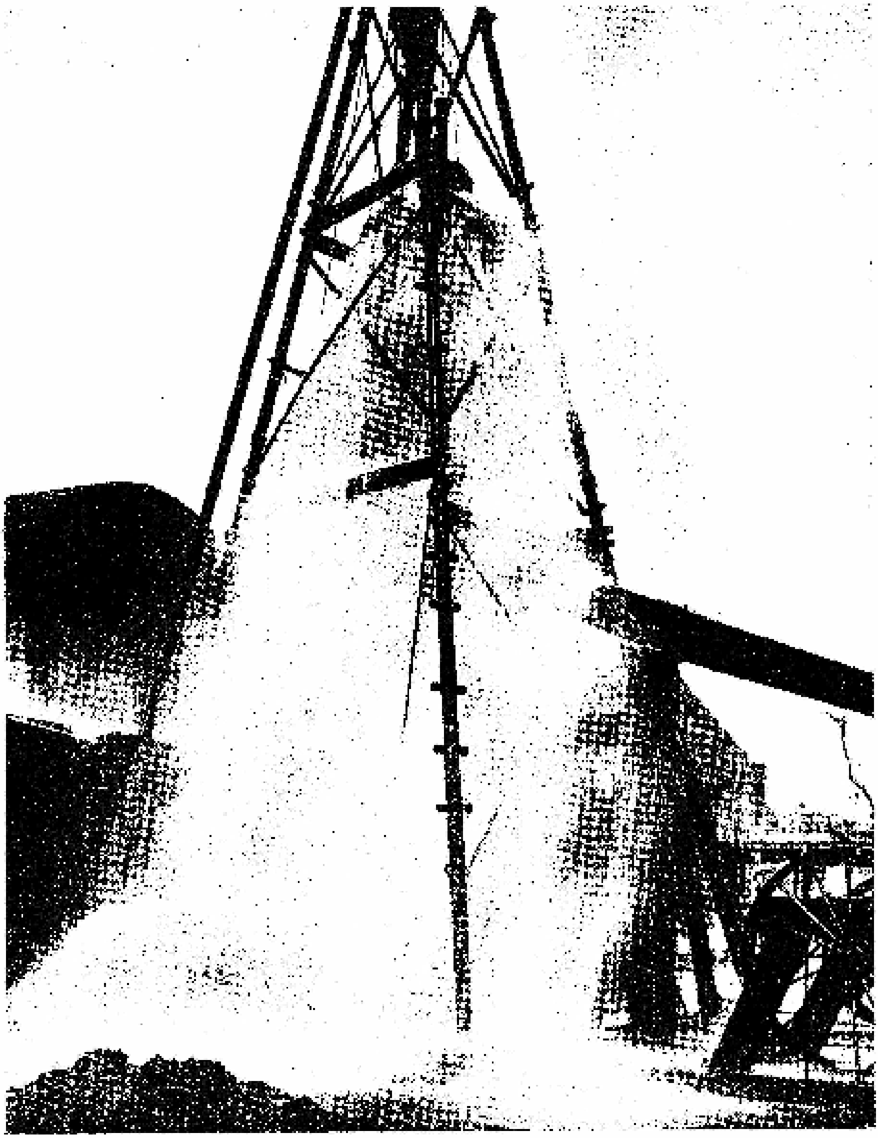
GEOLOGY AND OURSELVES



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An overflowing artesian well at Slough, Bucks

GEOLOGY AND OURSELVES

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PREFACE

During the course of his official duties a geological surveyor meets people in many walks of life who usually show a lively interest in his work, but who, for the most part, have little or no geological knowledge. Two questions that constantly arise are "What do you do?" and "What is the economic use of geology?" It is to the second of these questions that this book is designed primarily to reply, largely in general terms, but in some instances in detail.

There is a natural tendency to use the word geology not only for the science, but also for the actual physical structures, of the earth's crust. Normally it would perhaps be quibbling to object to this. Yet, strictly speaking, although these structures may have existed for millions of years, none of them becomes a geological one until it has been interpreted and accepted within the established principles of the science. Most of the earth's features known to us today existed during the time of Neolithic man, but they were not then geological features, for Neolithic man had no science of geology. The point is subtle, but it is material in the present context in order to make clear that the aim of the book is to show how the science of geology enters into our everyday life, rather than how geological structures, as such, affect us.

It has been deemed necessary to give a very brief description of what is included in geology, and of its historical development. The latter has been based largely on Sir A. Geikie's *Founders of Geology*, published 1905. The book is in no sense a text-book; it is intended for those unversed, or but little versed, in the subject. Jargon has been avoided as much as possible, and such geological terms as have been introduced have been fully explained.

In the nature of things, the author's outlook has been coloured by more than thirty years' experience on the scientific staff of the Geological Survey of Great Britain, and many of the examples of applied geology are derived from British sources. But the succession of strata as it occurs in Britain has been quoted in preference to one from some other area primarily because it most satisfactorily illustrates a specific point and only secondarily because of its location. It is hoped that the book will have more than an insular appeal,

and that it will prove of general interest to both non-scientific and scientific readers, including amongst the latter civil and structural engineers, water engineers, mining engineers and others.

The varied nature of the economic problems that a geological surveyor is called upon to discuss renders his outlook relatively catholic. Yet his personal knowledge still remains very limited when regarded within the whole field of economic geology. But he discovers a fund of goodwill amongst both colleagues and members of other professions who are widely experienced specialists in their several branches. Upon this fund the author has drawn deeply.

In the initial stages of the book the author received most helpful guidance from Mr. D. M. Desoutter. Invaluable aid has been received from Mr. P. Evans of the Burmah Oil Company; Mr. A. H. Toms of the Civil Engineers' Department, Waterloo Station; Mr. H. M. Gell, of Messrs. Le Grand, Sutcliffe and Gell, Ltd., and Mr. B. S. Furneaux. His thanks are also due to the Director of the Geological Survey of Great Britain for permission to draw from the reservoir of official information, and to numerous colleagues, in particular to Dr. F. W. Anderson, Dr. S. Buchan, Dr. W. Bullerwell, Mr. A. J. Butler, O.B.E., Mr. Wilfrid Edwards, Dr. V. A. Eyles, Dr. T. Robertson and Dr. P. A. Sabine.

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Fig. VII, 1 is included by courtesy of Messrs. Craelius and the Council of the Institute of Mining Engineers; Fig. XIV, 2 is based on a map lent by the Director of the East Malling Research Station, Kent, and Figs. X, 6, XII, 3 and XII, 4 are reproduced by the permission of Professor S. E. Hollingworth, Professor J. H. Taylor, and Mr. G. A. Kellaway and the Council of the Geological Society of London.

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August, 1955 F. H. E.

CHAPTER I

The Beginnings of Geology

THE complications of the present scientific age tend to obscure the simple fact that the earth's crust is the entire fount of the material part of our existence. House-building, water supply, production of solid and liquid fuels, supplies of metals and the maintenance and improvement of agricultural soils, are activities usually taken for granted. They are but some of the directions in which the rocks on which we live affect our everyday lives. The fact that they are taken for granted is perhaps natural: a simple relationship rarely exists between the source of the raw material and the end-product in which it ultimately reaches us; and it is the end-product, not the source of raw materials, that claims the interest of the majority of people. Again, in the fashioning of these products various other scientific or technical activities, of perhaps stronger immediate appeal, are usually involved. Finally, in spite of the very obvious importance of the earth's strata to us, Geology, the science which concerns them, is less widely studied, in Great Britain at least, than are many other sciences. Popular appreciation of geological facts and processes is limited.

Geology a recent science

As a formal science, geology dates only from the very end of the eighteenth century. The question, therefore, may justly be asked whether, as far as material wealth and development are concerned, geology has in actual fact made any really important contribution to our well-being. From the material point of view the world progressed reasonably well without its help during the centuries that preceded its birth. The simple precept that a house built on rock has greater stability than one built on sand was known before the nineteenth

century! Many magnificent buildings, bridges and aqueducts were erected without any geological aid. Sources of and methods of winning gold, copper and tin were known and understood before the Christian era, and coal has been mined for several centuries. Well-digging for water was practised by the ancients.

While the formal science of geology is of recent origin, there is little doubt that scientific method played an important part in that long series of discoveries and observations on natural phenomena which preceded its establishment and which date from the days of Plato and earlier. Such matters as the selection of good building stones or the excavation of an ore-bearing lode, or a seam of coal that came to the ground surface, all involved some degree of scientific method. In pre-scientific days, however, search for any form of mineral wealth was practically confined to the ground surface. With no set principles to guide the searcher it was largely a matter of trial and error, or even of luck.

One contribution of geological science is a great increase in the wealth of mankind over and above the restricted supplies, both in quantity and in kind, that had previously been rendered available through simple observation. The application of geological principles has disclosed vast hidden mineral resources of many kinds, which could not possibly have been otherwise located. Another contribution of geology is the provision of data without which many of our great engineering enterprises could not have materialized. From a negative angle, the science has greatly reduced the risks of costly failures which in many cases are necessarily attendant on purely haphazard procedures.

Geology, however, is not an exact science—it has on occasions been satirized as an art—and in the nature of things available geological information is insufficient to provide a full, or even a partial, answer to every problem where applied geology could be used with advantage. This must be so, for the complex pattern of the geological structure of the earth's crust is rarely, if ever, precisely the same even from one mile of the ground surface to another. Detailed information on many parts of the earth's crust is still very limited and is only acquired slowly. Geological science has already conferred great benefits on mankind, and will continue to do so in increasing degree as knowledge accumulates, but for many years to come a proportion of man's works directly involving the earth's crust is likely to suffer from primary miscalculations, and some part even to end in failure, as a result of insufficient geological information.

Ancient views on the earth's structure

The advent of geology as a science offers a remarkable study of sudden and late development. Many phenomena shown by the earth's crust are obviously of a type to call attention to themselves, and have been noted by thinking men from prehistoric times onwards. For a long time such phenomena were attributed to the supernatural; but even by the beginning of our era the more reflective minds accepted a view that much of what they saw could be explained by purely natural causes, basing their opinions on close study of the natural things around them. The Mediterranean region is one that is very favourable to the observation of two phenomena in particular, volcanoes and earthquakes, both of which may produce rapid and striking local modifications of the earth's surface. By those who were observant and critical certain scenic features of this area were easily recognized as having been produced by these two agencies. Further, successive periods of drought and of heavy rainfall were seen to cause alternating periods of low river flow and of heavy flood in the river valleys. It was noted that the latter spread over the low-lying countryside wide sheets of gravel and mud which the flood waters had brought down from the hills.

By the time of Aristotle, three centuries before Christ, many reliable observations concerning the Mediterranean area had been recorded, including some of particular pertinence by Aristotle himself. But scientific method—the careful observation and the patient collection and comparison of facts—was absent, although some slight elementary correlation of observations was attempted. Aristotle, for example, connected earthquakes and volcanic eruptions.

There was at that time a strong tendency to explain isolated phenomena by the elaboration of various baseless hypotheses, some extremely ingenious. This tendency is also instanced by Aristotle. Having traced a connection between earthquakes and volcanic eruptions, he proceeded to explain them by accepting a common belief that strong winds constantly circulated within the earth. He attributed both manifestations to an escape of these supposed winds through the earth's crust.

Ideas of the Middle Ages

In Europe the Middle Ages showed little or no advance in scientific method. From earliest times the presence of fossil shells in rocks far distant from the sea had aroused much speculation and controversy, but such was the ecclesiastical discipline of the Middle Ages that no one was found to question orthodox teaching that the

earth was but some 5,500 years old. Openness of mind was discouraged, and in consequence numerous 'escape' explanations of the presence of these fossil shells were made; such as that the fossils were in reality inorganic; or that they owed their presence to some occult influence of the stars. (It is on record that in England, even as late as the nineteenth century, a learned divine maintained that fossils had been purposely placed in the rocks by the Devil, in order to deceive and perplex mankind.)

Some of the observers of this period, however, found themselves unable to accept any explanation of fossils other than that they were in truth of organic origin. Their way of escape from an unorthodox conclusion to which dispassionate and philosophical study would have led them lay in the universally accepted version of the Deluge of Noah as having been a catastrophe which in fact drowned the whole earth.

Hypotheses of the seventeenth century

The interval between the Middle Ages and the eighteenth century apparently witnessed the same sterility of scientific geological thought, although the intellectual development of this period may well have paved the way unobtrusively for the immediate reception of the revolutionary views to be expressed a hundred years later. Numerous acute observations continued to be made. In 1686 Robert Plot, in a comprehensive description of the natural history of Staffordshire (which followed a similar volume on Oxfordshire published in 1677), described in great detail the strata of the mining areas, making the observation that "the Earth here . . . seems to be of a bulbous nature, several folds of divers consistencies still including one another, after the manner of the coats of a *pearl* or an *onyon*". Yet to him fossils, of which he made an extensive study, were but "*lapides sui generis*, naturally produced by some extraordinary plastic virtue, latent in the Earth". The seventeenth century as a whole was characterized by a remarkable series of speculative explanations on the origin not only of the earth but also of the universe; always within the orthodox views of the period. These explanations showed a considerable awakening of interest in geological matters, but very seldom proceeded along the path of scientific enquiry. Observed facts were still very few, and the various hypotheses consisted largely of highly imaginative pictures which, though for the most part confined strictly within orthodox bounds, certainly allowed of much controversy.

One of the most amazing of these imaginative pictures was con-

tributed by an Englishman, Thomas Burnet, who in 1681 published a *Sacred Theory of the Earth*, in some respects reminiscent of the Greek myth of Pandora. He asserted that up to the time of the Deluge of Noah there had been perpetual Spring on the earth, but that the wickedness of man led to a catastrophe in which the sun's rays split open the earth's crust, through which water then burst forth from a central abyss, to flood the land. An interesting comparison here arises with the views of Aristotle and his contemporaries that the interior of the earth was a space occupied by strong winds. It seems remarkable today that, so near to our own times, Burnet's absurdity was very widely accepted both in this country and in Europe.

A contemporary of Burnet, John Woodward (commemorated in the Woodwardian Professorship of Geology at Cambridge), also allowed his imagination full play, but he was in some respects more rational. He had made a remarkable collection of fossils, which today form a valued part of the fossil collection of the Sedgwick Museum at Cambridge, and he found himself impelled to believe in their organic character. But the Deluge again offered a satisfying solution of their origin. By making and studying his collection of fossils, however, Woodward does in some degree mark the beginnings of a new approach.

First foundations of geological science

It fell to a Scotsman, James Hutton (1726–97), to lay the main foundations of present-day geological science—to find the key, as it were, to the problems of the earth's structure that had hitherto occasioned so much speculation. And how obvious the key really was! It was simply the observation and appreciation of natural processes as they operate at the present time. This led to the recognition of the principle that just as today material from the land is washed into the sea by rivers and by marine erosion of cliffs, there to be laid down in stratified order, and just as volcanoes today pour out sheets of lava and send out clouds of ashes over their surrounding areas, so, with different geographical distributions, have these things happened time and time again in the past. Hutton's conclusions resulted from his careful collection and correlation of many observations over a period of some thirty years. They were based on true scientific method. Part of his great contribution to the founding of geological science was his break with the almost traditional habit of the past centuries of theorizing on the earth's structure from little or no evidence.

Hutton was born in Edinburgh, where he qualified both in law and medicine. After various changes of occupation, he took up farming in Norfolk, a district where the local geology is on the whole simple, yet where a number of problems that called for a reasoned explanation presented themselves. In his endeavour to discover the answers to them he travelled on foot over many parts of England. It is not unknown for an enthusiast to neglect his normal calling for his hobby, but Hutton was of larger calibre; he maintained his full interest in his everyday work, and he prospered. Later he returned to Scotland, where a remunerative business life enabled him ultimately to devote his whole time to his chosen field of study.

Scotland offered him a different set of problems on which to meditate; problems connected with the formation of granite and the many other rocks of Scotland. These rocks are now known to be of igneous origin (*see* p. 36), but most of the views then current held them to be precipitated from sea water.

CURIOUS IDEAS FROM FREIBURG

Paradoxically, the rapid dissemination of Hutton's views resulted in part from the work of the last outstanding survivor of what was soon to become the old regime, his contemporary Abram Werner, Professor of Mineralogy at Freiburg from 1775–1817. He was a man of tremendous enthusiasm and personality, and his scientific work on the description and classification of the many and various minerals of which rocks are composed was of the highest order. It is one of the foundations of the study of rocks. But by an almost incredible process of reasoning in circles, he evolved a theory that all rocks were chemical precipitates, deposited from an ocean which originally covered the whole earth, and which at its period of maximum development was certainly of a depth equal to the height of the highest mountains. This theory was taught as being ascertained fact. His views received world-wide acceptance, only to be completely discredited within a few years of his death. Like Hutton, he encouraged observation, but unlike him he collected information with a firmly closed mind. In spite of the rejection of his views, however, his influence has remained. His enthusiasm kindled like enthusiasm in a large number of his contemporaries and students. The many discussions that took place spread Hutton's ideas, and led to a great accumulation of detailed though uncorrelated knowledge of various parts and of different aspects of the earth's crust. Of the mass of data thus provided, geological science, soon to be established, took advantage.

EARLY WORK IN FRANCE AND GERMANY

Immediately following Hutton's work, other solid foundations of geological science were being laid in France, notably by Baron Cuvier (1769–1832), and by de Monet, Chevalier de Lamarck (1744–1829). The Paris neighbourhood, now known geologically as the Paris Basin, is one of comparatively simple structure, but with numerous divergent types of strata abounding in fossil shells. Lamarck's method of approach was akin to that of Hutton and he likewise established certain basic principles of geology, notably on the subject of the arrangement and sequence of strata; a subject that today constitutes stratigraphy. Lamarck also took particular note of the very varied assemblage of fossils, and recognized their affinity with modern shells. He was, indeed, the founder of invertebrate palaeontology, now an essential and major branch of geological science.

Cuvier, sometime Professor of Anatomy at Paris, was primarily a biologist; but just as Lamarck was led to compare fossil invertebrate shells with modern ones, so was Cuvier led to compare fossilized vertebrate bones with modern forms. Thus from Paris came the coincident development of both invertebrate and vertebrate palaeontology. But Cuvier, in conjunction with his friend Alexandre Brongniart (1770–1847), made further fundamental advances. Resulting from long study of many quarries and geological sections, a definite order of arrangement of the constituent beds of the Paris neighbourhood was recognized. Another contemporary, Von Buch (1774–1853), originally a pupil of Werner's, contributed to the developing science by his conclusions concerning the true nature of igneous rocks.

COMPLETION OF THE FOUNDATIONS

The foundations of the science were hitherto only partly completed. They were finished by an Englishman, William Smith (1769–1839), to whom, by general consent, has been awarded the title of 'Father of English Geology'. Smith was a surveyor by profession; today he would be known as a civil engineer. Working in his early professional years in the Gloucestershire-Oxfordshire-Somerset area, he became attracted by the nature and arrangement of the strongly divergent types of strata he encountered. For six years he was engineer to a canal company, during the great period of canal construction in Britain. This gave him unrivalled opportunities of observation on the nature and arrangement of the different strata that were cut through. Possibly through a natural

bent, and certainly by virtue of his engineering and surveying training, he made careful notes, a great many in map form. (It must be emphasized, however, that he was by no means the first thus to record the surface distribution of rocks.) He discovered that among the fossils contained in the several strata which he examined were some that were characteristic of, and restricted to, each particular set of beds. He then found that determination of these fossils offered a means of identifying the same bed in exposures many miles apart, and, in cases where strata had been disturbed by earth movements, at various levels relative to that of the sea. This was a discovery of major importance to the future development of geological science. By applying his discovery to his map-making, Smith constructed the first real geological map, that is to say, a map from which the structure of the earth's surface may be read as a three-dimensional form (*see* Chapter V). He thereby provided the science with a technique of surpassing value, and one without which little progress would have been possible.

The foundations had now been laid as four strong sections, on which scientific investigation of the earth's crust is today firmly supported. These sections, which are elaborated in the pages to follow, are: (1) procedure by patient investigation and recording in the field and interpretation of the recorded observations by reference to geological processes active at the present day; (2) the study of fossils from which correlation of widely separated exposures of rocks may be made, and from which important evidence may be deduced on the conditions of deposition of the various strata of sedimentary origin; (3) the critical examination of igneous rock types and their contained minerals, and comparison with present-day volcanic lavas and débris, by which it may be demonstrated that there has been volcanic activity at many places and at many different periods in the past; (4) the invention of the geological map, which provides a method by which the results of geological study may be graphically recorded and displayed.

The superstructure of modern geology, which has been erected on these foundations, is one of considerable dimensions. It is being added to today by workers in many countries and of many nationalities. The fact must not be forgotten, however, that both the laying of the foundations, and the erection of the scientific edifice, were facilitated by the existence of a well-founded access road, as it were, made by a succession of acute observers extending backwards through the whole of historic times.

CHAPTER II

Geology Today

IN its original and widest sense, geology was the science that concerned the earth in general, including (1) the atmosphere; (2) the water on the earth's crust and within its rocks (collectively known as the hydrosphere); (3) the crust itself; and (4) the interior of the earth. But the present-day meaning of the term is normally restricted to the science of the earth's crust alone. This modification is more in accord with the scope of research hitherto inherent in the subject itself.

Geology is essentially an inductive science based on direct observations of the materials comprising the crust, such as are to be made at the ground surface, and in mines and tunnels. The accumulation of detailed information concerning the rocks of the whole of the land areas of the earth's crust (which comprise that part of the globe of greatest concern to man), on which to found geological deductions, is thus a possibility. It is, however, one that is as yet very far from full attainment. But the land areas occupy only one-fifth of the globe's total area, and direct observation can only be made on the surface skin of the earth.

The field for direct observation is therefore limited. Even in Great Britain, which is geologically well-explored relatively to much of the world, the geological structure and the nature of the rocks are only known with a reasonable degree of certainty to an average depth of a mere 1,500 ft. In mining areas the depth is in the region of 5,000 ft. In certain other parts of the country, notably in parts of the Cotswolds and south-east England, the figure is as little as about 500 ft. As recently as 1953 a borehole at Cambridge provided a complete geological surprise at a depth of 450 ft. below ground surface.

The deepest boreholes in the world (put down in the search for

oil) reach depths of about 18,000 ft. to 20,000 ft., and very occasionally somewhat deeper. From an engineering point of view, these deep boreholes are tremendous accomplishments, but their depth—about three and a half miles—is little enough when compared with the 4,000 miles of the earth's radius.

The narrower significance of the term 'geology' is also the more in accord with actuality since today both the atmosphere and the hydrosphere are themselves subjects of specific sciences, and views on the origin of the earth and on the structure and composition of its deep interior are based very largely on interpretations of data provided by the science of physics. Yet the original comprehensive definition of geology was not without its merits, and there is a tendency in some quarters to bring it back into use. Air, water, crustal rocks, and whatever may be below the crust, make up one indivisible earth. The atmosphere and the hydrosphere are closely linked with each other. The surface rocks not only contain both air and water, but are continually reacting with them in one direction or another. Processes that occur within the earth's interior affect its surface; and an understanding of the various events of geological history which may be read from the crustal skin demands an appreciation of the interior structure in so far as this is possible. The science of geology as understood today needs perforce to be closely associated with findings of the sciences of biology, physics, chemistry, meteorology and hydrology.

Structure of the Earth

A generally accepted view concerning the body of earth is that there is (1) a crustal belt about thirty miles thick, composed of a complex series of consolidated rocks; (2) a dense core, of about half the diameter of the whole earth, and (3) homogenous material, less dense than the core, in the space intervening between the core and the crust (Fig. II, 1). This view is based very largely on interpretation of seismic data, and is, in the nature of things, hypothetical. Interpretations of this nature are essential steps in the investigation of crustal movements and their causes. Yet however reasonable they may appear, they still remain hypotheses, liable to be discarded when further information comes to light. For many years a theory has been held that the core of the earth may well consist of a mass of nickel-iron. This is the most reasonable explanation of certain observations based on physics—so much so that it is almost in danger of being accepted as ascertained fact. But it is not ascertained fact and it is not entirely unquestioned.

The outer part of the crust, to a depth of perhaps several miles, consists of a complex arrangement of rocks in which the substances silica and alumina are the most important constituents. These outer rocks are less dense than those of the inner part of the crust. The lower rocks also have silica as one main constituent but magnesia is their second. The upper group has been conveniently named 'Sial',

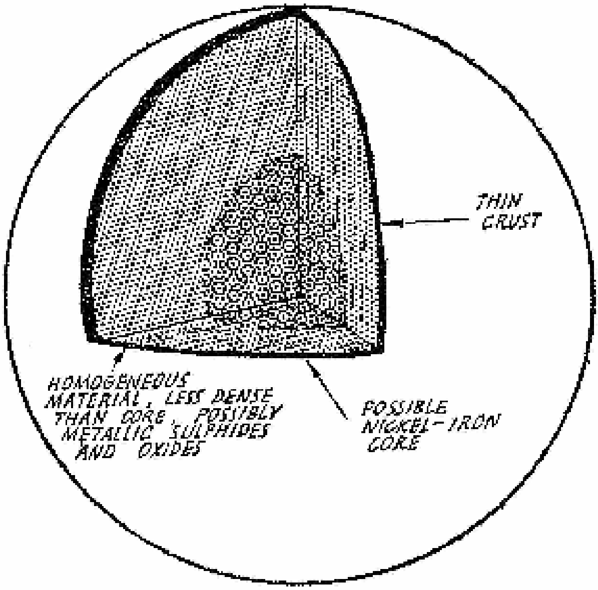


Fig. II, 1.—A hypothetical internal structure of the earth.

derived from *Si*lica and *Al*umina, and the lower 'Sima', from *Si*lica and *Ma*gnesium.

THE NATURE OF ROCKS

It has to be accepted as a fact that the first solid rocks of the earth's crust solidified from a molten state, and that at numerous times since other rocks have been formed in a similar way. It is very doubtful if any of the original rocks survive; certainly it would not be possible to recognize them even if they do. All rocks that have been formed in this way, irrespective of when they solidified, are termed igneous rocks. The word 'igneous' naturally brings to mind a picture of volcanoes and their accompaniment of fire; and indeed the word as used in geology owes its origin to observations on volcanoes and volcanic rocks. But in point of fact most igneous rocks have nothing

to do with fire. Just as ice is formed when water loses heat to a sufficient degree, so, as a group, do igneous rocks result through the cooling (or it may actually be said *freezing*) of a molten mass. The fire of volcanoes is a secondary effect in a special case of igneous activity. The great majority of igneous rocks have crystallized below the ground surface, quietly out of sight, and unattended by fireworks, as it were.

A great part of the sial consists of comminuted fragments, some inorganic, some of animal and plant remains that for the most part have been deposited in sea floors of past ages. These are generally compressed or cemented together, and constitute sedimentary strata.

Igneous rocks and sedimentary strata together comprise the great bulk of the visible rocks of the earth. The limited remainder include volcanic ashes and the like, and rocks which, like slate and serpentine, have been altered from their original solid state by heat and/or pressure. These last are metamorphic rocks.

MAJOR SECTIONS OF GEOLOGY

Modern geology includes four major sections:

(1) Physical geology; the study of the processes by which changes in the earth's crust are brought about.
(2) Mineralogy and Petrology; which deal with the composition of rocks.
(3) Palaeontology; the study of fossils, both from their interest as remains of plants and animals long dead, and from their ability to throw light on problems of historical geology.
(4) Historical geology; comprising (a) Stratigraphy, the determination of the succession and arrangement of strata, and (b) Palaeogeography, which automatically includes the reconstruction in imagination of former geographies.

The following pages, to the end of Chapter IV, contain brief accounts of these major sections of the science as they are understood today.

PHYSICAL GEOLOGY

Among the geological processes which operate every day upon the land surfaces of the earth are three which tend towards ultimate destruction of land areas. These processes are severally known as 'weathering', 'transport' and 'erosion'; collectively they are grouped as 'denudation'. Weathering is the decay and destruction of rock at or just below the ground surface. This is produced by a variety of

means: physical interactions of rock with air and water; changes of temperature; vegetation; animal activity; and chemical action. Water and frost in conjunction are particularly potent agents of destruction. Water, largely derived from rainfall, seeps into cracks and crevices in the rocks, and expands on freezing, to force blocks of rock apart. Were this process to be continued indefinitely without disturbance it would result in complete pulverization of a rock surface. Plant roots, which penetrate to depths of tens of feet, assist in this work, as do myriads of worms, grubs, small burrowing animals and such like.

The heat of the sun may cause disruption of rock surfaces, particularly where intense day heat is followed by cold nights. Igneous rocks in particular which are composed of various minerals, each with different specific heat, are especially vulnerable to this type of weathering. Internal stresses that are set up in the rock by the sudden changes of temperature produce firstly a scaling-off of surface layers and subsequently their complete disintegration. Much desert sand is formed in this way.

Many surface rocks contain minerals that are soluble in water or in the weak acid produced by carbon dioxide in conjunction with water. Removal of these soluble materials by percolating water is a very common cause of rock decay.

Rock waste, which includes surface soils, is ultimately transported from the place where it was formed by the carrying agencies rainfall, rivers, glaciers and wind. Except in the case of wind, these move material under the influence of gravity; movement, therefore, is continually from higher levels to lower. Rain washes soil down hillsides and delivers it to rivers, and these ultimately take it to the sea. Rivers also carry away much material in solution. Even the River Mole, one of the smaller Chalk streams of southern England with an average daily flow of about 70 million gallons (the River Thames has an average daily flow of about 2,000 million gallons), carries seaward some six tons of chalk in solution each day.

Glaciers pick up vast amounts of rock waste in their slow progress from ice-fields. This is transported to lower and warmer levels where the ice melts to form rivers, and is then carried to the sea by normal river action. Wind is a most potent transporting agent, both as regards the quantity of material it removes and distance over which this is carried. Desert dust-storms provide ample evidence of wind transportation.

Wind, glaciers, rivers and run-off from rainfall are not only carrying agents. Each is an eroding agent capable of wearing away

the land surface both by direct action and by employing the load it carries as cutting-tools.

Rivers are particularly efficient both as erosive agents and as transporters of rock waste, and their efficiency increases rapidly with a rise in velocity. The turbidity of rivers in spate indicates the vast loads they are capable of carrying even in flat country. Rivers constantly deepen their upper reaches, and in mountainous or hilly country a small stream with a steep fall may erode a very large gorge; the stream gorges of the Alpes Maritimes of the South of France are notable examples. The great power of a large volume of water when running down a valley with a steep fall was strikingly shown in 1952 by the River Lyn in Devonshire. During the disastrous floods of that year at Lynmouth this stream transported boulders each weighing many tons (*see also* p. 113).

As soon as stream velocity decreases carrying power lessens and the heaviest fragments are dropped. This unloading process continues with a progressively diminishing stream velocity and the rock waste is sorted into different grades. Sorting is resumed as velocity again rises, since the smallest fragments are then picked up first and are carried farther downstream. Large spreads of gravel, so valuable to man in this age of concrete, have been accumulated along the valleys in many of our rivers. As a result of various geological processes that have occurred subsequently to their deposition, some of these gravels at the present time have a temporary high and dry resting-place tens or even hundreds of feet above the present valley floor level, but their ultimate destination is the sea.

Glaciers also possess a great erosive and transporting power. Unlike the load of a river, their burden is not selectively dropped. Large tracts of land are covered by an unsorted mixture of boulders sand and clay, known as 'boulder clay'. This deposit was left behind when ice, which formerly covered much more land than it does today, 'retreated', that is, gradually melted from its front backwards, in response to an ameliorating climate. A release on land of water from melting glaciers, however, obviously gives rise to rivers, and in many glaciated areas there is a gradual lateral transition from unsorted boulder clay into well-sorted river deposits. In the northern and eastern parts of England boulder clay is commonly 200 ft. thick.

THE RÔLE OF THE SEA

The sea has a dual rôle. It is the recipient of all the material transported from the land which it sorts into the several grades of

mud, silt, sand, etc. On being deposited on the sea floor they are built up into definite beds. It is also a most destructive eroding agent, continuously at work. A single large wave hurled against a cliff face may exert pressure of several thousand pounds per square foot. Under this pressure, water is injected into every crevice and crack in a cliff face, to compress the air contained in them. On release of pressure the compressed air more or less explodes, to loosen, and then to remove, block after block of even the hardest rock. Air compression may even be sufficient to blow a hole upwards through strata many yards from the cliff edge. Destruction is augmented by boulders and pebbles which, wielded by the waves, deliver hammer blow after hammer blow against a cliff face.

Cliffs of soft rock such as clays and sands are easily undermined by sea action, and rockfalls and landslips are of frequent occurrence. Along the coasts of eastern and southern England, notably of Yorkshire, Norfolk, the Isle of Sheppey, Sussex (near Selsey and near Hastings), and Hampshire (eastward of Christchurch), the loss of land by marine erosion may be several feet during a single decade.

Peneplanes

All land surfaces of the globe are subject to denudation. Had no movements of the earth's crust occurred subsequently to the formation of the first-formed land, the original surfaces would have been lowered long ago to an almost level plain. Slopes on the ground surface that were just sufficient to allow rainfall to run off, but of insufficient gradient to permit material to be transported, may possibly have survived. The sea would have attacked coastlines, planing off the rocks of the foreshore into wave-cut platforms until such time as it was left with no further erosive power, its energy having been absorbed in travelling over them. It is even conceivable that all land surfaces would have disappeared entirely, since the final products of weathering might well have been removed by wind. This theoretical conception of an almost level surface is termed a 'peneplain' or 'peneplane'. (Latin *paene*, nearly.) The land surfaces of the earth have never undergone universal peneplanation, but extensive tracts have approached that state.

The succession of geographies

Had not earth movements intervened from time to time, complete peneplanation would conceivably have occurred, and after that there would have been no geological history to concern us. But the earth's crust is permanently in a state of movement, at one part or another.

Evidence of simple vertical elevation of land relatively to sea level is common around the coasts of Great Britain. At numerous places 'raised beaches' consisting of typical sea beach material are to be seen up to 100 ft. or more above sea level. Black Rock, Brighton, Portland Bill and Saunton near Barnstaple are some of the places where raised beaches may be seen most clearly. In other districts the general appearance of the land surface high above sea level is that of a horizontal plane. A surface of this kind some 400 ft. above sea level is particularly well seen in Cornwall (Plate VIIIA). These level surfaces are former sea beds which have been raised to their present positions.

Evidence of the converse process of depression that has caused drowning of previous land is also to be seen at various places around Britain. Trunks and stools of forest trees that were submerged when still growing, are visible at low spring tides off the coast of Sussex near Bexhill, off the coast of Lincolnshire and Norfolk, off the Welsh coast, and at various other localities.

Not all changes in land level relatively to sea level, however, necessarily imply crustal movement. Some actual movement probably results as one of the effects of an ice age, but land may appear to rise relatively to sea level through the abstraction from the sea of vast quantities of water which become locked up in the ice of glaciers, to cause a general lowering of sea level. Conversely low-lying forests may be submerged on the return of water from glaciers following the advent of a warm climate.

Facts of this kind indicate that periodically the disposition of land and sea areas over the globe has undergone great changes. The forces that produced them have defeated the efforts of denudation to produce a universal peneplane. There has been in fact a succession of geographies, each bearing little or no resemblance to its predecessor. The major causes of this succession are those which give rise to the elevation of new continents from the sea. They originate deeply beneath the earth's crust and can only be investigated by combining the results of direct geological observation on the crust with hypotheses concerning the earth's interior; hypotheses which are arrived at largely through the science of physics, particularly of that branch now known as geophysics.

Isostasy

Among the contributions which the science of geophysics has made to geology is the application of the principle of isostasy. This principle is normally explained by an analogy, provided by a simple

experiment with pieces of wood, showing the behaviour of several blocks of different heights as they float in water. A part of each block lies above the water, and a part below, the proportions being governed by the height of the block and the density of the wood; each block is in hydrostatic balance. A tall block rises higher above the water level and sinks to greater depth below than a short one (Fig. II, 2). Should a portion from the top of one block be taken away part of the loss in height above water level would be com-

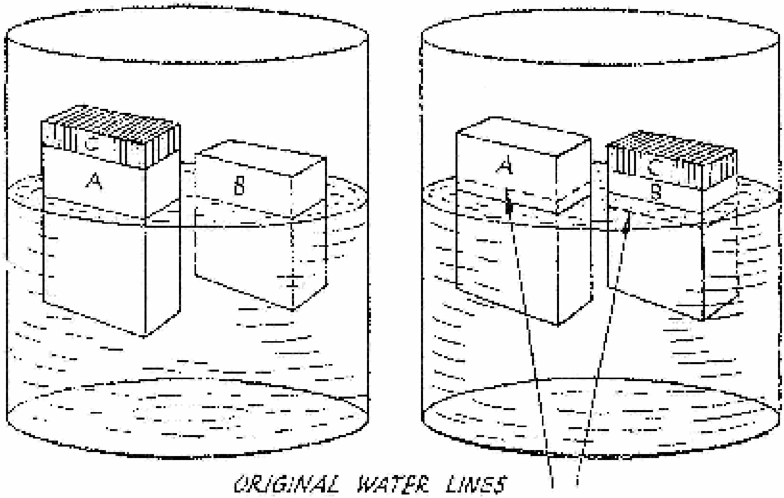


Fig. II, 2.—The principle of isostasy may be illustrated by blocks of wood floating in water. Should the part C be moved from A, part of the loss in height *above water level* would be compensated by a rise of the submerged part. Conversely, should C be added to B, part of the added height above water level would be lost by an increase in the amount submerged.

pensated by a rise of the block in the water; the actual loss would be shared between the submerged part and the part in the air. Conversely, if an addition were to be made, the gain in height above the water level would only be part of the extra length, since the block would sink deeper into the water. In its simplest form this illustration assumes that the blocks are made of the same kind of wood. Should different woods be used, a dense one such as ebony, or one of the ironwoods, would be submerged to a greater depth relative to its height than would a light-weight wood such as deal, and to a much greater depth than a block of the extremely light-weight balsa wood used for the famous *Kon-tiki* raft.

In the analogy, tall blocks of light-weight wood represent mountain masses, and light-weight blocks of intermediate length are the large plains and plateaux of the earth. The ocean floors may be represented by blocks which are composed of a heavy wood. The analogy, though valuable, breaks down in two important particulars: (1) Wood blocks are supported by water, which is a medium different from themselves, whereas those rock masses of the earth's crust which are in isostatic balance pass gradually into material of similar composition, which possesses some degree of plasticity possibly on account of its high temperature at depth. (2) Crustal masses are not separate units that act independently, as do the blocks of wood, but are joined to each other.

Isostatic balance in the earth's crust is continually being altered by the processes of denudation. The removal of a vast weight of material from a mountain range and its deposition on adjacent land at a lower level is the parallel of the removal of the top layer of a floating block of wood. Part of the loss in height resulting from denudation is regained by isostatic elevation; and the rise in height of the receiving area is partly discounted by isostatic depression. Such movements, although slow, are in themselves quite sufficient to produce definite, though relatively local, geographical changes. The great stresses and strains in the rocks which are set up give rise to many folds and faults, particularly in the transition zone between the part being raised and the part being depressed.

The raised beaches and submerged forests around the coastlines of Great Britain are to some extent an expression of isostatic movements related to the Great Ice Age. The great thickness of ice which accumulated over the northern hemisphere is thought to have so increased the load on the crust that isostatic depression occurred. As the ice melted the load was removed. Even today isostatic equilibrium has not been reached and parts of northern Europe are still slowly rising.

Isostasy is a theory. Yet so strong is the evidence provided by the correlation of observed geological facts with data provided by geophysics that the theory may be regarded as a fact.

Geosynclines

Isostasy can induce only vertical movements. These may cause important changes in geography around an existing land mass, but they cannot give rise to new continents nor to new oceans. Yet geological observations made from many angles lead inevitably to the conclusion that there have been periods of great disturbance

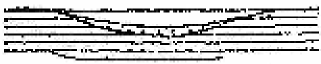
within the earth which have in fact produced vast new lands and new seas. Some other factor than isostasy, therefore, must be looked for. Not only are the summits of many of the highest mountains of the earth composed of rocks of marine origin but many mountain ranges are built of thousands of feet of deposits which can only have accumulated in shallow water. An accumulation of thousands of feet of shallow-water deposits demands an explanation, for it could not occur without some controlling mechanism within the earth to permit it. A tract that was covered by shallow water would be filled up after the accumulation of but a few hundred feet of detritus, and a sea that was sufficiently deep to permit the development of many thousands of feet of beds would obviously contain deep-water, not shallow-water, deposits.

A combination of geological and physical data provides an explanation of this immediate problem, in the form of a geological structure known as a 'geosyncline'. It seems that periodically in geological time, a long narrow stretch of the earth's crust, many hundreds of miles long, begins to sag and sooner or later it is occupied by the sea. Sedimentation on its floor more or less keeps pace with the rate of sagging. The actual sea floor therefore remains permanently at shallow though fluctuating depth, but ultimately the original floor lies many thousands of feet below sea level. A vast accumulation of shallow-water detrital material is thus gradually built up, slowly to become compacted into sedimentary strata.

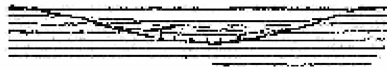
As sagging proceeds, strains and stresses are set up in the strata which compose the sides of a geosyncline. Molten material, often derived from the sima, may break out from fractures and displacements that occur at weak places, to form volcanoes which emit lava and ashes, or to be injected into the strata of the side walls, as it were, of the geosyncline.

There comes a time in the development of the geosyncline when crustal masses on either side appear to exert tremendous more or less sideways pressures on the deep-seated sediments, which are squeezed both upwards to form mountain ranges, and downwards, displacing some of the underlying material, to form mountain 'roots'. The pressure and heat generated give rise to both chemical and physical changes in many of the original sediments, to produce metamorphic rocks (*see* p. 44). This conception is illustrated in Fig. II, 3. An immense anticlinal fold is shown in Plate I.

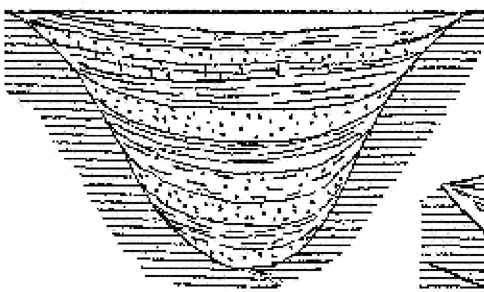
The tracts of country on each side of a rising geosynclinal mountain range are known as 'forelands' and cannot be insulated from the effects of the great pressures involved. Strata of the rising



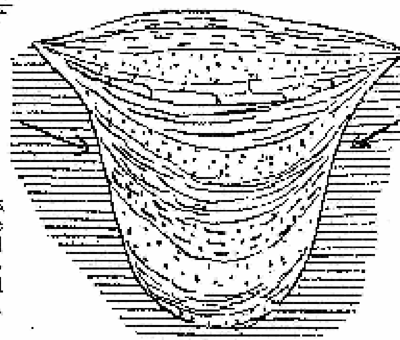
1. Depression begins over an elongated area of the sea floor. Shallow-water sediments (muds, silts, sands and limestone) accumulate.



2. Depression continues. The first-formed sediments sink with the floor. Other similar deposits are laid down on them.



3. Many thousands of feet of shallow-water deposits are ultimately formed.



4. The huge masses of the 'shield' areas on both sides of the geosyncline move towards each other. The geosynclinal sediments between them are forced upwards to become mountain chains, and downwards to become mountain 'roots'.

5. Geosynclinal strata are highly contorted and are forced over each other along vast 'sliding planes'. Folding and faulting may affect the foreland strata hundreds of miles from the main disturbance.

6. Structure of part of the Alps. (*Based on Lugeon.*)

Fig. II, 3.—Stages in the development of a geosyncline, and its transition into a mountain-range through lateral pressures of converging 'shields'.

geosynclinal area also spread sideways, often to be thrust over each other, and over the foreland areas. Strata may be cockled up in large folds over tracts stretching for several hundreds of miles from the centre of uplift. The Pyrenees, the Alps, the Himalayas, the Rockies and the Andes are typical mountain ranges rising from geosynclines. In the northern foreland of the Alps (Fig. II, 3), folds were produced in strata as far away as Southern England. The effects of the Alpine pressure are to be seen particularly well in the cliffs of the Isle of Wight, where at Alum Bay the strata, originally horizontal, are today almost vertical. Other areas along the Dorset coast and inland in Wiltshire and Dorset and along the Hog's Back of Surrey exhibit comparable folds. South Wales is in the highly disturbed northern foreland of an earlier geosynclinal mountain range which has largely disappeared. Highly contorted strata at Boscastle, Cornwall, are illustrated in Plate IIA.

Geosynclines are thus part of the mechanism which acts within the earth to produce new lands to replace worn-down continents. Many of the mountains to which geosynclines of the past have given rise are now worn down to stumps, while at the present time one is gradually deepening in the neighbourhood of Java and Sumatra.

The presence of geosynclines in the earth's crust, like the principle of isostasy, is to be accepted as fact. Various hypotheses concerning the causes that initiate them have been made, all based on geophysical deductions. Some of these may be very near to actuality; but it still remains true that the mechanism by which they arise is in point of fact really unknown.

Whether geosynclines are liable to develop in any part of the earth's crust or whether their formation is restricted to limited areas is uncertain. There is no doubt that some parts of the earth's crust, geologically termed 'shields', have been stable areas since early geological times. The Baltic area, Eastern Canada, a great part of India and the southern part of Africa are instances of geological shields. Recent work on the rocks of the Rhodesian and Tanganyikan shield have led to the conclusion that these are some of the oldest-known rocks of the earth's crust. Many of the rocks of great tracts of some of the shields however have been extensively metamorphosed apparently by great pressures, which points to movement at some early period or periods even in the shield areas.

A modern view is that just as shields appear to have been more or less permanent features, so have the very great ocean depths. This view is based largely on geophysical data but it is expected that in the near future a certain amount of direct observation will be

possible, since modern techniques in sampling the sea bed will enable specimens of even the hardest rocks to be obtained from the beds of the deep oceans. On the theory of isostasy, these should be dense rocks, of kinds to be associated with the sima.

If this idea be correct the earth's crust would seem to be divisible into (1) stable shield land areas; (2) stable sea depths; (3) intermediate areas between them which are subject to geosynclinal movements. Such a distribution of areas would reflect some unknown conditions deep within the earth.

CHAPTER III

On Minerals, Rocks and Fossils

WHATEVER may be the internal structure of the earth, there is little doubt that its crust developed initially by solidification on cooling of molten semi-liquid matter. Nor is there any doubt that matter in a semi-liquid state exists today beneath the rocks of the sima (p. 21). Matter in this form is known as 'magma'; a word in common use in the seventeenth century to signify any pasty mixture, and still so used today in some industrial processes. It has been most appropriately borrowed as a scientific name for what in effect is a natural viscous mixture of different chemical substances.

MINERALOGY

Common constituents of magmas are silica, alumina, potash, soda, lime, magnesia and iron. In addition, numerous rarer constituents are present. The materials of all rocks, of whatever kind, have been derived in the ultimate from a magma, although these may have undergone various changes to reach their present form. They are collectively known as 'minerals'.

But the word 'mineral' is difficult of precise definition. The earliest and simplest association of the word is with a mine; it was something that was mined, and it is still not uncommon for the word 'mine' to be used for the stratum of minerals worked as well as for the shaft or tunnel-like excavation made to get them. In everyday and commercial usages today minerals may be said to comprise all substances that can be got from underneath the surface of the earth for the purpose of profit, and which therefore have a value when transported from, and one independent of, the

ground in which they occur. Minerals are then held to include sand, sandstone, and limestone dug from quarries, brine and salt, oil, gypsum, gravel, and numerous other materials in addition to generally accepted substances like coal and metallic ores. In this sense it is an economic, not a scientific, term (*cf.* ore, p. 195).

In legal circles, there is designedly no hard and fast definition of a mineral. The position still depends upon the following authoritative opinion given by the late Lord Halsbury: "I cannot help thinking that the true test of what are mines and minerals in a grant . . . is a question of what these words mean in the vernacular of the mining world, the commercial world and land-owners at the time when they were used in the instrument." The implication obviously is that the definition 'of mineral' needs to be considered afresh for every legal case in which the word is used.

For scientific purposes, a mineral is best defined as any natural inorganic homogeneous substance of definite chemical composition, and it is in this sense that it is used in the present section. Even within the confines of this book, however, the more general meaning is conveniently applied in certain later chapters.

The earth's crust contains many hundreds of kinds of minerals which may be separated into two broad groups. The first contains a very few 'rock-forming' minerals yet these collectively make up some 99 per cent of the crustal rocks. The second group is numbered in hundreds and its members vary from the relatively common to the extremely rare. Among these come the gemstones, of which the value is in inverse ratio to abundance, and other minerals of immense importance in industry.

For many centuries much has been known about certain aspects of mineralogy but it was the more valued minerals, notably gemstones and the semi-precious stones, that attracted attention. Werner, at the end of the eighteenth century (p. 16), appears to have been the first to give systematic attention to minerals as a whole. He made meticulously careful descriptions of a great many and carried out or inspired many chemical analyses. Such was the state of laboratory apparatus in his day, however, that only specimens which were of sufficient size to be seen either by the naked eye or examined through a low-powered lens could then be examined and described. Werner's system has long been superseded, but through his work the science of mineralogy arose contemporaneously with, or perhaps even a little earlier than, formal geology itself.

During its progress since Werner's time mineralogy has still remained an essential part of fundamental geological study, since

minerals are the elements of rock structure. It has also diverged from geology, and one of its major concerns today lies in the chemical and physical properties exhibited by each individual substance. Mineralogy today demands the use of a well-equipped laboratory with complex optical instruments such as the spectrograph and X-ray apparatus, and comprehensive chemical equipment. In its advanced form it is more allied to physics and chemistry than to pure geology.

PETROLOGY

In the same way that the word 'mineral' has more than one significance, so has the word 'rock'. In common parlance it implies hardness and cohesion; members of certain technical professions regard all rocks as being either 'hard', or 'hard' modified by a colloquial adverb! In a geological sense, however, a rock is any natural agglomeration of mineral particles. A rock may be composed of almost infinitely minute particles, or of large boulders; or of materials of any and every intermediate grade; it may include one kind of mineral only, or a mixture; it may be very hard or very soft; and it may be cohesive or quite unconsolidated.

Compared with some other sections of geology, petrology and petrography, which cover the study and scientific description of the structure and nature of rocks, got off to a slow start, as it were. This was partly the result of a survival of wrong ideas that granites had been deposited in water (*see* p. 16) when, in fact, they had solidified from a molten state; and partly because the wherewithal for the study of rocks *quâ* rocks was not developed until after palaeontology had got well into its stride. Hutton, about 1790, had not only discovered that rocks such as may be seen at Dartmoor, at Shap in Cumberland or at Peterhead in Scotland, have been derived by solidification from the molten state to form great 'bosses' in the earth's crust, but he had also observed that molten matter had in many instances been forced into cracks of bedding-planes or joints of other strata, there to cool and to form thin sheets of solid rock. Sheets of igneous material such as these, that lie along bedding-planes of the containing rocks, are known as 'sills', and those that occupy cracks or joints, as 'dykes'. Hutton was the first to recognize their true nature.

In the early days of geology the nature and origin of sedimentary rocks had been noted, and many were in truth recognized as being

composed of an infinity of grains of sand such as would be laid down in water, but they inspired no further interest. For at least half a century after Hutton's death neither igneous nor sedimentary rocks, as groups, offered attractions for study at all comparable with those presented by fossils.

The birth of petrology

Petrology was born in Scotland. Somewhere about 1825, a lecturer at Edinburgh University, William Nicol, who invented the apparatus known as Nicol's prism which is now an integral part of almost every microscope used in petrology, evolved a process for examining very thin slices of rock; actually in the first instance of fossil wood. His method was to grind the face of a piece of fossil wood until it was perfectly flat, then polish it and cement it to glass by the resin canada balsam. The exposed surface was treated in the same way until all that remained fixed to the glass was an extremely thin plate of rock which was almost transparent. He was then able to examine this thin slice under a microscope.

The importance of Nicol's method of making these thin slices for microscope work was not appreciated in geological circles for many years. About 1850, and after Nicol's death, his rock slices together with others were examined by a very perceptive geologist, H. C. Sorby, who saw how valuable they could be. He himself made slices of Scottish rocks. Ultimately he made this branch of Nicol's work generally known. Nicol's method of preparing thin rock slices for examination under the microscope is now in world-wide use in petrological investigations, and his painstaking and slow way of making them by hand has been largely replaced by rapid work done by specially constructed machines.

Igneous petrology

A well-known cookery book contains in its instructions for cake-making details of four distinct basic mixtures of ingredients. Each of these is treated in a number of different ways, to produce from these four foundation mixes a large variety of cakes and pastries.

This analogy is applicable to the natural production of igneous rocks. Several variations in type of magma occur within the earth, each of which cools and solidifies under a variety of conditions. The combination of variation in magma composition and variation in solidifying conditions produces many different kinds of igneous rock.

The constituents of a magma form various minerals as cooling proceeds, and these gradually crystallize out in successive order, so

that at one stage in cooling there may be solid crystals of one mineral floating about in a still molten mass. As regards crystal size, slow cooling favours the growth of large crystals, whereas rapid cooling causes small ones. Extremely rapid cooling may inhibit crystal growth altogether, in which case the cooled magma forms a natural glass-like rock. The word 'crystal' is used advisedly, but few minerals that are constituents of an igneous rock have an outside shape commonly associated with the word. The natural outside shape of a crystal is a reflex of internal molecular structure and every crystalline mineral possesses its own characteristic molecular arrangement. A perfect outside shape can only be attained in nature when crystal growth is unrestricted by external conditions. The first-formed minerals that crystallize out from a magma are often well-shaped, but all, and particularly the later ones, have to accommodate themselves to such space as others may leave them. But their internal structure invariably obeys crystallographic rules. Determination of this internal structure under the microscope is one method by which minerals are identified.

THE PLACE OF SILICA

Silica is by far the commonest magmatic constituent and is a key substance in the process of crystallization. Most other substances in the magma, except those rarer ones forming the accessory minerals, show an affinity for it. Silica may be present in any proportion from about 30 per cent to 80 per cent.

If, to use a modern *cliché*, silica is in short supply, it is not shared on an egalitarian ration. Apart from the accessory minerals the first minerals to crystallize out from a magma are compounds of iron, magnesia and silica, to produce a 'ferromagnesian' group. This includes olivine, one form of which is the gemstone peridot (*see* p. 40) and numerous other minerals, one of which, mica, is of great value in electrical work. If only a low percentage of silica is present iron and magnesia together absorb the whole of it, and should iron be in great preponderance the final product of cooling may include iron ores. Some of the most important iron-ore reserves of the world have arisen in this way.

With a higher percentage of silica—say about 50 per cent—and a lesser proportion of iron and magnesia, such ferromagnesian minerals as the composition of the magma warrants are first formed, then soda, lime, potash and alumina combine to take their quota of silica to form a group of 'felspathoids' and 'felspars'. The word 'spar' is an old term certainly dating from the sixteenth century to

describe various common crystals which glisten. It is related to the word 'spark'. 'Fel' or 'feld' is a corruption of field; 'feldspar' is an alternative rendering which is still preferred by some geologists. The large pink crystals often several inches long, so notable in the granite of Peterhead and similar white crystals of the Dartmoor granite, are all types of felspar. 'Felspathoid' has been coined from felspar to denote minerals that are almost felspars, as it were, but not quite, owing to a deficiency of silica.

Finally a magma may contain a high percentage of silica. In that case ferromagnesian minerals, small in proportion to the whole, are first satisfied as regards their requirements, the felspars then are similarly accommodated, and what silica is left over crystallizes as colourless quartz, which is so extremely stable and hard as to be almost indestructible.

Four main types of magma

For purposes of systematic arrangement, magmas have been separated into four classes, according to the ratio of the amount of silica to other substances present. Those with a great deficiency of silica are classed as 'ultrabasic'; they are progressively succeeded by 'basic', 'intermediate' and 'acid' classes, the last-named containing sufficient silica to permit the presence of free quartz in rocks that crystallize from it.

Three conditions of cooling

Magmas may solidify slowly at great depth below the ground surface and in large masses, and those rocks formed under these deep-seated conditions are distinguished as 'plutonic' (from *Pluto*, Greek god of the Underworld). Since slow cooling favours the growth of large crystals, rocks formed at depth by the solidification of an acid magma contain large crystals of quartz, felspars and ferromagnesian minerals. These are granites. An ultrabasic magma, on the other hand, which solidifies under similar conditions, yields a peridotite (*see below*).

Magmas intruded into strata at shallow depths below the ground surface as dykes and sills yield 'hypabyssal' rocks, and the relatively rapid cooling they undergo produces the growth of myriads of small crystals. Hypabyssal rocks are accordingly of much finer grain than are plutonic rocks. But sometimes crystallization began in a plutonic magma, of which part has subsequently been intruded as a hypabyssal magma, and has carried with it in suspension such crystals as had already formed at plutonic depth. In consequence many

hypabyssal rocks contain large crystals in a ground-mass of minute ones, or even of a natural glass. These rocks are 'porphyries'.

Volcanic rocks result from magmas that reach the ground surface before they solidify into lava. Cooling may be so rapid that crystal growth is inhibited completely, so that some lavas are composed of natural glass.

Classification of igneous rocks

Some system of classification of igneous rocks is essential both for scientific and for economic purposes. The classification that has world-wide acceptance, is based on a framework that includes the four 'mixes' of mineral substances and the three distinct conditions of cooling outlined above. In nature there is, of course, every gradation from the deepest-seated, slowest-cooling, ultrabasic plutonic rock to the most rapidly cooled acid lava. This simple 4×3 conception, however, has been found to be somewhat over-simplified even for purposes of general classification, and the original grouping of the intermediate rocks has been enlarged, since there was too much variation between the acid end and the basic end.

The framework table of classification is as follows:

Conditions of Cooling	Composition of Magma				
	Acid	*Intermediate*		*Basic*	*Ultrabasic*
Extrusive (*Volcanic*)	Rhyolite	Trachyte	Andesite	Basalt	Ultrabasic lava
Intrusive (*Hypabyssal*)	Quartz-porphyry	Porphyry		Dolerite	Peridotite-porphyry
Deep Seated (*Plutonic*)	Granite	Syenite	Diorite	Gabbro	Peridotite

Interest of the rock names

At first sight the above names may appear to be somewhat formidable. Yet they have an interest all of their own, and they are bound up with the gradual growth of petrological science. Some have been acquired from old everyday descriptive names. 'Granite' is 'grain-ite'; that is, a rock consisting of visible crystals or 'grains'. In geological literature the word 'granite' carries no special suggestion of hardness, such as is commonly given it in non-scientific writing; a granite is hard; but so are many other rocks. 'Porphyry'

is of Greek origin, with an original significance of purple coloration. It first referred to a rock composed of large white or pink felspar crystals set in a fine-grained reddish ground-mass, which was quarried in Egypt long before the Christian era. The significance of the term, however, has been transferred from one of colour to one which indicates the characteristic feature of large crystals within a fine-grained ground, quite irrespective of colour.

