GEOLOGY APPLIED TO BUILDING AND ENGINEERING

Old and New Building at Avebury, Wiltshire *Frontispiece*

The standing stones are part of the oldest prehistoric stone circle in Britain. The stones are from sarsen stones left after the weathering away of Tertiary sandstones originally overlying the chalk. The village of Avebury in the background is in the centre of the stone circle, and is largely built of the broken up stones of the prehistoric circle. A deep ditch also surrounds the circle.

GEOLOGY APPLIED TO BUILDING AND ENGINEERING

BY

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PREFACE

BRITAIN has been much favoured in the variety and wealth of its natural resources, especially in non-metallic substances such as stone, clays, coal, and supplies of water. Most of the geological formations are present, giving the wide variety of landscape and agriculture which is such a noteworthy characteristic. It is natural, therefore, that geological science in Britain should early have reached a high standard. The application of geology to industries and professions other than mining is, however, of later date, but at the present time its importance is widely recognized in the building industry and in civil engineering.

This book, which the author hopes will be of use to students and practising builders, architects and civil engineers alike, deals with certain raw materials which are widely used. Some raw materials, such as sandstone and limestone, are of widespread occurrence, whilst others, such as bitumen, are more restricted. A knowledge of the properties, sources, and methods of testing of these raw materials is of immense practical value; but to have a more comprehensive knowledge of the geology and methods of production of the materials of everyday use is essential in awakening the germ of craftsmanship, which should be present in all builders and architects.

A short introductory chapter on the general principles of geology is given, which should meet the needs of most students, and make the rest of the work readily understood, whilst the glossary given at the end should serve for reference purposes. The chapter on quarrying and mining methods is given to enable a student to realize that the quarrying or mining of stone and ores is an industry in itself, and that the methods used in extraction may have a direct bearing on the cost and the size of the blocks of stone available.

The correct choice of materials which will be satisfactory under the conditions in which they are to be used is of greater structural importance than the choice of a material merely for its aesthetic effect. A correct understanding of surface deposits is essential in Britain, where so much of the solid rock is obscured by boulder clay and other materials. It is hoped that help in this direction will be provided by the chapter on surface deposits and sites.

The book covers adequately the new syllabus in Engineering Geology for Higher National Certificates and of the Union of Lancashire and Cheshire Institutes in Building.

The author is greatly indebted to Mr. J. G. V. Proudman, M.I.O.B., A.M.C.T., Head of the Building Department of the Wigan and District Mining and Technical College, for reading the manuscript, and making many helpful suggestions. The British Standards Institution have kindly permitted the incorporation of B.S. Specifications where they apply to the subject treated. The chemical analyses of rocks given in the chapter dealing with igneous rocks are compiled, with permission, from *The Petrology of the Igneous Rocks* by Hatch and Wells.

The author is also indebted to *Mine and Quarry Engineering* for permission to include the photographs of Figs. 9 and 15 which have appeared in that Journal, and to the Penmaenmawr and Welsh Granite Co. for the photographs forming Figs. 11A and 11B.

A. B.

THE MINING AND TECHNICAL COLLEGE,
WIGAN.

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CHAPTER I

General Geological Principles

To obtain an understanding of the mode of occurrence of the materials used in building and civil engineering it is essential to introduce the geological principles underlying their structure and origin. The first part of this chapter deals in a general way with these principles.

The Classification of Rocks. A rock is an aggregate of mineral crystals, the most abundant being quartz (silica), felspars (alumino-silicates of potash, soda, and lime), and micas (alumino-silicates of potash magnesium, iron and other substances in small amounts). Iron ores and small amounts of a great variety of other minerals often occur in rocks. Some rocks consist of one mineral only, whilst others contain a wide variety of minerals.

Rocks are divided into three main groups as shown below—

ROCKS

Igneous	*Sedimentary*	*Metamorphic*
(originally molten)	(formed as strata	(altered by heat or pressure or both)

The igneous rocks were sufficiently hot at one stage of their formation to be in the molten condition; subsequently they cooled and solidified so that they now consist of an interlocking aggregate of crystals. The sedimentary rocks, on the other hand, were mostly formed as a result of the weathering and erosion of land masses, and the washing down of the sediment so formed into lakes or the sea, where the material was deposited in layers or *strata*. These stratified rocks often contain the fossil remains of animals and plants which were living at the time the strata were being deposited. These fossils, being of a lighter colour than the ground mass, may give a limestone great beauty when it is cut and polished. Typical examples of sedimentary rocks are sandstone, limestone, and shale. The metamorphic rocks in type are either igneous or sedimentary, and have been altered subsequent to their formation by the heat of molten igneous rocks intruded into them, or by the intense pressures developed during periods of earth-movement. These rocks have usually suffered a mineralogical and structural reconstruction. Slate, schist, and gneiss are typical metamorphic rocks.

THE IGNEOUS ROCKS

All igneous rocks were in the molten condition at the time of their formation. They were formed at considerable depths in the earth's crust where the temperature is very high. The pressure of the overlying rocks at that depth is also very high, and in most cases is sufficient to keep these rocks from melting. Any relief from this pressure, however, may lead to the melting of the rock at this depth and to the formation of a molten reservoir or *magma* of igneous rock. This magma may be of enormous size and be thousands of cubic miles in volume. It may cool *in situ* at a very slow rate, and the heat given off into the surrounding and enclosing rocks may be so great as to cause considerable structural and mineralogical changes, converting them into metamorphic rocks. As a result of its slow cooling the igneous magma acquires a very coarse crystalline texture typified by the granites. These enormous masses of coarse-grained igneous rocks are grouped as *plutonic* rocks. The overlying strata concealing the plutonic mass may, with the passage of geological time, be worn off, and the igneous rock be thus exposed at the surface of the earth.

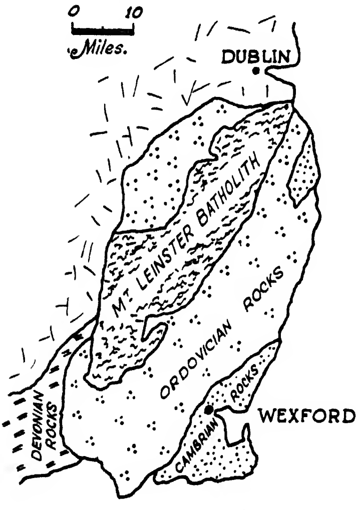

Fig. 1. Geological Map of th Mt. Leinster Batholith

Batholiths. This name is given to the enormous masses of plutonic igneous rocks which outcrop continuously for hundreds of square miles. The Leinster batholith of Southern Ireland extends continuously for almost sixty miles and is about twenty miles wide (Fig. 1). The sides or margins of batholiths are steeply dipping and end sharply against the enclosing rock which is highly altered, often for distances greater than a mile, from the contact with the igneous rock. Offshoots or *cupolas* of the igneous rock may enter fissures in the enclosing or *country* rock, and sometimes large masses of the country rock may be caught up and enclosed within the igneous rock itself. These included masses are very greatly altered by the heat of the intrusion and may be partly melted. The rocks forming these batholiths are mostly granitic in type.

Stocks or Bosses. These are masses of plutonic rocks which resemble batholiths because of their very large size. They are intrusive into the enclosing rocks, and surrounded by a zone of metamorphosed rocks. They are, however, rather smaller than batholiths, and they outcrop at the surface as a roughly circular or eliptical area. The Cornish granite masses and the granites of Criffel, Dalbeattie and other areas in Scotland are typical bosses (Fig. 2).

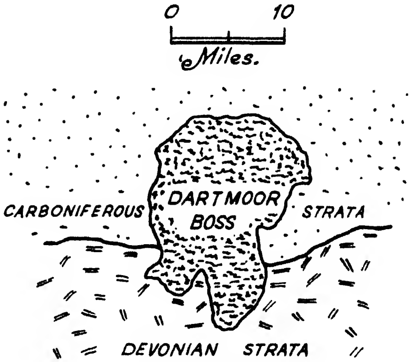

FIG. 2. GEOLOGICAL MAP OF THE DARTMOOR GRANITE BOSS

Large quarries can be opened in batholiths and bosses, and as these rocks cover such extensive areas, favourable points can be chosen for the opening of quarries. Many of these large intrusions show no prominent jointing, enabling long columns and large blocks of masonry to be extracted. In other cases a well-developed system of joints, both vertical and horizontal, is present, giving a wall-like structure known as *mural jointing.* If the joints are closely spaced this limits the size of the stone which can be obtained from the quarry, but it may enable the stone to be got more easily and without the use of much explosive.

Sills. Igneous intrusions may also take the form of sheet-like masses known as *sills* and *dykes.* Sills are thin sheets of rock which have forced their way into strata along the bedding planes (Fig. 3 (*a*)), and appear to be interbedded with the enclosing strata. They may range in thickness from a few inches to many yards, and may cover many square miles in area. The upper and lower margins of a sill adjoining the enclosing rock have cooled more quickly and may have a finer-grained structure than the interior of the sill. Fissures or joints running from top to bottom of the sill may develop a columnar structure throughout the mass. When igneous rocks in the form of sills are of sufficient thickness and the stone of good quality, they are extensively quarried for roadstone, concrete aggregate, and paving setts, as in the case of the Whin Sill, which extends across the North of England.

Dykes. These are vertical or highly inclined sheets of intrusive rock (Fig. 3 (*b*)). They have the same characteristic columnar jointing and finer-grained edges as sills, but they are rarely quarried on account of their narrow width and vertical position, which gives a very short working quarry face.

Volcanic Rocks or *lavas*, were poured out over the surface as molten rock from volcanoes or fissures. Individual flows rarely attain a thickness greater than about ten feet, but many lava flows may be present one on top of the other, building up great thicknesses of lava and forming a plateau-like topography. If lavas are tough and unweathered they may be extensively quarried for roadstone setts and aggregates. The lavas are usually fairly horizontally bedded, and excellent quarry faces can be opened up in them.

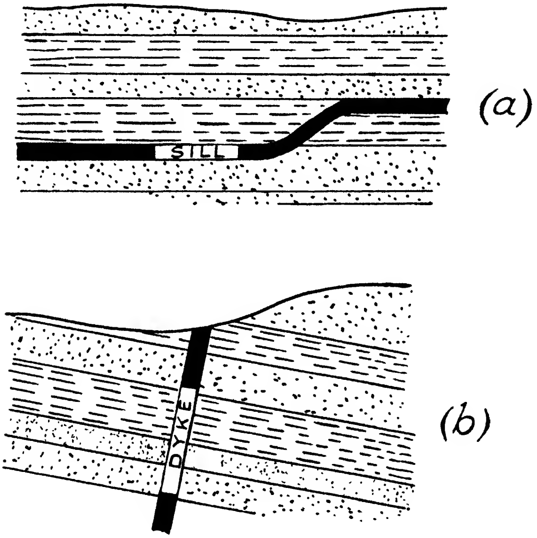

FIG. 3. SECTIONS SHOWING A SILL AND DYKE
(*a*) A sill. (*b*) A dyke.

The igneous rocks have a highly interlocking structure because of their crystalline nature, and consequently have a low porosity and water absorption. They have a density of 150–185 lb/ft^3 of the stone and have strengths in crushing of 800 to over 1 500 t/ft^2. The details of the types and the characteristics of the igneous rocks are given in Chapter IX.

THE SEDIMENTARY ROCKS

Formation and Structures. The sedimentary rocks are formed, in the main, from the debris of previously existing rocks which may have been either sedimentary or igneous in type. All land areas are subject to weathering and erosion by wind, frost, rivers, and chemical action. The surface is crumbled slowly to sand and mud, the softer rocks wearing most rapidly and forming valleys. Where long geological periods are involved, vast quantities of material are removed from the land surface and carried down by rivers and eventually deposited in the sea. The coarsest sands are deposited close inshore, the deposit becoming finer-grained in a seaward direction and gradually passing into muds far out to sea. The sediment is accumulated intermittently, layer upon layer, with considerable time intervals between the deposition of each layer or stratum, with the result that a plane of separation or a *bedding plane* separates each stratum. In the massive sedimentary rocks, the bedding planes may be more than three feet apart, enabling the stone to be quarried in large blocks. Where the bedding planes are a foot or less apart, only small blocks of stone can be obtained. Limestones and sandstones have prominent bedding planes, but shale does not show them very conspicuously. The dip of the strata can be measured by taking the inclination of the bedding planes with the horizontal.

Where the particles of sediment have settled vertically through the water, the rounded grains reach the bottom first, whilst the flakey, micaceous minerals take some time to settle. In this way thin layers of sand separated by a layer of flakes of mica are formed, giving a laminated structure to the stone. The bedded sandstones are often laminated in this way, and tend to split into thin slabs along these lamination planes. The stone has a lower compressive strength in a direction parallel to the lamination planes than at right angles to these structures.

If the sand grains are rolled along the bottom by currents in the water, a false-bedded structure is produced in the rock, consisting of planes of weakness developed at an angle to the bedding planes. Lamination and false bedding are almost restricted to the sandy rocks and are not commonly found in limestones and shales. These structures are discussed more fully in the chapter dealing with sandstones.

Classification of Sedimentary Rocks. Sedimentary rocks can be divided into groups depending on their origin and characteristic features, as given in the table at the top of page 6.

Details of the formation, structure, sources, and uses of these sedimentary rocks are given in later chapters.

Most of the sedimentary rocks contain fossil remains of animals and plants which were living at the same time that the sediments

SEDIMENTARY ROCKS

Arenaceous	*Argillaceous*	*Calcareous*	*Organic*	*Precipitations*
e.g.	e.g.	e.g.	e.g.	e.g.
Sand;	Clay;	Limestone;	Coal;	Salt beds;
Sandstone;	Mudstone;	Oolite;	Diatomite.	Gypsum beds
Conglomerate;	Shale;	Travertine.		
Breccia;	Fireclay;			
Flagstone.	China clay.			

were being deposited. They became entombed in the sediment, the soft bodies decayed away, but the hard shells and other structures were often preserved as fossils. Accumulation of these shells in sufficient quantity may give rise to beds of limestone, and where they have beauty of form or colour, a stone containing fossils may be polished as marble.

Classification of Strata. Fossils are also extensively used in the classification of strata. During the passage of millions of years of geological time, a considerable amount of evolution of plants and animals has gone on. The various evolutionary stages found in rocks as fossils are used in the zoning or classification of strata, which are now recognized by means of the fossils contained in them. A classification or table of strata from the youngest downwards is given below—

QUATERNARY	Deposits of boulder clay. Peat. River terraces.		
TERTIARY *or* CAENOZOIC	*Pliocene*		No important building materials except sand.
	Miocene		No Miocene deposits in Britain.
	Oligocene		No important building materials except sand.
	Eocene		Glass sand. Building sand.
SECONDARY *or* MESOZOIC	*Cretaceous*	CHALK	Cement manufacture. Lime.
		GREENSAND	Building sands.
		GAULT	Brick clays.
		WEALDEN	Building sands.
	Jurassic	UPPER JURASSIC	Purbeck and Portland stone.
		OOLITES	Bath stone.
		LIAS	Shale and limestone for cement.
	Triassic		Red sandstone. Salt and gypsum beds.
UPPER PALAEOZOIC	*Permian*		Magnesian limestone. Red sandstone. Gypsum.
	Carboniferous	COAL MEASURES	Sandstones, clays, coals.
		MILLSTONE GRIT	Sandstones.
		CARBONIFEROUS LIMESTONE	Limestone, cement, road metal.
	Devonian and Old Red Sandstone		Limestone, slate, red sandstone.
LOWER PALAEOZOIC	*Silurian*		Limestone.
	Ordovician		Igneous rocks, slate, building stone.
	Cambrian		Slate.
PRE-CAMBRIAN	Marble, jasper, igneous rocks, gneiss, schist.		

Not all the strata listed above are present in any one locality. Many groups were never deposited in some areas because those areas were land at the time, whilst in other cases they were originally present but have subsequently been weathered and worn away and removed. The map (Fig. 4) shows the distribution of the various groups of strata in Britain.

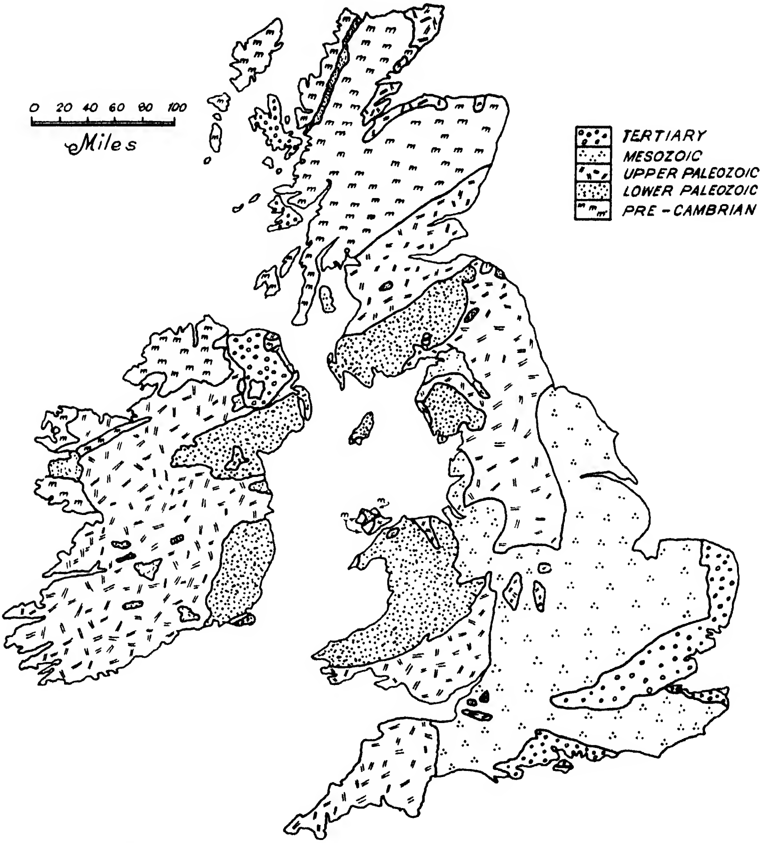

FIG. 4. MAP SHOWING THE DISTRIBUTION OF THE CHIEF STRATIGRAPHICAL SUBDIVISIONS

The Folding of Strata. The attitude or position, and the inclination or dip of strata are of great importance in questions of water supply and the choice of sites. The sedimentary rocks were originally deposited in horizontal layers below either lakes or the sea. At the present time, however, these strata occur on land, often in an inclined position and frequently folded or crumpled. This folding is due to pressures developed in various directions during adjustments of the earth's crust. If the strata are deeply buried whilst the pressures are active they may be greatly folded and crumpled. If the strata will not bend they may fracture or be faulted.

Where the strata come to the surface they are said to *outcrop*. The width of the outcrop of a stratum at the surface is determined by the thickness of the bed and its dip or inclination. The dip is the direction of greatest slope of a stratum, and the angle of dip is usually expressed in degrees with the horizontal direction. The direction at right angles to the dip is termed the *strike* and is always horizontal (Fig. 5).

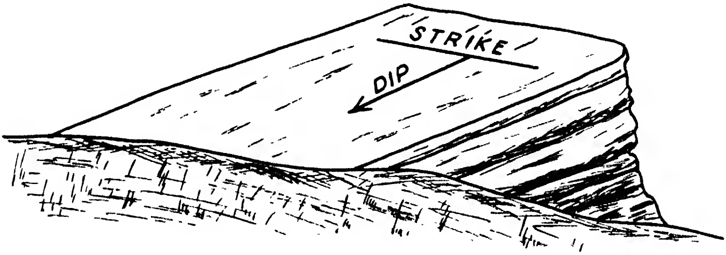

FIG. 5. SKETCH OF AN OUTCROP, SHOWING THE DIRECTIONS OF DIP AND STRIKE

The dip and strike of a series of strata may change from place to place, giving rise to fold structures many of which are given distinctive names. The direction and amount of dip is important in problems of water supply and in estimating the danger of pollution of wells from farms and other sources as described in the chapter on water supply. The stability of excavations and hillsides is also affected by the direction and amount of the dip of the strata outcropping on the slope.

Anticlines and Synclines. The commonest type of folding is the arch and trough. The arches are known as *anticlines* and the troughs as *synclines* (Fig. 6). The dip of the strata may be the same on both sides of the fold, when it is termed a *symmetrical* anticline or syncline, or the limbs may dip at different angles, when the fold is said to be *asymmetrical*. These structures may be only a few yards across, or they may be large folds several miles across from one side to the other. The flanks of folds such as these may be slightly corrugated, or the dip may change slightly from place to place whilst the general structure is an anticline or a syncline.

Monoclines. In many instances one limb of a fold is vertical whilst the other limb is gently dipping (Fig. 7). Structures such as these are termed *monoclines*. The outcrop of the vertical limb of the fold is narrow, whilst that of the same bed in the gently dipping limb may cover a large area. In districts where the strata are vertical, a slight shift of a projected site may place it on an entirely different kind of rock. The general structure of the Isle of Wight is a monocline with the vertical limb running in an east to west direction across the centre of the island.

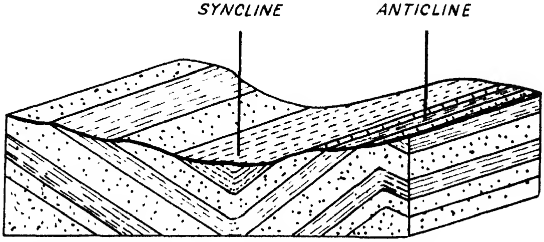

Fig. 6. Block Diagram of a Simple Anticline and Syncline

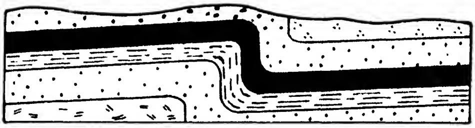

Fig. 7. Section of a Monocline

Recumbent Folds. In some areas such as Anglesey and parts of north-west Scotland, the strata are inverted so that younger strata come to be overlain by older ones. This structure is due to very intense pressures rolling the strata forwards until an "S" shaped bend is produced (Fig. 8), with gently dipping limbs. In the middle limb the strata are in reverse order, the oldest being at the top. Where the upper limb of the fold is eroded away the inverted strata are at the surface.

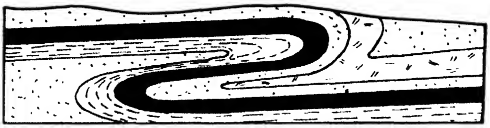

Fig. 8. Section of a Recumbent Fold

Sometimes, in highly folded areas, strata are much crumpled and buckled, or *contorted* (Fig. 9). Sharp bends and rapid changes of dip occur, and the softer shaly beds may be packed into the corners of the folds. There may also be much sliding and movement along the bedding planes. Typical examples of contortion are found in Dorset and other places. Areas in which the strata are contorted in this manner may provide difficult foundations for large buildings, as slight movements and adjustments of the strata may take place.

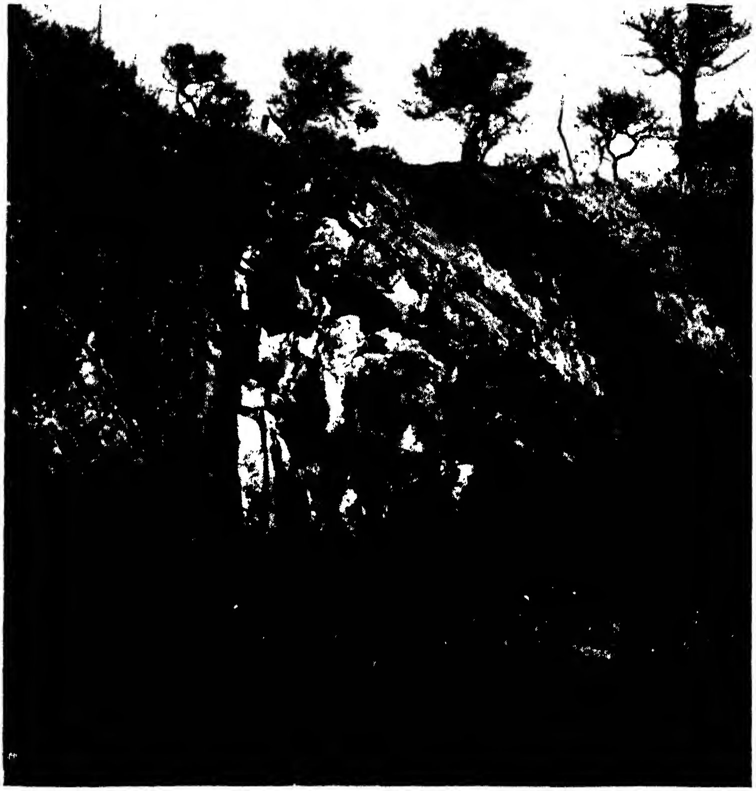

FIG. 9. FOLDED LIMESTONE STRATA NEAR CLITHEROE
(*Mine and Quarry Engineering*)

Faults. If strata are unable to adjust themselves to the earth pressures by bending, they fracture, or become *faulted*. Faults are fissures along which movement has taken place. The strata on one side of the fault have moved down relative to those on the other side (Fig. 10 (*a*)). Faults may run for miles on the surface, and the amount of downward movement may be a few feet to many thousands of feet in the case of large faults.

The terms used in describing faults are illustrated in Fig. 10 (*a*).

Most faults dip or hade at an angle of about 30° with the vertical, and the strata at the surface on one side of a fault may be quite different from those on the other side. The two are brought together as a result of faulting, and the two types meet along a well-defined line. A move of a few yards to one side may result in a change from damp clay to dry sandy foundations, so that a recognition of faulting and its effects may have some bearing on the choosing of a site for a building. Slight movement or slipping may occasionally take place along a large fault, and if a building is so placed that a fault crosses through the foundations, some danger of movement may be present.

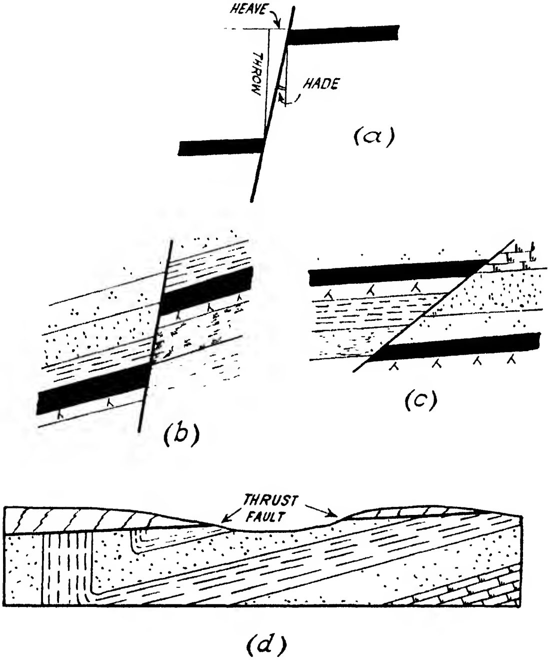

Fig. 10. Diagrammatic Sections of Faults

(*a*) The terms used in describing faults.
(*b*) Section of a normal fault.
(*c*) Section of a reversed or overlap fault.
(*d*) Section of a thrust fault.

Earthquakes are caused by movements along faults. In some areas such as Japan, Italy, and the San Francisco district of the United States, where the strata have been folded in recent geological times, movements along faults on a large scale may take place and disastrous earthquakes may result. Even in Britain, small earth-tremors associated with some of the larger faults are frequently recorded on instruments, whilst occasionally the tremors are intense enough to be felt by persons in the vicinity.

CLASSES OF FAULTS

Normal Faults. These are the most common type and in some areas, especially where the older rocks are at the surface, they occur in large numbers. Normal faults slope in the same direction as the downthrow side (Fig. 10 (*b*)). Some normal faults have displaced the strata for several thousand feet, whilst in other cases the amount of movement is almost negligible. Sometimes a number of normal faults occur together at a few feet apart. They have the effect of shattering the ground between them. These *shatter belts* should be avoided for use as building sites if it is possible.

Reverse or Overlap Faults. These are common in regions which have been intensely folded. The faults slope or hade at an angle of about 45°, and the rocks on one side of the fault have overridden those on the opposite side (Fig. 10 (*c*)). A shaft, or a borehole, put through such a fault, would pass through the same stratum twice.

Thrust Faults or Slides. In many cases where extreme earth pressures have been developed, very flat reversed faults may be formed in which the rocks on the upper side of the fault have overridden those on the lower side for a distance of many miles (Fig. 10 (*d*)). The Moine Thrust Fault situated in the north-west of Scotland, runs for a distance of sixty miles in a north-south direction, and pre-Cambrian rocks are thrust over Cambrian strata for a distance up to eight miles to the west.

Tear Faults. These faults have no downward movement, but blocks of the crust have moved horizontally forward along the tear fault. On a geological map they closely resemble normal faults. Tear faults are restricted to highly folded areas and are often associated with thrust faults.

THE WEATHERING OF STONE

The presence of hills and valleys and similar surface relief is ample evidence of weathering and the removal of rock, which can be accomplished by natural processes. The softer rocks such as shales are worn out into valleys, whilst the harder igneous rocks, limestones and sandstones, may stand out as high ground or even as mountains. The agents by which this effect is produced are frost, which can break off large blocks of stone; sand and dust-laden winds, which scour the surface of any projecting rocks; and the very potent effects of river and stream erosion and moving glaciers.

These weathering processes act on stone which is used in buildings, and there are in addition the chemical effects caused by acid and soot-laden atmospheres, and the effect of organisms such as bacteria and lichens. The effect of these processes will depend largely on the porosity and water absorption, and the chemical composition of the stone or its cementing medium.

Effect of Frost. Frost is a very potent agent in the decay of stone, especially where alternate freezing and thawing take place. When water changes its state and becomes ice it expands in volume by nearly one tenth. If the water is totally confined it will exert an expansive force of about 138 t/ft^2. If *all* the pores of a stone are quite full of water at the time of freezing, this pressure will be exerted, and the stone will suffer, but normally the pores are seldom completely full, and the forces of expansion can be relieved by water passing into empty intercommunicating pores.

The frost resistance of a stone will depend to a large extent on its porosity and on the arrangement of the pores. The more porous stones are usually, but not always, the most affected by frost action, and the crushing strength of a stone is not an index of the resistance of the stone to frost action. Some very open rocks such as tuffs, which have a cellular structure, do not suffer much from frost, as the pores are open and are interconnected, thus allowing relief from the expansion of the water on its conversion to ice.

In testing a stone for its resistance to frost action, the test sample is soaked in water and alternately frozen and thawed twenty-five times, and the loss in strength in tension and in crushing is noted. Sometimes the stone is soaked in solutions of sodium sulphate and dried out. Crystals of sodium sulphate then form and exert an expansive force in the same way as ice.

Action of Industrial Atmospheres. Ordinary rain-water, when not polluted with acids and soot, has but little effect in weathering stone. In most cases, however, even in country districts, some dissolved carbon dioxide gas is present in the rain, and this acidulated water has a slight solvent action on limestone. This is well shown in old limestone walls and in places where limestone has been exposed to the weather for long periods. The fossils usually present in the rock are harder and more resistant to weathering than the matrix, and they stand up above the general surface level of the stone.

In towns, however, the atmosphere is laden with industrial gases such as sulphur compounds, sulphuric acid, hydrochloric acid, and nitric acid. Soot and tarry substances are usually present, and fogs are of more frequent occurrence in towns than in the country. The effects of acids in causing the decay of stone are examined in the chapters dealing with sandstone and limestone. Soot in the atmosphere causes the blackening of buildings and acts as a holder of injurious substances. Fog is a very active agent of decay, as the acidulated particles of moisture condense on the surface of the stone.

Sea-water and the rain of seaside districts may contain sodium and magnesium chlorides which may attack lime, iron, and aluminium silicates, and may cause a greater degree of decay than in country districts.

Effect of Living Organisms. In country districts lichens may grow on masonry and roofing tiles, especially the calcareous types. The hyphae of the lichen may penetrate the surface of the stone to a depth of about 1 mm and assist in its decay.

Marine algae and sponges of various types may bore into the stone of sea walls and such-like structures and riddle them with small holes, causing a complete loss of strength. In some situations large mussel-like shells called *Pholas* bore holes up to ½ in. in diameter into masonry structures bordering the sea, causing very great damage and the need for replacement of stone after only a few years.

Mechanical Weathering. Mechanical wear of stone may be caused by sand-laden winds in districts adjacent to sand hills. Stone steps are subject to much friction and wear. The coarser and more friable current-bedded stones may wear badly and become unsightly when used for steps and treads.

Scaling and crumbling due to the effects of alternate heating and cooling is very marked in certain types of rock when used in sunny exposed situations. Coarse-grained rocks such as granites are composed of several different types of minerals, including quartz, felspar, and the white and dark varieties of mica, and the alternate heating and cooling may cause the rock to crumble due to the internal strains which are set up. The different types of mineral expand and contract at different rates, and these frequently repeated stresses may disintegrate the rock. If a hard granite is heated in a bunsen flame a few times it can frequently be broken and crumbled between the fingers. The close-grained rocks made of one or two minerals only, resist the effects of heating and cooling very well, especially if they have an interlocking structure.

The expansion of masonry blocks may have some effect on the joints of the building. The linear expansion of various rocks is given below (from various authorities). The small amount of expansion of long coping stones may loosen the joints and allow water to enter. A slight loss of strength may also result from the expansion and contraction of some stones.

Type of rock	Linear expansion per inch per 1° F
Granite	0·000 004 82 to 0·000 008 6
White Marble	0·000 005 67 to 0·000 006 13
Sandstone	0·000 009 53 to 0·000 001 74
Slate	0·000 010 4

CHAPTER II

Quarrying and Mining Methods

QUARRYING is an ancient art, and many old quarries are preserved in Egypt which were used to supply stone for the obelisks and other monuments in the Nile Delta. At Aswan is an incompletely quarried obelisk of granite, 137 ft long which, if extracted, would have weighed 1 168 tons. It had been abandoned because of unforeseen cracks. Where large blocks such as these were required, the form of the block was marked out in the quarry floor and a trench up to 3 ft wide was sunk round the margin of the block. Wedges and chisels were used and also stone balls probably placed on rammers. With large blocks it may have taken more than eight months to hammer out a trench round the block. On the completion of the trench the block was undercut in the same way, and then cracked loose. Limestone roofing slabs were also used several thousand years B.C.

The modern methods of obtaining the raw materials used in building operations are very varied, and depend to a great extent on the mode of occurrence of the material and the output required. Many quarries are simply holes in the ground from which material is extracted as required. Many of these are controlled by county surveyors, but the tendency nowadays is to amalgamate small concerns into large quarries with outputs of hundreds of thousands of tons per year.

Where only a certain well-defined stratum is of value, this bed may be extracted by underground mining methods as in the Purbeck stone mines of Dorset. Where several different products are obtained from a single quarry, special methods of quarrying may have to be used to keep the different classes of materials apart. In quarries with small outputs, hand methods may be used throughout, but the larger undertakings are usually highly mechanized, using mechanical excavators and washing, screening, and crushing plant. Where gravel, sand, or clay is obtained from stream beds or estuaries, dredges and grabs may be employed. The mining of the ores of metals and pigmenting materials is a highly specialized undertaking requiring much capital and plant. Explosives such as gunpowder or gelignite are extensively used for bringing down the stone, and in large quarries thousands of tons of rock may be blasted down in one operation by means of tunnel blasts, using large quantities of explosive at one time.

QUARRYING

The Site and Planning of Quarries. Quarries may be opened on hill-tops, in hill-sides, or as holes below plain level. Where a quarry is opened out on a hill-top, the quarry faces can be kept at a safe height and gravity chutes can be used to bring the broken stone to the crushers and screening plant at the bottom, or mechanical haulage using endless ropes and wagons can be employed to bring the quarried rock to a lower level. The rock passes in at the top of the dressing plant and this facilitates the handling of the stone within the crushing plant. The overburden of soil or boulder clay, if this is present, must first be removed and dumped away from the workings. The methods of quarrying can best be shown by descriptions of a typical quarry of each type.

The Hill-top Quarry of the Penmaenmawr Granite Co. This company works a very large stone quarry on a hill-top site at Penmaenmawr Mountain in North Wales (Fig. 11A), and a description of the workings well illustrates the method of hill-top quarrying where large tonnages per annum are required. The rock quarried is an *enstatite diorite* which has a close interlocking structure and is of great toughness and durability. The output is several thousand tons a day and is used as broken stone in various sizes, chippings from $\frac{3}{4}$ in. downwards, and setts. The sizes less than $\frac{1}{4}$ in. in diameter are used in concrete work and for the manufacture of flags. The mountain rises to 1 350 ft above sea level, and the top is being quarried off layer by layer. If the quarry had been started off into the hill *side* at the bottom, the faces would soon have become dangerously high.

The system of working is by means of *banks* or faces, each about 100 ft high. The original top of the mountain has already been sliced off by quarrying out one bank. Holes are drilled by machines to a depth of about 20 ft from the top of the bank, and charged with black powder which is fired by means of fuses. After blasting, the loose blocks of rock are cleaned off the faces and the bank is then ready for another round of blasting. Any very large blocks of stone too big for handling are broken again by means of explosives. The broken rock is loaded at the face into side-tipping wagons by mechanical shovels, and transported along steep inclines down the mountain side to the crushing plant. Some of the inclines are set at 1 in 12, and 1 in $2\frac{1}{2}$. The broken rock is discharged into primary crushers and then the crushed rock passes through screens. Conveyors pass the various sizes to large storage hoppers. This plant is over 1 000 ft up the mountain. The crushed stone from the hoppers is lowered down two inclines to a secondary crushing plant

FIG. 11A. HILL-TOP QUARRY OF THE PENMAENMAWR AND WELSH GRANITE COMPANY AT PENMAENMAWR, NORTH WALES

The quarry faces are clearly seen. The huge storage bins are seen half-way down the mountain. The rock is quarried for roadstone, aggregate, and setts.

(*Penmaenmawr and Welsh Granite Co.*)

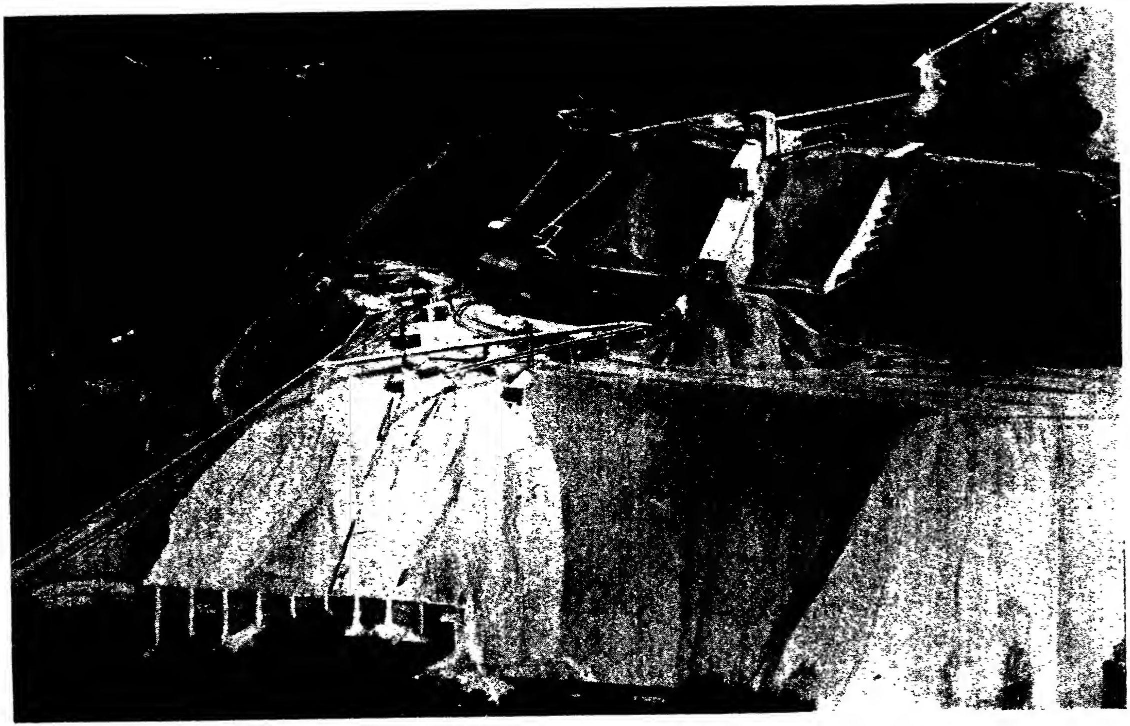

FIG. 11B. ONE OF THE GREAT STORAGE BINS AT THE PENMAENMAWR QUARRY

Its capacity is 200 000 tons.

(Penmaenmawr and Welsh Granite Co.)

where the stone is crushed in conical gyratory crushers. The various sizes of crushed stone are stored in large concrete hoppers, each having an enormous storage capacity (Fig. 11B). The crushed stone is distributed by road, rail, and sea, as the company has its own loading jetty adjoining the quarries.

By quarrying slices off the top of the mountain in this way, the quarry faces can be kept at a safe height and, if the crushing and screening plant is at the bottom, the stone travels always in the same direction and can be transported by gravity chutes and self-acting inclines.

A variation of this top slicing method is employed in some of the quarries in Liassic limestone used for manufacture of cement. This limestone occurs in thin beds interleaved with thin beds of shale. The quantity of shale is in excess of the amount required for cement manufacture. The layers of limestone are picked up by mechanical excavators working horizontally. After a bed of limestone is removed in this way, the underlying shale bed is removed and the excess shale over what is required is stacked on spoil heaps. On the removal of this shale bed the next lower layer of limestone is taken up. In this way the work proceeds as a series of horizontal slices.

Hill-side Quarry Sites. Quarries in hill-sides are very common, especially where the concern is small or the hill being quarried is not much above 100 ft high. If the hill is higher than this, however, the height of the quarry face becomes increasingly great as the face moves into the hill, and the danger of falls of rock from above increases. Where certain strata only are of value, it may be advantageous to extract them by mining methods by making an entry through the hill-side into the desired beds.

Where the face of a hill-side quarry is becoming unduly high, however, it may be stepped and thus rendered safe. Several *benches* or steps are formed, the upper benches being stepped back relative to the lower steps and the quarry floor. By having several of these benches in work at the same time, large tonnages of rock may be obtained whilst the individual benches or faces are little more than 100 ft high, and are safe. Most large slate quarries are operated as benched hill-side quarries in this way. The faces may be fully mechanized and equipped with excavators, and light railways may run along the floors of the benches. Inclines may connect the several benches with the crushing and dressing plant and the quarry floor.

Hill-side sites are particularly suited to comparatively thin deposits such as sills of whinstone or dolerite, and these are much quarried especially in Scotland and Northumberland, for setts, roadstone, and concrete aggregates. The Blue Whinstone quarry near Troon in Ayrshire is of this type. The stone which is quarried is a very tough, hard dolerite, occurring as a sill 80-100 ft thick, forming the Dundonald Hills. This sill shows a prominent columnar jointing structure which reduces considerably the amount of explosive required to bring down the face. The quarry is worked as a single face about 1 500 ft long. Shot-holes for blasting the stone are drilled to depths of about 14 ft and charged with blasting gelatine. About fifty holes are spread along the face and when fired may bring down about 20 000 tons of rock at a time. When any blocks of broken stone are too large to handle, a short shot-hole is drilled into it and it is broken with a small charge of explosive. The broken rock is loaded and taken to the crushers where it is reduced in primary and secondary crushers, and the sizes separated out by screening. The dust produced by crushing is ground fine and used as a filler for bituminous compounds and asphalt work. Conveyors move the stone to the crushers and screening plant.

Quarry Sites below Ground Level. In such cases the quarry is a large hole in the ground, and everything must be hoisted or hauled out of the quarry to the dressing and crushing plant at the surface. The drainage of the quarry may be a difficult matter, and, in this type of works, provision has to be made for pumping out the water which may have accumulated on the quarry floor. The greater the depth of the quarry, the greater are the pumping and haulage problems. Brick-clay pits are usually of this type. In the case of brick pits there is usually an incline leading from the quarry floor to the plant and kilns at the surface, and the quarry trucks may be hauled up by endless rope runways, the empty trucks helping to pull up the full ones.

In some instances, stone is also quarried below plain level. The Aberdeen granite at Rubislaw is obtained by this method. The granite improves in quality with depth, and there is, therefore, a tendency to deepen the quarries rather than to extend them laterally. The Rubislaw quarry is over 400 ft deep and extends well below sea-level. As the granite is required in large blocks the minimum of explosive is used in quarrying, full advantage being taken of the joint fissures in the granite. The larger blocks are set aside for monumental and engineering work, whilst the smaller ones are used for setts or are crushed for roadstone and aggregates. The large blocks are lifted out of the quarry by suspension cableways, which can handle such blocks expeditiously and deliver them to the surface, where they are sorted and classified for quality and size before being sent to the granite works for sawing, dressing, and polishing. Setts and building stone from the smaller stuff are prepared at the quarry. The material for roadstone and chips is crushed to size in the modern crushing plant at the quarry and dispatched by road.

Tunnel Blasts. Where very large tonnages of rock are required from a face, tunnel blasting operations may be carried out. These bring down thousands of tons of stone from a quarry face at one operation, and consume large quantities of explosives. The face and the area behind are carefully examined to discover any major joints or breaks. Small tunnels about 3 ft wide and 5 ft high are driven into the face for 20–30 ft. Branch tunnels are driven at right angles to the main tunnel for a distance along the fissure along which it is desired to break off the face (Fig. 12). Chambers are then excavated at the ends of these tunnels and afterwards filled with explosives such as black powder or blasting gelatine. The galleries are packed tight with broken rock, leaving a long fuse to connect with the explosive. When the galleries are tamped tight, the charges are fired, and the resulting explosion may bring down great sections of the quarry face. In this way, upwards of 100 000 tons of rock may be quarried at one time. Tunnel blasts are especially suitable for long faces where well-defined fissures are present, as in some limestone quarries.

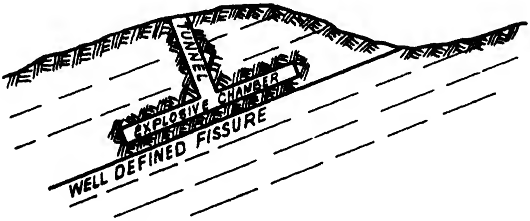

FIG. 12. PLAN OF QUARRY FACE READY FOR TUNNEL BLASTING
The tunnel to hold the explosive is placed along a major break or joint along which the face will be blasted off.

