it, sent to furnace since steel supplanted iron for armaments, has had an average iron content between 50% and 60%. The irregularly shaped ore-bodies vary in size from hundreds to several million tons. From the Hodbarrow Sop, half under the sands of the Duddon Estuary, nearly 20 million tons have gone. For many years it was worked at by more than 1,000 men, but now only the seaward margin remains to be exhausted. Egremont, Beckermet and Bigrigg, in Cumberland, and Roan Head in Lancashire, are the major centres of present activity, and Florence, near Egremont, has become the most productive mine. Cumberland hæmatite is always in demand, but despite intensive prospecting (by geophysical methods as well as boring) exploitation has outstripped discovery of workable ore masses, and the yearly output fell to half in the period between the wars; it was 800,000 tons in 1938.

Another area where high-quality but rather siliceous hæmatite is found as flats and veins replacing Carboniferous Limestone and sometimes sandstones where these have been covered by New Red Sandstone, is south-east



Dolerite

Coal Measure Sandstone



Garnetiferous mica-schist

Plate 1

Three sections, each magnified about twenty-five ti[illegible], showing the textures characteristic of an igneou[illegible] a sedimentary (clastic) and a metamorphic rock.

Plate 2

Mountain-building structures. The Matterhorn from the north-west, showing part of the gigantic overfolds of the Dent Blanche nappe. The Zmutt Glacier is in the foreground.

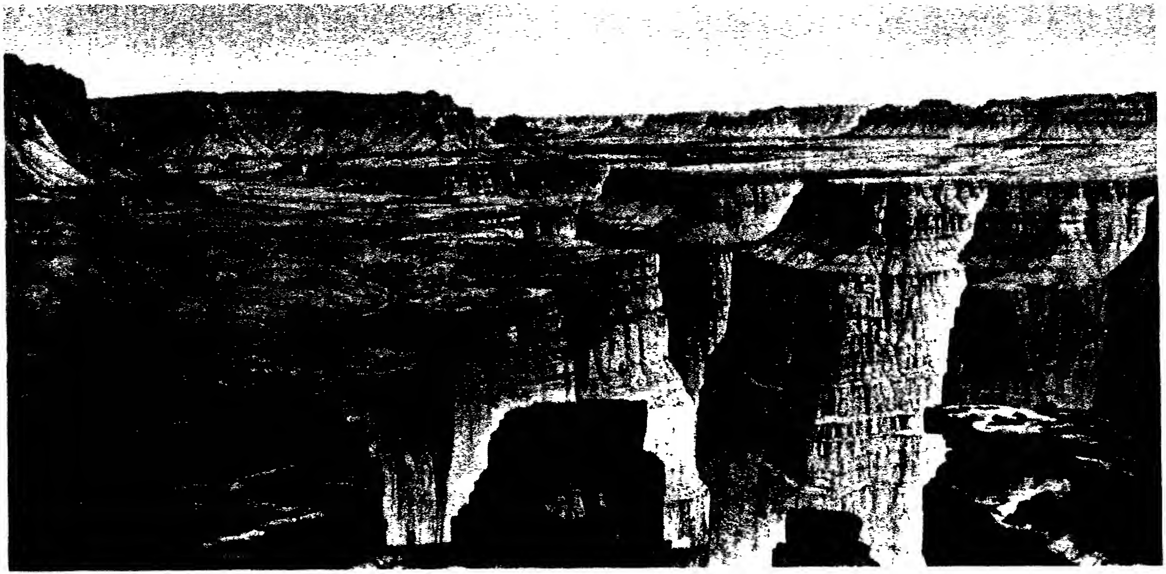


Plate 3

River erosion. The mile-deep gorge of the Grand Canyon carved by the Colorado River in geologically recent times through nearly horizontal Palæozoic sediments resting upon pre-Cambrian rocks.

Plate 4

Marine erosion. The Clett, a flat-topped sea stack on the Caithness coast, eroded along vertical joint-planes intersecting horizontally-bedded Old Red Sandstone. (Geol. Surv. photo., Crown Copyright reserved.)

Wales and Monmouth. The 'churns' of hæmatite at the edges of the Forest of Dean have been eaten into since Roman times and are wellnigh exhausted, but in recent years Llanharry mines, between Cardiff and Bridgend in the Vale of Glamorgan, have become a large undertaking, and their output (188,000 tons in 1938) has overtaken that of Lancashire.

Magnetite Ores

Most of the magnetite ores of eastern America and all those of Sweden are associated with gneissic metamorphic or igneous rocks. The high degree of alteration of the rocks throughout the areas in which large masses of magnetite occur makes the origin of these ores especially difficult to decide. Some of the gneisses are almost certainly of sedimentary origin, and the magnetite among them may well represent metamorphosed bedded iron-ores. Alternatively, they might be replacement ores, introduced later by mineralizing solutions associated with nearby igneous masses. Other gneisses are altered igneous rocks, and it seems likely that some of the very large ore-bodies associated with them originated in a process of magmatic differentiation. The northern Swedish ore-bodies of Kiruna and Gellivare are among the most concentrated and spectacular ore-masses in the world, one four-mile-long lens of over 60% ore at Kiruna alone has provided more than 300 million tons and at least as much simimilar ore is already proved below the 200 metre level. This mass lies between a footwall of streaky syenite and a hanging-wall of quartz porphyry, overlain by Pre-Cambrian sediments; by different authors it has been variously considered as a product of magmatic segregation, a metamorphosed bedded ore, and even an intrusion!

CHAPTER XI

Non-Ferrous Metals and Chemical Supplies

Types and examples of mineral deposits of economic importance. Gold, silver, platinum, uranium, copper, lead and zinc, nickel, cobalt, chromium, tin, tungsten, molybdenum, manganese, mercury, aluminium, magnesium, saline deposits, phosphates, sulphur, pyrites.

THE outermost crust of the earth consists largely of the products of chemical and mechanical weathering which have been re-deposited as sedimentary rocks, and into these recurrent additions have been made by the injection or outpouring of magmas remelted in the nether regions of the stony crust. This migration of material from depth brings up to surface not only igneous rocks, but with them traces of various metals and minerals which are the raw materials of the arts. Locally, where sufficiently concentrated, these constitute the workable ore-bodies of the miner. The igneous origin of some ore-deposits is easily recognizable by inspection; in others it is not so immediately apparent, and the processes of concentration and deposition may be entirely unrelated to igneous activity. As examples of the former, we may cite ore-bodies which have concentrated by crystallization within the molten magma and are essentially an unusual type of igneous rock. In illustration of the latter, we need only refer to the bedded iron-ores, to rock-salt, or to bauxite. But between these two extremes there is continuous transition, and on the whole it is unusual for an ore-body to occur in close contact with its parent igneous rock. Most have been precipitated from ascending magmatic emanations, gaseous or liquid, in regions of lowered temperature and pressure. Thus we may survey the range of ore-deposits as:

Magmatic: derived directly from igneous magma and retaining their connection with the parent-rock.

Pneumatolytic: produced by high-temperature gaseous emanations reacting with the marginal zone of the igneous rock or with the heated country-rock.

Hydrothermal: due to high-, intermediate-, or low-temperature ascending solutions separated from a cooling magma.

Supergene: precipitated from percolating waters of meteoric origin, or by desiccation.

Residual and detrital: deposits in which the concentration is by removal of soluble products during weathering and erosion.

MAGMATIC DEPOSITS

A magmatic ore-deposit is part and parcel of the igneous rock with which it occurs, and was formed when both cooled and solidified. To produce a workable ore-deposit, concentration of the valuable mineral by some process of differentiation is essential. Now, a process of magmatic differentiation seems the only plausible explanation not only of these mineral concentrates, but also of the range and variety of igneous rocks; but while its results are a matter of direct observation, the mechanism of the processes is, and can only be, arrived at by inference and deduction. Among possible causes of differentiation there have been suggested:

(i) Liquid immiscibility within the magma. Whilst possibly not of great importance in rock differentiation, the known immiscibility of sulphides and silicates (like oil and water) may be a potent factor in the segregation of sulphide ores.

(ii) Crystallization – either crystallization at the cooling margin with convection currents feeding the growing crystals at the chilled edge; or a sinking under gravity of the heavier, first-formed, basic crystal substances, resulting in what is called gravity segregation.

(iii) Filtration differentiation – a squeezing-out of the fluid portion through the crystalline mesh of the first-formed crystals in the magma, as an adjustment under pressure of earth stress.

(iv) Assimilation and magmatic stoping – the acquisition of foreign chemical substances by reaction of the molten magma with the country-rock.

Minerals of economic importance may be associated either with a basic residue or with an acid extract. With basic segregations occur such elements as platinum and carbon (diamond); oxides such as magnetite, chromite and corundum; and certain sulphides. The magnetites of Kiruna and elsewhere in Swedish Lapland seem of this type, and the iron-copper-nickel (sulphide) deposits of Sudbury, Ontario, have been quoted as examples. With the acid rocks come tin and tungsten. The rare-earths and many elements of very high or very low atomic weight are associated with mica and complex silicates, especially in those coarsely-crystalline pegmatite veins which represent the final, probably water, phases of an acid intrusion. 'Books' of mica which are really single crystals may be 8 feet or more across, in the pegmatites of Kodarma, India, and similar coarse pegmatites are worked for felspar in Canada and the Urals.

PNEUMATOLYSIS

If the material of a vein has a composition different from the igneous rock and has been deposited from aqueous solution rather than from a melt, it may generally be ascribed to magmatic emanations. Whether such emanations are gaseous or liquid depends on pressure and temperature. Above 365° C., water is gaseous whatever the pressure, but below that temperature it is kept liquid by sufficient pressure. Pneumatolytic deposits are due to aqueous 'solutions' in the gaseous state, but it is difficult to draw any sharp line between the products of pneumatolysis and reaction products made by solutions which arrived in the liquid state.

Along with water, emanations include 'fluxes' such as fluorine and chlorine, boron, phosphorus, etc., which act both as extractors and carriers. As the temperature falls, there may be reactions such as

$$SnF_4 + 2H_2O \rightarrow SnO_2 \text{ (cassiterite or tinstone) } + 4HF$$

and in such cases a powerful acid is liberated to react with the surrounding igneous and country-rock. A distinctive suite of gangue minerals ('spar' and other unsaleable minerals in the vein) results; fluorspar and topaz contain fluorine; rock apatites are fluoro- or chloro-phosphates; tourmaline and axinite are boro-silicates. Quartz, pyrite (iron sulphide) and calcite are ubiquitous gangue minerals.