'Gabbro' is an old Italian sculptor's name for an easily worked rock; but the geologist's 'gabbro' does not seem to be quite the same as was the sculptor's; unfortunately it is not possible to clarify this matter further. The name 'basalt', in the Latin form, goes back to the days of Pliny; but again Pliny's basalt was probably not entirely the same type of rock as basalt as understood today. For a great many years now the presence of columnar masses, so characteristic of the Giant's Causeway in Northern Ireland, has been regarded as an essential feature of a basalt. 'Lava' obviously has an implication of washing. Before its adoption by geologists the word originally meant a stream-gutter which heavy rainfall rapidly washed out of soft rocks, such as unconsolidated deposits of volcanic ashes. Its first application to a stream of molten matter was at Vesuvius; it now applies both to extruded molten magma, and to the rocks that result from its solidification. 'Peridotite' comes from 'peridot', a Middle English name probably with oriental association for the gemstone, now more commonly known as olivine (although peridot is still used) on account of its usual olive-green colour; a peridotite contains many minute crystals of olivine. 'Quartz-porphyry' and 'peridotite-porphyry' become self-explanatory.

'Rhyolite', 'trachyte', 'diorite' and 'dolerite' are early nineteenth-century descriptive names given by French geologists and are associated with the early days of petrology. They were invented for rocks for which no distinguishing name had hitherto existed, and represent an early attempt at systematic classification. They are all of Greek derivation, and are perhaps characteristic of a period when every person of education was conversant with the humanities.

It has been remarked above that silica crystallizes at a lower temperature than do other magmatic substances. It follows that a cooling magma that contains much silica retains its viscosity, and consequently a potential to flow after extrusion, longer than does a more basic one. Solidified acid lavas, therefore, tend to exhibit internal structures which show flow lines to a greater extent than do basic lavas, and to be glassy. These acid lavas were therefore named

'rhyolites', from *rheo*—to flow, and *lithos*—a stone. Many intermediate acid lavas contain much glassy material, but also many minute crystals. They are in consequence rough to the touch; their group name of 'trachyte' from *trakhus*—rough, refers to this roughness of feel. At the time when these names were first applied it was most difficult, if not impossible, to determine the constituent materials of some very fine-grained intermediate basic rock types. They were called 'dolerites' from *doleros*—deceptive, an agreeable way of confessing ignorance. 'Diorite' means nothing more than a rock type that has been clearly separated off from another. The name comes from *di(h)orizo*—separation, and it has the same root as 'horizon', which is a plane of separation. A diorite is actually a rock that is rather less 'granity', than a granite.

Some rock-type names are derived simply by adding '-ite' to a place name. Two examples of this occur in the above general table —'Andes-ite' and 'Syen-ite', the latter from Syene (now Assouan) Egypt. In the later years of petrology this method of naming new rock types became a general practice, now well established; unfortunately so perhaps, because these names give no idea of the composition or texture of the rock.

In view of the almost infinite variations in composition and texture possible between rhyolites and peridotites, the number of igneous rock names today is legion. Except to the specialist igneous petrographer, however, the names given in the above table are adequate for practically all purposes.

Sedimentary petrology

It is only in recent years that petrologists have given close attention to the sedimentary rocks. The characteristics of clays, silts, sandstones, sands and limestones had long seemed to be self-evident, and in the nature of things they do not present the great and varied problems that igneous rocks do.

At one time, limestones were regarded as being composed of comminuted fragments of shells; the explanation seemed to call for no further investigation. The Chalk formation for example (*see* p. 68) which has a thickness up to some 1,800 ft., was for many years thought to have been built up of shell fragments. Later it was seen that this explanation involved some insuperable difficulties. It was difficult to reconcile marine conditions which on the one hand produced completely pulverized shells and on the other allowed vast numbers of shells, now found fossil, to remain whole and unabraided.

Even under an ordinary microscope chalk was seen to consist

largely of a very fine powder plus many small spherical bodies. In consequence a new theory was advanced that the ground-mass of chalk and that of certain other limestones was largely laid down by chemical precipitation in warm seas. The presence of shells presented no difficulty on this explanation. But, as recorded below, even this theory has now been superseded.

The early deduction of formal geological science that the whole of the inorganic material that comprises sedimentary rocks had been derived originally from igneous strata must be accepted as an established fact. For the most part, however, all the crystalline materials (except quartz) of those igneous rocks which constituted the surface layers of the original crust have been destroyed. The felspars, for example, have largely been broken down into clay-forming minerals; from them has been derived the large aluminium content of certain clays. But quartz is seen to be practically indestructible, and also to an almost similar degree are some of the accessory minerals.

Through long weathering and much sorting by wind and water, most sandstones of today are composed almost entirely of quartz. Individual grains of a sand deposit may be, and often are, coated with iron, which gives sands and sandstones in the mass a red or brown appearance but the quantity of iron present is very small. Various surviving accessory minerals are very sporadically dispersed throughout the quartz.

Clay minerals are so extremely fine that even under the normal type of microscope specially constructed for petrological study they show no identifiable substances.

Sedimentary petrology today

In recent years the petrology and petrography of sediments have made a great advance on the rather obvious and elementary conclusions which earlier had seemed to satisfy enquiry. This is partly the result of a great improvement in laboratory apparatus and partly of an economic stimulus. Many industrial processes require raw sediments of standard composition, from which even minute departures, in the nature of traces of other minerals, are obnoxious. A pure white quartzose sand which occurs in southern England was recently investigated as a raw material for glass-making. Glass made from it, however, had a yellowish tinge. Petrological examination of the sand showed that it contained extremely minute traces of an accessory mineral; but sufficient to destroy the value of the sand for first quality glass.

The present-day petrology of sands and sandstones takes account of the accessory minerals. This is purely laboratory work requiring much patience and skilful technique. It involves the separation of the accessory minerals from the mass of the quartz, often ·001 per cent of the mass or even less, and then their identification under the microscope as is done with igneous petrology. Accessory minerals are sometimes given a similar rôle to that of zone fossils (*see* p. 48), for they may provide indexes by which a sample of one sandstone may be distinguished from another. This is important since in the nature of things many sands and sandstones which at one time contained shells have lost all trace of them through their complete solution and removal by percolating waters.

In very recent years another advance in sedimentary petrology has been possible through the use of the electron microscope. It was as late as 1953 that by its means the composition of chalk was finally determined. The finer material has now been shown to represent spore-bodies of very primitive marine plants with algal affinities. The modern spectrograph and X-ray apparatus have shown clays to have many and varied properties. Some of these had been previously found by experiment; for instance fuller's earth has been used for many centuries on account of its grease-absorbing properties. Yet the composition of fuller's earth remained unknown until very recently; trial and error was the only means of finding suitable material. Through the use of the above instruments, both constitution and physical properties of 'fuller's earth' are now fully understood.

Some clays make suitable material for pottery; others for bricks and the like; while others again, apparently closely similar, are not satisfactory. Much has now been learned as to the petrological differences in apparently similar materials which lead to these variations in behaviour in industrial processes.

Other common sedimentary rock types include iron ores, coals and chemical deposits like gypsum and salt. Representative of less common types are coprolite beds, and siliceous earths. The former contain phosphate-rich nodules derived from animal remains of various kinds, while the latter are composed almost entirely of skeletons of minute water plants (diatoms). All of these provide economic minerals of one sort or another, and many of them have been under petrological investigation in recent years in relation to their actual or potential industrial uses.

ASHY ROCKS

In the nature of things ashes that are blown out of volcanoes settle on the ground surface or in water in the form of sediments. They form, therefore, a small group of strata which, though of igneous origin, are more conveniently considered as sediments. In the course of time they become consolidated, to become 'tuffs', which, on account of the irregular sizes and shapes of the constituent particles, are usually porous. The name 'tuff' carries a suggestion of porosity. It comes from Latin *tofus*, a loose porous rubble. (It is closely related to 'tufa', the name normally applied to a calcareous porous rock, precipitated from lime-rich water.) Tuffs formed on land usually consist of volcanic ashes only; those formed in water generally contain a varying proportion of water-borne sediments, and often fossils.

PETROLOGY OF METAMORPHIC ROCKS

Great geosynclinal and mountain-building movements and their associated igneous activity generate great crustal pressures and high temperatures. The effects of these may be only local, or they may be felt over wide regions. Those rocks, whether they be igneous or sedimentary, which come under the influence of either one or the other, or more usually of both, are often changed both in mineralogical composition and in structure. The degree of change, that is, of 'metamorphism', depends partly on the degrees of temperature and pressure, and partly on the composition of the unaltered rock. At one extreme rocks are melted, to crystallize into forms quite different from those of the original rock; at the other extreme constituents are merely rearranged within the rock, with little or no chemical alteration. Absence of chemical alteration, however, may not necessarily imply a low degree of metamorphism. A pure limestone that has been melted re-crystallizes into a pure marble, such as the white Carrara marble of Sicily, and a pure quartz sand or sandstone yields a white 'quartzite'; in both of these instances there is no change in the actual chemical composition. Impurities in metamorphosed limestones often give rise to new minerals that, diffused through the stone, produce colours and patterns in much variety, many of great beauty.

THE FORMATION OF SLATES

Clays and silts, under appropriate conditions, react to pressure and temperature by undergoing a rearrangement of their particles, so that the long axis of each is parallel with all others; and some

degree of chemical change. In this way slates are formed. Their fissile character is the direct result of this regular orientation of the particles.

A further stage in metamorphism of clays and silts and of many tuffs produces 'phyllites' which split easily into glossy 'leaves'. Many of the rocks to be seen in the cliffs of parts of South Cornwall are phyllites. Yet a stage further in metamorphism and the original rocks become transformed into schists (Latin *schistos* = fissile). Garnet is among the new minerals that are formed in schists, provided of course that the original rock contained in other mineral forms the requisite chemical substances necessary to its composition. An impure sandstone or other coarse-grained sediment becomes a 'gneiss', which is somewhat like a granite, but has a foliated or laminated structure. The name is of German origin, and of pre-geological age. Slate, phyllite, schist and gneiss are four easily recognizable stages but (as is the case with igneous rocks) they have no hard and fast class boundaries. Each grades insensibly into the next.

Mineral veins and metallic ores: kaolin

Metamorphism also arises by the action of chemically active gases that are forced into crustal strata. Amongst the many chemical constituents of magmas are certain volatile substances. The progressive solidification of the several minerals concentrates these into the last stage, often as highly active gases. These gases attack any surrounding rocks and produce veins of minerals that include many metallic ores, and fluorspar, apatite, topaz, beryl and other minerals in considerable variety. Gases may even attack a great mass of rock. This occurred in the case of a great granite boss in Cornwall in which a very high proportion of the felspars have been converted into kaolin, which today is dug and exported all over the world. In Great Britain metamorphism has been brought about by mineralizing gases in Cornwall, the Mendip Hills, Wales, the Pennines, Cumberland, and parts of Scotland.

Because the crustal rocks of Great Britain have not lain directly along a major mountain-building axis since very early in geological history, however, metamorphic rocks are largely confined to the very ancient strata of the country which crop out in Cornwall, Wales, the Lake District, and Scotland. Local metamorphism in less old strata, associated with igneous activity, is occasionally present.

Many rocks and minerals that we prize today, some for use in

industry, some as ornamental building stones, and others as gemstones, are derived from metamorphic rocks.

PALAEONTOLOGY

The study of fossils is an integral part of geology. It is also a science in itself. The word 'fossil', derived from Latin *fodere*—to dig, was certainly in use in the sixteenth century, when it referred to any curious small object that chanced to be dug up from the ground. As has been the case with the name 'geology', it has later become restricted in meaning, and it now includes only remains of plants or animals of past geological ages which are embedded in the strata of the earth; but even so, its significance is wide.

The nature of fossils

Most fossils represent the harder parts of organisms, since except in very exceptional circumstances softer parts decay too rapidly after death to be preserved. A fossil rarely represents a complete animal or plant; it may even be but a fragment of an organism. Its dimensions may extend into feet, as in the case of skeletons of mammoth or of dinosaur reptiles, or they may be of microscopic order. Many 'micro-fossils' are almost invisible to the naked eye. A fossil may be but a mould; an impression formed in the material in which the original organism or fragment was embedded; and may be either an interior or an exterior. Moulds of shells are particularly common. In some strata indeed shell-moulds are far more common than shells, the original shelly material having been almost wholly removed, usually by percolating water. An example of this is a rock bed which overlies the well-known Portland building stone at Portland, Dorset. Stone in this bed is known as roach (= roche). It is crowded with moulds of a lamellibranch shell and the space originally occupied by the shells is now shown by voids. These Portland-fossils are known locally as 'horses' heads' from a fancied resemblance in shape.

A fossil may be but a 'cast', which is a consolidated infilling of mud or other material taking the place of the original material.

In fossils of any type it is rare for original constituent material to be present, although the form of the organism may be perfectly retained even to the minutest detail that may be seen under a microscope. During a fossil's long sojourn in the earth's crust, molecular replacement of the natural body-material by mineral matter usually

takes place. Silica is a common replacement mineral, and many shells which were originally composed of calcium carbonate are now represented by siliceous fossils. Even plant material may be affected in this way. Some of the oldest and most primitive plant fossils known, those of *Rhynia*, first found at Rhynie, Scotland, are so preserved. Whole tree-trunks, now completely silicified, are commonly found at Portland, and at one spot at the southern end of the Isle of Wight fossil wood of this kind is so common that it is known as the 'Pine Raft'.

The vast majority of animal fossils are remains of marine or fresh-water forms of life. Physical conditions on land are almost totally unfavourable to the preservation of even the hard bones of land animals. Generally speaking, the remains of land animals lie on or near the ground surface, and in the course of relatively a few years even the largest mammalian bones completely disappear. Even should there have been a chance covering of a kind to afford preservation of organic material, the normal processes of denudation on land surfaces would tend towards its ultimate disinterment and decay.

Marine, estuarine, and fresh-water lake conditions favour preservation. Organic remains tend to be covered rapidly with mud, silt or sand, and hard parts at least are often preserved. In exceptional circumstances impressions of such delicate animals as jellyfish have been retained. A great many fossils of land animals and plants owe their preservation to the fact that from one cause or another, such as floods, they found their way into a contemporary river and were buried together with aquatic remains; or were carried out to sea, there to be covered and preserved. At Ockley, in Surrey, many bones of land dinosaur reptiles have been discovered in a 'bone bed' in very old estuarine deposits (Weald Clay) into which they had been washed. Fossil wood is common in the cliffs at Sheppey, North Kent. This was originally brought into the ancient sea in which the beds of Sheppey were laid down, as floating boughs or logs. It is frequently to be found on the beach there.

The value of fossils

Fossils may be regarded in two extreme ways; either purely as specimens of organic life which existed in past ages, whose interest lies entirely in their anatomical characteristics; or at the other extreme they may be looked upon strictly as indexes for correlating strata irrespective of their biological connexions, according to the use as discovered by William Smith. In the latter case a knowledge

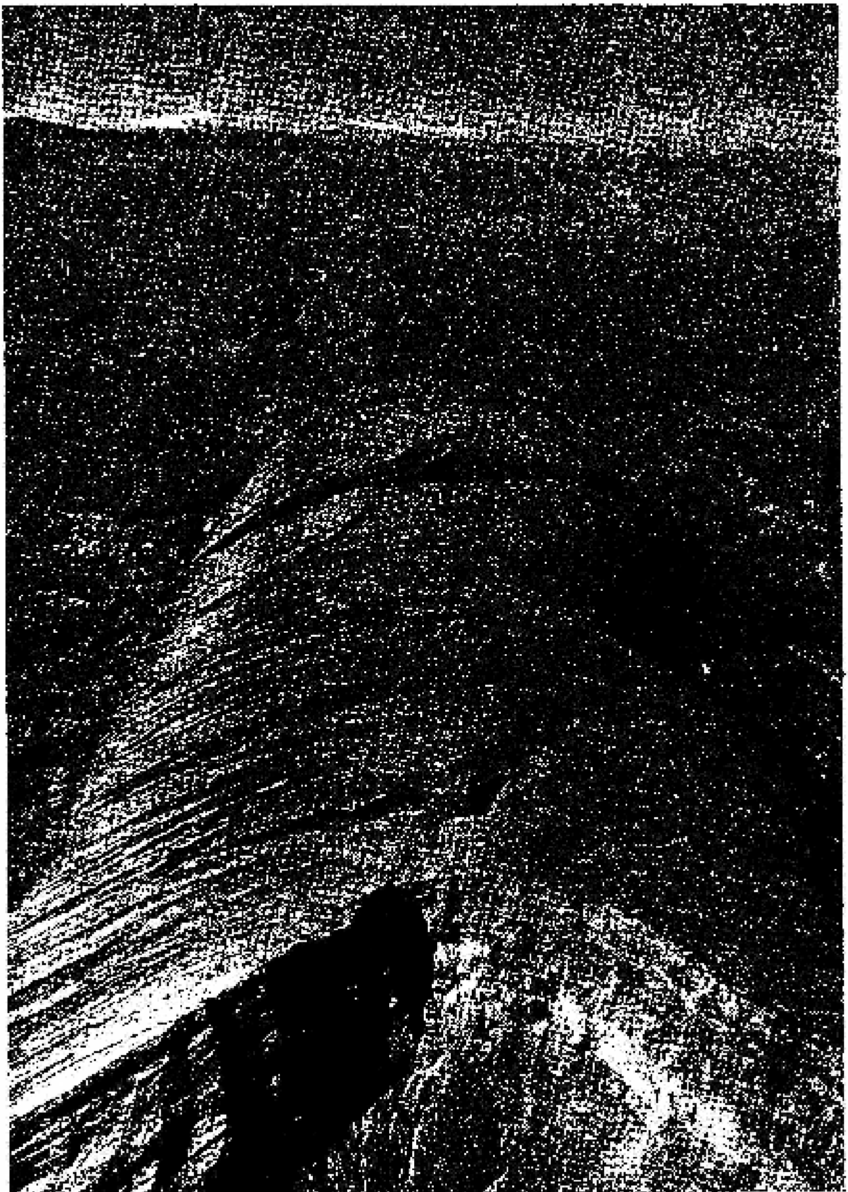
of the vertical and horizontal ranges of fossils is obviously necessary, which can only be obtained by detailed collecting from the rocks. In actual practice both views have to be taken equally into consideration. The biologist finds in palaeontology one of the main props of any theory of evolution, but accurate knowledge of the relative positions, both vertical and horizontal, of the various fossils in the strata before their removal is necessary to his conclusions. The stratigrapher cannot use specific fossils as indexes for recognizing different strata unless he knows something of their morphology, to enable him to distinguish one genus or species from another.

Fossils as stratal indexes

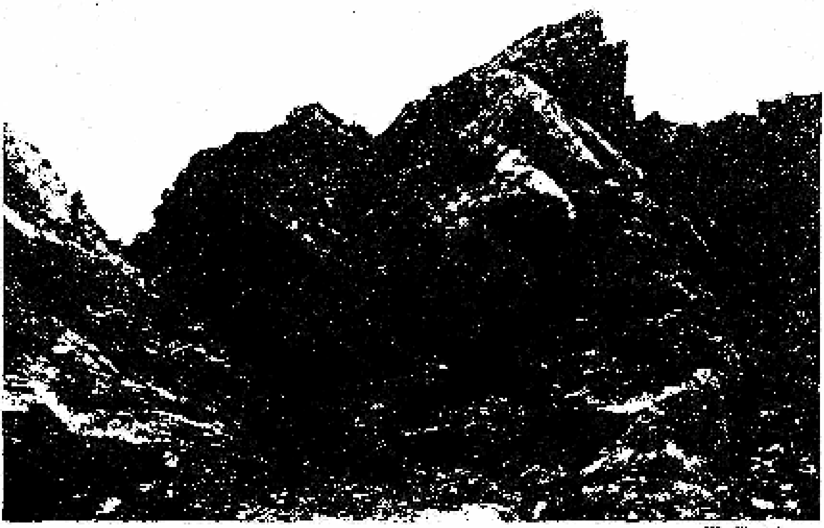
By a combination of biological examination and careful and extensive collecting and recording, it has been found that some fossil types have persisted unchanged through vast periods of time and are present in rocks of several different ages. Others have evolved quickly from one form into another and are found, therefore, in a very restricted vertical range of beds. It is the latter type of fossil which is used for identification of strata, provided the fossils are sufficiently abundant and widespread to be used for the purpose. It is of no use to select one that can scarcely ever be found. The deposits in which these selected fossils occur are known as 'zones' and the characteristic fossils are 'zone fossils'. The position of a zone within a detailed table of strata is the 'zonal horizon'.

All the strata within a zone are broadly contemporaneous; in fact, this is essential to the conception of a zone; but they do not necessarily consist of the same type of deposit. At any one period mud is laid down on one area of the sea floor, sand on another, and pebbles on a third. Coral reefs and shell beds also occur. Deposits of these kinds which were laid down in past ages, and which have since become consolidated to clay, sandstone, conglomerates and limestone, may therefore all lie within the same fossil zone. In such a case the selection of a zone fossil which is likely to be found in all four types of deposit can often only be made after a close study of a whole fossil fauna, which necessitates extensive and methodical collecting.

The biological approach to palaeontology shows that many fossils are remains of animals that had adapted themselves to special environments, for example to shallow water, or to sandy sea bottoms. Some of these fossils may answer the zoning requirement of a short vertical range, yet each may possess only a limited lateral range, confined to the single type or 'facies' of deposit. Such are generally useless as zonal fossils.



An anticlinal mountain ridge in the Middle East. The ridge is about ten miles long and two miles wide



W. H. Johnson

A. Contorted strata near Boscastle, Cornwall

H.M. Stationery Office

B. Unconformity at Siccar Point, Berwickshire, Scotland

Selection of a zone fossil is in actual fact not an easy matter. It is rare to find any one fossil that fulfils every requirement, and an assemblage of several fossils is often used, one of which provides the zonal name. By the collection and recognition of an assemblage of fossils in strata of a hitherto unknown horizon the zone may often be correctly identified, although the actual zonal index fossil may not even be discovered.

SOME ZONE FOSSILS

Once a fossil zone has been reliably established, it becomes of great importance in geological field work. The rocks of Wales and Cumberland include many thousands of feet of strata of a broadly similar kind, consisting of slates and other fissile material which were once muds and sandstones. These rocks have also been folded and faulted into most complex structures. Among zone fossils that have been used to subdivide these strata are the graptolites, a long-extinct group of animals which were allied to the corals. Their mode of life has been deduced from their form and structure as having been mainly that of floating organisms and they are, therefore, widely spread; they also show rapid evolutionary development. Consequently they make ideal zone fossils. By their help very complex geological structures have been unravelled.

Many, though not all, of the strata of a wide belt of country extending from the Dorset coast to Yorkshire (Jurassic strata, *see* p. 66) are zoned by the ammonites, an extensive group of extinct molluscs allied to the nautilus and squid of today. These strata comprise a varied succession of clays and limestones with some sandstones. One Jurassic clay is very like another, and one limestone is very like another. The ammonites were free-swimming, and as was the case of the graptolites, they display extraordinarily rapid evolutionary changes. Their shells occur in great profusion in each type of deposit. This group again, therefore, provides excellent zonal fossils. Ammonite zones, often only a few feet thick, are readily recognizable in the field, and most of the main groups of strata in the Jurassic sequence, and many minor ones, may be reliably identified wherever they may be exposed.

The various beds of much of the Chalk formation which is present over so great a part of southern and eastern England are identified by fossil assemblages rather than the specific fossils, but zoning of part of the upper half of the Chalk is remarkable, as it is done through the evolutionary forms of a single genus of sea-urchin, *Micraster*. The main features of progressive change in *Micraster* are

a deepening of certain grooves, an increase in thickness of the shell and a change in the position of the 'mouth'. Experience has shown that even a fragment of this fossil may be relied upon as an index to the position of the bed within the whole thickness of the Chalk formation in which it is found.

It follows from these remarks that when a field geologist collects fossils for zoning purposes it is incumbent on him to make careful and accurate descriptions of the precise location of the rock exposure and of the position within the exposure from which the fossils are obtained. Many a cabinet of fossils exists in the country today, the result of much patient labour, which from the scientific point of view is valueless or almost so, since this essential information is lacking.

Museum arrangements of fossils

Although the biological and stratigraphical aspects of palaeontology are interdependent to so close a degree, yet the fact that they are fundamentally separate is reflected in the arrangements of fossils in the two great national geological collections in London; those of the Natural History Museum, and the Geological Museum, both at South Kensington. In the former the basis is primarily biological. For example, all the graptolites are placed together, so are all the lamellibranchs, and so on. The known evolutionary sequence of every group of fossil animals is thus displayed. Arrangement according to age is secondary to the biological.

In the Geological Museum fossils are primarily exhibited in their assemblages as found in specific strata. Representatives of all the fossils to be found in the Chalk are shown together, as are those of the Great Oolite, and indeed of all the main stratigraphical divisions of British strata, usually with specimens of the rock in which they occur. But the fossils' names are those of type specimens of the standard biological collections.

CHAPTER IV

The History of the Earth

IN interpreting the earth's history, geologists in imagination raise on the earth's surface a continent here, and a mountain range there; they submerge vast tracts of land beneath the sea and cover others with ice. Their interpretations of geological history follow naturally from Hutton's discovery that the present external form of the earth results from a long succession of geographical changes, all of which have been produced by factors that have been active throughout geological time, and are still active today.

Geological time

The question of the time required for these changes to have taken place comes to the fore almost automatically, but the subject of geological time is not an easy one to grasp. As late as 1954, some structures found in rocks bordering Lake Superior were claimed to be remains of simple plants over two thousand million years old, and some South African rocks are thought to be some two thousand seven hundred million years old. If these claims be accepted, the age of the earth must needs be greater still. These fossil plants alone would require a further long period to have attained the developmental stage they had then reached. The present-day estimate of the age of the earth is some three thousand million years. This figure may or may not be near the truth but it rests on a reasoned basis. Yet it should be said that the estimated figure at the beginning of the present century was but a hundred million years. To certain specialists estimates of the age of the earth are important. To the vast majority of people their significance is quite beyond comprehension. Even the event of the finding of Moses in his basket by Pharaoh's daughter, which happened only about a million days ago,

seems to many of us to have occurred somewhere near the dawn of time!

It may well be that numbers in millions of years do enable some people to overcome a natural incredulity when first confronted with the time demands of the geologist. They may also help towards an appreciation of the fact of an orderly sequence of events. But the real essential to an understanding of geological history is not a row of figures, but an acceptance of the idea that without question the duration of geological time has been amply long to accommodate the sequence of episodes of mountain-building, land submergence, ice ages, and the like which geological investigation has shown to have occurred; that time has been in fact, to all intents and purposes, limitless, and therefore that except by the specialists interested, detailed consideration of the time factor in geology may be ignored. Indeed, for most people, geologists and non-geologists alike, nothing more than this is really possible.

The law of superposition

With an acceptance of the idea of limitless time a conception of long-continued orderly sequence of geological events, which is fundamentally important to historical geology, presents no difficulties. This conception itself introduces a basic geological principle that a sedimentary stratum which occurs at the ground surface was laid down at a later date than the bed below it, and that beds are progressively older as a succession of strata is traced to greater depths; a principle which becomes obvious on the mere statement. This is the Law of Superposition. It applies everywhere unless beds have been displaced relatively to each other by earth movements which occurred subsequently to their deposition. It should be noted that it applies to sedimentary strata only. Igneous rocks at depth may be younger than beds above them.

The chronological table

Recognition of this law permits the construction of tables to show the sequence in which the various strata of the earth's crust were formed. The details of these tables vary from country to country. They are, however, all related to an internationally accepted scale which divides geological time, whatever its duration, into units. The datum of this scale has been taken at the period when, as far as can be detected, animals and plants first existed in forms which permitted their preservation in rock to become fossils. Above this datum geological time is divided according to one

classification into four 'eras', Primary, Secondary, Tertiary and Quaternary. An alternative classification divides it into three eras; the Palaeozoic, coincident with Primary, the Mesozoic, the equivalent of Secondary, and the Cainozoic, which includes both the Tertiary and Quaternary. The terminal 'zoic' (from Gk., *zoon*-animal) indicates that the main grouping in the latter classification is based on the forms of animal fossils which occur in the various strata; the initial halves come from *Palaeos*, ancient, *Mesos*, middle, and *Kainos*, new or fresh. As in the case of certain petrographical names the Greek foundations of these words and of others given below, perhaps reflect the classical basis of education in the early part of the nineteenth century.

In the Palaeozoic or Primary era, all forms of life were less highly organized than they are today. Yet it is not advisable to regard these as 'simple' organisms, for many were in fact very complex. Molluscs, corals and allied animals, and fishes lived in the sea. Early insects and amphibians appear to have been the main forms of land life. In the Mesozoic or Secondary era, reptiles of the dinosaur groups, many of great size, were dominant on land, and other large reptiles were adapted to live in water. Mammals were small and primitive and from the point of view of numbers, they were not important. Marine animals were of far greater complexity than those of the Palaeozoic era. The Cainozoic era, i.e. the combined Tertiary and Quaternary eras, the latter of which includes the present day, is characterized by the complete disappearance of the dinosaurs and by the dominance of mammals on land, of which Man is the highest expression.

With the perverseness of human nature, the names of eras commonly in use, at least in Great Britain, are taken partly from one classification and partly from another. The normal is Palaeozoic, Mesozoic, Tertiary and Quaternary. The reason is perhaps not far to seek. Palaeozoic is definitely preferable to Primary, since it allows periods antedating the Palaeozoic to be included in a time scale. The apparently illogical preference for 'Tertiary' and 'Quaternary' over 'Cainozoic' is bound up with traditional usage. The latter is preferable, and indeed is internationally acceptable.

Each era is subdivided into 'periods' each of which is in itself a major division of geological time. Both eras and periods are named in the Table of Geological Formations, given on pp. 76, 77.

The upward sequence of names of the table of periods is thus a scale of continuing time. The divisions are artificial, just as the division of a day into twenty-four hours is artificial. But the periods

are founded on groups of strata that field observations have shown to have some character or characters in common. All the strata related to a specific 'period' are grouped as a 'system' and carry the period name. But there is not, nor can there be, any idea of equality or duration of time either as between the four eras or as between the several periods. The whole of the Quaternary era undoubtedly represents but a very small fraction of the time of the Palaeozoic era. To regard both the Quaternary and Tertiary eras, as generally accepted in Great Britain, as but two periods of the Cainozoic, is entirely rational; yet so vague is the conception of actual time inherent in geology that the retention of the older British usage, established as it has been over the years, may not be a real disadvantage.

Each 'period' is again subdivided into 'epochs', of which the corresponding strata are 'series'. And still further subdivisions are made for detailed work.

NAMES OF THE GEOLOGICAL TIME SCALE

The growth of the geological time scale illustrates, by the mixed origins of its names, the gradual growth of geological science, both in time and place. 'Cambrian' is derived from Cambria, and 'Ordovician' and 'Silurian' arise from Welsh tribal names. The Ordovices inhabited North Wales and the Silures lived in South-East Wales.

Sir Roderick Murchison introduced the name Silurian, which he applied to most of the Welsh strata. Professor Adam Sedgwick (whose name is commemorated in the Sedgwick Museum at Cambridge), working in North Wales, concluded (rightly) that the rocks there belonged to an age earlier than Silurian, and proposed the name Cambrian. Murchison disagreed. It is perhaps a sad commentary on human frailty that Murchison and Sedgwick were close friends when first associated in geological work in Wales, but they quarrelled so violently over this matter that they became permanently estranged!

'Ordovician' was proposed at a somewhat later date by Professor Lapworth, of Birmingham University (*see* p. 250). 'Devonian' comes from the name of the English county of Devon, and 'Permian' from Perm in East Russia; a name also given by Sir Roderick Murchison, who during the first half of the nineteenth century did much geological work in Russia. 'Jurassic' is from the Jura Mountains, and was given to the system as a whole by the German geologist, von Buch (*see* p. 17). The 'Trias' is a system comprised of three divisions in

Germany, although only two of them are present in Great Britain, but the Rhaetic (named from the Rhaetic Alps) subdivision is now usually considered part of the Trias. 'Carboniferous' and 'Cretaceous' are both named according to characteristic, though not necessarily thick, rocks of the respective systems; coal and chalk. Chalk bulks largely among the strata of the Cretaceous system; coal, however, comprises only about 1 per cent of the total thickness of the whole Carboniferous system.

The series of names 'Eocene', 'Oligocene', 'Miocene', 'Pliocene' and 'Pleistocene' is another example of the impact of Greek in the nineteenth century: These are derived from *eos*, dawn; *oligos*, little; *meion*, less; *pleion*, more; *pleistos*, most and *kainos*, new or fresh (seen also in Cainozoic above). The series was originated by a distinguished English geologist, Sir Charles Lyell. He based his nomenclature on the relative proportions of living to extinct forms of molluscs that are present as fossils in such of the Tertiary strata as he knew. The Pleistocene strata, therefore, contain a greater number of shells of living species than do the strata which he placed in the Pliocene system; the Eocene, which he so named as being the period which saw the dawn of mammals as the dominant form of land life on the earth, contains no living forms. His original scheme has been later expanded to include the Miocene and Oligocene. This series of names conveys some idea of the ages of the several formations in relation to each other and to the present day. It is the only part of the time scale which is so planned and it has been further continued to include the period in which we now live as 'Holocene' (*Holo*—entirely). But deposits of the Holocene period are more often called 'Recent'.

Unconformities

From the premise that at one time or another various parts of the earth's crust have been elevated above sea level and accordingly have been subject to denudation, it follows that nowhere on the land surface of the earth is there an unbroken series of strata extending from the base of the Palaeozoic to the Recent. Indeed, everywhere on the land tracts of today there are many gaps in the stratal succession, each of which may represent a vast period of time. Beds that have been laid down on an eroded surface of older rocks usually lie at an angle to the original floor; they are then described as being 'unconformable' to the lower strata. Unconformities are common features. They are often exposed in section in sea cliffs, in mountain sides and in quarries. One of the most striking is to be seen at Siccar

Point, Berwickshire, Scotland—where, as shown in Fig. IV, 1, and Plate IIB, a lower set of beds (of Silurian age) are almost vertical, and gently inclined beds (of Old Red Sandstone age) lie on their eroded upturned edges. This unconformity is of particular interest as it was one of those used by Hutton in his first scientific demonstration of an unconformity. Other excellent examples in Great Britain are to be seen near Settle in Yorkshire, at Frome in Somerset, in the Bristol district of Gloucestershire, and at Pegwell Bay in Kent.

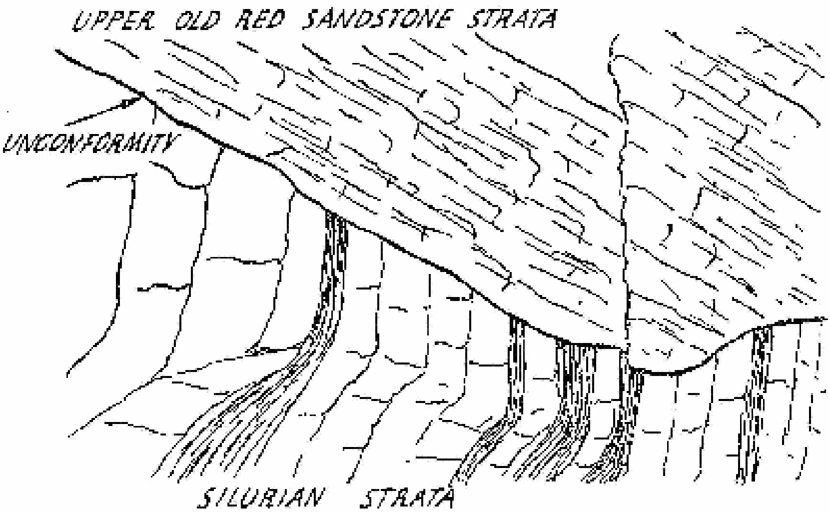


Fig. IV, 1.—Unconformity at Siccar Point, Berwickshire. The Silurian strata were first tilted to a high angle by earth movements. Then followed a long period of erosion, succeeded by the deposition of Old Red Sandstone strata. The whole was subsequently tilted slightly.

An unconformity where present clearly separates one geological bed or group of beds from another. Some unconformities are very extensive, others are very restricted; but none is world-wide. Nor do they necessarily make reliable criteria for separating one system of rocks from another, although they may clearly mark the separation of units of much less importance. In parts of Britain for example there appears to be a gradual transition from Palaeozoic strata into the Mesozoic, for it is impossible to delimit the Permian strata from Triassic (*see* Table of Strata on pp. 77, 78). In the London, North Kent and Essex areas, Tertiary strata are certainly delimited from those of the Mesozoic by a strong unconformity, at the base of the

Thanet Sand, but in the Pyrenees and in America there is a continuous transition from the Cretaceous into the Eocene. Fossils, rather than unconformities, are therefore most useful as the primary basis of separation of strata into groups and systems of world-wide application.

Names of strata

A stratum, or a group of strata, which is separable from beds above and below, on account of the general characters of the rocks, and is of sufficient importance to merit the distinction, is called a 'formation'. The term has somewhat vague implications and is particularly valuable on that account. It is customary to label a formation either from a locality where it is typically present or according to its general composition or by a combination of both methods. London Clay, Forest Marble (the forest being the Forest of Wychwood, Oxon), Millstone Grit, Shineton Shales, Spilsby Sandstone and Durness Limestone are examples of formational names.

In the nature of things, names of this kind have a limited validity. Strata of the same age, even within the same country, have received different names in different districts; and to a greater degree in different countries. No practical difficulty arises, however. The table of periods, representing as it does a continuous time sequence from the beginning of the Palaeozoic to the present day, is a standard reference table, by the use of which the mutual relationships of the main formations of an area may be broadly brought out. By its means formations of one district or of one country may be approximately correlated with those of another. It is, however, insufficient for detailed correlation which requires a linkage with the smaller time units of epochs, and, through them, with fossil 'horizons' and 'zones' described above (p. 48).

Puzzles of the Pre-Cambrian

The datum line of the time scale, placed at the base of the Cambrian, has no validity in nature, except that there is in general a world-wide absence of fossils in the Pre-Cambrian strata, and a sudden appearance of a fauna in a relatively advanced state of evolution in the Cambrian. No convincing theory has yet been put forward to account for this phenomenon, but it certainly does not support an argument that there is a world-wide unconformity at that level. It is true that there is a great unconformity at the base of the Cambrian in Great Britain, but it appears most likely that during

the period which this gap in the strata represents, deposition was taking place in other parts of the world. The value of the datum line is that of geological convenience.

Pre-Cambrian strata undoubtedly contain numerous large 'systems', related to various geosynclinal and mountain-building episodes of the very early periods of the earth's history, but it is not possible to place them in any systematic order. While those strata which are related to geological time above the datum line can be placed reasonably well in their correct order of superposition, those below the datum cannot, and they present many geological puzzles. Locally one system of rocks may be seen to be older than another in the same neighbourhood, but on existing evidence that is the limit of possible correlation. It is not certain even that all possible Pre-Cambrian systems are known; as lately as 1952 Russian geologists have claimed the existence of one that had hitherto been unrecognized.

From time to time various structures discovered in Pre-Cambrian rocks have been claimed as fossils, only to be proved on close examination to be of inorganic origin. There are, however, traces of primitive plants, including blue-green algae and simple forms of fungi. Some Pre-Cambrian rocks are igneous, others were probably originally sediments that have been metamorphosed in greater or less degree.

The geological history of Great Britain

The succession of strata in Great Britain is pre-eminently a suitable one to illustrate the historical side of geology. Within its small area the country contains representatives of every one of the geological systems from the Cambrian upwards, and of several Pre-Cambrian systems, all of which crop out at the surface; and if the proviso of 'cropping-out' be omitted, they are mostly present even in the area of the three counties of Kent, Surrey and Sussex. Except very locally and in minor degree, none of the strata subsequently to the Devonian has been changed in character by metamorphism. The British succession is seen to be the more remarkable when a comparison is made with those of many other countries. Each of the geological 'shields' of the Baltic, Africa, Canada, and India, for instance, is of vast extent. Since these tracts have been stable for the greater part of post-Palaeozoic time at least, and some for very much longer, only a few major formations are exposed at the surface, and these are mostly of ancient date. It may be necessary to travel over them some hundreds of miles from one spot to another in order

to meet with strata of greatly different ages. In the mountain belts of the Alps, Pyrenees, Himalayas, Atlas Mountains, Rocky Mountains and others, the strata, even those of Tertiary date, are often so tremendously disturbed and altered that recognition of age becomes difficult.

Three mountain-building periods

Since Cambrian times there have been three great periods of clearly defined geosynclinal movement, each followed by mountain-building upheaval. These have controlled the historical development of the geological structure of Great Britain.

The first of these, accompanied by much igneous activity, occurred during the Devonian period. The resultant mountain range, the Caledonian, extended through Scotland into Wales and Ireland. These areas appear to lie more or less near the main line of disturbance, and the phenomena of faulting, folding and metamorphism, characteristic of earth movements, are everywhere present in marked degree.

The end of the Carboniferous period and the beginning of the Permian saw the second period. Mountains of this episode ran roughly east-west through the north of France, and the attendant earth movements gave rise to land areas to the north, parts of which became hot deserts.

The third period was at the end of the Oligocene period, and during the Miocene. The Pyrenees, the Alps, the Caucasus and the Himalayas were all forced up along the line of the very elongated sea (known to geologists as Tethys) which had marked the geosyncline which had given them birth.

The areas of maximum disturbance of these last two mountain-building periods, however, were more distant from Great Britain than was that of the Devonian period. Although pressures were insufficient to produce metamorphism of British rocks, they subjected the crustal strata of the tract around and including Great Britain to great strains and stresses, in such a way that movements of depression and elevation continuously alternated. Moreover, premonitory crustal movements appear to have occurred long before the advent of each of these geosynclinal mountain-building 'earth storms' and movements continued long after, so that in effect the earth's crust of the British area has permanently been in a state of unrest.

Strata have been formed somewhere or other in this small tract during every geological period, and under many widely different circumstances. Igneous, sedimentary and metamorphic rocks are

present in great variety. There have been volcanic episodes. Deposition has occurred in shallow seas; in deep-water seas; in large estuaries; and in fresh-water lakes. There have been ice ages; times of temperate climate; and periods of tropical heat to produce both hot dry deserts and tracts of tropical vegetation. The net result has been the formation of rocks of many kinds, which yield us coal, iron ore, building stones in variety, road metal, roofing slates, sand for building, glass-making and moulding, clay for bricks and pottery, china clay, gypsum for the manufacture of plaster of Paris and other plasters, chalk and limestone for lime and cement, common salt and other kindred substances for many purposes, and gold, silver and other metals, gemstones and other less common materials both for everyday use and for luxury.

Pre-Cambrian Rocks

These very ancient rocks must obviously occur at some depth or other beneath the whole of the earth's surface. They are often very deep down, but at a number of separate localities in Great Britain they come to the ground surface, appearing through outcrops of newer rocks. Mostly they have been subjected to intense pressures and heat; they are all very hard, and many have been greatly compressed.

Much of Anglesey is built of gneisses and schists; largely metamorphosed igneous rocks, although some are altered sediments. Granites, pillow lavas and tuffs are also to be seen. Pillow lavas are extremely interesting igneous rocks which may be formed when a lava stream enters water. Still viscous masses break off, which immediately get a chilled outer skin, and, being soft within, each assumes a shape reminiscent of a pillow. Pillows may be piled up on each other or may roll down a sloping sea bed, or they may be disposed in a number of ways according to local circumstances.

Near Llanberis, rhyolitic lavas and tuffs provide definitive evidence of Pre-Cambrian volcanic activity.

In Shropshire there is a variety of Pre-Cambrian rocks, all metamorphosed. Some of these, as at Anglesey, were originally igneous rocks of various kinds, others were undoubtedly sediments, but others again have been so highly changed in character that in the first instance they may have been either.

At Charnwood Forest, Leicestershire, a great thickness of Pre-Cambrian rocks is largely volcanic in origin, but it also contains water-laid conglomerates, sandstones and clays now metamorphosed

into slates. Other areas of these ancient rocks in England are at Ingleton in Yorkshire, in Pembrokeshire, in North Wales and at the Lizard in Cornwall. Eddystone Lighthouse is built on rocks of Pre-Cambrian age.

In Scotland the oldest Pre-Cambrian system is the Lewisian of which the rocks are of very variable types, mostly gneisses. Strata of another system, the Dalradian, occur in the Southern Highlands of Scotland. They comprise a group of schists, gneisses and crystalline limestones, extending in a broad belt from the Firth of Clyde through Aberdeenshire to Banff. Rocks of a third system, the Torridonian, are largely red sandstones, conglomerates and shales. These occur over large areas of north-west Scotland.

Cambrian System

Cambrian rocks, largely gritty sandstones and black shales and slates, crop out over much of Wales. In Scotland they form part of the Highlands, where they include limestones and quartzites. Cambrian strata also occur in the English Lake District and come to the surface in smaller areas of the Midlands, notably in Shropshire, the Lickey Hills, Nuneaton and at Malvern. As with the Pre-Cambrian, earth movements that have acted on these old rocks have changed the form of many of the original sediments, so that slates now represent practically the whole of the original clay deposits. All the rocks of the Cambrian, therefore, are hard. Very little is known either of the geography of Cambrian times, or of the general distribution of those Cambrian rocks which now lie buried beneath newer strata. They have been proved in a few boreholes, notably in one at Calvert in Buckinghamshire and at another in Leicestershire. It is possible that they are present at other areas underground at greater depth than has yet been reached, but they definitely do not lie concealed everywhere beneath newer strata throughout the country where newer beds occupy the ground surface.

Ordovician System

Ordovician rocks also include both sediments and igneous rocks. They come to the surface over large tracts of Southern Scotland, the Lake District and North and South Wales and Shropshire, and also over a few smaller districts in Yorkshire and Cornwall. Ordovician sediments are of two distinct origins, shales and mudstones laid down in deep water, and shallow-water sandstones and limestones. Igneous rocks occur at intervals throughout the Ordovician sequence

of strata but volcanic activity appears to have been intermittent, and to have taken place only in some areas, although volcanic dust and ashes are widely incorporated in the strata.

It is possible that many of the Ordovician rocks of Wales were laid down in a shallow sea, and on the flanks of islands, of which Anglesey and the area of the Longmynd in Shropshire may have been two.

Silurian System

The great earth movements that took place at the end of the Ordovician period re-cast entirely the geography of a very wide area. In the Silurian, as in the Ordovician, both sedimentary and igneous rocks are present. They occur in many parts of Wales, in Shropshire and Herefordshire, at a small area in Tortworth in Gloucestershire, and at Girvan and at Moffat, Lanark, Pentlands and other places in Scotland. Some of the Silurian limestones contain vast numbers of beautifully preserved shells as fossils. Igneous activity occurred mainly in the North Welsh and Scottish areas, whereas strata of the Central England area appear to be largely sedimentary. During the latter part of the Silurian period a thick series of sands and sandstones, with conglomerates, known as the Downtonian Series, was deposited which is transitional into the overlying Devonian.

Devonian System

At the close of the Silurian period a gradual change in geography took place. Sea areas existed south of what is now the Bristol Channel area. For a great distance north of this area conditions seem to have been somewhat similar to those of the interior of South Australia today. The ground appears to have been fairly flat, so that after heavy rainfall shallow lakes were formed by torrents from the local hills, which also brought down vast quantities of mud and sands. During periods of dry weather these shallow lakes partly or completely dried up. Much of the finer material may have been transported and accumulated by wind.

Strata of Devonian age, therefore, are of two main types: marine beds, and red marls and sands which are termed Old Red Sandstone. Around Torquay the beds are of marine type, and are limestones. Kent's Cavern, well known to visitors to Torquay, has been formed in this Devonian Limestone. Strata of Devonian age that occur along the coast of North Devon and West Somerset were originally sandy and muddy deposits that have since metamor-

phosed into slates. They give rise to the remarkable coast scenery of Morte Point and the cliffs round Lynton. In the inland parts of North Devon the marine beds are also largely slates. Marine Devonian rocks underlie the London area at the considerable depth of about 1,000 ft.

The Old Red Sandstone type is present in South Wales and along the Welsh Borders. It covers a large part of the Midland Valley of Scotland, where the sandstones are usually coloured dull red or grey, and it extends up the east side of the country and northward to the Orkneys. To the palaeontologist the Old Red Sandstone has a particular interest, for the earliest known types of fossil fishes lived in the lakes of the period.

Beneath parts of south-eastern England the Old Red Sandstone lies at depth, and it probably occurs concealed under newer rocks over other large parts of the country. Under London it overlies marine Devonian.

The geosynclinal earth movements of the Devonian were accompanied by much igneous activity. Volcanic rocks are particularly well developed in the Old Red Sandstone of Scotland. The granites of Ben Nevis and the well-known Shap granite of Cumberland are also of Old Red Sandstone age. Pillow lavas (*see* p. 60) occur in Devonian strata around Tintagel, North Devon.

CARBONIFEROUS SYSTEM

The Carboniferous strata of Great Britain were laid down under very varied conditions both of physiography and of climate. Over wide tracts a clear-water sea stretched at first, although at the same time there were muddy-water conditions over the area of the present-day Devon and Cornwall and also over the northern part of England and parts of Scotland. The sandstones and shales which are so well exposed in the cliffs near Bude, Hartland Point and Clovelly and also in East Fife were laid down in this muddy sea. In the clear-water seas limestones were formed. These are the 'mountain limestones' of Somerset, Wales, Gloucester and the Pennines; some were coral reefs. The limestones themselves, however, include a great variety of rocks.

Marine conditions ultimately gave place to deltaic flats at or near the mouths of great rivers which flowed from the land areas of the time and were probably subject to intermittent periods of flooding (as are rivers today). In any event they brought down immense quantities of sand and gravel which have been compacted into stone, and are known today as the 'Millstone Grit', so named

because the hard gritty sandstone yields admirable material for millstones. In Derbyshire thick beds of cemented Millstone Grit sandstone form the well-known 'edges' which give the characteristic and extremely attractive scenery of Hathersedge and other 'edges' of that district. Grits are prominent around Kinderscout, in the Peak, one bed being named the Kinderscout Grit. After the Millstone Grit episode, continuing crustal instability gave rise to a number of basin-like depressions. In these great masses of sand and mud were laid down, and from time to time thick masses of decaying vegetation were accumulated which today form our coal seams. Some of the muds became impregnated with iron, to form clay ironstones. These muds, sands and vegetation constitute the 'Coal Measures' formation which alone is some 8,000 ft. thick at its maximum, of which actual coal, although of such great economic importance, is in fact but a very small percentage.

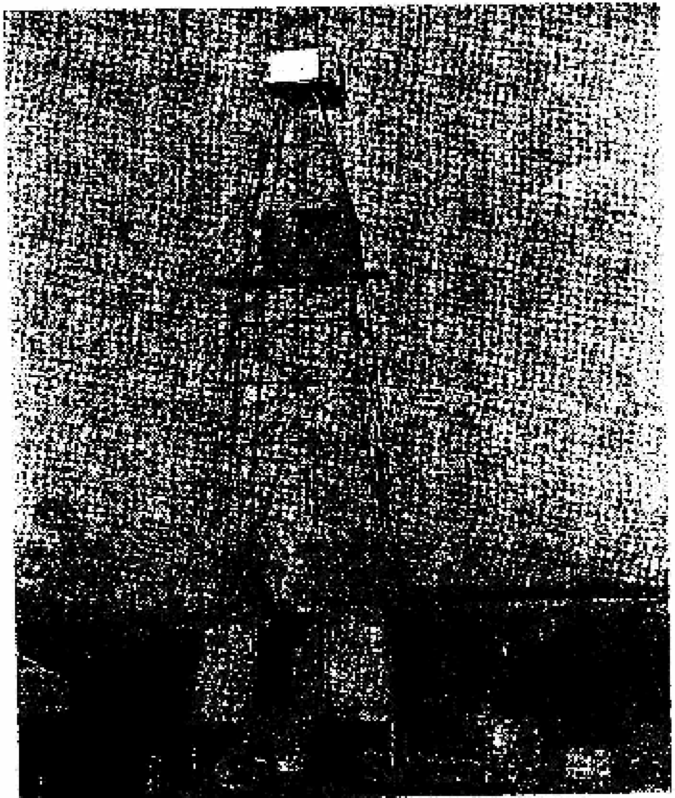
In the seventeenth century the word 'Measure' was used to describe an actual bed of mineral of any kind; obviously a bed which on account of its economic value was continually under measurement. Now only used in the plural, it includes as well as coal the strata in which most coal seams (though not all) are found. The Coal Measures are further described on pp. 175–194.

PERMIAN SYSTEM

The English Permian rocks contain two strongly contrasted types. In the north-east of England they are chiefly limestones which contain much magnesium carbonate as well as calcium carbonate, known as 'dolomite' (a name derived from the French geologist Dolomieu), or as 'magnesian limestone', and also pale yellow sands. These extend from Northumberland to the neighbourhood of Nottingham.

The second type is largely sandy, usually red or yellow. Sandstones occur in South Yorkshire, along the Welsh Borders, and in Somerset, Devon and Cornwall. The Permian red rocks of South Devon, to be seen so well alongside the railway between Exmouth and Teignmouth, give rise to much of the well-known red soil of Devon. These sandstones were formed largely from rock-waste derived from mountains lying even further south which were then slowly rising (*see* p. 95). The earth movements which caused them also produced in their northern foreland great east-to-west folds in the Carboniferous and lower strata of South Wales and Somerset.

Permian strata pass gradually upwards into Triassic. Both Permian and Triassic strata are often grouped as 'New Red Sand-



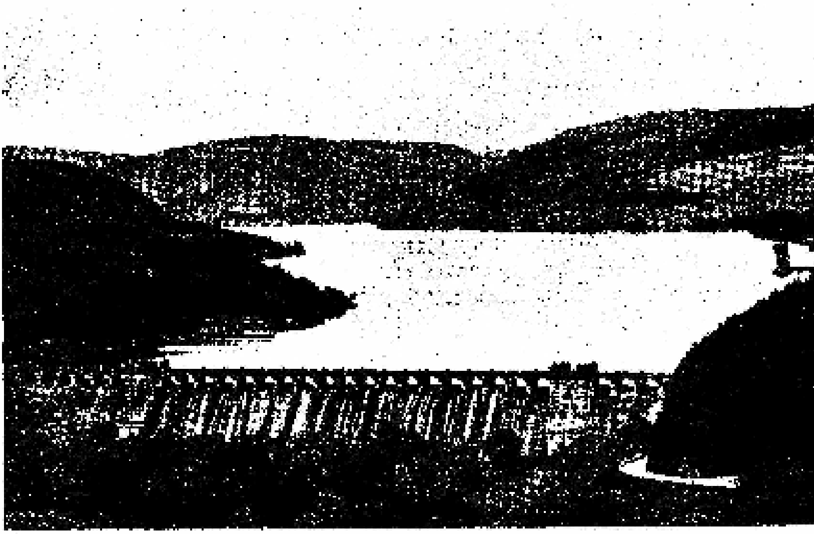
J. G. O. Smart

A. A modern drilling rig

Maryhill & Co.

B. Sandstone cores of 47 in. diameter from a borehole in Nottinghamshire

A. The Vyrnwy Valley, Wales, in 1890, before its conversion into a water Storage Reservoir. The dam is in course of construction



B. The Vyrnwy Reservoir today

stone' as distinct from the 'Old Red Sandstone', with which it has much in common in mode of origin. As far as Great Britain is concerned this is perhaps the most natural grouping. The New Red Sandstone, however, has to be accommodated to the accepted time scale. The arbitrary nature of the division between the Palaeozoic and the Mesozoic is clearly shown by the fact that it occurs in the middle of this locally indivisible group of beds.

TRIASSIC SYSTEM

Throughout the Triassic period climatic conditions generally were those of a hot desert and the great majority of the beds are consequently of desert type. The lower part of the Triassic system (commonly shortened to Trias) consists of mottled red and white sandstone locally several hundred feet thick; many pebble beds are present. This part is known as the 'Bunter' (German *bunter*, mottled). The upper part of the Trias is largely red marl, distinguished as the 'Keuper', an old name that was given by German miners to the red marls that were met with in their mines, and one of the borrowed geological names. During the Trias large lakes were formed into which rivers of considerable size drained. Both rivers and lakes intermittently dried up leaving behind in the lake-basins deposits of salt which had been brought into them by the contributing rivers. Thus this formation contains today the important salt beds on which much of the chemical industry of Great Britain is founded. In addition to salt, gypsum was deposited in these lakes, particularly in the Nottingham area and in Cumberland. A deposit which was laid down in the Bristol–Gloucester area is the less common mineral celestine (strontium sulphate), used extensively in many industries. The nearest present-day parallel of conditions which existed at the time of the Trias is probably to be found in America in the Salt Lake district of Utah.

The Trias is separated from the next great system of Great Britain, the Jurassic, by a thin series of rocks known as the Rhaetic. These consist almost entirely of marine beds, but climatic and other conditions were very unfavourable to animal life. Numerous marine shells are present as fossils but they are all of very stunted type. The Jurassic period on the other hand was characterized by an abundance of animal life. It is apparent that the Rhaetic period was transitional from the sterile conditions of the Trias into those of a more favourable climate. Indeed, the Rhaetic has been regarded as a separate system, and it has been included alternatively with the Trias and with the Jurassic according to personal veiws. In Great

Britain it is usually included with the Trias, although the fossils it contains are closely related to those of the Jurassic.

JURASSIC SYSTEM

During the Jurassic period there was again marked localized crustal subsidence first in one area and then in another. The result was that the Jurassic period saw the formation of great series of shallow-water marine deposits which today consist of clays, sands, sandstones and limestones. That the period was most favourable to marine animal life is shown by a great abundance of fossils.

Jurassic rocks come to the surface over a great belt of country extending from the Dorset coast to Yorkshire and they underlie much, though not all, of the country to the south-east. It is probable that at one period Jurassic beds extended a considerable distance to the westward, but if so they have been removed by erosion. This probability is shown by remnants that occur off the west coast of Scotland; in Skye beneath lavas of later age, in Rasaay and Mull and on the borders of Moray Firth.

The first of the Jurassic formations is the Lias, a great series mainly of clays which today have been consolidated into shales of medium hardness. There are also beds of limestone and ironstone, the latter providing a source of iron ore. Variations in thickness are great. In three basins in particular, in the Bristol-Gloucester area, under the eastern part of the Weald, and in the Midlands there are very thick accumulations. In the Bristol-Gloucester area a thickness of about 2,000 ft. has been proved in a deep borehole at Stowell, near Northleach, whereas in other areas it is not more than 200 ft. thick, and elsewhere again, even where other Jurassic strata are present, the Lias is absent.

Several derivations for the word 'Lias' have been suggested. It is undoubtedly an old countryman's term, and the most likely seems to be from Celtic *Lass*, a flat stone. In the clay-lands of the Lias stone beds have always been valuable. As in the case of the Coal Measures, an important product, though small in percentage of the whole, has given its name to a great containing mass.