Sand Quarries. Sand pits are very variable in type. They may be small concerns worked by one or two men, in which the sand is dug and loaded by hand with no, or only a rough, screening to remove any pebbles. In large mechanically operated quarries the sand may be dug by means of draglines or shovels and conveyed to washeries which wash the sand to remove any clay or stones which may be present. In some very large undertakings *blended* or *graded* sands, in which different sizes of grain are mixed together in definite proportions, may be produced. Where blended sands are required for the formation of dense concrete, it may be necessary to separate the sand from the quarry into graded sizes and recombine them in definite proportions as required for the blended sand. Blending is sometimes carried out because the natural sand of a deposit may vary from place to place and not be in the proportions of the various sizes which are required. The separation of the sand into different grain sizes may be carried out by settling in water or in special classifying machines.

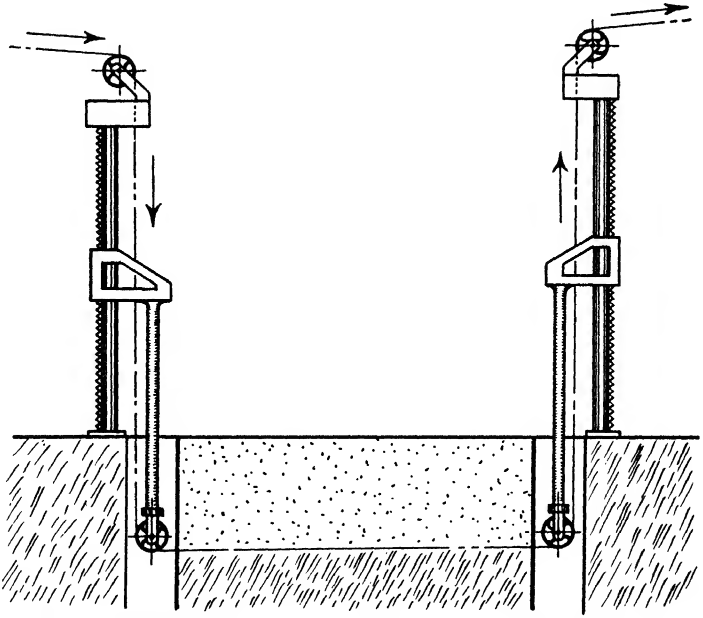

FIG. 13. SECTION SHOWING THE METHOD OF CUTTING MARBLE, USING WIRE FED WITH SAND

Holes or trenches are sunk at the end of the section to be cut. The cutting wire passes over pulleys which can be gradually moved as the wire is cutting the rock. The diagram shows a vertical cut being made.

Quarrying of Marble. The sawing and quarrying of marble is a very ancient industry. Stone saws were used in Egypt and some had rectangular teeth made of emery, but usually the saw used sand for cutting. By the fourth century A.D. power saws were used. The marble was usually cut into slabs and used as a veneer.

Statuary marble and the marble used for facings is now quarried by special methods. The use of explosives must be reduced to the absolute minimum to avoid shattering the stone, and to enable the largest sizes of blocks to be obtained free from flaws and cracks. The usual method is to *saw* the marble blocks out of the quarry, using wire saws armed with sand. Horizontal cuts or channels are made along the quarry floor 40–50 ft in length and 20–30 ft in depth, using wedges or other means. Posts are set up in the cuts or trenches and fitted with pulleys to guide a cutting wire (Fig. 13). The cutting wires are of high tensile steel and travel at over 1 000 ft/min, and may be up to 1 000 yd long. Wet silica sand is supplied to the wire as it travels between the pulleys. The sand is picked up by the wire and is the real cutting agent. The sand and water are mixed in tanks near the entrance of the wire into the cut and are supplied to the wire at this point. In this way slabs and blocks of marble are cut out of the quarries, which, as a result, show deep vertical faces where the stone has been cut out. The stone is then cut into suitable sized blocks which are hauled out of the quarry and sent to the cutting sheds where they are sawn into blocks of sizes such as are required.

MINING

Mining of Stone. Sometimes the stone which is of value occurs as a single stratum up to about 20 ft thick, or, in some cases, it may be only a few inches thick, as in some of the thin bedded limestones used as roofing slabs. In cases such as these, the stone is not obtained from open quarries, but is mined by underground methods similar to those used in the mining of coal. Entry to the stone-bed may be made by means of a tunnel or adit into the hill-side, or shafts may be sunk from the surface to the required stratum. The floor and roof of the stratum are bedding planes, and the stone breaks off along these fissures. The stone is usually mined by the pillar and stall method, in which tunnels are driven in a rectangular pattern, serving to block out the stone bed into a series of rectangular pillars. Slices are taken off the pillars in a methodical fashion until they are completely mined away. The stone is blasted out by drilling shot-holes either by hand or machines, to a depth of several feet. The holes are charged with explosive and fired by a fuse, or electrically. The pillars serve to support the roof whilst the working is proceeding. The stratum is not completely mined out, but some of the pillars are left in permanently to support the roof and keep the workings open. The size of the pillars left in for support depends on the strength of the roof and the value of the stone. So far as is practicable, the poorer quality rock is left in as pillars for support, whilst the better quality is extracted. Where the rock is strong and the roof is good, these stone mines remain open for very long periods without collapsing. Much of the Bath stone and the Purbeck stone is obtained by these mining methods, and the underground workings are very extensive.

Mining of Ores and Minerals. Ores and minerals such as those of lead and zinc and the non-metallic minerals such as barytes are usually found in veins. These lodes or mineral veins are faults which have been mineralized by the interaction of dilute mineral-bearing solutions. These solutions had their ultimate origin from the plutonic, igneous magmas. On the cooling of these magmas, the gases and solutions which often contained minerals, left the magma and passed up any faults and fissures which were available. Cooling and reactions between the substances in solution in many cases led to the deposition of ores of lead, zinc, barytes, tin, and other minerals, within the fissure or fault.

Mineral veins are steeply inclined, and they are entered by shafts which may be vertical or inclined, or by adits or tunnels driven into a hill-side to the vein. When the vein has been entered either by the shaft or adit, horizontal tunnels are driven in the vein itself in each direction. The shaft is continually being deepened, and other levels at intervals of 100-200 ft down the dip of the vein are set off. These levels are connected by *winzes* (or small shafts extending from level to level and about 100-200 ft apart). These winzes in the vein itself provide openings and working faces in the vein from which the ore can be blasted out. Samples of the ore for assaying can be obtained from the sides of the winzes before working is started. Most veins are usually patchy, some portions being rich and payable whilst other patches may be barren and contain very little ore. The object of driving levels and winzes in the vein is to locate these rich patches as well as to provide working faces. Only the payable portions of the veins are extracted. Where the vein itself is very narrow, much barren rock has to be mined with the ore to allow room for the passage of men and equipment to the workings. The ore may be roughly sorted underground, the waste rock being thrown back into the old workings. The *run of mine* ore is taken in trucks either by hand or locomotive to the shaft bottom and raised to the surface.

Before the ore can be sent to the smelters or other destination, it usually requires concentrating or, where different ores are found in the same vein, separation into the different products. This is done at the mine in the dressing plant, using gravity separation or other physical or chemical processes. The waste rock is sent to the dumps, and the clean ore is sent to the smelters or other users.

CHAPTER III

Surface Deposits and Sites

THE nature of the surface deposits which overlie the solid rocks is of great importance in the preparation of sites, and the carrying out of sewerage and drainage schemes. In most parts of the country solid rocks are not immediately at the surface, but are covered with soil and subsoil, or deposits of boulder clay, peat or sand, which may have no relationship to the type of solid rock underneath. The great variability of some surface deposits may make it difficult to estimate the cost of drainage and sewerage schemes unless a number of trial pits are put down first.

Some proposed sites for large buildings may prove unsuitable because of the unstable character of the underlying formation. In many cases it may be desirable to find a more satisfactory position a short distance away. The danger of land slips and cliff falls may, in some instances, prohibit building in the vicinity of such areas, and they may be laid out as grass beds or gardens. A thorough knowledge of surface deposits in relation to siting problems should be possessed by contractors and builders.

SURFACE DEPOSITS

SOIL AND SUBSOIL

Where solid rocks outcrop at the surface, frost, rain and the weather begin to act on the rock and tend to disintegrate it. This process has been going on for thousands of years, with the result that the surface rocks are broken up to a depth of several feet, depending on the type of rock and the rigour of the climate. This broken rock or *subsoil* passes gradually into the unbroken solid rock below (Fig. 14). The subsoil is usually light in colour and is deficient in organic matter. Nearer the surface the subsoil is broken up into fine grains making the soil layer, which may be from a few inches to over a foot in thickness. Organisms such as worms, plants, bacteria and fungi assist the climate in producing the soil layer, and this top stratum passes gradually downwards into the subsoil. The formation of soil is a slow geological process, so that the removal of the soil from an area should not be carried out without thought. On sloping ground the soil tends to creep downhill, so that soils are thicker at the bottom of slopes and in valleys than towards the tops of the hills. Vegetation and trees tend to fix the soil, and the removal of this cover may lead to the development of runnels and the washing away of the soil. The soil in the valley bottom may also be ruined by the washing over it of subsoil material, carried down from the hill-tops and slopes.

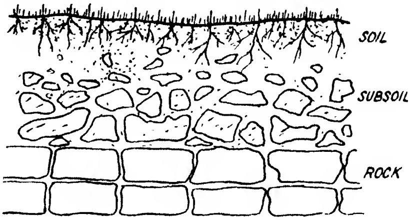

FIG. 14. SECTION SHOWING THE RELATIONSHIP OF SOIL TO SUBSOIL AND ROCK BELOW

Soils vary in the degree to which they corrode metal pipes embedded in them. A soil may badly attack iron pipes and not affect a lead pipe. The acidity of soils varies considerably, and they may also differ greatly in their electrolitic effects, causing pitting of iron pipes. Iron pipes may be protected by a coating of bitumen if they are to be buried in soil. Corrosion of iron pipes may occur in wet clay soils due to the action of sulphate-reducing bacteria. The bacteria act on sulphates in the soil and form hydrogen sulphide which reacts with the iron of the pipes to form soft iron sulphide. The affected pipes become soft and can be cut with a knife. The clay in contact with the pipe is blackened but readily oxidizes on exposure. Hessian and other packing material of pipes may form food for these bacteria, and treatment of the hessian with bitumen does not greatly help. Very great care should be taken not to damage the protective coating on pipes as they are being laid.

Sand and gravel subsoils, when not waterlogged, are healthy, but clay and alluvial soils may be damp. Clay, however, may be good if it is well drained. If subsoils are drained it may cause a settlement of foundations. Wells sunk even at some distance away may cause settlement and cracking of the walls of buildings.

CLAYS

Boulder Clay. Boulder clay, drift, or till is the most usual surface deposit found north of a line running from South Wales, through the Midlands, down to the London area. It is a residual deposit formed by glaciers and ice sheets. Areas south of this line were not covered with ice during the Ice Age, and consequently boulder clay is not found therein. The country north of this line, however, is covered over large areas by boulder clay except in certain small areas in the upland regions. In these small, unglaciated districts the surface rocks are very deeply weathered and decomposed to a considerable depth from the surface. In the glaciated areas the decomposed and rotted rock has been removed by the moving ice sheets, so that the solid rock beneath the deposits of boulder clay is usually fairly fresh and but little weathered.

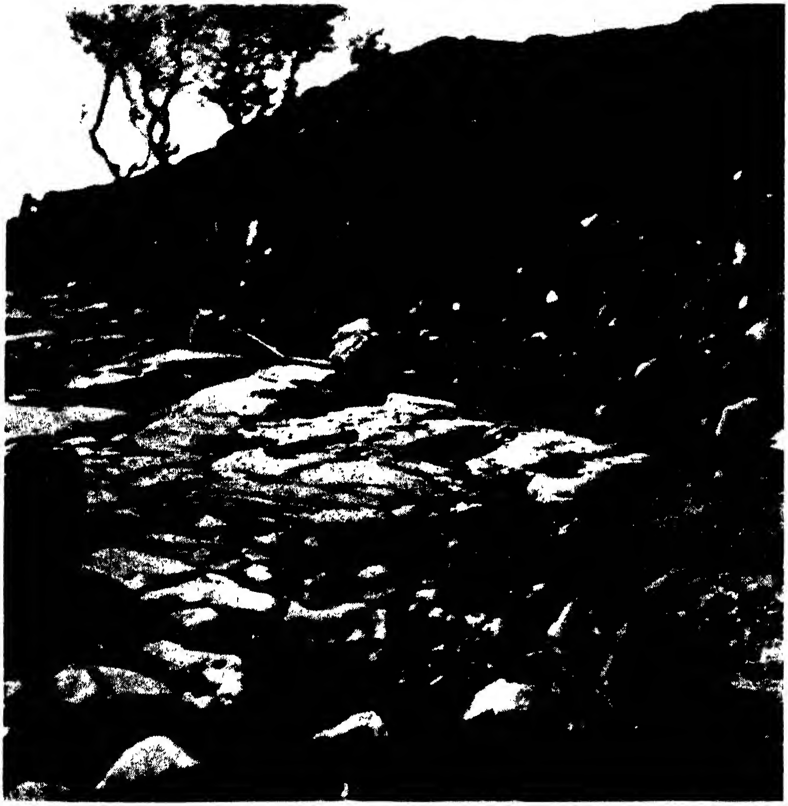

FIG. 15. BOULDER CLAY RESTING ON AN ICE-SMOOTHED SURFACE OF LIMESTONE

The clay contains blocks of igneous rock, sandstone, and limestone which have been carried by glaciers to their present position. The overburden of boulder clay is removed prior to quarrying at the Bold Venture limestone quarry near Clitheroe.

(*Mine and Quarry Engineering*)

Boulder clay is a stiff blue or brown clay in which are embedded pebbles and boulders of all shapes, sizes, and types, without any orderly arrangement (Fig. 15). The pebbles may be of igneous or sedimentary rocks, or a combination of the two; they are subangular in shape and have scratched, smooth surfaces. The great majority of the pebbles show sets of fine parallel scratches or *striae* on their surfaces, due to being scraped along the surface over which the glacier was moving, whilst the pebble was still embedded in the ice. If the pebbles consist mainly of igneous rocks, the boulder clay may be quarried for its pebble content for use as concrete aggregate. In some areas where limestone pebbles are abundant in the clay they are extracted and used locally for lime burning.

The matrix of boulder clay is soft and plastic, and, if but few pebbles are present, may be suitable for brick-making in some districts, if a machine for removing the pebbles is employed. In East Anglia the boulder clay is chalky in character, due to being transported from the chalk outcrops in the vicinity, whilst in some counties the deposit is more sandy than clay. Boulder clay is very variable in character and may change rapidly in short distances without any surface indications of the fact. The thickness may reach up to 100 ft in exceptional cases, or may be a covering only about 1 ft thick. The boulder clay surface may be hummocky, or it may form a smooth, fairly level, plain. The under-surface of a sheet of boulder clay adjacent to the underlying solid rock, however, may be very irregular, and considerable elevations and depressions of the sub boulder-clay surface may be concealed.

The present surface topography of a district may show no relationship to the old land surface of pre-glacial times. Old pre-glacial river valleys may have been filled in with drift, and give no indication of their presence by surface features. Where foundations must be placed on solid rock, trial pittings may reveal the presence of these buried channels. A much smaller depth of excavation would be required if the site were put a short distance to one side, so as to avoid the buried channel. In many cases also, boulder clay is banked up at one side of a stream valley, leaving the other side clear, with solid rock just below the subsoil.

Boulder clay is notorious for its variability. It often contains patches and *lenses* of sand from a few yards in length up to hundreds of square yards in area. The clay may pass into sand abruptly, and without any surface indication of the change. Sometimes also the clay changes to running sands or quicksands. These sands may cause great difficulty in trenching and surface works, as they are difficult to support and keep open. The sands may be covered with a few feet of clay, concealing their presence below. Should buildings be erected on such a site, subsequent trenching into the quicksands in a neighbouring area may drain the sands below the building, and cause settlement of the foundations and cracking of the walls of the structure.

Clay with Flints. Clay with flints is a surface deposit from 1 ft to over 5 ft in thickness. It is restricted to areas where chalk outcrops at the present day, or has been at the surface in past geological times. It is a residual deposit formed by the solution of the chalk in natural waters. The insoluble impurities of the chalk remain behind as a clay. The flint nodules present in the original chalk are made of silica, which is resistant to decay, so that they become incorporated in the residual clay, giving rise to the clay with flint deposits. Clay with flints is usually quite a thin deposit and very patchy in its occurrence. Hollows filled with the deposit may extend down into the underlying chalk. The clay with flints gives rise to clay or loamy soils, and is variable in the amount of flint nodules it contains. Clay with flints occurs in East Anglia, Buckinghamshire, Oxfordshire, and the downs of Kent and Hampshire.

Head. During the glacial period in Britain, the southern half of the country was not covered with ice, but the ground was frozen to a considerable depth, and there was a good deal of erosion. During periods of thaw or in inter-glacial periods, much of the eroded material slipped down into the valleys, forming a covering of pebbly material which, in some areas, is several feet thick.

PEAT

Peat occurs in beds from a few inches to, in extreme cases, ten feet or more in thickness. It is made of plant remains in a highly decomposed state, and is usually waterlogged. A saturated condition is necessary for the preservation of the vegetation as peat. Peat beds are usually underlain by impervious strata, such as shale, which prevent the water draining away. There is a gradual change in the nature of the peat with increase in depth; at the surface the vegetation is but little decomposed, and growing plants may be present, but at deeper levels the peat becomes darker, and obvious plant structures are not so prominent. At the bottom of deep layers of peat the substance may be almost black in colour. Peat is usually developed on sour water-logged soils, and is commonly found in areas with arctic or temperate climates. It may be found on upland moors or in lowland swamps.

Peat occurs at the surface over large tracts of the country, but these areas are unlikely to be used for building purposes. In many districts large areas of peat were formed in post-glacial times, shortly after the melting of the ice which once covered the country, when the subsoil was frozen. At a subsequent date this peat was covered over with clay or sand, often to a thickness of several feet, so that the presence of a buried peat bed may not be suspected. The erection of buildings on this type of site is fraught with danger unless special measures are taken in forming the foundations. Peat possesses very little strength, and if the water is drained from it, contraction occurs, and the bed may be greatly reduced in thickness.

Considerable areas of Lancashire and other counties are underlain by beds of peat. In Lancashire, the peat within a few miles of the coast is covered by a fair thickness of blown sand, whilst farther inland, clays may conceal the peat beds. Many of the buildings put up in these areas show evidence of movement and cracks in the walls a short time after they have been erected. Where buried peat-beds are suspected, trial pits should be dug to test the site. Monotonous, flat areas of sour, damp soils are often underlain by peat beds.

SANDS

The general properties and uses of sands are dealt with in Chapter IV. In this section the effects of sands on problems of siting and foundations are treated. Surface deposits of sand cover large areas of the country, especially in the vicinity of certain coast lines, in glaciated districts, and along the banks of the larger and more sluggish rivers.

Coastal Sands. These are usually of the wind-blown type, having the grains mostly of the same size and type as described in Chapter IV. They are blown inland and may form a covering over boulder clay, peat, or the solid rock, and may vary in thickness from a foot or so to several feet. The sands may form hummocky mounds or typical sand-hills when their true nature is apparent, or they may form plain-like features, in which case they may be mistaken for ordinary residual sandy soils, and the possibility of peat or boulder clay being present underneath may not be investigated. Where horizontal beds of blown sands are present, it may be a wise precaution to dig one or two pits on the proposed site to investigate the possibility of peat or other unsatisfactory beds being present below the sand.

Where buildings are erected on the landward side of sand-dunes, there may be much sand blasting of the walls, especially if the prevailing winds are strong. Unless the dunes are permanently fixed by the planting of vegetation or other means, there is always the possibility of the sand-hills shifting inland during storms when the winds reach gale force. Many coastal villages have been engulfed by sand-hills in this way.

Glacial Sands. These may cover areas of many square miles in glaciated districts, and may reach depths of many feet. They were deposited in lakes which have since disappeared with the melting of the ice, or as deltas of streams draining from the fronts of glaciers and ice sheets. The sands are usually well washed and current bedded and may contain gravel. They rest on the solid rock, or may overlie beds of boulder clay. Where such sands are of great extent, they form flat areas, often well above drainage level, and are very suitable for housing sites. Parts of many towns are built on glacial sands of this nature.

Sandrocks. Many sandstones, especially those of Mesozoic and Tertiary age, weather very easily, and crumble into sand, so that the outcrops of these strata are usually covered with a sandy soil passing downwards through sand into sandstone. It is very seldom that clay or peat is present below sands of this type. Where cuttings have to be made through sands of this nature, the sides of the cutting must be stepped back to a grade depending on the fineness of grain of the sand, its water content, and the angle of rest of the particular sand. A covering of vegetation helps to stabilize the slope.

Quicksands. This type of sand consists of very small, highly rounded grains. It runs very readily and will not heap up into a pile. When wet, it flows almost like water. Surface works in this type of sand are very difficult and costly. Trenches have to be closely timbered to prevent the sand running in, and the recovery of the planking is sometimes difficult. Patches of quicksand may be present in boulder clay and glacial sands, and, during trenching operations, they may be entered suddenly and without any previous indication of a change in the type of sand. Quicksands are of little use for building purposes.

PLAINS AND LIKE FORMATIONS

Flood Plains. Some of our larger rivers flow in wide valleys, and have flood plains hundreds of yards wide on each side of the river. These flood plains consist of sand and gravel built up by the river repeatedly overflowing its banks for long periods of time. They may be at a height of a foot or more above the present river level (Fig. 16 (*a*)). These wide, almost perfectly level, stretches of sandy subsoil appear to offer ideal sites for buildings and housing schemes, but they are, however, quite unsatisfactory for the purpose. The surface of the flood plains may be free from flooding, or flooding may be prevented by building walls along the course of the river. The danger, however, is due to the rise of the groundwater level up through the sand of the plain into the foundations of the buildings when the river is in flood. It is within the author's experience that the cellars of houses, over three hundred yards from the banks of a stream less than five yards wide, were inundated every time the river was in flood. The water rose up through the foundations, which were sandy, and the cellars often contained water over a foot deep. The ground to the stream edge was built over and the streets were paved, and there was no surface flooding.

Flood plains are extensively developed in the Thames Valley, along the Great Ouse and the Trent, and along a great many other rivers and streams in all parts of the country. These flood plains form rich arable land and may occasionally be loamy.

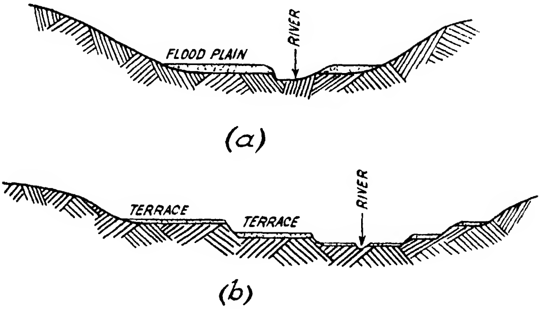

FIG. 16. SECTIONS SHOWING PLAIN FORMATIONS

(*a*) Flood plains on each side of a river.
(*b*) River terraces (formerly flood plains) which are now above present river level.

Terraces. Most of our large rivers, such as the Thames and Severn, and many streams in other parts of the country, have lowered their beds, and now flow at a much lower level than was formerly the case. Wide flood plains were developed at the former higher levels of the rivers, and these may now be many feet above the present river levels. These raised flood plains are known as *river terraces* (Fig. 16 (*b*)). They form level ground, sometimes of considerable area, and consist of gravel, loam or sand to a thickness of several feet. Their height above the present level of the river renders them immune from the rise of the ground-water level into foundations. River terraces may be worked for gravel, and the material is sometimes called *brickearth*. The uppermost terraces of the river Thames may be at a hundred feet above present river level, and several terraces may be present one below the other.

Raised Beaches. The wearing or erosive action of sea waves on cliffs and shores is well known. Cliffs of softer material such as sands are cut back rapidly, whilst hard granite cliffs may be very resistant. The result of long periods of wave action, however, is the formation of a fairly level beach platform, such as is found round most parts of the coast. Some of these wave-cut platforms are usually covered with sand and beach deposits, and may end in cliffs or rising ground at the landward side. The land areas, however, are notoriously unstable, and most parts of the coastal areas have been uplifted in fairly recent geological times. As a result of this uplift, the former level beach platforms are now raised above sea-level often to a height of many feet (Fig. 17). These raised beaches form tracts of level ground adjoining the sea, backed at the landward side by rising ground, and may extend for distances of some miles and be of considerable breadth. They are usually covered with beach sand and gravel. Because they run along the sea-front and are level, they form excellent sites for promenades and, if the raised beaches are wide enough, they may accommodate hotels and houses along the promenade. These beaches give good dry soils free from flooding.

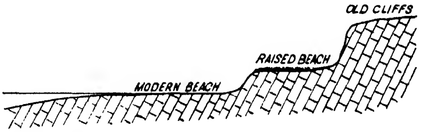

FIG. 17. SECTION SHOWING THE RELATIONSHIP OF RAISED BEACH TO THE MODERN BEACH

SITES

GEOLOGICAL AND OTHER FACTORS AFFECTING CHOICE OF SITES

Cliffs and the Stability of Slopes. Buildings are often erected on hill slopes, and in seaside towns it is sometimes considered desirable to be as near the cliff edge as possible. But, unless great care is taken in examining the stability of the proposed site, movement of the foundations may take place, causing cracks and other defects in the building.

The stability of slopes of sand and clay depends on the angle of repose of the material of which the slopes are composed. The slopes of excavations should be cut back below this angle, which is about 30° to 45° from earth and loam, 25° to 45° for clay, 30° to 40° for gravel, 25° to 35° for dry sand, and 15° to 30° for wet sand. The planting of shrubs and the cutting of a herringbone pattern of drainage channels may help to protect the sides of cuttings and excavations.

The stability of cliffs depends to a great extent on the structures of the rocks, and the amount and direction of the dip of the strata. If thin bands of clay are interbedded with harder rocks, they may create grave difficulties, and the liability to land slips is enormously increased. If the strata forming the cliff are horizontal, there will be little tendency for the cliff face to slip out (Fig. 18 (*a*)). If, however, the rocks of the cliff are well jointed, the joints will be vertical, and any degree of undercutting by the waves at the bottom may lead to blocks breaking off the face of the cliff at the joints. The obvious protection in this case is to prevent undercutting of the cliffs by the building of a sea wall, or by leaving large blocks of rock at the cliff base to break the force of the waves and prevent the full force reaching the base of the cliff. Houses may be put fairly near the cliff edge in cases such as these, but care should be taken to see that no large fissures or major joints are present behind the property, as the cliff may eventually break off along such fissures.

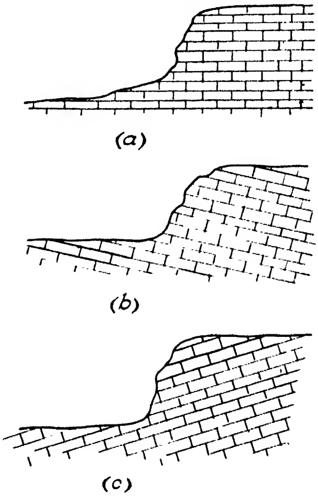

FIG. 18. TYPES OF STRUCTURES SEEN IN CLIFFS

(*a*) The strata forming the cliff are horizontal. This gives stable cliffs, although breakage may occur along the joints.
(*b*) Strata dipping into the cliff. This is also a stable structure.
(*c*) Strata dipping out of the cliff. This structure may be unstable.

Where the strata are dipping into the cliff, there is no tendency for them to slide out along the bedding planes. If the strata are traversed by open joints or fissures, however, undercutting of the base of the cliff may lead to portions of the cliff dropping out from the face along the joints as in the previous case (Fig. 18 (*b*)). The cliffs will, in this case, probably not be vertical but will slope back from the sea.

The most unsatisfactory structure from the building point of view is where the strata dip out of the cliff face towards the sea (Fig. 18 (*c*)), especially if the dips are steep. In this case the whole cliff may be unstable, and the possibility of land slips and cliff slides is always present. Movement and sliding along the bedding planes are frequent, and these may extend for a considerable distance back from the edge of the cliff. The bedding planes are fissures separating one stratum from another as stated in Chapter I, and there may be little cohesion between the beds on either side of such a fissure. If water is able to enter these bedding planes, it lubricates the fissure and an upper stratum may slide down over a lower one.

Portions of a cliff or hill-side may, therefore, slide out, irrespective of any undercutting or weathering action at the base of the cliff, and fissures or cracks may appear at the surface many yards away from the cliff edge. If thin bands of clay or shale are present, these will hold up the drainage water; their surfaces will become wet and be well lubricated. Portions of the cliff or hill-side, overlying the clay or shale beds, may suddenly slump, and slide down into the valley or to the cliff bottom. Cliffs and slopes should be carefully examined for the presence of clay beds. Where the rock structures are of this type, large portions of the cliff top may be suspect, and buildings should not be erected upon it. The width of the cliff top that should be left clear can be determined by projecting the bedding planes from the base of the cliff to the top. All the ground to the seaward side of this line should be left, and building restricted to its landward side. The seaward side could be kept well drained, and laid out as grass or promenade gardens. The instability of this type of cliff is due to the strata slipping seawards or into the valley, and is not dependent on undercutting by wave action or other means.

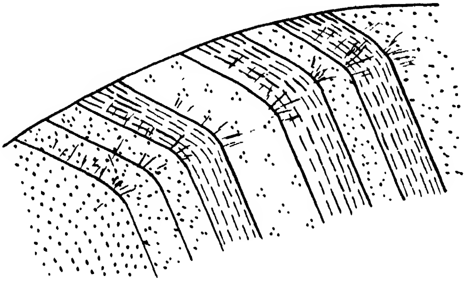

FIG. 19. DIAGRAMMATIC SECTION SHOWING THE CREEP OF STRATA DOWN A SLOPE

Cliffs of sand and boulder clay, which are present round many parts of the coast, are usually steep or vertical because rapid undercutting by the waves causes the upper part to crumble and fall in. Protection by a sea wall may effect an improvement, but atmospheric weathering may also cause the upper parts of sand cliffs to crumble, and buildings should be kept well back from the cliff edge in these cases.

In steeply dipping strata *terminal creep* may take place in which the strata at the outcrop may be turned over and bent downhill (Fig. 19). This structure at first sight may give quite a wrong idea of the dip of the strata.

Land Slips. Land slips are especially common on hill-sides and slopes (Fig. 20) where alternating beds of hard and shaly rocks are present, especially where the surface is not well drained, and where water can enter the bedding planes and fissures. Gravity slips occur where a rock is undercut by rivers or tides. The rock slips when the undercutting has undermined the rock too far. Where a structural break is present, the weight of the overlying rock may cause movement along a shear plane. Where strata dip in the same direction as the valley sides, they hold only so long as there is cohesion between the various strata. When the angle of dip of the rocks approaches the angle of limiting friction, the lubrication caused by the entry of water along bedding planes may upset the equilibrium, and cause portions of the rocks forming the slope to slide out (Fig. 21 (*a*)).

FIG. 20. LAND SLIP AT MAM TOR, DERBYSHIRE

Where cuttings have to be made in strata dipping in this manner, one side should be scraped back to a dip slope, whilst the other side may be left vertical (Fig. 21 (*b*)). Surfaced roads built across land-slipped material are very liable to be affected by slight movements of the foundations, and may be difficult and costly to maintain in good condition in these portions. The movement of the foundations may cause the surface of the road to crack and disintegrate.

The undercutting of hill slopes may be brought about by rivers undercutting the sides of their valleys at the bends in the meanders. Landslips are common in the Cotswold Hills, in the deep valleys near Bath, and in numerous other places. Near Dover, huge masses of the chalk cliffs occasionally break away.

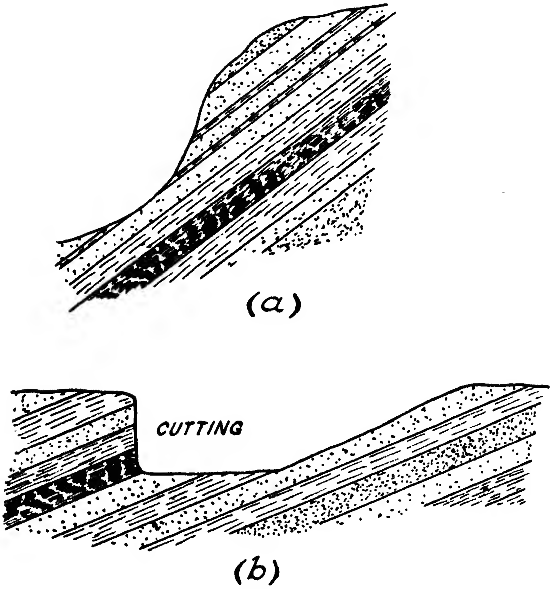

FIG. 21. LAND SLIPS

(*a*) An unstable valley slope. The strata tend to slip off along the thin shale beds.
(*b*) A cutting made in unstable dipping strata.

Valley Structures. In certain areas, especially in central and southern England, where clay beds underlie harder beds such as limestone, river valleys may wear through the limestone and expose the clay strata in the valley floor. Removal of the weight of the limestone cover in some cases has resulted in the limestone in the valley sides tilting or cambering towards the valley, and the clay beds below the limestone bulging up into the valley itself. The sides of the valleys where bulging has taken place may show the strata dipping at steep angles with the frequent presence of faulting. Sites at the sides of valleys where this has taken place may, in some cases, prove unstable. The excavation of deep trenches for dams and other structures often reveals that clay beds have been puckered and contorted due to the weight and movement of the overlying strata.

Subsidence. During coal and salt mining operations, material is extracted from underground whilst full support in place of the rock mined out is not usually provided. In this case the rocks, overlying the seam which has been extracted, may cave into the abandoned workings. If the workings are near the surface, subsidence may take place at the surface with grave effects to any buildings or property which have been built in the area. Subsidences of several feet may occur fairly suddenly, or gradually, and the natural drainage may be upset. Water may lodge in the hollows formed as a result of subsidence, forming *meres* such as those of the salt-mining areas of Cheshire and the *flashes* of the Lancashire coalfield. Some of these lakes caused by subsidence may cover many acres and be of a permanent nature.

The amount of the subsidence of the surface depends on the thickness of the seam extracted and its depth from the surface. In areas affected by subsidence, electricity, gas, water and sewage services may be interfered with by frequent breakages of the pipes and cables. Flexible joints should be used in fixing pipes in such areas. In coalfield areas likely to be undermined, houses should be built on reinforced concrete rafts, whilst concentrated loads should be reduced to a minimum. If possible, building should not be started until the seams have been mined and the surface has had time to settle. A further danger is that mining operations in one area may disturb the surface deposits of neighbouring districts, and cause some movement of the foundations of buildings. Salt beds cover large tracts of country, and it should be possible to mine salt away from towns and villages.

Faults. In many areas, especially in regions where the geologically older strata are at the surface, large faults may be present although they may give little surface indication of their presence. They are planes of weakness, and the rocks on one side of the fault may move slightly relative to those on the other side. If building sites are crossed by faults, slight movements of the foundations may sometimes take place. Fault fissures are seldom more than a few inches wide, and they run in straight courses, so that in most instances a slight adjustment of the site to one side would keep the foundations clear of the fault.

CHOICE OF SITE

Sites for Houses. A dry, well-drained situation is preferable for housing sites, and foundations on sand, sandstone, or limestone are better than those on clay, shale, or impervious loam. The character of the subsoil is of more importance than the surface soil. To be dry and healthy, the subsoil should be thick enough to allow the rain-water to percolate below the foundations of the houses, and the situation should be such that water will not rise up through the subsoil from the flooding of streams as stated previously. Where sands or gravels overlie clay or other impervious beds, the ground water will not drain away, and may rise to within a foot or two of the surface during heavy rains and cause basements and foundations to become damp.

Areas where chalk rock occupies the surface are usually dry and free from streams and surface water, but after prolonged wet weather streams or bournes may flow down the valleys. These dry valley sites should be avoided in chalk and limestone areas. In some chalk and limestone districts, furrows and hollows or *pipes* of considerable size and depth may be present. These pipes may be filled in with sand or clay and gravel, and occasionally subsidences may take place over these areas.

Clay soils, although impervious, absorb a good deal of moisture and may swell. In dry weather, however, much water is lost and the clay shrinks. Great cracks may form in very dry seasons, which may extend a yard below the surface. Because of this shrinkage and expansion due to variation in water content, buildings may be subject to irregular settlement, and cracks in the walls may develop. Very long periods of dry weather may dry out clay subsoils, and cause much damage to buildings with shallow foundations in these rocks. In clay areas it is, therefore, important to make the foundations of buildings sufficiently deep to extend below the region affected by the drying out of the clay. Where heavy massive structures are placed on clay subsoils, the clay may show some shrinkage due to the weight of the building. The amount of the shrinkage may require estimating before important structures are built. Heavy loading of clay sites causes appreciable settlement, the amount depending on the nature of the clay and the size and weight of the structure to be erected. The settlement is due to moisture in the clay being squeezed out under the load and may go on for years. So far as possible, the load should be distributed evenly over the foundations so that settlement takes place evenly. The weight of structures upon foundations is usually limited to that shown in the table at top of page 41.

To take heavy loads, the foundations may be widened and extended.

Foundation	Limit of load (t/ft^2)
Soft clay and loam	1
Dry sand and hard dry clay	3
Rammed dry clay and firm coarse sand	4
Hard shale	8
Sandstone	20
Limestone	25

Preservation of Amenities. Many quarries, surface works and brickpits are located within towns and villages, and detract greatly from their amenities. In many cases, works of this type could be restricted to localities well clear of any land likely to be absorbed into town planning schemes. Brick-clays outcrop over large areas, and usually keep their quality for considerable distances. New brickpits could, therefore, with justice, be kept outside the boundaries of villages and towns. Sandstone and limestone beds also cover large areas, and, since as good quality stone can usually be obtained outside village boundaries as within them, there would be little inconvenience or injustice in restricting their workings.

Salt beds also occur widespread, and much loss of property would be avoided were salt mining kept clear of town and parish boundaries. Ash pits and refuse dumps, especially in country districts where spring or well water is used, should not be so placed that the drainage from the dump may enter the well water.

MAPS

Geological Maps. Geological maps are published by the Geological Survey of Great Britain on the following scales: ¼ in. to 1 mile; 1 in. to 1 mile; and, for some areas, 6 in. to 1 mile. The 6 in. to 1 mile maps show all the topographical features such as walls and fences, with, in addition, all the geological features such as faults, types of strata, and types of surface deposits, with the boundaries between one type of rock and another. They are the most useful, as the scale is sufficiently large for most purposes. If these maps are not published for some areas, they can usually be consulted at the offices of the Geological Survey, or copies can be made by the Survey Office at the cost of copying, the original maps being held at headquarters. Boreholes put down for water or to prospect coal may give valuable information as to the depths of the surface deposits of a district. The position of these boreholes and the thickness of surface deposits and strata passed through are shown on these maps.

The maps on the scale of 1 in. to 1 mile are issued in two types for many areas. The *solid* edition shows the geology as it would be were the surface deposits removed. Boulder clay, gravel, peat, etc., are not shown. These maps show the details and outcrops of the solid rocks, and are invaluable where strata below the subsoil are being investigated. The *drift* maps of the same areas show the geology as it actually is at the surface. Alluvium, clay with flints, peat, etc., are shown, whilst in the areas where superficial material is not present, the nature of the underlying strata is shown. The drift and solid editions of the same map may appear at first sight to be entirely different. Where the extent of the superficial deposits does not merit a separate map, the areas of drift are shown on the solid edition map and a separate drift map is not published.

The areas shown on the 1 in. to 1 mile maps are described in an accompanying memoir, which sets out in fullest detail the geology of the area depicted, and gives numerous sections of strata met in the district. These memoirs are invaluable where detailed information of the geology of a district is required.

CHAPTER IV

Sands and Gravels

PERHAPS the most abundant material occurring on the earth's surface at the present time is the loose, incoherent rock known as sand. In many parts it is present in vast quantities, especially in south-east England, where sand rocks are at the surface over many square miles of the country. The ice sheets, which covered Britain over ten thousand years ago during the great Ice Age, left, on melting away, great thicknesses of sand and gravel scattered irregularly as surface detritus over most areas north of a line from South Wales, through the Midlands, to Kent. Sands vary greatly in character and value, and in the uses to which they may be put. Ordinary sand, possessing no special features, may cost only a few shillings per ton, whilst sands suitable for special purposes, such as glass-making, may command high prices, or even be exported.

NATURE OF SAND

COMPOSITION

Sand is an unconsolidated rock consisting of loose, incoherent grains. The material has been transported by wind, ice, or rivers, and only the more resistant types of grains can survive this process. Minerals which are soft, or easily decomposed, are lost during transport, and are not usually present in sands.

By far the greater proportion of the grains constituting a sand consists of silica or quartz (SiO_2). This mineral usually forms between 60 and 90 per cent of a sand, and, in exceptional cases, may reach 98 per cent. The other minerals present depend, to a large extent, on the type of material being worn away, to provide the sand. Felspar, a white or pink coloured soda or potash alumino-silicate mineral, slightly less hard than quartz, is fairly common, especially in the geologically older sands. The dark-coloured grains in a sand consist of minerals, such as the iron ores, magnetite, haematite and ilmenite, together with minerals such as garnet and anatase. Some sands contain small amounts of gold, platinum and gems, and are excavated for the recovery of these substances. Ilmenite, used for the production of titanium white paint, is obtained from shore sands in Travancore in India.

When sands are used for building purposes, the proportion and nature of these accessory minerals are of little importance, but if the sand is to be used for glass-making, and the manufacture of silica bricks, these dark minerals may make the sand valueless, if they are present in any quantity. Some sands formed under marine conditions may contain fragments of broken shells in abundance, giving the sand a fairly high lime content. The following table shows the chemical analyses of two typical sands—

Mineral	Content (per cent)	
	Leighton Buzzard	Barrow Moulding
Silica	99·58	87·03
Alumina	0·27	7·11
Iron Oxides	0·03	1·05
Magnesia	—	0·43
Lime	0·22	0·26
Soda		0·07
Potash		1·76

TYPES

Sands are usually classified according to their mode of origin.

Wind-blown or Aeolian Sands. Certain formations, such as the Permian and Triassic rocks in Britain, were deposited under desert conditions, and most of the sands and sandstones in these systems were formed by the action of wind. In modern times, wind-blown sands are found widespread as sand-hills or dunes, as on the coasts of Lancashire, near Blackpool and Southport, along the Moray coast of Scotland, and on parts of the Welsh coast. Sands which have been formed as a result of wind action possess characteristics of shape and grain size by which they can be easily recognized.

Aeolian sands are usually characterized by the almost complete absence of white mica, which is so common in other types of sand. Mica, being soft, is worn into dust during its travels, and is sifted out from the sand grains and removed by the wind. Very little carbonaceous matter is present. The sand grains, whilst being blown about, rub against one another and against any rocks obstructing their passage, and are worn to a spherical shape, which is characteristic of the grains of most wind-blown sands. The surfaces of the grains are smooth and have a frosted appearance (Fig. 22 (*a*)). The wind is a very effective sifting agent, so that these sands in any one area consist of grains of approximately the same diameter. The usual diameter of the grains is about 0·2 mm.

It is only with difficulty and in very strong winds that grains larger than this are transported.

It is in deserts that aeolian sands achieve their greatest development, but in Britain these sands are found widespread on some parts of the coast. Such sands may form a uniform layer over many square miles of the country, as in the case of the Shirdley Hill sands, which cover large areas of the West Lancashire Plain to a thickness of from 1–8 ft. In most instances, however, aeolian sands are in the form of dunes or sand-hills, which are constantly shifting their position unless fixed by the planting of marram grass, gorse, or pines. For the formation of these dunes, a long stretch of sand, exposed daily between the tides on a low, flat shore, is necessary where the prevailing wind strikes the coast at an angle of about 10–15°. Sand-hills may reach up to 50–60 ft high, as on the coasts of Norfolk and Lancashire, and may form a belt up to five or more miles wide. Such deposits of blown sands are found on the coasts of Lancashire, Cheshire, Cumberland, Wales, Devonshire, East Anglia, and East Scotland.

Sand-hills may move inland fairly rapidly, especially during periods of high winds.* Property built on the landward side of sand-hills will be subjected to heavy abrasion by the sand-laden winds, and, unless the dunes are fixed by the planting of vegetation, it may be overwhelmed by a rapid advance of the sand-hills.

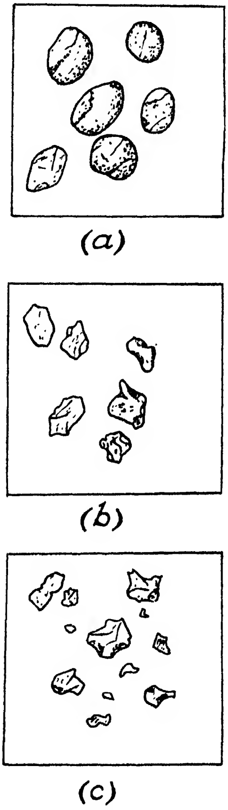

FIG. 22. THE SHAPES OF SAND GRAINS

(*a*) Wind-blown sand grains from the Egyptian Desert. Note the well-rounded grains.
(*b*) Beach sand grains. The grains are subangular.
(*c*) Grains from glacial sands. The grains are angular and of various sizes.

The soft red sandstones of Permian and Triassic age in Lancashire, Cheshire and the Midlands were formed largely as wind-blown sands, and they show the typical cross-bedded dune structure. They crush easily into sand, and large quantities are used as building sand, or, where the sand contains a fair proportion of clay, it may be used as moulding sand for the casting of iron.

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* Mellard Reade estimated that about 105 000 yd^3 of sand are moved yearly by wind on a 16-mile front in South Lancashire.

Marine and Estuarine Sands. This class of sand is, or has been in past geological periods, deposited on beaches, in the sea, or in river estuaries. It is formed from comminuted rock brought down by rivers, and from material obtained by coast erosion. There may be considerable drift of material along the shore, so that the sand may not consist entirely of material obtained from the adjacent cliffs or rivers.

Sea or shore sand is usually yellow in colour, although some sands, such as the *Calais Sand*, are almost white. Shore sands normally have some calcium carbonate content obtained from broken shells, and they invariably contain some salt. It is difficult to remove the salt entirely by washing, and, therefore, beach sands should not be used where the hygroscopic nature of the salt would be harmful. Efflorescences may form on the work, and tend to keep the surface damp if the sand used contains salt. Marine sands are variable in composition and mineral content; they are usually fairly coarse-grained, but may contain 2 or 3 per cent of material of the clay grade.

Water-borne sand grains are subangular in shape (Fig. 22 (*b*)), as a film of water protects the grains from rubbing against each other during transit. River sands are similar in type, and are variable in composition and thickness. The sand from rivers is usually free from salt, is fairly sharp, and well suited for use in concrete and mortar if it is free from clay materials. Sand and gravel are recovered from many rivers such as the Thames, Ribble, Trent, and Severn.