Pneumatolysis is not important in association with basic igneous rocks (which are generally poor in volatiles and fluxes), though some apatite deposits occur with gabbro-pegmatites in Canada. Acid pneumatolysis is far more common, and many important deposits of tin, tungsten, molybdenum, and vast masses of kaolin (china-clay) are associated with certain granites. Probably three-quarters of the tin of commerce is obtained by dredging and re-washing alluvial deposits (e.g., Malaya), but the primary occurrence of lode-tin (as in Cornwall and Bolivia) is as veins which are products of acid pneumatolysis.

These lodes are mainly fillings of cracks and fissures developed in the rocks surrounding the intrusion when temperature was falling, and less commonly the valuable mineral has impregnated crushed material or replaced the country-rock.

HYDROTHERMAL DEPOSITS

These occur as impregnations, replacements or cavity-fillings. Cavity-fillings occupy spaces in a rock which have

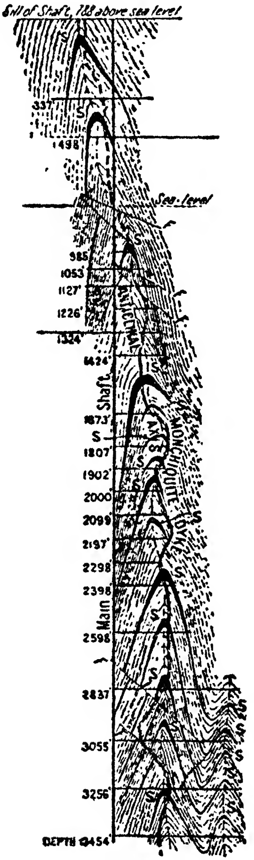


FIG. 37. – Section at the Great Extended Hustlers Shaft, Bendigo.

From a level 788 feet above the sea to a depth of 3,454 feet (2,666 feet below sea-level) showing the series of saddle-reefs (solid black, *S*), developed along the axial plane of the anticline. A dyke of monchiquite (an alkaline dolerite) follows approximately the axial plane. (From E. S. Hills, *Outlines of Structural Geology*.)

been previously occupied by air or water. At great depth where the rock begins to crush all such spaces are closed by pressure, but at intermediate depths fault-cracks, joints and bedding-planes, interstitial spaces between the constituent particles of fragmental rocks, steam cavities in lavas and the like, can remain open. The most important passages for mineralizing solutions are the faults, joints and bedding-planes. Gash-veins and saddle-reefs (Fig. 37) are special types which result from the filling of joints and gaping bedding-planes in folded rocks. Replacement is of importance where, for example, ascending solutions traversing cracks in limestone are turned aside against an impervious layer; igneous rocks and rocks composed mainly of grains or pebbles of resistant quartz are less susceptible to replacement, but impregnation in minor cracks branching from a major fissure is of common occurrence.

High-temperature deposits occur principally in the alteration zone of 'baked' rock (the metamorphic aureole) surrounding a plutonic intrusion, and there the gangue minerals may include such high-temperature minerals as alumino- or calc-silicates (for example, sillimanite, wollastonite or garnet), magnesian silicates (forsterite) and lithia mica or tourmaline; more usually a temperature below the critical temperature of water is indicated. The principal ore-minerals in this zone are sulphides of iron, copper, lead and zinc; pyrite (iron sulphide), galena (lead sulphide) and blende (zinc sulphide) being a common association. Bismuth, antimony and arsenic, with some gold and silver, may also occur. Thus at Mazapil in Mexico a pyrite-galena-blende ore is associated with a diorite intrusion, and in Korea copper, bismuth and gold (in association with lime-silicates, phlogopite-mica and tourmaline) are connected with a granite intrusion into calcareous rocks.

Intermediate-temperature deposits are less deep-seated in origin and are generally associated with hypabyssal or volcanic rocks. High-temperature minerals are absent, and the characteristic gangue minerals are chlorite, quartz, chalcedony, calcite and barytes. Copper pyrites, some lead and zinc, with traces of gold and silver, are typical, and there is a rather characteristic association of gold with copper and of silver with galena. The base metals are mostly combined as sulphides, but compounds with arsenic, tellurium and antimony are not infrequent.

The gold-quartz veins (saddle-reefs) of Bendigo, Australia, and the lead-silver field of Leadville, Colorado, are famous examples. The copper-deposits of Rio Tinto, Spain, are replacement bodies of cupriferous pyrite in porphyry, without gangue minerals.

Low-temperature deposits are found at shallow depths. Those related to fumaroles and waning volcanic activity are commonly associated with andesites. Replacement is rare, and the veins (cavity-fillings) show characteristic banded 'crustification' with successive layers deposited symmetrically on the two sides of the fissure.

Mercury and antimony ores are the most important metals of this group, and are associated with chalcedony, opal, and especially the zeolites (hydrated silicates of aluminium, sodium, calcium, etc.). These indicate a temperature not exceeding 200° C.

The famous silver-fields of Mexico and Nevada, and the Cripple Creek goldfield (Colorado), are deposits of this type. Also of low-temperature origin, but not satisfactorily linked with intrusive or extrusive igneous rock, are the galena- and blende-bearing veins in the limestones of Derbyshire and Alston Moor, and of the Middle West region of the United States. In these the gangue mineral is mostly calcite or dolomite, with an interior filling of barytes at depth and fluorspar nearer the surface.

Secondary Enrichment of Sulphide Ores

Ore-deposits, like any other rock, are subject to chemical weathering in the outermost layer of the earth's crust; and in sulphide ores particularly, secondary alterations are of great economic importance. In temperate climates, precipitation (of rainfall) is greater than evaporation, so that above the water-table there is a general downward movement of meteoric waters; thus above the water-table there is a zone of oxidation and weathering, whilst below it is a zone of reaction and cementation.

In the zone of weathering, sulphide ores oxidize to soluble sulphates, which in solution leach the other ores. Practically the only inert ore-mineral is metallic gold, which, except in the presence of manganese, remains in the zone of weathering and is concentrated as spangles and threads of free gold. The general result is the development, underneath the outcrop, of cavernous, rusty, iron-stained quartz 'mush' known as gossan, which, except in the case of gold-reefs, is of little value. But this material that has been carried away in solution may be redeposited at the water-table or in the zone of cementation. Near the water-table, sulphates from the oxidation zone come in contact with sulphides or other reducing agents, which may partly precipitate them as secondary sulphides. Thus copper sulphate reacts with pyrite to give cuprous sulphide (chalcocite) and ferrous sulphate:

$$2CuSO_4 + 2FeS_2 \rightarrow Cu_2S + 2FeSO_4 + 3S$$

or with chalcopyrite to give cupric sulphide (covellite) and ferrous sulphate:

$$CuSO_4 + CuFeS_2 \rightarrow 2CuS + FeSO_4$$

Some of the unwanted iron sulphide is thus replaced by copper-ore, and the ore-body hereabouts is made considerably richer in pay-metal than the unaltered ore at greater depths. The zone where this re-deposition occurs is known as the zone of secondary enrichment.

Secondary enrichment depends on what has come down from the zone of oxidation, and an impoverished gossan is no guarantee of good sulphide ore below. A quartz-vein containing much 'fool's gold' (iron pyrites) alters to a mass of excellent gossan without contributing anything of value to the reef below.

SUPERGENE DEPOSITS

Under this heading come the varied deposits which have been precipitated from solution in surface waters. Precipitation is effected either by evaporation (producing a general supersaturation) or by local chemical reactions (resulting in local supersaturation).

Desiccation

Valuable deposits made by the drying-up of sea-water consist mainly of chlorides and sulphates of alkalies and alkaline earths. When sea-water is concentrated by evaporation, the substances originally carried in solution are thrown down in an inverse order of solubility. A film of iron hydrate first appears, followed by carbonates of lime and magnesia; then come sulphates of the alkaline earths (principally calcium sulphate, in the form of gypsum or alabaster if cool, or anhydrite if above blood-heat); and only after that large quantities of common salt. Salt continues to crystallize almost pure until 95% of the water is evaporated, and after it come mixed chlorides and sulphates of potassium and magnesium, with smaller quantities of bromides, iodates and borates.

Partial desiccation of land-locked seas at many stages of geological history has given rise to extensive deposits of gypsum and rock-salt; but only rarely has evaporation been sufficiently complete to allow potassium and magnesium salts to crystallize. The classic example of a completed series is provided by the Stassfurt deposits of Germany. Here, above iron-stained sandstones of the Rotliegende, dolomite (Zechstein) and massive anhydrite is followed by a great thickness of rock-salt, overlain by banded potash salts capped by impervious clay. Above this the incomplete series anhydrite, rock-salt, clay, is several times repeated.

Since the soluble matter constitutes only about 1% by volume of sea-water, the formation of great thicknesses of rock-salt or even of gypsum is not easy to explain. According to the Bar Theory of Ochsenius, such deposits were laid down in seas separated from the open ocean by a submerged bar, as the Kara Boghaz Sea off the Caspian. Evaporation from the almost land-locked gulf is made good by intermittent influx of water over the barrier, and a very high salt concentration may result and be maintained for long periods of time. The salinity of the Kara Boghaz Sea is 284 parts per 1,000, compared with 11·9 in the Caspian. Even so, it is only when evaporation is 97% complete that soluble potash salts are deposited, and only if the last precipitate is promptly covered by a layer of impervious clay can they be preserved.

The proportion of nitrates in sea-water is minute and very seasonal, and the world's nitrate deposits are associated with volcanic emanations or the products of bacterial action on land. In the densely populated region of the Lower Ganges, putrefactive and nitrifying bacteria are responsible for the conversion of animal substances into nitrates; from early times the soils have been lixiviated with water and the nitre fractionally crystallized. Far more important are the nitre deposits of Chile, lying between the coastal mountains and the Andes in one of the most arid regions known. The workable deposit of 'caliche' is covered by 20–50 feet of pebbles, concretionary sulphates, sand and soil. It is said to be derived by leaching-out of ammonium salts * from the adjoining Andean volcanic areas by rainfall in the hills, migrating through the subsoil to the area of desiccation in the arid trough, though other agencies have also been invoked, such as the oxidation of guano by bacterial action or even atmospheric electrical discharge.

Local Chemical Reactions

The bedded iron-ores and the replacement hæmatite referred to in the preceding chapter are among the more important supergene deposits due to local chemical reactions. Oxides of manganese may be similarly concentrated, for many basic igneous and metamorphic rocks carry manganese 'replacing' part of the iron in certain ferromagnesian minerals and on weathering the manganese passes into solution, probably as a sol. If waters charged with this pass through swamps or shallow lakes where CO_2 is extracted by plant action, the manganese is thrown down as hydrated oxide.