Next in the Jurassic system comes a group mainly of shallow-water limestones, the Inferior Oolite Series. Many of these limestones are composed of small rounded grains, reminiscent in appearance of the hard roes of fishes. Each grain is an 'oolith' or egg-stone and a rock that is comprised of ooliths is an 'oolite'. But the series is extremely variable in composition and it contains numerous subordinate clay beds and sand beds. A deposit of special economic value,

fuller's earth (*see* p. 234) occurs in the middle of the series. The name has been borrowed and given capital initial letters to denote the group of beds in which it occurs. Hence 'Fuller's Earth' is a Jurassic formation, whereas 'fuller's earth' is a substance of commercial value, obtained both from the Fuller's Earth and from some other geological formations (*see below*, p. 70).

The Inferior Oolite Series is followed immediately by another limestone group, the Great Oolite Series from which, in the Bath district, great quantities of building stone have been quarried. These two limestone series are followed by a widespread but thin limestone, the Cornbrash, a name redolent of the countryside. Brash is an old country word for a rubbly soil, or for that matter, for rubble of any sort. It may well be connected with 'breccia', a deposit of angular rock fragments. This limestone country has long proved to be excellent corn-growing land, and where the limestone lies just below the ground surface, fragments are easily torn up during cultivation, to form a rubbly soil. The name Cornbrash was given by William Smith to the formation in 1815, but it may well be much older as a farmer's term.

The Cornbrash in the Bedfordshire–Huntingdonshire district is followed by a succession of clays, comprising the Oxford Clay, the Ampthill Clay and the Kimmeridge Clay; three formations with place-names. In the southern half of England this succession is interrupted. There the equivalent of the Ampthill Clay consists of sand and limestone beds somewhat similar to the Great Oolite. The limestone contains many fossil corals and is consequently known as the Corallian. The Kimmeridge Clay again was succeeded by another oolitic formation, present only in the southern part of England, the Portland Beds, from which the Portland building stone is obtained.

Similarly to the Lias, all these beds possess the characteristic of a thickening and thinning from place to place, resulting from slight and irregular crustal movements while they were being laid down. In the Kent–Sussex area the concealed Kimmeridge Clay was proved at Mountfield, north of Hastings, to be over 1,200 ft. thick, whereas at Dover it is only 8 ft.

The Jurassic period closed with the great part of the British Isles as a land tract, undergoing the normal process of erosion, but a large lagoon or lake or possibly series of lakes extended over the present south-eastern England. Over this area Purbeck Beds were laid down. These include characteristic Jurassic clay, limestone and sandstone types of rock, but whereas the fossils of the remainder of the Jurassic

are all marine, those of the Purbeck Beds are largely, though not entirely, fresh-water, the earlier part of Purbeck times having been marine. The climate seems to have been hot, for as happened during the Trias, and as happens in hot deserts today, the marine lagoons dried up and thick beds of gypsum were formed, that are now mined extensively in Sussex for the preparation of plaster of Paris and other cements. The Purbeck Beds contain shelly limestones, which were originally banks of living fresh-water shells. These take a high polish, and furnish the Purbeck Marble which has been used extensively for fine interior decoration in many of our cathedrals and churches.

The transitional Jurassic-Cretaceous interval was one mainly of erosion. The relatively minor earth movements that had caused crustal depression first here, then there, throughout Jurassic times still continued, and many areas of Jurassic strata were strongly folded before any newer rocks were laid down.

The Surrey, Kent and Sussex tract of country, however, appears to have remained below water throughout this transitional period, for sedimentation was continuous from the Purbeck into the lowest of the Cretaceous Beds. There is no denudation plane to mark the separation between the Jurassic and the Cretaceous, although there is a great unconformity elsewhere.

Cretaceous System

Strata of the Cretaceous system are to be found to the east and south-east of the Jurassic both at the ground surface and deep beneath still newer rocks. The most important formation is the Chalk, the topmost formation, which crops out to form Salisbury Plain, the Dorset Heights, the North and South Downs, and the Chiltern Hills, which continue into the Gog-Magog Hills of Cambridgeshire, and so through the Lincolnshire Wolds into Yorkshire. The central ridge of hills of the Isle of Wight is also Chalk. The lowest Cretaceous strata are those clays and sands referred to above which are continuous with the Purbeck Beds; they occur over a very restricted area of parts of Surrey and Sussex. The area of depression, marked originally by the Purbeck Beds of this district, gradually widened and deepened. Firstly the Hastings Beds—also sands and clays—then the Weald Clay were successively deposited. The latter is present beneath newer strata over much of south-eastern England as well as at the ground surface in the Weald. The Hastings Beds and Weald Clay were probably laid down in a great fresh-water estuary; at the same time a depression which developed in the

present Lincolnshire area was occupied by the sea, which gave rise to a group of marine sands and clays.

Ultimately the sea also broke into the hitherto fresh-water tract, to lay down a group of beds which are mainly sandy, but which also contain clay and limestones. These beds constitute the Lower Greensand, and today they furnish the bulk of the building sand used in the south-east of England. They also give much road-metal and, of great economic importance, fuller's earth. The limestones also make excellent building stone.

Crustal depression still continued after Lower Greensand times, and affected a great part of southern and eastern England. In the deeper-water sea which thus resulted, a clay stratum, the Gault, was laid down. In the West of England, gault, or galt, is a countryman's name for clay and it is still in use to mean clay in general. It is still another common word which has been borrowed for geology, to be retained for a specific formation. The Gault is succeeded upwards by the Upper Greensand; in fact, much of the Upper Greensand is the time-equivalent of the upper part of the Gault.

The names Lower Greensand, Gault and Upper Greensand are connected historically. The first is quite illogical, and it fully merits a frequently-made gibe that the Lower Greensand is never green, and often is not sand. Various early nineteenth-century geologists who worked in the West of England had noted a thick sand formation which often is of a definitely greenish hue resulting from the presence in the sand of a high proportion of the green mineral glauconite. This bed was called the Greensand; it is obviously below the Chalk. But the bed of 'galt' had not been traced across country. A bed of sand in the Weald, although of different kind from that of the West Country, but also obviously below the Chalk, had also been called the Greensand, and assumed to be the same formation as the other. For some years there was considerable confusion, but ultimately the true position was discovered (largely by a distinguished geologist, W. H. Fitton) that there was one 'Greensand' above the 'galt', and another below. The difficulty was resolved by calling one 'Upper Greensand', and the other 'Lower Greensand'.

The soft white limestone which constitutes the Chalk appears at first sight to be homogeneous throughout, except for bands of flints which appear in great number in certain areas. Flint bands are a marked feature in the cliffs of the Isle of Wight and of Sussex in particular.

But indications of the instability of the earth's crust show themselves even in the Chalk. After Upper Greensand times a submergence occurred of a vast tract including amongst other areas much of present-day North France, part of Germany, Belgium, Holland, Denmark and most of Great Britain. At first, rivers continued to bring in mud, as they had done into the Gault sea. As far as the Chalk of Britain is concerned, the lowest 150 ft. or so are in many places mixtures of chalk and clay, known as Chalk Marl. But the proportion of mud to chalk material gradually lessened, and the great mass is practically pure calcium carbonate.

There were at least three periods when chalky deposits laid down in fairly deep water were raised up at least to come under the influence of currents, and partly to be washed away and re-sorted.

The almost complete absence of river-borne mud in the Chalk sea is a geological enigma. It may be that the surrounding land areas were hot deserts, in which case there would have been no rivers; or land (except for a few islands) may have been so distant that no river-borne material could travel the distance.

The origin of flints is a second unsolved puzzle furnished by the Chalk, but it is generally thought today that flints which are composed of almost pure silica are concretions formed long after the Chalk was laid down.

STRATAL NOMENCLATURE: A DIGRESSION

The facts that the Lower Greensand is never, or almost never, green (the great bulk of its sand is either brown or a pepper-and-salt grey), and that it contains considerable thicknesses of clay, sandstone and limestone, serve to bring out an important point in the nomenclature of geological strata, namely that many names of formations include a common rock-name, which is then always spelt with a capital initial letter. Examples are Lower Greensand; Kimmeridge Clay; Lincolnshire Limestone; Forest Marble. Rendered in this way, the name covers all the strata that are included in the formation. Obviously the greater bulk of the beds so labelled would be expected to conform with the rock description, but a high proportion may not do so. Kimmeridge Clay includes many beds of limestone, as may be seen in the cliffs at Kimmeridge Bay, Dorset; but Kimmeridge clay with a small 'c', is clay substance from the Kimmeridge formation; similarly 'Chalk' implies the whole Chalk formation, whereas 'chalk' names the rock. Chalk alone, of all British formational names, may cause some ambiguity. When it commences a sentence, it takes a capital initial, even though it may

refer only to the substance; but the context usually clarifies the position. Further, the name of the System which includes the Chalk, *i.e.*, the Cretaceous, is derived from the Latin *creta*, chalk, although as is inferred on page 55, more than half its components are sandstones or clays.

EOCENE SYSTEM

The junction between the Chalk and the overlying beds of the Eocene system is marked by an unconformity which undoubtedly represents a vast interval of time. This interval saw a complete change in the geography of the European-Atlantic area. The area of Great Britain became land which, in the natural course of events, was subjected to considerable denudation. But at some time during the transitional Cretaceous-Eocene time which is marked by this unconformity a depression occurred in the crustal surface more or less along the line of the present Thames Estuary, shallowing westwards. This was invaded by the sea, and sandy beds were laid down. These sands are the 'Thanet Sands', so named from the area where they are most typically developed, as in fact are all the various strata of the Eocene. The next stage was that of a great river, which rose somewhere in the west, to flow eastwards. The northern bank lay along a line through Reading and North London. In its large estuary clays were laid down, which are particularly well developed around Reading, and as far south as Southampton. These estuarine beds gradually change into marine types as they are traced eastwards, and with the contemporary marine beds are collectively known as the Woolwich and Reading Beds. Depression of the crust continued, and a great area of south-eastern England was inundated. Further clay beds were laid down which are well known today as the London Clay. As depression ceased the inundated area became silted up, and sands again were laid down which today cover great areas of Bagshot Heath and the New Forest. These are the Bagshot Sands.

OLIGOCENE SYSTEM

Continued depression in the Isle of Wight area led to the deposition of a number of sand and clay beds which today are present only in the Island. These include the Headon Beds, the Osborn Beds, Bembridge Beds and Hempstead Beds. The only strongly characteristic rock in this series is a white limestone which occurs at the bottom of the Bembridge Beds and is known as the Bembridge Limestone. This has had a local importance as a building stone and may be seen in a number of the older buildings of the Isle of Wight.

MIOCENE SYSTEM

The Miocene period follows the Oligocene. During the period the whole of Great Britain seems to have been land area, subject to denudation. There are no Miocene deposits in Great Britain although they are present in great thickness in some other parts of the world. It was during this period that the Alpine mountain-building movements occurred.

PLIOCENE SYSTEM

The series of deposits next following the Oligocene are sands and clays which are present mainly in East Anglia. Traces appear along the crest of the North Downs and it seems probable that a certain degree of elevation locally took place after the episode of the Pliocene sea. This affected south-eastern England in such a way that the beds were gradually tilted towards the north-east. The Pliocene deposits of East Anglia are to be found today a little above or at sea level.

PLEISTOCENE DEPOSITS

The foregoing strata make up the solid fabric of the earth's crust beneath Britain. They are accordingly all placed under the group name 'Solid' strata. Over them is spread a series of uncompacted deposits, largely gravel, sands and clays. These belong to the present period of denudation, and from a geological point of view their lodgement is an interruption of their journey to the sea under the process of denudation. This superficial material is termed 'drift'. Formerly in Great Britain the division between the Pliocene and the Pleistocene was taken at the base of these drift deposits as seen over wide stretches of the country, although it was difficult to define a base in Norfolk, just as it is difficult to define a base to the Cretaceous strata in parts of Sussex and Surrey or to the Trias in Nottinghamshire. This general horizon was convenient for this country, but it was not suitable in other parts of the world. An international reference locality in Italy for the base of the Pleistocene was proposed at an international meeting of geologists in 1948, and agreed in 1952. In consequence the Pleistocene deposits of this country now include certain 'solid' marine deposits known as the Red Crag and Norwich Crag; beds found only in East Anglia—a 'Crag' there being a shelly sand, not a jutting rock. The Red Crag is to be seen largely around Walton-on-the-Naze. Although in some respects it is not entirely convenient to draw the line between the Pleistocene and the Pliocene at the beginning of the marine episode of the two

Crags, they actually do fulfil the requirements of the early significance of 'Pleistocene', that is, they both contain large numbers of shells of modern type, whereas the Coralline Crag immediately below them contains far fewer (*see* p. 55).

From the foregoing descriptions it will be seen that Anglesey is composed of some of the oldest rocks; that the newest, the Crags, are present in the eastern part of East Anglia; and that there appears to be a progressive decrease in age of strata as they are traced from west to east.

Such in fact is the general position as far as the ground surface is concerned. It comes about through the persistence of remnants of the Caledonian mountains, still to form the relatively low mountains of Great Britain, combined with a slight tendency of the stratal mass of the eastern and south-eastern parts of England to become tilted towards the areas of the present North Sea.

Even at the surface, however, this progressive arrangement is frequently interrupted, as is shown by the 'inliers' of Pre-Cambrian rocks in Shropshire, at Charnwood, in Yorkshire, and elsewhere. It follows of course from the law of superposition that lower beds are older than those immediately above them, and therefore that in normal circumstances a hole dug or bored into the earth encounters progressively older strata. But there is nowhere a general downward progression through all the main groups of strata of the stratigraphical table. The essentially basin-controlled conditions of deposition under which the bulk of the sedimentary strata of Great Britain were accumulated have resulted in great gaps in the sequence, occurring here, there and everywhere. At North Creake, in Norfolk, a borehole made in 1952 showed Trias to lie on Pre-Cambrian beds; under London, and beneath South Essex, Gault rests on Old Red Sandstone; in Kent and Sussex great thicknesses of Jurassic rocks occur, while the Trias is missing; and so on throughout the country. This complex underground arrangement of British sedimentary strata is illustrated by Fig. IV, 2, representative of the middle part of England.

The most important drifts of the country are those which were carried and ultimately deposited by ice during the Ice Age, and by torrential rivers which were later formed by melting waters. These were spread over the ground surface of great tracts of this country. In many areas the ice-laid deposits of Boulder Clay, which is a structureless mixture of clay and stones left behind by melting ice, completely obscures a pre-glacial topography.

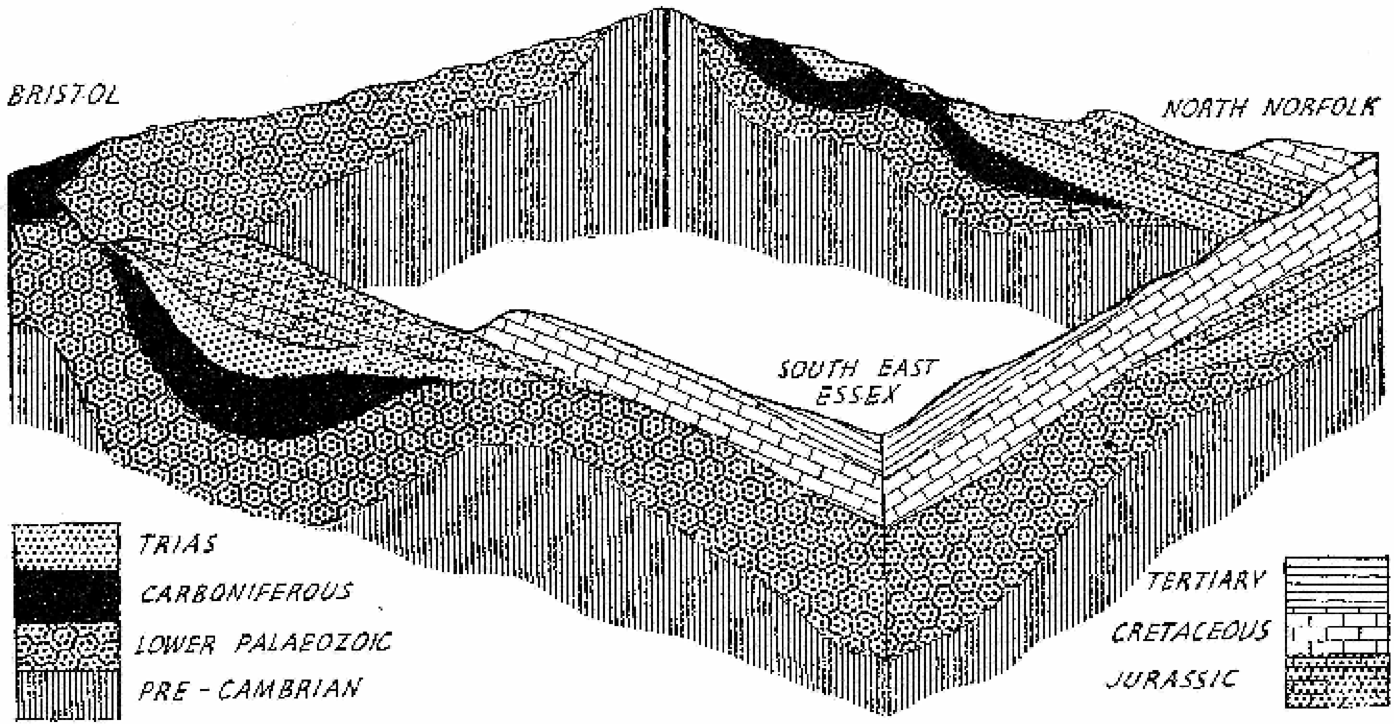


Fig. IV, 2.—This diagram, composed of four geological sections, arranged in the form of four sides of a box, shows that the concealed geological structures of the middle part of England bear little relationship to the general surface progression from ancient strata in the west to young strata in the south-east.

Boulder clay is consequently variable in thickness; glacial deposits are known up to a thickness of over several hundred feet in some localities, where they fill pre-glacial valleys, while short distances away they may be only 30 or 40 ft. thick. Southern Scotland, northern England, large tracts of the Midlands, and much of East Anglia are covered by Boulder clay with these characteristics.

During the Ice Age, flood water which was derived from the various glaciers laid down vast sheets of glacial, fluvo-glacial and river gravels. Many gravels can be traced as chain-like deposits known as eskers and kames, particularly in Scotland, the north of England and the North Midlands. Some of these mark the position of former englacial streams; other gravels form large terraces in river valleys. Since their deposition, a gradual amelioration of the climate has been accompanied by a diminution of the volume of water available for erosion and transport. The rivers which originally carried heavy loads of material have gradually lost their power and today comparatively little transport of material, compared with that of the late glacial period, takes place.

Rock hardness and age

From the foregoing brief account of the British strata it becomes apparent that as regards original composition and mode of origin the great mass of the sedimentary strata all fall within a few groups; they are either clayey, sandy, pebbly, or are limestones. They are distinguishable by their fossils, but it is sometimes said that they can also broadly be dated by the degree of hardness that they have attained through subsequent compaction; that the older the rock is the more compact it has become.

This is perhaps true of the clayey and silty deposits of Great Britain. Many of the original clays of the Cambrian, Ordovician and Silurian strata of this country have been so highly compressed through earth movements that they have been re-formed into slates or into phyllites, or, if not so transformed, have been indurated into mudstones. The original clays of the Carboniferous system have been compressed into very hard compact shales, the particles of which lie orientated more or less in the same direction, but they are not metamorphosed. Those of the Jurassic and Cretaceous systems are also shaly but less indurated, while Eocene clays, instanced by the London Clay, are compact but are not normally shales; while the recent alluvial clays of our river estuaries and the buttery clays of the Fenland are far from being closely compacted.

Sands and sandstones, and limestone, however, cannot be so

easily fitted into this generalization. Many sandstones and limestones of quite late geological age are very hard, while other sands, geologically much older, are still unconsolidated.

But induration as the result of pressure occurs irrespective of when pressure was applied. Many originally soft sediments, even of Tertiary age that have been closely involved in mountain-building processes are today very hard. The above generalization as regards original clay beds is reasonably true in Britain only because, as

TABLE OF THE MAIN GEOLOGICAL FORMATIONS OF GREAT BRITAIN

Era		*Period (and System)*	*Formation*	*Estimated Representative Thickness, in Feet*
QUATERNARY	CAINOZOIC	HOLOCENE (OR RECENT)	Terrestrial, Alluvial, Estuarine and Marine Beds of Historic Ages (Iron, Bronze and Neolithic Ages)	10–30
		PLEISTOCENE	Terrestrial, Alluvial, Estuarine, Marine and Glacial Beds of Palaeolithic Age Cromer Forest Bed and Norwich Crag Red Crag	as above (except Glacial Beds) 50
TERTIARY		PLIOCENE	Coralline Crag and Lenham Beds	40
		MIOCENE	No deposits in Great Britain	—
		OLIGOCENE	Hamstead Beds (in Isle of Wight only)	200
			Bembridge Beds (in Isle of Wight only)	100
			Osborne Beds (in Isle of Wight only)	80
			Headon Beds (in Isle of Wight only)	150
		EOCENE	Barton Beds	250
			Bracklesham Beds	600
			Bagshot Beds	100
			London Clay	400
			Oldhaven and Blackheath Beds	30
			Woolwich and Reading Beds	100
			Thanet Beds	100

SECONDARY OR MESOZOIC	CRETACEOUS		Chalk	1,000
			Upper Greensand	100
			Gault	300
			Lower Greensand	500
			Weald Clay	800
			Hastings Beds	650
	JURASSIC		Purbeck Beds	250
			Portland Beds	200
			Kimmeridge Clay	800
			Corallian Beds	50
			Oxford Clay and Kellaways Beds	400
			Cornbrash	20
			Great Oolite Series	140
			Inferior Oolite Series	150
			Lias	800
	NEW RED SANDSTONE	TRIAS	Rhaetic	40
			Keuper	1,800
			Bunter	1,000
PRIMARY OR PALAEOZOIC		PERMIAN	Magnesian Limestone	400
			Red Marls and Sandstone	800
	CARBONIFEROUS		Coal Measures	7,000
			Millstone Grit	2,500
			Carboniferous Limestone	2,500
	OLD RED SANDSTONE AND DEVONIAN		Upper Old Red Sandstone	4,000
			Marine Devonian	14,000
			Lower Old Red Sandstone	12,000
	SILURIAN		Downton Series, Ludlow Series, Wenlock Series, Llandovery Series	8,000
	ORDOVICIAN		Ashgill Group, Caradoc Group, Llandeilo Series, Llanvirn Series, Arenig Series	10,000 in North Wales
	CAMBRIAN		Tremadoc Slates, Lingula Flags, Menevian Flags, Harlech Series	up to 12,000 in Wales
	PRE-CAMBRIAN (not in sequence)		Uriconian; Longmyndian; Dalradian; Torridonian; Moinian; Igneous Rocks of Charnwood	

stated above (p. 59), no great mountain-building pressures have been applied to British strata since the Devonian period.

The thicknesses given in the Table of Formations on pp. 76 and 77 are described as 'representative' in preference to 'average'. A table of this kind cannot carry more than generalized figures, to convey some idea of the relative importance of one formation to others.

A sudden change in the order of thicknesses from hundreds of feet in the case of Tertiary and Mesozoic formations, to thousands for the Palaeozoic formations, reflects a comparatively high degree of knowledge concerning the former, and a limited idea of actual thicknesses of the latter. On an assumption that approximately equal thicknesses of sediments of similar kind would have been accumulated during periods of the same duration, irrespective of their place in geological time at least since the Cambrian, these figures also bring out the total lack of equality of duration between the later periods and those of the Palaeozoic. The Oligocene period, with only a little over 500 ft. of beds, is equated in the table with the Carboniferous period, and with other Palaeozoic periods each associated with some 12,000 ft.

CHAPTER V

Geological Surveys and Maps

ALL large countries of the world today, and most of the smaller ones, have official Geological Surveys, the nature of whose duties is summed up in the instructions given to one of the earliest surveys on record: "Ye shall describe the land and bring the description hither to me" (Joshua viii, 6). The particular function of a Geological Survey is to effect a stock-taking of its country's mineral resources of every kind, irrespective of any immediate values they may have. In this respect the normal work of the state-employed geological surveyor differs from that of the geological prospector, the latter using his scientific knowledge to search for specific materials such as ores of metal and other minerals, for which there is usually an immediate demand. In actual practice, however, there is a wide field of economic geology in which surveying and prospecting grade into each other. Information is accumulated impartially by a Geological Survey for the benefit of the general public, for whom it is codified and made available. One of the main vehicles by which it is conveyed is the geological map.

Early maps of surface strata

The idea of showing the surface distribution of rocks and minerals in map form is obviously one that would be likely to occur at any time to anyone conversant with the use of maps and charts. As long ago as 1683, the *Philosophical Transactions of the Royal Society* (Vol. XIV) record "An Ingenious proposal for a new sort of Maps of Countrys, together with Tables of Sands and Clays such chiefly as are found in the North parts of England, drawn up about 10 years since, and delivered to the Royal Society, Mar. 12th, 1683, by the Learned Martin Lister M.D." Some sixty years later, in France, one Jean Etienne Guettard produced a 'mineralogical map' similar in

conception to Lister's, and the ensuing hundred years saw, in various forms, other realizations of the same idea. Yet none of these maps, however valuable it may have been at the time, was a geological map in the sense that is understood today.

Topographical and geological maps compared

Topographical and geological maps are radically different from each other both in conception and construction. The former is a straightforward representation of surface features, both natural and artificial. Within the limitations imposed by the scale of a map, its boundary lines define precisely the areas and relative positions of the features shown, and it takes no cognizance of anything beneath the ground surface. It is to be taken strictly at its face value, so to speak. A geological map, on the other hand, is three-dimensional in conception, and basically is the pattern that is produced on the upper surface of a solid block composed of various layers, and sometimes irregular masses, of rock. These may be arranged in any manner from simple to highly complex. Such a pattern may be intricate even on a plane surface; but the pattern made on the ground surface by the outcrops of the strata is still further complicated by the irregularities of surface relief. On this view alone a geological map would seem to be largely a matter of solid geometry. That is true to a certain extent, but it is much more. It is vitally alive, as it were, not merely a cold piece of geometry. It carries a challenge to its user to interpret, from its face, the nature and arrangement of the strata which remain unseen below the ground as well as those which occupy the surface; and to read the geological history of the area represented.

Topographical and geological boundary lines

On a topographical map a boundary line normally represents an edge of a finite area—it may mark the limits of a field; the side of a building; the edge of a road—and it is precise. A geological boundary line is something quite different and it cannot always carry this attribute of precision. Excluding a 'fault line' (described below), at its simplest it is best conceived as marking the intersection of the basal plane of a geological formation with the ground surface. The precision of the boundary line depends on the precision with which it can be located in the field, which very often is far from absolute.

In cases where one bed overlies another of a radically different rock type, as for example sandy Thanet Beds resting on Chalk, the base of the upper bed (which obviously is also the junction of the

two formations) may usually be traceable with great accuracy in the field. On occasion even this may not be possible. It is not possible in the above instance in areas where the base of the Thanet Beds coincides very nearly with the contour of the ground surface. These conditions produce a 'feather edge' in which Thanet Sand may be only a foot or so thick over a belt of country half-a-mile wide. This is illustrated by Fig. V, 1. The boundary between the two formations is clear between A–A¹ but between B–B¹ and C–C¹ its mapped position would vary according to the personal interpretation of the surveyor as to where he considers the feather edge to cease. In other cases the base of a formation may not be traceable in

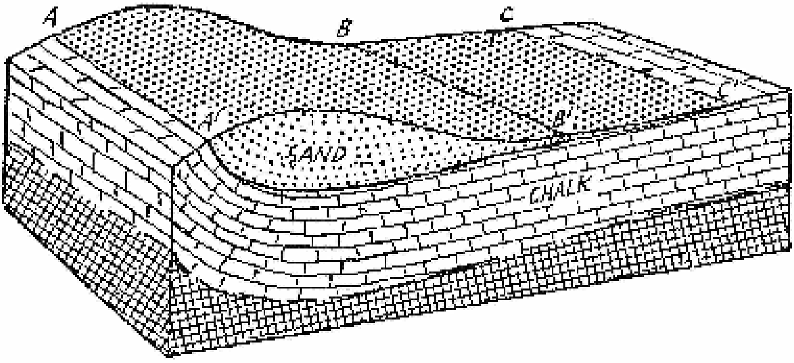


Fig. V, 1.—The position of a mapped boundary line along a 'feather-edge' of a geological formation is usually an interpretive one. Whereas the boundary A—A¹ is definite, a 'feather-edge' line may be correctly drawn anywhere between B—B¹ and C—C¹ according to the views of the surveyor.

the field over wide stretches of country, and its position at the ground surface may have to be determined by deductive reasoning from other evidence. Yet again, some geological formations pass into others through a series of 'passage beds' as shown in Fig. V, 2, and still others rest on lower beds of similar type. The very positions of the bases of such beds are, and can only be, matters of interpretation founded on evidence of various kinds, frequently data provided by fossils. In any of the above circumstances, were several surveyors each to map the same area independently each may produce a slightly different map; and each map would be of equal merit, provided it were self-consistent in its construction. In geological surveying the quality of consistency in selecting the criteria on which to insert geological boundary lines is fundamental.

A 'fault line' is a special type of boundary line. It marks the intersection of a plane of fracture and relative displacement of the strata with the ground surface, and is usually distinguished in some way from a boundary line drawn to show the base of a formation.

On a first reading, these remarks may well give an impression that the boundary lines shown on a geological map carry little conviction of precision. Such an impression would be quite erroneous; it would arise by a false comparison of geological with topographical boundary lines. Much care is taken in geological mapping to show them with the greatest accuracy possible. From a practical point of view, many potential slight differences of interpretation are automatically cancelled by the purely mechanical act of preparing a map. On a published map involving a reduction of a mile of actual country to the scale of one inch, draughtsmen's lines are normally of a width of about one hundredth of an inch; the line alone then covers a belt of land about seventeen yards wide. Again, it is current practice on many geological maps to show as continuous lines those boundaries which have been precisely determined, and by broken lines those which are less definite.

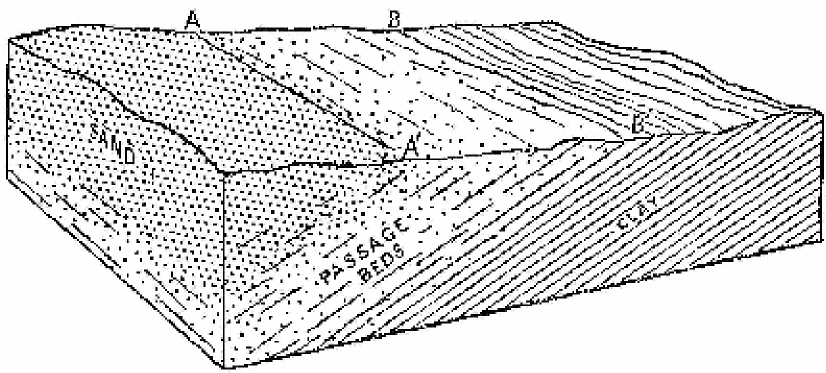


Fig. V, 2.—A mapped boundary line between two formations linked by 'passage beds' often depends on a personal interpretation. Different surveyors would place it in different places between A—A' and B—B'.

GEOLOGICAL EVIDENCE FOR MAP-MAKING

The field evidence on which a geological map is constructed is gathered from many sources—from natural cliff and river-side sections of strata, and from quarries; from records of wells and bore-holes and from records of strata encountered in mines; from casual excavations for building foundations and for civil engineering works;

from trenches dug for water, gas, sewerage mains and for telephone cables and the like; and even from spoil from rabbit holes; and of the greatest importance and irrespective of any of the foregoing, from the form of the ground surface. In recent years air photography has provided a further source of information. This proves to be particularly valuable in the less accessible and less populated parts of the world. The geological interpretation of air photographs is in reality a specialized form of reading geological structure from the features of the ground surface. Evidence from the above sources is often supplemented by numerous trial pits and auger holes, many made by geological surveyors themselves. To this is added laboratory work by palaeontologists, petrographers and others.

The direct information on concealed strata yielded by deep boreholes is invaluable. In most countries, however, the great majority of deep boreholes are made for prospecting purposes and they are put down in search for specific economic materials. Their distribution tends to be in groups. For example, the area of the Kent Coalfield has been proved by numerous closely spaced deep boreholes, while the remainder of south-eastern England has few. On occasion it may be concluded that the deep-seated structures of a large tract of country which appears to have nothing to offer in the way of encouragement to prospectors may hold a key to the interpretation of the geological structures of a very wide area. Many geological surveys today, therefore, commission deep boreholes purely for scientific exploration. In Great Britain recent explorations of this type include boreholes at Upton, Burford, Oxon. (3,770 ft., in 1953), Rashiehill, Stirling (3,860 ft., in 1952), Stowell, Glos. (4,500 ft., in 1952), Ashton Park, Bristol (2,195 ft., in 1953) and Canvey Island (1,750 ft., in 1953).

Reading a geological map

The art of reading a geological map requires that attention should be directed, not only to the boundary lines as such, but to the pattern made by the belts of colour or ornament marking the various outcrops, and to the characters of the strata which are represented.

A pattern standing by itself may often be indicative of more than one arrangement of strata. In Fig. V, 3, for example, A, B and C are three geological maps. Each could be the surface representation of several alternative solid structures, three of which, *a*, *b* and *c* are given in each case. Some pointer to the order of superposition of the

strata, therefore, is essential before the solid geometry, that is, the geological structure of the area, can be read. This essential information is normally provided at the side of a map in the form of a vertical index section, which is usually drawn to scale. This is

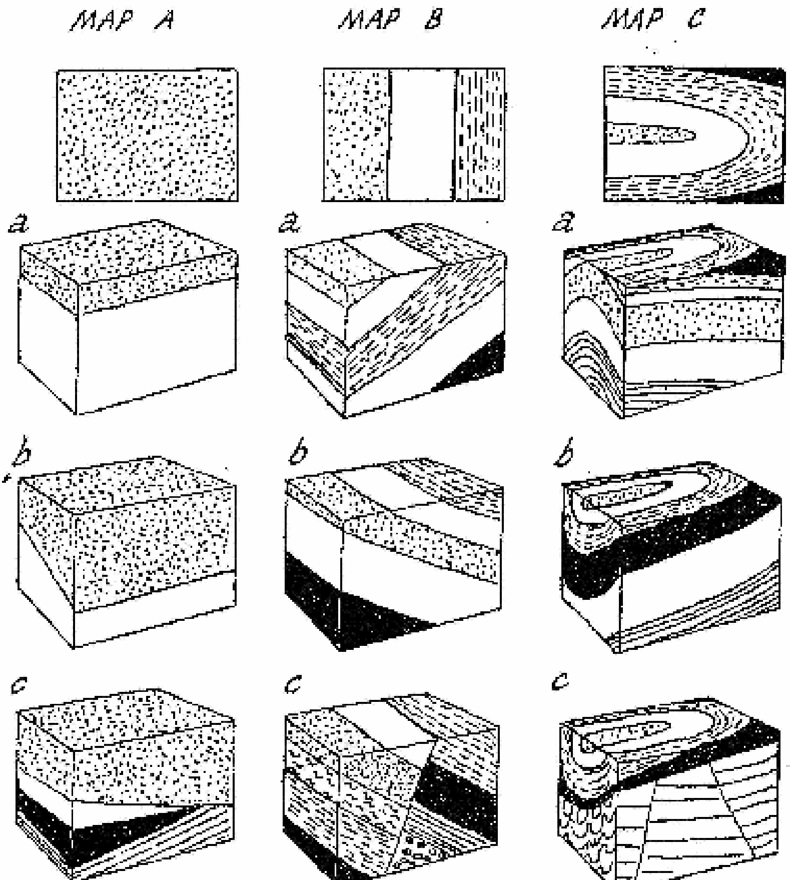


Fig. V, 3.—Each of three maps, A, B and C could be the surface representation of several alternative geological structures. In each instance three alternatives, *a*, *b* and *c* are shown. Further information is necessary in order to interpret the maps.

nothing but a stratigraphical column to show the order in which the strata were deposited, their average thicknesses, and any major gaps in the succession that may have been produced by the erosion of former surfaces. The different strata are named, and they are

normally placed in the geological system to which they belong. Fig. V, 4 is a geological map which shows this feature, and other items described below.

Certain conventional symbols are used. Perhaps the one most frequently used is the 'dip arrow', which shows the direction and usually the angle of the greatest inclination or 'dip' of the strata, as seen at the spot marked by the arrow point. Some geological surveys employ 'strike lines' to show the strike of a bed; that is, an imaginary line along which rocks of the same geological level (*see* p. 48) are horizontal. A frequently used analogy for 'dip' and 'strike' is the roof of a house; the pitch of the roof is the dip, and the ridge at the top indicates the strike.

Symbols are also used to distinguish the outcrops of the different strata shown on the map. Outcrops are normally picked out either in different colours or tints of colours, or by patterned ornamentation or by both. Colours (or ornamentation) and the symbols are both included in the vertical index section. On British Geological Survey maps a simple 'lower case' letter and number combination is used. The oldest fossiliferous strata, that is, of the Cambrian and Ordovician systems, are shown by 'a', and successively younger systems by 'b' 'c' etc., to 'l'. Subdivisions are shown by index numbers, the figure '1' always indicating the lowest member. Thus on these maps g^1 indicates the lowest formation of the Jurassic system, the Lower Lias, and g^{14} the topmost formation, the Purbeck Beds. This system may be elaborated by the inclusion of a third term, for example g^{14a}, where strata are further subdivided on the map. A representative vertical index is shown in Fig. V, 4.

A useful addition to a geological map is a section drawn to represent the pattern produced on a vertical plane as it would be seen along an imaginary face exposed by a cut across the country (Fig. V, 5). For very complicated geological areas a group of sections of this kind is frequently shown though the sections are rarely drawn to a natural scale, as they would then appear so flat as to be almost meaningless. The vertical is commonly exaggerated three times the horizontal, but this is by no means universal practice, and other ratios are used when desirable. On British geological maps these are called 'horizontal sections' but the name is not entirely a happy one, for they are in point of fact long vertical sections. In other countries a horizontal section is a section drawn on a horizontal plane, instanced by the *coupe horizontale* of French geologists.

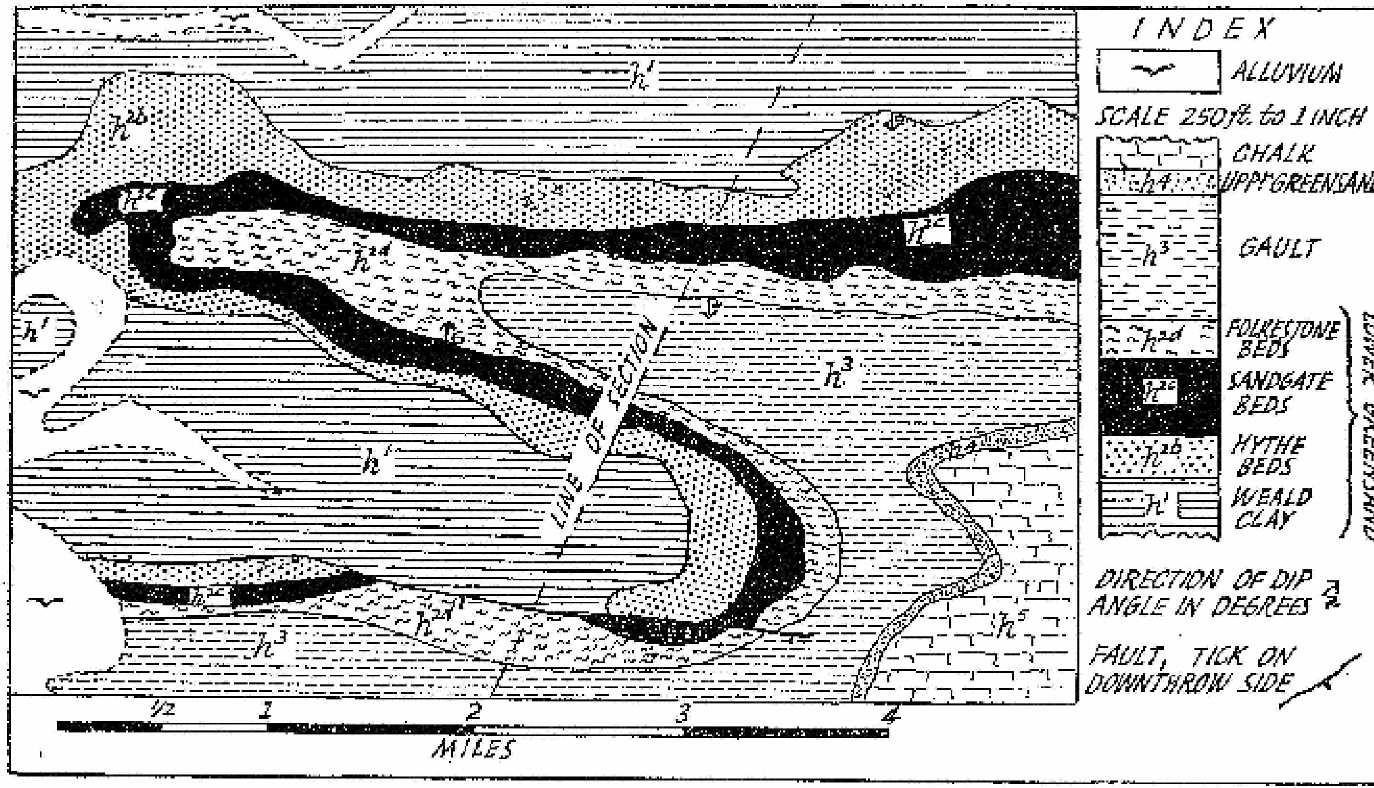


Fig. V, 4.—A simple geological map.

GEOLOGICAL MEMOIRS

Few geological maps, however, are complete in themselves. Obviously, over many parts of the world, much more essential geological information is to be gained over a square mile of country than can be conveyed, for instance, on the square inch of paper which is its equivalent on a 1 inch to 1 mile map. Maps require amplification by means of written descriptions, and by drawings, to give detailed accounts of the strata which cannot be printed on the map itself. These adjuncts are necessary to assist the map user to appreciate the method on which the surveyor worked, and so to aid him in interpreting the three-dimensional structure of the country represented. Geological memoirs, therefore, are normal complements to

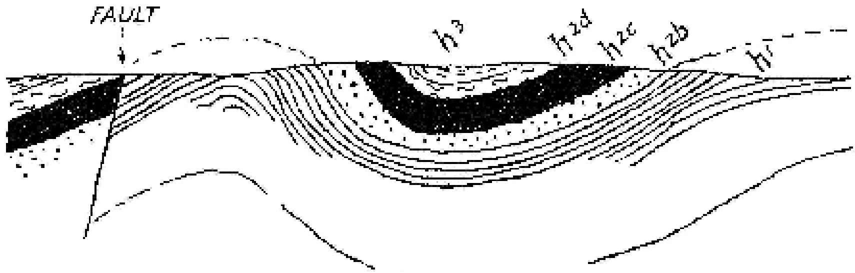


Fig. V, 5.—A 'horizontal' section along a line drawn on the geological map Fig. V, 4.

maps produced by all geological surveys. The use of such a written account may be well brought out by an apparent absurdity long current among geologists, yet one that contains much truth: that the function of a geological memoir is to contradict its map. In other words, geological maps are, in many cases, interpretative generalizations of a mass of detail.

Whether the fullest use of a geological map can be made by anyone who has no geological background depends partly on what is required from it and partly on its complexity. If information on the ground surface only is desired, any intelligent person can read a geological map within that limit provided he appreciates the true significance of its boundary lines. From maps of simple geological areas he may get a good idea of the underground structure; but he should not base any important decisions on his reading. Quite simple maps tend to present booby traps. But even an approach to an accurate and full reading of a map of a complex geological area necessitates more than a nodding acquaintance with geological principles.

While both topographical and geological maps are equally the products of highly scientific and technical skills, the former is the easier of comprehension, since it is a two-dimensional picture of the surface only of a tract of ground. A geological map is the more difficult, in that it attempts, by various devices, to show a three-dimensional feature in two dimensions.

The first geological map

Reference has previously been made (p. 17) to William Smith, whose great gift to geological science was the first real geological map. This he spent many years in constructing, following his discovery that many strata could be traced over the countryside by using their contained fossils as identification indexes. It was published in 1815. He had advanced far beyond Robert Plot, who had made the simple observation that the earth's strata were arranged somewhat 'like an onyon', and in map construction he had travelled equally far beyond that of Martin Lister and Jean Etienne Guettard.

In one of the publications of the National Museum of Wales, Dr. F. J. North has admirably summed up Smith's contribution in the following words:

"The effect of Smith's map upon geology, upon science generally, and upon industry, cannot be overestimated, for it provided a recognized, convenient and logical means of recording and communicating information relating to the earth's crust—matters no less important to agriculture, to mining and civil engineering, and to social development than to the science of geology itself."

Macculloch's geological map of Scotland

A geological map of Scotland begun by John Macculloch in 1811 has perhaps not received the attention it merits. At that early period in particular, Scottish rocks, which are largely igneous and metamorphic, were on the whole much less fruitful in yielding that evidence from which the structure of the country could be deduced with some confidence than was the greater part of the English strata, which are highly fossiliferous. Although Hutton's great 'first principles' resulted from his study of Scottish igneous rocks, yet the scales were heavily weighted against Scotland giving rise to the first true geological map. It was not possible—nor in fact is it possible today—to correlate widely separated exposures of igneous rocks and unfossiliferous schists with the same facility and confidence as was possible with the fossiliferous and well-bedded sediments of

the Bath district, on which Smith first worked. Macculloch, however, was far from ignorant of the approach to mapping *via* solid geometry, and he takes a rightful place among the two or three great world pioneers of geological surveying.

'Solid' and 'Drift' geological maps

Throughout the latter part of the nineteenth century, considerable emphasis was placed on locating deposits of what are usually regarded as economic minerals—coal, iron ore, non-ferrous ores and the like. Most of the late nineteenth-century geological maps reflected this trend in that they showed only the outcrops of those strata which are involved in the main structure of the earth's crust; that is, strata which were formed during geographical cycles previous to the present one. These strata are known as 'solid' strata; and 'solid' maps ignore the spreads of superficial deposits (*see* pp. 73, 75) which have resulted from the present cycle of erosion. The main objective of these maps was, in fact, to show where minerals of various kinds could be extracted from the earth.

But that objective, however important, is a limited one, and about 1860 it was recognized that the types and arrangements of rocks forming even the top twenty or thirty feet of the ground, irrespective of whether they were solid or superficial, were important. Their importance was not for the purposes of exploitation (although that has come to the fore in recent years), but in order to understand their relationship to the many problems affecting the everyday life of the community; problems of engineering such as foundations for building; of sites for reservoirs and dams; of provision of water supplies; of avoidance of contamination of underground water; and many others. An effort was made particularly in Great Britain to map and describe these superficial deposits, which are collectively known as 'drifts', In many areas 'drift' maps have an equal importance with 'solid' maps.

The first geological surveys

Smith's geological maps gave a great impetus to geological science. Their scientific and economic value received immediate and widespread recognition, not only by individual persons, but by various governments in many parts of the world. By 1822 the French Government had formulated a plan *de faire exécuter une Carte géologique générale de la France.* Two geologists were selected to prepare the map, and in 1823, before starting work, they were sent to England for six months to study the English methods. The first

completed geological map of France was published in 1840. Thus was established the first state geological survey.

THE GEOLOGICAL SURVEY OF GREAT BRITAIN

The British Geological Survey was established as a state institution in 1835, although previously to that event its first director, Sir Henry de la Beche, had been engaged in making geological maps of the West of England, and still earlier Maculloch was furnished with funds by the Treasury to enable him to complete his geological map of Scotland. From its inception the British Geological Survey has been catholic in its work. It has recorded and described with equal care geological structures, information on coalfields, and areas containing mineral ores (a Mining Records Office was opened as long ago as 1840) and occurrences of hard and soft rocks, from granite and limestone to sand and clay, irrespective of whether they appeared to have any immediate, or even ultimate, economic importance. In addition to publishing geological maps of Great Britain, the preservation of geological records is a major day-to-day duty. Many thousands of these, showing the strata that have been encountered in wells, trial boreholes for minerals, and in temporary exposures of strata, from all parts of the country, are filed and their information carefully collated.

SURVEYS OF THE BRITISH COMMONWEALTH

Canada founded a survey in 1842 and India followed in 1846. The establishment of the Canadian Geological Survey followed immediately upon the union of the two provinces of Upper and Lower Canada in 1840. By 1869, an inventory of the mineral resources not only of the two newly united provinces, but also of the maritime provinces which joined the confederation in 1867, had been compiled. The Survey's geological investigations in Nova Scotia brought home very clearly to the Nova Scotian colonists the importance to them of their new association with other provinces, and it is claimed for the Geological Survey of Canada that its mid-nineteenth-century work greatly assisted in cementing the confederation of provinces into the united country of today. That this claim has substance is shown by a stipulation made by British Columbia in its terms of confederation, that that province should receive adequate geological assistance.

A prospecting search for coal in India, undertaken in 1836, led to the setting up of the Geological Survey of India in 1846. This continued with excellent organization and with broadly based

functions until 1947, when it was split into two parts, one to be controlled by India, the other by Pakistan.

New Zealand's Survey, founded in 1865, is run on lines similar to those of Great Britain's. Australia followed rather later, the several provinces founding their own institutions at various dates between 1851 and 1896. Activities at first were directed very largely towards the discovery of mineral ores, with water supply as a second objective, particularly in South Australia and Western Australia.

In Africa geological surveys were somewhat late in starting, although a certain amount of geological investigation was carried out with official encouragement round about the beginning of the present century. The first survey as an institutional body was formed in the Transvaal in 1903 and was incorporated with the Geological Survey of the Union of South Africa when the Union was founded in 1910. Various surveys for other regions--Nigeria, Gold Coast, Southern Rhodesia, Tanganyika, Kenya, Sierra Leone, etc.—were established between 1910 and 1935.

FOREIGN GEOLOGICAL SURVEYS

A number of individual states in the United States of America set up early geological surveys. In North Carolina one was started in 1824 "to furnish the public an account of the various useful productions of the mineral kingdom", and it is interesting that the first item on the list of these 'useful productions' is building stone, followed by 'fossils' (which then included inorganic as well as organic substances) to be used in agriculture or domestic economy; metallic ores are lower down the list.

Several other American States set up geological surveys before 1840, and in 1879 the federal United States Geological Survey came into being, and today is one of the most important in the world. It has not absorbed the surveys of the separate States, but has assumed charge of those features which are of national importance.

Spain instituted its Geological Survey in 1846, and between 1850 and the end of the century surveys were instituted in Germany, Denmark, Sweden, Holland, Switzerland and Belgium. Thus it came about that in the first half of the nineteenth century countries widely spaced in Europe, North America and India adopted plans, under governmental auspices, for the scientific survey of their respective country's mineral wealth. They were followed during the second half of the century by almost every other country in the world. In the early years some geological surveys ran into difficulties and quite a number stopped working, in many cases even before

their projected geological maps were complete. The reason is not far to seek; it lay in an administrative view that once a geological map had been made survey operations would be completed. That this view should have been held is quite understandable, since there had been neither time nor opportunity for an appreciation of the significance of the new type geological map to develop. Unfortunately even today confusion of ideas concerning geological maps is still very prevalent.

Fortunately during these early years of development the British, Canadian and Indian surveys maintained their position, although not always without difficulty. The administrative view remained for many years substantially that of the beginning of the century. In Great Britain, for example, pressure was exerted from time to time on a succession of Directors of the Geological Survey to formulate plans for completing the geological map of the country, and for closing down their department. It was chiefly through the long-sightedness and ability of these same Directors that larger views gradually came to be appreciated and accepted; views which have led to the re-establishment of most, if not all, of those surveys which in the first instance fell by the wayside.

GEOLOGICAL SURVEYS AND THE PUBLIC

Up to and including the first decade of the twentieth century, the great majority of the public knew little of the work of these scientific institutions. However great the vision of a few far-seeing individuals may have been, geological surveys could not demonstrate their worth until they had the wherewithal, in the form of reliable geological information, to do so. This was only to be gained by slow and steady investigations. As time went on the cumulative value of the work enabled data to be furnished in increasing quantity to such specialists as mining engineers and civil engineers. The public, without being greatly aware of it, gained as a result.

With the outbreak of World War I, unexpected questions concerning natural resources of all kinds suddenly arose from many quarters. Geological surveys were able to answer many of these immediately from their accumulated knowledge, and in many other cases they were able to assist very materially in speedily providing answers. This drew wider attention to the facilities which these institutions offered, and the demand for geological information grew rapidly. It might be said, if the phrase may be permitted in the present context, that geological surveys were put on the map, in the eyes of the general public, by World War I.

In World War II, as in World War I, geological surveys everywhere were especially active. Geological maps of enemy territory were particularly valuable to all belligerents, as they formed a basis for the consideration of such diverse matters as water supply, landing-grounds for aircraft, 'going' maps for armoured vehicles, and many others. A war-time experience of personal interest to the present writer was to see a copy of a geological map of the south-east of England that had been captured from the Germans. This map had been copied from a Geological Survey of Great Britain publication written by himself, and had been overprinted in readiness for the projected German invasion of the country. It gave full directions concerning routes over open country to be taken by the different classes of armoured and other vehicles, according to the nature of the strata to be traversed.

These calls for information produced a further problem. As at earlier periods it had become apparent that the geological map by itself was insufficient, and that explanatory memoirs were a necessity, so later it became obvious that even so, only a part of the detailed information that was being gathered could be given in published maps and memoirs. The fact that members of the non-geological public as a whole, including many with professional and technical qualifications in other directions, are, in the nature of things, unable fully to interpret the geological map was also forcibly brought out. The duty of answering specific enquiries of a geological character has therefore gradually become a very important part of the routine work of most geological surveys of the world.

Special departments of geological surveys

With the advance of geological science, the technique of geological surveying has also progressed, so that today specialization in certain branches has become imperative. Every geological survey includes today a number of special departments that are essential to its proper functioning. Not only is a highly specialized knowledge of fossils, rocks and minerals demanded, but the study of specimens submitted to these departments from the field surveyors requires the employment of much laboratory equipment. In the early days of geological surveying both map and memoir were to a great extent individual efforts. The production of their modern counterparts results from team work, shared equally between the field surveyors and the palaeontologist, the petrographer, the chemist and the geophysicist.

Geological surveys and water supply

Following the establishment of sound geological principles at the end of the eighteenth century, it became clear that the characters of rocks and the geological arrangement of strata must affect the natural storage of underground water (*see* Chapter VIII). No longer was some hypothetical and mysterious body of water in caverns within the earth invoked to account for underground water. The conclusion followed that natural underground reservoirs of water should be capable of location by geological deduction.

Work on these lines has long been one of the most important functions of geological surveys everywhere. The federal United States Geological Survey possesses a very large separate hydrological department, which has carried out much experimental work on the movement of water underground. Holland has its important Government Office for Water Supply. Since about 1870 onwards the Geological Survey of Great Britain has taken much interest in underground water, and has published many data concerning it. A special Water Department, formed in 1934, today plays an important part in our national economy.

In Africa the search for underground water supplies is second in importance only to searches for gold and diamonds, and in some parts, such as Nigeria, it holds first place. Throughout the decade 1929–1939, the Nigerian Geological Survey, in the special circumstances then arising, undertook engineering duties as well as those of pure survey, and, working on geological data and the conclusions inferred from them, sank no less than 1,500 deep wells. It is scarcely necessary to stress the great influence of this work alone on the life of Nigeria.

Primary small-scale geological survey maps

Geological survey methods of working and of presentation of information to the public vary from country to country in accordance with factors which include the state of development of the country, the amount of geological surveying previously done, the nature of the strata, and the density of the population. Everywhere, however, after a preliminary reconnaisance, a primary survey is at first required, made usually on maps of small scale, e.g. 1/80,000 or on 1/200,000 (in Great Britain it was on the scale of 1 inch to 1 mile, or 1/63,360). This stage has long been completed in most of the older countries, and is well advanced in some of the newer, but very large tracts Asia, in America, Africa and Australia have not yet

been touched, although the deficiency is rapidly being remedied by the help of air photography.

For thinly populated tracts, except where economic minerals occur, economic conditions may never justify more than this primary map, and its attendant descriptive memoir. Areas that include economic minerals in their rocks obviously require closer study, controlled to some extent by the nature of the mineral. Much of the American technique of surveying and recording, for example, has been largely moulded by the search for oil.

DETAILED LARGE-SCALE GEOLOGICAL MAPS

The need for highly detailed geological maps is greatest in populous countries. Civil and structural engineering works are usually numerous. They include construction of foundations for houses, bridge-building, road-making, water-storage reservoir and dam-building, etc., trench-digging for sewerage, gas and water mains, drilling water wells and like activities. Further, as social development proceeds towards planning and regulation, as it is doing in Great Britain today, a geological map often becomes essential to an implementation of policies and decisions. For example, the British Geological Survey is the official geological adviser to the Coal Board, and its maps give much assistance concerning planning matters to the Ministry of Housing and Local Government.

Of all the present-day geological maps produced throughout the world, and planned on a grid to cover a whole country, the most detailed are those of the Geological Survey of Great Britain. These are on the scale of 6 inches to a mile, or 1/10,560; compared with maps of 1/25,000 of the German and some other European surveys. Mapping on this large scale is a long operation, and sometimes is regarded with a little impatience by those who view geological surveying from the angle of 'economic' mineral resources only. There is no doubt, however, that where accurate and detailed data about the strata have to be given, as is the case for so much of Great Britain, methodical mapping on these lines best produces that information which so strongly influences, directly or indirectly, our day-to-day activities.

GEOLOGICAL MUSEUMS AND OFFICES

In some countries the geological survey is linked with a geological museum, which is designed, not simply as a shop window to display the wares of its associated survey but chiefly as an educative agent to teach the public the general facts of geological science. A museum

of this kind both adds to cultural development, and enables members of the public to appreciate the many directions in which geological information may be usefully applied. One of the finest museums of this type in the world is that of the Geological Survey of Great Britain, in Exhibition Road, South Kensington, London. This is now visited by some 350,000 people annually.

A library open to the public is another usual feature. Many libraries hold copies of almost all the published geological maps of the world, and of their complementary memoirs, and a vast amount of other geological literature. In Great Britain the Geological Survey Library is housed in the Museum building. No charge is made there for geological services rendered to the public, which may consist of facilities for examining maps and literature, of identification of specific samples, or of giving unpublished geological information.

The Geological Survey of Great Britain has a headquarters and a library in Edinburgh, concerned particularly with Scottish geology, and offices at Manchester and Newcastle. It also carries out geological work for the Government of Northern Ireland, maintaining an office in Belfast. Up to 1922 the Geological Survey of Ireland was united with that of Great Britain.