Glacial Sands. These consist almost always of sharp, angular grains of various sizes (Fig. 22 (*c*)). They are formed by the wearing and scraping action of the glaciers and ice sheets which covered Britain during the Quaternary Period, and were washed out into lakes by the streams issuing from the ice.

The lower layers of an ice sheet are heavily charged with debris, which has been scraped up from the surface over which the ice is moving. Rivers flowing in natural tunnels in the ice itself pick up the sandy portions of this debris, and wash it away. When the en-glacial stream reaches the end of the ice sheet, it is deposited as a small delta. On the withdrawal and retreat of the ice, a mound of sand is built up which has a long, sinuous course, corresponding to the course of the stream within the ice. These sand ridges, or *eskers* as they are called, are fairly narrow, but they may run across country for considerable distances (Fig. 23). These sands are often fairly clean and free from clay.

During the Ice Age, lakes were often impounded between the higher ground and the end of the ice sheet, and the melt waters from the ice deposited their sand and gravel along the margins of these lakes. When the ice sheets melted away, the lakes, which were held up by the ice front, drained away, and the sands and gravels deposited in them were left as surface deposits. These deposits are extensively quarried, and, if much gravel is present in the sand, it may be washed clean and has a ready sale. These deposits are very irregular and some patches may be very pebbly, whilst other areas of the same quarry face may consist entirely of sand. Frequently there is an irregular admixture of clay, making it necessary to wash out the clay before the sand is sold.

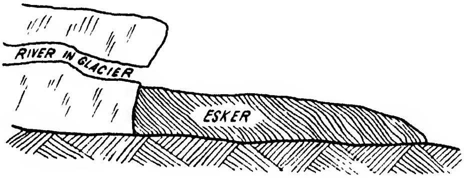

FIG. 23. SECTION SHOWING THE FORMATION OF A RIDGE OF SAND, OR AN ESKER, AS THE DELTA OF A STREAM RUNNING IN THE GLACIER ITSELF

TESTING AND USES OF SAND

The value of a sand for various purposes can be fairly accurately estimated as a result of tests which can be quickly carried out without a great deal of apparatus.

EXAMINATION

Examination by Means of Slides. A slide should be prepared for the examination of the sand by means of a hand lens or a microscope. For this purpose a microscope slide (a glass plate about 3½ in. long and ¾ in. broad) is cleaned, and a little Canada balsam, dissolved in zylol, is placed in the centre of the slide. A few grains of the sand to be examined are then sprinkled into the balsam, and a coverslip lowered gently on top. Slight pressure is applied to the coverslip to squeeze out the excess balsam, and to spread out the grains. It is a mistake to put too much sand on the slide, as the grains then become crowded together and are difficult to examine. The preparation should be left for several days until the balsam sets hard; the slide then becomes a permanent mount and, when labelled with the locality and other particulars of the sand, can be stored for reference. Any excess balsam on the slide can be cleaned off with a cloth dipped in benzine. The slide can be examined with a hand lens, by holding the preparation against the light.

By an examination of slides such as these, the shape of the grains can be ascertained, and any variation in their sizes will become apparent. The diameter of the grains can be measured in millimetres, if a microscope with an eyepiece micrometer is available. The presence of mineral grains other than quartz is also at once apparent.

GRADING

Mechanical Analysis. The mechanical analysis or *grading* of a sand gives information as to the percentage of grains of various diameters present in the sample. It is important for building and other types of sand, as it gives an estimate of the amount of the clay and other grades which are present in the sample. The separation of the various sizes of grain is carried out by means of standard sieves, or in elutriators by currents of water having various velocities.

P. G. H. Boswell has standardized the grade classification of unconsolidated rocks as follows, and this scheme is largely followed in Britain.

Diameter of the grains (mm)	Designation
Greater than 2	Gravel
1–2	Very coarse sand
0·5 –1	Coarse sand
0·25–0·5	Medium sand
0·1 –0·25	Fine sand
0·05–0·1	Coarse silt
0·01–0·05	Silt
Less than 0·01	Mud or clay

With most types of sand the mechanical analysis can be carried out by sieving the sample through a set of standard screens or sieves. Where, however, the sand contains much material of a grain size less than 0·05 mm diameter, elutriation may have to be resorted to, as screens with very small holes rapidly become worn and clogged. The British Standard sieves are extensively used. Their mesh size is indicated by numbers, e.g. No. 8 has apertures 2·057 mm in diameter, No. 16 apertures are 1·003 mm, No. 30 apertures are 0·5 mm, No. 60 apertures are 0·251 mm, No. 150 apertures are 0·104 mm, and No. 300 sieve has apertures 0·053 mm in diameter. A nest of sieves could, therefore, be made up as shown below, which would classify the sand into the grades shown in the previous table.

+ 2 mm
Sieve No. 8 . .
+ 1 mm
" " 16 . .
+ 0·5 mm
" " 30 . .
+ 0·25 mm
" " 60 . .
+ 0·1 mm
" " 150 . .
+ 0·05 mm
" " 300 . .
— 0·05 mm

The sand to be tested is thoroughly mixed, and piled up into a cone. This cone is divided into four quarters, and all but one of the quarters are discarded. The remaining quarter is again piled up into a cone and the process repeated until a sample of workable size is obtained. This sample is carefully weighed and put through the nest of sieves. The material is shaken thoroughly, but no attempt should be made to press the sand through the screens. When the operation is completed, the sand remaining on each sieve is weighed. When clay particles are present, they may adhere to the sand grains and be difficult to separate. In this case, the sand may be washed before further screening, the wash water being poured through the fine mesh: the wash water is then evaporated and the residue is weighed, its weight being added to that fraction of the separation.

The weights of the fraction remaining on each sieve may be tabulated as below. The figures are brought to percentages, and the cumulative percentages of each grade are obtained.

Sample *Locality* *Date*

Sieve No.	Diam. of grains retained (mm)	Weight retained	Percentage weight retained	Cumulativ percentag retained
8 .	+ 2			
16 .	1 -2			
30 .	0·5 -1			
60 .	0·25-0·5			
150 .	0·1 -0·25			
300 .	0·05-0·1			

For more detailed work, a greater number of sieves would be used in the separation of the sand, but the above sizes are, as a rule, sufficient for most purposes.

Elutriation Methods of Separation. Hydraulic methods of grading sand may be used, especially where the material consists mainly of very small particles. The method is based on the fact that if a particular grain falls through water, a current of water, flowing upwards against it with the same velocity, will just succeed in holding it steady in suspension, whilst a greater velocity will carry the particle away. Cold water will carry larger grains than warm water, so that separations should always be carried out at about a temperature of 15° C.

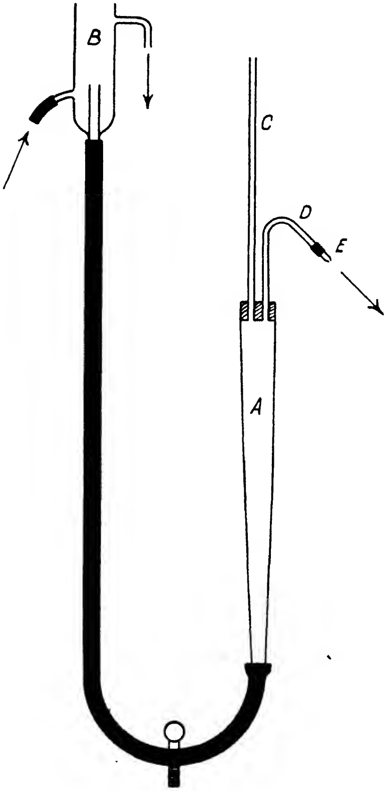

Fig. 24. A Single Vessel Elutriator

A = Separation tube.
C = Manometer tube.
B = Vessel giving head of water.
D = Outlet tube.
E = Jet.

The single vessel elutriator (Fig. 24), gives fairly accurate results and separates chosen grades one at a time. The apparatus consists of a wide glass tube *A*, 2 in. in diameter, and about 16 in. long, the lower 8 in. of which are drawn out into a conical shape. The separation tube *A* is attached to a reservoir *B*, which can be raised or lowered to adjust the head of water in the tube *A*. The latter is fitted with a two-hole stopper, through which is fitted a manometer tube *C*, and an outlet tube *D*, which is fitted with jets *E* of various sizes, depending on the grade of material being separated. A larger separation tube *A*, 3 in. in diameter, may be used. The jets are made of glass tubing of various diameters.

The size of jet and the head of water required to separate particles of various diameters are given by Boswell as shown in the table at top of page 51.

The velocity of the current at the top of the separation tube *A* can be determined by measuring the amount of water leaving the jet in a given time. If the tube *A* has an internal diameter of 2 in., its area of cross-section can be found. The velocity of the current

Separation tube diameter (in.)	Jet aperture diameter (mm)	Head of Water (cm)	Largest size of grain separated (mm)
2	7	188	0·4
—	3	140	0·2
3	3	70	0·1
—	2	40	0·05

in *A* can be found from the following formula—

$$Q = V \times C$$

where Q = the quantity of water leaving the jet per second,
C = the area of cross-section of the tube *A*,
and V = the velocity of the upward current of water.

The following table, given by Holmes,* gives the upward current velocities required to carry up particles of various sizes.

Velocity of current (mm/sec)	Diam. of particles moved (mm)
47	0·40
32	0·30
25	0·25
20	0·20
6·7	0·10
1·8	0·05
0·12	0·01

To use the elutriator, a weighed quantity of the material to be separated is washed into the separation tube *A*, and successively coarser grades are washed off, beginning with the finest. Each grade is collected, the water decanted off, and the sediment dried and weighed, and expressed as a percentage of the whole.

Graphical Representation of the Grade Sizes. The figures obtained by the mechanical analyses of sands are best understood and compared when they are expressed graphically, as shown in Fig. 25. The *cumulative* percentages by weight of the material above each grade size in turn are plotted vertically, whilst the grade sizes are plotted horizontally. The points found in this way are joined by a curve, which brings out the distribution of the various sizes of grains, and enables a comparison of one sand with another to be

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* Petrographic Methods (Murby)

made rapidly and more readily than could be done merely by reference to the figures. For the horizontal scale, showing the diameter of the grains, it is usual to use a logarithmic one to avoid having the graph too long.

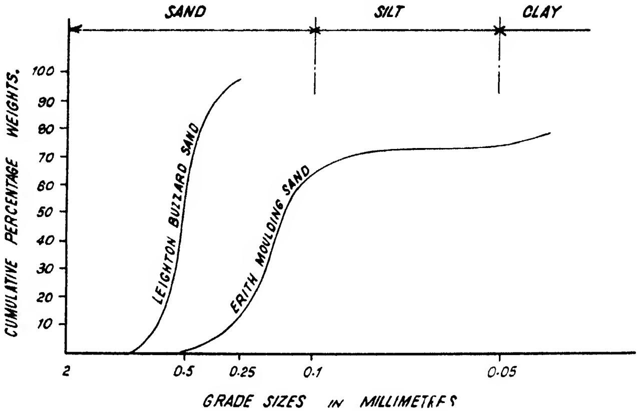

FIG. 25. THE DIAGRAMMATIC REPRESENTATION OF THE GRADING OF SANDS

The coarser grades of material plot towards the left. Where the curve is nearly vertical, the sand consists of material mainly of one grain size. Fig. 25 (after Holmes) shows the curves for some typical sands. Undernoted are the grade size of various types of sand—

Diameter of grain (mm)	*A* (Percentage)	*B* (Percentage)	*C* (Percentage)
> 1	—	—	11·8
1 –0·5	2	5·5	44·2
0·5 –0·25	91·2	39·6	41·5
0·25–0·1	3·3	32·6	2·2
< 0·1	3·5	0·075	0·3

A. Dune sand at Balgownie Links, near Aberdeen.
B. Moulding sand, Barrow.
C. Sand from the Red Crag deposits, Suffolk.

ESTIMATION OF IMPURITIES

Cleanness of Sand. The amount of dirt and organic matter in a sand can be estimated by shaking up, say, 500 cm³ in a 1 000 cm³ measuring jar with water. The clean sand settles first, and the dirt forms at the top of the clean sand layer. The depth of the clean sand and of the dirt layer can be measured by means of the graduations on the jar, and from these figures the percentages can be worked out.

Carbonaceous Matter. The presence of much carbonaceous matter is a disadvantage in sands to be used in concrete, since its presence may eventually lead to the production of holes in the concrete. A method of estimating if much carbonaceous matter is present has been suggested by Abrahams and Harder as follows: A medicine bottle is filled to the 4½ oz mark with sand to be tested, and a three per cent solution of sodium hydroxide added to bring the total volume up to 7 oz. The contents of the bottle are thoroughly shaken and allowed to stand overnight. The colour of the liquid at the top is then examined; if it is colourless or light yellow, the sand does not contain too much organic matter and is satisfactory, but if it is dark coloured, red, or black, the sand is suspect so far as carbonaceous matter is concerned.

Density. The weight per cubic foot of sand is variable, but is usually about 120 lb/ft^3. Fine sand which is slightly moist may have a rather lower density. Very wet sand weighs more than dry sand. To determine the volume weight of a sand, or its weight per cubic foot, a vessel of known capacity is weighed empty, then filled with the sand to be tested, and weighed again. The difference in the two weights gives the weight of sand in the vessel employed for the test, and from this the weight per cubic foot (including voids) can be calculated.

Standard Sand. In the testing of cements a standard sand is required with which to make the sand-cement test pieces. This sand should be very constant in character, so that the cement to be tested is the only variable factor. The British Standard sand usually used is from Leighton Buzzard. This sand consists of subangular grains, almost all of which are between 0·016 and 0·025 in. in diameter.

USES OF SAND

Glass-making. The sands used in the manufacture of glass are high grade silica sands, containing about 96 per cent of silica, by analysis, for use for plate glass, or up to 98 per cent of silica for the manufacture of optical glass. The percentage of coloured minerals, such as the iron oxides, must be very small, or less than 0·05 per cent, for making the clear white glass. The sand grains should be of about the same size, so that they melt at the same time in the furnace. Very refractory minerals such as zircon should not be present, as these may make the glass cloudy. Glass sands are obtained in Britain at Leighton Buzzard, from the Bagshot sands in the south of England, and from the Shirdley Hill sands in Lancashire. Glass sands have also been imported from Belgium.

Manufacture of Silica Bricks. Silica bricks are refractory, and will resist very high temperatures in furnaces and kilns without melting or fusing. Minerals such as felspar, and iron ores which lower the melting point of a sand should not be present in sands used for silica bricks. High grade silica sands are used, and silica rocks, such as the Holyhead quartzite of Anglesey, may be crushed and used for the same purpose.

Moulding. The sands used in iron foundries are usually red in colour, and come from the Triassic System. They may have a lower silica content than the glass sands. Whilst most of the sand consists of fairly coarse grains, there must be a proportion of very fine material or clay. Most of the moulding sands are obtained from the red Triassic rocks of Cheshire.

Building. Sand is also of very great importance in concrete mixing. The chemical and mineralogical composition of these sands is not of great importance, but the size of the grains or grade of the sand is, however, of considerable significance.

Sand has other uses as an abrasive in the cleaning of iron castings, and in the formation of filter beds where the water, on passing through the sand of the filter bed, is cleared of impurities, with a reduction in its bacterial content.

Importance of Grade Size in Building Sands. Sand is used in mixing mortar and concrete mainly to reduce the proportion of *voids* or spaces in the aggregate, and to cut down the amount of cement used. A dense concrete should have very few voids in its structure. In a well-mixed concrete the cement should do little more than coat the aggregate and the sand grains. A sand consisting of different sizes of grain will give a lower proportion of voids than one where the sand is *ungraded* or consists of grains mostly of the same size.

The percentage of voids in a sand can be determined approximately by placing 500 cm^3 of sand in a 1 000 cm^3 graduated measuring jar. A measured quantity of water, sufficient to cover the sand, is poured into the jar, and the sand is thoroughly agitated to remove the air from it. After the sand has settled, it is gently tamped down, and the amount of water standing above the top of the sand is measured. The difference between this quantity and the volume of the water put into the measuring jar at first is the volume of water which has entered the voids of the sand. The percentage of voids in the sand is therefore given by the formula—

$$\frac{A}{B} \times 100,$$

where A = water filling the voids (= difference between total water used and that remaining at top),
and B = volume of sand after wetting and tamping.

The percentage of voids in a sand is determined to a large extent by the number of different sizes of grain which are present. Some sands used in glass manufacture consist of grains which are all of approximately the same size, but most sands show some variation in the diameters of the constituent grains. For mortar and concrete mixing it is desirable to reduce the percentage of voids, and graded sands are desirable. Where the sand grains are all of the same size, the voids are the spaces between the grains. If smaller grains are present, they may pack in between the larger particles without forcing them apart, and in this way greatly reduce the percentage of voids in the sand. Artificially graded sands may have the percentage of voids as low as 25 per cent. The percentage of voids is a test of good grading. The following are some typical examples.

Coarse sand	35% voids
Fine sand	38% ,,
Standard sand	36% ,,
Artificially graded sand	25% ,,

When sand is mixed with lime or cement there is a reduction in the total volume of one quarter to one third, due to the closer packing of the material, and to a reduction of the percentage of voids.

Sources of Building Sands. Special types of sands, such as those used in glass-making, and the manufacture of silica bricks, and moulding sands, may be transported considerable distances from the restricted sources of supply to the seat of manufacture, but general building sands must, as a result of the need for economy, be obtained within reasonable reach of the site where they are to be used.

Loose sands are practically restricted to rocks of Triassic or younger age, and are especially found in the Tertiary strata and in glacial deposits.

The Tertiary System contains important beds of sand which are widely distributed in the London basin and the Hampshire area. Some of these sands, such as the Thanet sands which are developed in North Kent, are of considerable thickness and of high quality. The Bagshot sands are light-coloured, and the texture varies in different localities. They are extensively dug for glass and building sands.

The Cretaceous System contains, in the Greensand and Wealden beds, valuable and widely exploited sands. These beds occur widespread in Kent, Hampshire, and Wiltshire. The greensands are light greenish-coloured sands, containing the mineral *glauconite* (iron silicate) which gives them their typical colour. The Lower Greensand Beds are widely exploited for glass manufacture.

The Triassic System yields the Bunter sandstone which readily breaks down to a sand. It is red in colour, and is extensively used as a building sand. Where it is of suitable type, it is also used as a moulding sand for casting iron and brass.

Sands deposited during the glacial period are very variable in character, and may contain lenses of gravel or of clay. They may require washing before use, although some glacial sands are clean and sharp. Glacial sands are not present in the south of England, but they occur in most areas in the north which were covered by ice during the Quaternary Period.

GRAVELS

Gravels consist of pebbles with a diameter greater than about 2 mm. The pebbles are usually rounded and smoothed by the attrition they have undergone during transport, and a common size of pebble is about 2–3 in. in diameter, although much larger ones are common. Deposits of gravel occur as shingle beaches at high-water level round the coasts, in the beds of large rivers, and as gravel left by glaciers during the Ice Age.

Shingle beaches usually occur on exposed parts of the coast, and the largest pebbles are found at the landward margin of the beach. The pebbles are well rounded, due to abrasion in travelling along the shore. Usually the pebbles consist of fairly hard rocks obtained by erosion of the neighbouring coasts. In South-east England the pebbles are mainly flints obtained from the chalk cliffs. In Dorset, the pebbles are to a large extent limestones obtained from the Jurassic strata. Where cliffs are formed from boulder clay, the shingle may contain rocks of all types, and contain much material of igneous origin. Shingle beaches are usually fairly free from sand.

River gravels are sometimes used for concrete aggregates. They often have much sandy material mixed with the pebbles, which are seldom more than about 4 in. across. The pebbles consist of the various types of rock over which the river may flow.

Gravels of glacial origin are extensively exploited for concrete aggregates in the Midlands and the north of England. These pebbles may be of all sizes, intimately mixed, and the larger ones may require crushing to reduce them to a suitable size. The types of pebble in these gravels vary, but most of them are hard rocks, such as limestones, and quartzites, and igneous rocks, such as granite and whinstone, and they form excellent material for aggregates. The pebbles may not form continuous beds, but occur in patches in sands of glacial type. The proportion of sand to gravel even in the same quarry is very variable, so that the pebbles are usually screened or washed out, and sold separately from the sand. In river gravels the proportion of sand is often fairly constant, and separation of the gravel from the sand is not essential.

CHAPTER V

Sandstone for Masonry and Other Purposes

SANDSTONE is a solid, coherent rock which has been formed by the cementing, by natural agencies, of the grains of a sand. The constituent minerals of a sandstone are, therefore, the same as in sands, and consist mainly of quartz, making up to 95 per cent of the whole rock, together with grains of iron ores, felspar and broken shells, and the essential cementing material, which may be silica, iron oxide, lime or clay, as a coating round the grains. It will be seen that the degree of coherence or strength of a sandstone depends, to a very large extent, on the type of cementing material present in the rock. The constituent grains of a sandstone are very hard and resistant to abrasion. They have travelled far in rivers and the sea, and, unless they were resistant to weathering, would not have survived. Sandstones are sedimentary rocks which were deposited mostly in the sea, but were occasionally formed in lakes, or as cemented, wind-blown sands.

NATURE OF SANDSTONE

FORMATION

Origin. Most water-borne sands are deposited in a zone along the coast, fairly close inshore. Depending on the supply of sand and the type of rock being worn away to provide it, the width of the sand zone may vary considerably. The heavier, coarser grains are deposited close inshore, and the sand becomes finer out to sea, and may gradually pass into muds. The pebbly material or shingle is deposited mainly between tide levels or at high-water mark.

The deposition of sand does not proceed continuously, but there are long periods when little or no sediment is forming, alternating with periods of rapid sedimentation. The beds of sediment have time to settle, and become partly consolidated before another bed of sand is placed on top. In this way, separate beds or strata of sandstone are built up one above the other, separated by partings or bedding planes. The bedding planes are usually about 6 in. to 3 ft apart, and are well developed in hard, compact strata, such as sandstone or limestone, but in shales the partings may be indistinct (Fig. 26). Where the bedding planes are close together, large blocks of stone for masonry cannot be obtained. When the bedding planes are a good distance apart, the rock is said to be *massive*.

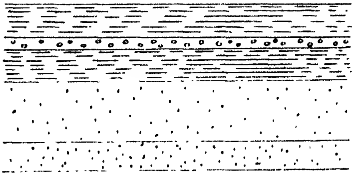

FIG. 26. BEDDING PLANES

The bedding planes separate layers of similar as well as dissimilar rocks.

Consolidation of Sand into Sandstone. A loose, incoherent sand can be converted into a solid sandstone by the provision of a cementing material which binds the grains together. The strength of the sandstone, and the purpose for which it may be used will clearly depend almost entirely on the nature of the cementing material. This has usually been obtained from the mineral grains in the original sand which have been dissolved by waters circulating within the sand. When the water dries out, the dissolved substances are deposited round the sand grains as a thin coating or *pellicle*, which cements the grains together at their contacts with each other. If the cementing material is excessive in amount, it may enter and fill up the spaces between the grains (Fig. 27).

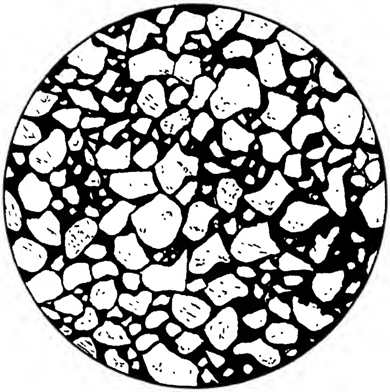

FIG. 27. THE APPEARANCE OF A CEMENTED SANDSTONE UNDER THE MICROSCOPE

The cementing material (black) holds the grains of quartz together. A stone such as this would have a low crushing strength and readily weather.

Shape and Degree of Interlocking of the Grains. The size, and especially the angularity, of the grains making up a sandstone are important factors governing its toughness and hardness. Where a stone is made up of wind-blown sand, the constituent grains are well rounded: there is then little interlocking of the grains, and consequently they are held together solely by the bonding action of the cement. The cementing material of these rocks is usually red iron oxide. Some of the rounded grained sandstones crumble into sand very readily, and are used as a source of sand rather than as masonry blocks. Many of the red Permian and Triassic sandstones of Cheshire and the Midlands are of this type. They were formed under desert conditions, and the grains are well rounded, giving little interlocking effect.

The subangular grains of many water-borne sandstones interlock with each other to a large extent. If the grains are of diverse size, the small grains pack in between the larger ones, and a more perfect interlocking structure is obtained (Fig. 28). This interlocking structure gives the rock a certain amount of strength and cohesion, quite apart from the cementing medium. The greater the degree of interlocking of the grains, the smaller will be the *porosity* and *absorption* of the sandstone.

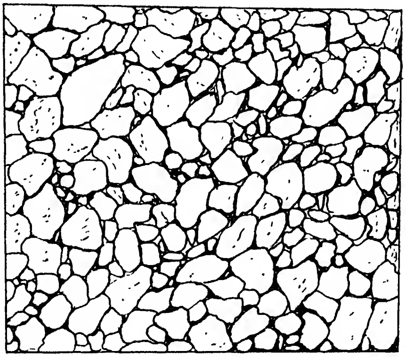

FIG. 28. THE APPEARANCE UNDER THE MICROSCOPE OF A SANDSTONE HAVING AN INTERLOCKING GRAIN STRUCTURE

The grains are of varying size and are well packed, giving a rock with a high crushing strength.

STRUCTURES OF SEDIMENTARY ROCKS

False Bedding. False bedding or *drift*, or *cross bedding* is a structure set at an angle, often of about 45°, with the bedding planes. The false bedding planes may be set at an inch or less apart, and are a prominent feature of some Carboniferous and Mesozoic sandstones. The rock may tend to break along the false bedding planes, or the structure may merely have the effect of lowering the *crushing strength* of the rock. False bedding planes are formed by the building out of a sand embankment, the planes marking the successive positions of the ends of the embankment from time to time. The red Triassic and Permian rocks of Cheshire and the Midlands show a very irregular type of false bedding, known as *dune bedding*, which is typical of wind-blown sands. When used as facing stone and in walls, the false bedding may show out strongly as a result of weathering.

Lamination. If the grains forming the sediment have settled vertically through the water, instead of being swept out as an embankment, *lamination planes* may be formed, giving the sandstone a striped or *flaggy* structure. This is due to the heavier, rounded grains of quartz settling through the water first, followed by the flaky, micaceous minerals which take longer to reach the bottom. Successive beds of sediment may be formed in this way, so that a bed of sandstone may consist of layers of sand an inch or less in thickness, separated by very thin layers of tiny flakes of white mica spread over the lamination planes. The rock splits along the micaceous layers with comparative ease into thin slabs of uniform thickness.

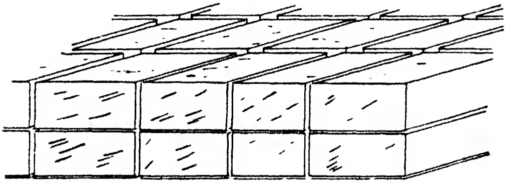

FIG. 29. BLOCK DIAGRAM SHOWING JOINTS AND BEDDING PLANES
The joints are vertical, and in two sets at right angles to each other. The bedding planes are horizontal.

Laminated sandstones or *flagstones* have been used extensively in the north of England for roofing tiles, and as flagstones for causeways and the flooring of houses. The crushing strength of these rocks is less in a direction parallel to the lamination planes than it is at right angles to them; therefore, if used for building purposes, these laminated sandstones should, if possible, be laid with the lamination planes set horizontal. In the case of arches and corners, however, it may be advisable to deviate from this rule.

There is usually much iron-bearing mineral in laminated sandstones which is inclined to oxidize if exposed to the weather, causing unsightly stains, and in many cases the stone soon begins to decay in these areas.

Joints. All solid rocks are affected by a rectangular series of cracks or breaks known as *joints* (Fig. 29). The joints occur in two sets at right angles to the bedding planes and to each other. They are thought to be caused by earth-movement, as the joints show some relationship to the direction of folding to which the rocks have been subjected. The joints are usually about 2–3 ft apart, and they have the effect of blocking out the strata into cuboidal blocks. This may make it easier for the quarrymen to obtain large, serviceable blocks of stone, without the use of explosives which might damage the stone. Where the joints are wide apart and the strata are thick, large blocks can be obtained, but where they are close together and the beds thin, the blocks are correspondingly smaller.

Joints do not have any effect on the rock once it is quarried, but a rock frequently has *slips* and microscopic cracks in it, and a dressed stone may break suddenly along these cracks. They are irregular and may run in any direction, and are difficult to foresee.

TYPES

Quartzite. The silica of the sand grains themselves is slightly soluble in natural waters. On the water drying out of the sand, this silica may be deposited round the grains, cementing them into a hard, solid stone. Sandstones with a silica cement are termed *quartzites*. These rocks are usually very hard, and may have a rather shiny appearance on freshly broken surfaces. Sometimes the quartz cement grows in optical continuity with the silica of the grains themselves, giving an interlocking structure, as in the red Penrith sandstone of Cumberland.

Quartzites are resistant to decay in town atmospheres. The silica cement has the same hardness and composition as the sand grains themselves, and ordinary acidulated waters have little effect on either. The cementing material is strong, and does not have cleavage planes or directions along which breakage easily takes place. The strength of these rocks against crushing is very high, and may reach to 800–1 000 t/ft^2. They are very tough and expensive to dress, but for the external facing of buildings in industrial towns, they serve extremely well. They are highly resistant to frost action, and, from the nature of their chemical composition, they do not decay very readily. Their high crushing strength prevents the rupture and scaling of the surface of the stone, should crystals of calcium sulphate begin to grow just under the surface. Some quartzites have too high a crushing strength to be used economically for building stone, but these high-grade quartzites are very suitable for use as concrete aggregates, and as kerb-stones and setts where the very highest resistance is required. The British Standard Specification (B.S. 706; 1936) states that sandstones used for kerbs, channels, quadrants and setts must be free from structural defects. The grains must be angular and closely interlocking, and the matrix be mainly siliceous. The strength in compression must be not less than 15 500 lb/in.^{3}, the absorption not more than 2·3 per cent, and the density not less than 155 lb/ft^3. The sandstones must be obtained from Carboniferous or older formations. The softer quartzites are ideal material for external use in important buildings, especially for string courses, corners, lintels, and projecting parts.

Quartzites are very restricted in their distribution. They very seldom occur in the geologically younger rocks, but are restricted to strata of Carboniferous or greater age. It follows, therefore, that many hard and suitable quartzites are often found in areas distant from towns and localities where they might be used. These quartzites may, in some cases, be quarried for local use as road-metal. The thin-bedded quartzites break into slabs too small to be used as building stone, as in the case of some of the Silurian quartzites of Yorkshire, and these are used as tarred roadstone, chips, and concrete aggregates.

Ferruginous Sandstones. Where the cementing material is iron oxide, the sandstone takes on a red or yellow colour, and is termed a *ferruginous* sandstone. The iron oxide is derived from the solution of a proportion of the grains of iron ore in the original sand, and its redisposition as oxide films round the surfaces of the grains. There is frequently an excess of iron oxide, and this fills the interspaces between the constituent grains, greatly reducing the porosity of the rock.

Iron oxides are soluble, to a fair extent, in rain-water acidulated with the smoke and grime of the atmosphere of industrial towns, and, in many cases, stains of yellow iron oxide form on the faces of buildings constructed of this stone. If the cementing material is gradually dissolved out from the surface layers of the stone, the rock will crumble and show signs of rapid decay. The crushing strength of a sandstone is dependent, to a large extent, on the strength of its cementing material. Iron oxides do not possess very great strength, and consequently the ferruginous sandstones have a fairly low crushing strength varying from 600 to 800 t/ft^2. This strength is sufficient to bear the load of all normal building work, but is insufficient to resist the action of frost and the growth of crystals, formed by the action of acidulated waters. For interior work, however, it may be very suitable, providing the stone is kept dry. Its softness makes the stone easy to dress and carve, and its red colour may be used to advantage in colour blending.

The ferruginous sandstones are especially characteristic of the geologically younger strata. Most of the sandstones occurring in the Permian and Triassic Systems of Cheshire and the Midlands are soft, red rocks, with a haematite (iron oxide) cement, and many of the harder types have been used extensively for building purposes. The Coal Measure and Millstone Grit formations of the Lancashire, Yorkshire and other coalfields provide many useful and extensively employed sandstones with ferruginous cements.

Calcareous Sandstones. In this type of sandstone the cementing material consists mainly of calcite (calcium carbonate, $CaCO_3$). This is derived from the solution of the broken shells which are present in most shore sands. Shells consist of calcium carbonate, which is readily soluble in waters circulating within the sand. On these solutions drying out, the grains of sand are cemented together to form a sandstone.

Calcareous sandstones are usually grey in colour, and, if much cementing material is present, they effervesce slightly when a drop of acid is placed on the rock. The calcite cement fractures easily, due to the mineral having a pronounced cleavage, and consequently the calcareous sandstones have a strength against crushing of about 600 t/ft^2. These rocks are unsatisfactory for the exterior facings of buildings in industrial atmospheres. The lime cement is readily soluble in town atmospheres which contain traces of sulphuric, nitric, or other acids. Removal of the cement from between the grains leads to the crumbling of the surface of the stone. If sulphuric acid is present in the atmosphere, it may act on the calcite cement, and form small crystals of calcium sulphate just below the surface. The growth of these crystals tends to disrupt the stone, unless its crushing strength is sufficiently great to withstand the strain. Calcareous sandstones, when used in towns, frequently show a scaling of their exposed surfaces due to this cause. For interior work where they are not exposed to rain, these sandstones may be quite suitable, and they may be quite satisfactory in country districts, or where the building is designed without projecting portions, which hold the drops of water.

Calcareous sandstones occur widespread in Britain, especially in Coal Measure and younger strata.

Argillaceous Sandstone. In some sandstones, clay material joins the grains together, forming the rock known as an *argillaceous* sandstone. These rocks have a very low strength in crushing, and are unsatisfactory for building purposes, as the clay easily washes out, causing the rock to crumble and fail under load.

The types of cementing materials above described are most common, but other substances, such as calcium sulphate, may form the cement, as in some sandstones in the Midlands. Barium sulphate forms the cementing medium in certain sandstones in Cheshire.

Conglomerate is shingle cemented into a solid rock. It is a common stone, and is especially found where one major geological system rests upon another. The rock may occur in thin beds, but some of the red conglomerates of Permian age in South-west England are several hundred feet thick. The pebbles of conglomerates are rounded, and may be of igneous or sedimentary rock. Conglomerate is not much used for building purposes, but is extensively employed in engineering work, such as sea walls and retaining walls.

Breccia consists of angular fragments, as distinct from the rounded pebbles of conglomerates, and they are of various sizes cemented together. They were originally scree deposits on hill-sides. A typical example is the Brockram of Permian age in the Eden Valley. These rocks are not extensively used.

Arkose is a coarse-grained, felspathic sandstone.

Grit is a coarse-grained sandstone. It is a very common type found in most formations, and is much used as building stone and for bridges and engineering work.

Flagstones are laminated sandstones which have the property of splitting along the lamination planes into slabs of even thickness. They are common in the Carboniferous System, and are used for causeways and occasionally for roofing slabs.

Siltstone is an extremely fine-grained sandstone, approaching the sandy shales in grain size. These rocks have a striped appearance, and are mainly used as concrete aggregate if they are sufficiently hard.

DISTRIBUTION

Sandstones of economic value are found in most geological systems, but those in the oldest rocks are somewhat inaccessible to the centres where they might be used, whilst the Tertiary sandstones are very soft, and of little value except as sand into which they readily disintegrate.

Hard grits and quartzites occur fairly abundantly in the pre-Cambrian rocks, but they are difficult to dress and are usually in remote localities, so that they are not much used except in areas where they outcrop. In the Cambrian rocks of Wales are found the Harlech and Barmouth grits of very great thickness. These rocks are durable, and have a pleasant appearance, but they are used only locally.

Other Cambrian quartzites occur in Warwickshire and Worcestershire, and have in places been worked for roadstone and other purposes. The Ordovician System also contains few good building stones. In the Silurian strata, flaggy beds have been worked in Wales near Aberystwyth and also near Ambleside and Ribblesdale, and used as roadmetal and concrete aggregates.

The Old Red Sandstone strata furnish many widely used building stones. Most of them are red and purple in colour, and have been much used for local building purposes in the Welsh Borders, Worcestershire, Shropshire, and parts of Scotland, where these rocks are at the surface. Much of the building around Hereford has been constructed of this stone. These sandstones, however, cannot compare with the sandstones obtained from the neighbouring Carboniferous rocks. The Caithness flagstone from Thurso in North Scotland is a tough, compact dark stone with a siliceous and calcareous cement. It is widely used for steps and landings.

The Carboniferous System provides the great majority of the good sandstones and grits of the country, and these come especially from the subdivisions, known as the Millstone Grit and the Coal Measures. The Lower Carboniferous rocks are mainly limestone and contain few sandstone beds, except in the Central Valley of Scotland and in Northumberland. The Millstone Grit series consists of thick grits and coarse sandstones alternating with shales. The grit beds may outcrop for long distances, but they change their character from place to place. They are quarried for local use, but they are often felspathic and some varieties weather fairly quickly. The Darley Dale stone from the Millstone Grit series in Derbyshire is a fine-grained, good weathering stone.

The Coal Measures contain valuable sandstones suitable for use as masonry, flagstones, setts and aggregates, and are widely used, especially in the coalfield areas. Many of the sandstones have received local names. The Elland Flags is one of the important Yorkshire stone beds, and is quarried extensively. It has a pale colour, is fine-grained and compact, and is quarried near Halifax and Elland. The Park Gate rock is extensively quarried near Sheffield, and is a massive, fine-grained rock suitable for masonry. Many other sandstones with local names are used in Yorkshire. In Lancashire many sandstones, such as the Upholland Flags, are quarried for flagstones and masonry. In South Wales, the Pennant rock provides massive sandstone, and its equivalent, the Forest of Dean stone, from Somerset, is widely quarried.

The sandstones from the Permian and Triassic Systems are usually bright red or yellow in colour. They are fairly soft, but some stones have been widely used. The conglomerate beds of Devonshire have been used in engineering work and sea walls at Torbay and other places. In Lancashire the Mottled Sandstone and the Pebble Beds have been used about Liverpool, Manchester, and Stockport. In Staffordshire, the Alton and Hollington stones are quarried from Upper Triassic rocks. They are cream to red in colour, and have been much used in the Midlands. In Cheshire a red stone has been quarried at Manley, and has been used in Chester and other places. The red sandstone of Penrith is of Permian age and has a quartz cement, but is not a durable stone. In Dumfries in Scotland, a fine, even-grained stone, which can be easily carved, has been quarried in the Annan district, giving the Corsehill stone. The stone is pink and red in colour, and has been much used in Edinburgh, London, Glasgow, and other towns where a red stone has been desired.

The Mesozoic strata are important as sources of limestone and clay, but most of the sandstones in these strata are too soft to be used for masonry. Many of the calcareous sandstones have, however, been used locally. The Bargate stone from the Cretaceous strata has been quarried near Godalming.

Sandstones from the Tertiary strata are usually too soft for use, except as sandrocks.

RECONSTRUCTED STONE

Artificial or *reconstructed* stone is, to a large extent, replacing natural sandstone for building purposes. It can be moulded to various shapes and, if necessary, be reinforced with steel. In the manufacture of reconstructed stone, the natural stone is crushed, washed, and graded and machine-mixed with cement. Pigment or colouring matter may be added, but care is needed that the material has no effect on the cement. The facing material of reconstructed stone may be different from the backing material, which may be granite or gravel concrete. The crushed stone and cement for the facing of the block are put into the mould first with the backing material on top, and the whole consolidated into a homogeneous mass. When set and hardened, the stone is removed from the mould, and may be rubbed or tooled just like natural stone, or may be carved. Reconstructed stone may be stronger than natural stone. Its cost is mainly in the face and may be but little, if any, cheaper than natural stone.

Sometimes cast or reconstructed stone has a tendency to *crazing*, or the development of fine surface cracks. This has been stated by the Building Research station to be due to the action of atmospheric carbon dioxide, which forms a skin on the stone. The surface can now be artificially carbonated to prevent this.

EXAMINATION AND TESTING OF SANDSTONE

EXAMINATION

Much valuable information about the structure of a sandstone may be obtained by an examination of the stone with a hand lens.

The size of the grains, their degree of angularity, and the interlocking of the grains can be judged. A much better method, however, is to make a thin slice of the rock and examine it by transmitted light, using a hand lens or a microscope. Slides, or thin sections such as these, can be prepared satisfactorily without any elaborate apparatus.

Preparation of Thin Sections. A small chip of the stone to be examined is broken off, and one face of the chip is ground down flat by rubbing it down on a glass plate, using coarse emery powder as an abrasive. A chip at least one inch square should be used, as it often becomes progressively smaller during grinding. When one face is smooth, it is polished by using successively finer grades of emery powder and finishing off by rubbing on a hone until the face is flat and highly polished. The chip is then turned over and the same process repeated, but great care must be taken to keep the two ground faces of the chip parallel to each other. Grinding down of the second face is continued as long as it can be held in the fingers. The chip is then cemented on a glass microscope slide, using Canada balsam as a fixative.

A small lump of Canada balsam is placed in the centre of the glass slide and warmed gently to melt, care being taken that the glass is dry, and that the balsam does not catch fire. When the balsam has been melted a short time, the polished and finished side of the rock fragment is pressed down into the melted balsam. The preparation should then be put aside for an hour to set and harden, after which the grinding can be continued, holding the glass between the fingers instead of the rock chip as before. The grinding is continued until light is transmitted through the slice, when it is held up to the light. At this stage only the finest flour emery should be used for thinning down the section. The rock section can finally be brought to a correct thickness by rubbing down on a hone or whetstone.

When the grains and the cementing material can be clearly seen by transmitted light, the slide can be finished and made permanent, by fixing a coverslip over the top. A little Canada balsam is melted on a coverslip, which is then pressed down on to the surface of the rock slice, and the whole left to set for a short time. The excess balsam, which may ooze from below the coverslip, can be cleaned off with the corner of a cloth dipped in benzine.

When finished and cleaned up, the slide should be labelled with the name and source of the stone, together with any other information which might be necessary. Such a preparation might form useful evidence should complications arise at a later date.

When the thin section is examined with a hand lens by holding the slide against the light, or better still by using a microscope, the shape of the grains should be apparent. The degree of interlocking, and therefore an idea of the toughness of the stone, can be obtained. Where non-siliceous grains, such as felspar, are present, the state of decomposition of these minerals can be seen, and this may influence the use to which the stone may be put. The amount of cementing material and its type can usually be made out. A careful examination of a thin section should, therefore, decide whether a sandstone falls into the durable masonry type and is suitable for exterior work in industrial atmospheres, or is suitable only for interior work, if at all.

MEASUREMENT OF PHYSICAL PROPERTIES

Crushing Strength. The crushing strength of a stone is the load it will bear at the moment of crushing, i.e. the greatest load a test piece can withstand before breakage takes place, and is expressed as tons per square foot or pounds per square foot, The test is carried out in machines which measure the pressure exerted, the pressure being increased until the stone breaks or crushes.

Practically all sandstones, however, are sufficiently resistant to crushing to be able to bear, with a good margin of safety, the loads due to the weight of the building in which they are used. The crushing strength is useful in indicating the resistance of a sandstone to the effects of weathering in town atmospheres. The higher the crushing strength, the greater the resistance of the stone. The crushing strength varies according to whether the test is made at right angles to the bedding, or is made *on end*. In a laminated sandstone, the crushing strength taken in a direction parallel to the planes of laminations is much lower than when it is taken at right angles to this direction. When the rock is saturated with water, a lower crushing strength is usually observed, and sandstone with a clay cement may fail when wet, although it may be strong enough in the dry condition. The strength may also deteriorate rapidly, on the stone being subjected to weathering.*

The strength in crushing, in the main, is a guide as to whether a stone should be classified as durable masonry. If the crushing strength is 500 or more t/ft^2, and the rock has a siliceous cement and an interlocking grain structure, it should withstand industrial atmospheres when used as facings in buildings. The London County Council regulations state that stone used in walls and piers "shall

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* Morton gives a case where a stone, fresh from the quarry, had a crushing strength of 250 t/ft^2, but, after seventy years of exposure to town atmospheres, this was reduced to 110 t/ft^2.

possess a resistance to crushing of at least 1 500 lb/in.^{2} and shall be free from cracks, sand holes and other defects which in the opinion of the district surveyor affect adversely its strength or permanence. Stone of a laminated formation which will be subjected to pressure shall be so bedded that the planes of cleavage will be at right angles to the direction of the pressure." The term *planes of cleavage* here means the planes of lamination.

The value of the crushing strength of sandstones varies from about 150 to over 1 500 t/ft^2. Where it is over 800 t/ft^2, the stone is expensive to dress for masonry, but is excellent for concrete aggregate, kerb-stones and setts. Sandstones containing much mica wear less slippery when used as setts than those containing but little of this mineral. Where the crushing strength is less than 550 t/ft^2, the stone would be put in the less durable masonry class, and restricted for use in interior work, or in districts where atmospheric pollution is not very great.

Density. The density of a sandstone is dependent on its porosity, the type of cementing material, and the specific gravity of its constituent grains. The great majority of the grains of all sandstones consist of quartz with a specific gravity of 2·5. A stone with a high porosity will have a lower density. Sandstones in the durable masonry class should have a density of about 150 or more lb/ft^3, whilst the less durable masonry types may have a density less than this.

The specific gravity of the rock in bulk, including the voids, or the apparent specific gravity, may be determined as follows—

Pieces of stone 2–3 in. across are taken. The larger the pores, the bigger the specimen should be. The stone is dried on a water-bath at 100° C to a constant weight: this may take several days. The specimen is then weighed in air and placed in a vacuum desiccator, and the pressure is reduced by a pump to about 1 mm of mercury. This process withdraws the air from the pores or voids of the stone. Boiled, cooled, distilled water is then admitted very slowly into the desiccator, through a tap funnel, until the specimen is covered with water, and the whole is left for several hours. The stone is then weighed in water and is afterwards removed, dried rapidly with a soft cloth and at once weighed in air.

Then $$G = W_1/(W_3 - W_2),$$

where G = apparent specific gravity of the stone in bulk;
W_1 = weight of the rock dried at 100° C;
W_2 = weight of the rock in water;
and W_3 = weight of the surface dried rock.

To find the weight per cubic foot of the stone, the figure obtained from the above equation should be multiplied by 62·37. This figure gives the density of the stone, including its voids.