Less comprehensible, perhaps, are the widely distributed supergene sulphide deposits. The principal ores are copper (chalcopyrite and chalcocite), often with some nickel, and less commonly lead (galena) and zinc (blende). These ores occur in shales associated with dolomite, and in red sandstones and marls. In this country, blend and chalcopyrite occur in the Marl Slate of the Permian, and, oxidized to carbonate, in the Triassic sandstone of Alderley Edge, Cheshire; but they are of no economic importance. The Mansfield ores, worked from time immemorial in Germany, are held to have been precipitated in a closed basin in an environment of decomposing organic matter, and traces of

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* Ammonia is among the gases evolved during later stages of volcanic activity.

the same metals are present in neighbouring volcanic rocks. Other 'Red Bed ores' may be of like origin.

Lastly, mention should be made of supergene phosphates. Primary phosphate, as dung, weathering to guano, accumulates in great thicknesses on the shore-rocks of subtropical oceanic islands frequented by sea-birds. It is a mixture of phosphates, nitrates and carbonates from which the more soluble or volatile constituents are extracted during its accumulation. Later, the phosphate may itself pass into solution, and, carried down into the underlying coral or volcanic rock, react with it to produce replacement phosphate-rock.

RESIDUAL AND DETRITAL DEPOSITS

Some important residual deposits have been mentioned in the chapter on Soils, where it was shown that in subtropical countries silicate rock may so weather that all the constituents are removed except hydrated oxides of iron and aluminium, leaving extensive sheets of laterite and bauxite. Here we may emphasize that bauxite is the most acceptable ore of aluminium, and that some laterite may be used as an ore of iron.

Detrital ores are sands and gravels, fossil or recent, which carry minerals of economic importance naturally concentrated because of resistance to weathering and their high specific gravity. Of the bulk constituents of igneous rocks, quartz and muscovite mica alone remain unaltered by chemical weathering, but several non-essential or accessory minerals are also resistant. Garnet, magnetite, zircon, tourmaline and topaz, in very small grains or minute crystals, are of common occurrence, and find their way into the majority of sands. Cassiterite (tin oxide), monazite (source of thorium and cerium), gold, platinum and diamond are resistant minerals of economic importance often recovered from detrital deposits. Where the concentration is sufficient, the deposits are workable, and are known as placer deposits. The famous gold-placers of Nome, Alaska, and the diamond gravels of South-west Africa are ancient sea-beach deposits; but stream tin and alluvial gold come mostly from river and stream deposits, sometimes (as in Bendigo and the Sierra Nevada) from ancient gravels sealed and mined under lava-flows.

Gold

Traces of gold are widely distributed in lodes and veins far out beyond the margins of igneous intrusions, but in some way related to them; and the juvenile waters which brought up the gold deposited with it much quartz, some sulphide minerals, chlorite and calcite as they traversed cracks in the country-rock. From the dawn of civilization, the recovery of nuggets from placer concentrates derived from such veins has been as widespread as any art. Placers and dredger washings still supply half of the gold won outside South Africa and Canada, and it may be that the so-called 'banket' reefs of South Africa originated as placer concentrations in Pre-Cambrian beach deposits which are now conglomerate. In most banket, however, the gold has been re-distributed by wandering hot solutions. Most lode gold is native, but occasionally gold occurs combined as telluride along with arsenic and antimony sulphides.

More than one-third of all gold wrought in this century has been extracted from the banket reefs of the Rand in South Africa, where mining round the edge of an area about as big as the South Wales Coalfield is undertaken on the largest scale. Mines have developed progressively down-dip from surface to a depth in some places exceeding 8,000 feet. One enterprise (Crown Mines) in 1940 secured a million ounces of gold, by crushing and extracting four million tons of rock. Seven other mines, all within thirty miles of Johannesburg, are each producing half a million ounces of gold per year. True lode-mining is most active in the Porcupine district of Northern Ontario, where the Hollinger mine output exceeded half a million ounces, and Lake Shore, Wright Hargreaves, McIntyre, Kirkland Lake and Dome mines together pass the million mark.

Gold lodes are unusually rich if they carry half an ounce to the ton; more than 200 million tons of rock is dealt with in supplying the 40 million ounces (1,500 tons) of gold which is mined and sold to governments each year.

Silver

Except in primitive countries, silver is no longer used as a standard currency, and to maintain its value in face of present production the United States has accepted from domestic producers and is hoarding in idleness over 110,000 tons of standard metal. Some silver is always associated with native gold, but most occurs as the sulphide argentite mixed with galena, and silver is recovered from the smelted lead. Occasionally, as at Cobalt (Canada), silver occurs in minor veins in igneous rocks with cobalt arsenide. Formerly the only silver-lead mines of much account were veins and flats in limestone, far from the parent igneous intrusion, and complex ores were neglected as unmanageable. More recently, with improved methods of ore-dressing, large mixed sulphide bodies, sometimes replacing schists and close up to the igneous rocks, have been dealt with successfully; and silver is one of the by-products from lead, zinc and copper smelters. Of the world's silver production (about 10,000 tons per year) more than a quarter comes from mines in the United States; Canada, Mexico, Central and South America are together responsible for a further half; smelters in Europe, Australia and Japan produce the remaining quarter and sell it at less than the U.S.A. domestic price.

Platinum

Metals of the platinum group occur disseminated sparsely in ultra-basic igneous rocks, and in recent years it has been found economic to mine and crush bands in the peridotites of the Bushveldt area of the Transvaal for separation and recovery of 40,000 ounces of the precious metal. Most of the world's supply of platinum in the past has come from placer washings in alluvium, derived from outcrops of serpentine and other basic rock, more particularly on the flanks of the Urals (lately yielding 150,000 ounces per year), in Alaska (30,000 ounces) and Colombia (40,000 ounces). The nickeliferous pyrite ores of Sudbury, Ontario, contain traces of most of the platinum metals, and from concentrates after the electrolytic separation of copper from the nickel, there and in Norway, almost as much platinum is produced as came from Russia; and with it most of the world's supply of palladium, rhodium, ruthenium, iridium and osmium.

Uranium

Rocks containing a few parts per million of this most heavy and dangerous metal are not less common than those which carry a similar proportion of gold; but because of the ready solubility of uranium minerals in slightly acid soil-waters, their dispersal is more widespread and complete. Even so little as 1,000 tons of rock containing the half of 1% of uranium may now be considered a matter of national interest.

The primary ore of uranium is uranium oxide, occurring as pitchblende or uraninite, U_2O_3, a dark brittle substance with a pitchy lustre, as heavy as iron filings and nearly as hard as felspar. Surface occurrences are usually accompanied by the brightly-coloured yellow or orange uranium ochres, to which pitchblende alters on weathering. It occurs generally in 'polymetallic veins', along with silver, cobalt, bismuth and arsenical minerals, in the metamorphic aureole of granitic intrusions. The ancient silver mine at Jachymov (St Joachimstal) in Czechoslovakia, became world-famous as the oldest uranium mine; and similar polymetallic uranium-radium veins have been exploited in Saxony and Silesia and in parts of the U.S.S.R. proper. For many years now the most productive of these lode-type mines has been Eldorado, on the shores of Great Bear Lake in Arctic Canada. The large uranium deposits of the Belgian Congo occur in small shear-veins in the ore bodies of the copper belt, and it is uncertain whether they are of magmatic origin, or are derived from the metamorphism of uranium-bearing sandstones and shales.

Carnotite, a hydrated vanadate of potash and uranium, is a soft powdery yellow mineral found replacing fossil wood and bone and impregnating sediments where uprising extract waters from distant granite soils have dried out under desert conditions. Carnotite deposits are known from Colorado and Utah in the United States and from various localities in the U.S.S.R.

Copper

Copper sulphide occurs as a minor constituent of large masses of pyrite which are replacements of brecciated country-rock alongside sub-acid or intermediate igneous intrusions. Copper ores are very frequently associated with porphyry. Hydrothermal quartz-veins bearing copper pyrites along with blende and galena are much more widespread, and it was from the gossans of these weathered outcrops that early man collected malachite (copper carbonate) to make his bronze. Between the surface and water-table level, copper-veins may be either improved or robbed by secondary enrichment, and it is in these intermediate depths that bonanzas and pockets of copper-rich minerals are located. Primary ore-bodies are accounted rich if they carry so much as 1·5% of copper; and either an igneous or a sedimentary rock with half this proportion of copper, either as sulphide or as carbonate (but not a mixture), pays well for treatment if the mass is large.

The world demand for copper is steadily increasing, and now exceeds 2½ million tons per year, America always producing and consuming more than half. The largest copper corporation now operating is the Kennicott group, which, with smelters in Utah, Nevada and New Mexico, treats 40 million tons of ore per year to produce about 1,000 tons of copper daily. Phelps-Dodge and Anaconda, also working in this region; International Nickel at Sudbury, Ontario; Braden and Chile companies in the Andes; the North Rhodesian group (Rhokana, Roan Antelope and Mufulira) and Katanga in Belgian Congo, are all giant producers of copper, the annual output of each greatly exceeding 100,000 tons of refined metal.

Lead and Zinc

In general, minerals containing these metals are found together, but in former days galena was valuable only when it could be picked clean by hand, and zinc where it is oxidized to calamine in the weathered zone. Hydrothermal solutions carry more lead farther from its source than zinc, and much lead and some zinc are won from narrow veins with fluorspar and barytes in joints and pockets in opened bedding-planes in limestone, not evidently in the neighbourhood of any igneous rock. Mines in Derbyshire and Durham work that kind of deposit; and so do those which produce one-third of the world output of lead and zinc from Missouri and elsewhere in the Mississippi Valley and along the Rocky Mountains in the United States and Mexico.

Other lead-zinc ore-bodies belong to deeper and once hotter zones within the region of thermal metamorphism. These often replace crystalline rocks other than limestone, and some are of enormous size; less than half a dozen of them supply half the world. From Broken Hill, South Australia, has come 50 million tons of lead in fifty years ; and a quarter of a million tons of lead with silver and 150,000 tons of zinc were produced in the year before the war. The Kimberley mine (British Columbia) is almost as productive, and with Flin Flon (Manitoba), Noranda (Quebec), Buchans (Newfoundland) and Bawdwin (Burma) allows the British Empire to fill its own requirements of these metals. A very few of the large ore-bodies, such as Franklin (New Jersey), are worked essentially as zinc mines, but elsewhere the 'black jack' or blende has to be taken out, and is accounted a by-product which might be discarded if the workings were on a small scale. The world consumption of lead is not quite two million tons per year, and of zinc some 10% less.