The above outline would place a false value on geological surveys and their work in relation to the acquisition of geological information were the impression to be given that this was acquired solely by geological survey officers. Few universities in the world today are without a geological department in which research in all its branches is a fundamental activity; the scientific staff of many museums, particularly of national museums, undertake many investigations particularly in the laboratory; various large commercial undertakings that exploit the earth's primary products employ geologists in many parts of the globe; and finally, a great band of amateurs, which includes many specialists of the first order, find relaxation in geology. The sum total of observations and conclusions from these sources is immense. Interchange of data and ideas freely takes place between official, academic and amateur geologists.

In the nature of things, however, in all countries the State Geological Survey is the central reservoir of information. Normally it alone is able to carry the expense of preparation and publication of geological maps and memoirs, and is in a position to acquire, study and preserve records from all parts of the country and to make their contained information accessible to all who require it.

CHAPTER VI

Geophysics and Geochemistry

IN the economic sphere in particular, geophysical science has in recent years concerned itself closely with strata near the ground surface, as well as with the unobservable interior of the earth. This has been stimulated largely by the use of geophysical methods of prospecting in a world-wide search for oil. Its development has been paralleled by that of geochemistry, which is the science of the occurrence and distribution of all the elements of the earth, and of their isotopes, both in its crust and in its interior.

GEOPHYSICS

Geophysical science has now become an essential adjunct both to geological prospecting and to geological surveying. Its aim is to furnish data that will enlarge the field of deduction as to geological structures both near the ground surface and at a greater depth than that attainable by purely observable geological evidence. In favourable circumstances, structures that on geological data alone would never have been suspected have been inferred when geophysical readings have been welded with geological records.

Four main methods are employed. These are based respectively on gravity differences arising from density variations of strata; on differences in their magnetic properties; on differences in their electrical properties; and on seismic phenomena.

THE GRAVITATIONAL METHOD

The most widely employed is the gravitational method. Newton's Law of Gravitation leads to the conclusion that a local mass con-

centrated beneath the earth's crust in excess of that of the surrounding neighbourhood will exert an additional downwards attraction. This may be detected and measured by a suitable gravimeter. Before interpretation is attempted the gravimetric readings are corrected for variations in latitude, elevation and topography and the results plotted as 'Bouguer gravity contours', so named from the eighteenth-century French mathematician Pierre Bouguer, who first showed why and how elevation corrections should be made. Variations from the normal for an area are known as 'Bouguer anomalies'. Local

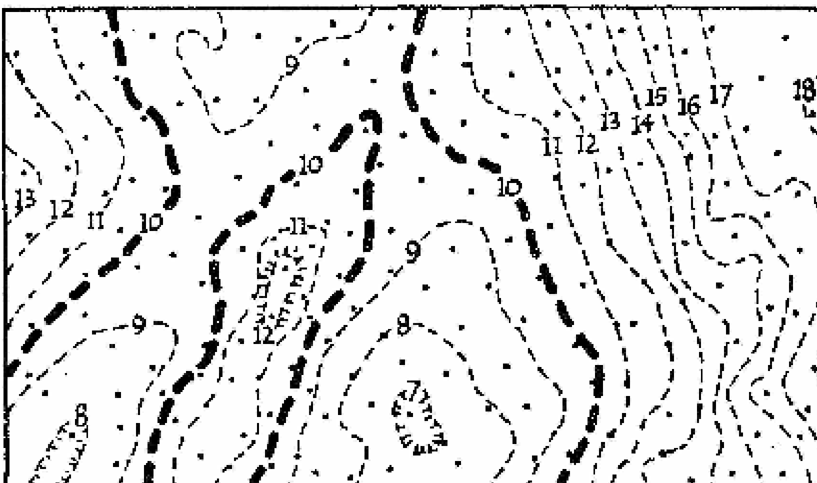


Fig. VI, 1.—Bouguer gravity contours (Isogams). The spots mark stations at which gravity measurements were made. The intervals are in 'milligals'. (A milligal is about one millionth of the average value of acceleration due to gravity at the earth's surface.)

occurrences of rock masses of high density near the earth's crust therefore yield anomalies of high value, while deep troughs of light rocks give rise to anomalies of low value.

Fig. VI, 1, shows some Bouguer gravity contours, or 'Isogams'. The gravity 'low' obviously means that there is something at depth different from the surrounding structure. It will be apparent that there are occasions when evidence such as this may provide the key to unravelling otherwise apparently insoluble structural problems.

The magnetic method

Some minerals, instanced by magnetite (lodestone), are strongly magnetic, and most rocks are slightly so. The local absence or

presence of magnetic minerals may cause a local variation in the general terrestrial magnetic field. These disturbances or local variations from the normal are measurable by a wide range of magnetometers. Otherwise the method of working and recording the results of readings is very similar to that of a gravimetric survey.

There are certain differences, however. A Bouguer anomaly may be the reflection of any one of a number of arrangements and types of deep-seated structures: it may indicate a thick but local mass of sands and clays, or, amongst other possibilities, a deeply buried mass of granite. But there are very few strongly magnetic rock-types in the earth's crust, so that the readings from a magnetic survey around an area that shows a strong magnetic anomaly usually point to a limited number of causes. A dyke of igneous rock occurring within a mass of sedimentary strata may be traced with great accuracy. In general, however, the economic application of magnetic surveying in its present stage of development is restricted. One great disadvantage is that the presence of metal—railway lines, water pipes, iron bridges, steel-framed buildings and kindred things —plays havoc with accuracy of instrumental readings. On the other hand, magnetic survey instruments can even be used in an aeroplane. Aero-magnetic surveys quickly give important information relative to very wide tracts of country.

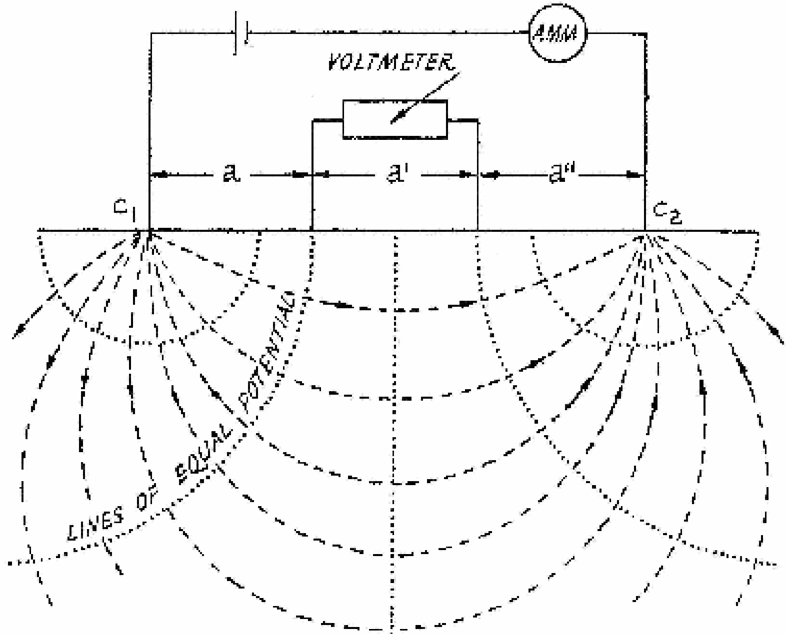
THE ELECTRICAL RESISTIVITY METHOD

Two or three methods of electrical surveying of the earth's crust are in use. One is by measuring and comparing differences of resistance to the passage of an electric current that is passed through the strata.

It has been found that a current that enters the earth takes the path of an elliptical arc, and that its penetration in depth bears a direct relationship to the distance between the point of entrance and the point of exit. To apply the electrical resistivity method, four metal electrodes are driven into the ground. The outer, as shown in Fig. VI, 2, the current or C electrodes, are connected to a battery or generator, and current transmitted. From the inner, the potential or P electrodes, readings of differences of potential are made from a connected voltmeter. Only the resistivity of the strata near the ground surface is measured if the distance between the C electrodes is small. As the distance between them is increased, so are readings of resistivity of a greater depth of strata obtained. Clays, shales, sandstones, limestones and igneous rocks of different types all possess

different resistance values, and in principle different beds within the earth's crust are to be detected and their extent and thickness determined by this method. But numerous complicating factors have to be taken into account.

The amount and chemical composition of water in rocks are two matters that have a marked effect on resistivity values. A highly porous rock that contains water is usually a much better conductor



a, a' AND a'' ARE ANY EQUAL DISTANCES

Fig. VI, 2.—An electrical resistivity circuit. Measurement of differences in resistance offered by different strata to the passage of an electric current are interpreted geological conclusions.

of electricity than is the same rock when dry, and therefore it gives lower resistivity readings than the dry rock. Igneous rocks, which are compact and contain little or no water, have high resistance values.

Whereas magnetic surveys depend on the chemical composition of rocks to give differences of readings, resistivity surveys depend primarily on the degree of rock-compaction and on water content, the latter itself a factor of porosity.

Resistivity surveys are used largely in problems of water supply, and of foundation work in civil engineering.

THE SEISMIC METHOD

The seismic method is an adaptation of principles gained from the scientific study of earthquakes. A charge of explosives is detonated in a specially drilled borehole, to produce shock waves in the surrounding rocks. Strata of different rock-types allow the passage of these waves through them at different velocities. But the beds also have a property of refraction, comparable with that which affects light waves and leads to the apparent bending of a straight stick when part of it is put in water. The refraction, and also the reflection, of shock waves occurs at an interface—that is, at the plane separating one stratum from another.

Where a group of strata of one kind rests on one of another kind, the seismic velocity of the upper group is first determined. A number of detectors (geophones) are placed on the ground surface, and a shot is fired from the prepared borehole. The depth to the reflecting surface (which is the upper surface of the lower group of strata) may be estimated from the times that the reflected waves take to arrive at the several geophone stations.

Seismic surveys have been shown to have been very successful in certain instances where the results have subsequently been proved by boreholes. One instance is that of a seismic survey of the Cambridge district carried out between the two world wars by members of Cambridge University. This led to a conclusion that Palaeozoic strata underlie Mesozoic at a depth of 450 ft. below ground surface. This was put to the test by a borehole made in 1953–54 and was found to be within 5 ft. of the actual depth—a remarkably accurate forecast.

Seismic work, however, is but little applied in Great Britain. It is very expensive and in the many urban areas of the country it is not always easy to find suitable sites for drilling. The justly stringent regulations against firing explosives in or near built-up areas make a formidable obstacle.

INTERPRETATION OF DATA FROM GEOPHYSICAL SURVEYS

For purposes of interpretation, many geophysical data are assembled in map form after the manner of the isogams of Fig. VI, 1, or of surface contours. In this lies a danger, for unless the user exercises considerable care and discretion he may be led into reading into such maps an interpretation which is unwarranted. None of these readings provides actual geological data. They are all physical measurements—gravitational, magnetic, electrical or seismic—and their representation in contour-map form is nothing more than a

convenient way of presenting them. Yet a special pattern that may be shown by these lines must obviously mean something geological provided there is no extraneous disturbing factor. The geophysicist, having shown that concealed beneath the ground surface of the area he has examined there lies some structure that can be differentiated from its surroundings, then requires the collaboration of the geologist in interpretation. It becomes easy to allow personal views and wishes and even 'hunches' to influence the interpretation of these contour-like lines. With proper safeguards against undue enthusiasm and loose thinking, however, geophysical work, although still in its infancy, often leads to geological conclusions of high importance. It promises to become a major influence in both geological surveying and geological prospecting in future years, and it is already incumbent on every wise university student who reads for a geological degree to acquire a good grounding in physics, and a working knowledge of geophysical method.

GEOCHEMISTRY

Geochemistry aims at a quantitative assessment of the composition of the earth, both as a whole and as regards its several parts, and at the discovery of laws controlling the distribution of elements, and their movements from one part of the globe to another.

The subject has come much to the fore during the past quarter of a century, but it is by no means an entirely modern conception. It had its birth in Europe, mainly in Switzerland and Germany, over a century ago, but for long it involved little more than detailed chemical analyses of rocks, natural waters, and natural gases; it was to a great extent an appendage of petrology.

Today very detailed chemical analyses are still required, but the data they provide are combined with others given by the more physical sections of mineralogy, and by geophysics in various forms.

The development of geochemistry into its present-day status of a discipline in its own right is largely the result of fifty years' research work carried on in the United States of America, in Norway and in Russia.

Among the many subjects that it has set itself to investigate, in conjunction with geophysics, are two allied problems. The first of these is the origin and structure of the earth, and of its nature in pre-geological time before the physical nature of its surface had been formed more or less as it is today; that is, before it consisted partly of

rocks, partly of water, with temperatures controlled by radiation from the sun. The second is the nature of the progressive development of the earth into its present-day form and structure. Implicit in these subjects are the origins and growth to their present composition of the atmosphere and hydrosphere.

The broad basis on which geology and geochemistry meet is well illustrated in diagrammatic form by a concept of a 'geochemical cycle' (Fig. VI, 3). As will be seen, its full cycle is from magma back

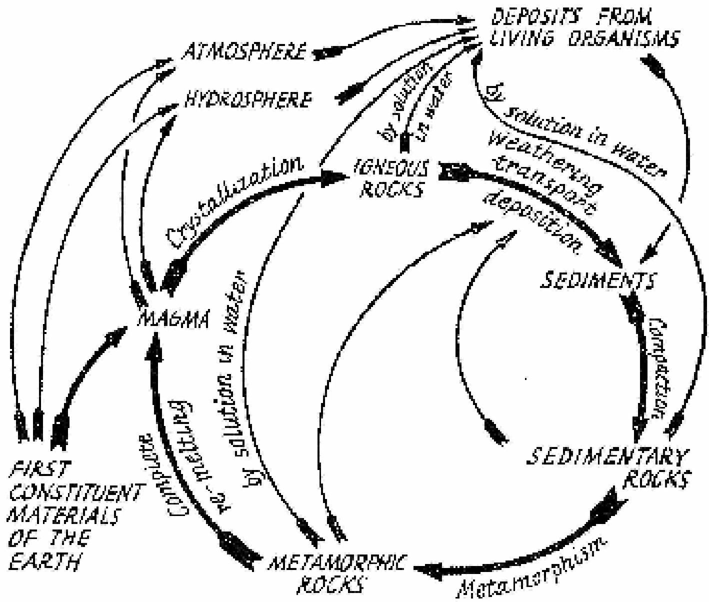


Fig. VI, 3.—The Geochemical Cycle. A full cycle is from magma back to magma, but various shorter cycles occur.

to magma, but short circuits may occur. In some ways the concept is very much of an over-simplification, but it is fundamentally sound.

Economic uses of geochemistry

Geochemistry today has numerous directly economic uses. Among modern techniques is one shared by geochemistry and mineralogy whereby the minutest traces of an element or of one of its isotopes can be detected and identified. When linked with geological study, some of the data thus provided have led to the recognition of the causes, and thence to prevention of certain diseases, both of man and of animals. Amongst these is fluorosis,

produced in man by an absorption of an excess of fluorine. Fluorosis is both an industrial and a natural disease. The normal cause of the latter has been traced to excess fluorine in solution in drinking waters, and these in their turn have been connected with certain identifiable fluorine-bearing strata. Fluorine produces decay of teeth, and a deformation of bones that gives rise to symptoms resembling those of acute rheumatism. A mild form, though none the less distressing, was prevalent in certain restricted parts of Britain up to some twenty-five years ago. The offending strata that yielded the local drinking water have been located, and wells in it are now closed.

An animal-wasting disease, teart disease of cattle, has been found to be due to traces of molybdenum. It has been discovered that not only are the soils that supply these traces of molybdenum to plants restricted to a definite geological formation, but that clover absorbs molybdenum to a greater extent than other forms. Great progress in the cure and prevention of teart has accordingly been made.

A remarkable geochemical prospecting technique has been evolved, in a search for minerals of particular application where normal geological methods could not satisfactorily be used, such as in country where a very thick soil completely blanketed the underlying 'solid' strata, and prevented any direct observation. Samples of soil are taken on a planned grid, and analysed for trace elements. Minute traces, brought up from greater depth by plants, are detected. The plotted results give an indication of the composition of the underlying strata, and in some instances have definitely given information by which ore-bodies have been traced, in situations where geological methods by themselves could not have been effective. A refinement of this method is to collect leaves from plants on a similar grid, burn them, and examine the ashes for trace elements.

CHAPTER VII

Bored Wells and Trial Holes

THE proof of all geological conclusions regarding concealed strata lies in actually making holes in the ground. Today much of our industrial activity needs hole-making in some form or other. Mining engineers, civil engineers, water engineers, oil engineers and others all require them either as preliminaries to further work, or as permanent features.

From earliest times in human development holes have been put down into the crustal rocks of the earth for two reasons: to extract something which is expected to be present though concealed beneath the surface cover; and to explore the unknown. Holes may be dug or they may be bored by some method of drilling. Some activities require digging, but unless it is essential to make large holes of the kind necessitated by mining or engineering, drilling has many advantages over digging, more particularly when it is desired to go deeply into the ground. In drilling, work can be controlled from the ground surface; holes can be taken to depths that would not be possible by digging; and only a minimum amount of rock needs to be removed. Boreholes may vary in depth from a few feet to many thousands of feet, and in diameter from an inch or so to some six feet. At Sutton, Surrey, some years ago a water-well of 8 ft. diameter was made by boring. The technique of drilling water-holes of these large diameters, however, has now largely faded out. Pumping machinery is now so much more efficient than it was, that it is more economical to dig and de-water, and have men working at the well bottom with automatic tools. Some relatively shallow boreholes for water (i.e. of depths of a few hundred feet) are still commonly drilled up to diameters of 36 in., but the average in Great Britain is of the order of

12 in. to 15 in. In countries like Africa the average water-hole is 6 in. to 8 in. in diameter.

The end in view has a strong influence on the method of drilling used. In what may be termed 'production holes' from which water, mineral salts in solution, oil or gas is to be obtained, the nature of any rocks that may overlie a bed is relatively unimportant to the ultimate end in view, except in so far as it may affect production. It is therefore not fundamentally necessary to take samples of rock for the immediate purpose of a hole of that sort.

A great many boreholes, however, are drilled for purposes of exploring the strata. Most of these are shallow, of depths from a few feet to two or three hundred feet. On the bare site of one of the new towns now under construction (1955) in England more than 5,000 shallow trial holes up to a maximum of 20-ft. depth have been put down. Many hundreds of similar, though slightly deeper, exploratory holes are made in connexion with digging coal at outcrop (*see* p. 193). As has been remarked previously, some exploratory holes, notably for oil, are very deep.

Methods of drilling

The drilling industry therefore is a liaison, as it were, between the science of geology and the technical and industrial world. On account of the two motives for boring, production and exploration, two main methods of drilling are in use. By one, rock is chipped or ground away until the required depth is reached. By the other, a 'core' of rock is cut out for examination (Plate IIIB). A 100-per-cent recovery of a core from a cored borehole would give a continuous section of the strata at the borehole site, as they exist between the ground surface and the bottom of the hole. The first method is usually the cheaper and the more rapid.

The oldest form of drilling is by percussion. This was used by the Chinese more than 3,000 years ago. Holes up to 3,000 ft. were made, although they took some fifteen years to complete. 'Bits' of various kinds according to the nature of the rock are suspended either from rods or from a long cable and are jumped up and down, to pound away the rock. Water is poured down dry holes to keep the bit clean and cool, and to mix up the pounded rock into a slurry. Periodically this is removed by a cylindrical 'baler' which is merely a tube with a simple non-return valve at the bottom. This valve opens as the baler is lowered into the slurry, and closes immediately it is raised. The slurry is then brought to the ground surface. This method is still in use for many relatively shallow boreholes for water.

It has been largely superseded by one in which the bit is rotated, but not jumped. It is suspended at the end of a sectional tube lowered into the hole made up of drilling rods or 'drill pipes', normally made in 20-ft. lengths and assembled in 2's, 3's or 4's according to the height of the tower-like derrick erected over the drilling site to support the tube (Plate IIIA). Thus effective operational lengths of 40 ft., 60 ft. or 80 ft., as the case may be, can be inserted at will, and the tubes extended to keep pace with the rate of drilling. The derrick is called on to sustain the whole weight of the drilling rods, and these may comprise several thousand feet of steel tubes, filled with a column of mud. The bit and the drill pipe are revolved by machinery at the surface; through them mud is pumped under high pressure. The drilling bits are of various designs. Some have cutting edges which chisel rock away, while others are complicated pieces of mechanism comprising combinations of cone-shaped, toothed rollers. All have holes through which the mud, pumped down from the drilling rig at the top, is extruded. This mud cools and lubricates the bit and then rises up the hole outside the drilling rods, to overflow at the ground surface. It brings with it the chipped or powdered fragments of rock which are screened out, and the mud is returned to the pump. One function of mud is to prevent a collapse of the borehole walls, and its density has to be carefully regulated to meet changing circumstances.

Core drilling needs bits different from the above, and different methods of extraction are necessary. A simple coring bit is little more than a steel tube fitted with a serrated cutting edge, but today a 'crown' set with industrial diamonds or with specially hardened steel alloys (an expensive item of equipment) is commonly in use. Others again combine cone-shaped toothed rollers and a coring bit.

As the bit is rotated at the end of the drilling rods, a core is cut out. This enters a core barrel, the length of which determines the maximum length of core that can be extracted at any one time. A normal length is 10 ft., but some are longer. Diameters vary according to requirements. Convenient sizes of cores drawn for sampling purposes vary from 2 in. to 4 in. When the barrel is full it is brought to the ground surface which necessitates the withdrawal, section by section, of drilling rods. The core is prevented by a spring clip from falling out of the barrel while this is being brought to the surface. The barrel is then again lowered into the hole, the rods being reassembled section by section. Some modern types of bit are illustrated in Fig. VII, 1.

The time taken by these operations in coring a deep hole

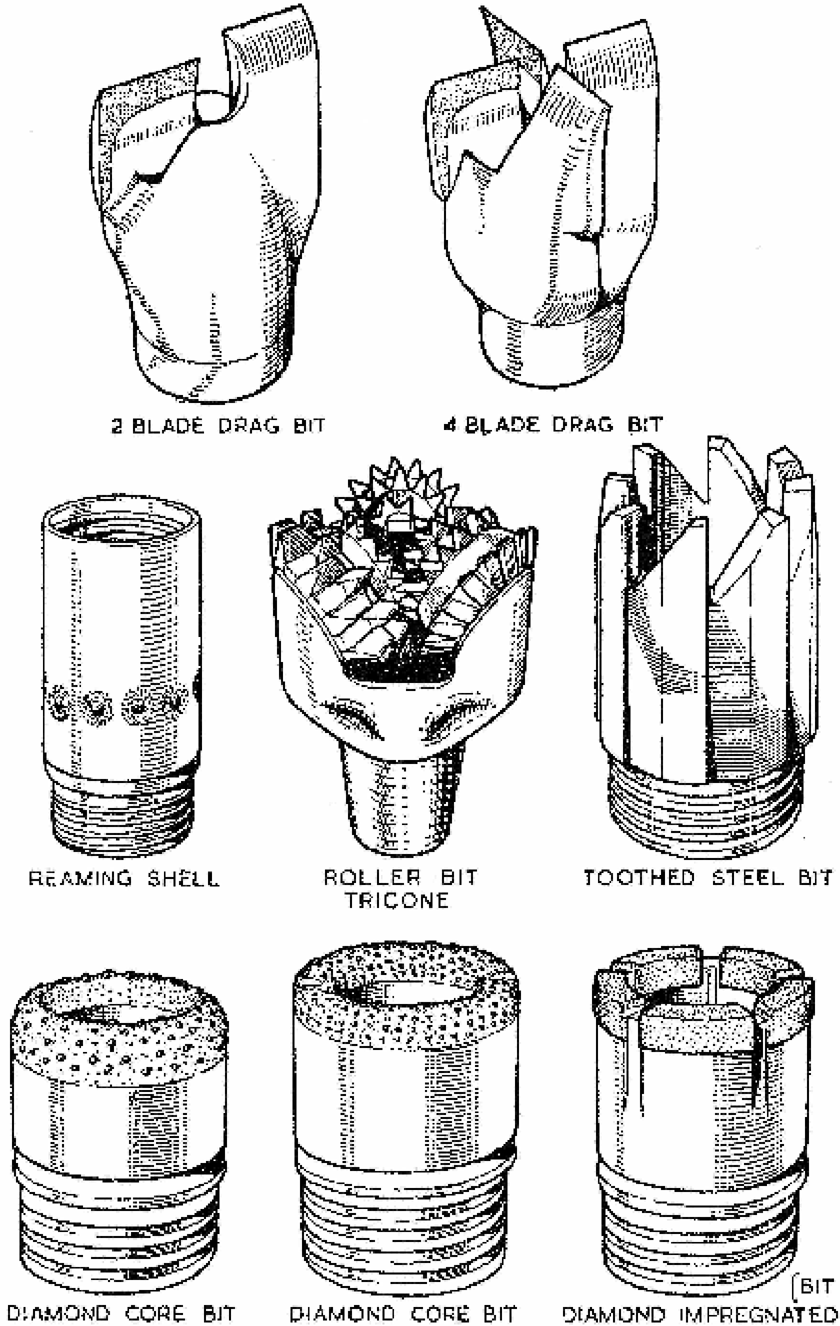


Fig. VII, 1.—Types of modern rotary drilling bits.

occupies a very great proportion of the drilling time. When drilling at a depth of 6,000 ft. for instance, and using 60-ft. lengths, withdrawal of the rods involves a hundred uncouplings; during each of which the length of tube still remaining in the hole has to be gripped to prevent it from falling back. After extracting the 10 ft. or so of core from the barrel, a hundred converse operations, of coupling and gripping, have to be carried out before actual drilling can be recommenced.

Lining tubes

All rocks at depth are under pressure from those overlying them. Unless they are naturally strong, as are limestones and sandstones, they tend to be squeezed into any excavation that may be made, and particularly so when the excavation is deep. The walls of boreholes therefore are particularly susceptible to collapse, and it is normal practice to line with thin iron or steel casing tubes those sections of a hole that appear liable to cave in. These linings are expensive, and even in exploratory holes they often have to be left in the ground. Where mud is employed in drilling, much expense over lining tubes can often be saved by controlling the density of the mud. In the relatively homogeneous deposits of some oilfields, holes to depths of over 10,000 ft. are drilled without casing. Where casing is required, however, and particularly where strata change repeatedly from one kind to another, with their varying degrees of hardness, unlined depths anywhere approaching this order are not possible. Nevertheless, during the present decade, by skilful drilling a hole in Staffordshire was kept uncased to a depth of 4,228 ft., and another in Kent to 2,800 ft.

One of the main functions of drilling mud is in fact to exert a pressure balancing that of the strata, and so to allow a uniform diameter to be maintained through depths of many hundreds of feet. Previous to its use a hole destined to be taken to a great depth was made of a very large diameter at the start, and after a depth of a few hundred feet this was lined with tubes. Boring was then re-started, with a smaller diameter, for another length and that again lined inside the outer tubes. Subsequent similar reductions each necessitated its own set of progressively smaller lining tubes. This method resulted in the employment of a telescoped string of casing tubes, sometimes with six or more concentric tubes at the top. Lining tubes are still generally indispensable in many boreholes through soft strata where coring is required, but the number of 'strings' is reduced from that formerly needed. Most holes required

for permanent use must in any event be lined on completion; and then cleared of mud.

Geological information and drilling

From all the foregoing points it will be apparent that the more information available on the strata expected to be encountered at a proposed borehole site, the more satisfactorily will be chosen the type of drilling rig, types of bit, size of hole, length and diameters of lining tubes and other details to be employed.

But more is required, if possible, than details of a simple sequence of strata. The inclination of beds and any likely rapid changes in the hardness of the rocks are highly desirable details. These are important because it is by no means easy for a driller to maintain strict verticality in a borehole. Deflexions from the vertical result from factors like joints, faults, and dip of strata, any of which may lead the bit away from the vertical by providing for it a less difficult path.

Deflexion is of more consequence in deep holes, say those more than 2,000 ft. in depth, than in shallow ones. It has been known for a deflexion of more than 90 degrees to occur, and even for a hole, which began vertically, first to travel horizontally, and then to veer round so that the bit actually travelled upwards. Extreme instances of wandering are avoided today by regular checks on verticality with elaborate surveying instruments, but it is no uncommon thing for part of a hole to be re-drilled to check deflexion that had started. In difficult strata this may need to be done several times.

It will be appreciated from the above remarks that drilling may be expensive. In point of fact, drilling-costs rise with depth. Very shallow holes cost but shillings a foot. The total cost of a hole 4,000 ft. deep may be £30,000 or more, and a very deep oil hole upwards of £250,000.

Liaison past and present

Unfortunately, in the past, the rôle of liaison that the driller holds between the geologist and the engineer or miner has not always been as effective as might have been desirable. Drillers have often been asked to do more than should have been expected of them. Boring demands a very high degree of skill—but it is an engineering and mechanical skill, not necessarily one of geological description. In the nature of things the average driller becomes well versed in the differences between certain grades of rock, but he cannot be expected to have that degree of geological knowledge that would enable him to recognize all those particular features of strata that may be

germane to a specific line of enquiry, particularly when he is dealing with deep boreholes. In one of the exploratory boreholes for the Kent Coalfield, made during the early part of the present century, a bed of hard rock was described in the driller's log as 'granite'. This material was never given geological examination and no samples have been preserved. Had it been true, both the economic and scientific implications would have been tremendously important. The record has been the cause of much trouble, but there is now no doubt that the 'granite' was either a hard limestone or a sandstone. Precise proof could now only be obtained by drilling another hole.

The position today is that very deep boreholes are mostly watched by trained geologists who take responsibility for the care and descriptions of samples from the hole. Most shallow holes are recorded by the driller. It is neither economically possible, nor is it necessary, for all of these to be watched by geologists. For most purposes driller's accounts of shallow trial holes, that is, of holes up to 100 ft. deep, and of many others that are considerably deeper, are fully adequate. This is particularly so since in recent years boring firms have endeavoured to train their drilling staff in careful observation of samples, and in the use of standard and precise descriptive terms.

CHAPTER VIII

Water Supply

IN no part of our day-to-day existence is geology of more direct importance than in the provision of a piped water supply to our homes, farms and factories. With a steadily increasing demand for water the problem of supply yearly assumes greater prominence in many parts of the world. In Great Britain this progressive increase in demand arises from two causes; a gradual rise in individual consumption which began in the middle of the nineteenth century, when two gallons a day were regarded as adequate for a cottager and twelve gallons for members of the upper classes, until today when the call is for about twenty gallons a head in our villages and small towns, and from thirty to forty gallons, or even more, in our cities and large towns. Coincident with this rise in individual requirements there has been the great increase in the population of the country from about ten millions at the beginning of the nineteenth century to some fifty millions today.

Some 100 years ago piped water supplies, and their counterparts, sewerage systems, were hardly existent; today every city and town in Britain and the great majority of larger villages have both a constant piped supply, and a water-borne system of sewerage. Indeed the hygienic and industrial needs of modern civilization are such that the daily supply of piped water in Great Britain is now something of the order of 1,400 million gallons; London alone uses 330 million gallons. For the great majority of purposes the water provided must be of a considerable purity and freshness, of a quality suitable for domestic use; and with rare exceptions, all organized piped supplies are of this quality, although they may be used in bulk for industrial purposes also.

RAINFALL THE SOURCE OF WATER

All water used for supply is ultimately derived from rainfall, which includes all forms of precipitation—rain, mist, hail, snow, dew and hoar frost. Over Great Britain as a whole, the rainfall is ample for all requirements. An inch of rainfall amounts to nearly 14½ million gallons of water a square mile. The cause of the Lynmouth disaster of 1952 may perhaps be the more readily appreciated if the recorded rainfall of over nine inches in twenty-four hours be translated into 130 million gallons, or 580,000 tons of water per square mile of the countryside affected.

The average annual rainfall over England is 32·6 in., which gives an annual quantity of some 470 million gallons of water a square mile. Scotland and Wales, each with an average rainfall of 50 in., receive about 725 million gallons a square mile annually. These quantities represent about 2,000 gallons a head each day in England and 7,000 gallons a head in Scotland and Wales—certainly sufficient for all our domestic needs even if only one-sixtieth part were available. Further, in many instances the same water is used a number of times, particularly where a series of towns lies along a river from which each town takes a supply, and to which it returns its waste after treatment in its sewerage plant.

The facility with which water is obtained, however, varies greatly from place to place, dependent on geological, climatic and other factors. There is great variation in annual rainfall from one locality to another. Wales, North-West England and the West Coast of Scotland receive about 80 in., and locally the rainfall may exceed 120 in. In East Anglia it is only about 20 in., and may be as little as 11 in. Also, only a fraction of the total rainfall becomes potentially available for our use. There is a return of water to the atmosphere, and indeed a constant interchange takes place between the atmosphere, the land and the sea. This interchange, known as the 'water cycle', is illustrated in Fig. VIII, 1. Rainfall is disposed of (1) by evaporation, i.e. water returned to the atmosphere in the form of vapour, (2) by a direct run-off from the ground surface into brooks and streams and (3) by absorption into the ground, from which, however, it may issue again as springs on land, in river beds, or in the bed of the sea.

The relative proportions of these three fractions of rainfall are difficult to assess. In Great Britian an old rule-of-thumb estimate is that in areas composed of absorptive rocks such as a porous sandstone, one-third is lost by evaporation and transpiration, one-third runs off the surface into rivers, and one-third is absorbed into the

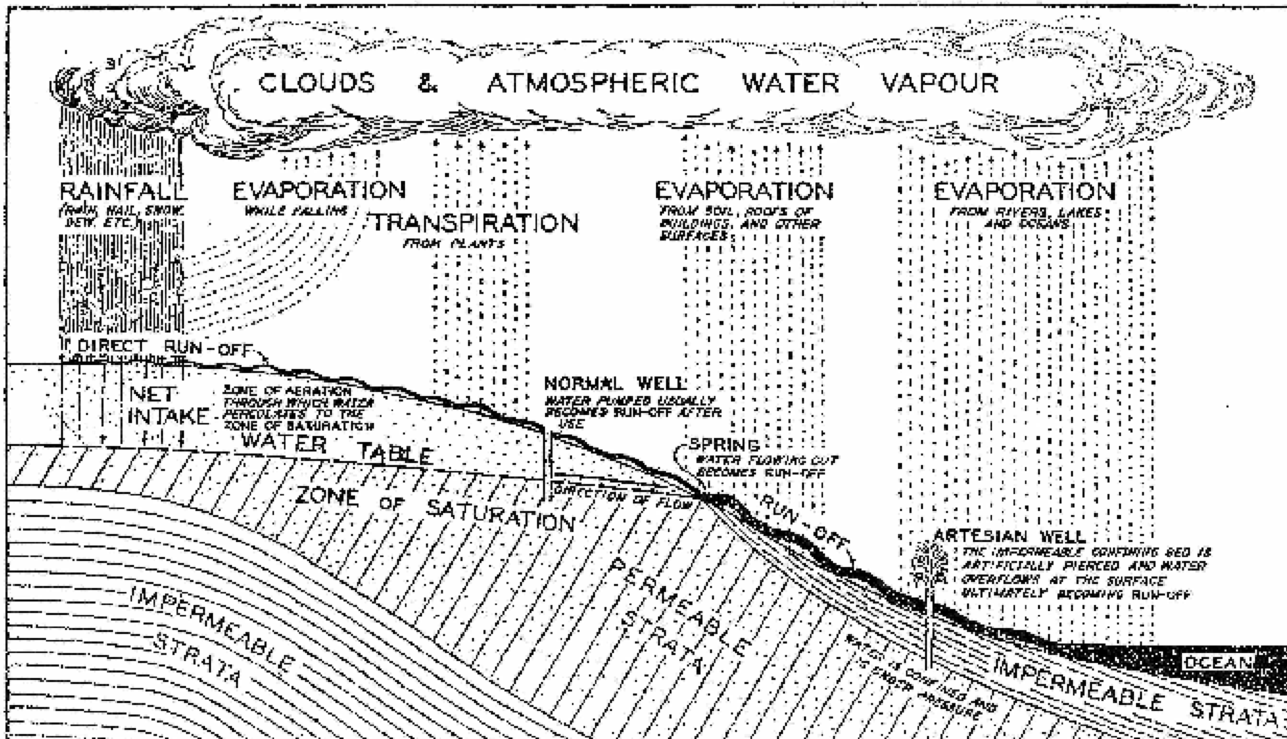


Fig. VIII, 1.—The Water Cycle. Rainfall returns by various routes to the clouds from which it originated.

ground. In point of fact the proportions as traced from place to place show very great variation largely related to the character of the strata cropping out at the surface. In recent years several more or less empirical formulae for the estimation of absorption into different geological formations have been used, in an endeavour to estimate potential water supplies.

The percentage of annual rainfall actually retained in the ground, considered over a period of years, is very small; indeed, it may be said that under completely natural conditions the whole of the absorbed rainfall sooner or later flows out again in the form of springs. In Great Britain in particular, rivers owe their steadiness of flow throughout the year to the balancing effect of absorbent strata, which store up rainfall during periods of heavy precipitation, gradually to release it to the rivers during periods of drought. Otherwise, our streams would all be 'flashy', flowing in spate or drying up in immediate response to heavy rainfall or drought, as do many rivers in the south of France.

The place of geology in water supply

From these introductory observations water supply would scarcely appear primarily to carry a geological interest. To provide ample and constant supplies, however, reservoirs are normally needed in which to accumulate water during times of high precipitation. It is almost wholly in connexion with storage of water in natural reservoirs within the earth's strata and its extraction therefrom, or in artificial overground reservoirs, that geology is brought into use. Only where water is obtained from natural lakes or directly from rivers is geological science called upon to make little or no contribution.

Natural divisions of water supply

It is far from being a fact that underground water is obtainable by sinking a well anywhere, provided sufficient depth is reached. Natural underground storage occurs in restricted belts of the country and only at certain localities within those belts. It is equally true that by no means every valley in our hills and mountains, if dammed up, would be capable of retaining water in store. Both types of storage could of course be found by trial and error, a proceeding which, considering the finance involved, would indeed be costly. Unfortunately even today many new wells are being sunk or bored on a trial and error basis, or as the result of a 'hunch' on someone's part. Failures that could have been avoided are by no

means uncommon. The contribution of geological science to our everyday water supply is that it permits a reasonable assurance of success before any constructional work is started, and, where troubles arise, it permits of an intelligent application of remedial measures.

Applied geology impinges on other aspects of water supply, notably contamination problems, and in certain districts the decay of buried metal pipes. Actual provision and distribution of water and maintenance of purity and supply, however, are almost entirely the concern of the water engineer. A discussion here of the part borne by geology in these specific matters would verge on the irrelevant.

Water supplies are grouped into two main divisions, underground supplies and surface supplies. In the former case water is brought to the surface for human use by artificial means.

Spring supplies occupy an intermediate position. They are derived from underground sources, but reach the surface by natural means. They are, however, usually grouped with surface supplies.

UNDERGROUND SUPPLIES

Rainfall which has been absorbed through the surface soil to become underground water moves through, and is stored in, the spaces between the constituent parts of the solid material composing the earth's rocks. The size and arrangement of these spaces, which may be classified either as 'pores' or 'fissures', are of great importance in controlling the rate of flow and the amount of water that can be held in the strata. Pores are interstitial openings, generally between individual grains or pebbles, which may or may not interconnect, whilst fissures are cracks, including bedding planes and joints across the bedding.

Porosity and permeability

The capacity for containing water of either a separate block of rock or of a rock bed as a whole depends solely upon the aggregate volume of the intercommunicating spaces, both pores and fissures, whatever their size. On this volume depends *porosity*. The freedom of movement of water, however, is in a large measure controlled by the openness or closeness of the intercommunicating voids. The degree of freedom of movement determines the *permeability*. The fact that a rock has a high porosity and therefore that it will hold a large

volume of water, is not necessarily an indication that it will freely yield a supply. Clays are extremely porous, some clays holding up to 50 per cent of their volume of water, but their porosity is of a fine or close type, and for practical purposes of water supply clays are impermeable.

Most strata have some degree of permeability, there being a gradation from those of high permeability to those of very low permeability. Loose agglomerates such as river gravels have high permeability, and in some parts of the world, though not to a great extent in Great Britain, very large water supplies can often be obtained from them. Well-jointed hard limestone strata are also highly permeable.

The softer limestones, such as chalk, absorb much water in small pores, in some cases (as it has also been noted is the case with many clays) up to 50 per cent of their volume. In these rocks the viscosity of water prevents the rapid outward flow from the minute spaces between the grains, consequently a well, of whatever type and size, constructed in unfissured chalk may give only a negligible yield. From the point of view of water supply, these softer limestones, although holding in the body of the rock much more water than do compact hard limestones, in point of fact behave similarly to them, since water circulates in, and is mainly yielded from, fissures.

Distribution of water within the rocks

Two influences, gravity and capillarity (surface tension), jointly tend to distribute water in pores and fissures. Capillarity is independent of gravity, and under its influence water may move upwards. It depends on close-quarters molecular attraction and it increases in intensity in passages of small dimensions. Thus the close porosity of clays gives more scope for capillarity than the open porosity of sand. Movement of water by capillary action has important bearings upon agriculture and irrigation, but is negligible as far as water supply is concerned. The only motive force that need be considered in the present connexion in relation to the movement of underground water, therefore, is gravity.

Under the influence of gravity rainfall which is absorbed at the ground surface endeavours to travel vertically downward (though its path may locally be deflected). Were the process of accretion to continue without a corresponding loss from springs and seepages quite obviously the whole of the pore spaces in the rocks would become filled: strata would become entirely saturated. Complete

saturation of a whole geological formation is so extreme a case as to be hypothetical, but saturation of a part is a normal feature, and without it there would be no effective wells.

Gravity tends to produce a universal upper limit of underground saturation more or less at sea level, but the action of the water-cycle, irregularities of surface relief, local variations in rainfall, local differences in permeability of strata from one cause or another, and artificial interference with natural conditions by pumping from wells, all militate against the attempt of gravity to establish equilibrium. On account of the non-fulfilment of this constant attempt, the surface of a zone of saturation, normally termed the 'water-table' (*see* Fig. VIII, 1), is irregular in form, often reflecting in a subdued way the contour of the ground surface above it, and the thickness of a saturated zone in any given bed often varies extremely from month to month. This thickness is the balance between rainfall absorbed and water lost, themselves both variable quantities.

Underground water movement

Underground water, in general, flows much more slowly than surface water; movement is more diffuse, and in most cases the flow may be regarded as a slowly moving wave, travelling along a broad front. It may take place as a movement along more or less defined channels which, in extreme cases such as occur in many limestone districts, produce true underground rivers. In Great Britain underground streams are usually associated with the massive limestones of the Mendips, the Pennines and elsewhere where they are common features, and they are not unknown even in the Chalk. It has been proved that certain streams in Hertfordshire, rising in the catchment area of the River Colne, disappear underground at North Mimms and South Mimms (Fig. VIII, 2) to reappear at the Amwell and the Chadwell in the Lea Valley, about 10 miles away, after a 4½-days' journey. Consideration of the earth's strata in general, however, shows that underground streams of this kind are exceptional, and that as a general rule underground water should not be regarded as moving along restricted channels, nor should the conception be held that underground lakes are present, except as extremely rare phenomena. In some instances of underground water movement may correspond in direction more or less closely with that of a surface stream overhead. But too close a comparison with surface movements is unsafe, since underground movements of water may be very different from their surface counterparts.

EXTRACTION OF WATER: DUG WELLS AND BOREHOLES

Geological factors have considerable bearing on the facility with which water is extracted from the ground, and on the nature and construction of wells. Up to the eighteenth century, most wells made in Great Britain were dug by hand. These hand-dug wells ranged in depth, according to geological circumstances, from a few feet to depths of 250 ft. or more. It is sometimes difficult to appreciate the

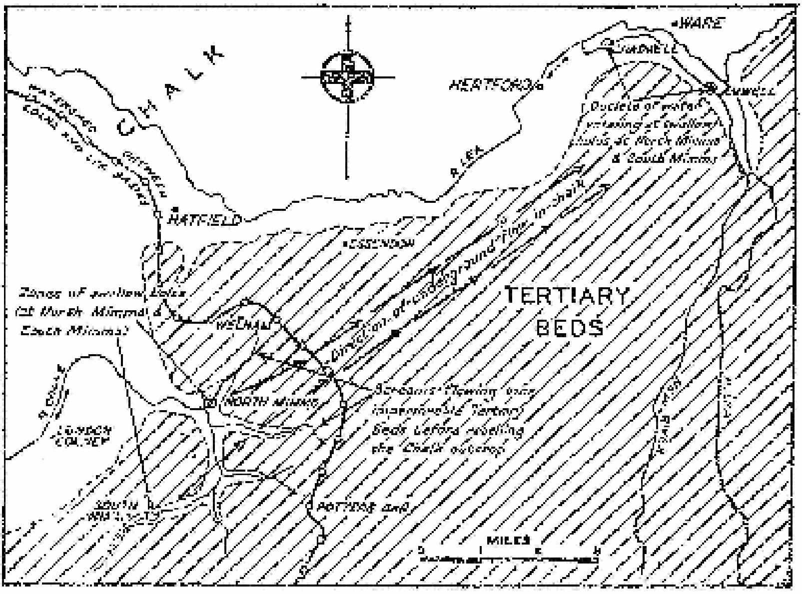


Fig. VIII. 2.—Underground movement of the water in the Chalk near Mimms, Hertfordshire. Water enters the Chalk through swallow holes at Mimms, and emerges at the Amwell and Chadwell springs some ten miles to the north-east.

skill of the old well-diggers, who, working only by the light of a tallow dip, sank to these depths beautifully circular and vertical wells of only 3½-ft. diameter. Large yields were then rare. Well-diggers, in the nature of things, were unable to dig more than a foot or two below the water-table of the stratum which they were tapping. The water-table controlled the standing water level in their well, and in consequence they exposed only a very limited surface to 'bleeding'. In areas where there are large seasonal fluctuations of the water-table, such as happen in many parts of the Chalk country, some of these wells were deepened from time to time as the water-table fell

below a well-bottom. Many old wells of this type indicate by their depths the lowest levels to which local water-tables have reached at any period since the wells were begun. In periods of high water level some of these old wells hold a depth of water of over 100 ft., whereas after long dry periods it is measureable in inches.

It may be appropriate here to add that water in quantity is not necessarily obtainable by penetrating a zone of saturation. It is by no means rare for a bed to contain so little pore-space or fissure-space as to render it almost impermeable, yet the few voids present may still be saturated. A water-table is then present, but it has practically no influence on supply.

Today most privately owned wells, and many wells constructed for public supply authorities, are boreholes. The limitation on working at the bottom of a well imposed by a water-table, that was encountered in the old-type dug well, is obviated, and boreholes may be drilled to any desired depth below the water-table to provide much larger yields than are obtainable from the average dug well. In Great Britain the depth of an average borehole for water is about 300 ft. from the surface but some are much deeper, occasionally up to about 1,500 ft., and a few are deeper still.

Modern dug wells

For very large supplies of underground water such as are required for towns and for large rural districts with piped supplies, recourse to the dug well is again often taken—but with considerable differences from the earlier types. In order to give a maximum bleeding area, vertical shafts of 8 or 10 ft. diameter are dug to the water-table, at which stage very powerful pumps are brought into use. Digging then proceeds, water being continually pumped out as fast as it enters, and at an appropriate depth below the water-table horizontal tunnels or 'headings' are driven, usually about 6 ft. high. Some of these tunnels are of considerable length, instanced by the Friston well of the Eastbourne Corporation Waterworks, which, constructed in chalk, has a single heading running northward from the well shaft for $1\frac{5}{8}$ miles. Five wells also in chalk, which supply Brighton, together have a total of nearly six miles of headings. Of necessity well-sinkers who are engaged in driving well headings err on the side of caution, and install temporary pumps capable of dealing comfortably with the maximum estimated flow from the new well. Even so, it occasionally happens that a very large source of water is unexpectedly tapped, of the order of four or five million gallons a day. This impels a rapid evacuation of the workings.

Equipment may then have to be left in the heading, where it may remain for years.

Whatever the type of well involved, geological factors have to be considered in its construction. In dug wells soft strata have to be protected from collapse into the well, usually by some form of masonry, termed 'steining'; boreholes are protected from collapse by driving down a string of metal lining tubes, which, as described on page 109, are placed through those strata requiring support.

ARTESIAN WELLS

The term 'artesian well' is one in common use, often with an implication of being something out of the ordinary, and not infrequently it is regarded as a synonym for 'borehole'. The term in fact has nothing to do with the construction of a well, and actually most wells are to some degree 'artesian'.

Entirely geological factors govern the presence of artesian conditions. They occur where a permeable formation, with an outcrop at the ground surface to form a catchment area for rainfall, dips beneath an impermeable bed. Water which travels down-dip is thereby confined within the lower bed, and is subjected to hydrostatic pressure by the body of water up-dip. When the overlying, impermeable, bed is pierced at a suitable place, the pent-up water rises up the vent, normally a borehole, in an effort to find its rest level, on the simple principle of water in a U-tube.

The word 'artesian' is derived from the name of the old French province of Artois (Pas de Calais) where water in the Chalk formation is confined by overlying clays. Pressure is derived from water absorbed at the Chalk outcrop of the surrounding hills. Wells of this type were dug in Artois long ago. They were also made by trial and error methods by the ancients at Thebes and elsewhere in North Africa. The term itself, however, dates only from the end of the nineteenth century, when the geological principles of artesian supply were elucidated.

A simple geological structure producing artesian conditions, known as an artesian slope, is illustrated in Fig. VIII, 3, this particular instance being that of the Spilsby Sandstone of Lincolnshire, a formation that occurs in the lower part of the Cretaceous strata. Here water overflows from the well, whose surface level is lower than that of the lowest part of the Spilsby Sandstone outcrop up-dip.

It is a moot point whether the name 'artesian' should be given a well from which water actually overflows, or to one in which artesian

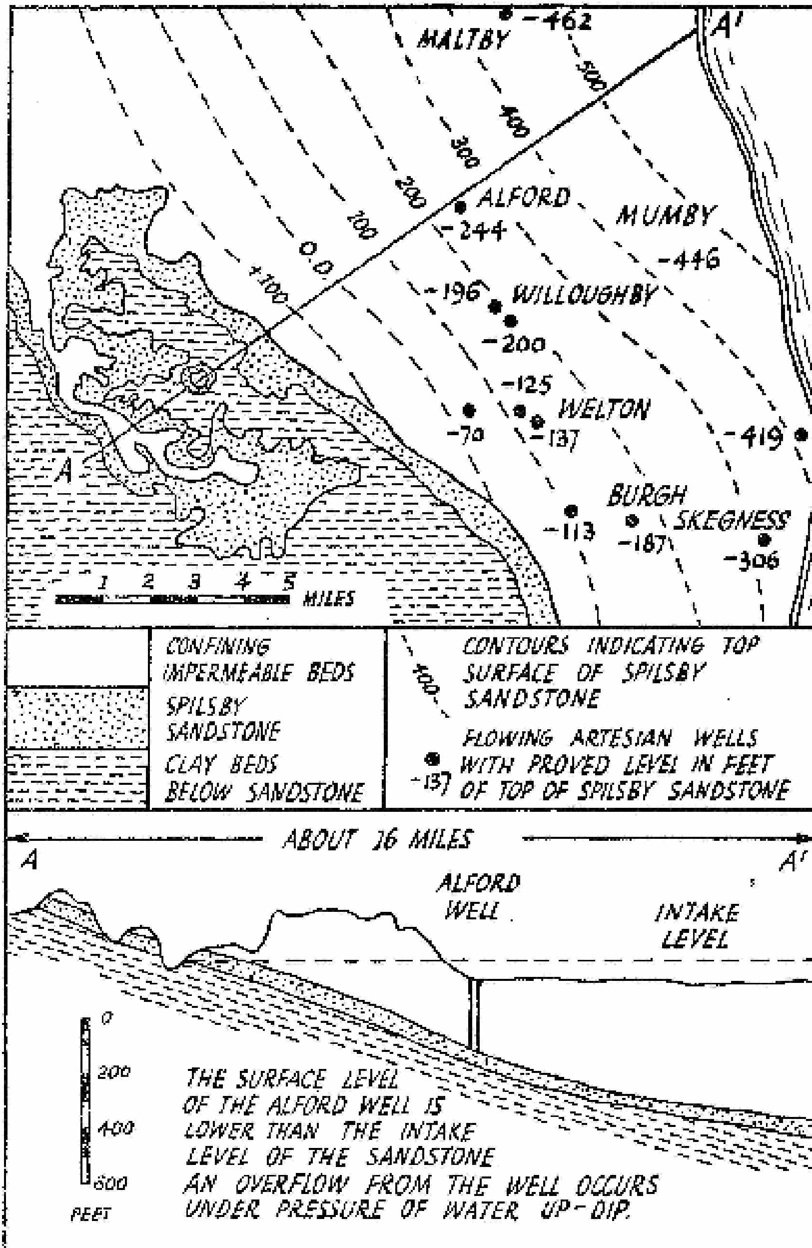


Fig. VIII, 3.—The dip slope of the water-bearing Spilsby Sandstone of Lincolnshire is an excellent example of an artesian slope.

pressure is present, whether water overflows or not. To cover non-flowing wells in which water is under artesian head, the term 'sub-artesian' has been used, but many wells overflow at some periods, and do not flow at all at others, so that it seems preferable to retain 'artesian' for the principle of water pressure, and to use 'flowing' and 'non-flowing' as the distinguishing adjectives. The outstanding example of an overflowing artesian well, shown in the Frontispiece, is described below (p. 127).

FLOWING ARTESIAN WELLS IN LINCOLNSHIRE

One of the most prolific areas for flowing artesian wells in Great Britain is the Bourne district of Lincolnshire, where a part of the Inferior Oolite Series, the Lincolnshire Limestone, dips eastwards from its outcrop at the Lincolnshire Wolds, to be overlain by a clay formation. Their geographical distribution is shown in Fig. VIII, 4. In areas such as this, once an artesian well is made it often becomes most difficult to plug it should it be necessary to conserve supplies, and many of these wells are now permanent springs. A very large spring at Bourne, the source of the small perennial stream from which the village takes its name, gives rise to a pleasant conjecture in this respect. This spring rises from the Lincolnshire Limestone through at least 70 ft. of clay. There is no evidence of any geologically weak spot in the clay, such as may be produced by a fault or fracture, and it is difficult to imagine a pressure head of water in the limestone sufficiently strong to force a way through such a mass. The site of the spring head and the thickness of clay proved in surrounding boreholes are also shown in Fig. VIII, 4. A feasible explanation, but one based entirely on supposition, and it must be emphasized devoid of any historical evidence, is as follows:

At some distant period, Roman or pre-Roman, local inhabitants, in a search for water by trial and error methods, may have begun to dig a well. When clay had been removed to a point where cover became insufficient to withstand the upward pressure of the water in the underlying limestone, a 'blow out' may have been produced. Water then rushed to up the surface, to flow permanently.

An authentic 'spring' of this kind does rise at Quarrington, near Sleaford, from a borehole, put down in a forlorn search for coal, made at the end of the eighteenth century. After drilling through about 90 ft. of clay, limestone was struck, water burst out violently, and gave rise to a small brook which has flowed ever since. Numerous similar 'springs' occur around the Saltfleetby villages, and some are indicated as such on the 6-in. scale Ordnance Survey maps of the

district. Here water rises from boreholes drilled through clay into chalk. Most of these artificially produced springs are adjacent to, and supply, private houses. From a casual glance at the map, a natural inference would be that the houses were built near to pre-existing springs. Actually the houses were there first.

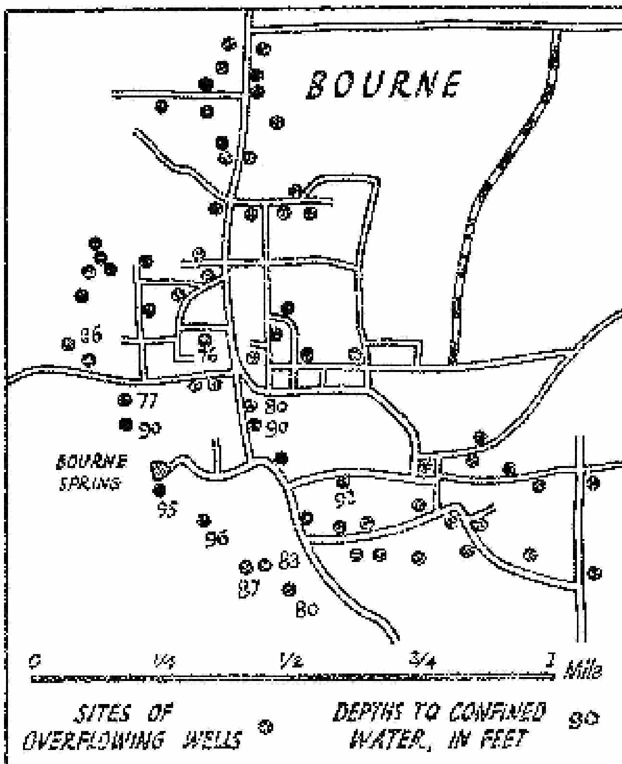


Fig. VIII, 4.—The Bourne district of Lincolnshire is particularly favourable to the construction of flowing artesian wells. It also contains a remarkable spring.

Variation in permeability around wells

Locally permeability may be lost, or it may improve, in course of time, depending on the reaction of the water-yielding rocks to the rapid movement of water through them. Of particular importance in the case of many boreholes is the fact that water movement may be extremely rapid in the rocks immediately surrounding them. Most percolating waters contain some carbon-dioxide in solution. Such have a solvent action on limestones, both compact and weak.

In limestone formations rapid movement tends to wash out fissures, and also to widen them by the gradual removal of their walls. Permeability is thereby increased, and consequently wells in limestone tend to improve their yielding capacity as time goes on. While many sandstones of open textures, such as are encountered in parts of the Midlands, also maintain their permeability over a long period of years under consistent conditions of heavy pumping, other sandstones, particularly in cases where they contain a proportion of material of silt and mud grades, or where the cementing material, such as calcite, is soluble in water, are not so reliable, for the underground flow of water towards a well may carry the finer grades of rock material with it, and these may in time fill up pores in the immediate neighbourhood of a well causing a serious loss of permeability. In extreme cases the well itself may become partly filled with silt. Solution of a calcite cement may convert a sandstone immediately around a borehole into a loose sand, causing collapse of the rock and an attendant restriction of flow. Various methods are employed to overcome these difficulties, such as by digging wells of large diameter to give extensive yielding surfaces; by employing sand screens of various types to keep out fine material, or by firing shots at the bottom of wells to shatter the rock and thereby to increase fissuring. But in most cases, where troubles of this type are to be expected, the most effective method of ensuring a consistent yield over a period of many years is restriction of the quantity pumped at any period to an amount which a well is capable of yielding without producing an unduly high velocity of flow in the immediately surrounding rocks; that is, without producing conditions which give rise to a constantly developed steep cone of depression.