The true specific gravity, or the specific gravity of the stone without its pores or voids, is determined by means of a specific gravity bottle. The stone is dried to a constant weight at 100° C, and is then crushed fine enough to eliminate all the pore spaces. A specific gravity bottle is cleaned, dried and weighed, filled to about $\frac{2}{3}$ full of the powdered stone, and weighed again. This gives the weight of the stone used. The specific gravity bottle and its contents are then placed in a vacuum desiccator, and the pressure is reduced. Boiled, cooled, distilled water is then introduced into the bottle, whilst still in the desiccator. When bubbles are absent, the bottle is taken out and left to stand for about $\frac{1}{2}$ hr. The stopper is then put into the bottle, the overflow of water dried off, and the whole reweighed.

Then $$G_1 = \frac{W_2 - W}{(W_1 - W) - (W_3 - W_2)}$$

where W_1 = weight of the bottle full of distilled water at 15° C;
W = weight of the bottle alone;
W_2 = weight of the bottle, plus the powdered stone;
W_3 = weight of the bottle, plus stone, plus water to fill the bottle;
G_1 = true specific gravity of the stone without voids.

Porosity. The porosity of a stone is determined, to a large extent, by the shape and the packing together of the grains, and the amount of cementing material present. Where the grains are spherical and all of about the same size, there is usually a high porosity, due to the large intergranular spaces. If the grains are subangular, they pack in closer together and reduce the porosity. If the grains are also subangular and of different sizes, the porosity is still further reduced, and the rock has an interlocking structure and greater strength. If the cementing material is large in amount it may fill the interspaces, greatly reducing the porosity of the stone, but increasing its strength.

The porosity of a stone is the volume of voids or pores it contains, expressed as a percentage of the total volume of the specimen.

$$\text{Porosity} = \frac{\text{Total volume of voids alone} \times 100}{\text{Volume of the rock substance, plus total volume of pores.}}$$

The porosity can be determined by calculation from the specific gravity of the powdered rock and the specific gravity of the stone as a whole, including the pores. Let

P = porosity of the stone;
G_1 = specific gravity of the rock powder;
G = specific gravity of the rock in bulk;
and d = the density of the rock at the temperature of the test.

1 cm^3 of the rock in bulk weighs Gd.
This contains $\{1 - (P/100)\}$ cm^3 of rock substances
which weighs $dG_1 \{1 - (P/100)\}$
and $G = G_1 \{1 - (P/100)\}$
or $P = 100\,(G_1 - G)/G_1$.

Absorption. The water absorption of a stone is, to a large extent, dependent on the porosity. The water absorption is the percentage by weight of water absorbed under certain standard conditions. The absorption is influenced by the size of the sample, the temperature of the water during immersion, and the time during which the stone is immersed. The method adopted by the British Standards Institution is as follows—

Three roughly cubical samples of the stone of about 50 g each are taken, and the sharp edges are filed down and the samples brushed to remove loose fragments. The test pieces are then dried in an oven at 100° C, for at least 72 hr, taken out, cooled in a desiccator, and immediately weighed to obtain their dry weight. The samples are then stood in a trough, and distilled water is allowed to creep slowly over them, until they are completely covered in about 4 hr, after which they are left under water for a further 72 hr to bring about the maximum saturation. The stones are then taken out of the water and loose surface water removed with a cloth, and the specimens weighed immediately to obtain the saturated weight in air. The absorption shown as a percentage of the dry weight is expressed by the formula—

$$\text{Absorption} = \frac{S - W}{W} \times 100,$$

where S = saturated weight of the stone in air,
and W = dry weight of the stone.

Where the stone is to be used as concrete aggregates, a representative sample weighing over 3 000 g is washed, and dried to constant weight. It is then immersed in water for 24 hr. The water is poured off, the stone wiped dry, and immediately weighed. This stone is placed in an oven at 100° C, and again dried till the weight is constant. The water absorption of the aggregate is the difference between the surface-dried weight and the final weight, expressed as a percentage of the final weight.

The hardest types of quartzite have a density of not less than 155 lb/ft³, and an absorption of less than 2·3 per cent of their dry weight. Sandstones suitable for exterior work in towns have a density higher than 140 lb/ft³, and an absorption of less than 4·5 per cent, whilst the less durable masonry, suitable for use in interior work, usually has a density of less than 145 lb/ft³, and an absorption of more than 4·5 per cent.

The following table shows the specific gravity, porosity, and absorption of typical sandstones (after Holmes).

	Specific Gravity	Porosity	Absorption (per cent)
Appley Bridge Sandstone	2·47	13·3	5·6
Darley Dale Sandstone	2·41	14·1	6·1
Nuneaton Quartzite	2·64	6·4	2·4
Blue Bristol Pennant Stone	2·76	-	3·4
Red Mansfield	2·18	14·9	5·8

CHAPTER VI

Limestone for Building Stone, Roadstone, Lime and Cement

LIMESTONE has been used as a building stone from ancient times, and has been widely used in ecclesiastical buildings because it can be easily carved, and because of its contrasting colours. A great many medieval castles were also built of limestone. Most varieties of limestone are, however, not suitable for use as facing stone, if exposed to the smoky atmosphere of industrial towns.

Limestones are found in the strata of most geological systems from the pre-Cambrian to the Tertiary. In some systems such as the Triassic, however, which was formed under desert conditions, limestone is rare, and is not of economic importance, although limestones are present in rocks of this age in other parts of Europe. Many limestone beds are so highly prized that they are followed underground and extracted by normal mining methods, as in the case of the Purbeck and Portland stones, whilst others, which are unsuitable for building purposes, are quarried for use as lime, for cement manufacture and other purposes, as discussed later.

These rocks consist essentially of carbonate of calcium ($CaCO_3$), and, like all carbonates, effervesce or bubble vigorously when a drop of dilute acid is placed on them. They range from white to black in colour, and are of all degrees of purity, some consisting almost entirely of calcium carbonate, whilst others may contain up to 30–40 per cent of clay material. Limestones containing much clay material may be unsuitable for concrete aggregates, as the clay may swell and crack the cement, especially if the clay is of a bentonic variety. Limestones are used for such diverse purposes as building stone, roadmetal, concrete aggregate, manufacture of lime and cement, as a filler in bitumen and similar material, in iron smelting and the chemical industry, and as a fertilizer. Britain is indeed fortunate in having limestone of good quality available throughout the country, and wherever these rocks are found they are extensively quarried.

NATURE OF LIMESTONE

FORMATION

Taken as a whole, the limestones were formed from masses of fossil shells accumulated in the sea, as in the case of the Carboniferous Limestone of the Mendip Hills and Derbyshire, or in large freshwater lakes, as in the Purbeck Limestones of Dorset. In clear water which is not too deep and into which little silt or mud is entering, animals enclosed in shells may flourish and be present in countless numbers. When these animals die, their shells are accumulated at the bottom of the water and, given sufficient time, huge and extensive shell banks may be built up. The shells and bones of animals consist largely of calcium carbonate. To a large extent, the material of which shells are made is soluble in natural waters containing dissolved carbon dioxide, and many of the shells

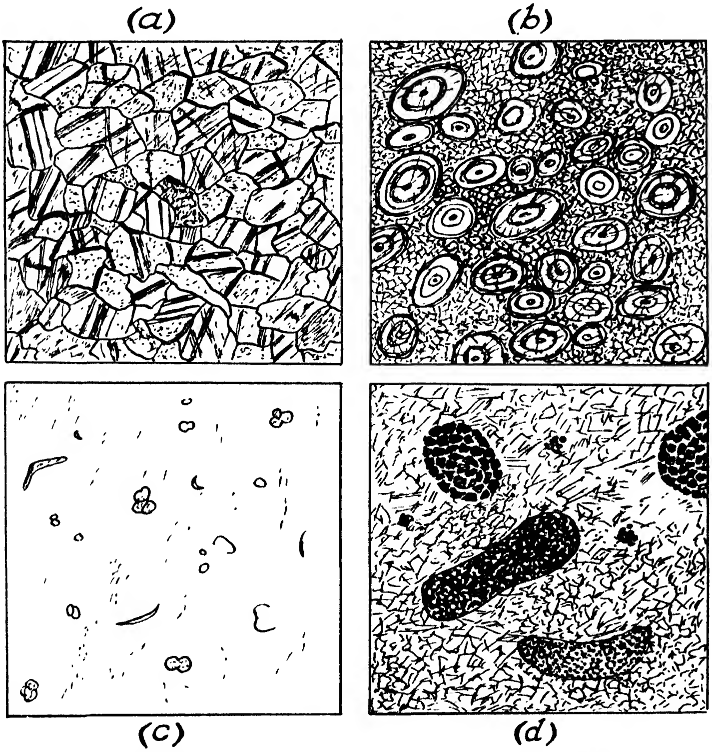

FIG. 30. THE APPEARANCE OF LIMESTONES UNDER THE MICROSCOPE

(*a*) *Marble.* The crystals of calcite are all about the same size and have an interlocking structure.

(*b*) *Oolitic Limestone.* The spherical ooliths show a distinct concentric structure and are set in a matrix of small calcite crystals.

(*c*) *Chalk.* The background material is extremely fine-grained and structureless. A few shells of microscopic foraminifera are present.

(*d*) *Bryozoal Limestone.* Bryozoal structures, consisting of polygonal cells, are present in a calcite matrix.

are dissolved away, the material which is dissolved being subsequently re-precipitated as crystalline calcium carbonate around the remaining shells, thus cementing the whole into a solid rock (Fig. 30).

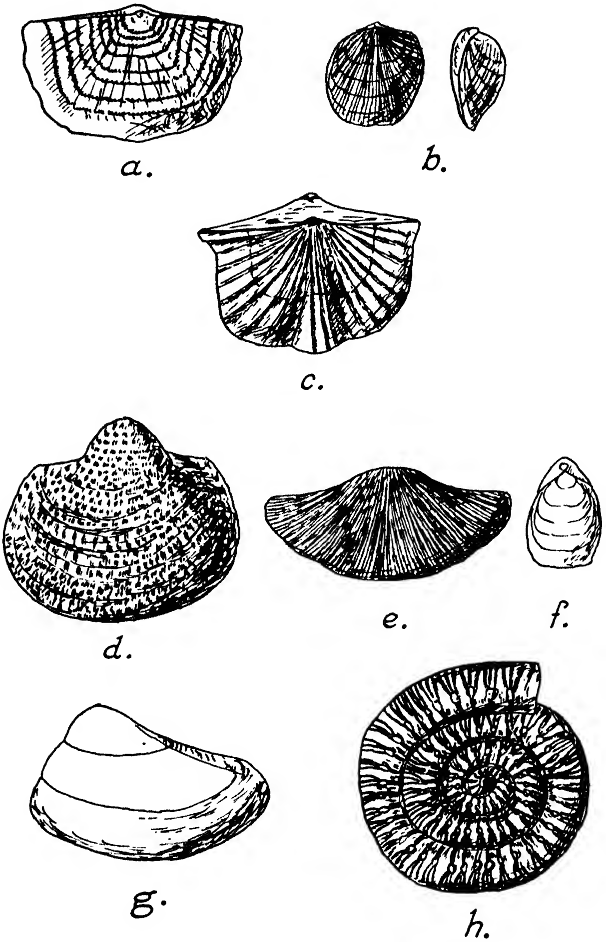

FIG. 31. FOSSILS FROM LIMESTONES OF DIFFERENT AGES

(*a*) *Leptaena rhomboidalis* } both from Silurian Limestones.
(*b*) *Atrypa reticularis* }
(*c*) *Spirifer verneuili* from Devonian Limestones.
(*d*) *Pustula pustulosa* } both from Carboniferous Limestones.
(*e*) *Productus* }
(*f*) *Terebratula punctata* from Lower Jurassic Rocks.
(*g*) An internal cast of *Trigonia gibbosa* from the Portland Stone.
(*h*) An ammonite *Stephoceras humphresianus* from Inferior Oolite Limestones.

The bulk of a limestone may come to consist of interlocking crystals of calcite, or crystalline calcium carbonate, in which are embedded numerous fossil shells, remains of corals, and crinoids. This interlocking crystal structure gives these limestones their low porosity and great toughness, whilst the lighter coloured fossil shells and corals may give the polished limestone great beauty, making it particularly suitable for interior finishes.

The geological formation from which a limestone has been quarried can usually be ascertained from an examination of the fossils it contains. Typical fossils, characteristic of limestones of various ages, are shown in Fig. 31, which may be of assistance in identifying the source of a particular limestone, where the rock contains characteristic fossils. Many limestones are crowded with fossil corals and were originally coral reefs. Some of the limestones of Devon are of this type.

TYPES

Oolitic Limestones. The *Oolitic Limestones*, which include such valuable stones as the Bath and Portland stones, are especially characteristic of Mesozoic strata, such as those of the Jurassic and Cretaceous Systems, although they may be found, to a smaller extent, in older rocks such as the Carboniferous Limestone. The Oolitic rocks or *Oolites* are chemical precipitates formed from sea water, which contained a high concentration of dissolved calcium compounds. The rocks were deposited on the floors of shallow, warm lagoons or seas, and consist of small spheres about ⅛ in. or less in diameter, cemented together into a solid rock. When examined with a hand lens, the small spheres or *ooliths* can be seen to be built up of skins one outside the other, giving the oolith a distinctly concentric structure. In addition there is usually a radial arrangement of the elements making up the successive layers of the oolith.

The oolites are chemical precipitates, and the grains have usually formed around a small nucleus, such as a fragment of shell, a grain of sand, or a pellet of calcareous mud. Sometimes one or two contiguous grains may touch each other, and all of them be coated with further layers of calcium carbonate, giving rise to compound grains. Many oolitic limestones contain considerable amounts of iron compounds, and the remains of shells are usually fairly abundant. Although some of our best and most widely used building stones are oolitic limestone, most oolites are soft, and readily disintegrate on exposure to industrial atmospheres. Locally, the thin-bedded oolites may be used as roofing slabs.

Chalk. Chalk is a very special form of limestone of great purity.

It is restricted in England to the uppermost portion of the Cretaceous System in a belt extending from the Dorset coast across England to East Anglia and the Yorkshire Wolds, and the downs of Kent (Map, Fig. 32). The rock is white to grey in colour, its whiteness depending, to a large extent, on its purity. The impurities vary from less than 1 per cent to upwards of 40 per cent in exceptional cases, and consist mainly of grains of sand or silica. Most varieties of chalk are very soft and crumble in water, which makes the rock eminently suitable for the manufacture of cement. In some areas the chalk is naturally cemented and is quite hard, as is the chalk near Corfe in Dorsetshire.

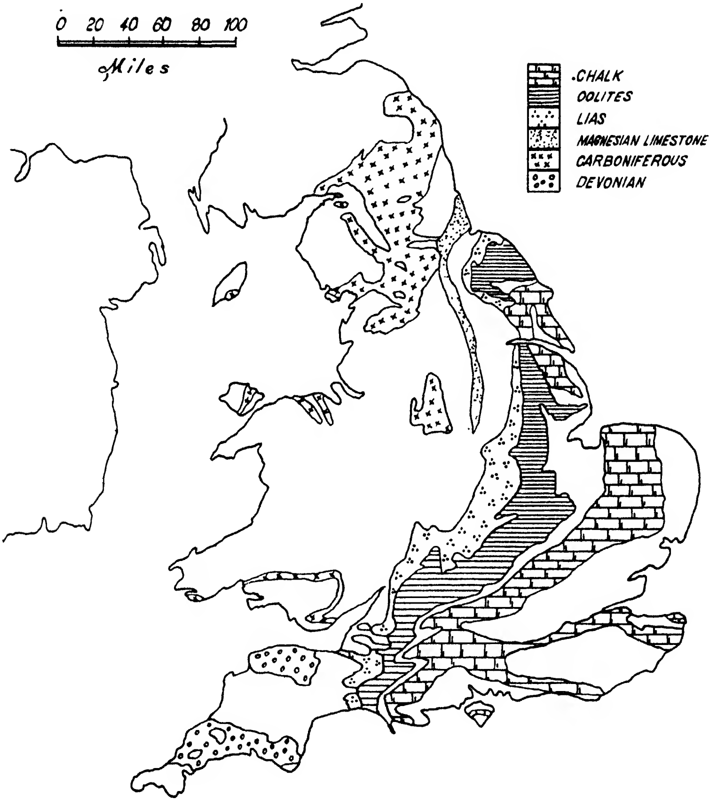

FIG. 32. MAP SHOWING THE DISTRIBUTION OF THE CHIEF LIMESTONE FORMATIONS

The chalk was formed during a period when the sea transgressed westwards over the whole of Britain with the exception of the highest ground in Wales and Scotland. Very little material was being washed down from the land into this sea, the bulk of the material deposited being a calcareous mud. The fossils in the chalk indicate that the chalk sea was not very deep, but fluctuated about a depth of a hundred fathoms. The mud was later hardened and consolidated into the chalk rock.

The upper part of the chalk strata characteristically contains rows of flint nodules of all shapes and sizes. They are very numerous and they usually weather to a white crust on the outside, but the fresh interior may be black, yellow or brown. Flint is composed of hard resistant silica. The nodules break easily, and have been extensively used locally in East Anglia for building purposes in churches and walls. The stone has been used as roadmetal, although it is fairly brittle, and tar does not adhere very well to its surface. Many beds of chalk have good local reputations as building stones where they have a greater hardness than usual.

Magnesium Limestone and Dolomite. Many limestones contain much magnesium in the form of magnesium carbonate, or more often in solid solution with calcium carbonate, forming the rock known as *dolomite* or *magnesium limestone.* The rock consists of calcium-magnesium carbonate $(Mg.Ca.)CO_3$, and often has about 20 per cent of magnesium carbonate in it. It has a higher specific gravity than ordinary limestone, and has a more yellowish appearance. Many magnesian limestones have been formed in inland seas or lagoons. Sea water contains up to 12 per cent of magnesium salts in some areas, especially where excessive evaporation takes place, and these salts may react with newly-formed calcareous sediments, converting them to dolomite. That the magnesian limestone of Britain was formed in seas containing a high concentration of dissolved salts is indicated by the frequent presence of thin beds of gypsum within this rock. The Magnesian Limestone of Permian age outcrops in a broad belt from the coast near Sunderland, southwards to Nottingham. A thin development is also present in the Vale of Eden (Fig. 32). Dolomitization of a normal limestone may take place subsequent to the formation of the rock. In this case, there is a shrinkage in the volume of the rock due to the conversion of the limestone to dolomite. The rock may become very porous with increase in the percentage of magnesium carbonate present. L. M. Parsons has shown that the porosity increases from 2·2 per cent, with a magnesium carbonate content of 10·7 per cent, to 5·8 per cent, with a magnesium carbonate content of 43·7 per cent. This increase in porosity applies only to limestones which have been changed since their formation into dolomites.

Dolomites do not effervesce as energetically in acid as do normal limestones, unless the acid is hot. They have a specific gravity of about 2·83 compared with 2·72 of most limestones, and they may be compact to granular in texture.

Marble. Marbles, from the strictly geological point of view, are pure limestones which have been completely recrystallized as a result of heat or pressure. The heat may have come from the intrusion of molten igneous rocks which have forced their way into the limestone strata. The heat from these melted rocks passes outwards through the limestones. If the limestones are under great pressures, the rock does not lose its carbon dioxide, and is not altered into lime. The gas is retained within the rock, and the limestone merely recrystallizes as a marble. A marble is therefore a rock consisting entirely of crystalline calcite, and it usually has a granular appearance.

When the original limestone consisted of almost pure calcium carbonate, the resulting marble is white, such as the Carrara marble. Many limestones, however, contain impurities of various types, and these have the effect of colouring the rock, when it is converted into marble, by entering into chemical combinations with the calcite. Where the limestone contained organic matter such as bitumen, or plant remains, the resulting marble may be black. The presence of iron compounds gives rise to red and brown colours, whilst copper minerals, chlorite and talc give green marbles. The serpentine marbles or *ophicalcites* are beautiful mottled green and white rocks. They are formed from limestones and igneous rocks which originally contained the mineral *olivine*, an iron magnesium silicate which readily decomposes to the green mineral serpentine, as in the Irish green marble of Galway. Many marbles have been broken and fractured as a result of natural earth pressures, and, in these cases, coloured minerals may form in the cracks, giving a veined or *brecciated* marble.

The White Marbles are obtained mainly from the Carrara district in Italy, and include the statuary marble which is pure white, but is too soft and expensive for use as facing material.

The Sicilian Marble is white and much used, and is also obtained from Carrara.

The Black Marbles are a clear, dead black, such as the Belgian Black quarried at Mazy near Charleroi. The Bleu Belge marble is a black marble containing thin white streaks. It is cheaper than the Belgian Black stone, and is obtained from Carboniferous rocks near Namur.

The Green Marbles. The Tinos green marble comes from the island of Tinos in Greece, and is a dark-green colour with lighter-green lacings. It is not a limestone, but is a soft serpentine and easily carved. Green marbles are also obtained from Sweden.

The Rose Marbles. The Breche Rose marble from Norway is a light rose colour mingled with white in patches.

The Yellow Marbles. These include the Siena Brocatelle marble which is a gold-yellow colour with a dark mixture. It is obtained from Siena.

The Buff Marbles include the Roman stones from Istria, and the Joinville group quarried from near Boulogne.

Blue Marbles. There are no true blue coloured marbles, the nearest approach being the Dove marbles.

Artificial Marbles. These may be prepared from Portland or magnesite cements. Coloured cements are used, and the stone may be pre-cast, or made at the site where it is to be used. The coloured cements are mixed in the proportions needed in the finished product. After the cement is applied, the surface is ground down with pumice until the veining appears and the surface is flat, after which the surface is polished.

Marbles do not have a very widespread distribution, and they show rapid variation even in the same quarry. Many different types of marble have been quarried locally from the pre-Cambrian rocks of Britain, such as the green Connemara marble from Galway, the cream-coloured Letterewe Limestone, and the Iona marble from the Inner Hebrides, but many of the more widely used marbles come from Italy and other places abroad.

Commercially, however, the term marble is often taken to include ordinary unaltered limestones, which can be readily polished and which possess peculiarities of structure or colour which make them of use as ornamental stone. These include some of the fossiliferous limestones from the Devonian, Carboniferous, and Jurassic strata.

Marbles possess delicacy of colour with permanence. They only need washing with soap and water to keep them fresh. If a caustic soap is used it will damage the polish. The stone is used mainly as a veneer, and for walls is used in slabs $\frac{3}{4}$–$\frac{1}{2}$ in. thick, laid with a space behind. For flooring, the slabs are $\frac{1}{2}$–1 in. thick, and laid in concrete.

Terrazzo is made from irregular fragments of marble laid in a matrix of Portland cement. It is laid in a plastic condition. It is very hygienic and effective.

Travertine. The material known as *travertine* is a fairly hard, compact limestone. It is crystalline, light coloured, and frequently shows a banding. Travertine is deposited from spring and river water which contains much calcium carbonate in solution. The carbonate is kept in solution by the presence of dissolved carbon dioxide gas in the water. When the water issues at the surface, as at a spring, some carbon dioxide is lost into the air, leading to the deposition of solid calcium carbonate or travertine. The porous cellular travertine called *tufa* is much used as a rockery stone and for walling. The compact travertine is light and strong, and in districts where it is abundant, as at Dursley in Gloucester and in North Wales, has been used for arches and vaulted ceilings.

Fig. 30 shows the appearance of various limestones when examined in thin sections under the microscope.

DISTRIBUTION

Limestones from the Palaeozoic Strata. The pre-Cambrian rocks do not contain limestones of any importance, and what there are, are situated in inaccessible places. Marbles have been quarried from a few places, such as Iona. Limestones are also of little importance in the Cambrian System in England and Wales, and in Scotland the thick Durness Limestone has been little used except locally, because of its distance from industrial centres.

In the Ordovician and Silurian Systems, limestones become more abundant, although most of them are unsuitable for building purposes, and are quarried for use in cement manufacture, as roadstone, and as fluxing material for iron smelting. The Bala and Llandeilo Limestones fall into this class, and are not of great commercial importance. The Wenlock, Woolhope, and Aymestry Limestones of Silurian age in Shropshire and other localities are much quarried for cement and roadstone, but are usually unsuitable for use as building stone.

The Devonian System contains much limestone, especially in the middle division of the system. Devonian Limestones mainly occur in Devon and Cornwall, and the limestones are quarried only in these areas. These middle Devonian Limestones are compact, and may reach a thickness of over 400 ft. They are grey in colour, and a characteristic feature is that they are often stained red along the joints, due to the infiltration of haematite into the rock. These limestones are quarried near Plymouth, Torquay, Totnes and in other localities, and are largely used for building purposes in towns in these areas, where they serve very well. The stone is grey to white in colour. Some types of Devonian Limestone are very fossiliferous, and contain abundant corals, which stand out white against a darker background when the rock is cut and polished. These fossiliferous varieties are often polished as marble, and used for interior finishes in large or important buildings.

The Carboniferous System is a great repository of limestones. All those of importance, however, are confined to the Lower Carboniferous or the Carboniferous Limestone, as it is usually called. These limestones are found at the surface, and are extensively quarried over large areas of the Mendip Hills, the Forest of Dean, South and North Wales, Derbyshire, Lancashire, and Cumberland. Farther north, in Northumberland and Durham, beds of shale break up the limestones, which are thin-bedded and not so important. In Scotland, limestones are not well developed, and are of little importance in the Lower Carboniferous strata.

Limestones of this age vary from white to black in colour. They frequently contain much bituminous matter, which gives the rock a black colour, and, when freshly broken, the limestone often emits a fetid, oily odour. The rocks vary much in their purity, and some types contain up to 40 per cent of material other than calcium carbonate. Dolomitization may affect some of the beds, and in many cases thin bands of *chert*, 2–3 in. thick, may be interbedded with the limestone. These chert beds are composed of black or brown silica, and may render the limestone unusable. Many of the Carboniferous Limestones are very fossiliferous, and contain shells and corals by which the rock can be identified. The purer varieties are often the whitest and the most fossiliferous.

Quarries have been opened in almost all localities where the Carboniferous Limestone outcrops at the surface. The stone, however, is not largely used as a building stone, but is extensively quarried as roadstone, for cement manufacture, and lime-burning, and as a flux for the smelting of iron. The stone is used in country towns for building where it is quarried locally. The limestone is extensively used for monumental work, landings and steps, and the fossiliferous varieties may be cut and polished as marble.

Limestones from the Mesozoic Strata. The strata of Mesozoic age contain numerous and important beds of limestone, including some of the finest and most extensively used building stones. Many of the more impure varieties are used in cement manufacture, and some are used as roofing tiles. Most of the limestones in the younger Mesozoic rocks are oolitic, and the uppermost beds contain the chalk rock.

The limestones of the Permian System are mostly dolomite. They are termed the Magnesian Limestone formation, and their outcrop runs in a fairly continuous band from Nottingham northwards to Knaresborough, and the Tees, and to the coast between Hartlepool and South Shields. These limestones were formed in a shallow type of sea. The thickness and amount of limestone present in the system increase as the outcrop is followed northwards away from Nottingham. The rock has been much quarried for building stone, and is of considerable commercial importance. The upper beds of limestone are thin and flaggy. The lower limestones provide the best building stones, and vary in thickness from about 40 ft in the south to over 200 ft in the north of the outcrop.

The colour of the Magnesian Limestone ranges from white and cream to yellow, and the freshly broken rock may sparkle, due to the presence of the rhombic crystals of dolomite and calcite. This sparkle is usually lost on weathering. The stone is quarried for building stone at Mansfield Woodhouse in Nottingham, at Bolsover Moor in Derbyshire, and at numerous other localities. The stone is dense and strong, but may show a tendency to decay in some atmospheres, unless the blocks are carefully selected. The stone has been used in the Houses of Parliament where it has shown some decay, and in the old Geological Survey building in Jermyn Street, where it has stood very well. The stone for this building was, however, very carefully selected. The Anston stone, quarried near Sheffield, is also from this formation. It often decays in polluted atmospheres.

The Triassic rocks of Britain were formed under desert conditions, and consist mainly of red sandstones and shales or marls. Limestones are not deposited under these conditions except the occasional chemical precipitates of calcium carbonate, which are of little commercial importance.

The Jurassic System is of very great importance as a repository of limestones which are worked for durable masonry, cement manufacture, roadstone and other purposes. These rocks were formed under open sea conditions when the sea encroached from the east over the Triassic desert landscape. The limestones formed at the end of the Jurassic period, such as the Purbeck Limestones, were deposited in freshwater lakes on the withdrawal of the sea again at the close of the period. The Jurassic rocks outcrop in a broad belt extending from the Dorset coast about Weymouth, through Oxfordshire, to the Yorkshire coast near Whitby. The limestone beds form prominent escarpments such as the Cotswold Hills, whilst the intervening shale beds form the valleys. Rocks of Jurassic and Cretaceous age in Britain are characterized by containing the coiled shells known as *ammonites* (Fig. 31). These ammonites are found in Britain in strata of no other period, and are of value in identifying the source of a stone.

The rocks of the Jurassic System are usually classified as tabulated below. The table also indicates the position of some of the more important building stones.

Subdivisions of the Jurassic	Building stones found in the subdivisions
Purbeckian . .	Purbeck marble, Swanage stone
Portlandian . .	Portland stone, Tisbury stone
Corallian . .	Calne stone, Wheatley stone
Great Oolite . .	Bath stone, Forest marble Bradford stone
Inferior Oolite .	Doulting stone, Ham Hill stone
Lias . . .	Hornton stone, Sutton stone

Most of these limestone beds, with the exception of rocks from the Lias, are predominantly oolitic in structure.

The Liassic rocks consist of thin bands of limestone alternating with beds of shale, and most of the stone of commercial value occurs in the lower portion. The Liassic limestones are not used except locally, for building stone, as in masonry the stone has a blue slaty colour, and a somewhat sombre effect. The Hornton stone quarried at Edge Hill, Warwickshire, is a brownish ferruginous limestone from the Middle Lias. It is oolitic, and has been used for external and internal work. The Lias limestones contain a high percentage of clay, and, therefore, are extensively used in the manufacture of cement. The rock is unsuitable for roadstone, as it easily powders, but it has been quarried for paving slabs at Shepton Mallet, and for paving stones in Warwickshire.

The Inferior Oolite overlying the Lias is about 250 ft thick. It passes into sands and ironstones in Northamptonshire, and, in Yorkshire, strata of this age are of an estuarine type and contain shale partings. Important building stones occur in Gloucestershire and Somerset. Amongst the more important stones of this subdivision of the Jurassic is the Ham Hill stone from the Upper Midford sands. This is a yellow current bedded oolite which can be obtained in large blocks. The Doulting stone from Shepton Mallet is a grey or buff stone which weathers well and hardens on exposure, and has been used in the construction of many cathedrals. The Ancaster stone and the Ketton stones are also widely used in buildings, and these also harden on exposure.

The overlying Great Oolite series contains some of the most widely used building stones. The limestone beds are best developed in the area around Bath, as the series changes its character when followed in a north-easterly direction, and in Yorkshire the Great Oolite is largely estuarine in type. Some beds of this series split into thin slabs, and are used for roofing material, such as the Stonesfield slate, which is not a true slate, but a thin-splitting, sandy limestone. The Bath stone is a light-coloured oolitic limestone, soft and easily worked. It hardens on exposure, and is frequently stored for seasoning before use. Particular beds of this rock are often worked by underground mining methods. There are several varieties of this stone. The Box Ground occurs in beds 12–14 ft thick, and blocks up to 16 tons in weight have been obtained. It has been extensively used in London, and is good for use in exposed situations. Other varieties are the Corsham Down stone, which is a freestone occurring in beds up to 4 ft thick, the Combe Down stone, and the Bradford stone from Bradford-on-Avon.

The Corallian beds show considerable lateral variation in lithology, and good building stones are not very abundant in this series.

The Upper Jurassic rocks contain two very fine building stones in the Portland stone and the Purbeck stone, which have been very widely used in important buildings in London and many other parts of the country. The famous Portland stone receives its name from Portland on the south coast, where it occurs in beds of Portlandian age, which are here about 170 ft thick, but the bed of stone of commercial value is only about 20 ft thick. The lithology of the beds varies from place to place, and when followed northwards they become thinner. The Portland stone is a marine oolitic and fossiliferous limestone. The lower portion of Portlandian beds is sandy and constitutes the Portland sands, followed upwards by the oolitic limestones. The general succession in these limestones in descending order is as follows—

4 . . . *Roach*
3 . . . *Whit Bed*
2 . . . *Curf*
1 . . . *Base Bed*

The uppermost bed, the Roach, is a pale-coloured oolite which has a great number of small holes scattered through it. These holes mark the former position of fossils, which have been removed by solutions circulating within the limestone. The Whit Bed is a freestone. It is brown when quarried, but becomes lighter on exposure. The bed is 4–15 ft thick, and is durable in exposed situations, but the presence of layers of shells may make it less suitable for fine carvings. The Curf may contain siliceous cherts, and is a band of stone often of poorer quality. The Base Bed is a good quality freestone 5–9 ft thick. It is a fine-grained oolite, whiter and softer than the Whit Bed.

The best varieties of Portland stone are freestones which can be carved for decorative work in buildings. The stone has been quarried in the Purbeck, Swanage, and Swindon districts, in addition to the type locality at Portland.

The Purbeck Beds have their greatest development in the Purbeck area near Swanage in Dorset, but they become thinner towards the north. These rocks were formed in a large freshwater lake, and the abundant fossils contained in the limestone are all of freshwater shells, such as those of water snails. The stone is not oolitic, and can thus be readily distinguished from the Portland stone. The strata of importance are about 50 ft thick, and many varieties of stone are produced for masonry, walling, roofing, and paving stones. The stone is usually mined rather than quarried, and has been obtained in the Swanage area from ancient times. The Purbeck marble is a grey limestone, crowded with fossil freshwater shells. It will take a high polish which tends to dim on exposure. It has been very much used in the past for building stone, lime-burning, and paving slabs. Strata of Purbeck age also occur in Sussex and in the Vale of Wardour.

The Cretaceous strata at the top of the Mesozoic rocks provide little material suitable for building stone. The earliest Cretaceous rocks were deposited in a freshwater lake occupying roughly the same situation as the lake of Purbeck times. The chief stone from these lower beds is the Sussex or Bethersden marble, which is a greenish-grey limestone full of the shells of the freshwater snail, *Viviparus*. The rock is similar to the Purbeck marble, and takes a good polish. The Kentish Rag is also an important stone in Kent, and is grey or greenish in colour, and impervious to water. It is hard and tough, has been widely used, and is quarried extensively near Maidstone. The chalk itself is usually too soft to be used for building, but some parts are harder and have been used, as in the case of the Totternhoe stone, quarried in Bedfordshire. This stone is soft when first obtained, but hardens on exposure and is suitable for interior work. The stone bed varies from 6–17 ft in thickness. The Beer stone is obtained near Axminster, and is a cream or nearly white rock, consisting of shell fragments cemented together with calcite. It hardens on exposure, and is extensively used for interior work. The more normal chalk is mainly quarried for use in lime-burning, and the manufacture of cement.

The Tertiary rocks provide little limestone of commercial importance in Britain, although in other countries Tertiary limestones may provide useful stone. The Pyramids of Egypt are built of limestone of Tertiary age.

PROPERTIES AND USES OF LIMESTONE

GENERAL PROPERTIES

The Hardening of Limestone. Many limestones, especially those of Mesozoic age, harden on exposure after being quarried. When a rock is in its natural position in a stratum, it may contain a considerable amount of water enmeshed between its constituent crystals. This water within the stone usually contains dissolved substances, such as calcium carbonate. On the blocks of stone being quarried out, however, this water tends in time to creep to the surfaces of the blocks and dry out. Any calcium carbonate, or other substances which the water contained, will be deposited in the surface layers of the masonry, and tend to cement these surface layers still further, and make them harder and firmer. This hardening takes place only in the surface layers of the stone. If this hardened or seasoned surface is removed by carving or other work, this portion may weather much more rapidly than where the seasoned crust has not been removed. The stone is often dressed or carved soon after being quarried, for this reason. A limestone may be left for several years after being quarried in order to become seasoned.

Analyses of Limestones. The following table gives the analysis of typical examples.

	Content (per cent)			
	Chalk	Lias Limestone	Portland Stone	Bath Stone
Calcium Carbonate	92·18	77·46	95·16	94·52
Silica	2·34	13·25	1·20	—
Alumina	1·84	5·72	0·50	1·20
Iron Oxides	1·49	1·97		
Magnesium Carbonate	1·16	1·35	1·20	2·50

Physical Properties. The table at top of p. 89 gives some figures for typical rocks. Different specimens may show slightly different results.

Stone	Density (lb/ft³)	Crushing strength (t/ft²)	Absorption (per cent dry weight)	Specific gravity	Porosity
Carboniferous Limestone .	158	---	5·5	2·54	12·7
Dolomite: Somerset .	165	577	13·2	2·7	8·1
Mansfield Stone (Permian)	140	577	7·5	2·25	7·5
Box Ground . . .	119·2	98·3	60·3	1·9	22·3
Corsham Down . .	138	223	7·76	2·2	16·8
Portland Stone . .	135	205	7·6	2·15	12·8

LIMESTONE AS A BUILDING STONE

Limestones are very extensively used as building stone. Not all types are suitable for this purpose, however, especially if used as a facing stone in the polluted air of industrial towns. Industrial gases contain sulphur and acid vapours, and these react with the calcium carbonate of limestone masonry to form calcium sulphate or *gypsum*. The attack begins at the surface layers of the stone. The volume of the calcium sulphate crystals developed is about 20 per cent greater than that of the calcium carbonate from which it was formed. The growth of these gypsum crystals disintegrates the surface layers of the limestone, causing them to flake off, and thus exposing fresh surfaces of the stone to the same disintegrating action. Limestone masonry should not be used in juxtaposition to sandstone, as the calcium sulphate may enter the sandstone from the limestone, and cause the decay of the sandstone. The white efflorescence often seen on masonry is due largely to the growth of these sulphates. In the case of the dolomite limestones which contain magnesium, the magnesium sulphate, produced by the action of sulphurous vapours in the air, is soluble in rain-water and is removed in the rain, leaving the surface of the stone in a friable state. Where limestone is used in situations exposed to sea air, salt may be deposited on the surface of the stone, and may absorb water and keep the outer layers of the stone damp, or, if it dries out, the formation of crystals of salt may disintegrate the stone in the same way as the formation of gypsum crystals. Where the sides of a building are exposed to rain wash, the dirt and the products of decay may be washed off before they have time to crystallize, and in this position the masonry may resist the atmosphere better than in cases where it is protected from rain wash. Some limestones tend to *clean* themselves. The calcium carbonate of which these rocks are composed is slightly soluble in water containing dissolved carbon dioxide, so that there is a slight, but continuous solution of the face of the stone which also cleans off the soot and dirt.

LIMESTONE FOR USE AS CEMENT

Cement has now become one of the most important of modern building products. Attempts at cement manufacture have been made from early times. In 1756 Smeaton used the Liassic Limestone of Somerset for making cement for the third Eddystone lighthouse. In 1811, Joseph invented Portland cement by burning chalk and mud dredged from the Medway, and, for a time, northern Kent was an important centre of cement manufacture.

Many natural rocks contain clay and lime in about the required proportions for making a cement, and these rocks may be crushed and burnt in kilns without any special blending or purification. Septarian nodules from Kimmeridge clay and the greensand, and those dredged from the sea near Harwich and Sheppy have been used for this purpose. A great disadvantage in using natural cement rocks is that the resulting cement may be very variable in composition, and not so strong as that made from clay and limestone under closely controlled conditions of manufacture.

Portland cement is now made by heating limestone or chalk with shale, marl, or clay, in the proportion of about three parts chalk to one of clay, at a temperature of over 2 000° F, when the lime fuses with the siliceous and aluminous material of the shale. The chemical analysis of Portland cement averages about as under—

Silica	22%
Lime	62%
Alumina	5%
Magnesia	3%
Iron Oxide	2·5%

There may be small variations in composition of cement from different localities. The calcareous portion of the raw materials may be obtained from chalk as in Kent and Sussex, where the clay is brought to the chalk for firing, or from limestone, such as the Carboniferous Limestone in Lancashire, Derbyshire, and North Wales. Analyses of these rocks are given in the previous section. Dolomite limestones are not used in Portland cement manufacture, as the magnesia is deleterious in this cement. Clays and shales provide the acid material to combine with the basic calcium carbonate of the limestone. The chemical composition of the shales and clays is unimportant, provided they do not have an excess of coarse sand, and stratified clays, glacial clays, and alluvial clays are used. If the clays contain lime, it is an advantage. If the clays contain iron much in excess of about 10 per cent of iron oxides, the cement may be dark in colour. The clays should be highly siliceous, and have about 60–70 per cent of silica and 6–20 per cent of alumina.

The impure, shaly limestone, which may be unsuitable for lime-burning, may be very satisfactory for cement manufacture. The limestones are quarried together with any intervening shale beds which may be present. The Liassic Limestones may contain sufficient clay material as an impurity as not to require the further addition of shale. If any more shale is needed, the intervening shale beds are picked up. The very pure limestones, such as chalk, require much shaly stuff, which may be obtained from the Gault clay below the chalk, or from river muds in the Thames and Medway or other rivers. A mixture of chalk and the neighbouring chalk marl also gives good results.

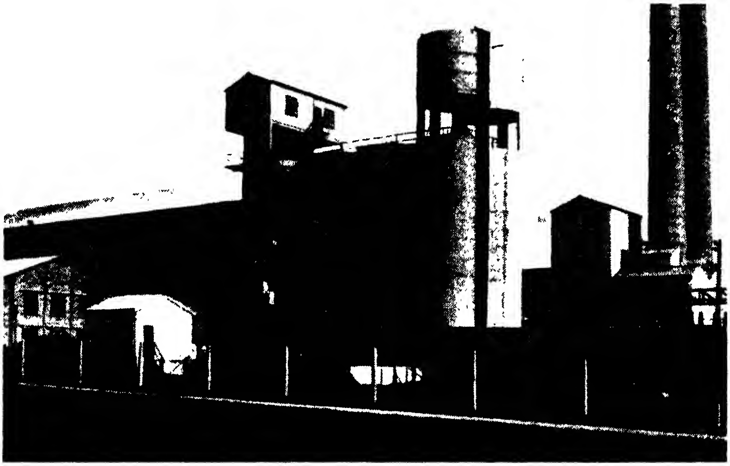

FIG. 33. GENERAL VIEW OF A MODERN CEMENT WORKS
The kiln house is in the background and the cement storage in the foreground.

Manufacture of Cement. The plant for the manufacture of cement (Fig. 33) from its raw materials is usually placed within reach of the quarries. The limestone is quarried and loaded by mechanical shovels into trucks which take the rock to the crushers, where it is broken up into small fragments. From the crushers, the rock is ground fine in tube or ball mills, and then put into storage bins. The shale material is treated in the same way. The shale and limestone or chalk are then blended to give a cement of the required composition. Shale or limestone may be added when necessary as indicated by samples which are regularly taken.

From the raw mix storage bin (Fig. 34), the mixed material passes to the rotary kiln where it is strongly heated. In some plants the raw materials are ground with water, and the wet ground material, as a *slurry* containing about 40 per cent of water, is pumped into the kilns. Sometimes the slurry is run into settling tanks, and the paste which settles at the bottom is pressed into bricks, dried, and then placed in the kilns. The kilns used for firing the mixture of shale and limestone are lined with firebricks to resist the heat, and are 150–350 ft long, and 8–14 ft in diameter. The kilns are rotated by means of a gear ring placed near the middle, and are set at an angle of about 1 in 25. They are coal fired, the fuel being injected as coal dust at the lower end, and the amount of the ingoing air is carefully regulated.

FIG. 34. THE MIXING TANK FOR THE RAW INGREDIENTS OF CEMENT
The ground shale and limestone are mixed with water and the slime agitated mechanically.

The raw material enters the kiln at the upper end, and meets the hot gases coming up and is dried. As the kiln revolves, the material passes down into the clinkering zone, where carbon dioxide gas and water vapour are given off. The limestone and the siliceous and aluminous material of the shale enter into chemical combinations and fuse together to form *clinker*, as the material passes down the kiln into the hottest zone at the bottom. The clinker is greenish in colour, and is in lumps about the size of peas. It passes out from the bottom of the kiln into a cooler, and when cooled passes into the storage bin. The clinker is ground with a little gypsum in tube or ball mills to a very fine powder. Raw clinker sets immediately, and to delay setting for a convenient time about 1 per cent of gypsum (calcium sulphate) may be added at the time of grinding. The finished cement is stored for seasoning, and then bagged for dispatch. Fig. 35 shows the sequence of events in cement manufacture.

In the rapid hardening cements, gypsum is added during grinding.

The British Standard for Portland Cement (B.S. 12: 1940)* is as follows—

Chemical Composition. The percentage of lime, after deduction of that necessary to combine with the sulphuric anhydride present, shall not exceed 2·8 times the percentage of silica, plus 1·2 times the percentage of alumina, plus 0·65 times the percentage of iron oxide, or be less than ⅔ of that amount. The ratio of the percentage of iron oxide to that of alumina shall not exceed 1·5.

Insoluble residue by weight
1% maximum.
Magnesia by weight
4% „
Total sulphur content, calculated as sulphuric anhydride
2·75% maximum.
Total loss on ignition
3% „

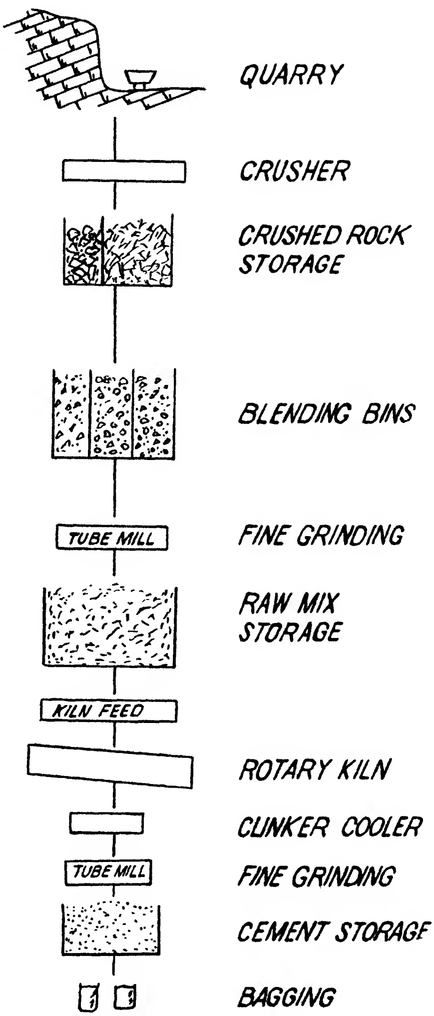

Fig. 35. Diagram Showing the Sequence of Events in Cement Manufacture

Other tests in the Specification are as given in the table on p. 94.