Nickel

Nine-tenths of the world's supply of nickel comes from segregated masses of pyrrhotite within and near the under-surface of the basic (norite) intrusion of Sudbury, Ontario, an igneous mass which is continuous over an area larger than the Yorkshire Coalfield. It has been said that the Sudbury ore-bodies settled out of the norite while it was still molten, but current opinion favours a later date for their concentration by hydrothermal action from the body of the cooling rock. The several ore-bodies are each compact and separate and of very large dimensions; five mines, operating at various levels, from surface to a depth of more than 1,000 yards, have furnished nearly eight million tons of ore, sorted, and sent half that quantity to the smelter in a single year. The nickel is present mainly as pentlandite

((NiFe)S), scattered in tiny plates and grains through a great bulk of pyrrhotite and chalcopyrite, from which the iron sulphide must be oxidized and slagged away before the matte containing nickel and copper is sent to the refinery. The yield of nickel and copper is each between 1% and 1½% of material taken from the mines.

Prior to developments about Sudbury, the commercial source of nickel was garnierite, a hydrated silicate occurring as nodules in residual soils over outcrops of basic rock in New Caledonia. Mines there produce about 10,000 tons of nickel from a quarter of a million tons of ore. Between the wars there has been much international interest in the discovery of nickeliferous pyrrhotite associated with serpentine about Petsamo, in the arctic tundras of Finland. Five million tons of ore containing 3% nickel and 1% copper were blocked out in 1938, and works almost ready to smelt it were taken over by the U.S.S.R.

Cobalt

For colouring blue grass, crusts of cobalt bloom have been hand-picked from copper-mine gossans in many countries from the earliest times. The uses of cobalt for hardening steel were developed when with each ounce of silver mined from Cobalt, Ontario, a pound of smaltite (cobalt arsenate) was produced. For a time this silver-mine by-product satisfied the market, but the demand encouraged other refineries to look to their residues. There is always some cobalt along with nickel in copper-speiss, and it was discovered that the copper-ores of Katanga (Belgian Congo) and Rhokana (Northern Rhodesia) carry a few tenths of 1%. This, recovered as a copper-cobalt-iron alloy, is now the world's principal supply for magnets and high-speed cutting steel. A new large source of cobalt-ore was being developed in French Morocco before the war.

Chromium

Yellow chromates and green oxide of chromium have long been appreciated for use in paint, and for fifty years ferro-chromium in small proportion has been added to special steel to make it tough; but stainless steels, which require the metal in large quantity, have been perfected only within the last quarter of a century. Chromite (Cr_2O_3FeO), the only abundant ore of chromium, is always associated with the ultrabasic plutonic rocks, peridotite and serpentine. As these rocks solidified, the chromite segregated into lenses and layers, which, where they are large enough to quarry or mine as rock containing one-third to one-half its weight of Cr_2O_3, are acceptable as ores. Of over a million tons used before the war, at least a third came from Africa (Selukwe and the Great Dyke of Southern Rhodesia, and the Bushveldt area of the Transvaal). In the open market just before the war, Turkey was almost as large a supplier as Rhodesia, and in the Urals, Russia was quarrying chromite on an even greater scale. In New Caledonia the French have always worked chromite alongside nickel, and in recent years Americans and Japanese have developed many chrome-mines in the serpentine belt along the west coast of the Philippines. Eastern Cuba for America, and Albania, Greece and the central Balkans for Germany, are the major supplementary sources of supply. About two-thirds of the chromite sold is for making stainless steel and chromium metal; the other third (and that the hardest and least friable, though not always the highest grade of ore) goes for making refractory chromite and chrome-magnesite furnace-bricks.

Tin

Cassiterite (tin oxide) occurs sparsely in quartz-veins traversing the margins of a special kind of granite which always carries tourmaline and sometimes topaz. Within the mother-rock and just outside, it is mined along with wolfram; farther out it is associated with arsenical pyrites and copper pyrites in the tourmaline-bearing 'peach'. Most tinstone is recovered as grains and pellets from placer washings in weathered soil or river-gravel, where, as a resistant heavy mineral, it has been concentrated from the wash of veins and lodes in the country-rock of neighbouring hills. Two-thirds of the world's supply of tin (about 150,000 tons a year) is thus secured by dredger or from washing loose material round about the granites which form the cores of the hill ranges extending from the Dutch East Indies through Malaya, Siam and Burma into China. From the Bronze Age, tin 'streamers' in Cornwall have washed similar weathered material, and miners working copper early discovered the tin-veins which through the ages they have followed down even to 1,000 yards below sea-level. In the East, only the Pahang, Billiton and Mawchi companies (each producing about as much as all Cornwall – i.e., between 2,000 and 3,000 tons a year) have developed the practice of mining; the really important tin-mines are those of Patino, Bolivia. Malayan tin being inaccessible to the Western Powers during the war, the complex tin-silver-arsenic-antimony-copper ores of Bolivia and the Argentine border were mined extensively and smelted in North America. The Belgian Congo, Nigeria and East Central Africa, and the borders of Spain and Portugal, also contribute substantial quantities of alluvial tin.

Tungsten

Wolframite, the double tungstate of iron and manganese, was for long regarded as the thief of tin; but since the introduction of the magnetic separator and the growing demand for tungsten carbide as the cutting agent in high-speed steel, wolframite has become as valuable as its companion cassiterite. Originally crystallized in pegmatite veins and lodes from tourmaline granites, tungstates of iron and manganese, or of lime (scheelite), are more widely distributed than cassiterite in the same type of country-rock. They suffer more by weathering, and are lost on the journey to distant secondary placer deposits.

The world has been getting more than half of its yearly requirements of some 20,000 tons as concentrates from the Malayan range, especially from Mawchi Mergui and Tavoy in Burma, and the Kiangsi, Kwangtung and Hunan provinces of China. Much of this was pebble-ore, hand-worked from river gravels, but lode-mines at Mawchi and Ta Yu in Kwangtung produced much wolframite along with tin. Under stress of war, mining of pegmatite veins was pushed in the United States in California, Nevada and Colorado. Other now important producers are the margins of the Bolivian and Argentine tin-fields, the north Portugal-Spain borderland, and in a small way, the Cornish mines.

Molybdenum

Molybdenite (MoS_2) in small quantities is widely distributed in pegmatites within and outside the boundaries of granite intrusions. Fifteen years ago molybdenum was considered rather a rare refractory metal, but for use as a constituent of shock-resisting, heat-resisting and high-speed steels, production has been so stimulated that almost as much molybdenum as tungsten is needed. Production had passed 15,000 tons a year before the war.

Ninety per cent of all molybdenum comes from the United States, half of it from mines high up on Climax Mountain, Colorado, where 12,000 tons of microgranite is mined per day and crushed so that its molybdenite can be floated out. By flotation also, other major supplies are separated from copper-ores at smelters in the Western

States. In Norway and Morocco, pegmatites are worked specially for molybdenite.

Manganese

There is some manganese in almost every kind of rock and in all countries, but manganese as oxide or carbonate in quantity sufficient to be exploited on a large scale is exceptional, and so occasional that all the steel works in Western Europe and America have to import the essential ores by sea. Over five million tons of manganese ore was thus transported during each of several years before the war, and much was stocked against the emergency. An acceptable manganese ore carries between 45% and 55% of the metal.

Before the war the leading producer was Russia, which was exploiting the basal Oligocene beds in the Ukraine and Georgia on a very large scale, washing from clays and sands more than a million tons of pyrolusite per year. At Nikopol, 200 miles up the river Dnieper from the Black Sea, the ore-bed lies in hollows on deeply weathered Pre-Cambrian gneiss. On the Chiaturi Plateau in the southern foothills of the Caucasus, between Poti and Tiflis, it rests upon massive Cretaceous limestone, and cannot have been locally derived. For the making of ferro-manganese, blast-furnaces calling for rock-ore have depended largely on India. Central Provinces and the south-east Deccan in some years have exported up to a million tons of hard ore, mostly from altered sedimentary rocks interstratified in the old Pre-Cambrian. The Gold Coast manganese is a crusty ore, but not so hard. It is a secondary concentration produced by leaching and replacement in the tropical forest of Pre-Cambrian manganiferous phyllites. Much of the best material is surface 'boulder ore'. About half a million tons of Nsuta ore is yearly exported through Takoradi, the port of Sekondi. Brazil's quarter of a million tons from the

Minas Gerães Pre-Cambrian sedimentary series is mainly hard. Ore from South Africa is quarried from a bed in coal measures not far above the glaciated pavement at the base of the Permo-Carboniferous near Kimberley; the ore is massive, but rather soft, and of intermediate grade. About half a million tons a year was produced in pre-war years, and most of it went to Germany. Similar ore was mined at the base of the Carboniferous Limestone in the Sinai Peninsula. Softer material was concentrated and sent to the United States from Cuba, and from the Philippines to Japan. For domestic supplies within the United States, manganiferous iron-ore with less than 10% manganese is the only important contributor. In Britain, the known thin beds in Cambrian and Ordovician rocks of Wales are of small economic import.

Mercury

Mercury is a rare metal of local and limited distribution. It occurs mostly as cinnabar (HgS), as a solfataric or hot-spring emanation, but is not associated with active volcanoes. From ancient times, quicksilver has mostly come from the Almaden district of Spain, or from Monte Amiata and Idria on the borders of Italy and Yugoslavia, each of which districts can produce about 1,000 tons a year. Western North America normally produces a similar quantity, but at greater cost, from more than 100 scattered mines, mostly in California, some in Oregon and Nevada, and with developments proceeding also in Mexico and Pinchin Lake, British Columbia.

Aluminium

Combined as silicate, aluminium ranks third in abundance among all elements in the crust of the earth, and of common rocks only limestone and quartzite are without it.

Yet aluminium as a metal was a rarity at the beginning of this century. It is the all-important base of clay, but the energy required to break its union with silica is so great that only those residues which by continued exposure on land to a tropical or monsoon climate have lost their silica are acceptable as ore. It matters little what kind of rock is weathered, if weathering conditions are just right.