Natural underground reservoirs

It will be immediately apparent that those portions of permeable strata which contain water under artesian head are natural underground reservoirs of water. A study of the geological factors concerning them leads directly to a consideration of the geological factors that are favourable to the formation of natural underground reservoirs in general.

Many reservoirs are to be found along the outcrops of permeable strata provided the beds are of sufficient thickness to retain a considerable quantity of water. Water tends, however, gradually to drain away from them at spring lines or seepage lines. The water-table within these strata will normally be liable to great fluctuation

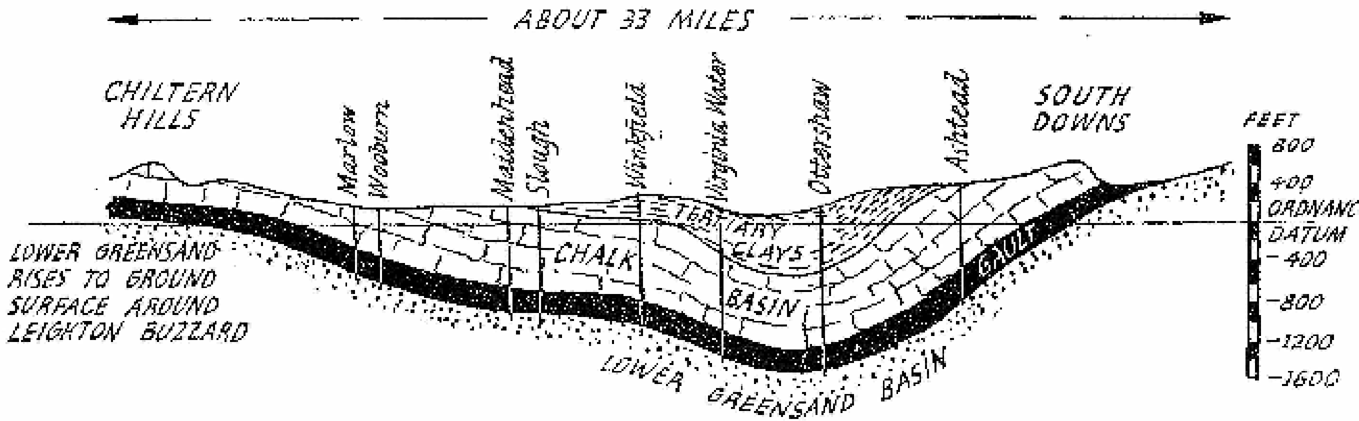


Fig. VIII, 5.—The geological structure of the district between the Chiltern Hills and the South Downs provides a double artesian basin. The upper is in the Chalk formation, the lower in the Lower Greensand.

in relation to rainfall. For example, a well at Chilgrove, West Sussex, has shown a range of fluctuation of no less than 140 ft. over a period of a century, and in a well at Litton Cheney, Dorset, the water-table fluctuated from 83 ft. below surface to 202 ft. below surface during the five years 1934–39. Nevertheless, in spite of this disadvantage, supplies are usually obtainable all the year round at places where a combination of thickness and high porosity of the beds involved, ensures that sufficient of the rainfall of wet seasons is stored comfortably to tide over all but extremely long spells of dry weather.

Artesian slopes, described above, are common geological structures. They occur wherever permeable beds dip under impermeable beds, and in theory any permeable stratum so arranged should provide an underground reservoir, but in practice efficacy often depends also on other limiting factors.

The geological structure known as an artesian basin is simply two opposing artesian slopes, and is exemplified by the Chalk artesian basin under London. This has a northward artesian slope from the North Downs and a southern from the Chiltern Hills. In point of fact, the western end of the London Basin shows a double artesian structure. Fig. VIII, 5, illustrates a geological section from the Chiltern Hills through Slough to the North Downs, in which the Chalk is seen to form an upper basin, in the lower part of which water is under pressure from that contained up-dip in the respective slopes towards the North Downs and the Chilterns. This is underlaid by the impermeable Gault, below which lies the permeable Lower Greensand, in which water is under pressure from that absorbed at the Lower Greensand outcrops in Surrey and Hampshire (Leith Hill–Hindhead areas) on one side, and in Bedfordshire around Leighton Buzzard on the other. This lower bed provides several outstanding examples of artesian wells. The Frontispiece shows the overflow from a borehole at Slough that gave 250,000 gallons an hour from about 1,000 ft. below sea level and formed a 'gusher' which rose, until capped, 30 ft. above the surface. There was a pressure of 43 lbs. to the square inch at the ground level. Another again, at Staines, touched the Lower Greensand at 1,240 ft. below sea level to overflow at 30,000 gallons per hour.

Geological factors adverse to natural storage

Some geological factors are adverse to underground water storage and often occur where conditions at first sight may appear favourable. It is by no means uncommon for a bed which is highly

permeable at the ground surface gradually to lose permeability as it descends underground, either as a result of actual change in rock-type, for example from an open sand to a clayey sand, or as a result of compression due to the weight of the overlying beds. It is rare for any large supply to be obtained from chalk which is overlain by more than 400 ft. of strata.

Geological faults often produce most complex conditions, that in some circumstances favour storage, in others militate against it. A fold may assist in, or it may prevent, the accumulation of bodies of water, according to local circumstances. The thickness of a permeable bed may be considerable at the surface, but beneath cover the bed may thin out rapidly, even to zero, and thus fail to give that storage which surface evidence alone would portend. Close geological investigation is therefore necessary to the task of detecting and delimiting natural underground storage areas.

Water-bearing formations in England and Wales

It is fortunate that the Midlands and eastern and south-eastern England, which have a relatively low rainfall averaging 30 in. (though much less in some districts), contain some of the chief water-bearing strata of the country. These strata comprise several extensive series of permeable geological formations, whose general distribution is shown in Fig. VIII, 6.

Of these, the Chalk is by far the most important. Numerous towns and villages are supplied from the chalk wells of Salisbury Plain, the Dorset Heights, North and South Downs, the Chiltern Hills and their continuation through Lincolnshire and Yorkshire. Along the south-east coast Margate, Ramsgate, Deal, Dover, Eastbourne, Littlehampton, Seaford, Brighton and Worthing all depend entirely on chalk wells, and other coastal towns such as Portsmouth, Southampton and Bournemouth do so in part. London takes about 45,000,000 gallons from underground sources daily—about 15 per cent of its total consumption. The Chalk also underlies large areas whose ground surface is occupied by more recent strata. Southend, Chelmsford, Colchester and other towns are fed either wholly or in part from wells put down into the Chalk at depth through overlying formations.

Another important group of permeable strata comprises the oolitic limestones of the Jurassic system. These crop out over a belt of country running through England from Dorset to Yorkshire, and include as their chief members the Great Oolite Series and the Inferior Oolite Series. Each of these groups of strata is a complex

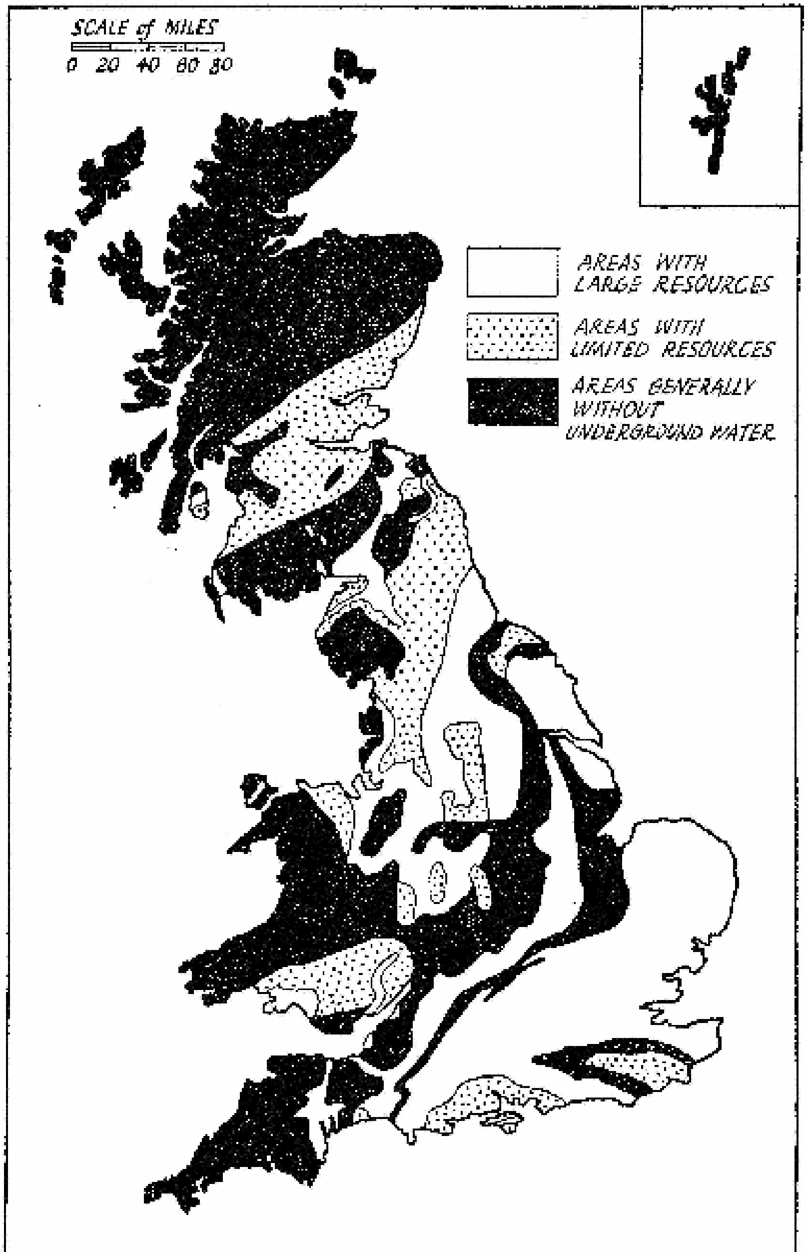


Fig. VIII, 6.—The water-bearing areas of Great Britain.

of superimposed sheets of limestone, clay and sandstone which change in character, thin out, or finger into each other laterally in a most disconcerting manner. Their variable nature is reflected in many vagaries in water supply in the Oolitic belt of country. Springs abound and some are very large. Most of them fluctuate in sympathy with rainfall, and may dry up after periods of drought. A detailed knowledge of local geology is particularly valuable in a search for new water-supply sites in these limestones.

Triassic sandstones constitute a third water-bearing belt. The permeability of these sandstone beds is very high and in consequence they yield their water readily and the water-tables are practically static. The difference between the maximum and minimum water-rest levels in certain wells connected by headings in the Bunter formation, from which 400,000 to 700,000 gallons a day were regularly pumped, measured only 10 ft. over a period of six years—an interesting comparison compared with the fluctuating water levels in the Chalk.

Other important water-bearing strata are the Magnesian limestones of Northumberland and Durham and the Carboniferous Limestone of the Mendips, North and South Wales, Derbyshire, parts of Yorkshire and Cumberland. In favourable circumstances these hold enormous quantities of water. The walls of the many fissures which characterize these limestones have been subject to the solvent action of percolating waters and many fissures are much widened. Numerous caverns have been formed which may contain underground streams or lakes and others are still being enlarged. The numerous channels which traverse these limestones usually come together to form chambers of increasing size from which there may be a feed both from and into surface streams. The presence of these caverns has given rise to the very strenuous—and adventurous—sport of caving. Since 1945 alone a number of new caves lying several hundred feet below the ground surface have been discovered in the Carboniferous Limestone both of Yorkshire and of Wales. The caves of Cheddar in Somerset and Ingleton in Yorkshire are well-known examples of limestone caverns formed by solution.

Impermeable strata of Great Britain

Although many parts of Great Britain are favourably placed as regards water-bearing strata, large tracts of country are not so fortunate. The hard rocks of pre-Cambrian and Lower Palaeozoic ages which occupy great parts of Scotland, the Lake District, Wales

and Cornwall, and the shales and clays of Mesozoic and Tertiary ages which stretch over large belts of England, hold practically no available water in storage. Generally speaking, no well in them is likely to be successful, however deep it may be taken, although exceptional cases may arise. Shallow wells a few feet deep often give supplies of a few gallons a day, not always maintained, from the weathered top of these impermeable beds. In the clay zones an occasional sandy bed will give water sometimes of good quality but often so hard as to be undrinkable.

From time to time small boreholes for private supply, particularly for farms, are put down in these clay belts in face of adverse geological conclusions, yet with every justification. In the absence of a piped supply the value of even a small yield of good well water in rural districts of this kind is very great. The remote, but not entirely negative, chance of success is outweighed by the prospective advantages that would accrue from a successful result. In these districts boreholes of this type are rather matters of a good (or bad) gamble rather than of scientific application. But no speculative borehole more than 300 ft. deep is normally justifiable, even as a gamble, in these generally waterless areas.

Strata of intermediate permeability

In addition to the generally highly permeable and the generally impermeable strata there are many from which large yields are not to be expected. Much is known concerning these intermediate strata and the prospects of a site can be gauged with a good degree of reliability. Under very favourable circumstances a supply adequate for a village or a small town is possible from these beds, but that is the maximum that is to be expected from them. Private wells often stand a good chance of being highly successful.

Great Britain's daily supply from underground sources

Today about a dozen towns with populations between 100,000 and 250,000, another 400 towns with populations between 25,000 and 100,000, and villages, have piped supplies derived from natural underground storage, and many thousands of private wells are in daily use. In Great Britain the total daily supply from underground sources lies somewhere between 400 million gallons and 500 million gallons. One of the factors leading to this result has been the possession of the detailed knowledge of the geological structure of the country as a whole. This has rendered possible the delimitation of the water-bearing areas and of the sterile tracts.

ARTIFICIAL RECHARGING

A question that periodically arises in the water engineering world is that of artificial recharging a depleted natural underground reservoir. This matter, considered from the angle of physics only, leaves no doubt of the conclusion that a well which will give water

Fig. VIII, 7.—Water-bearing areas of England scheduled for the conservation of underground water (1955).

out will take water in. It would seem an obvious procedure therefore to recharge a depleted reservoir from stream flood-waters. In point of fact in some areas recharging is a regular practice where conditions are favourable, but at present it is most effectively used where the water-yielding bed is relatively near the ground surface, that is, within about 100 ft, and the intake area near a river.

In many places, however, conditions are unfavourable to an economic recourse to artificial recharge. One controlling factor is the size of pore-spaces between the individual grains or stones of the absorbent stratum. Beds with very open pore-spaces are very favourable; rocks with small pore-spaces present difficulties. In Great Britain attention has been given to the possible recharge of reservoirs in the Chalk, particularly for the supply of the London district.

Over the wide expanse of the Chalk outcrop rainfall is automatically filtered in its passage through the soil, and is freed thereby from sand and sandy clay in suspension. Artificial recharge could be carried out either by distributing water over land surfaces or by pouring water down deep wells. The latter alternative would necessitate previous filtering, otherwise the absorbent pores and fissures around the walls of the Chalk wells would soon become clogged up; which would retard and ultimately prevent the ingress of water. The necessity to filter water before sending it underground manifestly introduces important economic problems.

The first alternative also has its difficulties. Suitable absorbent surface areas almost solely lie on hillsides and over areas well above the level of neighbouring streams, from which water would have to be obtained. Water therefore would have to be pumped. On economic grounds alone, it would appear preferable to pump water through pipes to known destinations than to pump it to a hillside for it to sink into the ground and go where it listed.

It may be remarked here that soakaways in permeable strata are common methods of disposing of surface water from roofs and streets. They have varying degrees of efficiency but the total quantity of water absorbed in any one area is negligible as compared with the quantity which would be required for a successful recharge scheme.

Future developments

The comparative facility and reliability with which our natural underground reservoirs may be detected and exploited has produced its own problems. Obviously a balance needs to be struck between the annual rate of extraction from a well and replenishment from rainfall. If the former exceeds the latter, the supplying reservoir suffers depletion; the well then lives on accumulated capital, as it were. Should this be long continued an extensive cone of exhaustion is produced, and it becomes impossible to maintain a full yield. Numerous instances of this have occurred in public-supply wells during the past two decades in particular, although they may

have been unknown to the consuming public, since difficulties have been overcome temporarily by various palliatives until the position has been rectified. This often has involved the acquisition of another source of supply. Such conditions cannot continue indefinitely. Over wide areas of Britain regulation, both as to present rate of extraction and as to future development, has now become essential. In these 'scheduled areas' indicated in Fig. VIII, 7, no new well to get water for industrial purposes may be put down without a licence to do so. No licence is required for wells for private domestic supply.

OVERGROUND SUPPLIES

It has been remarked above that British rivers, fed as they are by numerous springs, generally maintain a relatively high dry-weather flow. In lowland areas therefore they constitute dependable sources of water supply. To the provision of supplies of this sort, geological science makes little or no contribution; they come more particularly within the provinces of the meteorologist and the engineer.

In upland areas that are composed mainly of impermeable strata, and where rainfall is heavy, river flow is less regular. Conservation in artificial storage reservoirs of water derived during periods of heavy precipitation, to be used at a regular rate the year round, has been practised from time immemorial. During the last hundred years it has reached immense proportions in these upland areas, for the supply of towns often two or three hundred miles away. Manchester is supplied largely from the Lake District, Liverpool and Birmingham from Wales, and Sheffield, Nottingham, Derby and other towns from the Pennines. In recent years new hydro-electric schemes, particularly in Scotland, have necessitated the construction of a number of large impounding reservoirs.

Reservoir sites

Among the many considerations involved in the choice of a site for a surface storage reservoir, a number are geological; and these are, both literally and metaphorically, fundamental. An ideal site for such a reservoir is a large, elongated, steep-sided valley, that has been eroded out in impermeable rocks. Valleys of this kind are restricted to upland districts where the geological structure is frequently complicated and by no means everywhere favourable to retentive valley sides.

In Great Britain such steep-sided long valleys are normally developed in the mountainous areas of Wales, the Lake District, the

Pennines and Scotland; which are also the areas of high precipitation. It is in these areas, therefore, that the majority of large impounding reservoirs have been made, either by raising the capacity of a natural lake by damming, as has been the case of Thirlmere, or by damming stream valleys to produce artificial lakes, such as Vyrnwy (Plate IVA and B), the Ashopton reservoir in Derbyshire, and a large number of smaller reservoirs in the Pennines. By no means is every steep-sided narrow valley in these districts a potential reservoir site. Many valleys which superficially may answer requirements have been developed along deep-seated lines of weakness resulting from geological faults, along which water would escape. Faults, however, are only one of the adverse geological factors which have to be taken into account. In our mountainous districts in particular, the Great Ice Age has left a legacy in the form of deposits of gravel which floor to considerable depths many otherwise suitable valleys and through which water freely finds its way. Again a permeable bed may be interbedded with, or may underlie, the requisite impermeable strata in such a way that although water may not be lost along it under natural conditions, the changed conditions produced by filling a valley with water may produce the reversal of the natural underground direction of flow. None of these disadvantages necessarily rules out a valley. Engineering skill is able to overcome them in the majority of cases, provided they are known.

Resulting from incomplete geological data, failure or partial failure in storage-reservoir construction, or initial failures which have ultimately been converted to success only by the expenditure of greater sums of money than had been originally estimated, have not been unknown in the past. Fig. VIII, 8, illustrates the condition of a reservoir which was only partly successful. The sides and bottom were initially thought to be entirely satisfactory, but a wash of surface material masked a permeable bed up the valley side, rather lower than the proposed ultimate level of the impounded water as controlled by the dam. On completion of the dam, water accumulated according to plan until it reached the permeable bed at X through which it leaked to form springs in the next valley at Y.

London's surface storage reservoirs

London obtains the great bulk of its supply from the Rivers Thames and Lea. It has no deep steep-sided valleys for storage reservoirs in its vicinity. Recourse has been taken, therefore, to the digging of extensive holes in the ground, as it were. Each of these

dug-out reservoirs needs must cover a large acreage, and floor and sides must be watertight.

Excavated reservoirs of this type could not be placed haphazard in the London area. A thickness of several hundred feet of impermeable London Clay is known to underlie great parts of the district around the Thames and the Lea. In certain other parts the London Clay, although forming the surface, is underlain by beds of permeable sands at a considerably less depth than the floor of a dug-out reservoir would lie. Geological investigations have clearly defined both the favourable and the unfavourable areas, and the present

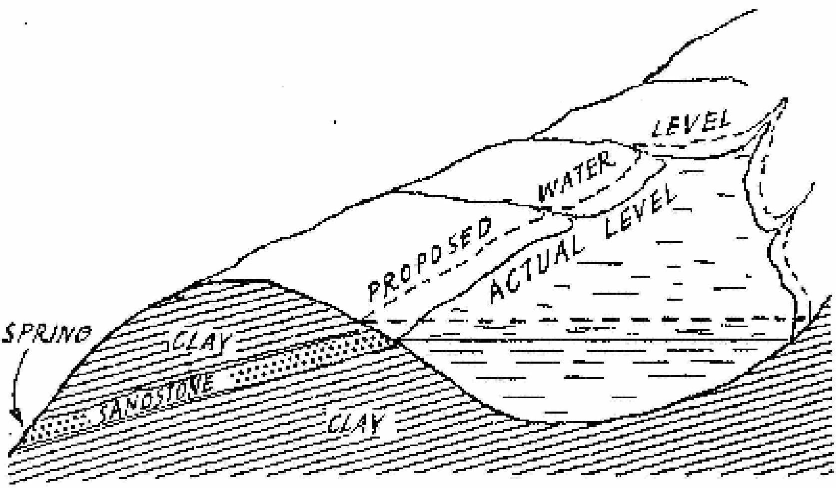


Fig. VIII, 8.—The level of water first proposed for this impounding reservoir was not finally attained because of leakage along a bed of sandstone.

reservoirs have been sited accordingly. Every potential site for a future storage reservoir is given a thorough geological examination. Some are rejected out of hand.

One of the most recent rejections was made in 1947. The Metropolitan Water Board, in the normal course of events, examine potential reservoir sites around London to meet possible eventualities necessitating increased storage over present capacity. In that year the Board considered the possibility of constructing a very large storage reservoir near Kingston, Cambridgeshire, by damming up the valley of the small River Bourne. A first examination in the field pointed to this valley as being eminently suitable for the purpose, and as regards water-tightness, the sides and floor apparently were

all in clay. A detailed geological investigation, however, showed that a widespread bed of sand which underlies the clay crops out over an elongated area along part of the stream bed, and that its disposition is such that, were a reservoir to be constructed, water would leak away underground through the valley bottom to emerge as springs in a hillside to the west (Fig. VIII, 9); a variant, in fact, of the conditions affecting the partially successful reservoirs described above. On the recognition of the implications of the geological structure of this district, the plan was immediately abandoned.

London is not alone in south-east England in establishing overground water supplies. A large reservoir for the supply of a large district of the Weald has been completed (1955) in the Ashdown Forest. There the River Medway is now dammed near Forest Row,

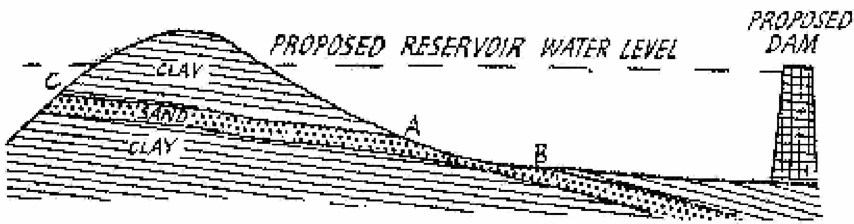


Fig. VIII, 9.—A site for a proposed impounding reservoir in a Cambridgeshire valley was abandoned because of a bed of sand that cropped out at A—B in the valley bottom. Were the reservoir to be constructed, water would escape at C.

and an artificial lake formed. A similar reservoir for the supply of much of Essex has been constructed at Hanningfield.

Relative efficiencies of surface and underground reservoirs

The efficiency of surface storage reservoirs is greatly superior to that of natural underground reservoirs. It is rare for a single large well to give more than about 4,000,000 gallons of water a day, which is a normal supply for a town of 130,000 inhabitants. Where underground water is the source of supply, for towns of larger size, therefore, several separate pumping stations are generally required. Brighton, for example, has five pumping stations. But a single very large storage reservoir is capable of providing many millions of gallons a day. Brighton is particularly favourably placed for an underground supply, much more so than many other towns, and in any event its population does not compare in size with the popu-

lations of many of our industrial areas. As a rule very large cities and towns must perforce have recourse to surface supplies.

London provides an excellent example of the relative underground and overground values. Its daily consumption is about 330 million gallons, of which 85 per cent is extracted from its two overground river sources. Few of our cities are as well situated as is London in relation to underground sources, yet to obtain the remaining 15 per cent—45 million gallons—a ring of no less than 15 wells into the Chalk, mostly with headings, is necessary.

CHAPTER IX

Building Materials

SANDSTONES and limestones in great variety, igneous rocks of many kinds, slates, gypsum, gravels, sands and numerous sorts of clays have all been used in building work from time immemorial. A few thousand years ago people in Cyprus were quarrying and transporting blocks of stone of over thirty tons weight and measuring some 12 ft. × 6 ft. × 6 ft. Throughout the long history of building construction these materials have largely, though not entirely, been excavated from surface quarries, at spots where both the outcrop and the nature of the rock have been easy to see. The Nubian Sandstone was quarried by the Egyptians from surface workings. One look at the Isle of Portland would have satisfied Sir Christopher Wren that there was ample stone there to build many cathedrals.

Numerous characteristics of rock germane to their suitability as building material are to be seen in working faces of quarries; among them are bedding planes, a feature of many sedimentary strata. Sedimentary building stones are normally very durable if they are 'flat bedded'; that is, if they are laid in a wall so that the natural bed of the stone, i.e. the bedding plane, lies horizontally. If they are 'end bedded', with the natural bed placed vertically, they tend to flake away under the disrupting influence of frost and other denuding agents, and particularly so if the bedding plane also lies parallel to the face of the wall with which the stone is built. It is only in a restricted number of sedimentary building stones that bedding planes are absent or are so undeveloped that weathering has very little effect upon them. These are the 'freestones' of the building industry. They free the mason from the limitations that other stones impose on him on account of pronounced bedding.

All rock features of this type may be explained today in geological terms; but that does not necessarily mean that geology, by explaining them, has made an economic contribution to the building industry. Like the bedding plane, for the most part they and their effect have been known to generations of quarrymen and stonemasons the world over; indeed, the almost uncanny knowledge that a quarryman possesses of the stone of his own quarry, gained from empirical sources and handed from one generation to another, is proverbial.

Were an appraisal to be made of the respective debts that geology and quarrying owe to each other, it is more than probable that the balance would strongly favour quarrying; for quarries have been a major source of evidence for geological deductions. They have given many clear sections of strata which have exposed folds, faults, sedimentary rocks of various kinds, igneous intrusions, old lava flows, and a great number of other items of geological interest. They have formed a major part of the collecting grounds for the fossils on which are based schemes of palaeontological zones.

On the other hand, although quite obviously in countries of the Old World geological science has in the past been generally unnecessary to quarrying, in countries of the New World, where no traditional knowledge of sources of building materials was available, early settlers were quick to realize the importance to them of systematic geological work. This was evinced by the 1824 Geological Survey of North Carolina and, also as noted on p. 90, the proviso made by British Columbia on joining the federation of Canadian provinces that it should be given adequate geological assistance.

The position in most countries today is that quarrying operations connected with building and other industries are so extensive that casual recognition of outcrops and trial and error methods can no longer satisfy demands. Many contracting and manufacturing organizations require detailed geological information at an early stage when consideration is being given to proposals for opening new quarries or for extending old ones, to ensure that the very large reserves of a rock of the right kind that are needed are available and are economically accessible. It is by systematic geological work both in the field and in the laboratory that new sources of even the most everyday kinds of rock required by large-scale industry are located.

Prospecting for building materials is perhaps less spectacular than prospecting for mineral ores and for coal, and in the nature of things it is more generally taken for granted. In Great Britain the preliminary geological survey of the country, completed about 1870,

gave a broad outline of its mineral resources of all kinds. But the information that the geological surveyors of the time then gathered and recorded has now become so much a part of everyday knowledge that probably few today appreciate its origin. Additions to this information are constantly being made, and there exists today a large body of co-ordinated data, not only on coal and ores, but on stones and clays.

BUILDING STONES

One of the first instances in which systematic geological work on building stones was carried out in Great Britain was in the preparation of a 'Report with reference to the Selection of Stone for Building the Houses of Parliament', dated 1839. Two of the subscribers to this were William Smith, the 'Father of English Geology' (p. 17), and Sir Henry de la Beche, the second Director of the Geological Survey of Great Britain. Building stones from some 300 quarries in Great Britain were reported upon and matters dealt with included the following: Name of quarry; Place; Names of quarry owners; Brief mineral designation (e.g. sandstone, oolite, etc.); Composition of stone; Colour; Weight of stone per cubic foot; Full depth of workable stone; Description of the beds; Sizes of blocks that can be obtained; Where known or reported to have been used; Effects of structural features, such as dip and overburden, on working.

In view of the fact that the stone ultimately selected was not the most suitable for the London atmosphere, this instance may not appear to be an unduly good recommendation for the use of geology. But it would be unjust to blame the geological advisers of 1839. Many causes of the failure of building stones lie in their use in wrong environments. In this case the cause of failure has been determined as having been a chemical reaction of the stone with the sulphur-laden atmosphere that afflicted London for many years.

Petrological examination of stones and other laboratory work on them to determine their microscopic structure, and to get information as to their behaviour under certain defined conditions, have assisted the architect and builder. It has given answers to a number of previously unexplained problems concerning an apparently erratic tendency to decay shown by some building stones that had been regarded as first-class material.

Various laboratory techniques have been applied to the examination of stones by the Building Research Station of the Department of Scientific and Industrial Research. Much information has been gained, particularly on the subject of decay. It has been

observed for instance that stone decay has occurred when sandstone and limestone blocks have been placed in juxtaposition. The blame in the past has often been placed on the stone. It is now known that decay of this kind often results from a chemical change that takes place between stones of dissimilar composition, and that if it is desired to lay them together certain definite precautions must be taken to prevent trouble.

Laboratory tests on stones, however, have certain limitations. No guarantee can be made that the weathering properties of each of many separate blocks of stone will conform to those that may have been estimated from laboratory tests on one or two small samples, since stones, even from the same bed in the same quarry, vary greatly in texture.

It is normally unnecessary to test stones for bearing capacity. No blocks of stone, even at the base of a building, are likely be called upon to withstand more than a fraction of the pressures that they are capable of bearing, whatever the erection in which they may be set.

Repairs to stonework

The decay of the original stone of the present Houses of Parliament, through chemical weathering, has necessitated an extensive programme of repair. As was the case in the original choice, new stone was selected in the light of the most recent scientific investigations. The choice was recommended after an exhaustive examination of many stones both in the field and the laboratory, by a committee that included an architect, a geologist, and a chemist and physicist experienced in laboratory work on stones. This combination well illustrates the position geology holds in relation to building stones, and the interdependence of science and art in the matter of selection.

A relatively minor, though in its place important, outcome of a geological examination of many building stones (an examination comprising their petrology, palaeontology and a survey record of their occurrences in nature) is that in repair work on ancient buildings it is now generally possible to replace decayed stone by new material that matches exactly that which had been originally used. In most instances the ancient quarries are no longer traceable, but new stone is usually obtainable either from the identical bed from which stone had first been quarried centuries ago, or from another of the same character.

An outstanding instance of geological work applied to archaeology

was the tracing of the precise locality in the Prescelly Mountains of Wales, and possibly the precise quarry, from which the stones of the inner circle at Stonehenge were quarried. Similarly, the sources of building stones and tesserae found in the remains of many Roman buildings in Britain have been discovered. In 1954 fossils contained in stones from Roman remains at Colchester proved diagnostic of their sources in Middle Jurassic limestone formations.

A geological study of the stonework of ancient buildings, notably of old parish churches, may add much to their history as recorded in documentary form. In many old churches that have architectural features belonging to various periods from Saxon onwards, the builders of each period used stones of different kinds and from different sources from those used by their predecessors. Determination of the localities from which the usual kinds of stone were quarried often throws interesting historical sidelights on local conditions.

Road metal

Closely allied to the building-stones quarrying industry is stone-quarrying for road metal. Good roadstones today have to satisfy stringent conditions. In many cases good or bad qualities lie in their microscopic structure, and so petrological and other investigations are carried out in great detail. The data given by examination of thin sections of rock under the microscope are correlated with those derived from various 'attrition tests' designed to simulate conditions to which stones are subjected by traffic on the road. This has contributed a large body of information on the factors that render some stones excellent as road metal, while others, superficially of equal durability, are in fact of poor quality. In Great Britain in recent years, two departments, the Road Research Laboratory and the Geological Survey, both under the Department of Scientific and Industrial Research, have collaborated closely in roadstones investigations. It is not only demands of road engineers, however, that have been kept in view. Airfield engineers are called upon to construct runways that will continually withstand sudden impacts of planes that weigh many tons, landing at speeds in excess of 100 miles an hour. The quality of the roadstone used in runway construction is of highest importance.

Limestones for cement, lime and whiting

Apart from their use as building stones, limestones provide either part or the whole of the raw material of lime, cement and whiting.

In past years limestones of all kinds, many from thin beds of local occurrence, have been used for lime burning. As in other industries modern trends are towards production at large works.

In Great Britain the two great sources of raw materials for these purposes are the Carboniferous Limestone and the Chalk formations. The constituent beds of all sedimentary formations vary in composition both vertically and laterally, and limestones are no exception to this rule. Some beds therefore are more suitable than others for specific industries. Modern manufacturing processes, whether for lime, whiting or cement, require, at each separate works, stone of a relatively constant chemical composition.

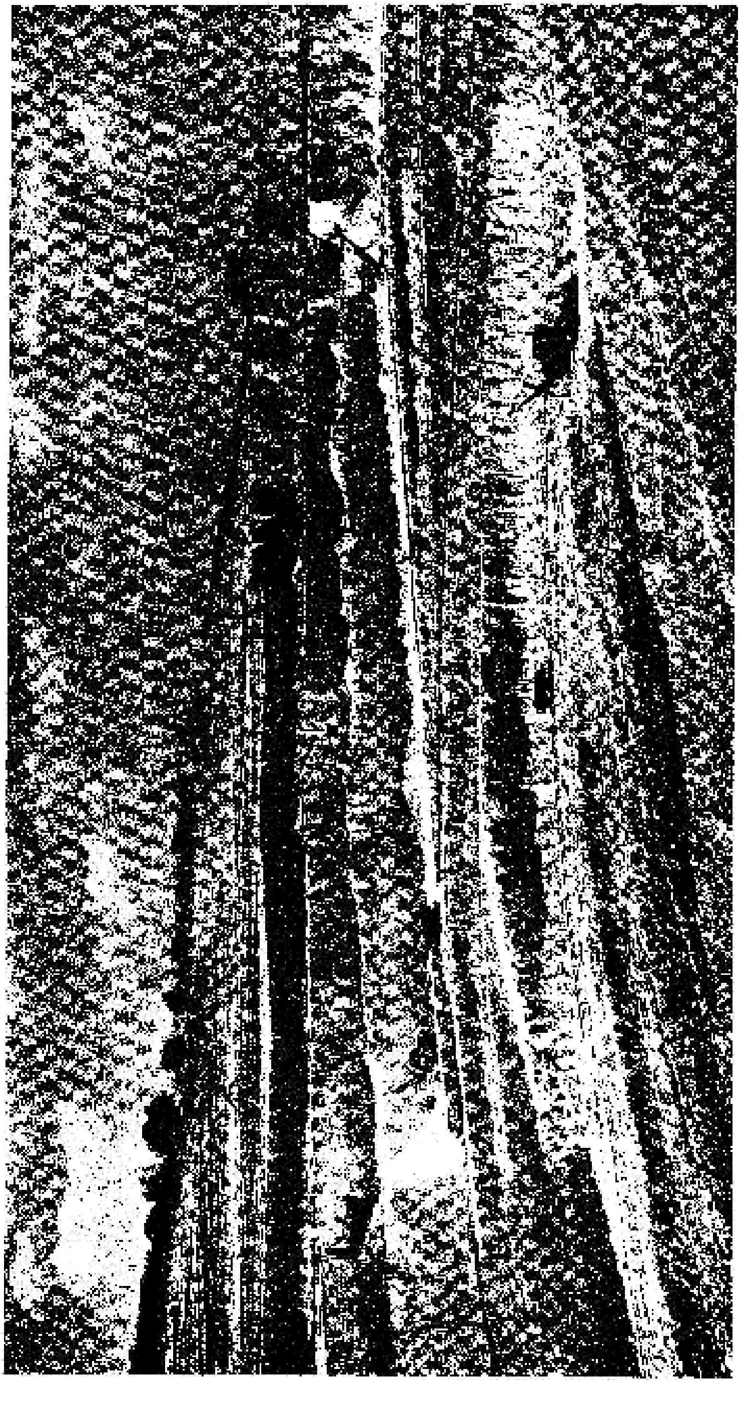
A superficial examination of chalk shows it to be apparently of much the same composition throughout. As described on p. 70, closer observation shows that some beds have different composition and texture from others. Some of these types are more suitable than others for specific industries. Certain beds are better for lime, others for cement, and others again are used to produce the very pure and fine powdered form of calcium carbonate known as whiting, used in distemper paints, toothpastes, rubber manufacture, paper manufacture and many other products and industries. Chalk has been used in Britain as an agricultural dressing certainly since the days of Pliny. Certain beds, notably the Totternhoe Stone, have been used as building stones, particularly for internal decorative work. A very long-continued use of chalk in Britain is shown by the many thousands of small quarries, now mostly overgrown, that mark its outcrop. It was not only worked at the surface; many extensive adits or mines exist. The location of many of these is now unknown, but from time to time they make themselves evident by sudden collapses of the ground in most inconvenient ways. Amongst these workings are the numerous deneholes of south-eastern England. These are shafts up to 100 ft. deep, many of them dug during the eighteenth century, but others are much older. Other chalk mines persist as 'caves' of which the well-known Chislehurst Cave near London is an example. Parts of the Chalk bordering the Thames in North Kent have been honeycombed with mines which were in use up to the nineteenth century. Plans of some of these old chalk mines have now been made, Fig. IX, 1 being one of a North Kent chalk mine that was recently discovered and surveyed.

Locally chalk of a special type was mined. This was the case with the Totternhoe Stone, formerly dug in the Chiltern Hills. No sites are known today of any of the Totternhoe Stone mines, but a most interesting account of them was written by a Swede, Pehr Kalm,

British Railways

'Overbreak' in the Woodhead railway tunnel, constructed in 1951, between Sheffield and Manchester

PLATE VI



Cement and Concrete Association

A large Chalk quarry in North Kent. Chalk is excavated for cement manufacture

who visited Britain in 1748. The following are extracts from a translation of Kalm's work made by J. Lucas:

"We went afterwards to a place where the white stone is hewn,

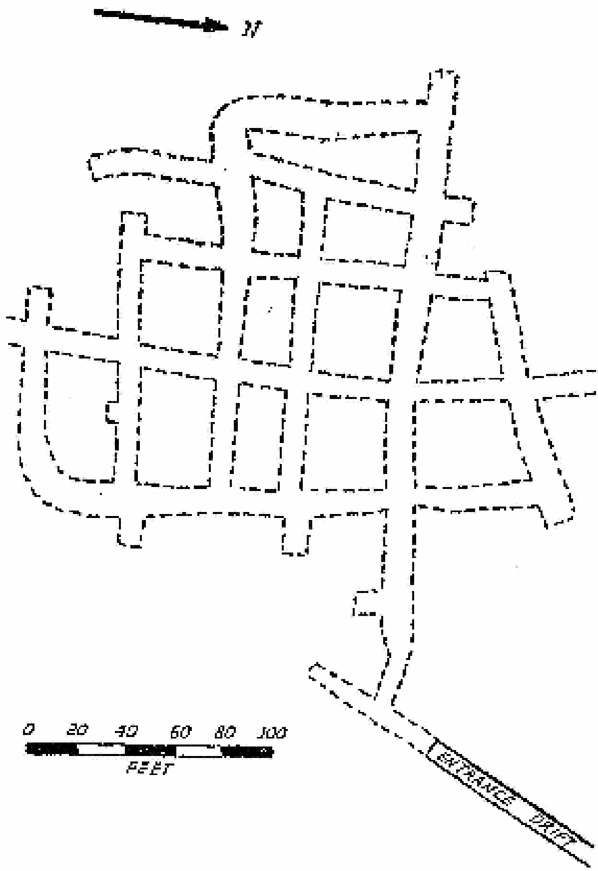


Fig. IX, 1.—Plan of an old chalk mine in North Kent. The floor level over the mine generally lies about 5 ft. above Ordnance Datum, the galleries average about 20 ft. from floor to roof, and there is an average of 40 ft. of chalk between roof level and the ground surface above.

which is here called Freestone, and of which churches and other houses, etc., are built. The place where it is taken out is one of the highest chalk hills in this district, situated in Bedfordshire, just six miles north of Little Gaddesden. The nearest village to it is called Tetternel, after which the mine or stone pit likewise got its name.

". . . This freestone is dug deep in the hills. Here were three places, where they had formerly hewn the same, and where adits down at the foot of the hill went far under the earth, or the Chalk hill.

"The adits into the Chalk hill went mostly horizontally, yet they sloped a little down in some places. On both sides of the main adits there were other adits both ad angulos acutos, rectos, et obtusos, so that if the entrances of all these cross galleries had been open this would have been to one unacquainted with them the worst labyrinth and maze there could possibly be.

"The use of this Freestone and the purposes it is used for, are various. The principal is to build houses of it, when it has first been hewn here at the mine into a four-sided oblong form. Likewise it is used for window frames and doorposts, and arches over fireplaces, windows and doors, for several kinds of pedestals and pillars, the bottoms of baking ovens and other such things.

"In several places appeared unsightly large pits, which now on the bottom were overgrown with grass, where they in former times had hewed up this stone. The workman told us that for one and each of the same pits there is a hole or adit under the ground, but that the entrances to them were now fallen in. The deepest hole, which was 40 poles into the hill where they were now working and in which I was, was said to be over 500 years old. The whole mine was said to have been worked for a thousand years."

This is a further instance of a building stone having been found by some chance or other. Since Kalm's day the whole of the outcrop has been traced. Should this stone be required in quantity again in the future—by no means an unlikely event—its position in the chalk hillside is known; as are its petrological characters. Reliable estimations of reserves could be made with little difficulty.

Materials for cement

The cement industry as understood today dates from the year 1824, when Joseph Aspdin, of Leeds, took out a patent for "an improvement in the modes of producing artificial stone". This stone, on hardening, was thought to resemble Portland Stone, and Aspdin's cement was accordingly called Portland Cement. Numerous other cements, both before and after Aspdin, have been made, but 'Portland' cement has survived the tests of time. In its manufacture, limestone and clay, after appropriate treatment, are fused in cement kilns. As far as Great Britain is concerned, suitable clays are to be found in many parts of the country. Most British limestones also are

suitable and there are plentiful reserves. Each kind of limestone, however, requires a special treatment in cement manufacturing. Chalk is widely used, but this formation, as outlined on p. 70, comprises a number of types. The Lower Chalk possesses a composition unlike that of the Upper Chalk. Jurassic limestones are also used, but these are extremely variable from place to place. In the Carboniferous Limestone formation some beds are composed almost wholly of calcium carbonate, and therefore are suitable either for lime-burning or cement manufacture, but others contain much magnesium carbonate (dolomite) and are of quite unsuitable composition.

Excavation of both clay and limestone in Britain today is on a very large scale. Indeed, cement-making is a major industry, and in 1950 alone the amount manufactured was not far short of 10 million tons. The location of adequate reserves of limestones of the right types both for present and future use, and their delimitation into beds of different qualities, are major geological contributions to the cement industry. An epitome of the kind of geological information that is available concerning the Chalk strata is given in the table on p. 148. Similar details of other limestone formations have also been recorded. A large chalk quarry in Kent, producing chalk for the cement industry, is shown in Plate VI.

Slates

The slate industry has probably given geological science very considerably more than it has received in return. In Britain vast quarries have been established in Wales, Cornwall, Cumberland and elsewhere. The evidence they have provided has been of immense value to geologists engaged in the study of crustal pressures and their effects. As in the case of building stones, a number of factors that govern slate quarrying and preparation are to be explained in geological terms. The fissibility of slates, their most important characteristic, is seen to be the direct result of earth pressures.

Brick clays

Many data concerning clays, as is the case with building stones, that were originally provided by the various geological surveys of the world, have been assimilated into the general background of communal knowledge.

Most clays are of sedimentary origin. Some clays, more compressed than others, have become shaly. The degree to which shales have developed is largely related to the age of the beds; the older

Table showing Main Divisions of the Chalk, and Thickness of the Beds (in feet)

	Isle of Wight	*Hampshire and Salisbury Plain*	*North Downs*	*South Downs*	*Berkshire*	*Chilterns*	*Cambridge-shire*	*Norfolk*	*Lincoln-shire*	*East Yorkshire*
Upper Chalk:										
Hard white chalk with bands of flints	1300	to 1000	300–500	600	300	220–300	50	1000	90	1000
Chalk Rock		rarely more than 10 ft., and locally absent								
Middle Chalk:										
White chalk with few flints	100–200	100–200	200	200	150	200	200	100	120	400–450
Melbourn Rock		rarely more than 10 ft., but present almost everywhere								
Lower Chalk:										
Belemnite Marls		a constant band of greenish marl, normally 2 to 5 ft. thick								
Grey Chalk	100	100	80	80	120	80	100	30–50	30	30–50
Totternhoe Stone		about				10–20	20	5		
Chalk Marl	100	100	80	80	100	100	70–80	20–70	50	25–80
Chloritic Marl	a greenish-grey bed a few feet thick present in the southern half of England									

the clay, the more shaly it is likely to be (*see* p. 75). Superficially one clay bed may look very much like another, yet each has its own characteristics, some of which are of great importance in brick-making. Oxford Clay, for example, contains carbonaceous matter. This clay alone is worked in England today to produce some 3,000 million bricks a year. Nearly twice as many again are produced by a group of rather smaller brickworks spread throughout Great Britain. Some 8,500 million bricks thus made annually in the country represent excavation of about 300 million cubic yards of clay. At the early brickworks that used Oxford Clay, near Fletton, Peterborough (from which place the 'Fletton' type of brick takes its name), it is doubtless the case that the special quality of the clay was first found by trial methods. Petrological examination by both chemical and physical means subsequently determined the carbonaceous nature of the clay; palaeontological work has delimited the fossil zones in which it is most common. Great brickworks are now established at Stewartby in Bedfordshire and Bletchley in Buckinghamshire (Stewartby is a new town named in honour of the late Sir Malcolm Stewart, one of the founders of the works).

Modern methods of brickmaking require that the chemical and physical composition of the clay used should be standardized to as great a degree as possible. In most large pits variations in type of clay are to be found. The different kinds are mixed in accordance with a geological record of the strata as measured in the pit and correlated with data given by laboratory tests. Even so, difficulties arise. Apart from depositional variation in composition, clay beds are often affected by faults and folds which may themselves cause secondary changes in the nature of the clay. This was found to be the case at a brickworks in Sussex, where for many years beds of a shaly clay that lay practically undisturbed by earth pressures had been worked. A few years ago, however, workings ran into a highly disturbed zone in which the clay had been strongly contorted by earth movements. A proportion of bricks made from this clay 'blew'—that is, the bricks showed unsightly eruptions over their surface, or even disintegrated in the kiln. Geological examination of the clay at the pit face showed that the earth movements had caused the originally tightly compressed shaly laminae to open out. Percolating waters carrying selenite (a form of gypsum that is common in many clays) in solution had deposited myriads of minute crystals between the opened laminae; these had caused the trouble.

Shelly clays also cause 'blowing', but this is usually avoided simply by discarding very shelly lumps in the quarry. Laboratory

investigations to determine the general treatment of 'difficult' clays lie within the province of the ceramic chemist; his findings are correlated with geological data.

DETERMINATION OF LOCAL RESERVES OF CLAY

Beds of clay of a special quality, sometimes only a few feet thick, are still worked at numerous small brickyards in Britain. It frequently happens that the reserves in the possession of a brickworks, though not the reserves in its neighbourhood, become exhausted. A common though perhaps minor problem of applied geology is to determine the lateral extension of some of these clay beds, to ensure that they are present on new land that may have to be bought to continue operations. One such problem arose recently in Hampshire. A brickworks had worked a 30-ft.-thick bed of clay, known from geological survey investigations of past years to lie in the middle of a thick mass of sands, thin clays and silts, all quite useless for brick-making. In 1953 those reserves owned by the brickworks were used up. It was desired to buy more land in which clay would be present and would lie at or near the ground surface. The strata were folded to a minor degree and available geological evidence was sufficient to indicate no more than the general direction in which to extend. Several trial holes, each 50 ft. or so deep, were put down in adjoining fields and details of the strata from each recorded. A little group of closely associated beds was recognizable as occurring in each hole, and it was seen also that stratigraphically this group lay beneath the clay. Those holes that showed the group as occurring near the ground surface obviously proved that in their neighbourhood the clay bed was absent, it having been removed by erosion. Other holes showed where the clay was thickest and most accessible, and land was purchased accordingly.

Some brick clays, or 'brickearths', are drift deposits. Such is their value that even where survey work has shown them to be thin, they are worked extensively, provided a sufficiently large area of brick-earth is present. South-East Essex is one district in Great Britain where this happens. As the brickearth there is only a few feet thick, large tracts of ground are rapidly stripped. Most clay pits in 'solid' formations are worked in some depth, and on their abandonment the superficial area of derelict ground is small and relatively unimportant, but where thin brickearths are used the matter is in a different category. In Essex reconditioning of land has been practised probably since the brick-making industry was started there. Today the only effects to be seen over the large worked-out tracts are that

roads are perched several feet above the levels of adjoining fields, and hedgerows between what were obviously different properties at the time of working stand on banks several feet high. Both road surfaces and hedge banks mark the original land level.

Gravel and sand

Gravel and sand are non-cohesive rocks. Commercially, gravel consists either of rounded pebbles, or of angular or sub-angular fragments of rock, or both. Finer matter—sand, silt or clay—is often included in gravel beds in amounts widely varying from place to place and from bed to bed. Gravel with a proportion of clay has binding qualities that render it suitable for garden paths. It is usually known as 'hoggin'. Sands are more closely restricted than gravel in grain size. Strictly speaking, sand grains lie between sizes of 0·1 mm. to 1 mm.

Mineralogical composition is not implied in the words 'sand' and 'gravel' although in practice 'sand' usually means quartzose sand; non-quartzose sands are rare. Small quantities of other minerals, however, are commonly found in quartzose sand. Iron oxide is very prevalent; in many instances the grains of quartz are coated with an extremely thin covering of iron oxide, to give a yellow, red or brown colour to sand in bulk, but the amount of iron required to do so is very small. Some sands are 'dirty', and contain a percentage of clay. Others are 'sharp', each grain being angular and usually of a large size. Others again are 'soft', with grains small and rounded. 'Gravel' never carries an implication of composition, unless specially defined. It may contain any and every kind of hard rock.

Approaching exhaustion of sand and gravel reserves in England

In the present age of ferro-concrete building construction, civil engineering work, and road-making, sand and gravel are so much in demand the world over that in some countries reserves are rapidly becoming exhausted.

Most gravels are drift deposits, generally of a thickness of the order of about 20 ft. and often much less. Rapid exploitation not only uses up reserves, but in doing so devastates large areas of land. In highly populated countries proposals for new workings not infrequently are little to the liking either of farmers, since gravel soils make some of the best agricultural land, or of residents, who quite naturally resent loss of amenity, unsightly workings and

noisy traffic. Some sands also are drift deposits, but many occur in solid formations, and lie in thicker beds than do gravels. Yet the available sand reserves of qualities suitable for special uses, such as concrete, may also be very limited. This is the case today in parts of Great Britain, where consumption is so heavy that it has now become imperative to regulate both gravel and sand digging. No regulation, however, can function unless a reliable appraisal of reserves, both as to quantities and location, has been made. A detailed geological survey is a prerequisite to any action of this kind.

In 1946 the British Government appointed an Advisory Committee on Sand and Gravel, to study and to make recommendations on the general sand and gravel problems of the country. This committee has issued a series of comprehensive reports, which include maps compiled largely from the maps of the Geological Survey of Great Britain, to show the distribution of sand and gravel deposits throughout the country. The Committee concludes that in the Great London area alone the average yearly demand is likely to rise to 10 million cubic yards, and it is computed that at this rate of consumption the available reserves in some of the chief gravel-producing areas will be exhausted in less than twenty years.

These reports not only form a basis for present regulation of sand and gravel digging, but give forewarning of near future conditions, when supplies of materials for concrete may have to be met from crushed stone, *i.e.* of artificially made gravel.

Gypsum

Gypsum is chemically a hydrated sulphate of calcium. It is of very widespread occurrence throughout the world, and is one of the commonest (and therefore lowest-priced) minerals. It is the raw material of plaster of Paris and similar building plasters, and is used in cement manufacture and in many other industrial processes.

Plaster of Paris was made in England at least as early as the reign of James II. Plot refers to it in his *Natural History of Staffordshire* (p. 14). It is chiefly manufactured by first powdering gypsum and then heating it to dehydrate it to a required degree. The dehydrated powder, which is plaster of Paris, avidly re-absorbs water that may be mixed with it and then sets into a hard mass.

Economic geology is mainly concerned with deposits of gypsum that are sufficiently thick and extensive for commercial use and are easily accessible. Single crystals or nests of crystals of selenite of the

kind noted above as commonly occurring in clays are valueless. In some districts gypsum takes a massive and compact form known as alabaster, used for carved work for indoor decoration.

Another form of calcium sulphate, anhydrite, often accompanies gypsum, and is frequently intermixed with it. As its name implies, anhydrite has no water of crystallization. It is much harder than gypsum, sufficiently so to spark when struck by a steel pick, a property that is used as a rough-and-ready means of recognizing it in a gypsum mine or quarry. For many years anhydrite was a waste product. It is now being increasingly used as a source for sulphur, but much is still discarded.

Geological study has thrown light on the mode of origin of gypsum deposits, and has delimited the strata in which the mineral is likely to occur in commercial quantities. The mineral is one of a group known as 'evaporites'—residual deposits left by drying up of inland seas. Complete evaporation of sea water from inland seas has occurred in one place or another on the earth's surface at various times during geological history, the various substances that the water contained in solution being left behind. Each of these substances possesses its own degree of solubility. As would be expected, the more highly soluble ones retained a stronger hold on the available water than the less soluble. In consequence, when water diminished to a point where there was insufficient to satisfy all needs, the least soluble substances, certain salts of iron, small in quantity, were first thrown out. The next group were carbonates of calcium and magnesium. As water still diminished, sulphates, largely of calcium (i.e. gypsum and anhydrite), were deposited. Then followed common salt, present in the earth in large quantity. Finally, when well over 90 per cent of the original sea water had been evaporated, there followed the deposition of a number of other substances, including potash.

All those thick gypsum and anhydrite deposits of Britain that have been known for several hundred years are now recognized as occurring in the Permian and Triassic strata (pp. 64, 65), gypsum-bearing formations that have been delimited as part of the geological survey of the country. The chief areas are around Carlisle in Cumberland, in the Midlands around Newark, Loughborough, Burton-on-Trent and Nottingham; and in Gloucestershire, Glamorgan and Somerset. Until about 1875 it was thought that gypsum was confined to these areas. In that year, however, another source was discovered. This discovery was a direct result of geological investigations, though perhaps it must be admitted that the science can justly take but

little credit for it, since the new source was accidentally found during a geological search for coal. The circumstances were that in the middle of the nineteenth century, R. A. Godwin-Austen, a Surrey landowner and a distinguished amateur geologist, had predicted the presence of Coal Measures beneath the Weald of Kent and Sussex. In 1875 the British Association for the Advancement of Science became interested in his views, and financed an exploratory borehole at Mountfield, Sussex, with the twin objects of proving Godwin-Austen's theory, and of investigating the structure of the Weald. Unfortunately for the first intention, the borehole proved that the Mesozoic strata there were much thicker than had been estimated, and money ran out before they were penetrated; and in any event it is now known that no coal exists beneath Mountfield. But the borehole proved thick deposits of gypsum in the Purbeck Beds at a sufficiently shallow depth from the surface to permit them to be mined at an economic rate.

The borehole was in point of fact a great success, although it proved no coal. It provided reliable evidence on which new ideas on the concealed geological structures of the Weald could be based, which ultimately led to the actual discovery of the Kent Coalfield. It also stands out in the annals of geology as being the first deep borehole to be made as a piece of pure research. Mountfield is now one of the chief production areas of gypsum in Britain.

The fortuitous discovery at Mountfield, however, is not a true index of the place of geology in gypsum-working today. Gypsum deposits, as was coal, were first worked at the outcrop and then followed underground as far as possible. But beds of gypsum are not continuous over vast areas. The vagaries of their behaviour were only understood after the mode of deposition had been deduced. That information, combined with an appreciation of local geological structure, enables an intelligent estimate to be made of the areas where gypsum is likely to occur, and guides exploratory drilling.

Gypsum in Great Britain is now both quarried and mined. In the same way that geology has a bearing on many mining engineering problems in coal mining, as outlined in Chapter XI below, so has it in gypsum mining. The same technique of exploratory drilling followed by interpretation and correlation of the evidence obtained thereby is used to determine the form and extent of the concealed beds. Gypsum mines, however, give one problem that the coal-mining engineer does not encounter; gypsum is relatively soluble in water; faults and other structural lines of weakness have allowed

local ingress of water to parts of some of the beds, and gypsum gradually has been removed in solution. An estimate of reserves, made even after an expensive programme of exploration, may be proved erroneous, for a seam may be found suddenly to be represented either by voids or by disturbed strata that had collapsed after the gypsum had gone.

CHAPTER X

Civil and Structural Engineering

THERE is a close relationship between foundation works for buildings, bridges, dams, and other structures, and the strata that support them. All these structures rest *in* the strata, rather than on the ground surface; consequently foundations and supporting beds have to be welded into a whole, as it were. Geological factors thus enter into the initial stages of all civil and structural engineering work. This applies in principle whatever the size or style of erection the foundations have to carry, or whatever the scale of excavation; whether for minor works such as house building or laying sewerage, gas and water mains, or for major activities connected with the construction of marine docks, railway tunnels and other large works.

It by no means follows that the geological nature of these factors is consciously appreciated in relation to everything that is built, nor that it is always necessary that it should be. For small and light buildings, satisfactory footings are normally designed in the light of a little common sense. Yet even in these cases the value of a commonsense approach is often found to be seriously at a discount should ground conditions be awkward.

FOUNDATION WORK IN PAST CENTURIES

It is well known that during the centuries preceding the founding of geological science, and stretching back into antiquity, immense engineering schemes were successfully undertaken. In view of the size and permanence of many ancient and mediaeval buildings and works—pyramids of Egypt, Roman viaducts and aqueducts, Norman castles, mediaeval cathedrals and bridges—the twin queries arise as to whether the long-tried methods of the engineers of those days are

not sufficiently adequate today, and whether geology as a science has in point of fact any additional advantages to offer civil and structural engineers.