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* Extracted from B.S. 12: 1940, by permission of the British Standards Institution, 28 Victoria Street, London, S.W.1, from whom official copies of the specification can be obtained. Price 2s., post free.

	Cement	
	Ordinary	Rapid Hardening
Fineness Residue by weight on No. 170 mesh B.S. Test Sieve.	Not exceeding 10%	Not exceeding 5%
Ultimate Tensile Strength (The tests are on cement-sand mortar briquettes under standardized conditions.)		
At 1 day (24 hours)	–	300 lb/in.² minimum
At 3 days (72 hours)	300 lb/in.² minimum	An increase in strength at one day but not less than 450 lb/in.²
At 7 days	An increase on 3 days but not less than 375 lb/in.²	
Compressive Strength (This is an alternative to the tensile test. The tests are made on cement-sand vibrated mortar cubes under standardized conditions.)		
At 1 day (24 hours)	—	1 600 lb/in.² minimum
At 3 days (72 hours)	1 600 lb/in.² minimum	An increase in strength at one day but not less than 3 500 lb/in.²
At 7 days	An increase in strength at 3 days but not less than 2 500 lb/in.²	
Setting Time		
Normal Setting Cement	Not less than 30 min Not more than 10 hr	Not less than 30 min Not more than 10 hr
Quick Setting Cement (to be particularly specified if required)	Not less than 5 min Not more than 30 min	Not less than 5 min Not more than 30 min
Soundness Expansion with the "de Chatelier" test	Not to exceed 10 mm (0·40 in.)	Not to exceed 10 mm (0·40 in.)

Aluminous Cement. High alumina cement is made by heating a mixture of limestone and bauxite (ore of aluminium), usually in the electric furnace, until they are completely melted, and then grinding the resulting clinker. Aluminous cement has an approximate composition as follows—

Lime	35–40%
Alumina	35–45%
Silica	5–15%
Iron Oxide	5–15%

Aluminous cement is resistant to sea water and sulphate solutions. It sets slowly but hardens rapidly.

The British Standard for High Alumina Cement (B.S. 915: 1940) is as follows—

Chemical Composition. The total alumina content shall be not less than 32 per cent by weight of the whole. The ratio of this percentage by weight of alumina to the percentage by weight of lime shall be not less than 0·85 or more than 1·3.

	Aluminous Cement
Fineness Residue by weight on a No. 170 mesh B.S. Test Sieve.	Not exceeding 8%
Compressive Strength (The tests are made on cement-sand vibrated mortar cubes under standard conditions.)	
At 1 day (24 hr)	Not less than 6 000 lb/in.²
At 3 days (72 hr)	An increase in strength at one day and not less than 7 000 lb/in.²
Setting Time The initial set	Not less than 2 hr or more than 6 hr
The final set	Not more than 2 hr after the initial set
Soundness Expansion with the "de Chatelier" test	Not to exceed 1 mm (0·40 in.)

HYDRAULIC LIME

This is prepared by burning limestones which contain a proportion of clay. The clay enters into combination with part of the lime, and forms a mixture of cement and quicklime. These materials slake less readily than lime and set hard. Its value depends on the extent of the combination of the lime and clay. The total calcium and magnesium content should be not less than 60 per cent by weight of the ignited sample. The total silica and alumina should not be less than 15 per cent.

Limestone and chalk consist mainly of calcium carbonate. The rock, however, is greatly affected by heat. At a temperature of about 750° C, the rock begins to give off carbon dioxide gas, leaving a residue of calcium oxide, or quicklime. The change is completed at a temperature of about 900°–1 000° C. The reaction takes place according to the following formula—

$$\text{Limestone} \rightarrow \text{Quicklime} + \text{Carbon dioxide gas}$$

$$CaCO_3 \rightarrow CaO + CO_2$$

The purer limestones are best for lime-burning. If the rock is too strongly heated, any clay or siliceous impurities may combine chemically with the lime forming calcium silicates, which are stony and which slake only slowly and very imperfectly. Magnesia should not be present to any extent, or a poor, almost unslakable lime is produced. Where thin shale bands are present in the limestone, the rock may be loaded by hand at the quarry face on to the trucks to prevent the shale reaching the kilns.

The limestone may be roasted in vertical kilns with a continuous run through of material, using producer gas as fuel, or by the older type of kiln, fired by coal, which is intermittent in operation, the kiln being emptied of lime before being recharged with limestone. The rotary kilns as used in cement manufacture are also sometimes used for lime-burning. The *fat limes* contain 95–100 per cent of calcium oxide, and slake rapidly with up to 100 per cent increase in volume. Poor or *lean limes* have 85–95 per cent calcium oxide. They slake slowly, and there is not such an increase in volume. Hydraulic limes contain some clay and set in about four days. There is little expansion on slaking. Fat limes may not be suitable where strength is required.

For most uses, quicklime is slaked by adding water. Eighteen parts of water react with fifty-six parts of quicklime, and much heat is produced. The hydration may be carried out mechanically or by hand.

Mortar is made by mixing slaked lime with sand and water. On drying, the lime absorbs carbon dioxide from the air, and sets hard, forming calcium carbonate. The sand content makes the mortar more porous, and reduces the amount of shrinkage when the mortar sets.

Limestones of all ages are used for the manufacture of lime, if it is near areas where it is likely to be used. The Silurian and the Carboniferous Limestones, the Jurassic Oolites, and the Chalk have all been extensively employed.

LIMESTONE AS ROADSTONE

A considerable proportion of the limestone quarried in this country is used as roadmetal. For use on modern roads the stone should be hard enough to resist the loads it may be called upon to bear, and tough enough to resist abrasion and the plucking action of the pneumatic tyres of vehicles using the road. A coating of tar should also adhere to the surface of the stone. The rock powder produced as a result of wear should also help in cementing the roadmetal together. Limestones are tough because of their interlocking crystal structure, and the dry, dust-free rock takes a coating of tar very well.

The dry, dust-free stone is placed in molten tar and heated. The limestone will stand the heat without disintegrating. Many limestones themselves are bituminous, especially those from the Carboniferous System. Not all limestones are suitable for roadmetal, however. The coarsely fossiliferous types may be unsatisfactory, as the fossils tend to break out; many of the soft Oolitic Limestones are also unsatisfactory. Most of the Carboniferous Limestones are extensively used as roadstone and chips, as they have a close-grained structure and readily take a coat of bitumen.

The limestone dust produced during the crushing operations at the quarries also has a use as a filler in bitumen. The dust must pass a sieve with 200 meshes to the inch.

SAND LIME BRICKS

These bricks are made by mixing crushed sand and milk of lime. Six to 10 per cent of lime is usually present. The mixture of sand and milk of lime is stored, and then formed into bricks under great pressure in machines. The bricks are put into kilns and heated by super-heated steam for eight to ten hours, when the bricks are ready for use. The bricks have a strength in crushing of about 128 t/ft^2. The hydrated calcium silicate, formed by the steam, forms the cementing agent, binding the sand grains of the brick together. The bricks are white to cream in colour, and can be used as a substitute for bricks made from clay. Their light colours make them suitable for use where reflection of light is required. The strength of sand lime bricks is dependent on the heat of the superheated steam producing lime-silicate materials to bind the sand grains together. If these materials are not formed, the brick is merely a mixture of sand and lime, and has little strength.

CHAPTER VII

Brickclays and Fireclays

MANY rocks, especially in the younger geological formations, are soft and plastic, and can be moulded. Other rocks, such as mudstones and some shales, when ground up and mixed with water, revert to clay, and can be used in the same manner, in the manufacture of bricks and terra-cotta. The fireclays are harder and have a different composition, and mode of occurrence, from the normal brickclays. Because of their particular mineral composition, they are heat resisting, and can be glazed and fired at a high temperature for the manufacture of such articles as wash basins, baths, and tiles. The china clays are much more restricted in their occurrence, and are only found associated with areas of granitic rocks.

Clays are rocks which have a wide distribution amongst the sedimentary strata, especially in the Jurassic, Cretaceous, and Lower Tertiary rocks. The mineral constituents of clays are all of minute size and are scarcely distinguishable under the highest magnifications of the microscope. Clays owe their distinctive properties to a large extent to this extremely small size of the constituent crystals, and the consequent enormous total internal surface area. There is also an indeterminable *paste*, the constituents of which cannot be made out even under the highest powers of the microscope. A certain amount of colloidal material is always present, and there may be a considerable amount of water present, which can be driven off on heating or air drying the clay. Carbonaceous matter, derived from the decomposition of vegetation drifted into the area in which the clay was being deposited, may give the clay a dark colour.

NATURE OF CLAYS

FORMATION

Origin. Almost all clays are of sedimentary origin, and most of the ordinary brickclays were formed under marine or estuarine conditions. Some of the mudstones quarried from the Coal Measure strata for brickmaking, however, were undoubtedly deposited in large freshwater lakes.

The material from which clay was formed was obtained from the denudation or weathering of land areas. Chemical changes and the effect of climate and ground water decompose many rocks and minerals. Chemical decomposition, especially of the felspars and biotite mica, leads to the production of secondary flaky minerals, which largely make up the material of clays. These products of decomposition and weathering ultimately find their way into streams and rivers, and are then washed down into the estuaries and the sea where the material is spread out in layers, the finer material being carried farthest out to sea before being deposited, because of the slowing down of the current carrying the mud. The deposit of mud may cover very large areas of the sea floor in some cases, and it is probable that most of the clay beds now worked for brick-making were formed in this way. Many of the sooty, black clays and mudstones have been formed in stagnant water in which oxygen was deficient. This is indicated by the presence of much carbonaceous matter and iron sulphide in the clays, and their not infrequent oily nature. The greenish or grey colour of the Gault clay of South-east England is due to the presence of the iron silicate mineral, glauconite.

Mineral Content. Clays have a very complex mineral content, which is difficult to study, but special methods of investigation, including the use of X-rays, are throwing some light on this problem. The predominant minerals of clay are alumino-silicates, and many are hydrated such as the hydrated aluminium silicate *beidellite* and the iron silicate *nontronite*. The *kaolin* group of minerals are also hydrated alumino-silicates, and are a fairly common constituent of the china clays. The flaky mineral *pyrophyllite* (hydrated alumino-silicate with a higher proportion of silica than kaolin), is also present in many clays. Decomposition products formed by the breaking down of other minerals are also abundant. These secondary minerals include the *clay slate needles* formed of *rutile* (titanium oxide), which may have been formed from the titanic acid set free during the decomposition of the dark mica, biotite. Sulphides and carbonates of iron are usually present, and there may be much colloidal ferric oxide mixed with the particles making up the clay. It is this iron content which gives many clays a red colour when they are burnt into bricks.

Structure. When first deposited, clays consist of about only 10–30 per cent of solid matter, the rest being water enmeshed between the grains. If more sediment is deposited on top of the clay, some of the water is expelled from between the particles by weight of the overlying strata, and the grains begin to pack together. The pore space may be reduced to less than 75 per cent, after which the material tends to become plastic. Further compression expels more water, and the constituent grains come closer together. Still greater pressures may remove most of the free water, and the grains come into actual contact with each other. The rock becomes harder, and some recrystallization may take place. The rock is now known as a mudstone to distinguish it from the plastic clays which still retain much free water. Further induration results in the formation of a shale which is comparatively hard and has a fissile structure. Clays and mudstones are the rocks which are plastic or become plastic when mixed with water, and they are, therefore, the materials which are used in the manufacture of bricks and moulded articles.

GENERAL PROPERTIES

Impurities in Clays. The essential characteristics of clays are extreme fineness of grain, the constituent minerals being mainly alumino-silicates of a flaky nature. Many clays, however, contain impurities from the brickmaking points of view.

Sand may occur as grains of sand, or as colloidal silica in the clay. Sand has the effect of reducing the plasticity of a clay, and reducing the amount of shrinkage on burning. Sand is often added to a brickclay for this purpose.

Lime Compounds. The chief lime-bearing impurities are lime and gypsum (calcium sulphate). If much lime is present and the clay is fired at a high temperature, it may fuse with the silica and alumina of the clay and form a hard, vitreous mass which loses its shape. Small particles of lime or gypsum may form blow holes in the surfaces of the bricks, due to expansion of the lime on exposure. Where soluble lime salts are present, they may dissolve in the water used in mixing the clay. During drying and firing this lime may form a white scum on the surface of the brick. Barium carbonate is sometimes added to make the lime salts insoluble, and so prevent scumming.

Iron Compounds. These are chiefly iron pyrite (iron sulphide), limonite (hydrated iron oxide) and silicates. During burning these are changed to oxides, and give the bricks their red colour. If much pyrite is present it may form black spots of slag on the surface of the fired bricks.

Carbonaceous Matter. Most clays contain some carbonaceous matter. This burns out during firing and may make the brick porous. Sometimes sawdust is added to a clay to make the bricks porous.

Shrinkage of Clay. Clay shrinks on drying. The amount of this shrinkage is roughly proportional to the plasticity of the clay, and is due to the removal of the water during the drying process. The amount of shrinkage varies in different clays, and can only be found by experiment on the clay to be used. For the manufacture of terra-cotta and moulded pieces which must fit exactly, the amount of shrinkage must be known to within close limits. If the clay from the quarry is variable in character it may be mixed and blended before use. Clays having a shrinkage greater than 1½ in. per foot length may be unsuitable, unless sand is added to reduce the plasticity and the amount of shrinkage on firing.

BRICKCLAYS

The Manufacture of Bricks. Brickclays are usually quarried in open brick pits near roads or railways. The clay may be dug by hand or mechanical excavators, and in many cases is left outside in the quarry to weather before use. The work in the quarries may be seasonal, and stop during the wet season. In many cases the clay from the quarry may only require kneading before use, whilst in other cases water, sand, and other substances may be added. If necessary, the clay may be crushed between rolls or in edge runner mills before being moulded.

The moulding of the clay into shape may be carried out by hand or by machinery. The hand-made bricks are moulded one at a time in wooden moulds which may be sand faced or dipped in water. In the wire-cut bricks the clay, after preparation and mixing, is extruded through a die, and comes from the machine as a rectangular band measuring about 4¾ in. by 9¾ in. This band of clay is cut into bricks of the proper width by wires stretched across a frame at the proper distance apart. Six or more bricks may be cut at a time. Wire-cut bricks do not have depressions or *frogs* on the top unless they are re-pressed. Both hand-made and wire-cut bricks must be dried before being put in the kilns. For this purpose they may be stored on steam-heated floors, or in the summer they may be stacked outside in open sheds for several weeks.

In the semi-plastic process of brickmaking, very stiff material is used for moulding. The rock such as mudstone and shale is screened and powdered, and pressed into moulds with very powerful presses. The bricks may be sent direct to the kilns without any preliminary drying.

The semi-dry process uses just enough moisture to make a brick, and is used with shales and clays which have almost no plasticity. The crushed powder is fed into the boxes of the presses, and very high pressures are used. The bricks are sent direct to the kilns for firing.

The kilns are brickwork chambers in which the bricks are burned.

The fuel may be kept separate in specially designed furnaces. Several types of kilns are in use, differing chiefly in the type of draught used. During burning, water is lost rapidly at 500° C from the bricks, and any carbonaceous matter is burnt out. The clay shrinks and chemical changes take place. Temperatures of 800° C to 1 000° C may be maintained in the kilns for several days. A brick should have a ringing sound when struck, and should be thoroughly burnt, and give a close-grained fracture. A porous brick encourages adhesion of the mortar.

The Colour of Bricks. The colour of the finished brick is of great importance, and depends on the iron content of the clay, and the condition of the kilns when the clay is being heated. The colour of the clay before burning is of no value as a guide to the colour of the finished brick, and many good plastic clays produce an unpleasant coloured brick which is unsaleable.

Red Bricks. These bricks have a good uniform red colour. The colour is caused by the presence of 3–6 per cent of ferric oxide in the clay. The iron content is probably present as nontronite. When the iron carbonate, siderite, is mixed with clay, it does not produce a good red colour.

Purple Bricks. Bricks of this colour are due to the reducing action of substances such as carbonaceous matter in the clay on the iron compounds present. Sometimes coal dust or sawdust may be added to the clay during mixing to alter any iron silicate minerals present. The addition of small amounts of manganese dioxide to the clay also produces purple bricks when the clay is burnt.

Blue Bricks. The colour is due to the presence in the clay of ferrous silicate together with carbonaceous matter. The clay must have at least 5 per cent of iron, together with sufficient lime and alkalis to make a brick which has vitrified without its losing shape in the kiln. The lime and alkalis lower the fusion point of the clay, and the slag runs together filling in the pores in the bricks. The Staffordshire marls are very good, natural blue-brick clays. Other clays may make blue-coloured bricks, if a reducing atmosphere is maintained in the kiln whilst the clay is being fired. A blue brick weighs 8–9 lb, whilst ordinary bricks weigh 6–7 lb each.

Yellow Bricks. The clays producing yellow bricks contain only a very small proportion of iron compounds. Sulphur containing materials may be added to a clay to produce the same effect.

White Bricks. Many clays, such as the china clays, are almost free from iron containing minerals, and when burnt give a white material. These clays are, however, too valuable to be used for ordinary bricks. Some brickclays, such as those used for producing the white Suffolk bricks, contain a little iron but also contain enough chalk or lime to prevent the red colour forming in the brick. White-burning clays may also be prepared by mixing up to 10 per cent of chalk with a red-burning clay. An excess of chalk will weaken the finished brick.

Vitrifiable Clay. This is used for the production of bricks of great strength which are impermeable to water and sulphate solutions. The degree of vitrification produced depends on the temperature in the kiln, and the amount of fusible material present in the clay. The clay should not lose its shape on vitrification. Vitrifiable clays are found in Staffordshire and the Midlands, and are used for the Staffordshire blue bricks.

Distribution of Brickclays. The plastic clays are restricted to the younger rocks and areas which have not suffered much crushing during periods of earth-movement, which would have converted the clays into shales and slates. The great clay belts, therefore, are found in South-east England from Dorset to Yorkshire. The Coal Measures in most coalfields contain beds of mudstone which are suitable for brickmaking, and are extensively quarried. Rocks older than the Coal Measures are not well endowed with brickclays. The age of the various clays can be identified by the fossils which are found in them.

The mudstones from the Coal Measures which are used for brickmaking are usually of freshwater type. These mudstones are restricted to areas where Coal Measures appear at the surface. Frequently coal seams are present in the brick pits associated with mudstones. This coal is used as fuel for burning the clay into bricks in the kilns. Brick pits working Coal Measure mudstones are located near most of the larger towns in the coalfield areas. A well-known example is the Accrington mudstone used in making the Accrington red bricks.

The Triassic System yields red shales and marls which are used for brick and tile making in Leicestershire, Nottinghamshire, and in Somerset. Some of the Triassic marls, however, contain gypsum, which renders the rock valueless for brickmaking.

The Jurassic System contains many good plastic clay formations. These clay beds usually form valleys between hills formed of more resistant limestones. The Jurassic rocks outcrop almost continuously across southern England from Dorset, through the Midlands, into Yorkshire (Map, Fig. 4), and the outcrops of the clay beds are marked by brick pits, especially near large towns and where good communications exist. The Lower Jurassic grey and blue clays give red bricks, and are frequently used as in Lincolnshire. Clays are important in the Upper Jurassic strata, where they form the Oxford and Kimmeridge clays identified by their typical fossils (Fig. 29). The Oxford clay is a stiff, blue clay, and is extensively used, as at Peterborough and Oxford, for the manufacture of red and *white* bricks and tiles. The Kimmeridge clay is also used where it outcrops near industrial centres.

The Cretaceous System contains fine brickclays in the Wealden Beds, and the Gault clay, which is a stiff blue clay. The outcrop of the Gault is riddled with pits, especially near the larger towns.

Several important clay beds are found in the rocks of the Tertiary period. The London clay is perhaps the most important, and is extensively used, especially where sand is available for mixing with it. This clay is extensively used in the Thames basin and in Hampshire. The clays of the Reading Beds are also widely used for bricks, tiles, and earthenware.

Clay pits are frequently opened up in, or on the edges of, towns and villages, tending to destroy the amenities of these areas. Clay of a suitable character can nearly always be found at a distance from towns, and new works should be restricted to these areas.

The crushing strength and porosity of bricks vary greatly. Accrington red pressed bricks have a crushing strength of over 660 t/ft^2. Staffordshire blue pressed bricks have a strength of over 1 000 t/ft^2, whilst other bricks have a strength of about 106 t/ft^2.

FIRECLAYS

The fireclays form a separate and distinct group of clays with the important properties of being resistant to high temperatures, and being capable of taking a glaze. These clays when burnt can be used as firebricks, or can be moulded to form the backs of domestic firegrates. When glazed and burnt, these clays can be used in the manufacture of tiles and fireplaces and sanitary ware such as wash and lavatory bowls and baths.

Fireclay beds are almost entirely restricted to strata of Coal Measure age, and usually occur in beds up to 10 ft thick, immediately below coal seams. The coal seams are often of poor quality, but are taken with the clays and used as fuel for firing the kilns. Fireclays are fairly hard rocks, and black in colour if much carbonaceous matter is present; otherwise they may be light in colour. They consist mainly of silica and alumina, and may be gritty to the touch if much silica is present. Alkalis, lime, and iron are present only in small amounts, so that the rock has refractory properties of a fairly high order, and can be fired in the kilns at a high temperature without fusing. The upper portion of a fireclay seam, immediately underlying the associated coal seam, is frequently lighter coloured and of better quality than the lower portion, and is often saved for the better class ware.

Fossil plant rootlets are abundant in most seams of fireclay, and this fact, taken with the low content of lime and alkalis, suggests that the clay was originally the soil upon which the vegetation, which eventually became coal, grew. The lime and alkalis would be used up by the plants, so that the fireclays represent exhausted soils. This would also explain the better quality of the upper layers of a fireclay bed. All fireclays are not of sufficiently good quality to be used. The good clays do not crack or fuse at the edges on firing.

Fireclays are either quarried or are mined in a similar manner to coal seams. Frequently the clay is left out on the surface for a considerable time to weather, so that it crushes more easily. Clay from various parts of the quarry or mine may be mixed to secure a uniform product with a constant amount of shrinkage on drying. The clay is crushed, mixed with water, and moulded into bricks or other articles. Shrinkage has to be carefully allowed for in producing work to definite finished dimensions. Complicated shapes, such as lavatory bowls, may be poured as a slime, whilst terracotta and glazed work may be cast in plaster moulds. Glazes may be sprayed or brushed on to the fireclay castings, and the work fired in the kilns at a high temperature, when the glaze becomes almost a part of the fireclay itself and cannot be chipped off.

Copper sulphides must be absent from fireclays used for glazed ware, as it leaves unsightly spots on the finished work. The large ornamental tiles used for the walls of important buildings are usually cut to the finished size by emery wheels after they have been manufactured.

A special type of fireclay with a different mode of origin occurs in North Wales. These are the pocket fireclays which occur in hollows and pockets in limestone areas. The clay is formed from the insoluble residue from the solution of the limestone, together with materials washed down into the hollows.

Fireclays are extensively worked in most of the coalfields. The production of the Lancashire, the Midlands, and the Scottish coalfields is noteworthy.

CHAPTER VIII

Slates and Other Roofing Materials

SLATE is one of the finest and most commonly used roofing materials, but other rocks, such as flaggy oolitic limestones, sandstones which split into slabs of even thickness, and tiles made artificially by moulding and burning brickclay, are also extensively employed. In the Cotswolds and other areas, thin-splitting limestones are widely used for roofing slabs, whilst in Lancashire and the North of England, the type of sandstone known as flagstone has been extensively employed in the older buildings, although in recent times it has seldom been used on account of its weight and usual lack of resistance to town atmospheres.

SLATE

Slates of good quality are amongst the finest materials that can be used for roofing purposes. A good slate is very fine-grained, has a low porosity, is resistant to weathering, and can be obtained in thin slabs. It resists the growth of mosses and lichens on its surface, and there is some choice of colour from dark purple to blue and green, and from very smooth micaceous surfaces to the rougher texture of the green slates from the Lake District.

FORMATION AND STRUCTURE

Origin. Slates are fine-grained rocks which have been subjected to metamorphism by intense pressures. They are found only in districts where the strata are highly folded and crumpled. Slates are not confined to rocks of any one geological period, but may be of all ages from the youngest to the oldest, although in Britain slates of commercial value are not found in strata younger than the Devonian.

The original material of slates was very fine-grained sediments, such as shales and mudstones, or beds of volcanic dust and ashes. Certain areas where these fine-grained sediments are found were folded and crumpled, and subjected to very great lateral pressures. As a result of this earth-movement, these fine-grained rocks acquired a new structure or *cleavage* in a direction quite independent of the original bedding planes. The slates now split or cleave in a new direction, which is largely determined by the direction from which the earth pressures were exerted.

The shale is greatly hardened, and its contained water and colloidal material are lost, and the rock takes on an entirely new mineralogical composition. The minerals making up slate are mostly of flaky shape, and have their long axes set at right angles to the directions in which the earth pressures were applied. It was formerly thought that the minerals of the original shales were merely swung round into a new direction by the pressure, but it is now believed that entirely *new* minerals are formed in the change from shale to slate. The new minerals are formed in the solid rock, and they find it easier to grow with their long axes at right angles to the direction in which the earth pressures were applied. The rock now consists of flaky minerals which all have the same orientation, with the result that the rock is fissile in a new direction, usually at a considerable angle to the former direction of bedding. This new direction of splitting is called *cleavage*, and is fairly constant over considerable stretches of country.

Cleavage. Cleavage or splitting in slates is not always perfectly developed. The perfection of this structure depends largely upon the fineness and the uniformity of the grains of the original rock, and the intensity of the pressure exerted to produce the cleavage. Many districts contain rocks which geologically would be called slates, but slates of good commercial quality are comparatively rare. The cleavage may be poorly developed, or the rock not greatly hardened, or gritty, uncleaved beds may occur frequently within the slates, making it difficult to quarry the slates economically. The original direction of the bedding planes of slates is often difficult to ascertain, but thin, gritty beds or coloured layers may enable the bedding planes to be recognized. Sometimes cleavage may be induced in a slate at several different geological periods, and from different directions. In this case, several conflicting directions of splitting may be present, and an otherwise good slate rendered valueless. Very rarely the direction of cleavage may coincide with the original bedding planes.

In some cases the development of new flaky minerals does not take place as a result of the pressure, but instead, a false or *strain-slip cleavage* is formed (Fig. 36). Strain-slip cleavage is caused by a series of close-set microscopic puckers or folds in the slate. These folds all have their axes parallel to each other, so that the slate tends to split along the axes of the microscopic folds. The perfection of splitting depends on the closeness of the fold axes and the degree of weakness induced by the puckering. Slates of this type do not usually show the same perfection of cleavage as the more normal type, and the slabs are usually thicker. The Skiddaw slates of the

Lake District and the Meadfoot slates of Devonshire have this structure in some areas.

Mineral Content. The mineral constituents making up a slate are all of very fine-grain size, and are essentially of a flaky type. They may be 0·002 in. or less in diameter. If thin sections of a slate are examined parallel to the cleavage planes, the appearance is quite different from that seen at right angles to this direction, where the flaky minerals are seen *end on.* Perhaps the most abundant mineral of slates is secondary white mica, lying along the planes of cleavage. Scales of iron oxides, such as haematite and ilmenite, are usually present in quantity, and they give rise to the red and purple colour of many slates. Quantities of very minute needle-shaped crystals of rutile (titanium oxide) are always present, and quartz and felspar may occur as scattered grains. There is also usually much chlorite present in slates.

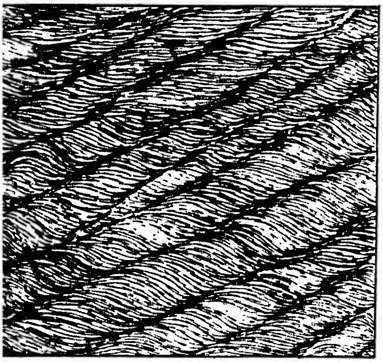

FIG. 36. FALSE OR STRAIN-SLIP CLEAVAGE IN SLATE

Magnified under low powers of the microscope, the slate is seen puckered into a series of minute folds. Splitting will take place from the top right- to the bottom left-hand corner.

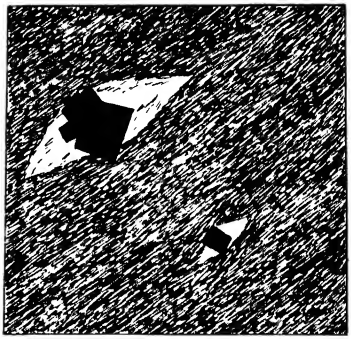

FIG. 37. CLEAVAGE IN SLATE SEEN UNDER LOW POWERS OF THE MICROSCOPE

The rock is composed of flaky minerals, which all have the same orientation in the direction in which the slate will split. Crystals of pyrite (shown black) have resisted deformation, and secondary quartz has been deposited at the sides of the crystals.

When the surfaces of many slates are examined, square, brass-coloured crystals of iron pyrite (iron sulphide) can be seen. Sometimes these crystals oxidize to a rusty or brown colour. These pyrite crystals are very hard, and have often resisted the deformation which has affected the rest of the slate. The new flaky minerals which were formed have *flowed* round the pyrite crystals, and as a result, gaps were left at each side of the crystal (Fig. 37). These spaces usually become filled with light-coloured minerals, such as quartz or calcite, so that the pyrite crystal comes to occupy the middle of a lens-shaped spot of light-coloured quartz or calcite. This produces small spots or *eyes* in the slate, and these are often present.

Many slates show large or small oval patches of a slightly different colour from the rest of the rock. These coloured areas may mark the position of small pebbles, or areas where the rock had a slightly different composition. They are oval in shape, because the pressure pushed the originally spherical structures to one side into an oval shape. The banding often shown by slates is due largely to differences in texture or composition of different layers in the shale, before the rock was converted into a slate. More gritty beds are often present in shales, and they do not take the cleavage as perfectly as the finer-grained types. The gritty beds are not suitable for use as slates. Where a quarry of otherwise suitable slates contains a great many grit beds, it may prove uneconomic to work the slate. Different coloured bands in the original shales may also appear as different coloured beds in the resulting slate formed from them. A single slate quarry may produce several different colours and grades of slate for the market.

PHYSICAL AND CHEMICAL PROPERTIES

Colour. The colour of slate varies considerably, and is a matter of some aesthetic importance, but no index of quality. It depends to a large extent on the proportion of ferrous iron oxide to ferric iron oxide in the rock. The red and purple slates contain very little carbonaceous matter, whilst the black carbonaceous slates contain an excess of ferrous iron oxide. Slates are red coloured only when the ferric iron oxide content exceeds twice the amount of ferrous iron oxide in the slate, whilst the green colour is developed only when the ferrous oxide is greater than twice the ferric oxide content of the slate. The surface of a slate may be rough and dull in appearance or may be micaceous and shiny.

Some slates are dyed artificially to green and other colours. The surface of the slate takes the colour, whilst the inside of the slate remains its natural tint. The *Rustic* slates have acquired their colour as a result of weathering, and oxidation of some of the iron and other minerals in the rock, by solutions percolating along the cleavage planes.

Physical Properties. The best roofing slates have a great resistance to weathering, and a very low porosity and absorption. The density of slate is about 162 lb/ft^3, and the specific gravity about 2·7 to 2·9. Welsh and Cornish slates as laid, weigh about 5–9 lb/ft^2

depending on the grade of the slate, whilst the thicker Westmorland slates weigh 9–15½ lb/ft^2 according to grade.

Some slates may possess a *grain*, making a small angle with the direction of cleavage. It may cause a tendency to fracture parallel to the grain, and in this way may weaken the slate. The grain may be due to some of the mineral flakes being arranged with their long axes in the direction of pressure, and at an angle to the cleavage planes. Roofing slates should be straight and flat, with a fairly uniform thickness. They should give a clear ringing sound when struck with a hammer, and should not contain clamps or lumps. The grain should run along the length of the slate.

Chemical Composition. The chemical analysis of a typical good quality Dinorwic or Velinheli slate is as stated below—

Silica,	SiO_2	66·45%
Alumina,	Al_2O_3	13·38%
Ferric oxide,	Fe_2O_3	1·71%
Ferrous oxide,	FeO	1·41%
Magnesia,	MgO	6·28%
Lime,	CaO	2·86%
Soda,	Na_2O	0·90%
Potash	K_2O	0·05%
Carbon dioxide,	CO_2	1·31%
Water (at − 105° C)		0·13%
Water (at + 105° C)		3·90%

The chemical analysis may indicate the amount of weathering which has taken place, especially by showing the amount of carbon dioxide, lime, and water present. Slates of inferior quality may contain much calcium carbonate and water, which may be driven off by heating at a temperature above 105° C. Slates containing much carbonate may weather easily and flake and crumble in a comparatively short time. Chemical analysis may reveal the presence of these decomposition products by showing a high calcium, water, and carbon dioxide content. A test sample of slate when placed in sulphuric acid, consisting of one volume of concentrated sulphuric acid with seven volumes of distilled water, for ten days, should show no signs of swelling, softening, flaking, or lamination, and bubbles of gas should not be given off from the slate whilst it is immersed in the acid. The specimens to be tested have their edges cut and honed before being stood upright in the acid for test. The maximum water absorption of a slate should be less than 0·3 per cent.

Although shale formed the basic material of the great majority of slates, any fine-grained rock, if subjected to great earth-pressures, may be converted to a slate. In the Borrowdale area of the Lake District are beds of volcanic dust which were discharged from the craters of volcanoes which were active in the Ordovician period in this area. This dust is extremely fine-grained, and was altered into a slate with a fairly well-developed cleavage. The slates have a rough surface and are usually green in colour.

Quarrying and Preparation. Most working slate quarries (Fig. 38) are of very large size, and, to ensure safe and economical working, the quarry face is stepped into benches from 30–70 ft in height.

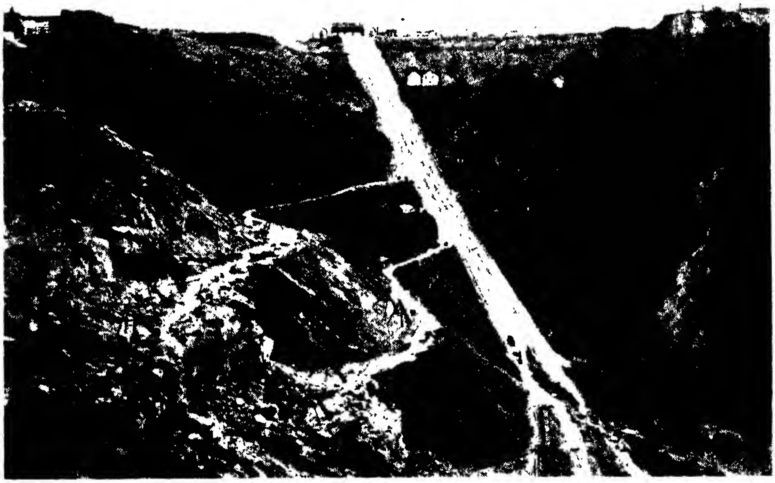

FIG. 38. INCLINE AT DELABOLE SLATE QUARRY

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In some areas the slate beds are mined by normal underground methods. The slate is broken out by explosives, and anything up to 90–95 per cent of the total tonnage of the slate quarried is waste or unusable rock, and is tipped on the spoil heaps which are such a feature of slate quarrying districts.

The large blocks of slate, which are good enough for use, are usually split into slabs of various thickness before leaving the quarry. These slate blocks are loaded into wagons and sent to the dressing sheds. The blocks to be used for conversion into roofing slates are split into slabs 2–3 in. thick, and then sawn to a size slightly larger than the finished slate is to be. The slate splitters then take the sawn slabs and split them into thin sheets by hand. The sheets then pass to the slate cutting machine which cuts the sheets to the size of the standard roofing slates.

The slate which is to be converted into slabs of large area is split into slabs about 12 in. thick, which are sawn square by means of a diamond saw. This is a disc about 42 in. diameter, set with 200 to 300 diamonds on its edge, and rotated at about 600 r.p.m. These squared slabs are split into slabs of the required thickness, and planed flat on machines. If a finer finish is required, the slabs are polished, using silica sand or carborundum discs.

Uses of Slate. By far the greater proportion of slate quarried is manufactured into roofing slates. These are usually classified into first, seconds, and thirds, according to their thickness, and the colours may be kept separate into purple, green, blue, rustic, etc. The rustic slates are red or brown in colour, due to staining material from the overlying soil and subsoil percolating into the slate along the cleavage planes, and depositing iron compounds on the cleavage surfaces. These slates may be slightly thicker than the other types, as the slate splitters must take advantage of the cleavage planes which have been affected by the colouring matter. Slates are sold by the count of 1 200 to the 1 000, or by the ton.

Slate slabs, which are usually polished, are an important product, and are used for flooring, window-sills, steps, wall copings, dairy and larder benches, and switchboards. Slate is also employed as a damp coursing for walls. Powdered slate or slate dust, prepared from the waste and trimmings of good quality slate, is important as an inert filler in the manufacture of paint and rubber, and in asphalt and bitumen mixes. It is marketed under trade names such as *Delafila* and *Fulersite*. Experiments are being carried out on expanding slate by heating at high temperatures. The exported slate can be used in the manufacture of lightweight concrete.

Occurrence of Slate. From the nature of the origin of these rocks slates are to be found only in areas which have been heavily folded and faulted, and subjected to earth pressures on a large scale. Slates are not, therefore, found in Britain in rocks of an age younger than the Carboniferous, and the bulk of them are found in rocks of Devonian or greater age. These older rocks are only found at the surface in the north and west of Britain, in Devon and Cornwall, Wales, the Lake District, and Scotland. It follows, therefore, that the quarrying of slates is restricted to these areas.

In North Wales, what are amongst the finest roofing slates in the world are mined and quarried. In strata of Cambrian age, the Llanberis slates of the foothills of the Snowdon Range near Carnarvon, are riddled with slate quarries. In the Penrhyn and the Dinorwic or Velinheli areas, enormous quantities of slates have been produced, and the working faces of the quarries are of very great height. The various bands of the slate differ slightly in lithological characters, colour and perfection of cleavage, and the different types may be given special names. At Penrhyn, Bethesda, the sequence of slates in descending order is as follows—

The Bronllwyd Grit

Upper green slate.
Soft purple slate.
Grey slate.
Grey hard slate.
Grey slate.
Grey purplish slate.

Hard Grit

Soft purple banded slate.
Soft purple spotted slate.
Soft purple clear slate.
Blue slate.

Red Grit

Hard red slate.
Hard blue slate.
Hard mottled slate.
Hard striped slate.

Green mudstone and conglomerate

Hard grit bands are present, and the section indicates the types of slate which are present. The total thickness is over 2 600 ft. The diagrammatic section of the quarry shows the method of quarrying the slate and the position of the slate beds (Fig. 39). A minor production of slates has also been obtained from the Cambrian rocks of the Dolgelley area, and in the Lake District.

Closely rivalling the Cambrian slates in importance are those obtained from the Ordovician strata. At Blaenau-Festiniog the black, smooth, fine-grained slates from the middle Ordovician strata are of great importance. They are often called Portmadoc slates as they were formerly shipped from that port. They are extensively mined and quarried, and the slate occurs in beds of upwards of 25 ft thick. Slates have also been quarried at Corris, and Dinas Mawddwy.

The Welsh slates are classified into grades depending on the thickness per hundred slates. e.g. the Velinheli best slates run 18–22 in. per hundred, seconds 23–29 in., and thirds 30–45 in. thick per hundred slates.

The Westmorland green slates are quarried from Ordovician rocks in the Lake District at Coniston, Buttermere, Elleswater, and Kentmere. There are many different shades of green, and they are coarser and of a more granular texture than the slates of North Wales. They are a good weathering type.

The Cornish slates are found in the Upper Devonian strata and are very extensively quarried at Delabole. These slates have also been altered by the heat of igneous intrusions. There are two main types of slates, grey-green and blue-grey. The thickness of the slates produced ranges from 20–22 in. per hundred slates to 40–44 in. per hundred slates. Rustic red and other shades of slates are also produced.

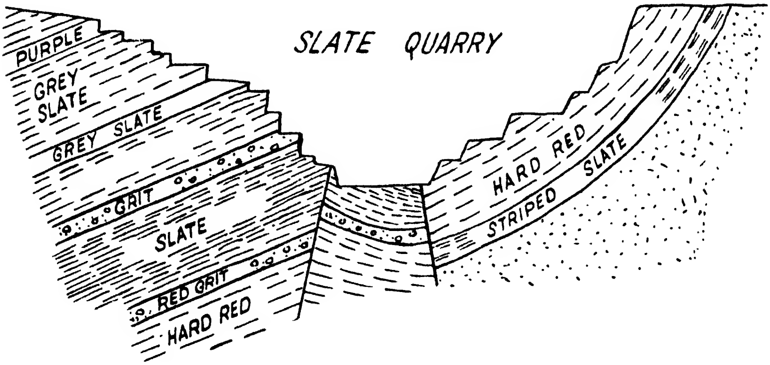

FIG. 39. DIAGRAMMATIC SECTION OF A NORTH WALES SLATE QUARRY

The steps or benches forming the working faces and the disposition of the slate beds are shown.

ROOFING MATERIAL OTHER THAN SLATE

Many other materials than slates may be used for roofing purposes. These tilestones may be natural thin-splitting rocks or artificial tiles made from the burning of clays as described in a previous chapter. These thin-splitting rocks do not possess any cleavage, but break along the bedding or lamination planes into thin slabs. Such thin-splitting or fissile rocks may be sandstones or limestones. Lichens and mosses often grow on these tiles, giving characteristic effects.

The Caithness Flags from the Old Red Sandstone formation of Scotland may be sawn into thin slabs for roofing tiles. They are bright red in colour. Wherever the Coal Measures and the Millstone

Grits outcrop, the flaggy sandstones and laminated beds have been used for roofing purposes, especially in the older buildings and houses. They are grey in colour, and the better types are very durable. They may be $\frac{3}{4}$–1 in. in thickness.

Many limestones are used for roofing slabs, such as the Collyweston slates which are obtained from quarries or underground workings in Northamptonshire and other localities. These rocks are found in a stratum 6–18 in. thick. The stone is got by means of wedges, as blasting tends to break the slabs. They are a bluish colour with a tendency to weather to a buff colour. The working of these slabs goes on only in the winter months, as the blocks cannot be split satisfactorily unless they have been acted on by the frost. The blocks are kept wet at the quarry until frosted, and then are split into slates. If the blocks become dry before being frosted, they cannot be split satisfactorily and are broken up for road material.

The Stonesfield slate is another limestone from the Jurassic System which is used for roofing material. It is an oolitic sandy limestone occurring in a bed 30–36 in. thick. The slates are blue to brown in colour and must be frosted before splitting. They are mined near Oxford.

The Forest marble, also from the Jurassic rocks, is used as a tilestone in Wiltshire, Gloucestershire, and other places. The Poulton slates from Cirencester and the Slatt Beds from strata of Purbeck age in Portland are other examples.

CHAPTER IX

The Igneous Rocks

THE Igneous rocks form a special group of rocks widely used for masonry, concrete aggregates, kerbstones, setts, roadstone, and other purposes. The more ornamental types may be used as polished slabs and turned columns. The term granite is usually applied by quarry owners to all rocks of igneous origin, and even to some hard grits and limestone. It is an unfortunate usage, as the various kinds of igneous rocks are not all suitable for the same purposes. Some stones may be quite suitable as setts, but entirely unsatisfactory when used as small chips in the top dressing of roads The name *granite* also has a definite geological meaning, and it would be much better if the geologically accepted names for particular rocks were used in the trade descriptions and specifications. The type of stone required could then be specified by name for a particular use in addition to stating the quarry from which it should be obtained.

The Formation of Igneous Rocks. Igneous rocks have all solidified by cooling from the hot molten condition. A familiar example is the cooling on the surface of the ground of lavas poured out from the craters of volcanoes. As a result of solidification from a melt, igneous rocks are wholly crystalline. The crystals interlock with each other, giving the rocks great toughness and strength. The size of the crystals formed depends on the rate of cooling of the magma or melt, the more rapid the cooling, the smaller the crystals that are formed. Some lavas extruded on the surface have cooled so rapidly that crystals have not had the time or opportunity to grow before the magma solidified, and the rock comes to consist of what geologists call a *glass*, i.e. a solid rock showing no crystal structure whatever. These rocks are naturally very tough, and eminently suited for concrete aggregate and roadstone. They have a wide distribution in Britain.

TYPES OF IGNEOUS ROCKS

Intrusive Rocks. Many igneous rocks, instead of being extruded as lavas on the surface, have been intruded, or have forced their way into already existing strata, and have cooled in this position, often at very great depth below the surface. These intrusive masses of igneous rock may be of enormous size. Many of them outcrop at the surface continuously over hundreds of square miles, and are of very great thickness. The granite masses of Dartmoor and Aberdeen are examples. Large intrusions such as these are termed *plutonic rocks*. Because of their large size and blanket of covering rocks, they have cooled very slowly. Any gases and fluxes contained in the molten mass may be retained within the magma itself, and cause it to remain fluid down to temperatures of about 500° C. Under these conditions, large crystals are developed up to several inches in length. Sometimes some of the crystals grow larger than the rest, and are set in a ground mass of smaller crystals. This is the *porphyritic* structure such as is found in the Shap granite, where the larger crystals are pink in colour, set in a grey ground mass, and the Dartmoor granite, in which the larger or porphyritic crystals have a white colour.

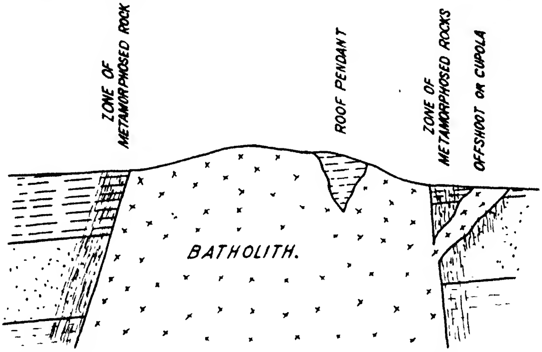

FIG. 40. DIAGRAMMATIC SECTION OF A BATHOLITH

The contacts of these plutonic masses with the enclosing rocks is always steep, and branches or cupolas may come off the main mass (Fig. 40). Large masses of the enclosing country rock may also be caught up and enclosed within the igneous rock, forming what are called *roof pendants*, which are always highly altered by the heat of the intrusion. The heat from the molten igneous rock passes out through the surrounding country rocks, and may cause profound structural and mineralogical changes in these rocks. The intrusion thus becomes surrounded by a zone of altered rock, or a *metamorphic aureole*. The aureole surrounding the Dartmoor granite mass is up to a mile in width, and, with larger intrusions, the zone of altered rock may be wider. The plutonic rocks are mostly granites (in the geological sense), although a few masses consisting of gabbro types are known. Where the intrusions have a roughly circular outcrop, they are known as stocks or bosses, such as the Dartmoor

Boss. If the intrusions are very large indeed, and elongated in shape, they are termed batholiths. These batholiths occupy the cores of mountain or hill ranges, and are often remote from centres of habitation where the stone might be of use. Where plutonic rocks outcrop near rail and road facilities, they are usually extensively quarried.