Bauxite takes its name from Baux, in the department of Var, France, which, with neighbouring parts of the Italian Riviera, has been supplying nearly a million tons per year from fossil soils between the Eocene basalt flows. Now British Guiana and Surinam in tropical South America are supplying even more of similar rock also from inter-basaltic soil floors. Under Nazi influence and control, the pre-Tertiary weathered surface of unconformity in the Balkans has been intensively exploited wherever it is accessible by railway, especially in the Balaton Lake area of Hungary and southward through Yugoslavia into Greece. From these areas more than a million tons of bauxite was sent to Austria and Germany in pre-war years; deposits in Dutch East Indies and Malaya were developed during the same period to supply Japan. Altogether about five million tons of bauxite is sent to factories for the making of nearly a million tons of aluminium per year. The major cost in manufacture is electric power; and the alkali used for the extraction of alumina from bauxite is more expensive than the ore itself.

Because of the difficulty of delivering bauxite to hydro-electric stations, war-time plants started to extract aluminium from nepheline in Russia, from labradorite (felspar) in Canada and Norway, from andalusite in Sweden, and from leucite in Italy. All these minerals are separated from coarsely crystalline igneous rocks. In Germany, sulphurous acid has been used to extract alumina from clay; more is likely to be heard of these processes in the future.

Magnesium

Magnesium is sixth in the list of elements which are major constituents of the earth's crust, but, like aluminium, it is difficult to separate because of the inherent stability of its compounds. Magnesite ($MgCO_3$), the favourite ore, occurs concentrated by local hydrothermal action along cracks in serpentine or permeating recrystallized limestone in the margins of a metamorphic zone. Dolomite, the double carbonate of lime and magnesia, is an abundant and widely distributed mineral, and magnesium silicate (olivine) is a major constituent of ultrabasic igneous rocks; but to meet the requirements of the steel industry, magnesite has to be imported both to England and America. Magnesium chloride, which is a by-product in the separation of potash from brines, is also a convenient raw material for electrolytic smelters. Lastly, to meet war requirements, magnesium hydrate was precipitated from sea-water in England and America, and notwithstanding that the concentration of magnesium in the ocean is little more than 1 part per 1,000, the cost is less than for separating magnesia from dolomite or serpentine.

Before the war the world supply of 'austrian' crystalline magnesite was quarried from altered bands of limestone in Styria, the Eastern spurs of the Alps in Austria and the western end of the Carpathians in Czechoslovakia, which together furnished about half a million tons. Quarries in the Urals delivered a like amount of similar but less pure material, and Manchuria was exporting half as much. The very pure, compact 'grecian' amorphous magnesite occurs in narrow veins traversing serpentine masses, and was favoured for chemical purposes and metal manufacture. The main source of such material was Eubœa, Greece, supplying about 150,000 tons a year; America, Germany, Italy, India and Australia also have smaller sources of this type.

Saline Deposits

Soluble salts have been concentrated by the drying-up of sea-water or other natural brine. Sea-salt, air dried, is collected in salt-pans on the shores of oceans in all sub-tropical, semi-desert belts, and it was for evaporation of sea-water that the mining of coal in Scotland and North England was first begun. Nowadays, though waters of the Dead Sea and other natural inland salt-lakes are similarly concentrated, much more salt is produced, either by mining, or controlled circulation of water delivered and recovered through boreholes drilled into the sediments of natural salt-pans, which represent arms of the mediterranean seas and oceans of long ago.

Common salt (sodium chloride) is a necessity for human and animal consumption, but four or five times as much is used for the manufacture of soda ash. Nearly half the salt used is taken as brine from bore-holes, and delivered to chemical works. The United States mines about two million tons per year as rock-salt, mostly in New York State; and from Michigan, Ohio, Kansas and other states about seven million tons is pumped as brine. Germany mines even more (about 2½ million tons) but until lately only about two million tons a year was produced as brine. Salt deposits occur mostly among red marls near the centre of synclinal areas. Most British salt-beds, such as those of Cheshire, Droitwich, Stafford and Fleetwood, were dried up in the desert period of the Upper Trias; but some in north-east Yorkshire like those of Stassfurt in Germany rest upon Magnesian Limestone and were formed in the later stages of the drying-up of the Permian sea. In the banded deposits of potash-magnesium salts at Stassfurt are preserved the products of the final stages of evaporation. When the Alpine Chain was rising in the midst of the Tethys sea, arms of the sea were cut off like the present Caspian;

several of these dried up, and their sites in Alsace, North-east Spain, Poland, and Austria have retained their saline deposits and are producing potash.

Of quite another class of soluble salts is Chile saltpetre ($NaNO_3$), which, in the face of competition with synthetic ammonia and nitric acid, is selling at the rate of two million tons per year. As caliche, it is dug close under the surface along an inland valley in the desert region of Northern Chile, and its probable mode of origin has already been referred to (pp. 171-2). The iodates, separated from the mother-liquors when caliche is purified by recrystallization, are the main source of the world supply of iodine.

Borax is also a soluble salt of sodium which crystallizes only during the final stages of desiccation. A small quantity of borax is still recovered from fumarole waters in Tuscany, but 95% of the world's supply (300,000 tons a year) is from America, from an underground deposit in the old lake-basin which is now the Mojave Desert. Sodium borate is also produced from saline lakes in California and Nevada, and minor supplies come from the Argentine and Turkey; at all these localities there is evidence of comparatively recent volcanic activity nearby.

Phosphate

As an accessory mineral, apatite (fluoro- or chloro-phosphate of calcium) is a constituent of almost every kind of igneous rock, but only in occasional pegmatites associated with deep-seated alkaline intrusions is it sufficiently concentrated for profitable quarrying. Such deposits are worked in Ontario and Quebec. Of bird guano, the South American desert coast supplies about 150,000 tons, while in the year before the war over a million tons of coral rock phosphatized by bird-droppings was shipped from Nauru and Ocean Islands; other islands far out in the Pacific and Indian Oceans also supply considerable quantities of similar rock. More accessible to European users are the extensive beds of fossil phosphate from the base of the Eocene in Northern Africa. Tunisia is the focus of this industry, and for more than a decade has shipped nearly two million tons per year. The export from French Morocco is growing, and has passed 1½ millions; Algeria and Egypt each produce about half a million. In Russia it had been reported that reserves of bedded phosphate were too meagre for exploitation, so it was decided to develop the apatite pegmatite in the Arctic tundras of Kola; lately 10,000 tons a day of crystalline rock were milled there, and for a considerable period a yearly production of over 1½ million tons of dressed rock-phosphate was reported. American output of phosphate is round about four million tons, and is mostly from Florida; the greater part of this is recovered in the form of pebbles by washing residual soils and dredging and washing sand and mud in lagoons and shallow channels along the coast. Vast reserves of phosphate rock have been prospected on the flanks of the Uinta Mountains, Utah.

Wherever the 'basic Bessemer' process is employed in steel-making, phosphides which have been reduced from the phosphate unintentionally introduced as fossil shells embedded in the iron-ore, or in the coal used to smelt it, are burnt out and accumulate in the final refining slag. When ground up, this is the 'basic slag' of the agriculturalist. One per cent of phosphorus in the unrefined iron is no high proportion, but extracted from 10 million tons of steel each year in Germany, it is an important contribution to the national economy.

Sulphur

Two million tons of sulphur yearly is melted out with live steam piped down boreholes in the margins of salt-domes found by oil prospectors near the Gulf of Mexico.

There are only five large operators, four in Texas and one in Louisiana, but each melts about 3,000 tons of sulphur rock per day. Some sulphur is mined by hand in Sicily, where it has evidently been formed by local reaction between escaping oil or bitumen and the gypsum deposits with which it is associated. The sulphur in the American salt-domes is almost certainly of like origin. Other Italian sulphur is from vents and solfataric fissures of dormant volcanoes.

Pyrites

Until the development of the Frasch sulphur-melting process, makers of sulphuric acid got their sulphur dioxide by roasting iron pyrites, or, if convenient, copper pyrites or other sulphide ore on its way to a wet refinery; and yearly 10 million tons of pyrite is still thus roasted. Pyrite is the most abundant of all sulphide minerals. It segregates in large masses alongside igneous intrusions which are poor in non-ferrous metals, and is the main constituent of all deep-seated primary copper and nickel ores. Before her revolution, Spain provided half the world with pyrite from the cupriferous pyrites mines of Rio Tinto, and Japan in 1939 sent two million tons to roaster; Norway mined more than a million, Russia, Italy and Cyprus somewhat less, the United States, Portugal and Germany each about half a million. Of industrial countries, Great Britain alone is entirely dependent on imported supplies; that position is unlikely to be changed unless by collecting the "brass" washed out of dirty coal, or by cleaning furnace gases at power stations, or by the reduction of anhydrite (calcium sulphate) of which we have plenty in the Upper Permian of northern England.

CHAPTER XII

Gemstones

The Diamond – Corundum (ruby and sapphire) – Beryl (emerald and aquamarine) – Semi-precious stones: topaz, tourmaline, garnet, peridot, zircon, spinel, quartz, chalcedony, opal, moonstone, turquoise, lapis-lazuli, jade.

It has been said that the three cardinal virtues of the gemstone are beauty, durability and rarity, and that the greatest of these is rarity. The discerning few who appreciate beauty in common things are artists, and who can doubt that were diamonds as abundant as the relatively common garnet they would be held in similar disdain? Rare as they are, the price of perfect stones is only maintained by a rigid system of control. To some extent, rarity is the concern of the geologist, for the special conditions which operate so infrequently to produce fine diamond in carbon-rich igneous rocks, or allow gem-quality ruby or sapphire to form in place of abrasive corundum and emery, are of great scientific interest. But such knowledge is of small practical value, and can hardly be applied in the search for more supplies, so that the more important applications of geology lie in recognizing and distinguishing the stones.

Durability is linked with hardness and chemical inertness. All true gemstones are stable, and do not deteriorate with age; but the pearl (which is organic, not mineral, in origin) owes most of its beauty to organic matter incorporated in its substance, and in time pearls steadily deteriorate and eventually go 'dead', and may even disintegrate. All true gemstones are likewise hard. On an arbitrary scale of hardness in which the diamond is represented by 10, rock-crystal is 7 and ordinary window-glass about 6, most semi-

Plate 5

A forest of oilfield derricks. Part of the Yenangyaung Oilfield, Burma, with the Irrawaddy River in the distance.