It cannot be questioned that the engineers and builders of old, like the old mining engineers, were fully alive to many features of the rocks which today have a geological connotation. Long ago it was known that a house built on rock was better founded than one built on sand. It is palpably inconceivable that the Egyptian, Greek, and Roman engineers, architects and builders, and the designers of our great mediaeval castles and cathedrals, did not possess well-defined ideas on the possible interaction of their proposed buildings and the supporting rocks. Yet these old engineers, considered as a group, were not always as successful as at first sight they may appear to have been. The works which we admire today are survivors; many others have been lost. Disaster overtook the mediaeval cathedral of Utrecht. The greater part of the nave of this building collapsed and has never been rebuilt; over its site a main street runs with the original cathedral tower on one side and on the other the present cathedral, composed of the original chancel and the remaining part of the nave. Many buildings show obvious improvisations, introduced to meet unexpected conditions; some, such as those of the Leaning Tower of Pisa, are contemporary with the buildings; others are of later date, and include buttressing and underpinning.

In many of these old buildings incipient damage, produced by differential subsidence, has been countered and rectified by ingenious adaptations which prove the builders to have been brilliant engineers, but also indicate that the means were not available to them of foreseeing in any detail all the strains and stresses likely to be produced by the interaction of the man-made superficial structure and the supporting rocks. Further, these earlier builders had the important advantage of a free choice of site; an advantage that, particularly as regards structural work, is often denied to architects and engineers today.

The menace of concealed peat beds

Not infrequently, building sites that are imposed on architects today, particularly those for factories, are on alluvial flats bordering rivers. Locally the surface alluvial clays of these flats conceal beds of peat which, unless detected and suitably dealt with, usually lead to trouble. This is especially so if the peat beds are dried out by drainage works, which usually accompany building operations. Peat shrinks

very greatly on drying out, and the action is commonly irreversible by re-wetting. Buildings erected over peat thus tend to tilt and crack, especially if the peat bed varies in thickness within short distances.

Various older buildings along the Thames Estuary suffer recurrent troubles from this cause, while within recent years a few miles north-east of London a group of buildings built on alluvium unfortunately lay over a concealed narrow peat-filled channel, in which peat was several feet thick at its maximum, but thinned rapidly away from the middle line of the channel. It was undetected at the time of building. The peat was subsequently drained and, as a

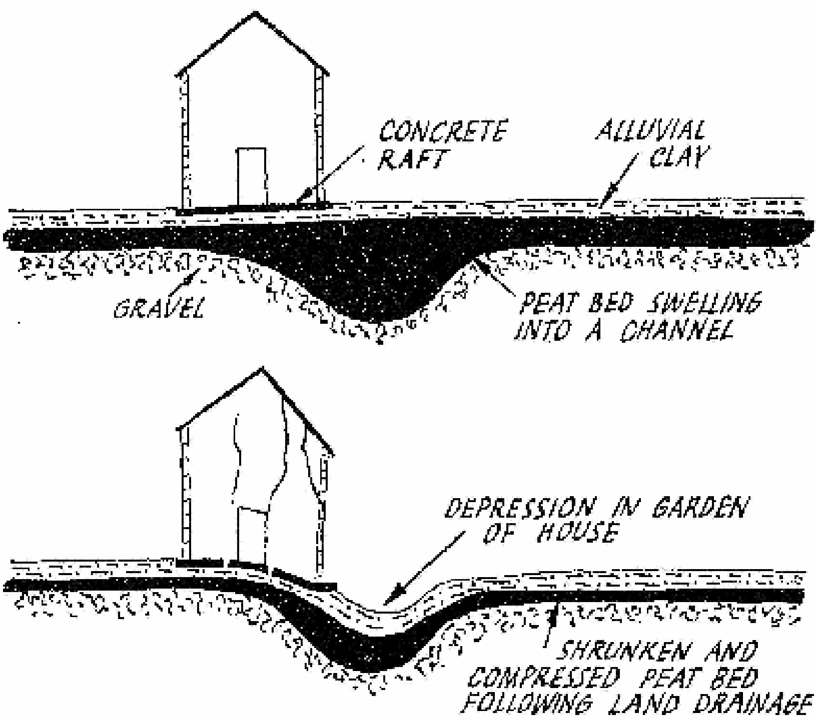


Fig. X, 1.—A few miles north of London some houses collapsed through having been built over a bed of peat that filled a former stream channel.

result of its shrinking, some of these new buildings were completely wrecked while others suffered very severely (Fig. X, 1).

'Rock' and 'Soil'

Geology affords to civil and structural engineering a method of determining the nature of the ground around a proposed site, and of estimating possible relevant effects that the geological structure of the

surrounding neighbourhood may be likely to have. Were it the position that 'solid' strata (*see* p. 72) alone are exposed at the ground surface, determination of the above data would usually not be unduly difficult. Such, however, is not the case; of equal or perhaps greater importance in an engineering connexion is the mixed group of 'drift' deposits (p. 72), those products of glaciers, rivers, wind and other eroding and transporting agents which cover large tracts of country and which have great variation from place to place both in type and in thickness.

From the engineer's point of view both solid and drift strata fall naturally into two groups: those soft and unconsolidated; and those hard and compact. All these materials are regarded as 'rocks' by the geologist but engineering nomenclature, diverging both from geological and agricultural usages, includes all unconsolidated (i.e. unlithified) material under the term 'soil' irrespective either of depth below ground surface at which it occurs or of its geological classification into 'solid' or 'drift'. It restricts the term 'rock' to hard, consolidated material, a bed of sufficient thickness and strength to afford a firm base for a heavy burden being a 'bed-rock'. For convenience this nomenclature is followed here, but it is restricted to the present chapter. In accepting the engineer's definition of soil there is a natural tendency to regard the word 'unconsolidated' as a synonym for 'soft'. In most instances soils are soft, but unconsolidated beds of pebbles, and even of boulders, are also soils.

Soils may be grouped into two divisions: those in which the particles cohere in the mass, whether wet or dry, instanced by clays; and those in which the particles do not cohere when dry (although some may have an apparent cohesion when wet resulting from surface tension between films of water around the grains), instanced by silt, sand and gravel. Rocks are of many types: conglomerates, sandstones and limestones of various kinds that were laid down in past ages as sediments; granites, basalts and kindred igneous rocks; schists and slates and others of metamorphic origin.

The engineer is normally concerned with rocks in the mass, when they possess features extra to those pertaining to small specimens. A thick deposit of soil usually contains different types of material in alternating beds ranging in thickness from a fraction of an inch to many feet. A reasoned assessment of probable variation and extent of the different beds is obtainable by recourse to a geological examination at and around the proposed site and by an understanding of the processes that led to the formation of these deposits.

REQUIREMENTS OF A SITE INVESTIGATION

A site investigation of modern times includes (amongst others) an examination of the following geological points:

(1) Nature of the strata; whether hard rocks or soils; if the latter, whether cohesive or non-cohesive; their composition; moisture content; grading and compactness; and their behaviour under specific laboratory tests (*see* below).
(2) Characteristics of the mass of each type of rock, e.g. whether bedded, or not; if bedded, thicknesses and variations in the thickness of the beds; the nature of fissures and joints in hard rocks.
(3) Arrangement of strata; alternations of different types; whether strata are horizontal, more or less uniformly inclined or faulted; whether broken or shattered.
(4) The arrangement of the strata and their reactions to the retention and circulation of water.
(5) The level of the water-table.
(6) Whether sulphates and other mineral salts are present.

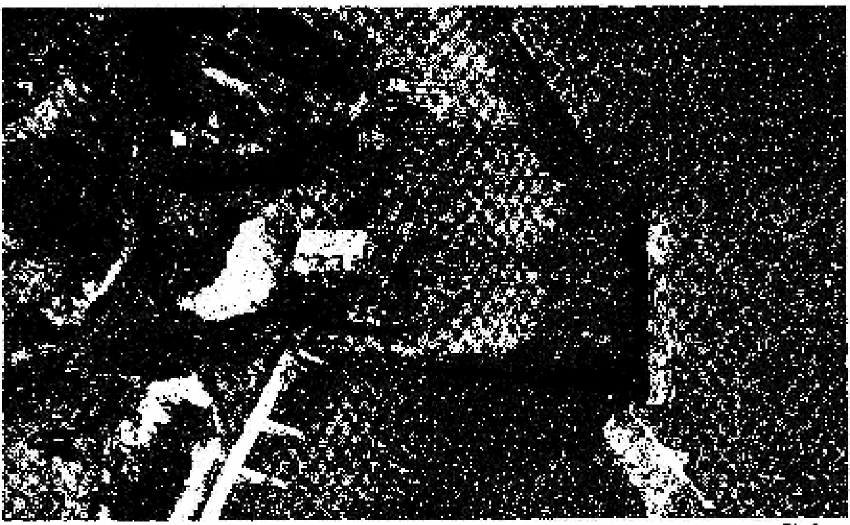
If one of these points is more important than the others it is the fifth. The presence or absence of water is a fundamental consideration both in excavation work and in estimating the load that the strata beneath a site will support. A bed of dry compact lightly bound sand may support heavy buildings, and, as may be seen in many sandpits, will often stand in a vertical or almost vertical face for many years. But the same sand, when saturated with water, may become 'quick' should the contained water be given the slightest opportunity to flow, and carry the sand with it. Its effective bearing capacity disappears.

WATER IN ROCKY STRATA

Even in stable rocky strata, water can add greatly to the difficulties, and consequently to the cost, of engineering work. In both limestones and sandstones it may be present in very large quantity. The wide fissures characteristic of limestone formations that lie below the water-table carry vast quantities of water. The chalk of the Dover district, for instance, is very highly fissured; one fissure encountered in the headings of the Folkestone waterworks, between Dover and Folkestone, was six feet wide. Chalk that forms the sea bed of Dover harbour is similarly affected. During the construction of a new dock basin there during the years 1935–36, it was at first

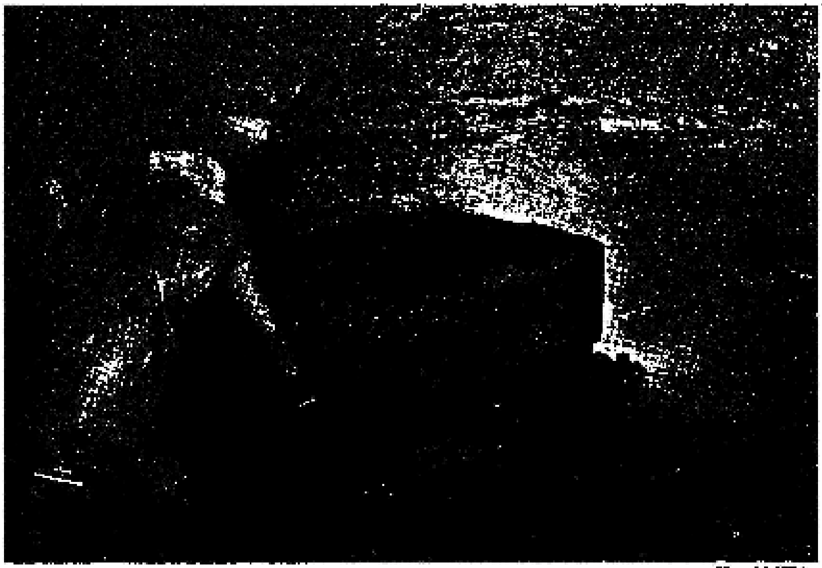
British Railways

A. The Folkestone Warren landslip of 1915



Skyfotos

B. Aerial view of engineering works designed to prevent future landslips at Folkestone Warren



Harold White

A. Coal-cutting at a colliery in Fife, Scotland

Marshall & Co.

B. Opencast coal working at Smalley, Nottinghamshire

found impossible to lower the level of water in an area that had been completely surrounded by a wall of steel (sheet piling) driven into the sea bed to form a large tank, as it were. Water continually entered the enclosure from fissures in the sea bed at as fast a rate as it could be pumped out. Matters were further complicated by the presence in the immediate neighbourhood of a channel infilled with gravel in the sea bed. The causes of the trouble were revealed by an examination of the geology of the Dover district and an engineering plan was ultimately evolved which overcame the difficulties.

Prior knowledge of the level of the water-table coupled with details of the geological structure may on occasion be determining factors in selecting a precise location for working. At the new satellite town of Hemel Hempstead a sewerage tunnel was sited so that the tunnel invert level (that is, the level of the tunnel base) was fixed to lie above the highest level that the water-table had been known to reach. The result was that, as had been anticipated, water problems were non-existent. On a job worth somewhere between £60,000 and £80,000, some £20,000–£30,000 was saved that would otherwise have been spent had water troubles been encountered.

WATER IN CONFINED SAND-BEDS: KING GEORGE V DOCK

Water in confined beds of sand carries potential difficulties that are avoidable by foreknowledge of the local geology, and on occasion of the geology of an area extending several miles around the particular site. During preliminary work for construction of the King George V dock at Southampton, a strong artesian pressure-head of water under the proposed dock site was detected. A study of the geology of a wide area around Southampton showed that at the dock site, at a depth of about 100 ft. and beneath impermeable clay, there lies a water-bearing bed of sand that gradually rises northward. This comes to the surface several miles away near Romsey. There the River Test flows over its outcrop and feeds water into the sand. This water exerts a pressure-head down the dip of the strata (Fig. X, 2). In a trial borehole made at the dock site this pressure raised the water to a level several feet above the ground surface. Under natural conditions, therefore, the pressure head at the bottom of the dock, which is about 100 ft. below ground surface, would be that of more than 100 ft. of water. The dock was designed to meet this condition. Special works keeps the water pressure continually stabilized and under control. Plate IXB is an aerial view of the dock during construction.

WATER ALONG GEOLOGICAL FAULT-PLANES

Geological faults are always lines of weakness in relation to engineering structures. Often they are accompanied by 'shatter belts'. These are bands of broken-up rock sometimes several feet wide, produced during the differential movement of the blocks of strata at either side of the fault plane. They are to be seen particularly where rocky strata of types that occur largely in Wales and the Lake District are faulted. Fault-lines may often, though not always, be closely located by geological examination of the ground surface, and their positions at depth deduced.

Deductions of this type were most valuable during the construction of the Haweswater Tunnel for the Manchester Corporation waterworks. There the general run of strata was in hard impermeable rock, but it was known from previous geological study of the ground surface along the line of the tunnel that faults were present and

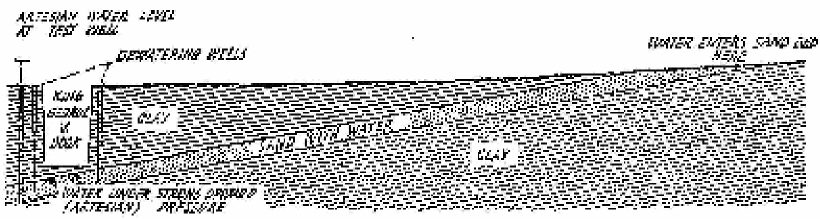


Fig. X, 2.—Artesian water pressure beneath the King George V dock at Southampton is relieved by a system of de-watering wells.

were accompanied by shatter belts. The surface indication of a shatter belt is often the presence of a stream valley along it; the crush-material being more easily eroded than the unbroken rock. Since this crush-material is permeable and is sandwiched between impermeable rock, it was anticipated that each belt might be charged with water, fed into it both from the streams at the surface and from direct run-off from the hillsides (Fig. X, 3). At Haweswater the forewarning made it possible to take precautions to deal in advance with the heavy flow of water which was intermittently encountered during excavation.

Tunnels, in common with other building structures, require maintenance and repair. A common cause of trouble is water that from one cause or another seeps around tunnel walls, particularly in those railway tunnels that were constructed a century or so ago. It softens soil carrying the load of the tunnel, thereby reducing its bearing strength, and it may even remove some of it. Unless this condition be corrected, tunnel collapse would occur.

Unfortunately in many instances no record survives of the strata through which these early tunnels were driven, yet it becomes imperative to determine the predisposing causes of water movement around them. Much can be done to rectify the deficiency by research. During 1952 the Bo-peep railway tunnel at Hastings showed signs of collapse. A geological examination was made of the country around the tunnel, of the cliff sections at Hastings, and of the strata exposed in neighbouring railway cuttings. Research into all available literature was undertaken, including editions of the local Hastings

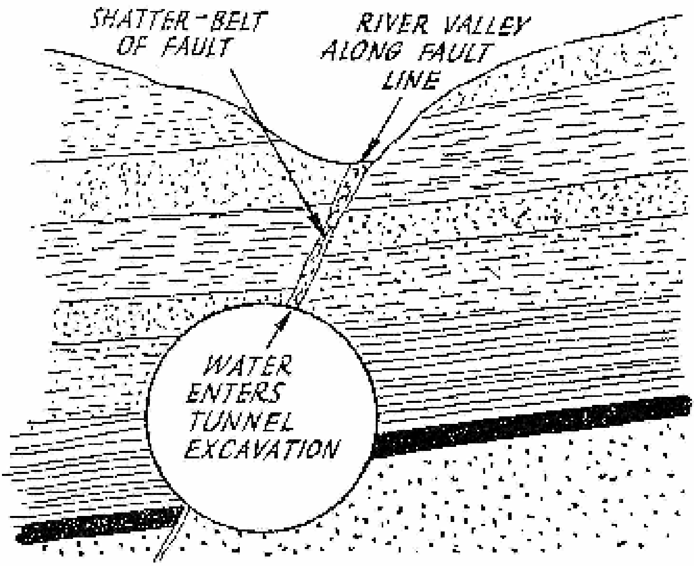


Fig. X, 3.—Geological faults make natural conduits for large volumes of unwanted water that may be encountered during the construction of new tunnels.

newspaper contemporary with the construction of the tunnel. A summation of the information so obtained gave data that led to a definite conclusion that the trouble was occasioned by a 'fault' which was accurately located behind the brickwork of the tunnel lining. The physical effects of water on the soil were investigated by 'soil mechanics' methods (*see* below). Bo-peep tunnel was closed for some months for engineering measures to be taken, both remedial of the immediate trouble, and preventive of its future occurrence.

'OVERBREAK' IN TUNNELLING

Another feature in tunnelling is 'overbreak'. In those tunnels designed to be supported from collapse by a lining of steel or cast-

iron rings, or by a brick or concrete lining, or by some other framework, it is desirable to excavate as little rock as possible beyond the perimeter of the lining. The excess amount of excavation over the minimum necessary is termed 'overbreak'. Not only does undue overbreak entail needless removal of rock but it entails undue use of concrete, for cavities left by overbreak between the lining and the natural rock face have generally to be filled in.

The amount of overbreak, however, is normally dependent on the nature of the rock and the direction of the bedding in relation to the line of the tunnel and also on the manner of drilling and blasting. Soft clays may be excavated with negligible or even zero overbreak. On the contrary it is difficult or even impossible to excavate a circular hole in highly dipping well-jointed rocks, and particularly so in highly cleaved slaty rocks. The directions of strike and dip in these kinds of strata, in relation to the line of the tunnel, are important factors in the production of overbreak, and need to be determined in advance of excavation work. Fig. X, 4, shows the effect of well-jointed rock on overbreak, and Plate V the overbreak in the recently constructed railway tunnel at Woodhead.

LANDSLIPS

Landslips are large masses of rock or soil, or both, that move under the influence of gravity. In nature they form part of a normal cycle of erosion, and in many mountainous areas they occur from time to time on a colossal scale, in which case there is nothing man can do about them. Some masses are shaken from their position by earthquake shocks, others move over a water-lubricated surface where permeable rocks rest on an impermeable bed of clay. These, however, are not the sole kinds of landslips. Many occur in clay and shale strata through a slow absorption of water following a relief of lateral or overburden pressures. This may result either from natural processes of erosion such as undercutting along a river bank or sea cliff, or from artificial excavations. It leads to 'shear' failure, that is, failure to resist transverse pressures in the soil mass. This is quite apart from, and perhaps more common than, water-lubricated slips. Numerous slips in railway cuttings arise from this cause.

One reason for the civil engineer being much concerned with landslips is that in the course of excavation work he tends to upset to an appreciable degree the natural equilibrium of the strata surrounding his site. Whether he does so or not depends much on local geological conditions.

A simple example of interference is afforded by a landslip that

was produced in 1930 by a road-widening scheme in Surrey. The local strata of a hillside consisted of sand underlain by a bed of clay, which again rested on sand. An old narrow road ran along the bottom of the hill; road-widening operations involved the removal of much material from its hillside bank. The strata at the site of the slip dipped towards the road. A permanent feature of the site had been that rainwater percolating through the upper sand had been held by the clay bed and had travelled down its dip slope. Previously to excavation the hillside had obviously been in a state of very

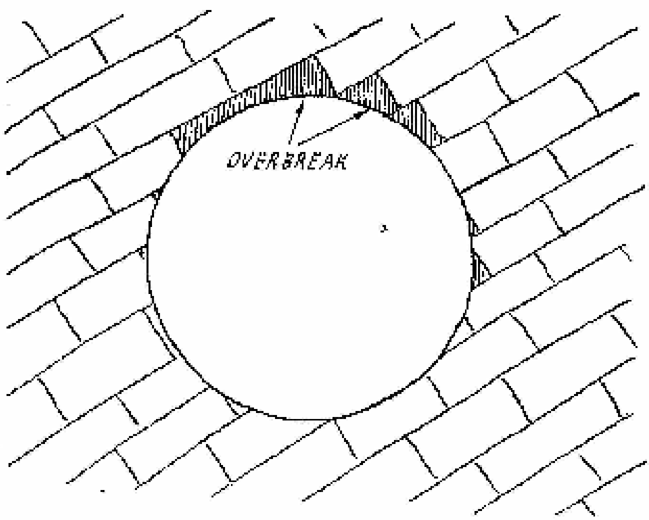


Fig. X, 4.—'Overbreak' in a tunnel excavation in well-jointed rock. (*See also Plate V.*)

delicate balance. Excavation at the bottom of the hillside removed the toe, so to speak; with their support gone, the beds commenced to slip, and movement continued slowly for a number of years. A minor point of interest in this slip is that the line of parting at the surface ran beneath a large chestnut tree. One half of the roots was anchored in stable beds, one half in the slip; the tree was gradually split up the middle.

Preventative precautions are widely taken today wherever geological examination of a site shows that there is a possible chance of slipping. At some sites where an excavation is later filled in the danger is temporary, but where an excavation remains permanently open, as along railway cuttings or canal cuttings, it is ever-present. In practice, landslips along railways are fewer than they might well

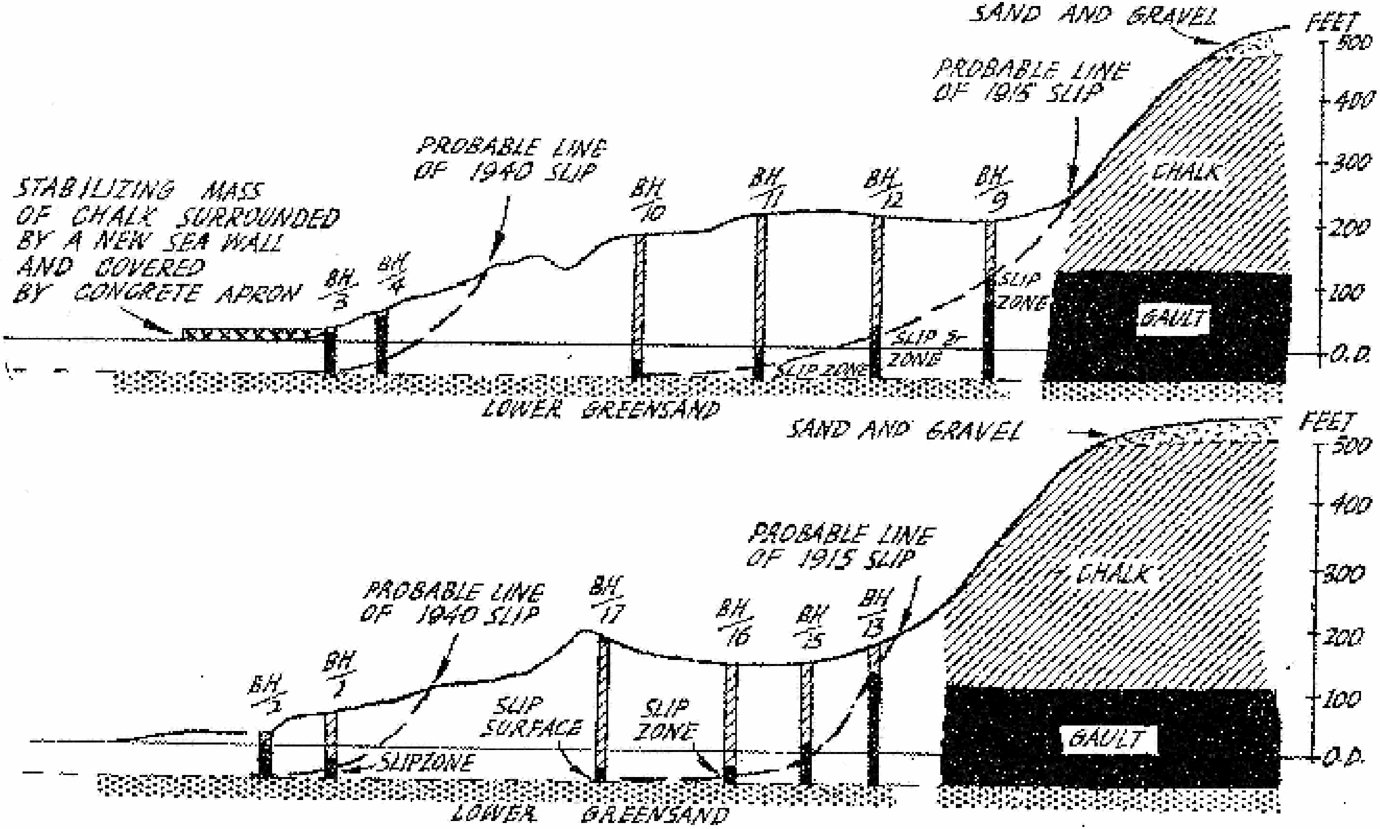


Fig. X, 5.—The probable slip lines of landslips that occurred in 1915 and 1940 at the Warren, near Folkestone, were located by numerous trial boreholes. Cores showed zones of disturbed material most probably marking the actual line of rotary movement of the slips (based on Toms). The slips have been stabilized by a great weight of concrete and chalk. (*See also Plate VII, A and B.*)

be. Many elaborate and expensive preventive works, designed in the light of local geological conditions, are regularly under construction. But slipping is not entirely avoidable, and each abnormally wet season brings its quota.

On occasion natural landslip sites have perforce to be used for engineering purposes. The railway between Dover and Folkestone is laid on chalk that has slipped over, and rests on the Gault, also disturbed. In past ages huge masses of chalk and clay have slipped to form what is now known as Folkestone Warren, and occasional slips have taken place since the railway was built. Geological research over the whole district and investigation of the slip itself, both by purely geological means and by soil mechanics, have elucidated the main cause. This is 'shear' failure in the clay, caused by erosion of the cliff base by the sea. An unbalance of the natural forces operative in the strata occurs. The Gault has proved unable to sustain the great weight of the overlying mass of Chalk that is present, and has yielded. Extensive engineering works have recently been undertaken to construct a counterpoise, so to speak, to prevent any further movement. Plate VIIA, shows the Warren landslip of 1915, and VIIB, the present remedial counterpoise. Fig. X, 5, shows sections across the slip.

Roads and railways

The above examples of landslips indicate the importance of adequate geological information in road and railway maintenance. It is doubly valuable to engineers concerned with building new roads and railways. Many considerations govern the general choice of routes, in which geological factors may or may not predominate. But a geological survey of a proposed route greatly assists the engineer in avoiding pitfalls and future troubles, either by making minor deviations from the original plan, or by constructional preventive works.

Dam sites

Dam building provides many instructive examples of the alliance of geology and civil engineering. Rocks at a site selected for a dam for water storage reservoirs have to satisfy two main requirements. They must be capable of supporting the dam, which is not only a weighty structure, but is also one that is subject on one side only to the heavy pressure of the retained water. The bonding of a dam into the natural rocks must also be virtually impermeable, otherwise an excessive amount of water would escape beneath or around it.

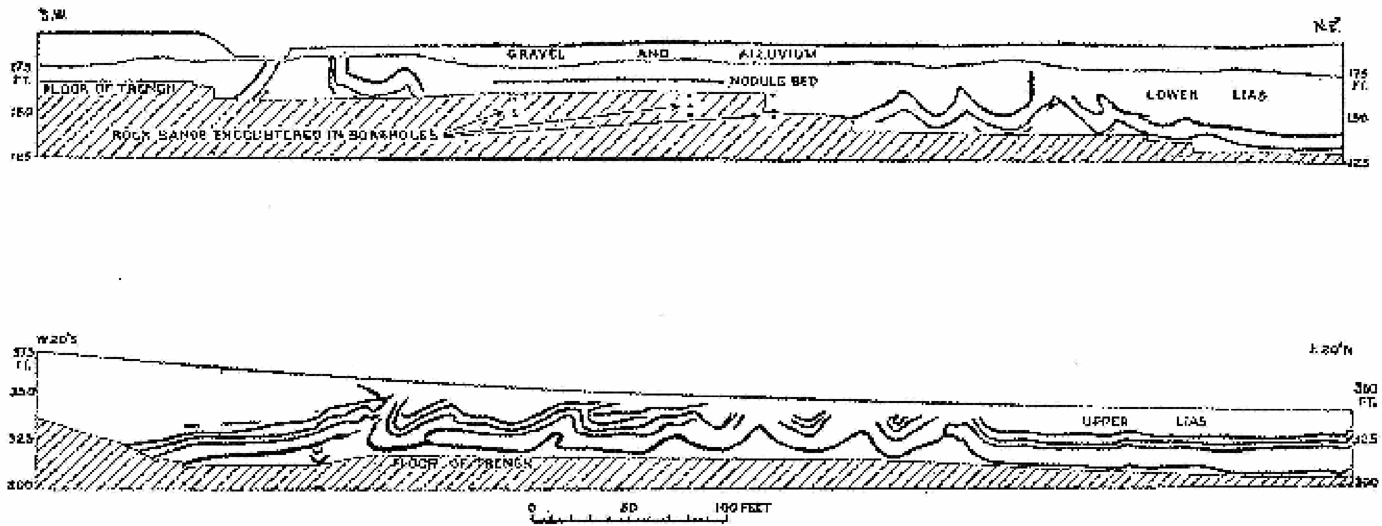


Fig. X, 6.—Geological sections showing disrupted strata exposed during excavation work for dam foundations. The upper section is at the Eye Brook Reservoir, Leicestershire, and the lower at Hollowell Reservoir, Northamptonshire. (After Hollingworth and others.)

In the nature of things a dam is normally situated in a river valley. A number of points concerning the geology of river valleys generally therefore become relevant. As remarked on p. 75, as a result of the study of the effects of the Great Ice Age it is known that beneath each of the present beds of many river valleys suitable for impounding water there lies a drift-filled channel, or a bed of a former glacial lake. This implies that at one period the valley had been cut much deeper, and that it had subsequently been partly filled with a rubble of boulders, gravel and sand.

Should a valley with a concealed drift-filled channel be used as a water-storage reservoir, the dam needs must be founded below the base of the drift, whatever its depth from the surface may be. Thicknesses of 100 ft. or more are not uncommon. Even under natural conditions water travels through these concealed drift deposits as well as over the bed of the stream. Unless flow beneath a dam be prevented, the normal rate of sub-surface flow would be greatly increased over the natural rate on account of the hydrostatic pressure afforded by the dammed-up water. This in turn would cause the removal by 'internal erosion' of smaller stones and sand from beneath the dam, leading to its ultimate collapse. Legacies from the Ice Age, however, are not all disadvantageous. Geological work has discovered that in some valleys glaciers had cut basin-shaped hollows in the upper part of the valley floors to leave a 'rock-barrier' on the down-stream side of each basin. These rock-barriers may now be obscured by river débris of more recent origin, but they are present none the less. The great Welsh reservoir of Vyrnwy which was constructed towards the end of the nineteenth century takes advantage of a glacially formed basin and rock-barrier. The existence of a barrier having been deduced, its position was located by a number of trial holes. It has been put to good use as the firm base of the reservoir dam. The reservoir, which holds approximately 12,000 million gallons of water when full, is thus linked through geology with glacial action of some 100,000 years ago. Plate IVA shows the dam under construction and IVB the present reservoir.

Disruption of rocks in a valley floor, as noted below (p. 204) is now known to be common, and it is part of the preliminary investigations for dam-buildings to determine the degree, if any, to which this has occurred. A section of the strata across the valley of the Eye Brook Valley, Leicestershire, and another for the Hollowell Reservoir, Northamptonshire, provided excellent instances of this phenomenon. These sections are shown in Fig. X, 6.

SOIL MECHANICS

Of recent years it has been appreciated that in many instances where soil is concerned, geology as normally understood is inadequate to answer fully many of the questions the engineer asks. He desires to know, for example, what pressure can be imposed on the ground at his proposed site without causing its immediate failure as a support, or without incurring excessive long-term settlements of the structure to be built.

Few geologists are able, except on the basis of experience gained from close association with civil engineers, to give any very informed estimate of the pressures which a soil is likely to exert on structures such as tunnels, retaining walls and the like which have themselves to support masses of earth. It is a matter outside their normal sphere of work. But until relatively recently civil engineers themselves lacked precise scientific information on the physical and engineering properties of soils with which they were called upon to deal. They relied on their own, and their predecessors', experience in constructional work.

During the past two centuries there have been sporadic theoretical and experimental attacks on these problems. Out of this pioneering work has arisen a new science, that of 'soil mechanics', developed from a pressing need for fuller information concerning the strength and other physical properties of soils in the many and various conditions in which they are encountered in civil engineering work.

The name for this study is perhaps not the most suitable that could have been chosen. Except to the initiated, the word 'soil' causes confusion. Further, investigations are not necessarily kept directly within the sphere of soils. The continental use of the term 'geotechnique', which covers work on all and every kind of soil and rock, has much to commend it. The use of soil mechanics, however, has become so well established in the English-speaking world that it might be difficult to supplant it, however desirable a change might be. Soil mechanics can truly be said to be a meeting ground of physics, civil engineering and geology.

Clays are exceptionally sensitive to the effects of addition or removal of water from them. By the addition of appropriate amounts of water a clay that when air dry shrinks and cracks up into a mass of hard rock-like pieces, can be converted progressively firstly into a firm, greasy, but not plastic, mass; then into a softer and truly plastic state, and finally into a semi-liquid 'slurry'. Thus the mineral particles of clay are seen to be extremely cohesive.

Particles of clay minerals are in a very finely divided state; some

are of complex chemical composition, all retain very thin 'adsorbed' films of water. These clay minerals together with their adsorbed water films, have a strong affinity for still more water. Swelling and softening therefore occur wherever clay is in a position to draw water into itself. This can result in high swelling pressures.

Conversely, if pressure is applied to wet, and therefore swollen, clays, water is squeezed out, and the volume shrinks. This is, in fact, the process of compaction that muds undergo to become clays and shales.

Reliable figures for potential degrees of shrinkage of different soils when subjected to pressures calculated to be those to be exerted by the weights of proposed buildings or other structures are among the scientific data that soil mechanics now provides. One method of obtaining them is to place a sample of soil, carefully taken from the ground so that the natural arrangement of its particles is not disturbed, in a steel cylinder. This is compressed with gradually increasing pressure by a porous piston. A point is reached when water is squeezed out. By relating the piston pressures with the calculated pressure, say per square foot of ground surface of the proposed structure, it is possible to make very satisfactory estimates of the amounts and nature of the settlements the structure may undergo.

A different apparatus measures 'shear' strengths of soils under any system of pressures that are likely to affect them in practice, and in any conditions of wetness at which their shear strength needs to be known.

From data of this kind, the load that foundations will support without disruption of the soil may be calculated, and also the probable pressures to which tunnels, retaining walls and other such structures must be designed to sustain. These data also influence the design of earth banks and cuttings, and of remedial measures to arrest landslips.

But small samples of soil in the laboratory cannot have all the characteristics of beds of soil as they lie in the ground, and laboratory investigations taken by themselves are incomplete. It is very necessary to relate data given by soil mechanics investigations in the laboratory with data that are more strictly geological. This linkage is normally initiated by putting down a number of trial holes over a site area, making careful records of the strata encountered and taking soil samples at specific intervals. The records of these holes are correlated much in the same way as those of the deeper coalfield boreholes illustrated on p. 188.

A 'Code of Practice' drawn up for the general guidance of civil engineers, and issued in 1950, gives standardized symbols for different types of soil, and methods of recording them from trial boreholes. These symbols are given in Fig. X, 7.

Other methods of site investigation

Another method of site investigation, to the same end as soil mechanics much in use today, and one that also combines physics with geology, is 'pre-piling'. By this method, a pile of known size (generally small scale) and weight is driven into the ground by hammer blows of known power. The depth of penetration is measured

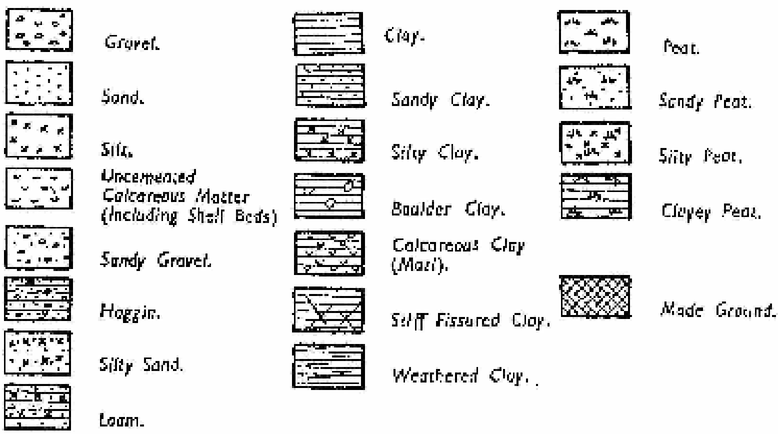


Fig. X, 7.—Some soil symbols as used in graphic sections in soil mechanics investigations.

for each stroke and the resistance offered by the strata at the different depths is recorded. A number of penetrations are made and the records correlated as for trial boreholes.

Finally, geophysics gives its quota of data. The chief geophysical method employed is the measurement of electrical resistivity as described on p. 99 by which local variations in rock-type and in water content of the soil can often be determined. In both these methods, again, the readings obtained must be interpreted with reference to geological considerations.

Made ground

In all populous areas the natural conditions of the ground surface are rapidly undergoing alteration through the removal of material from one spot to another. At times this is a potential source of

engineering trouble, for 'made ground' through lack of compaction has not the bearing strength of compact soils. During an examination for a site for a new bridge in Kent, a report was submitted which asserted that the abutments would be on Chalk. This appeared to be discordant with the known geology of the area and a further examination showed that chalk was indeed present, but it had been dumped at the spot many years previously. It was underlain by soft soils. But it is not unknown for geologists similarly to fall into booby traps. Some time in the 1930's a paper describing a granite from beneath London appeared in a foreign geological journal. The writer did not appreciate that the granite was merely part of the foundations of Waterloo Bridge! It was, in fact, 'made ground'.

Made ground occurs in many parts of the country and is not always easily detected. An interesting case of this occurred at a site proposed for a large factory in Surrey. According to geological data the site was on clay, and clay soil appeared throughout, but the engineer rather suspected the form of the ground. Fortunately he found some fossils. These were entirely foreign to the country rock, and it was ultimately discovered that the site had been used as a dump for clay from a railway cutting some miles away. Much of the surface was made ground with poor bearing capacity, and the foundations were designed accordingly. This instance also emphasizes the importance of trial borings and soil tests, to avoid such pitfalls.

SOURCES OF MATERIAL

Civil engineering, similarly to so many other industrial activities, derives benefit from the purely recording work of a geological survey. Transport of material is a heavy item in costs. A knowledge of the location of building stones, sand, gravel and other material in relation to the constructional site may have an important bearing on the type of construction to be employed. This particularly applies in the case of dam sites, where very large quantities of material are often required, either for concrete or for 'fill'.

Ignorance of local geology may involve unnecessary expenditure on this score. Various stories of waste of this kind, mostly apocryphal and perhaps slightly malicious, circulate from time to time. Occasionally, however, a true bill arises that serves to point the moral. One authentic instance of recent years involved the transport of stone a distance of twenty miles to a site where the strata consisted of precisely the same type of rock.

RECORDS OF SHALLOW TRIAL BOREHOLES

One of the most useful functions of the science of geology in relation to engineering is the collection and correlation of records of shallow trial boreholes. Unfortunately, records of many boreholes in the past have been lost, and indeed many are today. It may be true that their value to the person who commissioned them goes once their immediate use is over. Yet in future years, when combined with others that are made from time to time in the same area, they prove of inestimable economic value to someone else.

For example, it is known from borehole records that most, if not all, of the river valleys of southern England contain a drift-filled buried channel, eroded at a time when land stood more than 100 feet higher above the sea than it does today. Land has subsequently been depressed, and the deeply cut valleys have been filled with unconsolidated river or marine drift. This has only a fraction of the bearing capacity of that possessed by the surrounding solid strata in which the valleys have been cut. Many records of shallow boreholes have been made along the Medway Valley between the Thames Estuary and Maidstone. These show that the buried channel of the Medway is at least 100 ft. deep near Chatham and is still 40 ft. deep as far upstream as Maidstone. As a hypothetical case, were a new bridge projected to cross the Medway southward of Chatham, the abutments in each side would rest securely on Chalk at or almost at the ground surface. But some of the piers to be built in the alluvial flat would not be founded on Chalk except at a depth of some 60 ft. from the surface.

Similarly it is known that at Newhaven a buried drift-filled channel is over 80 ft. deep, of which there is no indication at the ground surface. Here again the alluvial deposits are far from being closely compacted, and their thickness varies from the maximum to but a few feet according to their position in relation to the line of the buried valley. Were a heavy building to be erected on a part of the alluvial flat where alluvium is thick, special and expensive types of foundation would be required to counter the differential subsidence that would otherwise arise on account of the differences in compressibility, and local variation in thickness, of the soil.

Records of boreholes made in past years in London and the Thames area regularly furnish much valuable information today in connexion with such proposals as the construction of underground car parks and flood prevention works, and in many other directions.

CHAPTER XI

Coal and Coal Mining

EXCAVATIONS at or within the earth's crust for the purpose of extracting minerals—metallic ores, coal, salt, precious stones, building stones, etc—have been made from time immemorial, the word 'mineral' here being used in the everyday and commercial sense and not in the scientific sense of Chapter III. The Romans exploited metallic ores in Cornwall, but they were late-comers in mining. Coal has been mined in Britain for many centuries. It was certainly worked in Yorkshire and Derbyshire in the thirteenth and fourteenth centuries for in 1274 one Richard le Neyler paid sixpence for a license to dig coal at Hipperholme. In 1315 the monks at Beauchief Abbey were licensed to get coal locally, and J. Lister (in W. Wheater's *Old Yorkshire*, 2nd Series, 1885) records that in 1378, also at Hipperholme, one Johannes Stra de Handesworth Woodhouse "venit juxta unum colepitte et subito per infortunium cecedit in puteum unde submersus fuit". 'Colepitte' is a most attractive word in this context!

The lay-out of mines, sinking of shafts, driving roads, prevention of roof falls, and a hundred and one other technical matters are the immediate concern of the mining engineer, not of the geologist. In the natural course of events, vagaries of the strata in which minerals occur present numerous difficulties that the engineer is called upon to overcome, and there is every reason to assume that throughout mining history engineers have applied scientific method to this end. It seems likely from Plot's record that the strata of Staffordshire were like an 'onyon', that the Staffordshire miners, as well as Plot himself, were not ignorant of the general lie of the local Coal Measures. It would therefore be wrong to assume that geologists of the early nineteenth century, who founded

the science, suddenly gave mining engineers something of a revolutionary nature that they could put to immediate use. But it would be equally wrong to assume the converse, that geology has given little or nothing. Since its foundation a century and a half ago, it has given much indeed.

Coal includes all those solid fuels contained in the earth's crust. These have been formed by the chemical alteration of plant matter that has been carbonized to a greater or lesser degree; that is, the ratio of carbon to the other contents has been increased over that present in the original component plants.

At one end of the scale of carbonization come anthracitic coals, which have an extremely high carbon ratio; these coals are black and shiny. At the other end come 'brown' coals, some of which scarcely merit the name of coal and are often referred to as lignite. (An alternative name for lignite, 'surturbrand', was in use in England a century ago but now seems to have fallen into disuse. The word is interesting as a rock-name derived from the name of a character in Icelandic mythology; *Surtr*, the black, was a fire giant, the world-destroyer; *brand*, his firebrand or torch.)

Carbonization, and with it the thermal value of coal (though not necessarily the economic value), appears to increase with depth. This view is so firmly established that it has been incorporated into a 'law' known as Hilt's Law, although the word 'law' is perhaps not fully justified. Coals are placed in order or 'rank' according to their thermal qualities, and Hilt's Law states that where several coal seams occur in a vertical section, the rank of coal increases with depth. The words 'vertical section' mean vertical as regards the present-day arrangement of strata.

FORMATION OF COAL

Many of the benefits that the coal-mining industry has received from geology have arisen directly from those investigations of the early nineteenth century which first provided a true picture of the conditions under which coals were formed. Prior to that period there seem to have been no clear ideas on the matter. The teaching at the important mining academy at Freiburg, for instance, had been that coal and other natural inflammable materials were amongst the chemical precipitates laid down from that universal ocean which Werner's imagination had conjured up (*see* p. 16). Today we know this to be absurd.

Early scientific geological work showed conclusively that coal has been formed from decaying vegetation. In the natural course of

events amplifications of this conclusion have occurred. The question has arisen as to whether coal represented forests that had decayed *in situ*, or whether the original vegetable matter had been accumulated by drifting together in some very extensive river estuary or lake, there partly to rot and then to be buried by silt and mud and ultimately to become consolidated. But points of this kind are nothing but variations upon the main, fully substantiated, theme.

Present-day views are that most coal seams represent actual forests that were destroyed *in situ*. The coals of these seams have largely a wood basis, and they are accordingly known as 'humic' coals. Another variety of coal of much less wide extent than the humic type is 'sapropelic' coal (Gk. *sapros* = rotten), the foundation of which is non-woody. Sapropelic coals were formed from masses of minute unicellular plants, mostly algae, and of spores of tree-ferns and other plants, all of which accumulated in ponds, lakes and clear still backwaters, there to decay and settle as a mass of rotting vegetation—that is, of 'sapropel'. These coals include cannel (= candle) coals which burn with a very clear flame but produce much smoke. During the seventeenth century cannel was used in northern coalfield areas of Britain in place of candles.

Although the foundation material of coal has suffered much chemical change during the process of carbonization, humic coal in particular still retains many traces of tree-trunks, bark, leaves, spores and pollen grains and still more so do many of the shales and silts of the Coal Measures in which isolated plant-fragments were buried. The nature of the plants of the Carboniferous period is known in considerable detail.

Sapropelic coals contain much less matter recognizable as plant material than do humic coals, but they furnish spores and pollen grains which were blown or floated into marshy water. These plant micro-fossils, present in coal of all kinds, possess coats which are highly resistant to decay. Many have been preserved in an almost unaltered state, and by skilful treatment it is possible today to isolate them for examination under the microscope.

Deposition of the Coal Measures

For long after the maximum intensity of the Devonian earth storm which raised the Caledonian mountain range (p. 59), the crust in the foreland areas remained very unstable. Extensive tracts of country then tended to subside to form basin-like depressions which became fresh-water lakes. Downward movements were intermittent rather than continuous, and occurred to a greater

M

degree near the centre of each basin than around the periphery. These large basins were separated from each other by more stable ridges that remained above water. A land ridge of this kind certainly lay to the south of present-day Staffordshire, to which the South Staffordshire Coalfield (*see below*) owes its separation from the Bristol-Gloucester Coalfield. Similarly at no time has the Kent Coalfield had a connexion with other British coalfields.

Sand, silt and mud were brought into these depositional basins by rivers in the normal process of denudation of the surrounding land. During periods of stability these materials were gradually built up to water level, to form sandbanks and mudbanks, which spread outwards from the periphery. Forest swamps grew upon them, and as silting still proceeded, the forests extended farther and farther into the basin areas and the trees, though of botanical orders akin to those of the club mosses and ferns, were of sizes comparable with tree forms of today.

Lengthy periods of extremely slow subsidence favoured the accumulation of plant débris, to thicknesses of tens or even hundreds of feet, in the form of tree-trunks, branches, leaves, spores and pollen grains which fell into the stagnant marshy waters. But the more rapid periods of subsidence caused whole forest tracts to be submerged, and gradually to be covered with progressively thickening beds of mud, etc., built up from materials that were continually being supplied from the adjacent land. At times a sea broke into a fresh-water basin, although its tenancy was usually short—that is, short in a geological sense. On occasion marine invasion appears to have occurred simultaneously over all, or almost all, of the Coal Measures basins not only of Great Britain, but of north-western Europe. This was a result of a regional rather than of a local subsidence.

After a period of local crustal depression and submergence following upon a re-establishment of relative stability, each basin again gradually became silted up. Again deposits ultimately reached surface water level; sandbanks and mudbanks were formed anew, to be colonized with a fresh swamp-forest growth.

Coal Measures rhythms of deposition

Repetitions of submergent and emergent episodes suggest rhythmic movement, and in fact rhythmic sequences of beds of different rock-type are characteristic of the Coal Measures. A full depositional rhythmic sequence, commencing from a forest period, is as follows:

(1) Forest growth: very slow subsidence of land, permitting accumulation of vegetable matter, but without actually drowning the growing forest.

(2) Incoming of the sea, bringing much mud to cover the forest area. Marine animals lived in the sea and their remains were incorporated in the mud, to be preserved as fossils. It is still a matter of discussion in the geological world as to whether the sea invaded a swamp area because of actual subsidence of its foundations, as it were, or whether the ground surface of the forest swamps was lowered through the compaction and consequent decrease in volume of the underlying sediments; or indeed whether some local rise in water level occurred. It may well be that all processes were involved at one time or another.

(3) Lowering of the ground surface continued; the sea was gradually excluded from the immediate area by silting up of the points of entrance, and the water became brackish or fresh, in which lived freshwater snails and bivalves. Muds were accumulated that formed shales in which freshwater or brackish water shells are preserved as fossils.

(4) Subsidence ceased; as a basin became gradually filled up the type of deposit coarsened; muds gave place to silts, and silts to sands.

(5) Sandbanks and mudbanks were formed at surface water level and became colonized by vegetation. A 'seatearth', that is, a soil and subsoil that were penetrated by rootlets, was formed on which a new forest grew. The seatearth may be a shale, a siltstone or a sandstone.

A complete set of beds, however, is not necessarily present in every rhythmic sequence; for instance, a forest may have been drowned by fresh water, without the assistance of an inbreak of the sea. Variations in Coal Measures rhythms are shown in Fig. XI, 1.

Split coal seams

Subsidence of a basin floor tended to be a more or less continuous but very slow depression near the periphery. This allowed forest swamps to grow with little or no interruption and thus to give rise to an accumulation of a very great thickness of decayed vegetation. Downward movement was of progressively increasing degree towards the centre. In consequence there was periodic interruption of forest growth, and drowning and burial of the forest by an accumulation

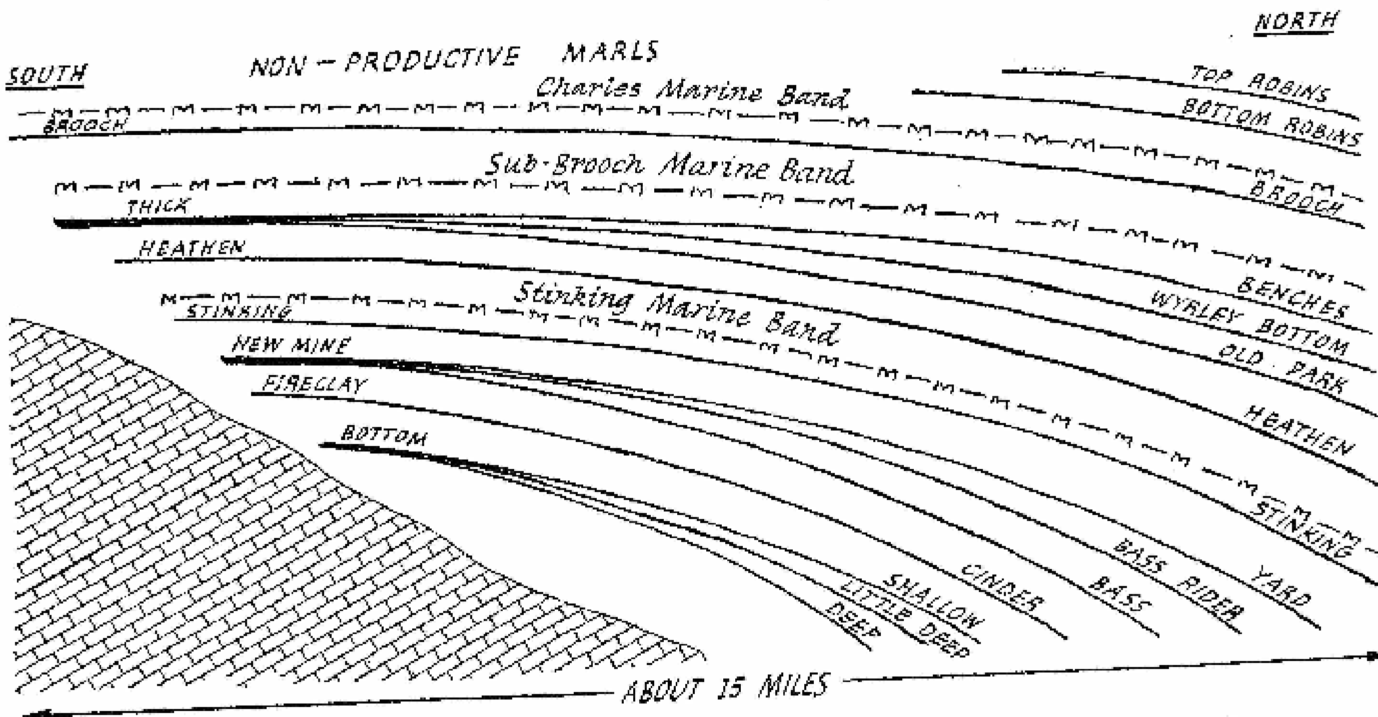


Fig. XI, 2.—Split coal seams originated through intermittent subsidence of parts of a coal-swamp area. In South Staffordshire the Thick Coal, the New Mine, and the Bottom seams each split into a number of seams as they are traced across the coalfield from south to north. Seams have been correlated largely by the help afforded by marine bands.

of clays, silts and sands. Sometimes the coal seams resulting from these forests comprise a single, very thick but composite bed in one district, which, as they are traced towards another district, are seen to be divisible into a number of thinner beds, separated by progressively thickening beds of other sediments.

An actual example of this occurs in South Staffordshire. In the Dudley district a coal seam known as the 'Thick Coal' has a maximum thickness of 30 ft. Although apparently one seam, it is actually

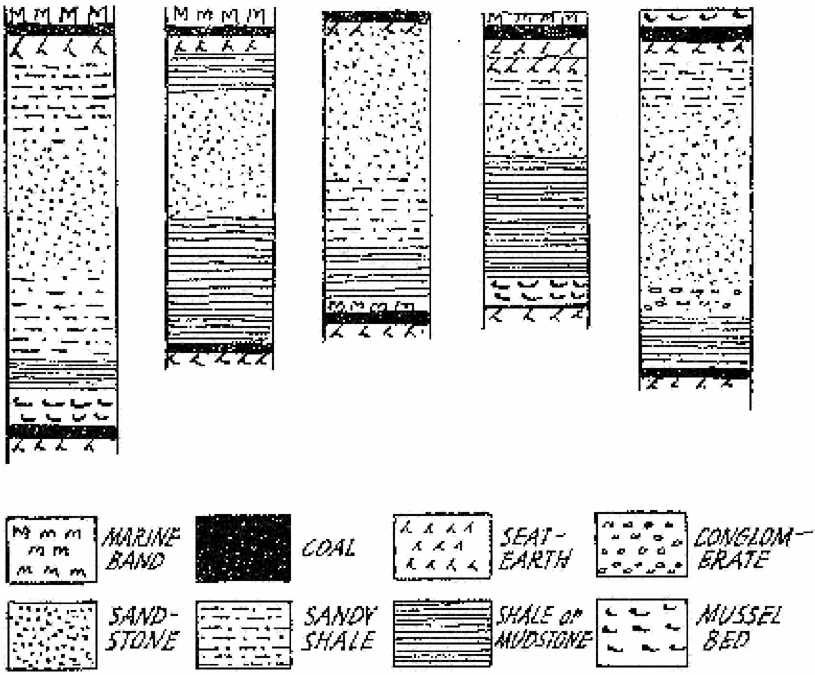


Fig. XI, 1.—Variation in rhythmic sedimentation in Coal Measures.

made up of a number of distinct layers (Fig. XI, 2). As the seam is traced northward these layers become separated by a gradually increasing thickness of muddy sediments, until at Littleton the thickness of the deposits which corresponds to the 30-ft. coal at Dudley, but which now includes much shale and silt, is about 170 ft. It is clear that around Dudley depression was so slow that to all intents and purposes forest growth was uninterrupted, but around Littleton subsidence was intermittently much more rapid. Growth was interrupted from time to time by submergence. Farther north again, intermittent subsidence was still more rapid and still greater

thicknesses of silt were accumulated between each submerged peat-bed.

Around Stourbridge the seatearths of several coal seams lie vertically close together and give rise to the important fireclay industry of that area.

In the Lower Coal Measures of Yorkshire and Lancashire many seatearths are represented by a hard almost pure siliceous rock known as ganister, of great value as a refractory mineral. In some instances the appropriate coals are mere films of black smutty material, each representing a forest swamp of very short life.

GEOLOGY AND COALFIELD DEVELOPMENT

At first glance the foregoing brief geological description may appear to have more of an academic interest than a practical one. Yet detailed knowledge of the principles and facts of sedimentation and of the fossil fauna of the Coal Measures is fundamentally important to coalfield development today. Most coal is got by mining, the bulk of it being cut today by mechanical means (Plate VIIIA). Present-day industrial development demands the correlation of coal seams from colliery to colliery. Even were the factors of sedimentation to be the only ones necessary to be considered, the difficulties of doing this would be far from negligible. But the Coal Measures have been much contorted and broken in post-Carboniferous times. Earth movements have produced folds and faults to greater or less degree in all the Coal Measures of Great Britain and north-western Europe. During post-Carboniferous land episodes, erosion removed the Coal Measures from many wide tracts so that the original depositional basins are now fragmented into a number of smaller ones. Within its small compass Great Britain alone possess some twenty-three coal-bearing areas, as follows: (1) Central Coalfield of Scotland (Clyde Basin), (2) Stirling, Clackmannan and West Fife, (3) Central and East Fife, (4) Lothians, (5) Ayrshire, (6) Douglas Valley, (7) Dumfries, (8) Argyll, (9) Cumberland, (10) Northumberland and Durham, (11) Lancashire and East Cheshire, (12) Yorkshire and East Midlands, (13) North Wales, (14) North Staffordshire, (15) Leicestershire and South Derbyshire, (16) Warwickshire, (17) South Staffordshire, (18) Forest of Wyre, (19) Coalbrookdale and Shrewsbury, (20) South Wales, (21) Somerset and Gloucester, (22) Forest of Dean, (23) Kent. Their distribution is shown in Fig. XI, 3.