Igneous rock can be recognized by the fact that they consist of crystals of light-coloured quartz and felspar, and dark-coloured crystals of a ferromagnesian mineral such as mica. Structures typical of sedimentary rocks, such as lamination and bedding, are absent. Igneous rocks are harder than shales, do not effervesce in acid like limestones, and are distinguishable from sandstones as the latter consist almost entirely of rounded grains of the light-coloured mineral quartz.

In addition to the large-sized plutonic masses, there are smaller sheet-like intrusions known as sills and dykes. Dykes are intruded along vertical fissures or faults, and make a large angle with the bedding planes. They may outcrop for hundreds of miles and be only a few feet thick. Dykes are not usually quarried, because their small width makes quarrying on a large scale difficult. Sills, on the other hand, are squeezed along the bedding plane fissures of the enclosing rock. The thickness of sills varies from less than a foot to fifty or more feet, and they may be present over hundreds of square miles. The great Whin Sill, for example, is present over large areas of Britain in the Tweed area. It forms a bold feature; Hadrian's wall, built in Roman times, is for a considerable part of its length built on the hill formed by the resistant outcrop of the Whin Sill.

Extrusive Rocks. These are lavas or volcanic rocks which have been poured out, in the molten condition, over the earth's surface from fissures or volcanoes. The steam and other gases contained in these lavas are given off rapidly to the atmosphere, and, as a consequence of this loss of fluxes, the rock soon becomes viscous and crystallization is rendered difficult. Lavas, therefore, always have a very fine-grained structure, contrasting them with the intrusive rocks. In many cases they fail to crystallize at all, and become stony glasses. When the gases bubble out of a molten lava, blowholes may be formed in the rock as in the case of pumice-stone, which is a highly vesicular lava. Lavas have a very fine, close-grained structure, and are eminently suitable for roadstone and concrete aggregates, and for this purpose they are extensively quarried in Britain. Individual lava flows are seldom more than about 10 ft thick, but they are usually found as flow after flow, one on top of the other, so that in the aggregate great thicknesses of rock may be built up. The extent of the area covered by lava flows varies considerably. Volcanic rocks are found in most geological systems, and are of widespread occurrence in Britain, especially in Scotland, the Lake District, and Wales.

THE MINERALS OF IGNEOUS ROCKS

Igneous rocks are aggregates of mineral crystals. There are about seven minerals of common occurrence in these rocks, and it is necessary to know something of their hardness and resistance to weathering in order to assess an igneous rock and decide the purpose for which it may be used. Igneous rocks are named according to the mineral constituents present, and whether the rock is intrusive or volcanic.

Felspar. This mineral is present in practically all rocks of igneous origin. Its colour ranges from white to red, and it is too hard to be scratched with a knife. The surfaces of the crystals have a bright vitreous lustre. Where the crystal shape is shown by this mineral it is usually rectangular, but in the plutonic rocks it may be of irregular shape, depending on the space which was available to the crystal in which to grow. The crystals often show straight cleavage cracks parallel to each other, and, if the rock is held to the light, one half of the felspar crystals may appear a darker shade than the other.

The felspars are aluminium silicates with the addition of soda or potash. They are divided into two groups, the *orthoclase felspars*, which are potash alumino-silicates ($K_2O.Al_2O_3.6SiO_2$), and the *plagioclase felspars*, which are mixtures of soda alumino-silicate ($Na_2O.Al_2O_3.6SiO_2$) and lime alumino-silicate ($CaO.Al_2O_3.2SiO_2$).

The felspar minerals make up the bulk of most igneous rocks. The mineral decomposes fairly readily, in waters containing carbon dioxide, to secondary mica and kaolin. When examined in thin transparent sections, with a hand lens or a microscope, the felspar crystals usually show signs of this decomposition. If the felspars are badly decomposed, the rock may lose its value for many purposes. In thin sections, the felspars are colourless and do not show much surface relief.

Quartz is present in abundance in the granitic rocks only. It consists of silicon dioxide (SiO_2), and is very resistant to weathering. It is harder than felspar, and cannot be scratched with a knife. It shows no cleavage cracks, and can be recognized in igneous rocks by its hardness and appearance as glassy grains with pellucid aspect.

In thin sections, when examined with a hand lens, quartz is distinguished from felspar by the absence of decomposition. It is transparent and its surface appears to have a low relief. If quartz is present in abundance in any coarse-grained igneous rock, it can be definitely identified as a granite.

Mica. This mineral is soft, and can be easily scratched with a knife. It can be split or cleaved into thin laminae which easily bend, and are flexible. There are two main types of mica. The dark mica or *biotite* appears in igneous rocks as small, black, shining flakes, easily scratched with a knife. In thin sections, when examined by transmitted light, biotite appears as brown or straw-coloured ragged flakes, and a series of parallel cracks or cleavage cracks are usually present. Biotite is a complex silicate containing potash, magnesia, alumina and iron, and it easily weathers to a green mineral called chlorite. Biotite is seldom found in abundance in sedimentary rocks, even though the rocks being eroded to form the sediment contained biotite in abundance. During its travel in the rivers, the biotite disintegrates and disappears into clays.

The white mica or *muscovite* resembles biotite in its properties, but is distinguished by being colourless or white. In thin sections it appears as colourless, transparent flakes. Muscovite is extremely resistant to weathering, and for that reason is often found as small flakes on the lamination planes of sandstone.

Muscovite and biotite are especially typical of granite rocks, although biotite is found in a few other types of igneous rocks. The softness of the mica crystals is often an asset when an igneous rock is used as paving stones. The mica wears more rapidly than the quartz and felspar, and creates a slightly rough surface which prevents the setts becoming slippery.

Hornblende. This mineral is an alumino-silicate of iron and magnesia with small amounts of other substances, and is very abundant in certain types of igneous rocks. It appears as small, black crystals in the rock, and can be distinguished from biotite by being too hard to be scratched with a knife. It has a vitreous or bright lustre on smooth surfaces, and can be distinguished by the shape of the cross-sections of the crystals (Fig. 41 (*a*)). When thin sections are examined with a lens by holding them up to the light, hornblende appears green and translucent, and shows distinct cleavage cracks. It is often decomposed.

Augite resembles hornblende and has a somewhat similar chemical composition. It is black in colour, and is too hard to be scratched with a knife. It has a vitreous lustre on smooth surfaces. It is distinguished from hornblende by being roughly octagonal in shape.

In thin sections, when examined with a hand lens, it is colourless or a pale brown colour (Fig. 41 (*b*)). Both augite and hornblende have a tendency to decompose to green chlorite or serpentine, and in many rocks the extent of the decomposition which has taken place may render the rock very suspect when used as a building stone.

Olivine is a silicate of iron and magnesia, and is very prone to alteration to the soft green mineral serpentine. In igneous rocks it is recognized by its black, green, or yellow colour. It cannot be scratched with a knife, and is distinguished from the minerals described above by the rounded shape of the crystals, and the absence of cleavage. In thin sections, olivine is colourless, and has a very bright surface. It shows irregular cracks along which the mineral has decomposed into serpentine. In some cases the decomposition has progressed very far, and the crystals may be entirely altered to serpentine. This decomposition is accompanied by expansion in volume, so that, if the olivine of a rock is badly decomposed, many of the other minerals will have been cracked and strained as a result of this expansion of the decomposing olivine. If a rock contains badly decomposed olivine crystals, it may be useless for building or other purposes. Olivine is not a constituent mineral

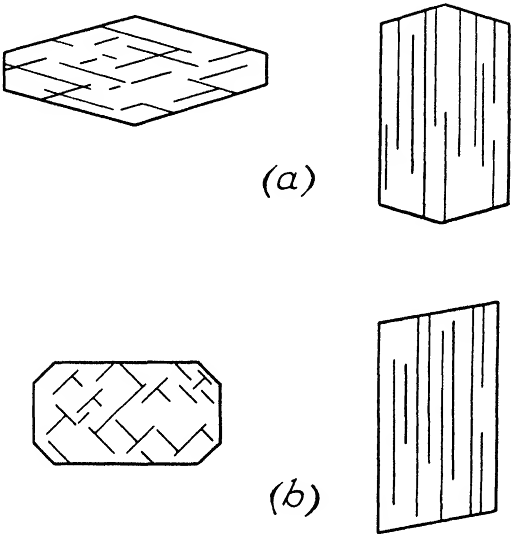

FIG. 41. MINERALS OF IGNEOUS ROCKS

(*a*) A crystal of hornblende. (*b*) A crystal of augite.
The drawings on the left are basal sections; those on the right sections of the crystals in other directions.

of the granitic rocks, but is restricted to the dark-coloured basic types such as gabbro.

The Classification of Igneous Rocks. Igneous rocks are classified by the presence or absence of certain of the above minerals, so that the recognition of these minerals is a matter of some importance. Igneous rocks are subdivided into acid, intermediate, and basic types, according to the amount of silica they contain. The *acid* rocks always contain quartz crystals, and their silica content, as shown by chemical analysis, is over 66 per cent. The *intermediate* rocks do not usually contain quartz crystals, distinguishing them from the acid rocks. Hornblende or augite crystals are usually present, whilst mica is more characteristic of the acid rocks. The silica percentage on analysis is between 66 and 52 per cent. The *basic* rocks contain less than 52 per cent of silica; quartz is absent, and augite and olivine are especially characteristic. Basic rocks are dark in colour, distinguishing them from the intermediate and acid types.

All the igneous rocks contain some felspar, and this mineral is used as a basis of further subdivision of these rocks. The rocks containing mostly an orthoclase felspar are grouped as *alkali rocks*, and those with plagioclase as the predominant felspar as the *calc-alkali* group. A few rocks contain both orthoclase and plagioclase in about equal amounts, and these form a passage between the alkali and calc-alkali types.

As a final subdivision, igneous rocks are classed as *plutonic*, *hypabyssal*, or *volcanic*. The plutonic rocks are coarse-grained, whilst the volcanic rocks are distinguished by being extremely fine-grained or glassy.

THE PLUTONIC ROCKS

These are coarse-grained, igneous rocks in which most of the mineral grains are clearly visible without using a lens. Most of the crystals are ¼ in. or greater in diameter. Very often some of the felspar crystals may be very large, and be set in a finer-grained ground mass. In the Dartmoor granite from Cornwall, the larger white felspar crystals may be more than 2 in. long.

The plutonic rocks can be identified by means of the table given on page 123.

The table should enable a student to identify the coarse-grained or plutonic igneous rocks fairly readily in the mass, and in thin sections. A hand lens and a knife are invaluable in helping to identify the minerals in the rocks.

	Characteristic Features	*Alkali* Types	*Intermediate* Types	*Calc-alkali* Types
ACID	Contain abundant quartz crystals. Much mica. Often have large felspar crystals. > 66% silica on analysis.	**Granite** Quartz. Orthoclase. Biotite. Light-coloured rocks.		**Granodiorite** Quartz. Plagioclase. Biotite. Often hornblende.
INTERMEDIATE	Few or no quartz crystals. Rock is light coloured. Hornblende more common than biotite. 65 to 52% silica on analysis.	**Syenite** Orthoclase felspar. Hornblende. No quartz. Light-coloured rocks. Not common in Britain.	**Monzonite** Orthoclase and plagioclase in equal amounts.	**Diorite** Plagioclase felspar. Hornblende. Little or no quartz. Light-coloured rocks.
BASIC	No quartz crystals. Augite abundant. Olivine often present. Rock almost black in colour. < 62% silica on analysis.	**Alkali Gabbro** Like gabbro, but contains much orthoclase. Not common in Britain.	**Kentalenite** Like gabbro, but contains orthoclase and plagioclase in equal amounts.	**Gabbro** No quartz. Plagioclase felspar. Much augite. Much iron ore. Olivine common. Almost black colour.

The plutonic rocks occur in large masses and outcrop over many square miles of country. Large quarries can be opened in these rocks, and they are extensively quarried especially near rail and road centres. Many of these plutonic rocks possess great beauty when cut and polished, and are used as ornamental stones in addition to their more ordinary uses. Differences of colour and texture are common, and several varieties of stone may be produced from a single quarry. The plutonic rocks from different localities usually possess distinctive characters either of colour or texture by which their place of origin can frequently be readily determined.

The plutonic rocks are all coarse-grained. They have a crushing strength of 900 t/ft^2 or more, and their close interlocking structure gives them a very low water absorption, often less than 1 per cent. Plutonic rocks are extensively used as setts, although in some situations they tend to become slippery, and as kerbstones. In the localities where they outcrop they are used widely as building stone, whilst the more ornamental varieties may be cut and polished as pillars, etc., in important buildings. These rocks, on account of their hardness and strength, are very suitable for concrete aggregates and roadmetal, but if used as small chips for the top dressing of roads, they may be unsatisfactory, as they break up into their constituent crystals and easily crush.

GRANITES

Many rocks have been called granites, but the name should be restricted to those plutonic rocks which contain abundant crystals of quartz. Granites consist almost entirely of the three minerals quartz, mica, and felspar. The quartz is present in small blebs whose boundaries are mostly determined by the space left after the other minerals have crystallized. The felspar is the most abundant mineral, and is easily recognized by being opaque, hard, and white or pink in colour. It may occur as crystals in the same way as the quartz, but frequently the felspar occurs in addition, as well shaped,

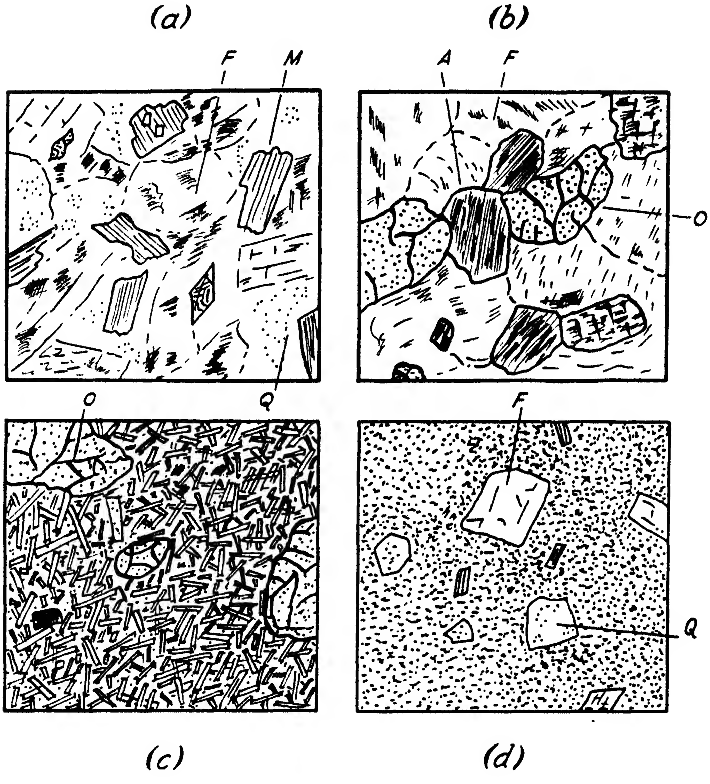

FIG. 42. THE APPEARANCE OF IGNEOUS ROCKS IN THIN SECTIONS SEEN BY A LENS OR LOW POWERS OF THE MICROSCOPE

(*a*) *Granite.* M = Brown mica. Q = Quartz. F = Felspar. The structure is coarse-grained and interlocking. Such a rock makes a good building stone and aggregate.

(*b*) *Gabbro.* O = Olivine. A = Augite. F = Felspar. The structure is coarse-grained Such a rock tends to decompose due to the olivine.

(*c*) *Dolerite.* The lath-shaped crystals are felspar and the large ones olivine. The structure is coarse-grained and interlocking. Such a rock makes a good aggregate.

(*d*) *Rhyolite.* A few larger crystals of quartz and felspar are set in a very fine-grained ground mass. This rock is very tough and close-grained.

straight-sided crystals of large size, as in the case of the Shap and Cornish granites (Fig. 42).

The granites are subdivided into three groups, according to the type of felspar present. The granites in the strict sense contain a predominant orthoclase felspar, whilst the *granodiorites* contain plagioclase as the most abundant felspar. The granites, with equal amounts of plagioclase and orthoclase, are sometimes termed *adamellites*. These distinctions are not of great technical importance, however, and cannot be made out without a petrological microscope. It is a correct usage to term as granites all coarse-grained rocks consisting of quartz, felspar, and mica. The dark mica, biotite, is more usually found than muscovite, and is usually present as small crystals.

Structures Present in Granites. Granite, in common with most other igneous rocks, does not show the bedding planes typical of the sedimentary rocks such as sandstone and limestone, as the plutonic rocks were intruded in the molten condition, and not deposited bed upon bed. Joints, both vertical and horizontal, are, however, usually well developed in most igneous rocks. The horizontal joints may closely resemble the bedding planes of sedimentary strata. This combination of vertical and horizontal jointing gives a wall-like structure known as *mural jointing*. The direction of the joints is usually fairly constant for long distances. The stone adjoining the joints may be much weathered.

Rift and Grain. These are inconspicuous structures which, however, can be of great importance in dressing the stone, after quarrying, for setts and other purposes. The *rift* is a direction within the stone along which the stone shows a marked tendency to split, whilst the *grain* is a second direction along which the stone will split with rather less ease than along the rift. The direction of the grain is usually at right angles to the rift, and this fact enables blocks suitable for setts and pavings to be hammered out with comparative ease. The direction of the rift and grain may remain the same over considerable areas, or may change direction rapidly in different parts of a quarry, or in different layers, and may be vertical, horizontal, or inclined. The development of rift and grain may be due to many causes. There may be a rough parallelism of the mica or felspar of the rock when there will be a weakness in this direction. Many granites with a well-developed rift and grain, however, do not have this parallel arrangement of these minerals. The structure in this case is often due to a regular arrangement of rows of minute bubbles, microscopic in size, within the crystals of the quartz and felspar. These rows of bubbles are very abundant in some granites, and are often arranged in two sets roughly at right angles to each other. The rift and grain directions are parallel to the rows of bubbles in the minerals.

Colour of Granites. Colour is of importance in granite, except perhaps where it is used only on account of its great strength, in engineering projects. The granites show a great variety of colour, including shades of pink, red, green, and grey, and a single quarry may produce stone of several shades of colour. The felspar crystals, being the most abundant mineral, are largely responsible for the dominant colour, but sometimes the darker minerals such as mica and hornblende may be abundant, and be segregated into patches, giving the stone a darker colour. The polished rock usually has a darker colour than the rough-dressed stone. Sometimes a granite may show an indistinct banding, due to the rock flowing slightly before it finally solidified. In other cases, a porphyritic structure may be developed, as in the Shap granite, giving characteristic colour effects.

Chemical Composition and Properties. Most granites have a silica percentage of over 66 per cent, on chemical analysis. This does not mean that the rock has this amount of quartz, but that this is the total silica content of all the minerals together. An analysis of a typical granite is shown on page 131. Howe quotes the mineral content of a typical red granite as follows: Felspars 65 per cent, quartz 28·6 per cent, and mica 5·5 per cent. Some variation in mineral content may be shown in different granites. The specific gravity of these rocks ranges from 2·6–2·8, and they have a density of 160–200 lb/ft^3. Their strength in compression is usually 1 000–2 000 t/ft^2, but some samples may fall below this.

The granites, on the whole, weather fairly well, but some varieties are not so resistant. The quartz is definitely resistant to industrial atmospheres, but the felspars are readily attacked by acidulated waters, and altered to kaolin, which may be washed out of the rock. In most granites, the felspar is slightly weathered, but, if the decomposition has gone very far, the rock should be suspect for many purposes. The extent of the decomposition of the felspars can be ascertained by making a thin section of the stone in the way described in Chapter V, and examining it with a hand lens or a microscope. The unweathered felspar is clear and transparent, but becomes cloudy and grey in patches where altered to kaolin. Although the felspars of most granites may show a little decomposition, types occur in which the mineral is badly attacked. The biotite may, on occasions, be altered to a green chloritic mineral. In some areas, as in parts of the granite masses of Cornwall, gases containing carbon dioxide emanated from the rock as it was cooling from the molten condition. The carbon dioxide attacked the felspars of the rock, and altered them to china clay or kaolin, so that the granite now consists of a mixture of quartz grains, china clay, and biotite. The great deposits of china clay of Cornwall were formed in this way. All grades from china clay rock to unaltered granites are found.

The medium- and finer-grained granites are usually superior in toughness and resistance to attrition. Granites, such as the Groby granite of Leicestershire, which have their quartz and felspar crystals intergrown with each other are usually tougher than the more normal types.

Granites should not be employed where they may be subjected to great heat. When heated the different minerals expand at different rates, due to their different coefficients of expansion. Similarly they contract at different rates on cooling. Great strains are thus set up, and the rock may break up into its constituent grains. The finer-grained hypabyssal and volcanic rocks may, however, stand up to great heat.

Distribution of Granites. Britain is well endowed with granite rocks which have a wide distribution in Scotland, Wales, and Western England and Ireland (Map, Fig. 43). Many of these occurrences have distinctive characteristics of colour or structure by which they can be readily identified.

The Scottish Granites. Scotland contains the most extensive granite areas in Britain situated in the Southern Uplands and the Grampian Mountains. Granite is quarried in Aberdeenshire, Kirkcudbrightshire and Kincardinshire, and in the Western Isles. Many granites occur in localities in remote districts and are too inaccessible to be of commercial value.

The Aberdeen granite is a grey-coloured stone containing much orthoclase felspar and biotite. The granite from Kemnay is often used for sills and lintels, whilst that from Rubislaw, Oldtown and other places is used for domestic architecture and constructional engineering. The Peterhead granite is red or grey in colour, and is a biotite granite. It is not porphyritic and has a moderately coarse texture. Orthoclase and plagioclase felspar are both present. The red stone is mostly polished and used for decorative finishes and columns. The Kincardinshire granites resemble the Aberdeen granites, and are dark grey medium-textured rocks which have been widely used as roadstone.

The Kirkcudbrightshire district contains the large granite masses of Dalbeattie and Criffel, the Cairnsmoor of Fleet and the Loch Dee masses. The main quarries are in the Dalbeattie and Criffel intrusions, and the rock is a bright grey colour, moderately fine-textured and made up of quartz, orthoclase, plagioclase, and crystals of dark mica and hornblende. These granites are largely used for architectural work, setts, roadstone, and granolithic slabs. Granite masses also occur in the South-west Highlands as at Rannoch Moor and Loch Etive where the Bonawe quarries are situated at Taynuilt. This is a fairly fine-grained grey rock, largely used for roadstone and setts.

The granites from Devon and Cornwall are grey in colour and are muscovite-biotite granites consisting of white felspars, quartz, muscovite and biotite micas. The black mineral tourmaline is often present. Most of the granite is porphyritic, with large well-shaped crystals of white felspar set in a finer-grained ground mass.

Granite is found in small masses in Leicestershire and Worcestershire. The Mountsorrel granite of Leicestershire is a dark grey colour, whilst a reddish brown variety also occurs. Both hornblende and biotite are present. The rock is largely quarried for macadam and setts.

The Shap granite obtained from a small boss at Wasdale Fell in Westmorland is a justly famous rock, widely used for decorative purposes, as it takes a good polish It is also used for concrete aggregates, kerbs, artificial stone, and in engineering work. The stone can be obtained in large blocks, and a characteristic feature is the occurrence of large, square, flesh-coloured porphyritic crystals of felspar, set in a ground mass which is grey or pink in colour. Some varieties are darker than others.

Other small masses of granite, such as the Skiddaw granite, occur in various parts of the country, but are not extensively quarried.

In Ireland, granite is quarried in the Newry area of County Down. This rock is a greyish-blue colour, and consists of quartz, orthoclase, plagioclase, biotite, and hornblende. The rock is widely used as a building stone, for setts, and as a polished monumental stone. Red and gray granites are quarried in Donegal and Galway.

Granites are also imported into England, especially from Scandinavia, and used for ornamental work, setts, and kerbs. The *red Swedish granite* comes from Smoland, and is a medium-grained type. The *Swedish Rose* granite has red felspars and blue quartz, and comes from the Graverfors district. Quantities of kerbs and setts come from Norway, and the grey architectural stone comes from the Liholt quarries in the Idefjord.

Granites are the most quarried igneous rock in Britain on account of their excellent resistance and toughness, and also they are amongst the most abundant and widespread of plutonic rocks. The following table gives some of the physical characteristics of typical granites.

Granite	Specific Gravity	Density (lb/ft^3)	Crushing strength (t/ft^2)	Absorption (per cent of dry weight)
Shap . . .	2·57	160	1 200	1·30
Peterhead . .	2·53	158	1 469	0·26
Rubislaw . .	2·6	162	1 288	0·1
Dalbeattie . .	2·89	179	1 635	0·18
Mountsorrel . .	2·65	165	2 086	0·13

SYENITES

Syenites resemble granites in appearance, but are distinguished by the absence of quartz crystals. Chemical analysis also shows that they have a lower silica percentage than the granites. Muscovite is not usually present in these rocks, and biotite is replaced by hornblende and augite. True syenite is not a common rock in Britain, but some varieties are imported from Norway for ornamental purposes. The *larvikites* are coarse-grained and take a high polish, and are obtainable in large blocks. They show a slight play of colour, or a *schiller* structure. The dark royal blue and the lighter emerald green are typical examples quarried at Larvik in southern Norway, which are extensively used for facings of shops and buildings in Britain.

DIORITES

These rocks are characterized by a coarse-grained texture, and the absence of quartz crystals. The predominance of plagioclase felspar distinguishes the diorites from the syenites. Hornblende is usually present, and there may be a little biotite, and the rocks are darker coloured than granites or syenites. The diorites have a specific gravity of 2·8–3, and a porosity of about 0·25 per cent, whilst the strength in crushing may be well over 1 000 t/ft^2. The diorites are difficult to dress and are not extensively quarried. They are found in the southern uplands of Scotland and in South-east Ireland, but they are worked only locally.

GABBROS

These are black or dark-coloured rocks with a coarse-grained texture. The gabbros consist essentially of plagioclase felspar and augite, but some olivine and other minerals may be present. Quartz is absent from these rocks. When the stone is polished, some of the minerals may show a play of colours. Gabbro masses may show much variation in mineral composition from place to place, and a good deal of iron-bearing mineral may be present. Their specific gravity is higher than that of the granites, ranging from 2·7–3, and they have a low porosity. The gabbros, however, are very easily weathered if used in exposed situations. They weather to a brown colour. Gabbro rocks have not been extensively used in this country, except for memorials and wall decorations. Gabbros are found in Cumberland, Skye, Cornwall, and the Channel Islands.

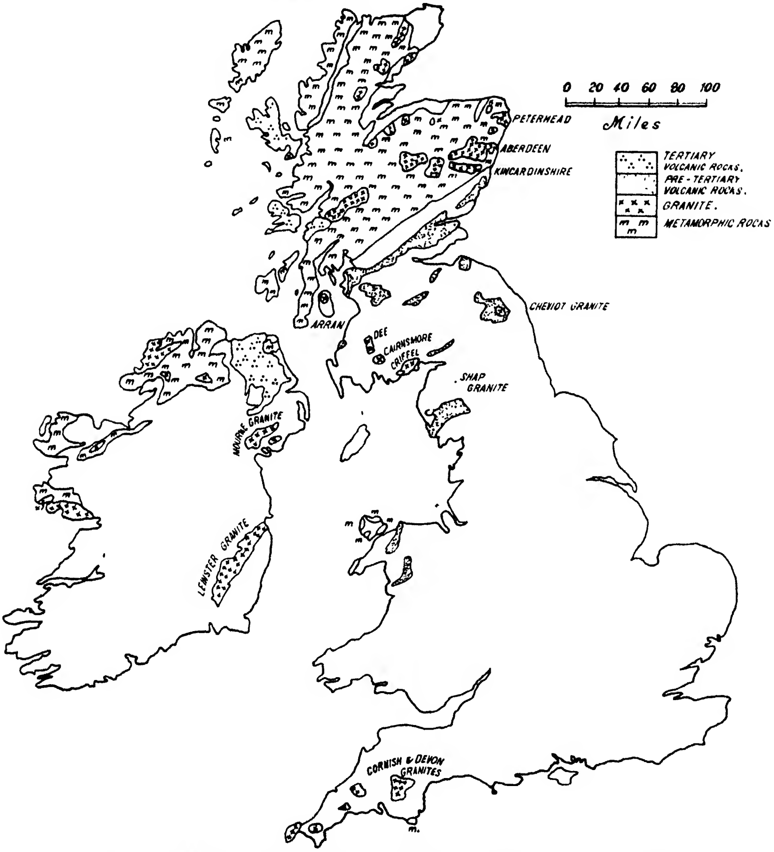

FIG. 43. MAP SHOWING THE DISTRIBUTION OF THE CHIEF IGNEOUS ROCKS

The map (Fig. 43), shows the distribution of the igneous rocks.

The following table* shows typical chemical analyses of the plutonic rocks.

Mineral	Content (per cent)			
	Dartmoor Granite	Hornblende Syenite (Dresden)	Diorite (Scotland)	Olivine Gabbro (Skye)
Silica (SiO_2)	73·16	62·49	54·09	46·39
Alumina (Al_2O_3)	13·81	16·49	16·72	26·34
Ferric oxide (Fe_2O_3)	0·21	2·36	—	2·02
Ferrous oxide (FeO)	1·51	2·04	9·38	3·15
Magnesia (MgO)	0·45	1·87	5·58	4·82
Lime (CaO)	0·67	4·23	8·35	15·29
Soda (Na_2O)	2·89	4·38	1·23	1·63
Potash (K_2O)	5·02	4·65	0·97	0·20
Titanium oxide (TiO_2)	0·16	0·85	—	0·26
Water (H_2O)	1·66	0·60	2·58	0·58

The physical properties are summarized below—

Rock	Specific Gravity	Density (lb/ft^3)	Crushing Strength (t/ft^2)	Absorption (per cent of dry weight)
Creetown Granite	2·73	169	1 630	0·24
Diorite	2·8–3	170	1 640–1 830	—
Syenite	2·5–3·6	180	1 170–1 280	—
Gabbro	2·7–3	186	1 830–2 200	—

THE HYPABYSSAL ROCKS

These rocks are intrusive into other rocks, but differ from the plutonic rocks in that they occur in much smaller masses, such as sills and dykes as described in Chapter I. Sills may be extensively quarried for roadmetal and setts. A general classification of the hypabyssal rocks is given on p. 132. The similarity of the scheme with that for the plutonic rocks will be noted.

The hypabyssal rocks have a much finer-grained texture than the plutonic rocks, and usually some of the crystals of quartz and felspar, if present, are larger than the crystals of the ground mass, giving what is termed a porphyritic structure.

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* Compiled from *The Petrology of the Igneous Rocks* by Hatch and Wells (Allen & Unwin).

	Characteristic Features	*Alkali* Types	*Intermediate* Types	*Calc-alkali* Types
ACID	Larger crystals of quartz and felspar set in light-coloured, fine-grained ground mass.	QUARTZ, PORPHYRY AND MICROGRANITE		
INTERMEDIATE	No quartz. Larger crystals of felspar in light-coloured, fine-grained ground mass.	PORPHYRY *or* SYENITE PORPHYRY	PORPHYRY	PORPHYRITE *or* DIORITE PORPHYRITE
BASIC	Dark greenish colour. Small felspar crystals. Much augite.	ALKALI DOLERITE		DOLERITE

QUARTZ PORPHYRY

When a granite melt has cooled more quickly under hypabyssal conditions, it takes on a finer-grained and porphyritic structure, and is termed a *quartz porphyry*, or, if it does not contain crystals of larger size, a *microgranite*. Larger crystals of quartz, felspar, and occasionally biotite, are set in a finer-grained crystalline ground mass. Quartz porphyry rocks have a wide distribution in this country. They are abundant in Devon and Cornwall, where they are known as *elvans*, and have been quarried for building stone as in the case of the Pentuan elvan, which is a buff colour. Other sills of quartz porphyry have been quarried for roadmetal. This rock and microgranite occur abundantly in North Wales and the Lake District. Extensive quarrying is carried out in the microgranite mass at Threlkeld near Keswick, where the rock is made into setts, roadmetal, and concrete paving slabs. This rock is a light greenish colour and contains small garnets. Quartz porphyries are also common in Scotland and are quarried, for example, at Ailsa Craig.

DIORITE PORPHYRITE

These rocks are distinguished from the syenite porphyries, which are uncommon in Britain, by the felspar being mainly of the plagioclase variety. Quartz crystals are not usually present. The porphyrites are used for roadstone, setts, concrete aggregates, and sometimes in polished work, and are quarried in Somerset, near Shepton Mallet, and in Leicestershire, at Markfield, and other places. Porphyrites are also quarried for roadstone in the Lleyn Peninsula, in North Wales.

DOLERITES

These rocks have a widespread distribution as dykes and sills. They are dark-coloured or greenish rocks with a fairly fine-grained texture, and are always completely crystalline, consisting of lath-shaped crystals of felspar enclosed in larger plates of augite. This interlocking structure gives the rock great toughness. When weathered, the rock takes on a dull-brown colour due to the presence of much iron-bearing mineral and olivine, which is often decomposed. The much decomposed dolerites are often called *diabase*. The rock is difficult to polish because of its great hardness, and is mostly used for roadstone and aggregates.

Some dolerites may occasionally contain *chlorophoeite*, a green mineral rapidly weathering to a black colour. This oxidation and the subsequent hydration are accompanied by considerable expansion in volume. Dolerites containing this mineral should not be used as concrete aggregates, especially in the fine material, as it would cause the concrete to crack. Most dolerites, however, are free from this mineral.

Small masses of dolerite are common in Devon and Cornwall and are quarried, e.g. near Padstow, for roadmetal and rough walling. Trusham granite is a dolerite from Trusham in Devonshire, and is used for setts and roadstone. Dolerites are also abundant in the Midlands, the Clee Hills, and the Malvern Hills, where they are frequently quarried. Many intrusions of dolerite are also found and quarried in North and South Wales. In the north of England is the well-known Whin Sill, running for about seventy miles from Cross Fell to Dunstanburgh Head in Northumberland, the Acklington Dyke, extending from Northumberland to the Cheviot Hills, and the Cleveland Dyke, which can be followed for over ninety miles. These occurrences have been extensively quarried at various places along their length, and used locally for building stone, whilst they also make an excellent roadstone.

THE VOLCANIC ROCKS

There have been many periods from the pre-Cambrian onwards when volcanic activity took place in Britain. These rocks were poured out from the craters of volcanoes and spread as lava flows over the surrounding country-side. Whilst individual flows may be quite thin, the cumulative thickness of successive flows may reach thousands of feet. The lavas rapidly lost their contained gases and fluxes into the air, and consequently cooled rapidly and solidified at a higher temperature than the plutonic and hypabyssal rocks.

The volcanic rocks are, therefore, extremely fine-grained, and the crystals can be made out only by means of a good hand lens. Some of the more siliceous types were so viscous that they were unable to crystallize at all, and these solidified as an opaque glass. Movement of the lava sometimes occurred before it was completely solidified, and the rock shows a banding or a striped effect, due to the drawing out of coloured patches into bands.

Volcanic rocks are formed from the same magmas as the plutonic rocks, the only difference being that the former type cooled on the surface. It follows, therefore, that a similar classification can be used for the volcanic rocks as for the plutonic types as under—

	Characteristic Features	*Alkali* Types	*Intermediate* Types	*Calc-alkali* Types
ACID	Light-coloured. Often banded and greenish colour. Not crystalline.		RHYOLITE	
INTERMEDIATE	Light-coloured. Very small crystals visible.	TRACHYTE Very light-coloured.	TRACHY-ANDESITE	ANDESITE Moderately dark-coloured.
BASIC	Dark or black colour. With close examination, small crystals can be made out.	ALKALI BASALT	CIMINITE	BASALT Heavy, almost black colour. Minute crystals

Extreme fineness of grain is characteristic of the volcanic rocks, but the colour and specific gravity will usually indicate the class. The nature of the minerals in volcanic rocks cannot usually be made out unless a thin section is made as described in the chapter on sandstones, and examined with a hand lens or a microscope. Because of their extreme fineness of grain and interlocking structure, the volcanic rocks are very tough and have a high strength in crushing, and are largely used for concrete aggregates and roadstone. Many volcanic rocks are full of blow-holes formed when the gases escaped from the viscous rock. Pumice is an example of such highly vesicular rhyolites.

RHYOLITES

The *Rhyolites* are light-grey rocks which very often have a greenish tint. In the mass the rock is very fine-grained, or crystals may be absent altogether, although sometimes an occasional larger crystal of quartz and felspar may occur. Flow structure is common and can be seen, especially on weathered faces, as a streaky structure, the streaks all having a rough parallelism. This structure is due to the lava flowing before it became completely solid. Some rhyolites known as *obsidian* resemble black bottle glass, and break with the same splintery fracture. The light-coloured, highly vesicular variety of rhyolite is known as pumice, and represents the froth formed by the liberation of gases.

The rhyolites weather well. Many of the geologically older rhyolites have been impregnated with silica and are extremely tough and resistant. The rock does not take a good polish. They have not been extensively used as building-stone in this country, but they are much quarried for roadstone and aggregates in North Wales and other districts.

Pumice is so vesicular in the mass that its specific gravity may be as low as 0·3 to 0·9, and it will often float on water as the bulk of the rock is air space. When mixed with milk of lime, crushed pumice is used in the manufacture of the artificial stone known as *Nudermendiz Sshwammstein*, used as an insulator. Pumice blocks made of pumice and Portland cement are light in weight, and have good sound and heat insulating properties. They are supplied under various trade names. The *Pozzolanas*, which have constituents which combine with lime and water at ordinary temperatures to form insoluble cementitious compounds, are obtained from clayey or siliceous, pumaceous material from Vesuvius, South-east France, the Azores, and the Canary Islands. *Trass* is a pozzolanic material, or yellow pumice-like rock, obtained near Coblenz in Germany. In the Mediterranean region where pumice is readily obtainable, it has been used as a building stone, and was used by the Romans for building arches on account of its lightness. Crushed pumice is also used as a basis of polishing powders, as the crushed grains retain their angularity during the polishing process.

TRACHYTES

These are light-coloured rocks which are not as siliceous as the rhyolites. They are usually completely crystalline, as can be seen in thin sections of the rock, and the crystals are usually arranged with their long axes in the same direction, giving a typical flow structure. There are usually a few larger crystals of orthoclase felspar set in a very fine-grained ground mass consisting of lath-shaped crystals of orthoclase felspar, with a little hornblende or augite. The dark-coloured minerals are always small in amount. Trachytes are not much quarried, and are used mainly as macadam and ashlar.

ANDESITES

Andesites are darker coloured lavas than the trachytes. Quartz is absent and the dominant felspar is plagioclase. These features can only be seen when thin sections of the rock are cut, and examined with a microscope. The rock may be porphyritic with larger crystals of plagioclase set in a fine-grained ground mass of hornblende, plagioclase, and other minerals. Andesites are used for the same purposes as the trachytes, and are common in Wales, the Lake District, and Scotland.

BASALTS

These are dark-coloured lavas consisting of minute crystals of plagioclase felspar and augite. Olivine may be present. The rock is the volcanic equivalent of a gabbro. They possess great toughness and have a crushing strength often over 2 000 t/ft^2, with a specific gravity of 2·8–3. When fresh, basalts are black or very dark in colour, but they weather to a brown crust, due to the large amount of iron-bearing mineral they contain. Many basalts contain so much iron mineral that they deflect a magnetic needle. The stone should not be used in continuously damp situations as it then weathers badly, nor if examination of thin sections shows that the minerals making up the rock are badly decomposed.

Basalts are mainly quarried for roadstone, for which purpose they are very satisfactory. They are seldom used in building except for rough walling. In Ireland, the Giant's Causeway is formed of basalt and shows the columnar jointing typical of these rocks. In Scotland, basalts are found in the Edinburgh district, Ayrshire, Fifeshire, and Linlithgowshire. They are also quarried in Derbyshire, Devonshire, and Cornwall.

The following table compiled from *The Petrology of the Igneous Rocks* gives typical chemical analyses of volcanic rocks—

	Content (per cent)			
	Rhyolite (Snowdon)	Trachyte (Haddingtonshire)	Andesite (Edinburgh)	Olivine Basalt
Silica (SiO_2) . . .	73·5	62·61	57·53	49·07
Alumina (Al_2O_3) . .	11·98	18·71	16·47	19·43
Ferric Oxide (Fe_2O_3) .	1·14	0·32	4·42	10·58
Ferrous Oxide (FeO) .	2·40	4·25	3·23	2·35
Magnesia (MgO) . .	0·76	0·74	1·32	4·36
Lime (CaO) . . .	0·32	4·58	6·16	7·87
Soda (Na_2O). . .	0·53	6·49	4·13	3·31
Potash (K_2O) . .	7·38	4·02	2·09	0·98
Titanium Oxide (TiO_2) .	0·12	—	0·91	—
Water (H_2O) . .	1·75	0·80	1·02	2·26

Some of the physical properties of hypabyssal and volcanic rocks are as follows—

Rock	Specific Gravity	Density (lb/ft³)	Crushing Strength (t/ft²)
Quartz Porphyry	2·4–2·8	159	1 645–2 740
Dolerite	2·8–3	180	1 000–2 200
Rhyolite	2·3–2·7	156	—
Andesite	2·2–2·7	155	455–730
Basalt	2·8–3·3	180	2 010–3 200

The British Standards Specification (B.S. 435: 1931), regarding the use of granite and whinstone kerbs, channels, quadrants, and setts, says that the term granite and whinstone shall include all rocks of igneous origin. Kerbs and channels are required to be good, sound, and free from defects. Standard sizes of width, depth, and length are fixed, and the types of dressing are given. If natural pumice is used in the manufacture of pre-cast concrete partition blocks, the B.S. 492: 1944, and 728: 1944, says that the material shall be free from material not of volcanic origin, and shall be free from volcanic dust.

IGNEOUS ROCKS AS ROADSTONE

Igneous rocks are extensively used as setts, macadam and chippings, and in concrete aggregates for roads. The same stone, however, may not be suitable for all these purposes. Setts are expensive and are now used only where the traffic is very heavy. They should be able to withstand heavy loads and impacts without fracturing, and they should not develop a slippery surface. The presence of some mica may prevent the setts wearing smooth. Granites, such as those from Aberdeen and Shap, are often used for setts. Dolerites and quartz porphyries such as the Threlkeld microgranite are also widely used.

For use as small stone or chips, a very superior stone is needed. The chips are $\frac{3}{4}$ in. long, or smaller, and to have a long life they must be of very high grade, with high impact values. A stone quite satisfactory as a sett may be unsuitable as chippings even where the traffic is light. The fine-grained volcanic or hypabyssal rocks with a closely interlocking structure, such as the Penmaenmawr so-called "granite" and the rock of the Whin Sill of the north of England, are very suitable for this purpose. The material used as chippings should be free from cracked or fissured quartz grains, and the felspars should be almost free from decomposition.

For macadam, the stone should be in pieces $1\frac{1}{2}$–3 in. across, and be angular in shape, so that they interlock when they are laid and rolled. Most igneous rocks are suitable, as the tar adheres satisfactorily to their surfaces if they are dry and free from dust.

Tests for Roadstone. The National Physical Laboratory carries out various tests on roadstone as detailed below—

Attrition Test. This test is made to determine the rate of wear due to the grinding action under the pressure of traffic. Eleven pounds of rock consisting of about 50 pieces are placed in the cylinder of a Deval type machine, and the machine is revolved 10 000 times. Only the material worn off which will pass a $\frac{1}{16}$ in. mesh sieve is considered in determining the amount of wear. In the wet test 1·1 gal. of water are added.

Abrasion Test. This is used to find the resistance of the stone to traffic, when used for paving a road. The specimen is ground to 1 in. diameter and 1 in. long, and held with its axis vertical and its lower end pressed with a force of 3·5 lb/in.^{2} against the surface of the revolving disc of a Dossy type machine. Sand obtained from quartzite is fed continuously to the disc. After 1 000 revolutions of the grinding disc, revolving at about 28 r.p.m., the loss in weight is obtained in grammes and pounds.

Impact Test. The behaviour of the stone under repeated impact is determined by this test using a Page Impact Machine. The specimen is prepared to 1 in. diameter and 1 in. long, and placed on an anvil with its axis vertical. In contact with the upper surface of the specimen is the spherical end of a small steel plunger. A hammer weighing 4·4 lb strikes the plunger at definite intervals, and the height of the fall increases by 0·4 in. after each blow. The number of blows to cause failure of the stone is taken to represent the toughness of the rock.

Cementation Value. The finer particles of a stone used for water-bound roads forms under pressure a cement, uniting the larger stones. A paste is made by grinding a mixture of coarsely crushed rock and water in a ball mill. The paste is moulded under pressure to form blocks 1 in. diameter and 1 in. long. The blocks are then tested in an impact machine. The effective drop of the hammer is always 0·4 in. The number of blows required so that there is no rebound of the plunger is taken as a measure of the cementing value of the stone.

Absorption of Water Test. The sample of about 50 g weight is dried until of constant weight and then immersed in water. The stone is weighed immediately after immersion and also after immersion for three days. The result is the average of three samples.