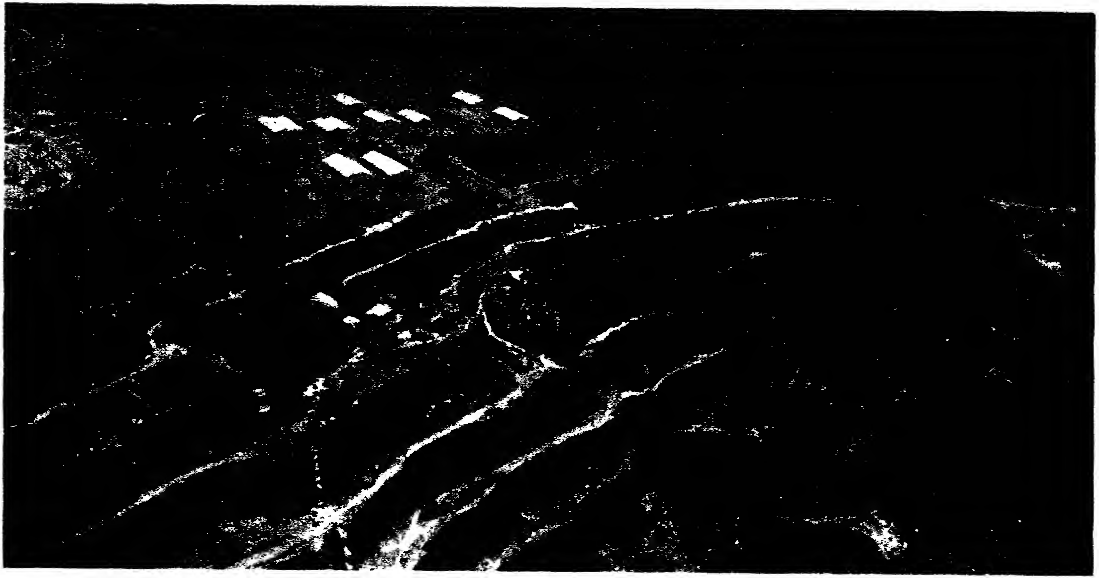


Plate 6

Penrhyn Slate Quarry, North Wales, one of the largest open-workings in Britain. Each of the ledges is about seventy feet high.

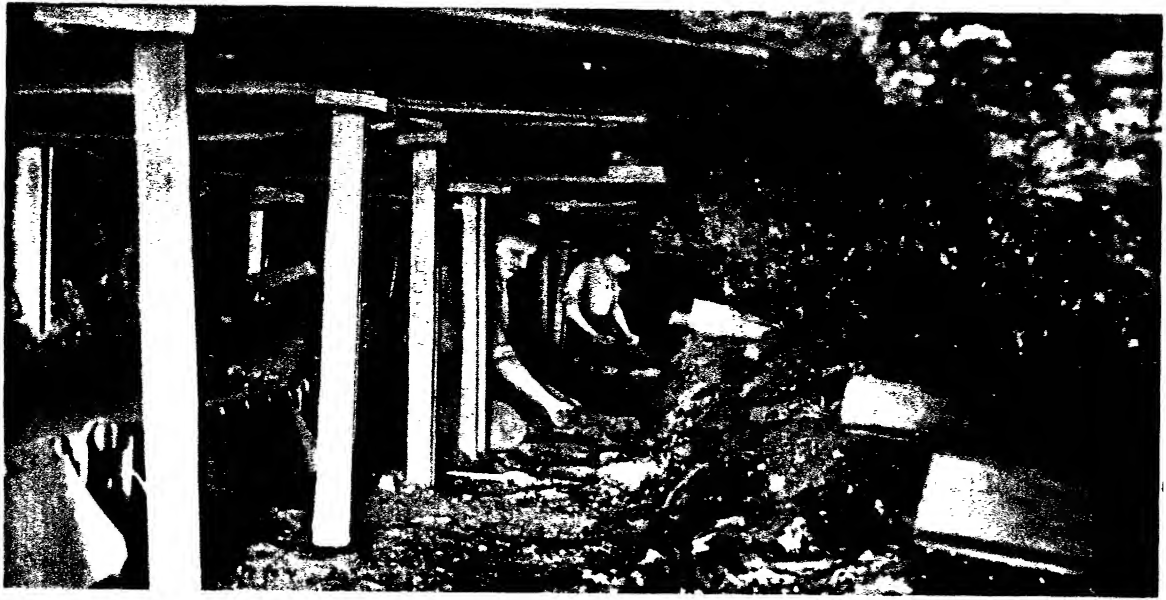


Plate 7
Loading coal on to the conveyor, Wath Main Colliery, Yorks.

Plate 8

Excavating Middle Jurassic iron-ore from under seventy feet of over-burden at Irchester (Northants). The digger handles about 250 tons of rock per hour.

precious stones have a hardness of 7 to 8, and the precious stones 7½ to 10. The facets are accordingly not liable to casual scratching by dust particles, nor are the edges appreciably abraded by ordinary wear.

Beauty in a gemstone is usually an attribute of colour and lustre. Such stones as lapis-lazuli and turquoise, being opaque, are admired for their colour alone; other translucent stones owe their beauty partly to colour, but also to opalescence resulting from reflection of light by minute inclusions within the stone; but the majority of gemstones are transparent and have a brilliant lustre. This lustre is associated with high refractive index, in consequence of which more incident light is reflected at surface than from substances with lower refractive index, while more of what light does enter is reflected back within the stone to emerge again from its upper facets. Both lustre and colour are enhanced by cutting and faceting. The design of facets to reveal all qualities of a gemstone at their best is an exact, almost a mathematical, science, and the cutting is a most highly skilled technical operation. Curiously enough, it is a modern art, and diamond-cutting dates back only 200 or 300 years to the discovery that only diamond (or diamond dust) cuts diamond. In early times, cabochon-cutting, or the polishing of smooth more or less hemispherical masses, was the accepted treatment for most gems.

THE DIAMOND

In ancient times, and through the Middle Ages, India was the only source of the diamond, which was obtained from placer deposits in recent and fossil river gravels. The finding of diamonds in Brazilian rivers in 1725 was quickly followed by so large a production as to cause a slump in prices, but soon the output was taxed and controlled by Government, and in the next century so fell away that India regained her supremacy. A hundred years later followed greater discoveries in South Africa, which put India back to second place.

South African discoveries have proved of extraordinary interest in providing evidence of the origin of the diamond. India and Brazil are both 'alluvial' producers, the stones being washed out of conglomerates believed to be Pre-Cambrian in age. Their primary source was therefore unknown. Nor did the first South African discoveries appear to be in any way different. The first stone was picked up in 1867 by children on a Boer farm, and for some time was not even recognized as a diamond. Diamonds were next found in gravels which form the banks of the Vaal River, and the diamond-rush began. A few years later more stones were discovered on de Beer's farm and other places on an arid plateau, and the mining town of Kimberley sprang up almost overnight. All the early finds were in loose soil and sub-soil occupying shallow, circular depressions; and had to be exploited by dry-diggings and hand-sorting, the absence of water being the greatest handicap to the expansion of the industry.

Diamonds were then found quite unexpectedly and still more abundantly in the friable yellow sub-soil which had been regarded as bedrock under the diamond-bearing gravels, themselves then thought to be patches of river gravel. This oxidized rock, being soft and friable, was still easy to work, but as the excavations were carried down deeper, this 'yellow-ground' gave place to a very dissimilar, unweathered, compact bluish rock called 'blue-ground'; and again it looked as if the properties were worked out. Experimental spreading-out of blue-ground rock in fields for weathering, however, was rewarded by the discovery that it too contains diamonds, and this blue-ground, which is in fact simply unweathered yellow-ground, is the source of the present mined supply.

On account of the small size of individual 'claims' or holdings – each only about 30 feet square – difficulties arose as the workings were carried deeper. At first, holders in the central portion of the area travelled and moved material to and from their tiny claims along a complicated spider-web of overhead wires by travelling cradle. But this was not a permanent solution, and the difficulties were not overcome until the amalgamation arranged in face of much opposition by Rhodes at de Beers and Barnato at Kimberley.

The blue-ground (called kimberlite) is a peculiar ultra-basic volcanic rock very rich in magnesia; it is essentially a basalt without felspar, carrying olivine, pyroxene, garnet and other magnesia-rich ferromagnesian minerals. Yellow-ground is its weathered upper surface, extending below the completely disintegrated surface soil to a depth of more than 100 feet in places. Development has shown that each kimberlite plug or pipe is more or less circular, tending to a more elongate cross-section at depth, and is the filling of an ancient volcanic neck. At Kimberley the pipe has been followed down to a depth of 1,300 feet as open working, and mined to nearly 4,000 feet. Originally the material was spread out upon 'floors' for a year or so, frequently ploughed over and occasionally watered, by which process of accelerated weathering it was converted to yellow-ground. To-day it is crushed and taken to the washing and concentrating mills without pre-treatment. The concentrate is washed over gently inclined greased plates, where the diamond is easily separated because of its unusual property of sticking to grease. The proportion of diamond present in blue-ground is rather less than five-millionths per cent.

Similar ultra-basic rocks, less richly diamond-bearing, are now known from other parts of the world (e.g., British Columbia, New South Wales, etc.), but are of no competitive importance. It may also be noted that microscopic diamonds have been found in stony meteorites. So far as is known, these are their only primary occurrences, and except that the carbon belongs to the igneous rock, it is of unknown origin.

Diamond is not the only form of crystalline carbon. Graphite, one of the softest mineral substances, and therefore useful as a lubricant as well as for pencil-making, is chemically identical. But because the specific gravity of diamond is so high (3·52 as compared with 2·2 for graphite), it is generally assumed that its crystals grew under considerable pressure. Diamond is the hardest substance known, natural or artificial, and the difference between diamond (10) and corundum (9), the next hardest natural substance, is far greater than any other interval on the hardness scale. Apart from its value as a gemstone, diamond has therefore important uses in industry for cutting and drilling hard metals and for wire-drawing. One of Britain's first acts under the mutual-assistance agreements when Germany attacked Russia was to ship a plane-load of industrial diamonds to the Soviet Union.

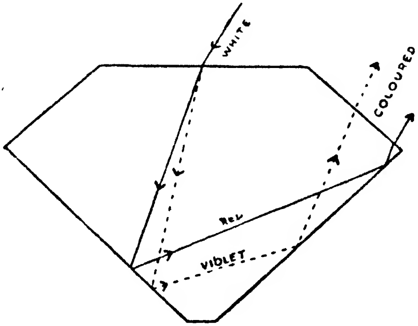


FIG. 38. – Diagram to illustrate dispersion of light in a Brilliant-cut Diamond.