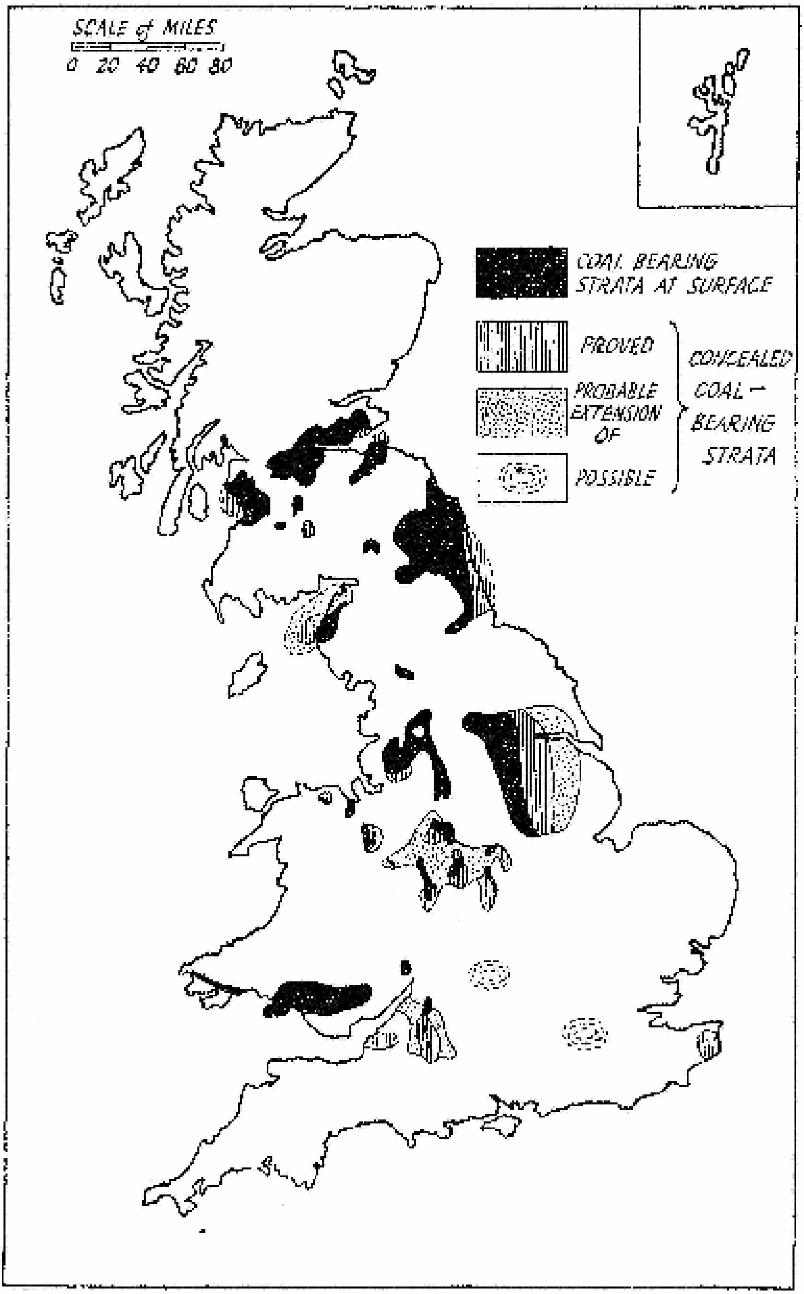


Fig. XI, 3.—Coal-bearing areas of Great Britain.

In some of these areas folding and faulting is intense. The South Wales Coalfield was involved in the foreland upheavals of the Carbo-Permian mountain-building period (p. 59) with drastic effects on the Coal Measures, whose originally continuous strata, in addition to having been folded into innumerable anticlines and synclines, have been broken and displaced by innumerable faults. Some of these displace beds several hundred feet. Fig. XI, 4, shows a representative diagrammatic section across part of the South Wales Coalfield.

While there is no doubt that before the nineteenth century mining engineers generally understood much concerning their respective mines and the seam or seams they were working, they possessed few or no means of identifying a seam in one colliery with

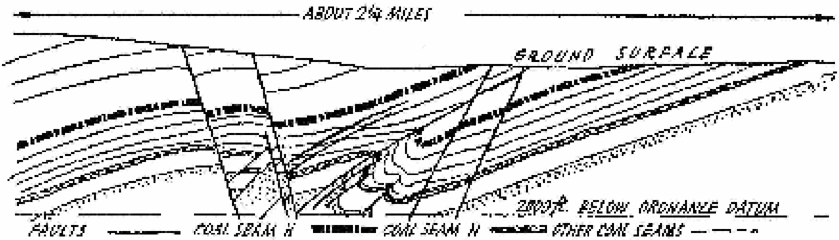


Fig. XI, 4.—The Coal Measures of South Wales are heavily folded and faulted. Some of the most important economic work of recent years has been the elucidation of the complex structures of this coalfield.

the same seam in another, though in certain instances identification was possible on a limited scale. For example, in Staffordshire one particular seam contains sufficient sulphur to produce on burning a smell of sulphur dioxide, and is known as the 'stinking coal'. It was recognized wherever it was encountered.

Essential geological information

It mattered little in the earliest days of coal mining, when the industry was small, that the general distribution of coalfields in the country was little known, and that methods of working in adjacent mines were in many cases discordant, and that each colliery was a law unto itself, as it were. With the great and ever-growing demand for coal that accompanied the industrial revolution in Great Britain, and has continued until today, more and more detailed information has been required on which to base plans for coal-getting in ever-greater quantity. It has become progressively more and more important to know (1) the general distribution and limits of coal-

fields in the country as a whole; (2) a general scheme of correlation of Coal Measures applicable to all coalfields; (3) detailed correlation of coal seams in each coalfield; and (4) an understanding of the pattern of folding and faulting in the Coal Measures over a wide area to assist individual collieries to overcome the difficulties which folds and faults produce. Amongst other matters, information of this kind minimizes blind exploration, which can be very costly.

In the Old World, those areas where Coal Measures come to the surface were recognized centuries ago. Geological investigation, however, has been responsible for the discovery of those tracts where coal lies concealed beneath newer rocks. It is by no means certain that the whole of the coal reserves of Britain have yet been determined. It is still possible that coal exists beneath parts of Oxfordshire, Northamptonshire and the Weald; and there is a possibility, albeit a very slight one, that it may underlie the eastern parts of Essex.

While geological work has been responsible for the elucidation of the complexities of the geological structure of many coalfields, it must be emphasized that even today a complete picture of the arrangement of the coal-bearing strata does not exist. From time to time long-established views are still proved to be wrong, sometimes with vastly important bearings on future prospects of a colliery or a group of collieries. Within the past few years the potential life of at least one British colliery has been prolonged a great many years through the correction, on geological grounds, of a former mis-identification of a coal seam that is there being worked.

Negative conclusions of value

An extremely valuable, though negative, contribution of geology to coal economics has been the determination of criteria by which certain groups of strata can be definitely ruled out as possible sources of supply, and further that where certain of these strata occupy the ground surface, no coal will occur within those areas. In England during the eighteenth century much money was wasted in excavations for coal at sites which it is now known cannot possibly yield coal. Even during the early part of the present century this important geological attribute was by no means fully appreciated, for in Wales in at least one instance about 1902 a costly exploratory excavation for coal was undertaken, starting in Silurian strata. Even after its sponsors had been informed of the true position, it was continued on the grounds that in appearance the rocks resembled those of some of the coalfield areas! This last conclusion

was probably incorrect in itself, but in any event the fossils told the true story.

In the eighteenth century a shaft for coal was sunk near the coast at Bexhill. A reputed seventeenth-century excavation in North Dorset, in a field still known locally as Coalpit Field, was commenced in Kimmeridge Clay, but was most probably in search for 'Kimmeridge Coal', an oil-bearing shale known in the Kimmeridge Clay cliffs of South Dorset, but not a coal at all.

Data for correlation of Coal Measures

Correlation of coal seam from colliery to colliery and from place to place is based on several lines of geological evidence. As has been remarked above, the great bulk of Coal Measures was laid down in brackish water or fresh water, the exceptions being those thin deposits, widely spaced in the sequence of strata, that were left behind by marine invasions. At all geological periods, however, fresh-water and brackish-water shells have been few in species and very slow in evolutionary development, and in the Coal Measures they are sparsely distributed. But marine life has comprised very numerous genera, many of which were subject to appreciable evolutionary changes. The Coal Measures marine bands, which are often a matter of inches only in thickness, or at most of feet, contain numerous highly diagnostic fossils. When detected, these bands clearly mark off thick groups of fresh-water and brackish-water strata above and below them. But certain of the non-marine shells have also been long used with great success in broad correlative work.

Much geological work has been done on fossil plants, many of which are of common occurrence, but hitherto these have not proved to be as helpful as had been hoped. The various plant forms appear to have had a very long geological life and consequently the same forms appear more or less throughout great thicknesses of strata. Plant spores, however, are proving very serviceable in certain areas.

The resultant marine bands of those extensive incursions of the sea that appear to have affected simultaneously many, if not all, of the basins of Great Britain and probably those of north-west Europe, are traceable over very large areas. One very widespread bed in Britain is known in the Midlands and elsewhere as the 'Mansfield Marine Band', and in South Wales as the 'Cefn Coed Marine Band'. It provides a datum line of widespread validity. Other somewhat less widespread bands have a regional value in correlation,

and others again, produced by very restricted invasions of the sea, have local use. In Staffordshire fourteen marine bands have been detected, and eighteen in the Yorkshire and East Midlands Coalfield. To these bands the coal seams in the two districts are now related.

In correlative work geological surveys of the whole of the ground surface of a coalfield are equally as important as the use of marine bands. They naturally have less bearing in completely concealed coalfields such as the Kent Coalfield than in areas where coal-bearing strata crop out. In order to obtain samples of strata it is a routine procedure to put down exploratory boreholes, some of which are taken to depths of 5,000 ft. or more. Finally, many old mine plans and records of workings contain information which, though directly related to disused and abandoned workings, hold details which are very relevant to present-day problems.

DETECTION OF MARINE BANDS

The requisite geological evidence from the various sources, however, is not easily acquired. The study of the Coal Measures is one of the most difficult and most highly specialized branches of geology. In the case of marine bands, for example, Mrs. Beeton's famous injunction concerning jugged hare applies with great force; for they are not easy to find. On occasion a band may be detected during surface surveying; more often they are located either by geological examination of strata exposed in coal pits (Coal Measures geologists spend much time underground) or by examination of material from exploratory coal borings.

This last entails observing, measuring and recording all variations in rock-type, and searching for, and identifying, fossils. Both examination of borehole cores and examination of strata in the walls of coal mines are activities for which the geologist needs the attribute of great patience as well as scientific knowledge. In addition to knowing what to look for, and how to recognize it when seen, he must know how to look. This implies amongst other things a readiness to crack, inch by inch, a core which may be 3,000 or 4,000 ft. long, and to record descriptions in great detail.

GRAPHIC SECTIONS

Records of boreholes thus compiled are summarized in 'graphic section' form, as illustrated in Fig. XI, 5. In Great Britain, these graphic sections are normally drawn to a scale of 100 ft. to an inch, but sometimes to one of 40 ft. to an inch. As is the case with ornamented (as distinct from coloured) geological maps, conventional

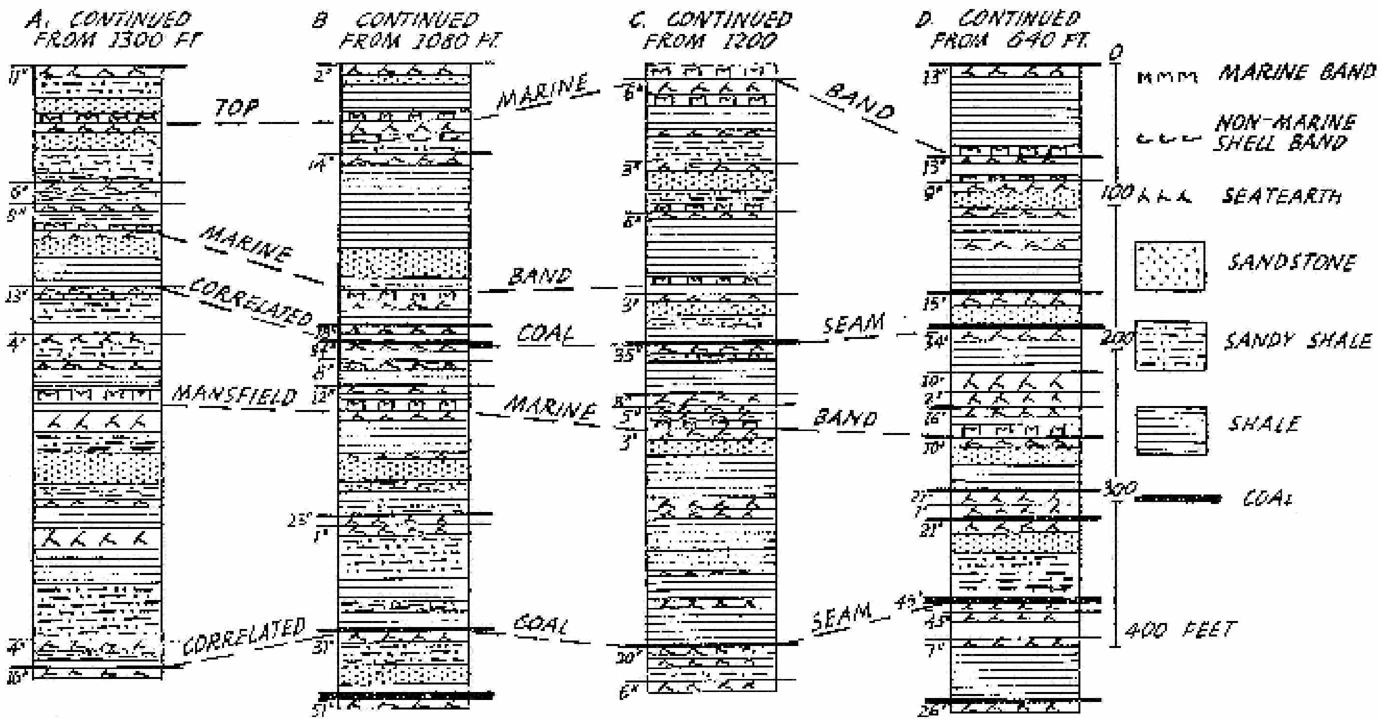


Fig. XI, 5.— Parts of graphic sections of borehole logs of Coal Measures, showing correlation by means of marine bands.

ornaments are used on graphic sections to distinguish coals, sandstones, clays, limestones and other characteristic rocks.

Groups of local graphic sections of boreholes are then compared to determine if possible some definite horizon common to all. A compared group of sections often conveys some general, though not detailed, idea of structure. For example, the positions of a marker band in two adjacent boreholes may show a great discordance relative to ordnance survey level, thereby indicating a probable disturbed zone between the two borehole sites. The determination of its nature and precise position, however, depends upon subsequent geological investigations. The sum total of these activities leads to a reasonably accurate three-dimensional picture of the general structure of an area.

GEOLOGICAL OBSTACLES IN MINING

Contortions in the Coal Measures, that is, folds and faults, may prove to be serious obstacles to economic coal mining. No British Coal Measures are free from disturbances, but on the whole these are less pronounced than they are in some continental coalfields, although in Somerset and in South Wales many of the beds have been tilted to very high angles by folding and they are also greatly faulted.

The Franco-Belgium Coal Measures are so greatly disturbed that some pit shafts pass through the same seam several times. At Liége the vertical pit shafts actually encounter Devonian rocks (p. 62) *above* the Coal Measures, so great has been the contortion in this area. The British Coal Measures are much more disturbed than are those of some of the countries of the New World. It will be apparent that the less the disturbance, the less costly is the process of extraction of coal.

One feature of the section shown in Fig. XI, 4, is the presence of geological faults. A problem of pre-geological days was to determine which way strata had been displaced when a fault was encountered in a coal mine. It has previously been remarked that in many instances local knowledge, when scientifically applied, gave answers to questions of this kind. But investigations were often blind, and wasteful both of labour and of material. A geological appreciation of the structural pattern of a district and detection of some marker horizon or horizons, which may be a marine band, a recognizable rhythm of strata, or some other feature, today obviates many inherent difficulties of this nature.

Water in mines is another obstacle. In general, British coal mines

are relatively dry, and pumping out water that enters a mine from the surrounding strata is normally a routine engineering matter. In certain circumstances, however, especially in the case of coalfields concealed beneath newer strata, it is of the greatest importance to know in detail the geological structure of the whole coalfield, both as regards the Coal Measures and the overlying strata. Only then can heavy and sudden inflows of water be guarded against. For example, in Fig. XI, 6, were the coal seam shown in the upper diagram to be

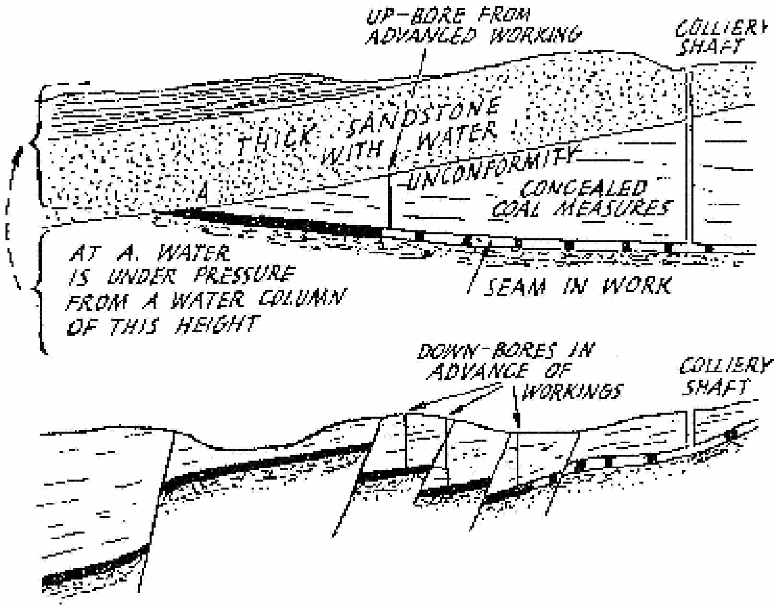


Fig. XI, 6.—Precautions taken to guard against sudden inrushes of water in coal mines include making boreholes in advance of workings. These may be up-bores as in A, or down-bores.

worked right up to the unconformity with the overlying sandstone, water would certainly break in with a sudden rush if removal of coal reached a critical point when insufficient had been left to balance the pressure head of water in the sandstone above. The Knockshinnock mining disaster of 1952 in which a superficial deposit of water, mud and peat entered into the coal workings resulted from an insufficient knowledge of local geological conditions.

In collieries where it is known that the geological structure carries a potential menace of this nature, it is everyday mining practice to probe the overlying strata by drilling test holes either

upwards from the most forward sections of the coal workings, or downwards from the ground surface a little in advance of the underground position, to produce cores which are subjected to geological examination (lower diagram, Fig. XI, 6).

Local mining terms

One of the lesser functions of the geologist is to interpret local terms used by miners, quarrymen and others. Every country has a large quota of such words, which are mostly meaningless to the layman, though many have a precise local significance. Generally their etymology appears reasonably clear when the local meaning is appreciated.

A few illustrative British terms of this kind are:

Blaes—blue shale.

Brazils—pyritous coal. Probably a corruption of 'brassy', referring to the appearance of flakes of pyrite, or 'fool's gold'.

Cank—a very hard sandstone, siltstone or mudstone. Possibly an onomatopoeic word, representing the sound when 'cank' is struck with a hammer; or maybe from an Old English word.

Clunch—in the North Midlands a seatearth, underclay or fireclay, or a weak mudstone. In East Anglia a hard chalk, and commonly a heavy clay that forms clods.

Devil's dough—a rock with an appearance somewhat like dough but extremely hard; doubtless a character conferred on it by the devil in order to plague miners.

Dun—in Somerset a clay-slate. In the North Midlands a carbonaceous dirt-parting. Probably connected with the colour of the material.

Fakes—thin sandstones and siltstones.

Gees—alternative layers of hard and soft coal-partings.

Jacks, jays, jay coal—inferior cannel. Possibly connected with a widespread country use of 'jack' to denote something inferior.

Jakey—inferior hard coal. (*See* above.)

Raddle—decomposed earthy haematite in North Midlands; weathered red shale (and a nuisance in excavations) in the West of England. The word is connected with red coloration.

Ratchel—any loose rock at or near ground surface.

Simon-strings—cracks, often filled with calcite or dolomite, in ironstone and cementstone concretions.

Sloom—soft seatearth, especially when wet, or a clayey and shaly coal seam.

Even the word 'fault' as employed by miners has not necessarily a strict geological significance. It may denote anything which interrupts a coal seam or causes a local deterioration in the coal. A fault may then include a geological fault; an intrusion or igneous dyke; a local bending in a seam which makes for difficulty in workings; a 'washout'; or some other less common feature. A well-known feature in the South Staffordshire Coalfield, known as the 'Symon Fault', is an unconformity. Washouts are local replace-

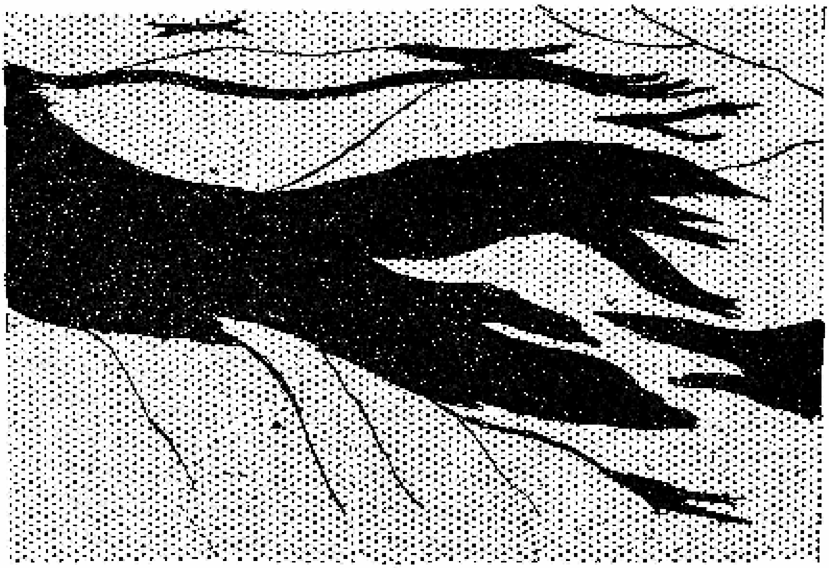


Fig. XI, 7.—The edge of a 'washout' in a coal seam in Northumberland. Layers of coal become split apart by wedges of sandstone, and ultimately sandstone completely replaces coal. (After Raistrick and Marshall.)

ments of coal in a seam by sandstone, silt or shale, and occur commonly. Many of them mark the courses of Carboniferous streams which flowed through the forest land clearing their beds of vegetable matter, and depositing mud, silt or sand; thus along these courses little or no coal-forming material remained. A washout in a Northumbrian coal seam is illustrated in Fig. XI, 7.

Cleat

Most coals show the interesting feature of 'cleat', that is, of vertical planes of cleavage along which coal, when hammered,

splits into small dice; a feature known to every housewife. Cleat occurs in two directions more or less at right angles to each other and these are constant over wide areas. In the Northumberland-Durham district cleat runs roughly north-south and east-west. It influences the direction and method of working coal since by utilizing the cleat planes coal is more easily got, and is less broken than it would be if they were to be ignored. The cause of cleat is still a matter of geological discussion. Some regard it as having resulted from earth pressures and therefore as being akin to the cleavage of slate, while others consider it to be more in the nature of ordinary jointing, such as occurs in most hard rocks, and is produced by the process of simple consolidation.

Opencast working

Coal mining as generally understood implies working underground. The earliest method of getting coal was to dig coal at the outcrop on the ground surface, then to follow the seam underground for such distances, always short, as were safe. It is but a short step in method from working the actual coal crop to the removal of overlying strata to expose the coal seam and to exploit it by quarrying. The degree to which this 'opencast' method is applied today depends on the economic factors that determine the cost of removal from the bed. Some of these factors are geological. They include in particular the 'lie' of the coal seam to be worked, and the thickness of coal in relation to the thickness of overburden.

In Great Britain opencast working on a large scale is a very recent development, greatly stimulated by the exigencies of the 1939–45 World War. Its economic continuation during post-war years has been rendered possible by the progressive development of mechanical bulldozers, heavy draglines and mechanical shovels for excavation work. As a generalized figure for Great Britain, the economic ratio of thickness of overburden to thickness of coal some years ago was about 4 to 1, or even 3 to 1. Today it is very much higher. An extensive open-cast working in Nottinghamshire is shown in Plate VIIIb.

A detailed geological survey is an essential preliminary to opencast coal mining. This is not only required to delimit the likely production areas and the actual outcrops of coal, but is necessary to determine the dip of the beds, the probability of faults and other structures. From the detailed survey also some idea of the probable thickness of coal seams underground is obtained. These primary geological contributions having been made, trial boreholes are put

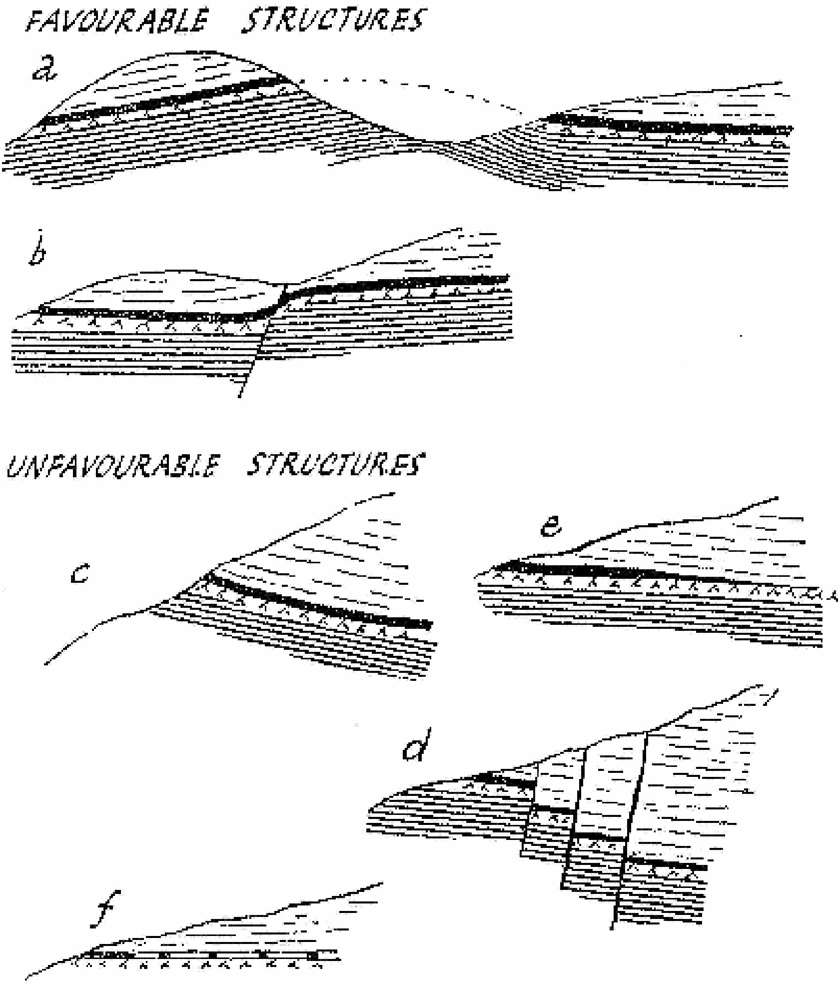


Fig. XI, 8.—Some favourable and unfavourable geological structures, having regard to profitable 'opencast' coal getting.

down, which at the present time in Britain rarely exceed more than 100 ft. depth. Fig. XI, 8, shows (*a*) some structures where opencast working is profitable and (*b*) structures where it would be uneconomic.

CHAPTER XII

Ores—Prospecting and Mining

THE word 'ore', derived from an Old English name for brass, denotes a rock that contains a metal or metals in sufficient quantity to make extraction economically profitable. The 'profit motive' is an essential part of the definition. The term, therefore, is not a geological one at all. There is a modern tendency to include as ores some other minerals that are often got either with them or from the same mines; minerals such as fluorspar and barytes. The convenience of this usage does not seem to be an adequate recompense for the loss in definition that the word 'ore' then suffers.

It will be apparent that a metalliferous rock that is valueless as an ore at one period may later be promoted to rank as one through the discovery of some new or improved process for extracting the metal it contains. This is the case with aluminium ores. Aluminium is one of the most abundant constituents of the earth's crust. Except in such rocks as are composed almost solely of non-aluminous material, notably limestone and quartz rocks, it is present in most common rocks, whether sedimentary, igneous or metamorphic.

Half a century ago small aluminium medallions were objects of great interest, and the metal was little used in the industrial world. The development of electric power has provided an economic method of separating the metallic from the non-metallic constituents of certain rocks, which today rank as ores, although they may not have done so at the turn of the century. The most important of them is the weathered clay known as bauxite, so named from Les Baux in southern France.

Conversely a rock that at one period is an ore may later be de-graded. In the Wealden district of south-eastern England ironstone

was mined and smelted certainly from Roman times until the nineteenth century. Wealden ore included clay ironstone and a pale grey carbonate of iron (siderite). Much was mined from bell-shaped pits, each with a narrow opening at the top, and widening with depth. The walls were thus dome-shaped, a stable form that provided a safety factor against collapse. These pits were rarely more than 20 ft. deep although some were upwards of 40 ft. Many quarries, especially in the Wadhurst Clay, that were opened up to get marl for the land or in some instances possibly a clay with grease-absorbing properties for 'fulling' wool, encountered bands of ironstone which was also utilized for smelting.

Although the Wealden iron industry lasted some twenty centuries it was always decentralized, and was minute as compared with present-day industry. Over 225 smelting sites and forges are known, but these are spread in time over several centuries and in space over the counties of Kent, Surrey and Sussex. The life of many was short. The scale of working may be judged from the fact that a furnace at Ashburnham, Sussex, a veritable giant amongst others, had an output of about 350 tons a year; this was also the last ironworks to be closed, ceasing in 1828.

The final attempt to treat Wealden ironstone as an ore was in 1857–58 at the Snape mine near Wadhurst, Sussex. Two beds were worked, one up to two feet thick; both were irregular in thickness, sometimes dying out completely for a distance. The composition of the ironstone varied much from place to place. The roof of the mine was bad and required timbering, and the attempt ended in failure.

The Snape mine occurrence is representative of Wealden ironstone generally. It cannot be worked profitably today, and strictly speaking it is no longer an ore. By association with its past ranking, however, it is often still referred to as one; it holds brevet rank as it were.

Three main classes of ore

Ores, being rocks, are contained within the general classification of rocks, as given in Chapter III. They may be igneous, sedimentary or metamorphic.

The general principles of the geology of igneous rocks apply to the development of igneous ores. Some crystallize out at an early stage in magmatic differentiation; amongst these are ores of platinum and nickel. Other igneous ores are not formed until the very last stages of magmatic crystallization; by then their constituent materials

have become part of a liquid magmatic residium that contains highly concentrated ore-making substances. Some iron ores crystallize out directly from a magma of this kind. The most volatile parts of an original magma may ultimately leave it in the form of very hot highly charged watery solutions or even of gases; lead and tin come from these late fractions.

Geological work in mines, and at the ground surface in appropriate areas, combined with mineralogical and petrological laboratory work, has shown that concentrated liquids, hot aqueous solutions and gases from former magmas have all tended to penetrate into cracks and fissures in surrounding strata, often under pressure by those earth movements that are associates of igneous activity. Some parts of them consolidated as dykes and sills as do any non-metalliferous injections of molten matter. Gases and aqueous solutions may either have given rise directly to minerals of various kinds, or they may have attacked the country rock alongside the cracks into which they penetrated. In the latter event they produced metamorphic ores—minerals of different nature from those derived directly from a magma. All these last injections produced veins or lodes of ore that follow the pattern of pre-existing cracks or voids in the country rocks.

The word 'lode' is but a variant of 'load'; the latter, now literally something carried, originally signified an actual way or track. Lode is still used for a watercourse in Fenland districts. In mining it is synonymous with a mineral vein.

The occurrence of veins or lodes may be instanced by reference to the Carboniferous Limestone formation. It has been recounted in Chapter VIII that large cavities have been produced in parts of these strata, as the result of solution of the limestone by water that has percolated along joint-planes, bedding-planes and other cracks. This is no recent geological phenomenon but has been a continuing process ever since the limestone became consolidated.

In parts of the Carboniferous Limestone of Derbyshire and of the Mendip Hills of Somerset, for example, some cavities were in existence at a time when hot solutions were rising from a magma at depth. They were entered by mineralizing solutions that left in them fillings of lead and zinc ores. The solutions also combined with some of the limestones to produce new minerals of which fluorspar is an example. This is well known from the noted 'Blue John' mine of Castleton, Derbyshire. Fluorspar, possibly Blue John stone from Derbyshire itself, was greatly treasured by the Roman nobility, to whom it was known as 'Murrhine'.

The most notable sedimentary ores of today are those of iron and aluminium. Normally called 'bedded ores', they occur as stratified deposits, in contradistinction to veins and lodes, and are subject to the geological laws that govern all sedimentary deposits.

Geological prospecting

The mining prospector of today is almost invariably a highly qualified university graduate versed in all branches of geology, and particularly in structural geology, petrology and mineralogy. Through him, geological research has paid high economic dividends in the assistance it has given in searches for new resources of ores of all kinds. It has established the ways in which the various ores were formed and has traced the connexion between these and the modes of occurrence in the earth's crust, taking into account also the facts of earth movements subsequent to ore-formation. This has led directly to the delimitation of areas where prospecting for specific ores is likely to be successful. It has given a lead in planning exploratory work at likely sites, particularly in the siting of trial bore-holes.

As in the case with so many other facets of economic geology some of the more obvious ore-bearing strata were probably chance discoveries. The value of scientific geology to modern prospecting is immense, yet consideration of the past gives a salutary check on over-emphasis, for mining history provides an example *par excellence* of the inheritance that organized science has received from the past. In Great Britain alone, lead mines are thought to have been worked by the Romans in North Wales and in Northumberland, although no actual written records have been preserved. Documentary evidence is available that it was mined in the twelfth century, and from then onwards a long succession of records of grants exists. In the Middle Ages, for instance (when there appears to have been an influx of miners from Germany), Queen Elizabeth I formed a 'Society of Mines Royal' and in 1563 granted the mines and minerals of Wales and of several English counties to various people to work. From time to time new bodies of lead-ore were found in the Halkyn district of North Wales; new, extremely rich ore-bodies were discovered as late as 1728 and again in 1770. It is unknown, and perhaps profitlesss, to speculate how ores of this kind were first discovered.

Neither the tin-bearing gravels of Cornwall that gave rise to the industry of tin-streaming, nor the more recently found gold-bearing alluvial deposits of the Yukon, to be worked by hundreds of gold-panners during the nineteenth century, were discovered by the

application of geological principles. However, although chance has played a part in the discovery of valuable ores it is unlikely that sudden lucky strikes were ever very common. The once-favoured sudden-success theme of boyhood stories in which the prospector-hero, desperately up against it, suddenly recognizes in his immediate surroundings rocks reminding him of ore-bearing strata he had seen elsewhere (with appropriately satisfactory results), was founded on no more than very occasional fact.

From present-day experiences it is apparent that the successful miners of all periods were of necessity impelled to study both the behaviour of an ore-body and of its surrounding rocks as mining developed from outcrop workings in shallow trenches into underground excavations. Mining throughout the long period of its recorded history has ever demanded a truly scientific approach, and so it developed a technique of a very high order, and accumulated a mass of observed facts, some of which were recorded, some handed down orally from generation to generation. It is upon this approach-work that organized geological work in mining has been grafted, as it were.

Modern mining geology includes not only field work, both at ground surface and deep in mines, and laboratory work, but the less spectacular but highly important 'office' work of gathering together mining records and mining plans from various sources and from wide areas; and the plotting and correlating of data they provide. It is by combining investigations of all kinds that a picture may be built up that is not only of value to an immediate district, but is one applicable to new areas.

In present-day prospecting geophysical methods are widely used as adjuncts to those of more orthodox geology. Checks by these methods have on occasion proved of outstanding value. It has been said that in South Africa a highly important gold ore body was located by geophysical means, in ground that geological deduction had indicated would most likely be barren. This may well be true; it emphasizes the fallibility of geological deduction, which can only be founded on experienced interpretation of such evidence as is available. It also stresses the point that an occasional failure by no means constitutes a case against it. Rather it reinforces the accepted scientific procedure of utilizing every possible method likely to yield evidence of value.

Modern methods of geochemistry are also applied to mineral prospecting. One of these is to examine the ash from burnt plants, or from thin soils for trace elements. This in some instances leads to

locating an ore deposit that more orthodox geological investigation could not possibly have found. A very recent instance was a discovery of stibnite (antimony sulphide) at Camaano Point, Alaska, made on the basis of geochemical testing on soil samples from a layer of matted roots 2 to 5 ft. thick, that formed so complete and extensive a cover that observations on rock surfaces were quite out of the question. Even so, no picture so obtained can do more than act as a guide. There are still factors which influence richness and character of metalliferous lodes that are but little understood or not understood at all.

The union of geochemistry and the more physical side of mineralogy forms the main prospecting equipment for a search for uranium ores and other radioactive minerals, to which end the more normal methods of geological prospecting are of little value. Indeed, so accurate are some of the geophysical instruments that, in favourable circumstances, a geological junction between rock beds of different kinds may be accurately detected from a suitably equipped car travelling at moderate speed.

IRON ORES

Iron in one mineral form or another is present in most of the earth's crust. Even a small quantity in a rock provides a definite coloration that sometimes gives an illusion that a high proportion of iron is present. It has been remarked previously (p. 151) that the colour of many almost pure quartz sands varies from deep chocolate brown through red to pale yellow, and this colour is merely the result of a very thin film of oxide of iron covering each individual grain. The iron content in sands of this type is of the order of 2 or 3 per cent only.

Iron ores are to be found in all three of the main groups of rocks —igneous, metamorphic and sedimentary—and all three types are represented in the British Isles. From the economic point of view, magmatic ores, only known to occur in Shetland, are small and unimportant, though during the last war some 1,000 tons of nearly pure magnetite was mined there. Geological investigation has shown that at least 18,000 tons are present in one ore body, and geophysical surveys have indicated the presence of other similar ore bodies. This, however, has yet to be proved by drilling. The great iron ore deposits of Petsamo in Finland are of magmatic origin.

During the several centuries immediately preceding the beginning of the present one, unbedded ores were the main sources of supply for Great Britain. Geological work has shown that most of these

should be grouped broadly as metamorphic ores of kinds that were introduced into cavities and fissures in pre-existing strata. Some of these were brought into the fissures by iron-rich magmatic solutions. Others appear to have been carried by rainfall waters that percolated from the ground surface through iron-containing rocks before they reached the fissures in which the ore now occurs. During its progress through these rocks the water is thought to have taken up iron compounds in solution, to deposit them again at depth.

The bulk of these were kidney ores or haematite, so called because the shape and red brown colour of the masses of ore are reminiscent of kidneys. They occur notably in and south of the Lake District, the northern part of the Pennines, in South Wales and in the Forest of Dean of Gloucestershire. Fig. XII, 1, shows a haematitic mass contained in a solution-hollow of Carboniferous Limestone in Cumberland. All these districts have seen several centuries of haematite working; in West Durham it has been dug since the eleventh century. During the nineteenth century many of the more obvious deposits were exhausted but geological and geophysical surveys combined have indicated a number of spots where other ore bodies are likely to occur at depth. Some of these have already been proved by exploratory drilling. In any event, known reserves are very limited, and the present yield of haematite ore is less than 5 per cent of the total British output of iron ore which in 1942 was some 20 million tons. The importance of these haematitic ores lies in their high iron content, which is from 50 to 60 per cent.

Well over 90 per cent of iron ore now dug in Britain comes from sedimentary deposits. Investigations into the origin of these bedded ores have shown that they probably originated for the most part as chemical precipitates in sea water of shallow depth, but that algae and bacteria also may have played some part. In Britain these bedded ores are almost entirely confined to the Jurassic formations. Only one ore of Cretaceous age is now worked, around Claxby in Lincolnshire.

Geological surveying has thoroughly delimited all the British iron-ore reserves. Their distribution is shown in Fig. XII, 2. So detailed is our knowledge that no outstanding new discoveries seem possible. This standard of knowledge has been rendered the more easy of attainment since all the areas of bedded ores are of simple geological structure; an important matter in the economics of getting the ore. All these ironstones are low grade; they contain from 18 to 35 per cent of iron only, but the simplicity of geological structure has rendered digging in large opencast pits an economic

project and, as is the case with opencast coal, the great development of excavating machinery now renders it a paying proposition to remove upwards of 80 ft. of overburden to get from 7 ft. to 12 ft. of iron ore. Some of the larger opencast workings produce 10,000 tons a week; an interesting comparison with the early nineteenth-century output of the Wealden furnace at Ashburnham. The extent of the fields of bedded ore has been determined partly by geological mapping and partly by an extensive programme of test drilling.

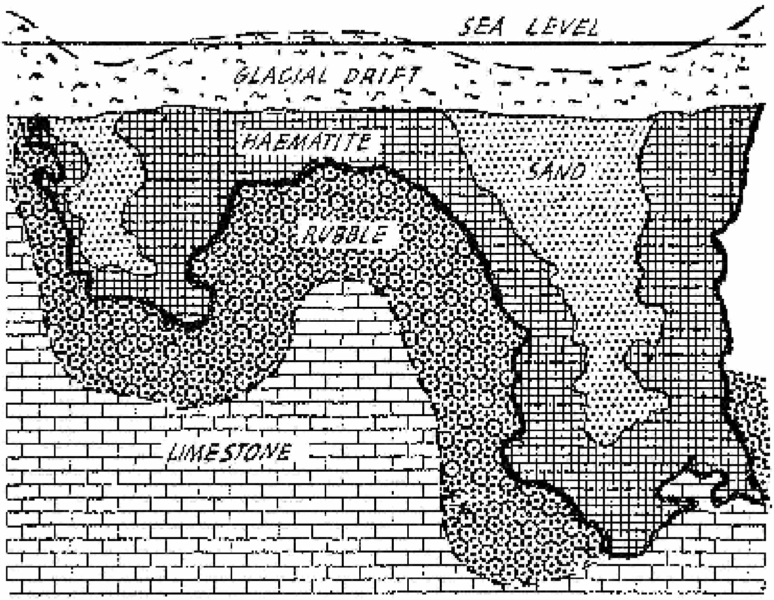


Fig. XII, 1.—A mass of haematite lying in a solution hollow in Carboniferous Limestone, Roanhead mines, Cumberland. The depth of the haematite from top to bottom is about 500 ft. (*After Dunham.*)

The correlation of evidence from these main sources has given reliable data of reserves which are of the order of 2,400 million tons, with a possibility of extension.

The great development of these orefields began only in the middle of the last century—indeed it was a direct result of geological investigations of the earlier part of that century—and already more than 800 million tons have been extracted.

It is common to find that geological work carried out for one purpose often yields information of value in another quite unrelated direction. Such has been the position in the investigation of bedded

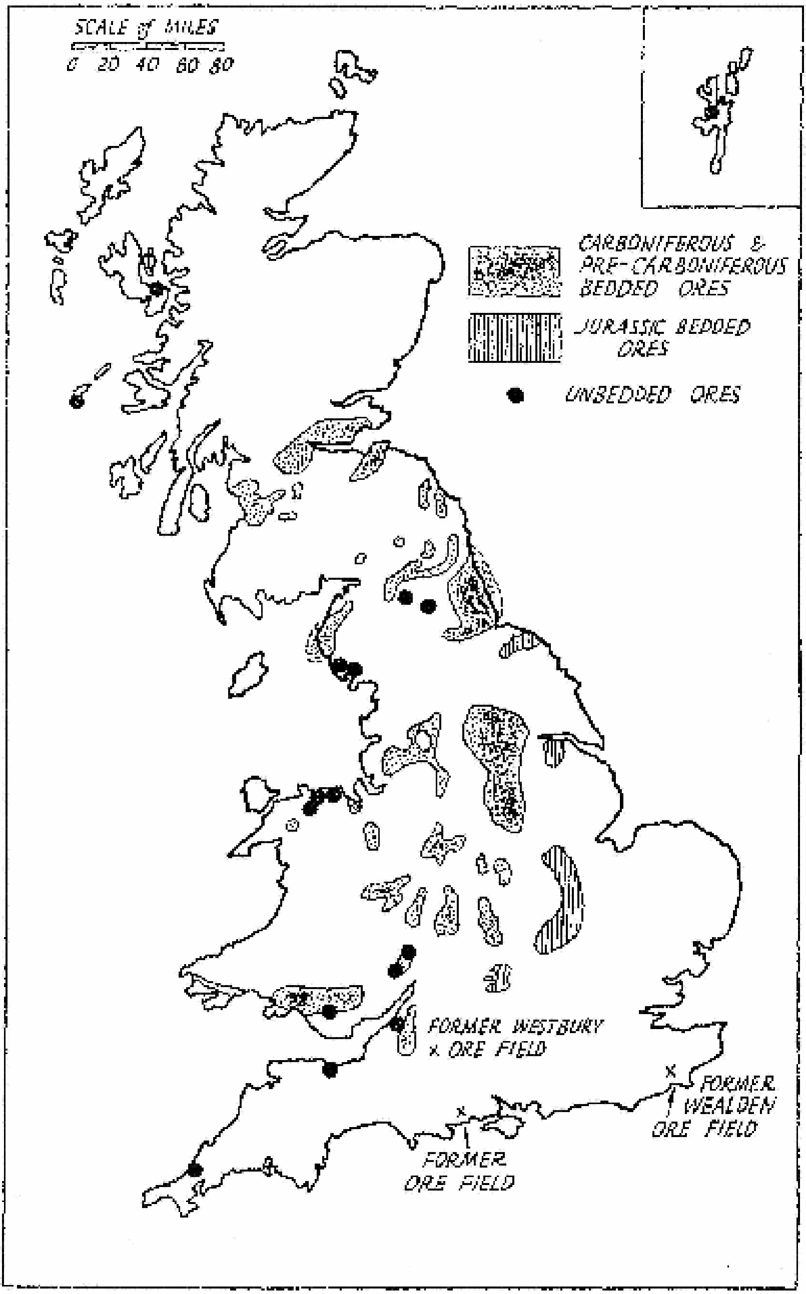


Fig. XII, 2.—Distribution of iron orefields in Great Britain.

ores. One of the largest British ironfields is in the Northamptonshire, Rutlandshire, southern Lincolnshire and eastern Leicestershire areas. Here the ore is overlain by some 20 ft. of oolitic limestone. The combined limestone and iron-ore formations constitute a mass of inclastic hard rocks that overlie the Lias clay. In common with most similar beds this mass is broken up into separate blocks by a system of vertical or nearly vertical joints. It has been found that where streams have cut through them into the clay the separate masses tend to travel down the valley sides to a slight degree. The vertical joints open out into wide 'gulls' (cf. gullies) and the whole of the hard rock beds tend to form an umbrella-shaped mass, as it were, over each hill instead of lying in one plane, which is their undisturbed natural position. The process by which this occurs is known as 'cambering'. The cambered nature of the beds mapped in Fig. XII, 3, is shown by the contours of the base of the Northampton Sand, ascertained by means of boreholes. This has now been found to be a most widespread phenomenon, a geological discovery that has repercussions on local estimations of reserves of ore, on quarrying methods, on civil engineering foundation works, and in other directions.

Another feature closely investigated during work on the ironstone fields is that of valley 'bulging'. Not only do the heavy masses of hard rock tend to camber, but their weight appears to cause disruption of clay or shale beds in valley bottoms to depths of 100 ft. or more below the ground surface, and to force them upwards in a kind of isostatic adjustment, as it were. Fig. XII, 4, show some bulged valleys in South Lincolnshire and Rutland. Isolated examples of this were recorded many years ago in civil engineering records, but lack of co-ordination between the engineering and geological professions prevented their coming forcibly to general notice. A scientific explanatory account only appeared in 1950. Bulging is also now known to be common, and economically to be equally important with cambering, particularly in regard to civil engineering.

NON-FERROUS ORES

Aluminium

Aluminium-bearing rocks, although constituting a great proportion of the earth's crust, are rarely 'ores' at the present time. The metal is usually combined with silica (with or without other elements) for which it has an affinity so strong that it is difficult to break. Those aluminous rocks that are devoid of silica however, are

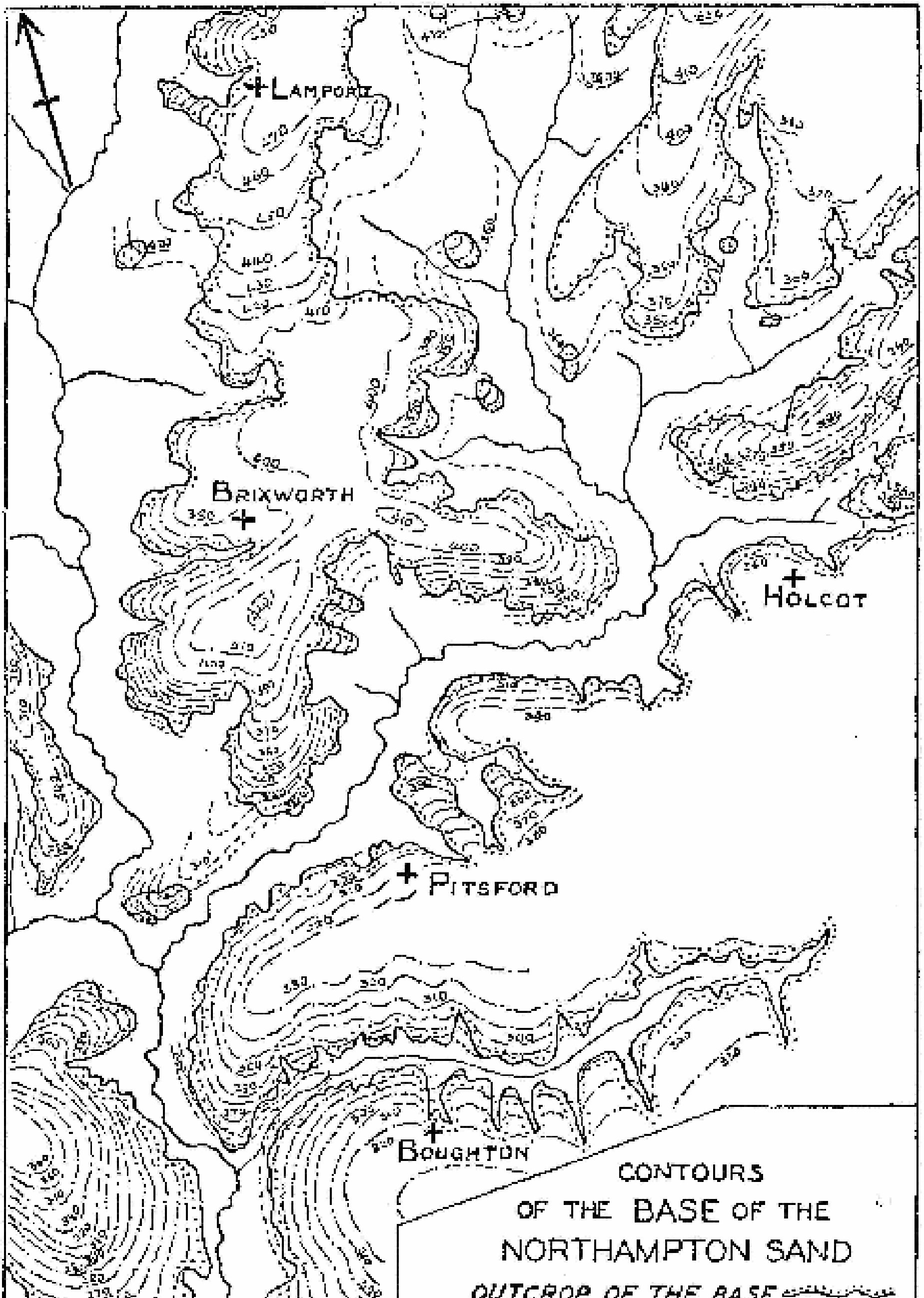


Fig. XII, 3.—An example of 'cambering'. (*After Hollingworth and others.*)

capable of being smelted economically and are the ores of today. But this class may well be enlarged should other processes be developed of separating the metal from the other rock minerals.

A fundamental geological discovery leading to the recognition of certain rocks as being possible aluminium ores was the fact that under a tropical climate, and also in monsoon lands, surface soils gradually lose their silica. This loss not only occurs at the present time; it also occurred in past geological ages. A geological prospector looking for bauxite, therefore, seeks, *inter alia*, evidences in the strata of former climatic conditions that would have favoured the formation and preservation of aluminous soils that had been desilicified by weathering.

Many sources of aluminium ore have now been discovered, and equally important, many tracts have been eliminated as likely sources. Among the latter is the greater part of the British Isles, over which bauxitic deposits are definitely known to be absent, except for an area in Northern Ireland. In County Antrim, however, highly aluminous clays associated with iron ore occur between old lava flows. These have long been known, and the first scientific account of them was made in 1912 by officials of the former Geological Survey of Ireland. During the 1939–45 war the geological field relations of the Antrim ore were closely re-examined (by an officer of the Geological Survey of Great Britain acting for the Geological Survey of Northern Ireland) and a great amount of petrological and chemical work in the laboratory was carried out on many samples, including their examination by X-ray methods. As a result of this there exists today a very full knowledge of the potentialities of Antrim as one of the sources of bauxitic ores.

Other non-ferrous ores

The economic value of geology lies with a different emphasis on prospecting and mining for ores of copper, lead, tin, zinc, gold, silver and numerous less common metals, than it does on prospecting and mining for iron and coal. In the latter stratigraphy is one of the most important elements; in the former mineralogy and petrology.

The magmatic liquids and gases from which most non-ferrous ores were originally derived penetrated into such voids in strata in their vicinity as they were able to enter; to that extent, therefore, they travelled where they listed. The lodes to which they gave rise are accordingly very irregular in shape and extent. They may swell into large ore-bodies or may thin to zero, or show other

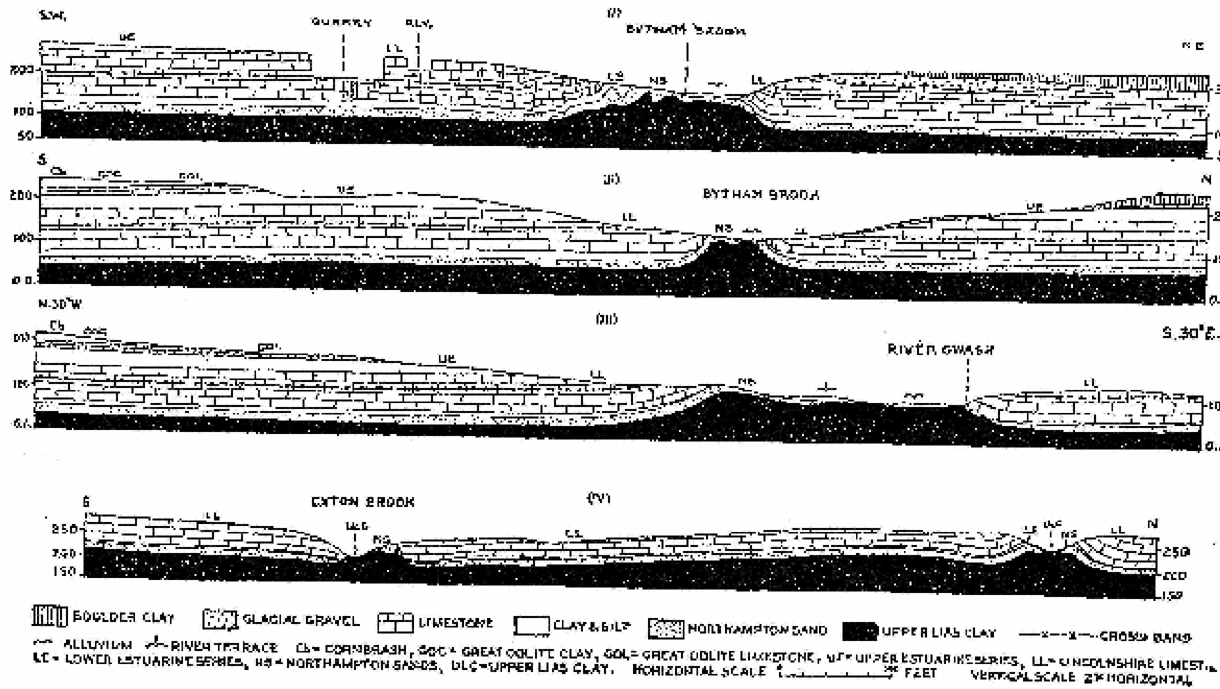


Fig. XII, 4.—The strata underlying valley-bottoms are in many cases contorted, or 'bulged'. (*After Hollingworth and others.*)

differences of form in a most haphazard fashion. Haphazardness, however, is more apparent than real. Geological field work has disclosed that fissures are present to a greater extent in some strata than in others and that joint-planes and fault-planes often follow a definite and ascertainable plan in response to some crustal movement or other. Beds of fissured type offered to the invading liquids or gases greater hospitality, as it were, than did other less accommodating strata in the same localities. In ore-bearing districts, therefore, strongly fissured strata tend to contain more lodes than do non-fissured or weakly-fissured beds.

The relationship of ore bodies to specific strata may be illustrated by the occurrence of lead and zinc ores in parts of Northumberland, North Wales and Derbyshire. In each of these districts lodes are practically confined to, and carry well in, the Carboniferous Limestone and the immediately overlying beds, mostly sandstones or gritstones. All these are widely fissured; the limestone particularly so. In general veins are thin and poor where they traverse shales above and below these beds.

This illustration, however, by no means carries even a generalization that limestones are the most likely vein-bearing rocks; it merely happens that geological survey work has determined them to be so in the above areas. Lodes occur both in granite and slate, instanced by those of zinc and copper in Cornwall, or in ancient lavas and other volcanic rocks and in folded shales and mudstones, as happens in the Lake District. As regards direction, a record of 282 copper lodes in Cornwall, made in 1843, showed that 117 dipped north, and 90 south; the rest lying in other directions.