The following table gives a general idea of the interpretation of the results of the foregoing tests—

	Attrition Test (per cent of wear)		Abrasion Test (coeff. of wear)	Impact Test (No. of blows for failure)	Crushing Strength (lb/in.^{2})	Absorption (lb/ft^3)
	Dry	Wet				
Very good .	2 and under		19 and over	19 and over	Over 20 000	0·10 and under
Good . .	2·1–2·5	2·1–3·1	17–18·9	16 18	15 000–20 000	0·11–0·40
Fairly good .	2·6–3·1	3·2–4·0	16–16·9	13–15	10 000–15 000	0·41–1·00
Rather poor .	3·2 4	4·1–5·0	15–15·9	8–12	5 000–10 000	1·01–3·00
Poor . .	Over 4	Over 5	Under 15	Under 8	Under 5 000	Over 3

The following table gives a rough average value of the above tests for each group of stones—

Trade Name	Attrition Test (per cent loss of weight)		Abrasion Test (coeff. of hardness)	Impact Test (No. of blows)	Cementation Value	Absorption (lb/ft^3)	Crushing Strength (lb/in.^{2})	Specific Gravity
	Dry	Wet						
Granite .	2·6	2·6	18·7	14	17	0·28	26 000	2·65
Gabbro .	2·8	2·8	18·8	20	7	0·32	30 000	3·17
Porphyry .	2·8	2·4	19·3	19	23	0·63	33 900	2·65
Andesite .	3·0	5·6	18·0	19	46	0·17	21 000	2·79
Basalt .	3·5	6·1	17·3	17	54	0·53	27 200	2·87
Quartzite .	3·2	3·9	18·8	13	12	0·47	36 000	2·63
Grit . .	3·0	4·8	18·3	18	21	0·49	31 000	2·66
Limestone .	5·2	9·4	16·4	16	17	1·03	19 400	2·67
Schist . .	2·9	3·1	19·1	17	13	0·13	36 400	2·69

Individual stones may show some variations from the average values shown in the above tables.

Trade Grouping of Roadstones. For trade purposes rocks are grouped as under. The various rock types have similar properties and can be used for similar industrial purposes.

The Granite Trade Group

Granite
Granodiorite
Granulite
Gneiss
Syenite
Pegmatite
Quartz diorite

The Porphyry Group

Aplite
Dacite
Felsite
Granophyre
Keratophyre
Microgranite
Porphyry
Quartz porphyrite
Rhyolite
Trachyte

The Gabbro Group

Basic diorite
Basic gneiss
Gabbro
Hornblende rock
Norite
Peridotite
Picrite
Serpentine

The Basalt Group

Andesite
Basalt
Basic porphyrite
Diabase
Dolerite, Theralite
Epidiorite
Hornblende schist
Lamprophyre
Quartz dolerite
Spilite

The Hornfels Group

Contact altered rocks of all types except marble

The Gritstone Group

Agglomerate
Arkose
Breccia
Conglomerate
Greywacke
Grit
Sandstone
Tuff

The Limestone Group

Dolomite
Limestone
Marble

The Schist Group

Phyllite
Schist
Shale
All severely sheared rocks

The Quartzite Group

Ganister
Quartzitic sandstone
Recrystallized quartzite

The Flint Group

Chert
Flint

CHAPTER X

The Metamorphic Rocks

Formation. The metamorphic rocks are those rocks, either sedimentary or igneous, which have been altered structurally and mineralogically by heat or pressure or both acting together. The ~~heat causing~~ these changes is obtained from molten igneous rocks which have forced their way into other rocks. The heat is dissipated outwards through the enclosing rocks over long periods of time until the igneous rocks cool down and solidify. The pressure responsible for the structural changes is exerted by crumpling and folding of rocks during periods of great earth-movement.

The metamorphism or changes brought about by the heat of igneous intrusions is termed *contact* or *thermal metamorphism*, and the extent of the change is dependent to a large degree on the size of the intrusion responsible for the metamorphism. Small intrusions such as dykes and sills may merely bake and harden the adjoining rock, but large plutonic intrusions may cause profound changes for distances of several miles from the contact with the igneous rock. The changes are greatest, as might be expected, close to the contact where the temperature was highest, and decrease in intensity at a distance, gradually passing into the unaltered rock.

The changes in the rocks enclosing an intrusion take place in the solid. The rock is not first melted, but minerals quite stable at normal temperatures and pressures may become unstable at the higher pressures developed during metamorphism. These unstable minerals react with other minerals in the rock and form new chemical combinations, i.e. new minerals. Where the constituent minerals are such that new combinations cannot take place, the rock on metamorphism may merely recrystallize as in the case of many of the true marbles. During these mineral transformations, profound structural alterations may be induced. This type of alteration in the country rocks around an igneous intrusion depends to a very large extent on whether the rock is limestone, shale, sandstone, or an igneous rock.

THERMAL METAMORPHISM

Shale. Where the strata surrounding the igneous intrusion consists of shale, the zone of alteration, or metamorphic aureole, may be quite wide. The first sign of change at a distance from the intrusion is the formation of small spots of graphite which give the shale a spotted appearance. The spots are due to the gathering together and the recrystallization of the carbonaceous material in the shale. At this stage there is no structural alteration noticeable in the shale itself.

Nearer to the contact with the igneous rock, a certain amount of mineralogical change takes place. Long needle-shaped crystals of *chiastolite* (aluminium silicate) are formed, running in all directions within the shale, giving it a distinct spotted appearance. Some new biotite mica may form, together with andalusite and secondary muscovite mica. Close to the contact with the intrusion the high temperature mineral *sillimanite* forms together with garnets, and other minerals. Sillimanite, andalusite, and chiastolite all have the same chemical composition, but sillimanite is the high temperature form. The shales near the intrusions are baked and hardened, and any contained water is driven off. In many cases the shales develop a rough *schistosity*, with a tendency to break into slabs and elongated fragments. They are useless for brickmaking, and most other purposes, and are too irregular to be used as good building stones.

Limestones. Where limestones form the country rock around an intrusion, an entirely different set of minerals is developed. If the limestone consists of almost pure calcium carbonate, the rock recrystallizes as a marble. With dolomitic or magnesian limestones, the magnesian portion of the rock may be converted to the mineral *periclase* (magnesium oxide) and the rest to marble, giving the rock known as a periclase marble. If satisfactory in colour and strength, these marbles may be of value as building and statuary marble.

Where the limestone contains siliceous impurities, the calcium carbonate reacts with the silica, even at low temperatures, and forms calcium silicate minerals such as *wollastonite* ($CaO.SiO_2$) in large white crystals. If a little clay material is present as an impurity, calcium-alumino-silicate minerals such as *anorthite*, *idocrase* and garnets are formed. These metamorphosed limestones, with the exception of the marbles, are not of great value.

Sandstones. Pure sandstones, when metamorphosed by heat, recrystallize as even-grained quartzites. Where the rock contains calcareous or clay impurities and cementing materials, secondary muscovite mica, biotite mica, felspars, quartz, and other minerals may be developed. The bulk of the rock consists of a mosaic of quartz and felspar with the other minerals embedded in it. In the sandstones, which have been subjected to the highest grade of metamorphism, there is a tendency for the minerals to segregate into lenticles, each containing particular minerals. The quartz and felspars form together into bands, whilst the coloured minerals tend to be in other distinct bands. The rock is thus coarse-grained, and when large pieces are examined, the rock exhibits a rough banded structure. Coarse-grained rocks possessing this banded structure are termed *gneisses*, contrasting with the *schists* which are fine-grained and fissile, and easily split into thin layers.

REGIONAL OR DYNAMIC METAMORPHISM

During the long history of the earth, there have been several periods when great earth-pressures were developed which resulted in the rocks being folded and buckled and broken. In many cases, the pressures were sufficiently great to turn strata, originally deposited in horizontal beds, into the vertical position. Where the pressures were sufficiently great, profound structural and mineralogical changes were brought about in the rocks subjected to these pressures. These pressures were directional, and led in many cases to the production of banded structures in the rocks.

Cleavage, and false or strain-slip cleavage, is one of the commonest structures developed as a result of pressure on fine-grained rocks, giving rise to slates such as those in North Wales, which are described in Chapter VIII. Cleavage is a structure restricted to fine-grained rocks, and it was formed without any great rise in temperature.

In other cases there is evidence of some rise in temperature accompanying the development of pressure. New mineralogical combinations take place, the new minerals formed having a denser structure and a higher specific gravity than the constituents from which they were made. Many of the mineral crystals may be broken and strained, and in many cases they are bent and twisted. The finer-grained rocks are usually foliated, and split readily into irregular slabs. There is much development of secondary mica, garnet, graphite, and talc. These rocks are termed schists, and are usually subdivided according to their chief minerals, e.g. talc schist, mica schist, etc. These schists may outcrop over hundreds of square miles of country, and are not restricted to the vicinity of igneous intrusions.

Schists are mainly restricted in Britain to the pre-Cambrian rocks, and are present over large areas of Scotland north of the Central Valley. They occur in the Isle of Anglesey and the neighbouring mainland of North Wales, at The Lizard, in South Devon, and in other small areas various types of schists are found. The stone may be used locally, in areas where these rocks are at the surface, for walling and cottage buildings, but it is not suitable for roadstone or concrete aggregate on account of its fissility. There is a considerable difference in the resistance to crushing of schists when tested parallel to the direction of foliation, and at right angles to this structure. The figure is much lower parallel to the direction of schistosity.

Where the rocks which have been subjected to regional metamorphism are coarse-grained, such as sandstones and igneous rocks, the resulting altered rock becomes a gneiss. New secondary minerals, such as muscovite, quartz, felspars, biotite, etc., are formed, and these tend to be segregated into bands, the light-coloured quartz and felspars separating from the darker biotite, chlorite, and other minerals. The rock acquires a coarse-grained structure with a rough banding when seen in the mass. Any coarse-grained rock can be metamorphosed into a gneiss. Gneisses are hard and tough, and are sometimes quarried for local use. Some types make good paving setts. Gneisses are found over large areas of the north-west highlands of Scotland and the Outer Hebrides, whilst small areas are found in North Wales and Shropshire. They are pre-Cambrian in age.

Several minerals which are used in the paint manufacturing industry and for other purposes are obtained from regions where metamorphism has taken place. Talc or soapstone, used in paint and for processing roofing felts, is obtained from rocks rich in magnesia, occurring as pockets and lenses in regions of intense folding. Graphite also occurs associated with metamorphic rocks.

The rock known as *jasper* is usually found in areas which have been highly metamorphosed. It is a red iron-stained siliceous rock. It is hard and resistant to weathering, and takes a good polish, and has been used for ornamental finishes in important buildings. The jasper quarries are usually small, and the rock may be badly broken and difficult to obtain in large blocks.

CHAPTER XI

Water Supply

THE provision of supplies of water suitable for domestic use is of extreme importance, especially in rural districts and villages out of reach of town supplies. A chemically pure water is not enough; it should be free from harmful bacteria, and, what is just as important, it should be protected from contamination by sewage and other substances of a dangerous nature. In country districts, cesspools and septic tanks are used where sewage schemes are not available, and, unless great care is taken, these may seriously endanger the water supply of a large area, especially if the rocks from which the water is drawn are well jointed or fissured. Many wells used by farms and small villages are very suspect in regard to the purity of their water supplies. Refuse dumps and ash pits should be so placed that drainage will not enter and contaminate water supplies.

WATER IN ROCKS

The Water Table. Water which falls on an area in the form of rain is disposed of in three ways. Some of it invariably evaporates and is returned to the atmosphere as water vapour, the amount lost in this way depending on the temperature, the steepness of slope, and the porosity of the ground. Another portion forms the *run-off* which runs down the hill slopes into the streams at the bottom. This amount also depends on the porosity of the surface rocks and soil, and on the degree of slope of the ground. The more porous the ground, the less is the run-off. The remainder of the rainfall seeps into the ground and becomes *ground water* which is the water that is available to wells and boreholes. This water travels downwards through the rocks until it meets an impervious bed such as shale or clay, when further downward progress is stopped. The porous stratum may then tend to fill up with water. The upper level of this water body within a stratum is known as the *water table* (Fig. 44). The water table is not horizontal, but rises higher under hills and is depressed under valleys. It follows the surface features of the ground but in a less accentuated manner.

The level of the water table within a rock is of great importance as wells and boreholes must be sunk below this level if they are to be productive. The general position of the water table in a district can be estimated by measuring the stand of the water in the wells of the area, relative to the surface of the ground. Above the water table for a distance up to about 10 ft is a capillary fringe in which the rocks are damp. This damp fringe is due to the drawing up by capillary action of water from the water body which is below the water table. Where the water table actually reaches the surface of the ground, the ground becomes damp and swampy. Where there is a seasonal rainfall, as in most parts of Britain, the height of the water table fluctuates, rising in the winter or rainy season, and falling again shortly after the advent of the drier season. Maps showing the level of the ground water table (*isopietic* maps) by means of contours showing the position of the water table are available for some areas. They give a clue to the hydrostatic head in a locality. The direction of flow of the ground water is at right angles to the water contours.

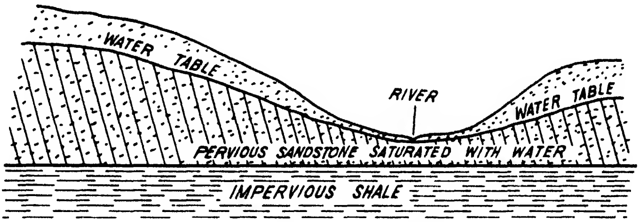

FIG. 44. THE WATER TABLE

The diagram shows the rise of the water table with rise of the surface. The water travels down through the rock until impounded by the impervious shale bed.

Gathering Ground. It is seldom that the water obtained from a particular well has been obtained from the rainfall arriving on the ground in the immediate vicinity of the well. The water is usually obtained from the rainfall arriving on gathering grounds some distance away, which has sunk into the strata and percolated to the well. Good gathering grounds should be of large area, the most satisfactory being areas where porous rocks such as sandstone, limestone, or sands and gravel outcrop at the surface. In this case much of the rainfall may percolate into the rocks of the gathering ground and gravitate downwards to lower levels. If shales or clays are present as the surface rocks, the rainfall will be unable to penetrate below ground, and the surface may become damp and waterlogged. New supplies of water taken in at the gathering ground may take months or even years to reach a well some miles away.

Effect of Porosity and Permeability. Rainfall arriving on the gathering ground seeps into the underlying rocks and becomes ground water. This water is held in the pore spaces between the grains of the rock, or in joints and fissures. The more porous rocks may contain a greater quantity of ground water per acre. The porosity, as stated in a previous chapter, is the percentage of voids in the rock, and under favourable conditions these voids may become filled with water. If the pores are excessively minute, however, the water within the pores will be tightly held by capillarity and will not be given up to wells. Shales and clays possess considerable porosity, and may contain water, but the pores are so minute that the water is tightly held, and will not pass through the rock or be delivered to wells. Clays and shales are, therefore, said to be impermeable, and wells should not be sunk into these rocks.

Sands and gravels, on the other hand, are very porous, and also highly permeable, and they readily yield up their water to wells and boreholes. The pores in these rocks are comparatively large, and the water easily passes through them. A great many sandstones are porous and permeable, but they must be treated with caution when sinking wells. In some cases the cementing material of a sandstone is present in large amounts, and not only coats the grains but also fills up the interspaces between them, thereby greatly reducing the porosity of the rock. If the sandstone is tightly cemented there is no room for any water, and wells sunk in such rock may not have a very high yield. The cementing material may be irregularly distributed within a sandstone stratum, so that many areas may be productive of water whilst the heavily cemented areas of the same bed yield very little. This is the explanation of many cases where one well is productive and a neighbouring well is dry, although they were both sunk to the same bed. Important British water producing sands and sandstones are the Old Red Sandstone, the Bunter Sandstones of Triassic age, the Lower Greensands of Cretaceous age, and the Eocene Sands of Tertiary age. The sandstones of the Carboniferous System are often of low porosity due to the presence of much cementing material, although many beds produce copious supplies.

Limestone rocks are frequently prolific in the amount of water they contain. This rock has a low porosity, but is characterized by a well-developed system of joints and bedding planes. These are usually open fissures, and the water can pass through them like water going through pipes, in contrast to the molecular flow of the water through the pore spaces of a sandstone. Where limestone or chalk form the surface rocks of a district, the rainfall sinks rapidly underground, and it is a characteristic of these areas that there is an absence of surface water and streams. The water moves through these rocks readily, and with ease, and wells sunk into limestones are usually very productive if the stratum is connected with a large gathering ground.

Igneous rocks, on the other hand, are not usually rocks into which wells can be sunk with much hope of success. These rocks have a very low porosity and permeability, and, whilst joints may be present, they are not on the same scale as in limestone. The occasional small supplies of water which are obtained from igneous rocks are got from the joints. The following table indicates the rocks which may yield water, and those from which water is not commonly obtained.

Favourable Rocks	Unfavourable Rocks
Limestone and chalk	Clays
Dolomite	Shales
Gravels	Marls
Sand	Igneous rocks
Many sandstones	Metamorphic rocks
Breccias and conglomerates	

The permeability or otherwise of the surface rocks is of some importance in fixing the sites of housing estates. Where the surface rocks are highly permeable, such as sand and gravel, the surface will be dry, but if the rocks are clay or shale, the site may be cold and damp. Where glacial drift covers the surface, the nature of the site will depend on whether the deposit is predominantly sand or clay.

The porosity of a sandstone also depends to a large extent on the shape and the diversity of size of the grains. The porosity of a rock is greatest where the grains are rounded as in the Permian and Triassic sandstones which form good water-bearing rocks. Where the grains are subangular in shape and of different sizes, they pack together more closely, thereby greatly reducing the porosity of the rock. Oolitic limestones resemble sandstones in this respect. The water is held between the ooliths or grains. If much cementing material is present, the pore spaces are closed, and the water content of the rock may be much reduced. It is often found by experience that certain strata in a district produce more copious supplies of water than other strata in the same area, and efforts are made to recognize this bed and reach it in wells and boreholes.

Quality of Water from Rocks. The nature of the gathering ground exerts a considerable influence on the quality of the water drawn from strata which outcrop in that area. If farms or villages without mains sewage are present on the gathering ground, there is a considerable danger of contamination of the water supply by seepage from these habitations and farm buildings, especially if the surface rocks are very porous or much fissured. The contaminating effluent may easily reach the supply of water tapped by a well (Fig. 45). It is for this reason that water from deeper sources, protected by an overlying impervious shale or clay bed, is preferable as a source of domestic water. This deeper water will have come from a gathering ground farther away, and the distance it has to travel through the rocks to the well will have the effect of filtering out a great deal of the bacterial content of the water. Sewage farms, cemeteries, and other works likely to contaminate the water supply of neighbouring wells should, if possible, be placed on shale or clay outcrops where the drainage will not enter porous beds below, and so enter the water supply. If shale or clay beds are not present, sources of possible contamination should be placed to the stratigraphical dip side of a well, so that the effluent may drain away from the water in the well. To fully protect a well used for domestic water supplies from contamination, it may be necessary to purchase an area of ground around the well especially at the side of the well where the strata are rising, and prevent the grazing of animals and the erection of works on this protection area.

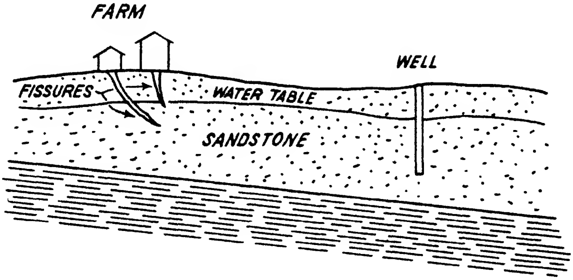

Fig. 45. The Contamination of Ground Water by Surface Impurities Passing through Fissures

Well or spring water is seldom chemically pure; it always contains a greater or less proportion of dissolved salts, especially of calcium carbonate or lime, but it is only in exceptional cases that the water is rendered unpalatable because of a large percentage of dissolved salts. The hardness of a water depends on the type of rock from which it was obtained. Limestones and chalk always yield very hard water, due to the amount of calcium carbonate dissolved by the water during its passage through these rocks. Sands and sandstones give a much softer water, especially the rocks with an iron, clay or silica cement. The igneous and metamorphic rocks almost always give a noticeably soft water.

The dissolved salts contained in natural waters may settle out as an incrustation on the insides of pipes and water mains, and in a short time seriously reduce their capacity unless they are periodically cleaned out.

WELLS AND SPRINGS

The Siting of Wells. The sinking of a well or a borehole is often a haphazard undertaking. The chances of success are, however, greatly improved if geological principles are followed in deciding in what position to put the well and to what depth to sink. A well should reach a porous, water-bearing stratum, or aquifer, and be of sufficient depth to extend well below the level of the water table. Where the water table fluctuates considerably with the season, the well must be deep enough to extend below the water table in the dry season, or it will not be productive all the year round.

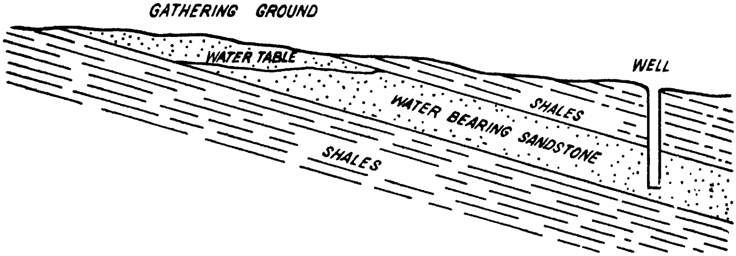

FIG. 46. DIAGRAMMATIC SECTION SHOWING THE TRAVEL OF WATER FROM THE GATHERING GROUND TO WELLS DOWN DIP OF THE STRATA

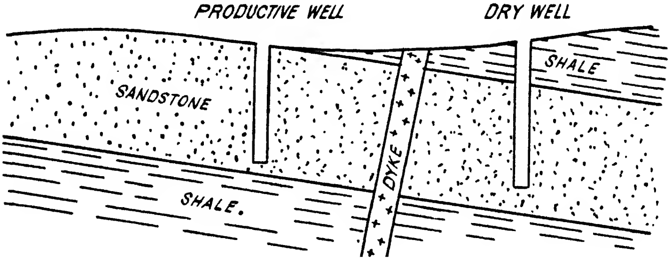

FIG. 47. DIAGRAM SHOWING THE EFFECT OF A DYKE OF IMPERVIOUS IGNEOUS ROCK ON THE PASSAGE OF WATER DOWN A POROUS SANDSTONE BED

The well beyond the dyke is cut off from the gathering ground and will not yield water.

Water taken in at the gathering ground travels down the dip of the strata until the water-bearing stratum is saturated, so that a well put down to reach the water-bearing bed at its deepest point will probably be successful (Fig. 46). Faults or dykes of igneous rock, however, may cause considerable complications, and in many cases may cut off a porous bed from its gathering ground, so that this section of the bed is dry and wells sunk into it will be barren (Fig. 47). In all cases, except for inexpensive and shallow wells, it is very necessary to study closely the geological conditions of the area, and for this purpose the large-scale geological maps prepared by the Geological Survey are most useful.

Artesian Wells. Under certain structural conditions the water from a well may rise up the well and flow over the top under considerable pressure. These artesian wells do not require any pumping to raise the water. The essential condition for flowing wells is that the level of the water table should be higher than that of the top of the well or borehole, so as to give a hydrostatic head sufficient to force the water up to the top of the well and cause it to overflow.

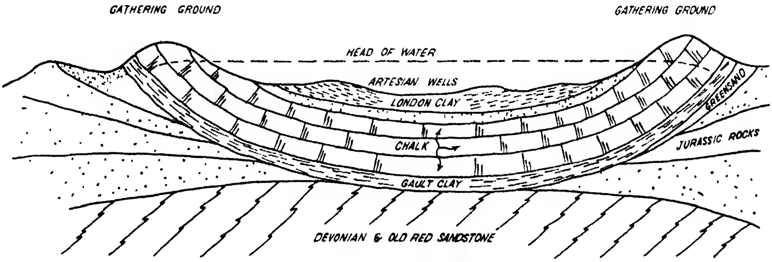

FIG. 48. A SECTION SHOWING THE GENERAL SYNCLINAL STRUCTURE OF THE LONDON BASIN

The head of water is such that flowing wells can be sunk in the centre of the area.

Sometimes large areas form artesian basins within which most of the wells are flowing wells. The best British example is the London basin, covering most of the Thames Valley, and extending northwards to the Chiltern Hills and southwards to the North Downs of Kent (Fig. 48). Here the gathering ground is the chalk outcrop over many square miles to the north, and the chalk outcrop of the North Downs. These chalk strata dip in the form of a syncline below the London area, and are enclosed within thick clay series above and below. The water table near the gathering ground is at a much higher level than the surface of the ground in the Thames Valley. There is thus a considerable hydrostatic head between the top of the wells and the water table in the London area. If water from an artesian basin is used excessively and to a greater extent than it is recovered as rainfall, the level of the water table will fall, the artesian condition will be lost, and the water have to be pumped. In addition to the great artesian basins covering very large areas, flowing conditions may occur locally at individual wells as shown in Fig. 49, as a result of faulting or igneous intrusions, or other causes.

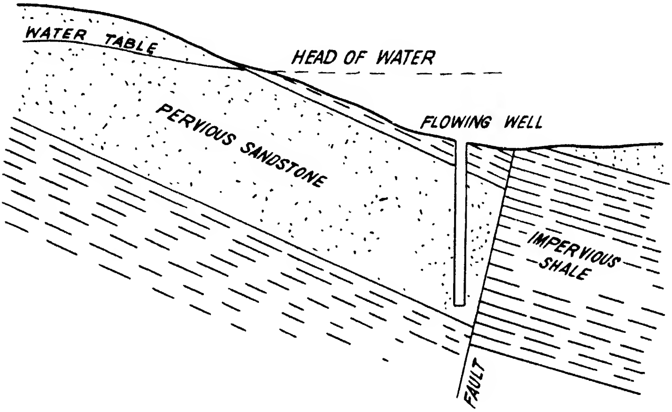

FIG. 49. ARTESIAN CONDITIONS FORMED AS A RESULT OF PERVIOUS WATER-BEARING SANDSTONES BEING FAULTED AGAINST IMPERVIOUS SHALES

The water is held up above the top of the well, forming flowing wells.

Springs. Where the water table comes to the surface, either swampy ground or a line of springs is formed. Where a thick series of water-bearing strata is underlain by impervious shale or clay and is cut by a valley side, the contact is marked, as a rule, by a line of springs, or by a band of damp ground. Faults also often bring impervious shales in juxtaposition against water-bearing beds, and in this case the fault is often marked by a line of springs ranged along the outcrop of the fault at the surface. Many springs are seasonal and are dry in summer, due to the lowering of the water table during the dry season. In limestone and chalk districts much of the drainage is underground, but where the base of the limestone is cut, as in valleys in the Mendip Hills and the Yorkshire Dales, a small river may issue to the surface from the base of the limestone strata.

Small and often seasonal supplies of water may often be obtained from surface deposits of sand and gravel, and, in mining areas, old shafts and mine workings may provide large supplies of water.

The disposal of effluents into porous strata is sometimes resorted to by small works. The fluids are pumped into boreholes and wells, and, if the rock is porous, the liquids drain away into the porous beds. Such practices are extremely undesirable, as they may pollute neighbouring water supplies.

SURFACE STORAGE OF WATER

Much water is stored in reservoirs and tanks utilizing the run-off and surface streams. Often the water obtained from the run-off is supplemented by water obtained from wells and boreholes. These reservoirs may be natural lakes, such as some in the Lake District and North Wales, or be artificial lakes constructed by damming up suitable valleys. Suitably strong and watertight foundations must be found for the dam, and the sides of the valley must be of such impervious rock and structure that leakage will not take place. The construction of reservoirs and dams both for domestic water and hydro-electric schemes calls for much geological experience and consideration, and even small tanks and ponds may be better sited if cognizance is taken of the structure and geology of the foundations. As in the case of wells, large areas of the catchment ground of reservoirs may need taking over to ensure the purity of the water by removing all the farms and by preventing the grazing of animals. The amount of land rendered sterile in this way depends again mainly on geological considerations, such as the dip of the strata and the presence of fissures, and each case must be considered individually.

Sand beds may be used in the filtration of the water, and the construction and constitution of sand filters depend on the degree of purification desired. Sand used for filtration should be clean and free from silt or clay, and should have a high porosity. All the sand should pass a $\frac{3}{16}$ in. sieve, and the bulk of it pass $\frac{1}{16}$–$\frac{1}{44}$ in. sieve.

Where streams running into ponds are turbid and carry much sand and silt, it may be desirable to remove it, or the pond may be rapidly silted up and its capacity much reduced. The silt may be removed from the stream by the construction of a settling tank about ten feet square and several feet deep. When the stream enters the settling tank, the current is slowed down and the sediment is deposited in the tank which can be cleaned out periodically. The water leaving the tank for the reservoir or pond is then almost free from sand or silt.

The requirements of water for domestic use in towns is up to forty gallons per head of the population per day, whilst in villages supplied by stand pipes in the road, up to ten gallons per head per day may be estimated. The amount used varies considerably at different times of the day. In estimating the quantity likely to be used, allowance should be made for possible increases in the population. Interference with the flow of streams or the diversion of water from streams may require special powers.

CHAPTER XII

Materials Used in Paints and Pigments

THE paint industry is largely dependent on mineral substances for its raw materials. In many cases, however, these materials have important and vital uses in other industries. Lead and zinc are two cases in point. These are used mainly as metals in industry, but have also important uses as oxides and carbonates in the paint industry. Other minerals such as talc are used mainly in paint manufacture, but are used to a smaller extent in other industries. Substitutes and new materials are constantly being used, and some of these are not toxic and have other properties which make them preferable. Many minerals such as *barytes*, used in the manufacture of the pigment *lithopone*, require no other preparation than fine grinding, after which the powder is ready for use, but in many cases the mineral has to be chemically treated and its composition altered before use. Lead is found in nature mainly as the sulphide mineral *galena*, but, before using it in paint, it must be converted to the carbonate, or in some cases to the oxide. Even the lead paints are being replaced by non-poisonous substances such as lithopone and titanium compounds.

Fillers are also extensively used in the paint manufacturing industry. Fillers are used to fill up voids in the paint, and as a reinforcement and cheapening agent. They are inert substances which give no chemical reaction with the substances with which they are mixed. Fillers in paint are used as extenders and flatting agents. A substance used in paint manufacture should possess good colour and have permanence. It should retain its colour when mixed with inert bases, its absorption of oil should be low, and it should be plastic and smooth when mixed with water.

Paints with a Lead Basis. Basic lead carbonate forms the basis of the white lead paint which has been the standard paint for a long period. All lead paints, however, suffer from the fact that they are highly poisonous, and that the substance remains and is accumulated in the human body even if taken in very small amounts. This fact has led to the introduction of substitutes for lead paints, such as titanium oxides and white paints containing barytes, which are non-poisonous.

Both white lead and red lead are obtained from the naturally occurring ores of lead. The lead minerals are found mainly in veins. As stated in Chapter II, veins are more or less vertical fissures in which the minerals were deposited, chiefly as the sulphides. In some of the mines of Derbyshire, horizontal flats and vertical wings containing ore are present as offshoots from the main veins. In almost all cases, ores of zinc in varying amounts are present with the lead minerals. The lead ores always contain a greater or less proportion of silver in their molecular structure. The silver is extracted from the lead during the refining of the metal.

Galena (lead sulphide, PbS) is the most important and widely distributed ore of lead. It occurs at all depths in the mines, from the surface to the deepest levels, and is found as masses of crystals of cubical shape, as shapeless lumps, and as fine grains. The ore has a lead grey colour, and is very heavy, with a specific gravity of 6·5. When the mineral is rubbed on a piece of ground glass or a tile, it leaves a characteristic grey shining streak on the surface. The galena, as mined, is mixed with other and worthless minerals which are removed by gravity separation or other means during the treatment of the ore at the mine.

Lead also occurs in the mineral *cerussite*, the lead carbonate ($PbCO_3$). This is a white mineral often occurring as aggregates of needle-shaped crystals or massive. It is found only in the upper portions of lead veins, where it has been formed by the weathering and alteration of the original galena. In some mines, as at Broken Hill in New South Wales, Australia, cerussite is a very important ore in the upper workings of the mine.

The ores of lead are separated from the worthless minerals associated with them before leaving the mine. The clean ore is then sent to the works where the lead metal is extracted by smelting. Any silver in the ore is recovered from the lead by cupellation or other means.

The uses of lead are very varied. The bulk of the metal is used in the manufacture of the plates in accumulators. Much is used as pipes and sheet lead for building purposes. Other uses are in the making of lead tetra-ethyl to impart anti-knock properties to petrol, and as a component in various types of alloys and solders.

The manufacture of pigments such as white and red lead consumes quite a proportion of the output of metallic lead. White lead is basic lead carbonate ($2PbCO_3.Pb(OH)_2$). It is prepared artificially from metallic lead by the action of acetic acid forming lead acetate, which is then converted to the basic carbonate by means of carbon dioxide gas, obtained by the fermentation of tan bark and other substances. When pure, white lead paint is labelled as "genuine," and when adulterated it is labelled as "reduced." The usual adulterant is barytes.

White lead paint has great opacity and durability, and is widely used. It is usually bought as a paste containing 9–10 per cent linseed oil. It is, however, very toxic. Red lead is prepared by heating lead metal to make the yellow lead monoxide, and reheating this again to a lower temperature.

Ores of lead are found in almost all countries in greater or less amounts. During the four years 1934 to 1938 over 1 500 000 tons a year of metallic lead were produced, the United States being the largest producer, followed by Australia, Mexico, and Canada. In 1938 the production of lead within the Empire was 631 000 tons, of which Australia produced 222 583 tons, mostly from the Broken Hill Mines. Canada produced 178 912 tons in 1938. Burma is also a producer of lead of some importance. The United Kingdom has been a producer of lead ores since Roman times, but its output has declined due to a variety of causes. 9 800 tons of lead were obtained in 1938 from British ores. The chief British leadfields are in Derbyshire, where the Mill Close Mine in Darley Dale has been the chief producer of late years, and in North Wales, where Halkyn Mines have been important. Other important mines are situated in Weardale and the Lake District.

Zinc Compounds. Compounds of zinc are important as paints, and, together with barytes, form an important constituent of the non-toxic white paint lithopone.

The chief ore of zinc is *zinc blende* or *sphalerite.* This mineral occurs in cubic crystals, but is more often found massive. It is brown to black in colour and has a characteristic lustre on its surface. It gives a typical brown powder when it is crushed, and has a specific gravity of about 4. Zinc blende occurs in veins in exactly the same way as the lead ores. In fact, in almost all mines zinc ores are present with the lead ores, and the two are mined together and are separated by gravitational methods or by froth flotation in the subsequent treatment of the ore at the surface, after which they are sent separately to the smelters for the extraction of the metals.

As in the case of the lead ores, the zinc carbonate mineral, *calamine* or *smithsonite* ($ZnCO_3$) is an important ore in some mines where it is found in the upper levels and was formed by the oxidation of zinc blende by waters percolating into the veins. Calamine is a white or pale-coloured mineral, gives a white powder on crushing, and has a specific gravity of about 4. The mineral is found massive and as incrustations.

The zinc metal is recovered from the ores by heating in retorts at high temperatures. The zinc is volatile and distils off, and is condensed and collected. Metallic zinc is also produced electrically by extracting roasted zinc sulphide with sulphuric acid, and electrolyzing the solution between aluminium cathodes and lead anodes. Zinc of a high degree of purity is produced by this method. Zinc or *spelter* has a great variety of uses. It is used extensively in galvanizing iron sheets and pipes to prevent corrosion of the metal. It is a constituent of brass and other alloys, and is used in the chemical industry, and as a wood preservative in the form of the chloride.

Zinc oxide and zinc sulphides are used extensively as a basis of paint. Their covering power is somewhat inferior to lead paints, but they are less poisonous, and tend to retain their colour better than white lead. Their colour is not affected by sulphur fumes as in the case of white lead. Lithopone is a mixture of about 70 per cent of barium sulphate and 30 per cent of zinc sulphate, and is used extensively as a paint, especially for interior work. It is a substitute for white lead, is non-poisonous, and is not discoloured by sulphur vapours. The addition of small amounts of cobalt prevents the paint darkening in sunlight.

The annual production of zinc metal from 1934 to 1938 was about 1 660 000 tons of metal. The United States is the chief producer, followed by Australia and Canada. Great Britain was once a big producer of zinc in former times, but many of her lead-zinc mines are now abandoned. In 1938 about 11 480 tons of metallic zinc were produced from ores mined in Britain, chiefly from Cumberland, North Wales, and Derbyshire, but this output has since declined.

Barium Compounds. Barium compounds are extensively used in the manufacture of pigments, and as extenders in paints. There are only two barium minerals of any commercial importance—the sulphate, *barytes*, and the carbonate, *witherite*. Great Britain is an important producer of these minerals and is the only commercial source of witherite.

Barytes occurs in veins in a similar manner to lead and zinc ores. The mineral is white in colour, or may be slightly coloured. Its composition is barium sulphate ($BaSO_4$). It is fairly soft, has a pearly lustre, and a specific gravity of 4·5. Barytes is used to a large extent, when ground to a fine powder, as an extender in paints. It is also used when mixed with zinc compounds in the manufacture of lithopone, of which it forms about 70 per cent. *Blanc fixe* or precipitated barium sulphate, also known as *permanent white,* is manufactured from barytes and witherite, and is whiter than the natural mineral barytes. It is used as a pigment base and as a filler in enamel paints.

Witherite is the barium carbonate ($BaCO_3$) mineral, and the only deposits workable on a commercial scale are found at the Settlingstones Mine in Northumberland. Witherite is white and heavy and effervesces in acid, and may be used to prevent the scumming of bricks, but its greatest use is in the chemical industry, and for other purposes such as sugar-beet refining.

Barytes veins are worked in Scotland, Devonshire, Shropshire, Derbyshire, Northumberland, and Durham In 1938 over 13 900 tons of barytes were mined in Britain. Germany and the United States are big producers and exporters of barytes.

Titanium Compounds. Titanium and its ores have been known for a long period, but it is only in recent years that uses have been found for this mineral. Its principal use is in the paint industry, where it is to a large extent replacing lithopone, lead and zinc pigments, on account of its cheapness and other qualities.

There are many minerals which contain titanium, and they are found in many different types of rock, but the only two minerals of any commercial importance are *rutile* and *ilmenite.* Ilmenite (iron titanate, $FeTiO_3$) is an almost black, metallic looking mineral, which has a metallic lustre and usually occurs massive. Its specific gravity is 4·5–5. Rutile (titanium dioxide, TiO_2) is a reddish brown or black mineral, with a very bright lustre, and a specific gravity of 4·2. In spite of the black colour of the source minerals, the oxides obtained from them are white.

Titanium is used in the paint industry as the titanium oxide (TiO_2). This substance is a white pigment which possesses very great opacity. It has good covering powers, is inert and non-poisonous, and is largely used in the manufacture of enamel paints. Titanium oxide may be mixed with 75 per cent of barium sulphate or with about 70 per cent of calcium sulphate for use in paints.

Titanium minerals do not usually occur in veins as do lead and zinc ores, but are found disseminated in igneous rocks such as granites. Ilmenite is especially found in basic rocks, sometimes as ore bodies of large size which have crystallized out from the igneous rocks in which they are found.

The production of ilmenite is about 266 000 tons, and of rutile about 2 500 tons annually. Titanium minerals are mainly obtained from the state of Travancore in India, where the mineral is recovered from beach sands. The mineral has been liberated by weathering from igneous rocks, and the ilmenite concentrated in the sands by the jigging action of the waves. The Travancore sands in 1938 produced about 252 000 tons of high grade ilmenite. Ilmenite is also recovered from gravels in Malaya during the extraction of tin ores from river gravels, Titanium minerals are also worked in Canada, the United States, and Norway.

Talc. This is a peculiar mineral, sometimes called *steatite* or *soapstone*, which is a hydrous silicate of magnesia. Considerable quantities of impurities may be present in the mineral, which is also popularly known as French chalk. The substance has a characteristic soapy or greasy feel, and is so soft that it can be easily scratched with the finger nail. It is white to green in colour, has a pearly lustre, and a specific gravity of 2·8. It is usually found massive, but in some deposits is fibrous.

The paint industry is a large consumer of talc, utilizing about a quarter of the total production of this mineral. It is ground very fine before use. Talc is used as an extender in paint, and in distemper, especially the fibrous forms which help to bind the paint film together. The manufacture of "roofing papers" and felts also uses considerable quantities of talc.

Talc is found in rocks which have suffered changes and alterations due to the circulation of natural hot solutions. Magnesian Limestone, which has been attacked by solutions, may have its magnesium content changed to the mineral talc. Basic igneous rocks may also contain deposits of talc. Much of the world's supply of talc is produced in the United States, Manchuria, France, Italy, and Egypt. The chief Empire supplies come from India and Canada.

China Clay. Kaolinite or china clay is a hydrated aluminium silicate ($Al_2O_3.2SiO_2.2H_2O$) which is used in a great variety of industrial processes. It is a soft, white, clayey material with a greasy feel, and a smell of clay. Its specific gravity is 2·6. The mineral is used extensively in the paint industry as a substitute for talc and other substances, although the bulk of the clay production of Britain is used in the papermaking and other industries.

China clay is always, without exception, associated with granitic rocks. It is a product of the decomposition of the felspar crystals of these rocks by carbon dioxide and water vapours. The felspars only are affected by the decomposition, so that the resulting rock consists of china clay mixed with quartz, sand, and mica. The clay is dug from large and deep pits, and is washed out free from sand and mica. The clay settles in vats, and is then dried free from water ready for marketing.

Britain is a large exporter of high-grade china clay, which is obtained from the granite areas of Devon and Cornwall. Here it is dug from pits, in some cases over 300 ft deep. The British clay is of very high quality.

Diatomite. This substance is used as a light-weight filler in the paint industry. Its sources and properties are described in Chapter XIII.

Iron Ochres and Oxides. The iron oxides are usually brightly coloured in reds and yellows, and considerable quantities are mined and prepared for use in the manufacture of paints and as linoleum fillers. The iron oxide mineral *haematite* (Fe_2O_3), when ground to a very fine powder, gives a red colour such as Persian red, which contains 60–70 per cent of iron oxide, and Spanish red, containing 80–90 per cent of the oxide. Other red pigments are produced by grinding red ochre, the hydrated iron oxide limonite, and burning it to convert the powder to ferric oxide. The ochres are hydrated ferric oxides, giving yellow or brown shades. The pigment permanent yellow is of this type. Sienna and umber are silicates of iron and alumina with manganese, and are extensively used as pigment materials.

Minor Pigmenting Materials. Vermilion pigment is prepared from the mercuric sulphide mineral *Cinnabar* (HgS), which occurs in veins as a bright red mineral with a high specific gravity; it is found mainly in Spain and the United States. Cobalt blue is obtained from cobalt minerals, mainly sulphides, and their oxidation products, which are mined from veins in Northern Canada. The black, inert carbonaceous pigment, Biddeford Black, is mined from carboniferous rocks near Biddeford in Devonshire. The substance is obtained from a highly crushed anthracite coal seam. The comminution of the seam was a result of the intense earth-movement which this region has suffered.

Some water paints and washable distempers have a lime body, whilst the cementing material is casein. On exposure, the paint forms an insoluble calcium caseinate. The lime is obtained from limestone as described in a previous chapter.

CHAPTER XIII

Gypsum, Diatomite, and Vermiculite

GYPSUM is the mineral forming the basis of plaster of Paris. It also has a number of other applications in the building and paint industries. The mineral was formed as a precipitate in salt lakes which were drying up, and is intimately associated with beds of rock salt. In Britain it occurs chiefly in strata of Permian and Triassic age.

GYPSUM AND ANHYDRITE

Composition. The chemical composition of the mineral gypsum is hydrated calcium sulphate ($CaSO_4.2H_2O$). When found in the crystalline state it has the form shown in Fig. 50. Frequently, however, it does not occur as crystals, but is fibrous or in compact masses. The crystals readily split or cleave, giving thin, flexible, transparent plates. These thin plates have been used occasionally in olden times as window material. The crystals are colourless, grey, yellowish, or red in colour. The mineral has a glistening or silky appearance, and is so soft that it can be easily scratched with the finger nail. Its specific gravity is about 2·3. *Selenite* is the name often given to the crystalline varieties of gypsum, and *satin spar* to the fibrous varieties. *Alabaster* is the saccaroidal variety much prized for carving and for ornamental work and vases. This variety has been obtained from Chellaston in Derbyshire.

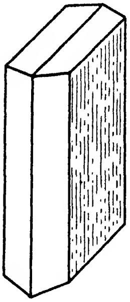

FIG. 50. A TYPICAL CRYSTAL OF GYPSUM

The crystals are fibrous and when grown together have an interlocking structure.

The mineral anhydrite resembles gypsum in chemical composition, except that it possesses no water of crystallization. Its composition is calcium sulphate ($CaSO_4$), and it may occur crystalline or in compact masses. It is harder than gypsum and is slightly heavier, with a specific gravity of 2·89–2·98. Gypsum can be converted to anhydrite by strongly heating, when the water of crystallization is given off and its composition becomes the same as that of anhydrite. Anhydrite and gypsum are formed in the same way, and are frequently associated with each other. Anhydrite cannot be used in the manufacture of plaster of Paris.

Origin of Gypsum and Anhydrite. Deposits of gypsum and anhydrite of commercial importance usually occur in the form of beds in sedimentary strata, and were laid down as saline residues precipitated during the drying up of salt lakes. It is for this reason that beds of gypsum are frequently associated with beds of rock salt.

Sea salt has the following composition—

Sodium chloride	77·758%
Magnesium chloride	10·875%
Magnesium sulphate	4·737%
Calcium sulphate	3·600%
Potassium sulphate	2·465%
Magnesium bromide	0·217%
Calcium carbonate	0·345%

Calcium sulphate is present in quantity in the water of most salt lakes such as the Dead Sea and Lake Utah, where this substance is at a high concentration. The salt is brought in solution by rivers, which obtain it from the decomposition of igneous rock minerals and from the cementing materials of the rocks from which they drain. If evaporation of water from the salt lake balances, or is in excess of, that brought in by rivers, there will be a gradual increase in the salinity of the lake until a stage is reached when the water becomes saturated with a particular salt. Any further supplies of this substance entering the lake in the river water will, therefore, be precipitated as a layer on the bottom of the lake or around the mouth of the incoming river.

Salt lakes contain many substances in solutions, but these are precipitated in a definite order, which is determined by the solubility of the salt and the presence of other substances in solution. Amongst the first salts to be deposited are iron oxides and calcium carbonate, followed by gypsum and anhydrite. Gypsum is precipitated at lower temperatures, whilst anhydrite is deposited at higher temperatures above 25° C. In many cases anhydrite has subsequently been altered to gypsum, and alternatively gypsum, by loss of its water of crystallization, has been converted into anhydrite. Beds of gypsum formed by precipitation in this way may attain thicknesses of several hundred feet. Rock salt begins to be precipitated subsequent to the formation of gypsum, but there is a zone of overlap when both gypsum and rock salt are formed together. The complete drying up of salt lakes may lead to the deposition of potash and magnesium salts, but in Britain this sequence is seldom complete, and potash and magnesium minerals are not mined here.

Gypsum may also be formed by the reaction of naturally formed sulphuric acid, obtained from the decomposition of minerals such as iron pyrite, on limestone or shells in clay beds. This process has formed the large crystals of selenite or gypsum common in the London clay and the Oxford clay beds. This, however, is not an important commercial source of this mineral. In areas where volcanoes are present, the sulphuretted waters given off may attack limestones and produce workable deposits of gypsum.