The dispersion or separation of the red and violet ends of the spectrum is, of course, highly exaggerated.

The remarkably high refractive index of diamond (over 2·4, as compared with 1·5 for glass) is the cause of its luminous sparkle, while its peculiarly high 'dispersion' is the cause of the 'fire' or brilliant flashes of colour from a well-cut stone. The refractive index for red light (2·407) is so markedly different from that for violet light (2·465) that ordinary white light is dispersed or split up into a much wider spectrum-band than by any other medium. The brilliant-cut (Fig. 39*a*) takes advantage of this, and is so designed that most of the light reflected back through the lateral facets on the upper surface is coloured light (see Fig. 38).

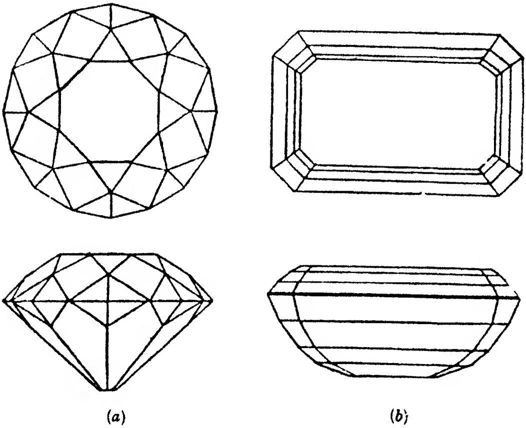

(*a*) (*b*)

FIG. 39. – (*a*) Brilliant-cut and (*b*) Step-cut stones in top and side view.

Best-quality diamonds have a faintly bluish tinge (blue-whites); absolutely colourless stones rank next; whilst the slightest tinge of yellow is regarded as a serious defect. The cloudy and black varieties known as bort and carbonado have great value in industry.

Some of the world's finest diamonds, with their cut weights in metric carats, are: from India: Koh-i-noor, 108;

Pitt or Regent, 135; Orloff, 199; Hope Blue, 45. From Brazil: Star of the South, 128. From South Africa, the Cullinan easily eclipses all others; its weight uncut was 3,106 carats (about 1 lb. 6 oz.) and from it were cut two fine stones of 530 and 317 carats, as well as more than 100 smaller stones. Sixty-five stones each weighing more than 300 carats have been recorded from South Africa.

During the period between the two wars a large proportion of the world supply of diamonds was washed from recent and ancient gravels and raised beaches near the mouth of the Vaal River in South-west Africa; West Africa also provided a considerable contribution.

CORUNDUM: THE RUBY AND SAPPHIRE

Composition: aluminium oxide, Al_2O_3; hardness, 9; refractive index, 1·8; specific gravity, 4.

Corundum, the common form of alumina, and especially its iron-bearing variety emery, has been widely used as an abrasive; for many purposes it is now largely replaced by the cheaper, artificial carborundum (silicon carbide), which, though much more brittle, is appreciably harder. When absolutely pure, corundum is colourless and transparent. If transparent, it is most valuable when coloured by traces of impurity, and the gem varieties are known by different names, according to their colour. Traces of chromium make the ruby red; the characteristic blue colour of sapphire is probably due to titanium; the yellow stone known as oriental topaz owes its colour to iron; and colourless crystals of alumina are called white sapphire.

No colourless stone, except perhaps the zircon, can stand comparison with the diamond, and white sapphire is not highly valued in jewellery; it is the blue and red varieties which are so esteemed, and they are step-cut (Fig. 39*b*) to forms best calculated to display the colour. Rubies are so rarely found as large stones that even a five-carat ruby is more costly than a diamond of the same weight; large sapphires are less uncommon, but still exceptional.

Corundum is not rare as a primary constituent of igneous rocks; especially those plutonic rocks which have a high alumina content and low iron-magnesia (as, for example, certain syenites), and, curiously enough, also in some rocks with low alumina and high ferromagnesian content, like some of the peridotites. Corundum in igneous rocks, however, generally takes the form of emery; and most of the gemstones come from metamorphic rocks, either from limestones altered by pneumatolysis or from regionally metamorphosed limestones associated with gneisses. As with most gemstones, considerable numbers are produced from placer deposits or gem-gravels. The world's most famous ruby-mines are at Mogok, near Mandalay, in Upper Burma, where the gem occurs in a metamorphosed crystalline limestone associated with spinel; it is also found in alluvial deposits in the same district. In Siam and Ceylon, the ruby is mainly alluvial; the country-rock consists of ancient gneisses traversed by pegmatite veins from which fine corundum crystals are probably derived. Both areas, and particularly Siam, are big producers of sapphire, with which in Ceylon are associated oriental topaz and garnet. Very large sapphires come also from Kashmir, in northern India, where they occur in pockets of china-clay which may be weathering products of pegmatite. Poorer-quality gem-corundum has been obtained from gem-gravels in Montana (red and blue), Queensland (blue and yellow), Russia, Rhodesia and elsewhere.

Both sapphire and ruby stones can successfully be made to order artificially. Pure alumina, chemically precipitated, is fused in an oxy-hydrogen flame with small quantities of chromium or titanium oxide to produce ruby and sapphire respectively. The artificial stones are rarely free from minute bubbles, but their optical and physical properties are almost identical with those of natural stones, and only by their inclusions can they be distinguished. Cape Ruby is the name given to flawless red garnets from South Africa, which found no market under their proper name, but have a considerable sale under this more poetic title.

BERYL: EMERALD AND AQUAMARINE

Composition: silicate of beryllium and aluminium, $3BeO,Al_2O_3,6SiO_2$; hardness, 7½; refractive index, 1·57; specific gravity, 2·7.

Like so many minerals, beryl is colourless when absolutely pure, but more usually it is bluish, green, yellow or even pink. Bluish and blue-green stones are known as aquamarine; the grass-green variety is emerald. Emerald is so rarely unflawed that when of good colour it ranks with the most precious of all gems. Aquamarine as large unflawed stones is not uncommon, and commands a much lower price. Emerald is generally step-cut to show its colour to advantage, while aquamarine is more usually brilliant-cut to sparkle with reflected light.

As might be expected of a compound containing beryllium, beryl is generally found in pegmatites associated with pneumatolysis; emerald in altered crystalline limestones and mica schists, and aquamarine in decomposed pegmatites in granites.

The emerald-mines of Upper Egypt, excavated in micaceous schists, were worked under the Pharaohs, subsequently 'lost', and rediscovered only during the last century. They have not been much worked in recent times, and most of the supply comes to-day from South America (Colombia, Ecuador and Peru), where the occurrence is in calcite veins in an impure Cretaceous limestone. There are less important sources in Russia (Siberia and the Urals).

Aquamarine is more widely distributed, though the main supply is again South American (Brazil). India, Ceylon, Siberia and the Urals are also important producers. Rose-pink beryl (called morganite) comes from Madagascar, and has also been found in California. Crystals of blue beryl, not of gem quality, occur in the Mourne granite in Ireland.

SEMI-PRECIOUS STONES

Topaz

Fluo-silicate of aluminium, $Al_2O_3,SiOF_2$; hardness, 8; refractive index, 1·62; specific gravity, 3·5.

Colourless, commonly yellow or brown, rarely blue, pink and green. Much of the 'topaz' sold by jewellers is yellow or brown-stained quartz (citrine or cairngorm); true topaz (sometimes called 'Brazilian topaz') is heavier and harder, and has a somewhat higher refractive index. It can be electrified by rubbing. As a pneumatolytic mineral, it is a constituent of pegmatite veins, etc., and occurs in gem-gravels derived from such rocks. It is commonly associated with tinstone, and often found (though not necessarily of gem quality) in tin-gravels. In Brazil and Russia (Urals and Siberia) there are many widespread occurrences in alluvium.

Tourmaline

Boro-silicate of aluminium with alkali, magnesium or iron; hardness, 7–7½; refractive index, 1·63; specific gravity, 2·9–3.

Yellow ceylonese peridot, yellowish-green brazilian peridot, green brazilian emerald, blue brazilian sapphire, pink rubellite, and red siberite are well-known marketed varieties of tourmaline, and there are also shades of brown and greenish-brown; individual crystals of tourmaline often show zones of different colour. When rubbed, tourmaline is even more strongly electrified than topaz. Always pneumatolytic in origin, large crystals occur in pegmatite veins and in altered schists and limestones. Gem varieties come principally from Brazil, the Urals, Western U.S.A. and Madagascar, and from the gem-gravels of Ceylon.

Garnet

$3R''O,R_2'''O_3,3SiO_2$, where R'' represents calcium, magnesium, ferrous iron, manganese, etc., and R''' represents aluminium, ferric iron, manganese, chromium, etc.; hardness, about 7; refractive index, 1·75; specific gravity, 3·5–3·7.

The chief defect of this attractive gem-stone is that fine crystals are not rare. Garnets are of variable composition, different varieties having different combinations of divalent and trivalent metals, and a correspondingly wide range of colour. The gem varieties are green (uralian emerald and 'olivine'), pink, red (cape ruby), yellow and orange (hyacinth and cinnamon-stone); other varieties may be brownish-green, brown or black. Garnet is essentially a metamorphic mineral, and most garnet of gem quality occurs either in limestones or in crystalline schists. More rarely it is a constituent of igneous rocks, sometimes occurring in granite, and more abundantly in ultrabasic rocks such as kimberlite. It survives through cycles of weathering and is very abundant in gem-gravels.

Peridot (Olivine)

Silicate of magnesium and iron, $2(MgFe)O,SiO_2$; hardness, 6½–7; refractive index, 1·6–1·7; specific gravity, 3·3.

Its green colour is due to ferrous iron; highly ferriferous varieties are almost opaque. Practically all the supply of gem-quality peridot comes from St John's Island in the Red Sea; but the mineral is widely distributed in all basic and ultrabasic rocks; as the variety forsterite, it occurs in metamorphosed dolomite limestones. Queensland and

North America are small producers. Serpentine is hydrated and otherwise altered olivine, and the most beautiful semi-precious marbles and 'ophicalcite' consist of altered olivine-bearing rocks.

Zircon (Jargoon, Hyacinth)

Zirconium silicate or double oxide of zirconium and silicon, ZrO_2SiO_2; hardness, 7–7½; refractive index, 1·9–2; specific gravity, 4·7.

A very attractive gemstone having properties which most nearly approach those of diamond and give such brilliance and fire that it is occasionally passed off as diamond to the unwary. Its lower hardness affords a ready method of discrimination. Sometimes colourless, it may be green, red, yellow or blue. Present everywhere as an accessory mineral in acid and intermediate igneous rocks, zircon is especially abundant in syenites; but gem-quality stones are mostly obtained from alluvium. The best come from the gem-gravels of Ceylon; others from Australia, South Africa and Russia.

Spinel

Oxide of magnesium and aluminium, MgO,Al_2O_3; hardness, 8–8½; refractive index, 1·71–1·73; specific gravity, 3·5–3·7.

The best-known spinels are the red stones known as balas ruby; but a wide range of colours from red to steely-blue in gem-quality stones is available. It is often associated with corundum, as in the Mogok limestones and gem-bearing gravels of Burma and Ceylon.

Quartz

Silicon dioxide, SiO_2; hardness, 7; refractive index, 1·55; specific gravity, 2·66.

Water-clear when pure (rock-crystal), but sometimes coloured by traces of manganese (purple or violet, amethyst), iron (yellow, citrine and brown, cairngorm, commonly but mistakenly called topaz); or ? titanium (pink, rose-quartz). Quartz has an extremely wide distribution in acid igneous rocks, sedimentary and metamorphic rocks and in many mineral veins; but most of the best pebble and gem-quality rock-crystal is from pegmatites of igneous origin. Brazil, Uruguay, India, Ceylon, and Russia are noted producers. Rose-quartz is of limited occurrence, the best-known being one pegmatite dyke in Bavaria and from unknown localities in China. The cairngorm is named from an occurrence in granite in the Central Highlands of Scotland.

Secondary Silica

Chalcedony (a minutely crystalline aggregate) and its varieties *carnelian* and *jasper*, and the banded cavity-filling *agate* and *onyx* have been held in great esteem from ancient times. The majority of the early engraved gems are carnelian, and banded onyx was frequently carved as cameos. All these are forms of secondary silica, deposited in cavities from aqueous solution.

Opal is a form of secondary silica containing water, and is cryptocrystalline or amorphous. Its play of colour is due to interference of light reflected from films within the mineral substance. These were originally formed as contraction cracks, and subsequently filled with fresh opal material; this, containing a different water-content, has a different refractive index, and interference-colours are produced in the same way as by a soap-bubble in air. White, black and fire opal are the three varieties of 'precious opal'. Originally obtained almost exclusively from the mines in Hungary, where it occurs as cavity-fillings in a Tertiary lava, the best and largest pieces now come from filled bedding-plane and joint cracks in Cretaceous sandstones and shales in New South Wales, and some are recognizable as replacements of fossil bone and wood.

Moonstone

A variety of orthoclase felspar ($K_2O,Al_2O_3,6SiO_2$) which owes its pearly opalescence to interference of light reflected from microscopic inclusions of albite felspar in the host orthoclase. Gem moonstone comes mainly from Switzerland and Ceylon.

Turquoise

Phosphate of iron, aluminium and copper; hardness, 6.

An amorphous substance precipitated as a cavity-filling. Being porous, it is spoiled by contact with soap, grease, etc. The most famous occurrence is at Nishapur, Persia, where it encrusts and occupies cracks in a brecciated Tertiary lava. Mexico, Sierra Nevada, Arizona and Russia have local sources of supply.

Lapis-lazuli (Lazurite)

Silicate of sodium and aluminium, combined with sulphides. Powdered lapis-lazuli was the original ultramarine, but now a brighter 'ersatz' lapis is made artificially by heating china-clay (hydrated aluminium silicate) with sodium carbonate, charcoal and sulphur in a muffle kiln. It often occurs as particles disseminated through finely crystalline metamorphic limestone, often containing grains of pyrites; lapis-lazuli is therefore a rock, and the colour and quality depend on the amount of the mineral lazurite present. The best slabs come from Afghanistan; but beautiful blue material is also known from Siberia.

Jade

This name is used for two mineral substances of different chemical composition, but very similar in appearance.

True jade (nephrite) is a pale green silicate of magnesium and calcium belonging to the amphibole group; jadeite is a silicate of sodium and aluminium related to the pyroxenes. Both are remarkably tough, take a high polish, and both are extensively employed in the celebrated Chinese carvings. True jade (specific gravity, 3·0–3·1; hardness, 6½) is a felted aggregate of microscopic needles occurring in hornblende schists in China and Turkestan. A darker-green variety from New Zealand (containing a little more iron) is associated with talc and serpentine schists. Jadeite (specific gravity, 3·3; hardness, 6½) is more granular, its grains of pyroxene generally interspersed with altered felspar. The best pieces come from Upper Burma, where jadeite-albite rocks are intruded into serpentines and peridotites. It is more variable in colour than nephrite, and along with white and green, pink and lilac shades are not uncommon.

APPENDIX I

A. *Tabular Classification of Igneous Rocks*

	Acid	Intermediate		Basic	Ultra-basic
SiO_2,%	75–65	65–55		55–45	45–35
		Alkaline	Calcic		
VOLCANIC	Pumice, Obsidian, Rhyolite.	Trachyte, Phonolite	Andesite	Basalt	
HYPABYSSAL	Felsite, Quartz porphyry, Micro-granite	Porphyry	Porphyrite	Dolerite	
PLUTONIC	Granite	Syenite	Diorite	Gabbro	Peridotite, Serpentine
PRINCIPAL CONSTITUENT MINERALS	Quartz, Orthoclase felspar, Muscovite, Biotite, Hornblende	Orthoclase felspar, Plagioclase felspar, Biotite, Hornblende	Plagioclase felspar, Hornblende, Augite	Plagioclase felspar, Hornblende, Augite, Olivine, Leucite, Nepheline, Iron ores	Augite, Olivine, Iron ores

Some Common Rock-forming Minerals

Quartz: crystalline silica, SiO_2, transparent, no cleavage, hardness 7.

Orthoclase felspar: silicate of potassium and aluminium, K_2O, Al_2O_3, $6SiO_2$, two cleavage directions at right angles, hardness 6.

Plagioclase felspar: soda-lime felspars, an isomorphous series from Na_2O, Al_2O_3, $6SiO_2$ to CaO, Al_2O_3, $2SiO_2$, block cleavages nearly at right angles, lamellar twinning, hardness about 6.

Mica: complex orthosilicates of aluminium, potassium and hydrogen with magnesium and ferrous iron, cleaves into flexible sheets, hardness 2½–3. White mica = muscovite, black mica (rich in magnesium and iron) = biotite.

Augite: metasilicates of magnesium, ferrous iron and calcium, with some aluminium and ferric iron, prismatic cleavage nearly at right angles, hardness 5–6.

Hornblende: metasilicates of magnesium, calcium and ferrous iron, with some aluminium, ferric iron and sodium, fibrous prismatic cleavage at nearly 60°, hardness 5–6.

Olivine: orthosilicate of magnesium and iron, $(MgFe)_2SiO_4$, glassy fracture, hardness 6½–7, hydrates to soft serpentine.

B. *Tabular Classification of Sedimentary Rocks*

Fragmental or clastic deposits

Rudaceous rocks: gravels, conglomerates and breccias; boulder-clay may also be included here.

Arenaceous rocks: sands and silts. Limits of grain-size are arbitrary and different authorities employ different limits. Lower limit of sand generally taken at 0·05 or 0·1 mm.; lower limit of silt at 0·005 or 0·01 mm. Sands derived from undecomposed crystalline rocks and carrying much felspar are called arkose.

Argillaceous rocks; muds, marls and clays; shales and slates; loess, etc.

Chemical deposits

Bedded iron ores.

Inorganic limestones and dolomites, calcareous tufa, etc.

Rock salt, gypsum, nitrates, borates and other saline deposits.

Organic deposits

Carbonaceous deposits – Peat, lignite and coal.

Organic phosphates – Bone beds, guano, etc.

Siliceous deposits – Diatomaceous and radiolarian earth, sponge spicule deposits.

Calcareous deposits – Shell limestones, coral reef limestones, algal limestones, chalk, calcareous oozes (foraminiferal, pteropod, etc.).

Pyroclastic deposits

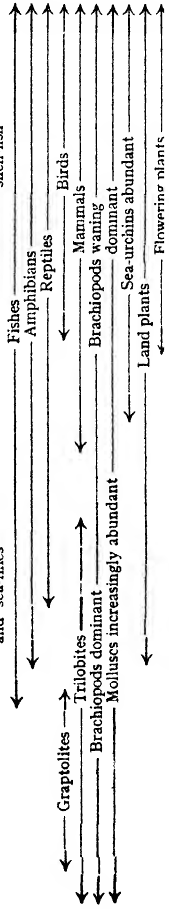
Volcanic ashes, tuffs and breccias.

Residual deposits and soils

APPENDIX II

Geological Systems and Formations

Era	System and approximate age in millions of years	Principal Formations	Fossils
	Recent	Soil and alluvium	Age of Man
Quaternary	Pleistocene 1	Boulder Clay, sands and gravels	
Tertiary 54	Pliocene Miocene 19 (20)	Cromer Forest Series East Anglian Crags not represented in Britain	Dominance of mammals and 'shell-fish'
	Oligocene Eocene 35 (55)	Isle of Wight marls and limestones Bagshot sands, etc. London Clay Thanet Sand	
Mesozoic 120	Cretaceous 50 (105)	Chalk Gault Lower Greensand Weald Clay and Sands	Dominance of reptiles and ammonites
	Jurassic 40 (145)	Purbeck and Portland Kimmeridge Clay Oxford Clay Bath Stone (Gt. Oolite) Lincs. Limestone (Inf. Northants ironst. Oolite) Lias	
	New Red Sandstone Trias 30 (175)	Keuper Bunter	
Upper Palæozoic 160	Permian 30(205)	Magnesian Limestone Penrith Sandstone	Dominance of fishes and amphibia, corals and 'sea-lilies'
	Carboniferous 80 (285)	Coal Measures Millstone Grit Carboniferous Limestone	
	Devonian 50 (335)	Torquay Limestone, etc. or Old Red Sandstone	
Lower Palæozoic 150	Silurian 40 (375)	Downton Sandstone Ludlow Shale Wenlock Limestone Llandovery Sandstone	Dominance of trilobites and brachiopods
	Ordovician 50 (425)	Bala Series Llandeilo Arenig	
	Cambrian 60 (485)	Tremadoc Lingula Flags Menevian Llanberis States Basal Quartzite	
	Pre-Cambrian 1,500 (2,000)	Torridonian, Uriconian, Charnian and Lewisian	



Suggestions for Further Reading and for Reference

(Prices of books are those at time of going to Press)

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