Uses of Gypsum. When gypsum is heated to a temperature of 110° C, the mineral loses more than half its water of crystallization, and becomes a white powder known as plaster of Paris. This powder, when mixed with water, will reabsorb some of its lost water and set to a hard mass of interlocking, needle-shaped crystals of gypsum. Calcium sulphate plasters differ in this way from the lime plasters. The lime plasters have no chemical set, and have little strength, except in the surface layer which absorbs carbon dioxide from the air. If gypsum is raised to a temperature much above 120° C, it loses *all* its water, becomes *over burnt,* and will not set when mixed with water alone.

The hemihydrous plasters or plaster of Paris set quickly unless retarded by the addition of glue-like retarders. The unretarded plaster sets in about five minutes, whilst the time of setting of the retarded plasters is regulated by the manufacturer, viz. for undercoats the initial set is in about two hours, and less for the finishing coats. Plaster of Paris gives a stronger finish than lime plasters, but has a more porous and less strong finish than the anhydrous plasters manufactured from anhydrite. If mixed with hemihydrous plasters, sand may contain up to 6 per cent loam with advantage. Sea sand should be avoided. Retarded hemihydrous plaster is also sold as "hardwall" plaster, and there are a great variety of patent plasters on the market, the composition and nature of which are not disclosed by the manufacturers.

In the manufacture of plaster of Paris the mineral gypsum, as mined, is broken up and heated in vats. At a temperature of 212° F, steam comes off the heated gypsum which now runs like water, but at 240° F, the mass loses its fluidity, and is taken out and bagged ready for the market. Great care must be taken to see that gypsum is not overheated, as if it is *deadburnt* it will not reabsorb water or become plastic. The presence of any anhydrite with the gypsum used in the process is very undesirable, as it represents so much deadburnt gypsum. Plaster of Paris expands slightly on setting, and for this reason is used in making moulds for the metal beating and similar industries, as its expansion causes it to take complicated shapes very well. Plaster work is light-weight and will take a good finish, and is extensively used in interior and exterior finishes. It is also used in the manufacture of wall boards and plaster plates.

Raw gypsum, when ground very fine and sifted, is used as mineral white (*terra alba*) in paints, and also as a filler. Up to 3 per cent of gypsum may also be added to Portland cement during the grinding process, with the object of retarding and controlling the time of setting. Plasters made of a mixture of gypsum and the mica-like mineral *vermiculite* are used for insulating and fireproof plasters, and have good acoustical properties. Gypsum is also used as a fertilizer, and for improving and making permanently hard (or *Burtonizing*) the water used in brewing. Gypsum is used as polishing beds in the manufacture of plate glass.

Over a million tons of gypsum a year have been produced since 1936 in Britain.

Uses of Anhydrite. Anhydrite, or deadburnt gypsum, is utilized in the manufacture of anhydrous plasters. Used alone, this plaster will not set, but accelerators such as alum, lime, and potassium sulphate are added, when the plaster sets in 2-8 hr, giving a dense, hard surface, free from either contraction or expansion. Anhydrous plasters are generally used for finishing coats, often over cement. The accelerators added to the plaster may render it acid and corrosive to iron and steel if it becomes damp.

Keene's cement was an anhydrous calcium sulphate plaster with alum added as an accelerator. The term Keene's cement has now but little meaning, however, as the type varies with the manufacturer, both in setting time and the nature of the accelerator. Most Keene's cements are acid, but neutral and alkaline types are obtainable.

Parian cement is made in a similar way, but borax may be used instead of alum. The term now has but little meaning as there are so many types on the market.

The mineral anhydrite is also used extensively in the chemical industry, being treated with ammonia to make ammonium sulphate used as a fertilizer. Much is used to make sulphur dioxide gas, used in the manufacture of sulphuric acid.

The Distribution of Gypsum Deposits. The world's annual output of gypsum exceeds 10 000 000 tons and many countries possess workable deposits. The Empire production in 1938 was about 2 500 000 tons. Canada produced over 1 000 000 tons mainly from Nova Scotia, much of which is exported. Extensive deposits of gypsum are quarried near Montmartre, north of Paris.

The bulk of the British gypsum and anhydrite production is obtained from strata of Permian and Triassic age. Most of the

Triassic rocks were deposited under desert conditions, but in Upper Triassic times large salt lakes existed in Cheshire, Cumberland, and other places. In these lakes, beds of gypsum were formed varying in thickness from a few inches to many feet. Gypsum deposits of Triassic age are mined near Whitehaven, and Nottingham, and in Derbyshire and Leicestershire.

The Permian strata were formed under similar conditions to the Trias. Lagoons and seas of the Caspian Sea type existed in Eastern England, but the climate became drier, and beds of gypsum and anhydrite were precipitated at the bottom of the lagoons. Gypsum deposits of Permian age are mined near Penrith and at places from Nottingham to Durham. Deposits of anhydrite are mined at Billingham to supply the chemical plant erected in the vicinity.

Gypsum beds also are found in Jurassic strata of Portlandian age, and have been mined at Battle in Sussex. These beds were also deposited during the drying up of large lakes.

In some cases, gypsum forms the cementing material of sandstones, as in the red Permian sandstones of the West of England and the Midlands. Gypsum is slightly soluble in natural waters, 1 part of gypsum dissolving in 372 parts of water at a temperature of 26° C. Water drawn from sandstones with a gypseous cement will, therefore, contain traces of calcium sulphate and be permanently hard. Such water cannot be softened by ordinary processes, and if used in boilers may form scaly deposits of gypsum.

DIATOMITE

This mineral is also known as *Kieselguhr*, *tripolite*, *celite*, *infusorial earth*, and *fossil flour*, and under a number of different trade names. It consists of hydrated silica, and is made up of countless myriads of the shells of microscopically small plants such as diatoms. A cubic inch of this material may contain over fifty million of these shells. The material is white in colour, and chalky in appearance, and has a density of 7–20 lb/ft^3. The lump material containing impurities as quarried may weigh up to 60 lb/ft^3. The true specific gravity of diatomite is about 2·1–2·2, and its fusion point is 1 710° C. It possesses excellent absorptive properties, and is capable of absorbing over three times its weight of water.

Diatomite is an organic deposit occurring in beds up to several hundred feet thick. They were formed in ancient seas, or as deposits adjacent to lakes. Diatoms also flourish at the present day in swamps and at the bottoms of lakes, and beds of diatomite are now forming in this way in some localities. The chief deposits of commercial importance are of Tertiary age, and in California, beds of diatomite are over 1 000 ft in thickness.

Diatomite is used extensively in light-weight bricks, and also as a powder for insulating furnaces and boilers, and for covering steam pipes. It is used as a light-weight filler in paints and varnishes, and also, mixed with cement, in certain types of concrete, and as an insulator in sound-proofing rooms. Impure varieties containing clay are moulded and calcined, and used as light-weight insulating bricks; in addition, the material is used very extensively as a filtering agent, and as a mild abrasive.

In 1938, the world's production of diatomite exceeded 250 000 tons of which the United States produced over 100 000 tons, and Denmark 90 000. Other important sources are in Algeria, Japan, and Russia. Deposits of diatomite have been worked in Westmorland, which produced 2 150 tons in 1938, and other beds occur in Northern Ireland, which produced 5 280 tons in 1938. Diatomite is also obtained from other parts of the Empire.

VERMICULITE

This mineral is a peculiar variety of chlorite (hydrated silicate of aluminium, iron, and magnesium), which closely resembles the dark variety of mica known as biotite. It occurs in tabular, radiating, and granular forms, and in shears in basic, igneous rocks, where granitic rocks occur in the vicinity.

The characteristic feature of vermiculite, and one which makes it commercially valuable, is that when heated it loses water and swells to over ten times its original volume, and weighs less than 10 lb/ft^3. The mineral is soft and dark brown in colour, but on heating expands and assumes a pale yellow tint. The value of the mineral varies with its degree of exfoliation.

Over half the total consumption of vermiculite is used for insulating the walls of buildings as a heat and sound-proofing material. Its use depends to a large degree on the permanence, incombustibility and lightness of the mineral, and the fact that it is vermin and fungus proof. Vermiculite is used as a loose filling for the heat insulation of houses. It is poured as a loose powder into the wall cavity with little or no tamping; about 3 in. thick of vermiculite gives the thermal insulation of a 9 in. brick wall. The mineral is also used as a loose filling for sound-proofing cinema projection rooms, and engine test sheds. When mixed with Portland cement, vermiculite forms a light-weight, fireproof concrete for fireproof partitions and for use in steel framed buildings. Plasters made from gypsum and vermiculite are also used for sound- and fire-proofing purposes, whilst the mineral may also be used as a filler in paint, and instead of graphite as an oil-less lubricant.

The mineral is crushed and dressed at the mine before heating and exfoliation. The weight of the material before exfoliation is about 80 lb/ft^3, whilst after exfoliation it only weighs 6·8 to 8·1 lb/ft^3. The mineral is chiefly obtained from the United States, whilst a production of several hundred tons is obtained from Australia.

CHAPTER XIV

Asbestos

From a commercial point of view, the term "asbestos" includes a variety of different minerals, all of which may be easily separated into thin fibres which can be spun or woven into fabrics which are resistant to heat. Most varieties are also resistant to acids and sea water. The first serious attempt to utilize asbestos was by a London company which attempted to develop asbestos deposits in the Italian Alps in 1865, but the extensive use of asbestos began only in the present century.

Properties of Asbestos Minerals. Asbestos is infusible and incombustible. It has a low heat conductivity and can be used for heat insulation, and is used in the lagging of steam pipes. The minerals have a high electrical resistance, and do not decay, and most varieties are inert to chemical action. The fibres are flexible, and of considerable length, and usually have a silky lustre.

The Asbestos Minerals. Commercial asbestos includes the following minerals, all of which break easily into fibres.

Chrysotile. The great bulk of commercial asbestos (about 90 per cent of the world's production) consists of the fibrous variety of serpentine known as chrysotile (hydrated magnesium silicate, $3MgO.2SiO_2.2H_2O$). Serpentine is a rock formed by the alteration of rocks rich in magnesium, i.e. those containing the minerals olivine, augite, and hornblende. The chrysotile occurs as veins ramifying in all directions through the serpentine rock. The specific gravity of the mineral is 2·5–2·6. The fibres may be up to ½ in. long and are extremely fine, and have a high tensile strength. Chrysotile is attacked by weak acids and sea water, but the strength and flexibility of the fibres make chrysotile the most valuable form of asbestos.

Actinolite. This mineral is asbestos in the strict geological sense. It is a calcium-magnesium-iron silicate ($CaO.3\ (Mg.Fe)O.4SiO_2$), and is dark green in colour, with a specific gravity of 2·9–3·2. It is usually found as fibrous aggregates, the fibres having a vitreous sheen. Actinolite is mined only in metamorphic rocks, especially those of the basic and ultrabasic types, such as actinolite schists. It is not extensively used, and is mixed with other varieties of asbestos.

Anthophyllite. This is a magnesium-iron-silicate ($(Mg.Fe)O\ SiO_2$).

It has a specific gravity of 3–3·2, and is coloured in shades of brown. Its usual method of occurrence is as aggregates or radiating aggregates of fibres. Anthophyllite is used mainly in cements and plasters, and in paint and as an insulating material.

Amosite is a variety of anthophyllite, occurring in unusually long fibres up to 8 in. in length. The fibres are harsh and do not spin satisfactorily, so that this type of asbestos is used mainly for insulation purposes. This variety is obtained only from the Transvaal in South Africa.

Crocidolite or *Cape Blue Asbestos* is blue in colour, and is a silicate of iron and sodium ($2NaFe\ (SiO_3)\ FeSiO_3$). It is resistant to acid and sea water, and is largely used in marine insulation. The mineral is fibrous in structure, and is mostly obtained from Cape Province and the Transvaal in the Union of South Africa. The fibres of crocidolite are about 1 in. long, and are not so easily spun as chrysotile, but they are stronger. Sometimes crocidolite is hardened by silicification when the mineral has a limited use as an ornamental stone.

Tremolite or *Italian Asbestos* is white in colour, and its fibres may occasionally be of great length, but they are brittle, and have a low tensile strength. The mineral is mainly used in wall insulation, boiler insulation, and in acid filtering processes. It is found in metamorphic rocks such as schists, where the fibres are set along the foliation planes of the schist. Actinolite is a calcium-magnesium-iron silicate $CaO.3(Mg.Fe)O.4SiO_2$, and has a specific gravity of about 2·9.

Origin of Asbestos. With the exception of chrysotile, the asbestos minerals are all of metamorphic origin, being found in tremolite and actinolite schists. Chrysotile, however, is restricted to districts where serpentine rocks are present. Over 90 per cent of the world's supply of asbestos minerals is obtained from serpentine, and the bulk of it comes from the eastern townships of Quebec in Canada. In this area asbestos occurs in serpentines as narrow veins, ramifying in all directions through the rock. The veins are up to 6 in. wide, and the fibres grow inwards at right angles to the walls of the veins (Fig. 51).

Down the centre of the asbestos veins may be a line of small crystals of magnetite or chromite. The origin of chrysotile is somewhat controversial. It may have been formed by gases and solutions, emanating from igneous rocks such as granite, circulating through cracks in the serpentine, and altering the walls to chrysotile. Other authorities believe that the chrysotile was formed by waters circulating within the serpentine before it was completely solidified.

In Canada the asbestos occurs in an area of basic rocks, probably of Devonian age, up to a mile in width. These basic rocks have been altered to serpentine, especially where granite dykes are prominent. The veins are restricted to the areas of serpentine. The reserves of asbestos in this area are almost inexhaustible.

Chrysotile is also mined extensively in Southern Rhodesia, where it is again associated with serpentine rocks. The mineral occurs in short, roughly parallel discontinuous veins. The fibres are pale green, silky, and $\frac{1}{2}$–$\frac{3}{4}$ in. long. Granite rocks occur in the vicinity of the ore body as in Canada.

Because of the peculiar nature of asbestos minerals, special methods for the extraction of the fibres have to be used. Explosives have to be used sparingly, and special care must be given to the crushing of the ore prior to the working up of the fibres.

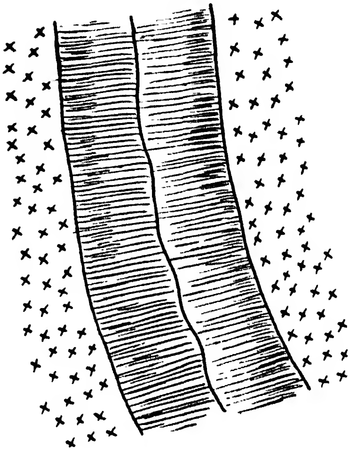

FIG. 51. VEIN OF ASBESTOS IN SERPENTINE

The fibres grow inwards from the walls of the vein.

Uses of Asbestos. The properties of asbestos are unique, and there is at present no substitute for the mineral. Its fibrous nature enables it to be spun and woven into fireproof cloth and clothing, especially the chrysotile varieties of asbestos. The infusability of all varieties of asbestos finds a use in the manufacture of fireproof paints, as asbestos paper and corrugated sheets. Much asbestos is used in the making of roofing cements, roofing tiles, pipes and slabs, where the asbestos is mixed with cement and cast into the shape required. The constituents of asbestos cement are Portland cement and asbestos in the form known as *mineral flax.* These two materials are passed through rolling-mills as layers of cement and asbestos. The layers are interlaced to give a non-laminated fabric. Asbestos cement sheets can be obtained in many finishes. Asbestos is also used in brake linings and cylinder packings. The mineral has a low electrical conductivity and this enables it to be used as insulating material in cables, wire, and switchboards. Some varieties, such as crocidolite, are chemically resistant to acids, and are, therefore, suitable in the filtering of acids. Much asbestos is also used for the insulation of boilers and steam pipes, and as sound insulating material. Micro-asbestos is very fine asbestos dust which passes through a 200 mesh sieve. It is used as a filler in paints and in asphalt.

The inhalation of asbestos dust can be very dangerous to health if breathed in any quantity. The dust produces a type of fibrosis in the lungs, and, unless protective measures are taken, it may attack workers engaged in sawing and grinding manufactured articles containing asbestos (except those in which bitumen is used as a bonding agent) and others subjected to asbestos dust. The effect upon the workers closely resembles the silicosis of the lungs, which may be set up by breathing silica dust during the quarrying and dressing of sandstones.

Production of Asbestos. The British Empire is by far the world's largest producer of asbestos, mostly from the colonies and dominions. About half the world's production is obtained from Canada, which in 1939, exported over 160 000 tons in addition to manufactured asbestos products. Southern Rhodesia is a big producer, especially from the Victoria and the Belingwe districts. The production in 1939 was over 52 000 tons. The Union of South Africa has important deposits of chrysotile, crocidolite, and amosite asbestos. Amosite with fibres up to 7 in. long occurs in Lydenburg and Pietersburg, which produced over 10 000 tons in 1939.

Chrysotile is worked in the Troödis Range in Cyprus, and Italy has a small production. Soviet Russia also has a large production of chrysotile from the Bazhenov area of the central Urals.

CHAPTER XV

Bitumens and Bituminous Products

THE various types of bitumen are of increasing importance as raw materials in building and road construction. Bitumen is much used as a water and weather resistant binder, and as flooring material on account of its damp-resisting properties and the fact that it is practically non-absorbent, frost-proof, sanitary, and vermin-proof. Bitumen is also used in the manufacture of wall boards, roofings, wrapping papers, paints, varnishes, and enamels, and in electric cable fillings as an insulator, also as a binder in road coverings. Coloured asphalts are now available.

The manufacture of roofing material uses over 30 per cent of the production of asphalt. Bituminous felts consist of a close-textured felt made from a mixture of animal and vegetable fibres. The whole is impregnated with heated asphaltic bitumen. The sanded felts are similar but have the surface covered with clean, washed sand, whilst the asphalt is still hot. The self-finished felts are surfaced with talc or mica. Various asphaltic substances are used as damp-courses, and some, such as the "ledcore" type of damp-course, have a thin sheet of lead between layers of asphalt. In 1938 over 78 733 tons of asphalt were imported into the United Kingdom, the chief source being the natural asphalt from Trinidad, which, in 1938, produced over 127 800 tons, chiefly from the pitch lake occurring in that island. Bitumen is also produced from the Bermudez pitch lake in Venezuela. Rock asphalt, or sands and limestones impregnated with bitumen, are obtained from Val de Travers in Switzerland, Seyssel in France, Mons in Belgium, Asi and San Valentine in Italy, from Sicily, and Texas and Kentucky in the United States. Veins and massive deposits of natural bitumen are also mined in Syria, Egypt, California, Utah and elsewhere. The distillation of petroleum and coal also produces large quantities of bitumen. During the refining and cracking of natural petroleums, solid bitumens are one of the by-products, and over 80 per cent of the world's supply of bitumen is obtained from this source. Pitch is also obtained from the distillation of coal during gas and coke manufacture.

The *natural bitumens* are residues from the drying out or inspissation of petroleums. Where oil-bearing rocks outcrop at the surface, the lighter fractions of the petroleum dry off, leaving the solid residues. Where the oil is paraffinic in type, waxes such as *ozokerite* are deposited, but if the petroleum is asphaltic, solid bitumens such as *manjak* are formed. Occasionally the bitumen is deposited in hollows forming pitch lakes, such as that in Trinidad, or it may seep into fissures, faults and joints, and form veins of bitumen, such as the gilsonite veins of Utah. In some areas, such as at Val de Travers in Switzerland, the bitumen has impregnated sandstones and limestones forming *tar sands* and *bituminous limestones*. Natural asphalt is often too hard for direct use, and must be softened by mixing with petroleum residues.

THE NATURAL BITUMENS

Bitumen is a mixture of natural hydrocarbons and their derivatives which are soluble in carbon disulphide. The bitumens are usually classed into *asphalts*, which are bitumens containing a certain amount of mineral matter, and *asphaltites*, which consist mainly of bitumen. These substances are black or brown in colour, and of a pitch-like consistency, although some types may be very soft. They melt readily when heated. The terms pitch, asphalt, asphaltum, and bitumen have been used indiscriminately, and some confusion in the nomenclature still exists.

ASPHALTITES

This is a group of naturally occurring bitumens which are of dark colour, are comparatively hard, and composed of hydrocarbons substantially free from oxygenated bodies and crystalline paraffins. This group includes gilsonite, glance pitch, and grahamite. *Gilsonite* is an asphaltite which is characterized by its bright lustre, black colour, curved fracture, and its red-brown colour when finely powdered. Its specific gravity is 1·01–1·10, and its melting point 250° F–350° F. *Glance pitch* is harder than gilsonite; its powder has a black colour, and its specific gravity is 1·10–1·15. *Grahamite* is black, has a specific gravity of 1·15–1·20, and is hard and infusible.

Gilsonite is practically restricted to a belt about 65 miles long, extending from Colorado to Utah, and occurs in veins from a few miles to 40 miles long, enclosed in limestone and shale. The veins are vertical and may be several feet wide. The gilsonite is obtained by simple mining methods, and very little machinery is used. In some veins the bitumen is mined to depths of over 700 ft from the surface. The gilsonite is screened, and put into bags ready for transport.

Other solid bitumens are grouped as *asphaltic pyrobitumens*, and include *albertite*, which is a hard, black solid, with a very bright lustre. It has a curved fracture, and a specific gravity of 1·07–1·10, Albertite occurs filling fissures, and is mined in New Brunswick in Canada. *Elaterite* is a bitumen closely resembling old rubber; it is flexible, brownish in colour, and has a specific gravity of 0·9–1·05.

ASPHALTS

The asphalts are brown to black in colour, and have a specific gravity of 0·95–1·07. They include manjak and the material from pitch lakes.

The Trinidad Asphalt Lake. All the asphalt lakes are closely and genetically associated with petroleum deposits. When the petroleum has an asphaltic base its inspissation, or drying out, leads to the deposition of asphalt or manjak. If the oilsands reach and outcrop at the surface, the oil will ooze out and dry up, and deposits of asphalt of greater or less extent will be formed.

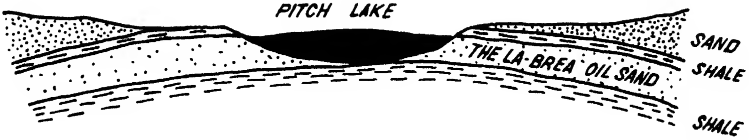

FIG. 52. DIAGRAMMATIC SECTION SHOWING THE RELATIONSHIP OF A PITCH LAKE TO THE CREST OF A FOLDED OILSAND

The pitch lake of Trinidad is on the crest of a plateau 137 ft above sea level, and covers an area of about a hundred acres. Oil springs and wells occur in the vicinity. The source of the pitch is the La Brea Oilsand, which is here folded into the form of a gently dipping anticline. The oilsand is covered with a thin bed of clay, and wherever this is at the surface, asphalt is exuded. The pitch lake is on the crest of the anticline, and is 6 in. higher in the centre than at the edges (Fig. 52). The pitch is harder near the edges and softer in the centre, where renewal of the asphalt still takes place. A little hydrogen sulphide gas is given off. The asphalt deposit is at least 135 ft deep in the centre.

As obtained from the lake, the asphalt contains much mineral matter, water, gas, and organic matter other than bitumen. Richardson gives the average composition as follows—

Water and gas	29%
Organic matter other than bitumen	7%
Mineral matter	25%
Bitumen	39%

The mineral matter present in the bitumen consists of fine sand and clay, and is mainly silica and alumina. The organic matter, which is not bitumen, is mainly material absorbed by the clay.

The Origin of the Lake. The La Brea Oilsand forms an anticline running in an east to west direction. The denudation of the crest caused the sand to outcrop with the consequent exudation of oil. Bituminous material destroys the cohesion of sandy strata, and the cavity would be gradually enlarged to the present size of the pitch lake. The drying out of the oil would lead to the formation of asphalt filling in the hollow already formed. At times the lake overflowed with bitumen, as deposits of asphalt are found filling gullies in the vicinity of the lake. The process of asphalt formation is still going on in the lake as the centre portion is still being renewed. The pitch lakes in other parts of the world were formed in a similar manner. The Bermudez lake in Venezuela is of larger size than the Trinidad lake, and the asphalt is softer and purer and more difficult to work. This asphalt may contain less than 4 per cent of mineral matter.

The Preparation of Lake Asphalt. The asphalt obtained from pitch lakes is not fit for immediate use, but must first be treated and refined. The raw material is put into refining tanks which are heated by steam coils. The leaves and twigs float to the top of the melted asphalt, and are skimmed off. The clean asphalt from the refining tanks is passed to the mixing tanks, which are also heated by steam coils. Here flux oils and other materials are added, giving a softer and refined asphalt. The material from the mixing tank is combined with a mineral aggregate, and is then ready for use and export.

Manjak Veins. Manjak is found where impervious strata overlie a source of asphaltic oil, and where conditions are such that the intrusion of the bitumen into cracks and fissures can take place. Manjak veins are usually steeply inclined. and may reach up to 30 ft in thickness. The veins do not always outcrop at the surface, and the contents may become harder towards the surface. The asphalt has been intruded into its present position in the liquid state, and always contains a little water and inorganic impurities, together with a little volatile matter. The veins are usually worked by opencast methods. In the Barbados Islands, manjak veins often end in tar sands.

OZOKERITE

In addition to the solid bitumens as described above, there are a series of natural waxes known as *ozokerite.* They are yellow to white in colour, and have a specific gravity of 0·85–1·0. The material resembles beeswax and is fairly soft. It is obtained in Galicia and the United States. It is not used in building or road surfacing, but is refined and used in the manufacture of candles and similar articles.

BITUMINOUS SANDS AND LIMESTONES (ROCK ASPHALT)

These are sands and limestones impregnated with asphalt. Rock asphalt is a naturally occurring consolidated calcareous rock, impregnated with bitumen exclusively by a natural process. The bitumen is finely disseminated, and is a cementing medium, fulfilling a similar role to an infiltrating mineral solution. The relationship of the bitumen to the rock which it impregnates can best be studied with the aid of carefully prepared microscopic slides of the rock (Fig. 53). In sandstones, the bituminous material acts as a cementing medium, filling the voids and pushing its way along the bedding and lamination planes. In limestones, the bitumen may enter and fill the empty chambers of shells, or be confined to cracks and voids in the rock. In some limestones, seams of almost pure bitumen may alternate with non-impregnated rock, giving a banded structure. Marls and such-like rocks may exhibit a patterning effect on the bituminous material.

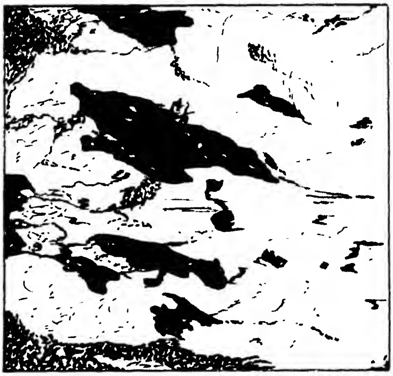

FIG. 53. THE APPEARANCE UNDER THE MICROSCOPE OF A LIMESTONE IMPREGNATED WITH BITUMEN (BLACK)

Apshalt Mastics. Mastic asphalt is widely used as damp-coursings, water-proofings, and roofs. It is a mechanical mixture of a rock aggregate and an asphalt cement in proportions which will give a product which, when heated, can be worked into the desired position, where it sets into an impervious, non-porous compact mass.

Natural asphalt mastic is a bituminous limestone ground to a powder. The material is then put into cauldrons, and heated with mineral tar, and continuously agitated for several hours until it is reduced to a mastic, when it is run into circular moulds. Some grit may be added during the process. The solid mastic blocks are taken to the site where they are to be used, reheated, and applied at once. Artificial asphalts are made from mixtures of coal-tar, chalk, sand, or ground slag. They are usually considered inferior to the natural asphalts because the adhesion between the bitumen and the added mineral matter may not be so complete. These synthetic mastics are made from crushed British limestone and bitumen intimately mixed together. The asphalt used for mixing with limestone may be obtained from the refining of petroleum or other sources. The crushed limestone is mainly obtained from the Carboniferous formation.

The natural asphalts can be distinguished from the artificial mixtures by a study of the non-bituminous residues left after the bituminous material has been dissolved out. Most limestones have a characteristic non-calcareous residue, and a study of this enables an investigator to trace the source of the limestone which has been used. By this means, natural asphalt mastics can be distinguished from those in which Carboniferous limestone has been used. This enables a check to be kept where natural asphalts have been specified.

The British Standards Specification (B.S. 986: 1941) of mastic asphalt is a limestone aggregate incorporated with asphaltic bitumen. or equal proportions of asphaltic bitumen and refined lake asphalt. It should have 11·5–14·5 per cent of soluble bitumen; of the aggregate 50 per cent should pass a 200 mesh sieve, and not more than 20 per cent pass an 8 mesh sieve, and be retained on a 36 mesh sieve. If grit is incorporated, it should not exceed 20 per cent by weight of the total mastic asphalt. When used for flooring, the coarse aggregate should be added during remelting the mastic on the site.

If ordinary paints are used, they may substantially damage asphalts.

GLOSSARY

Absorption. The percentage by weight of the water absorbed by a rock under certain standard conditions.

Actinolite. A green fibrous mineral which can be used as a form of asbestos. It is a calcium-magnesium-iron silicate.

Adamellite. A coarse-grained, plutonic rock consisting of quartz, orthoclase and plagioclase felspars, and biotite.

Alabaster. A form of gypsum (hydrated calcium sulphate) used for carving into bowls and ornaments.

Albertite. A bituminous substance occurring in veins in Canada. It is fairly hard, has a vitreous lustre, and a specific gravity of 1·07–1·10.

Alluvium. Sandy and gravelly deposits formed by rivers.

Ammonites. Coiled shells found as fossils only in strata of Mesozoic age.

Amosite. A variety of anthophyllite occurring in long fibres and used as asbestos, and mainly for insulation purposes.

Andalusite. An aluminium silicate mineral restricted to shaly rocks which have been metamorphosed by the heat of igneous intrusions.

Andesite. A volcanic rock of intermediate silica content, consisting of plagioclase felspar with hornblende or biotite. Some augite may be present.

Anhydrite. A white coloured mineral consisting of calcium sulphate. Used in manufacture of anhydrous plasters.

Anthophyllite. A fibrous mineral sometimes used as asbestos. Coloured in shades of brown. A magnesian-iron-silicate.

Anticline. The name given to a structure in which the strata are folded into the form of an arch.

Artesian Well. A well from which the water overflows without pumping.

Asbestos. The name given to a number of minerals which have a fibrous structure and can be spun and woven.

Asphalt. A mixture of different hydrocarbons occurring as a black or brown pitch-like substance. Formed from the drying out and oxidation of petroleums. Contains some mineral matter.

Asphaltite. Pitch-like substances which consist mainly of bitumen.

AUGITE. A black-coloured mineral characteristic of basic rocks such as gabbro and dolerite. It is a silicate of calcium, magnesium, aluminium, and iron, and occurs in eight-sided crystals.

BACTERIA. Unicellular plants of microscopic size. Often called "germs."

BARYTES. A white mineral consisting of barium sulphate. It is very heavy, and is used in the paint industry.

BASALT. A fine-grained volcanic rock, black in colour, consisting of augite and plagioclase felspar. Olivine may be present.

BATHOLITH. The name given to the occurrence of plutonic rocks in enormous masses. Batholiths have steep dipping sides, and may outcrop over hundreds of square miles.

BEDDING PLANE. The plane of separation between a stratum and the overlying or underlying strata.

BEIDELLITE. A mineral occurring in minute crystals in clays. It is formed by the decomposition of other minerals and consists of hydrated aluminium silicate.

BIOTITE. A dark mica, characteristic of granites and other acid rocks.

BITUMEN. Hydrocarbon substances. Includes asphalt and ozokerite.

BOULDER CLAY. A surface deposit formed from the material carried in the ice sheets which once covered Britain. Consists of a stiff clay containing boulders of all sizes and types.

BRECCIA. A rock consisting of angular fragments cemented together.

CALAMINE. A white mineral consisting of zinc carbonate. Used in the paint industry.

CALCITE. A white or coloured mineral consisting of calcium carbonate. Occurs in mineral veins, in limestones, and as a cementing material in calcareous sandstones.

CAPILLARY FRINGE. The thickness of damp ground immediately overlying the water table.

CEMENT. A substance prepared by heating material such as clay or shale with limestone or chalk, and fine grinding the product. The name is also applied to the material in a sandstone, which causes the grains to adhere to each other.

CERUSSITE. A white-coloured lead ore composed of lead carbonate. Found in the upper part of lead-zinc veins.

CHALK. A calcareous rock. White in colour and usually fairly soft and of high purity. Found only in the upper part of the Cretaceous System. Extensively used in cement manufacture.

Chert. A grey to black form of silica occurring in bands and nodules in limestone. Resembles flint.

Chiastolite. A variety of andalusite found in shales which have been slightly metamorphosed by the heat of igneous intrusions. Occurs in long, needle-shaped crystals.

China Clay or Kaolin. A white clay substance consisting of hydrated aluminium silicate. Formed as a result of the decomposition of felspars of granites.

Chips. Small stones $\frac{3}{4}$ in. downwards in diameter, used in top-dressing roads and for small aggregate in concrete.

Chlorite. A hydrated silicate of aluminium, iron, and magnesium. It is a soft, green mineral formed from the decomposition of biotite, hornblende, etc.

Chlorophoeite. A green mineral sometimes occurring in dolerites. On oxidation it expands considerably in volume.

Chrysotile. The most important asbestiform mineral. Is a fibrous form of serpentine.

Cinnabar. A heavy, red mineral, consisting of mercuric sulphide, used as a pigment, and as a source of mercury.

Clay. A soft, plastic rock, with a very fine-grained structure, containing much water. On strongly heating it loses its plastic characteristics.

Cleavage. In slates, is the direction in which the rock cleaves or breaks into thin slabs. In minerals, is a well-defined direction along which a crystal easily breaks.

Conglomerate. A rock consisting of rounded pebbles cemented together.

Crocidolite. A variety of commercial asbestos, blue in colour, consisting of sodium iron silicate.

Crushing Strength. The weight a rock will bear at the moment of crushing. Usually expressed in tons per square foot or pounds per square inch.

Crystal. Most minerals take up a definite shape, which is characteristic and diagnostic of the substance. The shape of the crystal is due to a regular arrangement of the atoms of the substance in a lattice work.

Density. The weight in pounds per cubic foot of a stone.

Diatomite. A white, absorbent rock, consisting of the loose siliceous shells of microscopic plants called diatoms. Used as an absorbent and as a filler in paints.

Diorite. A coarse-grained plutonic rock consisting of plagioclase felspar and hornblende or augite.

Dip. The angle of greatest slope that a stratum makes with the horizontal.

Dolerite. A hypabyssal rock, greenish in colour, consisting of augite and plagioclase felspar. The felspar crystals are lath shaped.

Dolomite. A limestone consisting of calcium magnesium carbonate. Heavier than normal limestone.

Dyke. An intrusive igneous rock in the form of vertical sheets.

Elaterite. A soft, elastic, brownish bitumen resembling rubber.

Elutriator. A piece of apparatus used for separating sands into their separate grain sizes.

Esker. A long, sinuous mound of sand formed by steams issuing from the front of an ice sheet.

False Bedding. Structural planes formed at an angle to the bedding planes of shallow water strata. They are due to current action.

Fault. A fissure along which the strata on one side have moved relative to the strata on the other side.

Felspar. A group of minerals consisting of alumino-silicates of soda, potash, and lime. Characteristic of igneous rocks.

Fireclay. A hard, grey or black, fine-grained clay, occurring below coal seams. If sufficiently refractory is used for firebricks, tiles, etc.

Flagstone. A laminated sandstone which splits easily into slabs of even thickness.

Flint. Nodules composed of silica found in chalk.

Flood Plain. Level ground bordering rivers at a variable height above present river level. They are covered with alluvium.

Flow Structure. A structure present in igneous rocks due to the magma moving slightly whilst the rock as a whole is still viscous. Shows as a banding.

Fold. The name given to strata which have been tilted into a definite structure.

Fossil. The remains of plants and animals found in sedimentary rocks.

Freestone. A rock which will break with comparative ease in any direction.

Gabbro. A dark-coloured coarse-grained plutonic rock consisting of plagioclase felspar and augite. Olivine may be present.

Galena. The chief ore of lead. A lead-coloured mineral consisting of lead sulphide.

Gathering Ground. An area of the surface on which the rainfall seeps into the ground to feed wells sunk into a particular stratum.

Gilsonite. An asphaltite, black in colour, with red and brown streaks. Specific gravity of 1·01–1·10. Occurs in veins in Utah.

Glass. An igneous rock which has cooled from the molten state without crystallizing.

Gneiss. A coarse-grained, metamorphic rock, in which the light and dark minerals are arranged in roughly parallel bands.

Grahamite. An asphaltite which is hard and infusible, with a specific gravity of 1·15–1·20.

Grain. A direction in granite rocks along which the rock will break. The direction is at right angles to that of the rift.

Granite. A coarse-grained, plutonic rock with abundant quartz, felspar, and mica. Light in colour.

Granodiorite. A coarse-grained, plutonic rock with abundant quartz. Distinguished by the presence of plagioclase felspar.

Gravel. An accumulation of loose, rounded pebbles.

Grit. A coarse-grained sandstone.

Ground Water. Water found underground in rocks.

Gypsum. Hydrated calcium sulphate. A white mineral occurring in beds in Triassic, Permian, and other strata. Used in manufacture of plasters.

Haematite. An iron oxide. Used as an iron ore, and as a red pigment.

Hornblende. A black-coloured mineral characteristic of the intermediate igneous rocks. Is distinguished from augite by its lozenge-shaped cross-section. Is an alumino silicate of iron, magnesium, calcium, and sodium.

Hypabyssal. The name given to the occurrence of igneous rocks as small intrusive masses. These hypabyssal rocks are finer-grained than the plutonic rocks.

Idocrase. A mineral characteristic of metamorphic rocks.

Igneous Rock. A crystalline or glassy rock, which has cooled and solidified from a molten magma.

Ilmenite. An iron titanium oxide mineral. Is a black metallic mineral used as a source of "titanium white" pigment.

Jasper. A red siliceous rock consisting of quartz, impregnated with haematite. Resistant to weathering and takes a high polish. Used as an ornamental stone.

Joints. A series of cracks or fissures which have the effect of dividing rocks into rectangular blocks.

Kaolin. See China Clay.

Kerbstones. Stone used for the edging of footpaths.

Lake Asphalt. Bitumen obtained from pitch lakes such as that in Trinidad.

Lamination. A structure found in sedimentary rocks which runs parallel to the bedding planes and enables the rock to be split into thin slabs. The lamination planes may be less than ¼ in. apart.

Lava. An igneous rock poured out on the surface from volcanoes.

Lichen. A plant which is a combination of a fungus and an alga, which can live on stone. Its hyphae may penetrate the stone and assist in its weathering.

Lime. Calcium oxide formed from the expulsion of carbon dioxide during heating of limestone. Slaked lime is formed by adding water to quicklime.

Limestone. A calcareous rock consisting essentially of calcium carbonate. All limestones effervesce in acid.

Limonite. An iron ore consisting of hydrated iron oxide. It is brown in colour, and is used as pigmenting material and an iron ore.

Lithopone. A material used as paint. Consists of about 70 per cent barytes and about 30 per cent of zinc oxide.

Loam. A mixture of sand and silt.

Magma. Igneous rock in the molten condition.

Marble. A limestone which has been recrystallized by the heat of igneous intrusions or intense earth-movements. The rock takes a polish. The term is also applied to any rock, such as fossiliferous limestones and serpentines, which are ornamental and take a good polish.

Marl. A calcareous shale. Often red in colour.

Metamorphic Aureole. The zone of metamorphosed rocks surrounding an igneous intrusion.

Metamorphism. The mineralogical and structural alteration of rocks by heat or pressure.

Mica. A series of minerals which readily split into very thin laminae which are flexible.

Microgranite. A fine-grained, hypabyssal rock resembling granites in mineral composition, consisting of quartz, felspar, and mica.

Monocline. An anticlinal fold in which the middle limb is vertical.

Montronite. A mineral characteristic of clays. An iron silicate mineral occurring as very small crystals.

Mudstone. An argillaceous rock between the clays and shales in structure. Becomes plastic when mixed with water.

Mural Jointing. The type of jointing found in granites. A combination of vertical and horizontal joints, blocking out the rock so that it resembles a stone wall.

Muscovite. A light-coloured mica found in the highly-siliceous igneous rocks. It is also common in sandstones in small flakes, because of its great resistance to decay.

Normal Fault. The most common type of fault in which the plane of the fault dips in the same direction as the downthrow side.

Obsidian. A lava of the same chemical composition as rhyolite which has cooled without crystallizing, and is now a black glass.

Ochre. Brown and yellow earthy forms of limonite used as pigments.

Olivine. A mineral characteristic of basic rocks such as gabbro and basalt. A silicate of iron and magnesium.

Oolite. A type of limestone consisting of spheres or ooliths of calcium carbonate cemented together. Formed as a chemical precipitate.

Orthoclase. A felspar mineral consisting of potassium alumino-silicate.

Outcrop. The area where a stratum or rock is at the surface.

Ozokerite. A brown, waxy, bituminous material associated with petroleum deposits.

Permeability. The ability of a rock to allow water to pass through it. Permeability is greatest in the coarse-grained rocks, such as gravels, and is almost nil in shales and clays.

Plutonic Rocks. Deep seated intrusive igneous rocks occurring in masses of very large size.

Porosity. The volume of voids a rock contains, expressed as a percentage of the total volume of the specimen.

Porphyrite. A porphyritic, hypabyssal rock consisting of crystals of plagioclase felspar with hornblende. Biotite or augite may be present.

Porphyritic Structure. The structure shown in igneous rocks, where some of the crystals are of larger size than the crystals of the ground mass in which they are set.

Pozzolana. Material which has constituents which, when mixed with water, will combine with lime at ordinary temperatures. Often obtained from pumaceous material.

Pumice. A volcanic rock of rhyolitic type which is highly vesicular.

Pyrite or Pyrites. A brassy mineral consisting of iron disulphide.

Pyrophyllite. A mineral commonly occurring in clays and schists. Resembles talc and is a hydrated aluminium silicate.

Quarry. Open pits or workings from which stone, sand, clay, etc., are obtained.

Quartz. A very common mineral consisting of silicon dioxide. Is the chief constituent of sands, and is abundant in the acid igneous rocks.

Quartz Porphyry. A hypabyssal, igneous rock consisting of large crystals of quartz and felspar set in a ground mass of quartz, felspar, and mica.

Quartzite. An arenaceous rock with a quartz cementing material, or a sandstone which has recrystallized as a result of metamorphism.

Quicklime. Calcium oxide formed from the burning of limestone.

Quicksand. A sand which consists of very fine grains and which, when wet, has no strength.

Raised Beach. Former beach platforms which are now above present sea level.

Recumbent Fold. A structure in which the strata are folded in the form of an "S," and in which the middle limb is inverted.

Reversed Fault. A fault in which the strata on one side have slid over the strata on the other.

Rhyolite. A volcanic rock, very fine-grained or glassy, and of a similar chemical composition to the granites.

River Terrace. Former river flood plains which are now above present river level.

Rock Asphalt. Rock such as sand or limestone naturally impregnated with bitumen.

RUN-OFF. That portion of the rainfall which runs down the surface to the rivers and streams.

RUTILE. A mineral consisting of titanium dioxide. Reddish brown or black colour. Used for manufacture of "titanium white" for paints.

SAND. An arenaceous rock consisting of loose grains mainly of quartz.

SAND LIME BRICKS. Bricks formed of sand and lime treated with superheated steam.

SCHISTOSITY. The structure developed in fine-grained rocks on metamorphism due to pressure. The rock is fissile and breaks along the planes of schistosity. The flaky minerals all trend in the same direction.

SELENITE. The crystalline form of gypsum.

SERPENTINE. A rock formed by the decomposition of igneous rocks rich in olivine, hornblende, or augite. Often polished and used as a "marble."

SETTS. Cuboidal blocks of stone used for paving roads.

SHALE. A very fine-grained argillaceous rock, possessing fissility.

SIDERITE. An iron ore consisting of iron carbonate.

SILL. An intrusive igneous rock, which has been intruded along the bedding planes.

SILLIMANITE. A mineral occurring in needle-shaped crystals in metamorphic rocks close to the contact with igneous intrusions. Consists of aluminium silicate.

SILTSTONE. A very fine-grained arenaceous rock approaching the shales in type.

SLATE. A fine-grained rock in which cleavage has been developed.

SOIL. Surface deposit formed by weathering of the underlying rock. Contains humus and colloidal material.

SPECIFIC GRAVITY. The weight of a substance in air compared with the same volume of water at 15° C.

SPRING. An issue of water at the surface.

STOCK. A form of occurrence of plutonic rock which has a roughly circular outcrop. Boss has the same meaning.

STRAIN-SLIP CLEAVAGE. The type of cleavage developed in slates, in which the rock cleaves along the axes of microscopic puckers and folds.

STRIKE. The horizontal direction in a stratum.

Subsoil. The broken rock underlying the soil and overlying the solid, unweathered rock below.

Syenite. A coarse-grained, plutonic rock consisting of orthoclase felspar and hornblende. Augite or biotite may be present.

Syncline. A fold in the form of a trough.

Talc. A mineral occurring in metamorphic rocks. It has a soapy feel and consists of hydrated magnesium silicate; used in the paint industry.

Tar Sands. Sands impregnated with bitumen.

Tear Fault. A fault in which the movement is entirely in a horizontal direction.

Terrazzo. Fragments of marble set in Portland cement.

Travertine. A calcareous rock which has precipitated from water containing calcium compounds held in solution by dissolved calcium carbonate. Usually shows a banded structure.

Tunnel Blast. A method used in quarrying when large tonnages of rock are required. Tunnels are driven into the quarry face and the ends filled with explosive.

Vein. A fissure which contains mineral.

Vermiculite. A micaceous mineral which, when heated, exfoliates and increases in volume.

Voids. The pore spaces of a rock.

Volcanic Dust. The dust thrown out by volcanoes during eruption.

Volcanic Rock. A lava.

Volcano. A conical hill built up during the eruption of volcanic rocks.

Water Table. The upper surface of the ground water.

Whinstone. The name given to fine-grained, igneous rocks.

Witherite. A white, heavy mineral consisting of barium carbonate.

Wollastonite. A mineral characteristic of metamorphosed limestones. Consists of calcium silicate.

Zinc Blende. The chief ore of zinc. Consists of zinc sulphide.

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