An important modification of the pristine condition of many lodes has been detected and its cause discovered. In the copper mines of Cornwall and Devon (counties that in the past have yielded vast amounts of copper and that during the early part of the nineteenth century yielded more than half of the world's output of copper ores) it was observed that where underground water had come into contact with some of the copper compounds of the lodes (particularly chlorides and sulphates), these had firstly been dissolved by circulating water and then redeposited at a lower level. Thus was a natural process of a secondary enrichment carried out. Natural secondary enrichment is now known to be a widespread feature in copper-bearing lodes the world over.

Non-ferrous ores, though they may have originated in lodes, are not necessarily confined to them. Much mineralized rock has been eroded in the normal processes of denudation of the earth's crust.

Where material has been transported by running water, particularly a river, a natural sorting action has taken place to give rise to alluvial 'placer' deposits. Although some of these are extremely important, they are but a small part of the world's sources of non-ferrous ores.

CHAPTER XIII

Mineral Oil and Natural Gas

IT cannot be claimed that oil was a geological discovery, although the world of today owes a heavy debt to geological science in respect of its supply of mineral oil and natural gas. References to natural oil springs and seepages occur in literature long predating the Christian era, and later historical references are worldwide.

Water, particularly saline water, and oil often occur together, and the first wells that are known to have produced oil were put down in China some 2,000 years ago, as brine wells. Indeed, a characteristic of some oilfields is the presence of great masses of salt that possess a remarkable quality of internal movement beneath covering strata. Masses of salt there form great cones and force the covering bed into domes. Some of these produce structures that in oil-bearing strata are favourable to the retention of oil or gas. Each dome may be two or three miles in diameter at the top and may extend downwards to unknown depths. Several have been drilled to thousands of feet in unsuccessful attempts to find their base. A salt dome is illustrated in Fig. XIII, 1. In Burma several hundred hand-dug wells were yielding oil in the eighteenth century. In America during the initial years of the nineteenth century, oil rose with water from wells of a thousand feet or more in depth. These, like the Chinese prototypes, had been drilled for brine, but by 1920 they had yielded many barrels of oil. The first known well actually drilled by machine for oil was in America in 1859. The basis of the first drilling developments to produce oil, therefore, was purely an extrapolation from known surface sources or from accidental discoveries.

The extremely rapid increase in demand that followed the invention of the internal combustion engine, a demand accom-

panied by a comparable increase in the use of petroleum products in industry generally, has progressively led to the vast requirements of today. This increase necessitated an immediate consideration of questions of new supplies. It soon became apparent that a scientific approach to the problem was necessary. Primary considerations

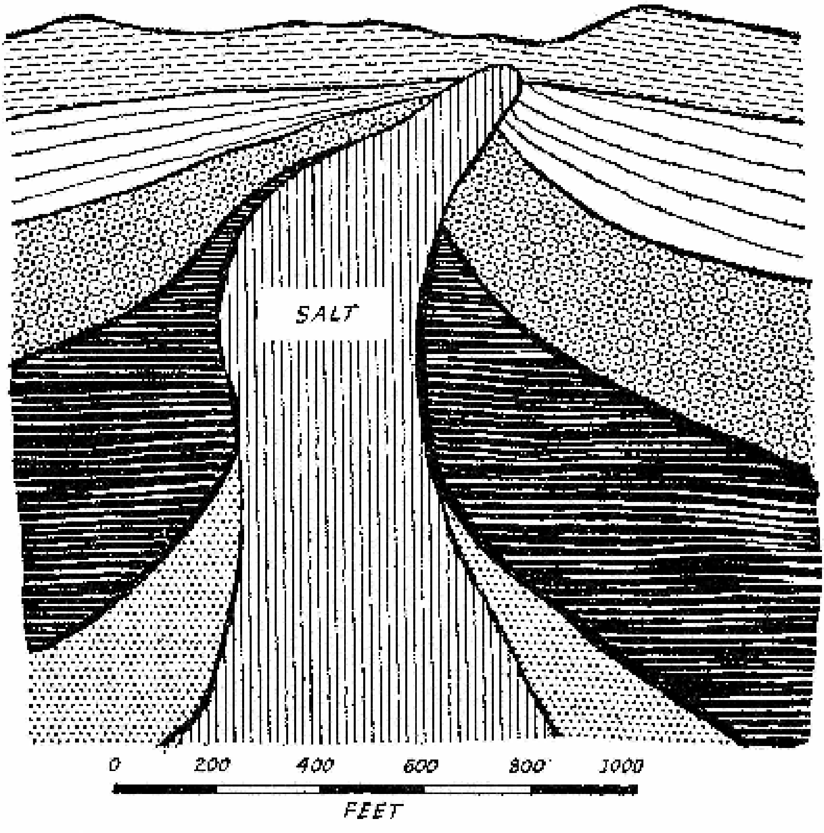


Fig. XIII, 1.—Salt domes are characteristic of various oilfields. They are often of great extent. (*Based on Emmons.*)

were, and still are, directed along two main interdependent lines, biochemical and geological; the first being concerned with the mode of origin of oil, the second with the nature and structure of strata that contain it, and of their contiguous strata.

In the early days exploratory holes were drilled for oil without geological or other substantial evidence, and were known as 'wild-cats'. Wildcatting in this sense proved quite inadequate for the job,

and has been discarded. Exploratory holes now number thousands every year, and few are made without geological or geophysical backing. But the name 'wildcat' still survives in oilfield terminology, to indicate any exploratory hole put down to discover a *new* oil pool.

The origin of oil

Information on the origin of oil has an important bearing on the search for new oilfields. For many years the problem of origin has occupied the attention of oil geologists, both in the field and in the laboratory. The subject, however, is still at the stage of theory although during the last decade ideas have tended to crystallize.

Some hypotheses of the later part of the nineteenth century hold that oil is of inorganic origin. Several of them assumed that, by some process or another, acetylene, subsequently converted into petroleum, had been formed in the crustal rocks, one view being that this gas was produced from certain unspecified deep-seated rocks at high temperature. Another theory was that petroleum is an original product formed during the period of consolidation of the earth. These views were but speculations, and are reminiscent of some other unfounded guesses of pre-geological days.

The gradual accumulation of facts concerning oil generally has led to the abandonment of these guesses in favour of other more soundly based hypotheses that ascribe an organic origin to petroleum. All organic material, whether plant or animal, is potentially able to supply the elements required to produce the hydrocarbons constituting the natural bituminous compounds—asphalt, petroleum, natural gas and the others.

Some investigators concluded that decaying plants, chiefly seaweed and swamp forest vegetation, supplied the hydrocarbons. Others have been led to regard animals as the main contributors. The suggestion was made that fishes of the past have been the main source. But it seems unlikely that fish-remains that became buried in silts and muds were ever sufficiently abundant to produce the vast supplies of oil now known to be present. There are no means of making a quantitative estimate of fish that throughout geological time have been buried in the sea bed to decompose under anaerobic conditions (and otherwise the products of decomposition would be largely water and carbon dioxide), but on general grounds it would seem to be relatively small. In the economy of the sea, small live fishes tend to become food for larger fishes, and dead fishes food for

bottom feeders of all types. Consequently body materials from dead fishes and from larger marine animals generally tend to remain in circulation, as it were.

The seas of all recognized geological periods have been inhabited by myriads of minute forms of life. The vast bulk that these animalculae assume in the aggregate in the seas of today is an indication of the bulk that they have doubtless assumed in seas throughout geological time. Presumably this bulk has been sufficient both to provide food for larger animals, and to contribute enough remains to have provided the raw material for the formation of the great volumes of oil that exist. Animalculae, on account of their minute size, are easily trapped and buried in the sand and mud of the sea bed, there to undergo anaerobic decomposition. While animalculae are thought to have made the major contribution to oil formation, it cannot be precluded that other animal and plant remains have done so in some measure. A replacement of the materials so lost to circulation in the sea occurs primarily through the photosynthetic activity of marine plants of all kinds.

Petroleum geologists today are satisfied that source rocks of oil, that is, rocks in which it originates, are all shallow-water marine sediments, and that freshwater strata seldom or never give rise to oil in commercial quantities. Accordingly oil geologists in the field search particularly for sedimentary strata that indicate for themselves a shallow-water marine origin.

ACCUMULATION OF OIL

From the above assumption, each decaying animalcula individually contributes a minute quantity of oil. These small drops must therefore gradually coalesce, and become bulked together in natural underground reservoirs, akin to those that hold underground water in quantity (p. 118). Experimental work to ascertain the way in which coalescence comes about, as in so many other problems of today, involves a combination of geology, chemistry and physics. The presence or absence of water in the rock, the relative surface tensions of water and oil, the nature of the source rocks, the possible effect on them of earth pressures and heat, are all relevant factors. The specific gravity of oil is less than that of water, and its surface tension is only about half. Open-textured sediments allow of freer movement than do close-textured. Compression of strata by earth movements, or even by weight of a gradually increasing thickness of superincumbent beds, tends to force oil out of the finer-grained rocks. Heat may cause oil to become volatilized and so to force its

way out from clays and shales into more porous strata. Oil ultimately accumulates in open-textured sandstones, fissured limestones and other strata which are marked by adequate voids.

Natural oil reservoirs

The immediate importance of geology in oil explorations is the location of geological structures in strata that might be associated with oil, and that are capable of forming natural reservoirs. Early in geological work of this kind the simplest oil trap was seen to be a dome-like anticlinal arrangement of strata in which highly porous beds were overlain by an impervious layer, usually of clay or shale. It has been found that where these dome-like structures occur, oil that may be present gradually migrates to the top of the domed porous beds, and is held there partly by water below (which is normally under hydrostatic pressure itself) and partly by the retaining impervious bed above. Consequently when the top of a dome is penetrated by a borehole, oil may be forced up by the artesian head exerted by water below. Trapped oil is often accompanied by gas under compression. On release of pressure by the borehole this expands, and also assists in forcing oil to the surface. Diagrams of two simple oil-trap structures are shown in Fig. XIII, 2, but in nature there are many other types. All traps have the common factor that they must possess a retentive roof to imprison the oil, and they are usually referred to as 'closures'.

In those oilfields where salt domes are present the salt possesses a remarkable quality of internal movement beneath covering strata. The great masses of salt possess the faculty of forcing the covering beds upwards (Fig. XIII, 1). Some of these produce structures that in oil-bearing strata are favourable to the retention of oil or gas. In some oilfields salt domes are very numerous; each dome may be of two or three miles in diameter at the top and may extend downwards to unknown depths. Several have been drilled thousands of feet in unsuccessful attempts to find their base.

The detection of closures

The above principles were established in the latter part of the last century. That period, and the beginning of the present century, then saw the dispersal of large numbers of geologists over the most likely (which often included some of the wildest) parts of the earth's surface. Their work was to discover by examination of the surface rocks sites where geological structures likely to produce oil traps

would be present at depth; in other words, to find oilfields. Deep boreholes were put down on their advice but they had little to do with development.

The work of an oilfield geologist has changed greatly from its

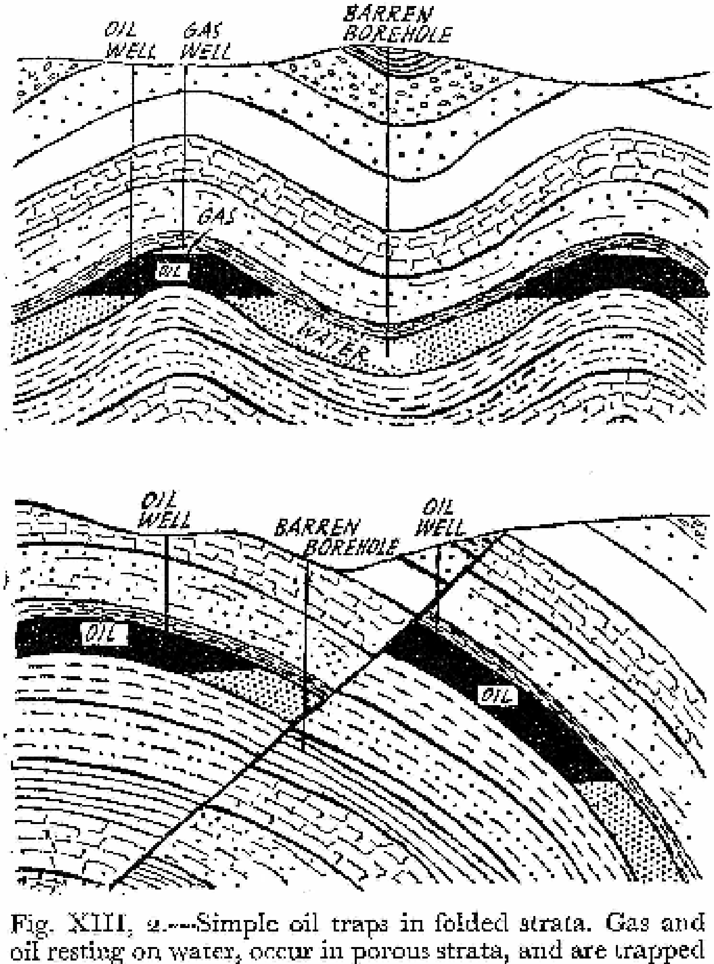


Fig. XIII, 2.—Simple oil traps in folded strata. Gas and oil resting on water, occur in porous strata, and are trapped by overlying impermeable strata. (*After Uren.*)

purely exploratory nature of forty years ago. Probably more geologists are now engaged on the problems that arise in the productive oilfields than on purely exploratory work. The geologist is now called on to estimate the amount of oil recoverable from the oil-bearing beds. He determines the location of new wells, their spacing in the

oilfield, their depth and the appropriate rates of production from each well. His duties further include the preparation of drilling programmes in order to maintain production of an oilfield to meet requirements. Close association with developmental work has led to some degree of specialization and there are sub-surface geologists, development geologists, petroleum technologists and others. But all are essentially geologists.

Microfossils and borehole records

In the oil industry in particular, the economic importance of a detailed record of strata as proved in a borehole is fully recognized, whether the hole is successful or not. On general geological principles it would be expected that from the information yielded by a large number of boreholes a body of fossil evidence would be built up that would lead to the establishment of a number of recognizable fossil horizons and that this evidence, combined with descriptions of the rocks, assembled in graphic section form, would throw light on geological structure. Such has been the case. In many productive rocks, however, large fossils are rare and in any event the number of large fossils to be found in borehole cores often would not provide sufficient material for the purpose. Further, except in special circumstances, most oil boreholes are made by a rotary grinding method (*see* p. 107), core boring being very costly. Material taken from them is brought up in the form of small chips or even as mud. Thus, no large fossils normally become available.

Many of the microscopic animalculae that are thought to have contributed to the supply of oil possessed hard though very delicate shells which have been preserved as fossils. In many strata these occur in vast numbers and are of numerous genera and species. Equally with larger fossils they may provide fossil indexes by which the strata can be recognized from locality to locality. The shells of these micro-organisms are so small that, though fragile, many survive without damage by rock-cutting or grinding by the drill, even in small chips of rock. Micropalaeontology is an important aid in correlating the strata recorded in an exploratory well with beds that come to the surface some distance away, in relating one outcrop of rocks with another, and in correlating beds of one oilfield with those of another. Today its use is being extended into other branches of pure and applied geology. The micropalaeontologist's technique necessitates the constant use of a microscope and the development of processes for extraction of the most delicate and minute fossils from their matrices.

GEOLOGICAL MAPPING AND GEOPHYSICAL EXPLORATION

If the hypothesis be accepted that oil is derived from decaying organic matter, and that it can migrate from one set of strata to gather in another, there would seem to be no reason why oil should not occur, other circumstances being favourable, in any sedimentary stratum, whatever its age. Such is the case. Oil is now known to occur in quantity in beds of all periods from Silurian to Tertiary, and some is known in Cambrian and Ordovician strata. The tracts of the earth's surface to be covered in the search for oil are very large. As part of the process of discovery, a programme of geological mapping is undertaken, but this takes a long time. In oilfield work it falls into three phases. First, in an unexplored region, reconnaissance work on small-scale maps of several miles to an inch (or other equivalent) is carried out over a large tract of country. This is to get general information on the succession of strata, and on the general geological structure, and to discover potential reservoir structures in rocks that are at least not of unsuitable types. Some of these structures are then mapped on a large scale (of six inches or eight inches to a mile) to determine a position for a test well. Then, if an oilfield is found, re-mapping in extreme detail, on a scale of as great as twenty-four inches to the mile, is done.

But in the natural build-up of the crustal strata with their present arrangement, structures that are capable of acting as oil reservoirs may be completely concealed beneath a covering of alluvium or by newer, non-oil-bearing, strata. As is the case with completely concealed coalfields, surface geological mapping is then of no avail.

As oilfield technology has stimulated the growth of micro-palaeontology, so has it encouraged the development of geophysical exploration. Today teams of geophysicists and their apparatus are often transported by helicopter to otherwise almost inaccessible tracts of the globe. Plate IXB shows an explosion from a 100-ft. borehole, detonated for seismic work in one of these tracts. The transporting helicopter is standing near. Geophysical work of the kinds referred to in Chapter VI has been widely used in conjunction with geology. Data given by geophysical observations, surface geological evidence, micropalaeontology and correlation of borehole records are combined in an endeavour to determine likely geological structures, and they govern the siting today of wildcat wells. Many of these are 12,000 ft. deep, some very much deeper.

In a producing oilfield, the correlation of strata from well to well is today largely based not on actual samples of rock, but on geo-physical observations.

Electrical resistivity and other kindred properties of the various strata penetrated—beds of limestone, shale, sand, etc.—are measured and recorded throughout the length of each borehole. Thus here again physics joins with geology, to give data on the porosity and permeability of the reservoir rocks and on the nature and properties of the fluids—oil, water, gas—that they contain.

SUCCESSFUL AND UNSUCCESSFUL EXPLORATION

There is no question of the value of geological and geophysical work in oil exploration. Even so, both branches have a long way to go before it can be claimed that they are entirely satisfactory guides to new oil reserves. Every year the American Association of Petroleum Geologists publishes an analysis of the results of its exploratory drilling. Practically all drilling sites are determined on geological or geophysical evidence, or on both. Yet in 1953 wildcat drilling (in the present-day sense) had the following results: 0·4 per cent discovered oilfields likely to be worth 10 million barrels or more, or good gasfields; 1·1 per cent found small oilfields or gasfields; 12·5 per cent located oil or gas, but not in quantities likely to be remunerative; and 86 per cent found nothing. Figures for the two earlier years show that 1 per cent found large oil or gasfields, 2·6 per cent small ones, 10·4 per cent unremunerative ones, and 86 per cent found nothing.

Estimated figures of success of wildcat drilling in Canada are: 2 per cent found remunerative oil; 2 per cent remunerative gas, 13 per cent found oil or gas in unremunerative or barely remunerative amounts and 83 per cent found nothing. The ratio of success to failure in Burma, India, Pakistan and Great Britain is of about the same order. It is, however, much higher in parts of the Middle East, which, in relation to oil, have been specially favoured by nature.

Thus at the present time in most parts of the world and including Great Britain, the chance of getting a profitable return from an exploratory well (not to be confused with a production well in a known oilfield) is about 1 in 20. Retention of the term 'wildcat' seems fully justified!

Failures of exploratory wells arise from numerous causes. Some of these are explicable after drilling; the structures of the concealed strata at depth, from which oil had been expected, proved to be more complex than had been anticipated, or beds have proved to be non-porous, where porous beds had been looked for. But more frequently the almost infinite variation of geological pattern from place to place

gives no real clue as to the reason of failure; through some unknown episode in the geological history of an area, oil had been prevented from entering into, or from remaining in, an apparently favourable structure; strata that on available geological evidence ought to have been source rocks were not source rocks, as a result of some undetected adverse geological factor; and so on.

Natural gas

Whatever the origin of oil may be, it is the same for natural gas. Where oil is, there also is gas in greater or lesser degree. But it does not follow that gas is accompanied by oil. Except for the fact that if given the opportunity gas escapes from a trap more easily than oil owing to its powers of diffusion, it may be considered as but a variant of oil. The same conditions of natural storage apply. A 'closure' with a gas-tight cover must be available.

Gas reserves in some of the larger oilfields are enormous. An estimate of the reserves of the United States of America alone is some 200 million million cubic feet. The Pyrenees area holds a supply sufficient to last a large area of south-western France for at least another forty years or so.

Oil shales

There are many close-textured shales that yield oil and other substances although they do not hold them in a free state. Some of these compacted muds and clays appear to contain a high proportion of organic material which has not gone through the whole process of transformation into oil but does so on appropriate treatment, usually by heat. Some shales may be evidence of former oil-bearing conditions; the oil they contain may be vestiges of the large reservoirs of the past, from which oil has been lost through erosion of the closure.

Oil shales have been worked extensively in Scotland since about 1847 and they have furnished a basis for the geological study of similar deposits throughout the world. Geological prospecting has located many oil shales in various countries, the estimated potential yield from which is immense.

Oil and natural Gas in Great Britain

The results of geological research of the past century in Great Britain show both favourable and unfavourable features as regards the potentialities of oil and natural gas reserves. The following points are favourable: many of the strata were laid down in seas that were populated by prolific animal life, and therefore (assuming the

modern hypotheses as regards the origin of oil to be correct) there has been ample source material; some thick formations are sandstones, others limestones, both of which may act as reservoir rocks; from time to time these strata have been folded by earth movement, so that the presence of a number of closures is a strong likelihood.

Among the unfavourable points is the complex structure to which the chequered geological history of this country has given rise. Many folds giving closures that were produced by one series of earth movements have been eroded, and their closures broken by subsequent periods of erosion and of movements. Some of these folds doubtless held oil at one period, but it escaped geological ages ago. There is also no doubt that actual closures still exist, though as is common elsewhere, few contain oil. Two oil-bearing closures, however, at Eakring and Plungar in Nottinghamshire, have provided oilfields. During the 1939–45 war, sufficient oil was obtained from it to represent what was broadly the equivalent of the quantity carried by one tanker in continuous operation. The present annual output (1955) of oil produced in Britain is about 15 million gallons. Though valuable, this is small indeed when compared with an annual British consumption of some 9,000 million gallons.

Most closures that are likely to occur in this country, however, are small when compared with those of some of the continental areas of the world. The occurrence of large oil reservoirs here is not to be expected.

As regards natural gas, many years ago a gas pocket was struck accidentally in a drilling for water at Heathfield railway station, Sussex. This supply, of very small dimensions, still persists. For some years it was used to light the station. A number of other boreholes were sunk in the vicinity, but struck no gas.

Rather more favourable conditions are perhaps to be expected in parts of Scotland.

All views that are expressed on such geological observations as are possible on deep-seated structures are, and can only be, interpretation; they are not proved facts. Otherwise the world-wide chances of finding oil or gas in experimental boreholes would be much greater than the existing 1 in 20. Even if some gas accumulations do exist in commercial quantities in Britain, the chances of finding them by drilling are small. On this account it is unfortunate that exploratory drilling for gas is liable to be misinterpreted, and it is regrettable that an impression that the prospects of finding useful accumulations are much better than they really are, tends to be fostered by various purveyors of news items to the general public.

CHAPTER XIV

Geology and Agriculture

WHILE soil as understood by the civil engineer (p. 158) is any unconsolidated rock-material that may occur at any depth beneath the ground surface, the soil of agriculture is spread over the ground surface as a thin mantle. At the most this is but a few feet thick. It is a mixture of unconsolidated mineral particles of various kinds derived from weathered rocks, decaying organic material (humus), air and water. It is populated by myriads of insects and the like and by immense numbers of bacteria, and it supports vegetation.

During the last half century the study of soils has developed its own science, often referred to as Pedology. This has trended towards dichotomy, one branch geological, the other biological and chemical; but both branches have concerned themselves with the physics of water-movement through soils.

This dichotomy is perhaps a natural development. Whilst many factors of soil growth are obviously of direct geological concern, the teeming microscopic life of soil is biological. Further, the objective of the farmer and horticulturist is to grow plants, and their primary interest in the soil lies in its ability to produce the plants they require. Consequently a first place in their outlook is occupied by the relationship of soil to plant nutrition, with its emphasis on manures of various kinds, on climatic conditions, and other non-geological matters.

The importance of the biological and of the air-water fractions of soil is brought out on comparing present-day soils with certain soils that have been preserved from past geological ages. But ancient soils are not common; which is to be expected on the general principle that all land continually suffers from erosion. Very rarely in certain geological formations, however, former soils have been preserved

through sudden invasions of the sea over low-lying land of the period. A particularly good example occurs in the Isle of Portland, where a bed that was once a soil has been preserved in the Purbeck Beds together with many forest trees that grew on it, and are now fossilized. The material of this bed, known as the Dirt Bed, is now closely compacted and it is sterile. It contains the mineral particles of the original soil as it existed during Purbeck times but it is devoid of humus and of microscopic life. It is no longer a soil in the accepted sense of the word.

Climate and soils

The mineral content of soils is modified by chemical reactions that occur between some of its constituents and by removal of others in solution by percolating waters. Both these processes are largely influenced by climate. Some soil scientists concluded that in soil formation climatic factors have a dominating influence over all others. The view has been held that the six main world climates—tropical, hot, warm temperate, temperate, cool temperate and cold, combined with variations from humid to arid, have between them produced a number of world soil-types. As a corollary, it has followed that under extreme climatic conditions of both heat and cold the nature of the rocks that provide the soil minerals may be a quite secondary factor. But in many parts of the world, particularly in the productive temperate zones, it has also long been apparent that geological factors as well as climatic are of first importance, especially in areas of varied agriculture such as Great Britain. Soil science being a relatively new study, its conclusions, as with all new developing sciences, undergo constant change. In soil science today there is a strong tendency for geological factors to be rated progressively more and more highly. Some of the points on which geology has contributed to it are indicated in the following paragraphs.

Soils and parent rocks

Rocks of geological formations, whether 'solid' or 'drift' that give rise to the mineral particles of soils, are referred to as 'parent' rocks. Were there no transport of weathered material, the composition of the surface soil would obviously reflect very closely that of the parent material; that is, of the geological formation on which the soil rests. Many soils that hitherto have been unmoved or but little moved from their source of origin actually do so. At the other extreme, a soil material that may have been blown long distances by wind may

bear no relationship whatever to the rock bed on which it rests. There is every gradation between these two extremes.

The grain sizes of the mineral particles of soil, varying from clay grades through silts to sand, are partly those of the constituents of the disrupted parent material, and partly the direct result of weathering processes that break down some of these constituents. The relative amounts of water and air in soil, which perhaps rank equally in importance with mineral composition, both depend largely on the porosity of the underlying rock and the depth from ground surface to the water-table. Upon these geological factors rest the fundamentally important matters of drainage and aeration of soils.

Land drainage

Apart from its place in modern research on soils, geology perhaps makes closest contact with agriculture in the matter of land drainage. Among the relevant matters concerning drainage comes the nature of the soil and of the underlying rock, the geological structure of the locality, and the topography of the area. Many soils that rest on permeable strata and lie above the water-table are naturally well-drained, and the agriculturalist needs no assistance in determining their whereabouts. It is areas of impeded drainage that require study. Except in valley bottoms, poor drainage is often connected with the strata that lie below the soil.

Many drainage problems affect very small areas; often they are pertinent to single fields, in which springs and seepage lines are common sources of trouble. These cannot be dealt with adequately unless the direction underground of flow of water towards them is determined, and this in turn depends on the nature of the beds concerned, and their local arrangement. Problems of this kind are common in sand and sandstone areas, particularly where the strata include intercalated beds of clay. Even clay beds but a few inches thick are sufficient to cause trouble. A thick sand bed overlying a thick clay produces its own drainage problems, as do numerous other geological factors.

The southern face of Leith Hill in Surrey (the highest point in south-eastern England) is composed of sands and sandstones in the upper part and clay in the lower. Rainfall that falls on the sands percolates downwards, to be thrown out at a seepage line at or a little above the sand-clay junction. This seepage is traceable for long distances. But the arrangement of strata is conducive to landslips, and much of the slope of Leith Hill is mantled by a slipped mass of sand and sandstone, extending well below the level of the

sand-clay junction. Water that is thrown out at that level creeps over the concealed clay surface. It breaks out through the slipped masses at any spot it is able to, and it accelerates slipping and soil-creep (*see* p. 230).

Drainage, to be effective in conditions of this kind, needs to be tackled at the real sources of the springs or seepages.

Springs, however, are special though relatively common cases. The chief function of land drainage is to de-water soils that tend to retain much water over long periods to the detriment of plant growth and so to induce and increase aeration. Various drainage methods are employed. The efficacy of one method over another usually depends on the nature of the material that lies at a depth of two or three feet below surface.

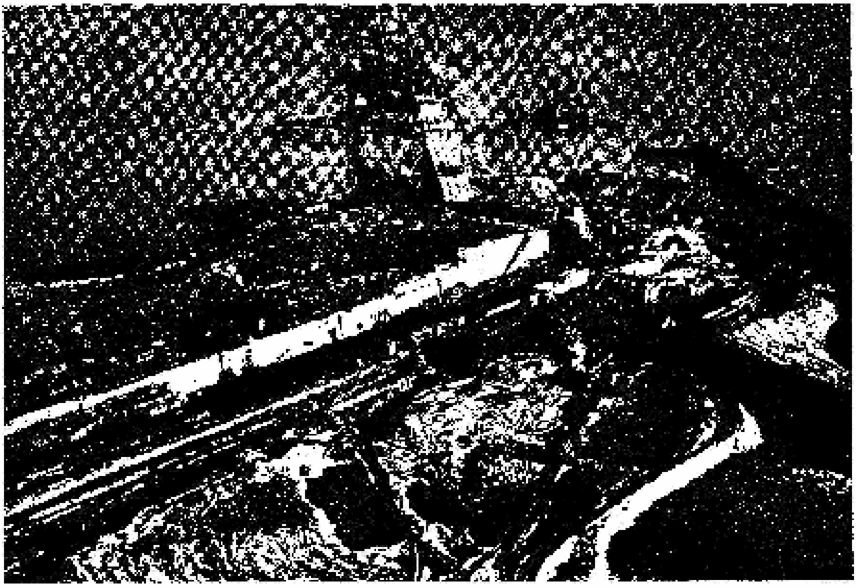
Mole and tile drainage

A common form is mole drainage. A 'mole' is a steel cylinder about 2 ft. long, and some 4 in. in diameter, and with a pointed end. Today this is dragged through the ground at a depth of about 2 to 3 ft. by steam engine or, more commonly now, by tractor. It thereby produces a pipe-like channel, the walls of which are but the country material that has been compacted by the mole. Mole drainage also disrupts the couple of feet or so of soil above the channel level and increases the permeability.

This type of drainage is most effective in homogeneous clayey soils, in which it will remain operative for many years. It depends for its success on an uninterrupted compaction of the walls. A large stone in the path of the mole breaks the continuity of the compacted clay. As it is pushed out of the way it disrupts the channel side, which then collapses: the channel becomes blocked, and drainage ineffective. Mole drainage, therefore, tends to be unsatisfactory in many boulder clays which contain numerous stones, and in strata that are mainly clay, but in which thin beds of limestone or sandstone occur.

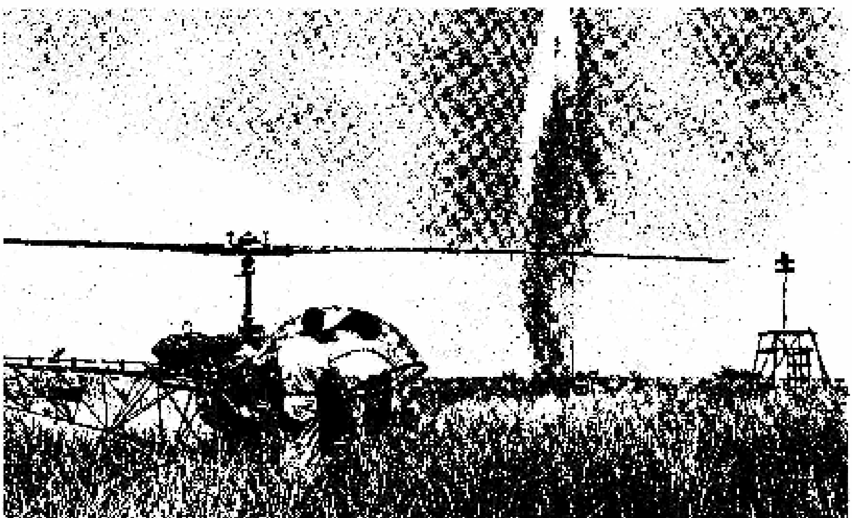
Some parts of the outcrops of the Weald Clay, the Kimmeridge Clay, the Oxford Clay and the Lias are entirely suitable for mole drainage, but other parts, well delimited by geological investigations, are not satisfactory on account of thin beds of stone or of silt.

Sandy soils obviously do not require draining, but silts do. These again, however, are normally unsuited to mole drainage. Deficiency of clay in their composition leads to an absence of binding capacity, and mole channels quickly collapse. Where mole drainage has been carried out in land composed of alternations of clay and



British Transport Commission

A. Aerial view of King George V Dock at Southampton during construction



Shell Mex

B. Geophysical work on Marsh Island, off New Iberia. Mud and water are erupted from a borehole as a shot for seismic work is detonated. Transport is by helicopter

PLATE X

Nottingham Corporation

A fissure produced by subsidence of the ground surface following coal mining

silt, often the last state has been worse than the first. Those sections of the channels through clay land have tended to remain open, those in the silts to collapse. In consequence a series of blocked drains has resulted. Excess rainfall, instead of being led off, as had been intended, or of remaining dispersed over undrained land as it did before moling, first accumulated in pockets underground, and then, under gathering pressure, erupted in considerable volume at various points over the ground surface.

In these soils, drainage channels need support. Burnt clay tubes or 'tiles' are commonly placed in trenches dug for the purpose, which are subsequently filled in. Even tiles, however, are ineffective in many fine-grained silts. These are notoriously difficult of treatment, but in some instances success has been obtained by digging trenches and filling them with brushwood, clinkers or other materials.

In the nature of things farmers from time immemorial learnt the general nature of the soils of their fields, and the past centuries have seen much drainage work carried out without geological assistance. But drainage is a continuing activity, and the detailed grasp of both hydrogeological principles and of local geology that is now possessed has greatly facilitated land-drainage work in hitherto difficult cases, and in recent times has brought into use many areas that previously had been regarded as intractable.

Agricultural water supplies

Land drainage introduces a converse idea, that of water supply. The intensive methods of modern farming, both arable and dairy, demand supplies of water far in excess of those required even half a century ago. In so far as the provisions of these extra supplies is a geological matter, it may be said that geology also enters into this aspect of agriculture. But it does so only secondarily. In the final event water supply, for whomever it is procured, lies within the province of the water engineer, as outlined in Chapter VIII.

Geological maps and soil maps

In the early days of geological science one of the benefits expected from the geological map was that it would be of great assistance to agriculture. This anticipation has been fulfilled, but not as directly as perhaps it was then thought. That maps to show in detail distribution of soils must possess a high value in soil science will be apparent, but this is a matter that is normally beyond the capacity of a geological map. Unfortunately lack of appreciation of this fact leads to misconceptions.

It has previously been remarked that a geological map cannot by any means show all the geological information concerning an area and that it needs to be accompanied by an explanatory memoir. Still less can it show soils which, although of primary importance to the agriculturist, are relatively unimportant as geological formations. It is exceptional for a geological map to take cognizance of any surface deposit within 18 in. or 2 ft. of the ground surface, and often still greater thicknesses are of necessity ignored. But in agriculture the top 6 in. to 9 in. is usually vital.

Soil maps are thus concerned with the upper foot or two of surface material that the geologist normally ignores. They are constructed on various criteria, and on various scales. Some cover large tracts of the earth's cultivatable surface, and are designed for generalized studies; these carry the disadvantages of generalizations. Other maps, or more correctly plans, are large-scale records often on the scale of 25 in. to 1 mile. These cover a few fields only, and are produced for guidance in cropping individual fields and farms. Although they are not geological maps, they are in part extrapolations from geological data.

Fig. XIV, 1, is a soil map, reduced from one of larger scale, of part of the grounds of the East Malling Research Station, Kent, made by Mr. B. S. Furneaux.

In modern soil surveying, soils are divided into different 'series'. Several criteria are taken into account, including the geological nature of the soil and subsoil, method of accumulation, colour, chemical reaction, natural drainage, topography, climate and soil profile (*see below*). Mostly each series is distinguished by a local place-name or field-name, and should occasion require it, a series may be sub-divided into 'phases'.

In the area of the present soil map seventeen soil series have been delimited, and of these nine have been sub-divided. These series, and their subdivisions, together with their distinguishing symbols on the map, are:

Ct	Chart Series
CtS	,, ,, shallow phase
W	Wierton Series
My	Medway Series
MyW	,, ,, poorly drained phase
Mg	Malling Series
MgS	,, ,, shallow phase
MgE	,, ,, eroded phase
Bg	Barming Series

Bg/R	Barming Series shallow phase over ragstone
Bg/S	,, ,, ,, ,, ,, Sandgate Beds
Bg/F	,, ,, ,, ,, ,, Folkestone Beds
D	Ditton Series
Ly	Langley Series
Ly/S	,, ,, shallow phase over Sandgate Beds
Ly/F	,, ,, ,, ,, ,, Folkstone Beds
Bs	Brices Series
R	Roseacre Series
SH	Stone Hill Series
H	Highworth Series gravelly phase
Sn	Sevington Series
SnG	,, ,, gravelly phase
Bd	Bearsted Series
BdS	,, ,, shallow phase
BdG	,, ,, gravelly phase
BdSG	,, ,, shallow gravelly phase
Ls	Lowlands Series
LsG	,, ,, gravelly phase
Be	Bradbourne Series
Bef	,, ,, improved drainage phase
Ml	Millhall Series
T	Twisden Series

'Made land', that is, land on which a considerable dump of material has been put, is not classified, and is shown by the symbol Uc.

For purposes of comparison, a geological sketch map of the same area is given on Fig. XIV, 2.

It will have been noted that among soil-surveying criteria comes natural drainage, already described as being largely a function of the geological strata beneath the soils as shown on the soil map. Roots of many plants, not only forest trees and fruit trees, but such plants as mangolds and swedes, may, under suitable conditions, penetrate many feet into the ground. In order to make a proper appreciation of soil conditions, therefore, it is often necessary first to make a soil map, and to read it in conjunction with a geological map; the two are complementary. Many of the 'phases' do in fact take this into account, instanced by three phases of the Barming series.

There are various matters in which, while it cannot be claimed that geology makes any direct contribution to the economics of agriculture, yet in which it shares a mutual interest with soil science. These may be instanced by the scientific description of soils as they occur in nature, and the processes of soil creep and soil erosion.

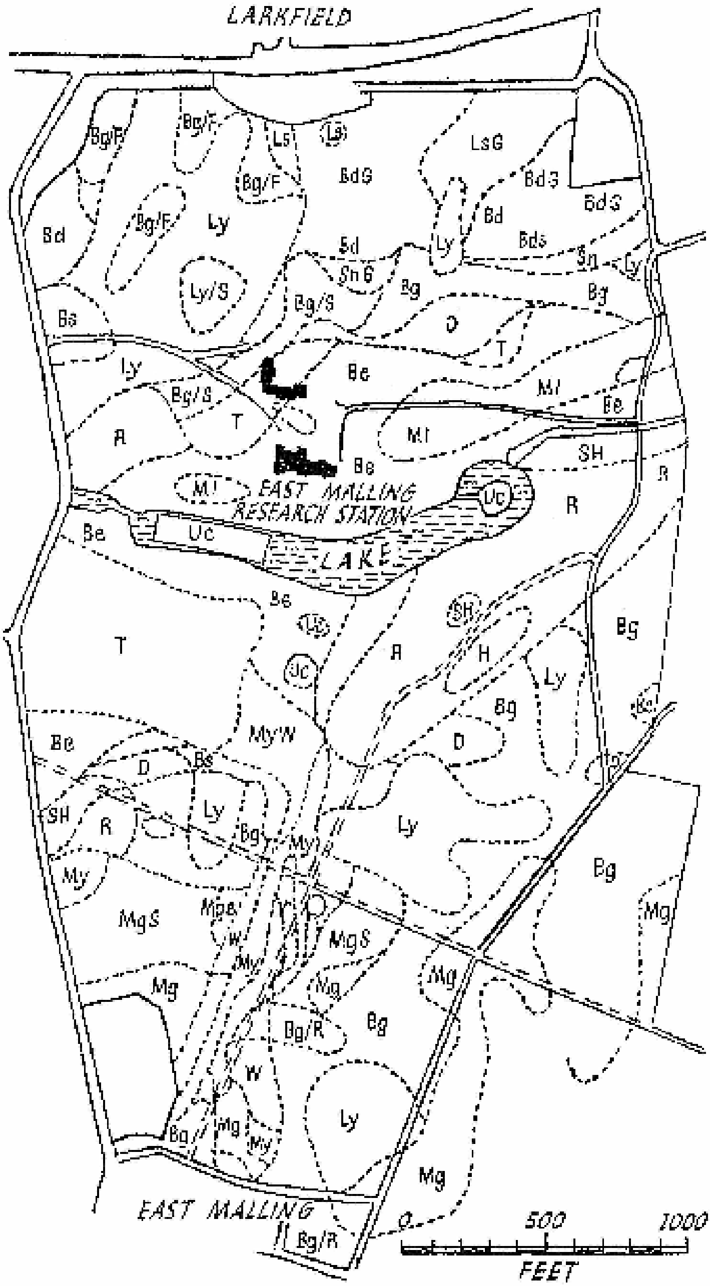


Fig. XIV, 1.—Seventeen soil series have been determined in the part of the lands of the East Malling Research Station, Kent, shown above. (*Compare Fig. XIV, 2.*)

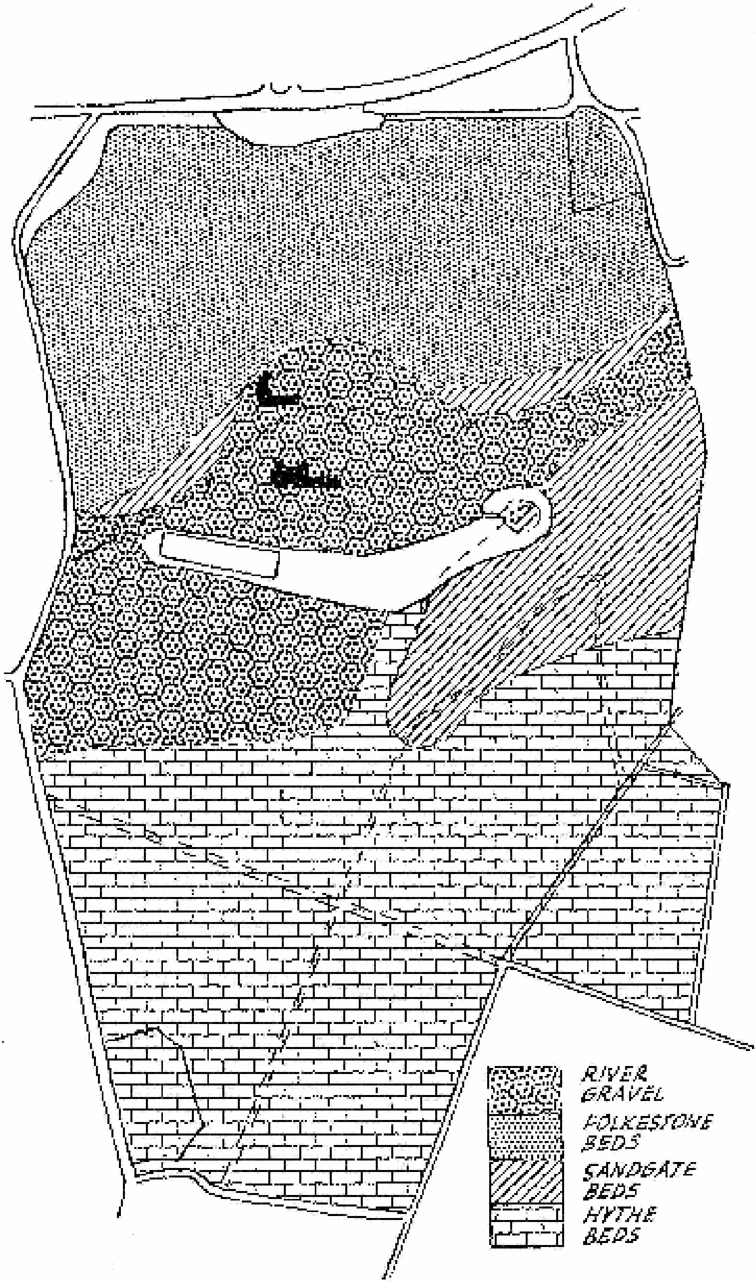


Fig. XIV, 2.—Geological map of the area of East Malling Research Station shown in Fig. XIV, 1.

THE SOIL PROFILE

The mineral components of all soils consist of weathered rock-material, but the average soil itself consists of several distinct layers. In most soils in temperate regions these are readily separable into three, the A, B, and C layers.

The A layer is at the ground surface. Apart from any effect vegetation may have on it, it is constantly losing both its very fine-grained material and its soluble constituents which are dissolved by percolating rainfall. These are all carried downwards by rainfall, the first group in suspension, the second in solution. The A zone, therefore, is one of constant depletion. This often results in some apparently curious paradoxes. Many soils on chalk and other limestones, for example, are, in their natural state, deficient in lime.

But the transporting power of percolating rainfall is soon lost in friction, and at a shallow depth beneath the surface, generally a matter of 9 in. to 18 in., an accumulation of the finer particles removed from the A layer takes place. This B layer is therefore denser than the A layer, and is generally more highly coloured. It holds up water, to a greater or lesser degree, and is constantly being enriched by salts, as well as by clay and silt particles, brought down from the A layer.

The C layer consists of partly weathered parent rock.

A record of a vertical section of these layers (which are themselves often separable into subordinate layers) constitutes a soil profile, as illustrated in Plate XIA, and Fig. XIV, 3. To this is sometimes added a D layer. This is unweathered rock, and strictly therefore it is not part of the soil according to definition.

SOIL EROSION AND SOIL CREEP

The discrete mineral particles of the soil, lying loose, or loosely packed, on the surface, are all destined ultimately for transportation to the sea. However slowly these particles may travel, it is in the interests of mankind to prevent their removal as much as possible. Movement is not necessarily slow, a fact that has been brought much to the fore in recent years by instances of soil erosion on a vast scale in various parts of the world. The occurrence of soil erosion in Great Britain, though less spectacular than it has been elsewhere, is frequently demonstrated by the turbidity of rivers in flood, caused by loads of mud, silt and sand. These are soil that is being carried away.

Part of the process of transportation is a gradual movement downhill of soil over the ground surface. This occurs naturally under

the influence of gravity, and is known as 'soil-creep'. Its effect is commonly to be seen at the top of a quarry face, as shown in Fig. XIV, 4, and is beautifully exhibited at the tops of some of the cliffs of the Cornish coast. Movement of this type is accelerated by the cul-

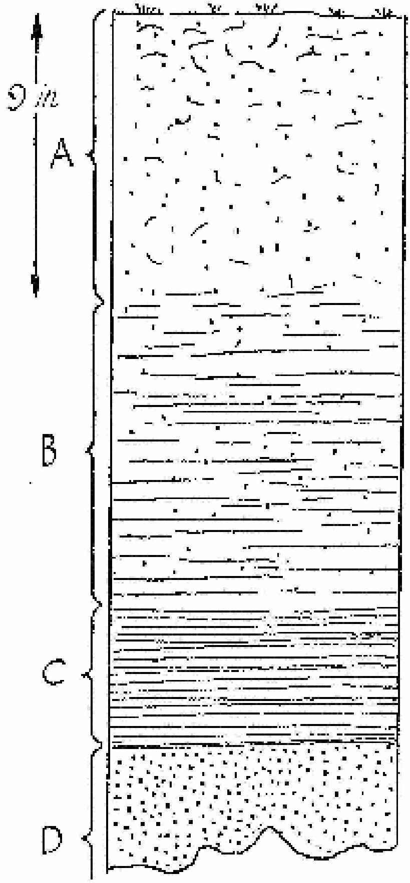


Fig. XIV, 3.—A soil profile. 'A', 'B' and 'C' layers comprise a normal agricultural soil.

tivation of sloping surfaces, where it results in the formation of 'lynchets' at hedge boundaries at the bottom of slopes. In two adjacent arable fields the ground level on one side of a hedge may be several feet higher than on the other. A notable example of lynchet formation was demonstrated recently by road-widening operations

near Charing in Kent. These exposed a lynchet in cross-section, and showed that during long-continued cultivation, soil material had been built up to a thickness of more than 9 ft. on the upper side of a hedge line. Thickness gradually tailed off up the slope and at the top end of the field true soil was but an inch or two thick. Rock from the underlying 'solid' was there turned up by the plough. Soil was equally thin on the lower side of this hedge.

A special case of soil erosion characterizes the Fenland area of

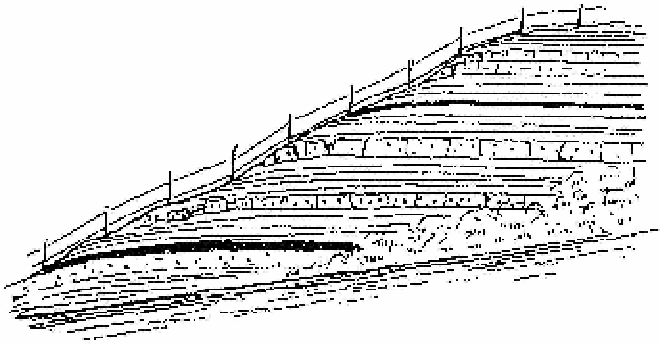


Fig. XIV, 4.—'Soil creep' or slow movement under gravity of soil and subsoil down a hillside as shown in a road-cutting in Sussex.

Britain today. Cultivation of peat beds there present has led to their shrinkage and desiccation. During periods when crops are off the ground wind blows vast quantities of soil into the water drains, to be carried away to rivers, and thence to the sea. In some areas the surface is today some 18 ft. lower than it stood a century ago, and over others the fertile soil has largely disappeared, leaving a surface of heavy, intractable clay.

CHAPTER XV

Planning, Mining Subsidences, and Other Matters

PREVIOUS chapters have been concerned with some of the more apparent uses of geological science. From time to time geology lies behind the scenes, as it were, in rather unexpected places, and the present chapter indicates some of the less obvious, but still important, ways in which it enters into our lives.

PLANNING

Geological information is a fundamental necessity to planning of the kind as commonly understood in Great Britain today, which implies the regulation by local authorities of various activities under the authority of the Town and Country Planning Acts of 1947 and 1954.

One aspect of planning of this kind, and perhaps one of the most difficult of its tasks, is regulation of new excavation sites for minerals, again using the word 'mineral' in the wide commercial sense defined on p. 33. New workings, especially surface workings of the large-scale type essential to present-day economy, are normally and understandably displeasing to some persons or others. Planning authorities are required to strike a just balance between divers conflicting interests.

Planning in a general sense has ever been an essential feature of business organization. As far as mineral development is concerned it has always been incumbent on the producer to satisfy himself among other things that there are adequate reserves of material of the right chemical and physical properties for his purposes to justify

a proposed capital outlay; that the thickness of any overburden that may be present is not so great as to render working at a site uneconomic.

The planning authority must of necessity be acquainted with these things and, in addition, with information on the geographical distribution over a very wide area of the sources of minerals proposed for working, and their relationship to centres of demand; The weight to be given to the geological data in each planning episode obviously depends on circumstances. In some instances geological factors weigh heavily, in others they are of little importance.

For example, were a proposal made to establish a new brickworks in a residential district it seems likely that today planning authorities would forbid it. Brick clays extend over wide stretches of the country, and it would be pointed out that there were many other less controversial sites available. Yet even in connexion with brickworks the matter is not entirely simple, as indicated by the following quotation from *The Times* of May 4th, 1955, relating to a proposal to work clay at Woburn Sands, Buckinghamshire: 'The Minister recognizes that the prospect of extended clay working and of the development of a large modern brickworks is unwelcome to residents in the area, and agrees that in general extension of large-scale industry in an area of that character would be undesirable. "There is still, however, a need for expanding and re-equipping the brick industry, and, although the Oxford clay deposits are of widespread occurrence, sites suitable for working are limited to those consisting of clay of suitable quality and of sufficient depth without excessive overburden and close to transport facilities." '

A different approach would be likely in connexion with some economically valuable deposit that may be known to occur only over small areas. The remarkable deposit of the special type of clay known as fuller's earth, which has many industrial uses, is one of this type. It was known to the Romans as *terra fullonica* (a term perhaps legitimately though broadly interpreted as 'laundry earth'), to whom its cleansing and degreasing properties were well understood. (It has been claimed that the village of Bletchingley, Surrey, which lies near an outcrop of fuller's earth, signifies the bleaching or cleaning place; but this place-name derivation, though attractive, is perhaps too facile to be convincing, especially as 'bletch', 'blech' and 'blach', all forms of the same word, appear in other place-names quite unconnected with the fuller's earth deposits.) In Britain the distribution of fuller's earth, as determined by geological investigations, occurs over

narrow belts and in limited quantity in Surrey, Bedfordshire and Somerset; indeed, until the end of the last century the English deposits of fuller's earth were almost the only ones known in the world, but prospecting based on data acquired from the examination of English deposits and their associated strata, has disclosed new sources both in Europe and in America. If it were to be proposed that a new excavation should be opened for fuller's earth, the site would of necessity be located in one of these restricted areas, in which case amenities and other factors would lie in the balance perhaps rather lightly against the economic one of production. These are two simple examples. Normal planning problems are more complex, in which numerous factors, including the geological, have to be balanced against each other. Between the limits set by these two examples, in fact, there lies an infinity of variation.

The point at issue is that to planning of this kind adequate geological information is essential. Its importance is recognized in Government circles; the Ministry of Housing and Local Government maintains a staff of scientific officers expressly to gather and assimilate evidence relevant to the many planning problems that arise. But much research work relative to planning yet needs to be done in the wide field of economic geology.

Geology may or may not be concerned in the selection of the sites of the planned new towns now growing in Britain. For the most part it would seem to have little influence except in so far as it is responsible for our general knowledge that almost the whole of the wide tract that contains these new towns offers suitable conditions for building. It does assist, however, in avoiding pitfalls of certain kinds. For reasons given immediately below, it would be manifestly unwise to place a new town over an area known to be salt-bearing, or over a coal area either riddled with old mines or where coal was known to occur and would be likely to be worked. Certainly each new town must be provided with an adequate water supply. Yet it is not necessary for the source of water to be near at hand. When for various reasons a site becomes desirable for human habitation, the absence of an immediately local supply is no deterrent to its use.

At every new town site some civil engineering problems of geological import arise in the normal course of events, but these are matters of detail, and have no bearing on the main point of primary siting. Such items as the lay-out of roads, the location of factory areas, and the design of foundations for heavy buildings, are often governed by local geological factors.

MINING SUBSIDENCE

It is a general principle that if rock material in great quantity is taken from below the surface of the earth's crust, the ground above will ultimately sink into the gap; that is a physical effect that often cannot be avoided. Within limits, however, it can be controlled or its probable local effects anticipated.

The thickness of the excavated bed and the nature and thickness of the strata that overlie it all combine to influence both type and rate of subsidence. In a narrow mine little or no sinking is likely where there is a sufficiency of hard rock immediately above the void to hold up the strata above it, whatever their nature may be. In these instances old mines remain as caverns comparable with the natural caverns such as occur in many limestone formations. The old chalk mines referred to on p. 144 and many abandoned non-ferrous ore mines are of this kind.

Subsidence is more to be expected where mines cover wide expanses. In Great Britain it occurs mainly over old coal workings, some old ironstone mines, and over old salt workings.

Coal Measures as outlined in Chapter XI consist primarily of bedded clays, sandstones and shales. Mostly these have little supporting value but in any event the method of extraction of coal leaves voids of too great area for effective bridging generally to come into play, and ultimately subsidence results. Mining engineers exert a local control by leaving pillars of unworked material under tracts where subsidence would be known to be harmful to surface features. These pillars are of sizes, shapes and spacing designed to accommodate local conditions. Churches, large houses and even villages are so protected. The Netherton Canal tunnel in Staffordshire is a specific instance. Subsidence to some 40 ft. occurred in the neighbourhood but the mined material, in this case coal, was left under the canal which for a short distance now runs on a ridge of land 40 ft. above the surrounding countryside. Had this not been done the water-carrying tunnel would have been ruined. Railways in the Midlands have been similarly protected and again, notably between Birmingham and Wolverhampton, parts of the lines stand some feet above the land alongside. Various methods of packing voids with waste material are also employed to arrest collapse.

While it may not matter in a great many districts if locally the ground surface drops a few feet relatively to sea level, in others the

economic effects are serious. Built-up areas may suffer severely through cracking of walls, fracturing of water mains, gas mains, drains, etc. Still more disturbing from a long-term view is subsidence of low-lying areas. In various parts of Britain large tracts of low-lying ground have gradually sunk either below the normal level of a neighbouring river or below sea level and have either become permanently drowned, or have had to be protected by embankments. A fissure produced by mining subsidence in Nottinghamshire is shown in Plate X.

Much research, in which geology has a place of importance, has been undertaken concerning the mechanism of subsidence, and much has therefore been learned. Such are the forces of nature, however, that if through mining there is a local tendency to subsidence, there is little that man can do to prevent it.

Subsidence over salt workings is particularly difficult to deal with. Salt, like gypsum, is an evaporite. It is a common constituent of the earth's crust in the neighbourhood of former geosynclines where inland seas have been cut off by mountain-building processes or former oceans, and have then dried up.

Worked deposits of salt in Europe are not of the order of salt domes in extent, yet they are very thick. In Great Britain, most, if not all, of the general salt-bearing areas have been located, and are known to be confined to the Permo-Triassic formations, as would be expected from geological deductions concerning the origin of these beds. They occur in Cheshire, Worcestershire, Staffordshire, Yorkshire, Durham, Lancashire, Shropshire and Somerset.

In Northwich there is a thickness of about 180 ft. of salt; five miles away at Winsford it is about 240 ft. thick, at Plumley, north-east of Northwich, there is nearly 600 ft., and in Yorkshire, near Middlesborough, a thickness of over 850 ft. has been proved. In Britain little salt is obtained by mining; mostly it is extracted as brine either as a natural solution or by pumping water into the salt beds and pumping it out after it has become saturated. Whichever method is used, however, the net result is the extraction of salt that until disturbed existed as a solid rock, and the creation of a void in the strata.

Geology makes its contribution to the salt industry, as in other mining industries, by enabling the maximum of information to be obtained through the interpretation and correlation of data given by the numerous exploratory boreholes that are put down as a matter of normal procedure. As regards subsidence, in Britain it may offer some assistance to the salt engineer in controlling the rate and direction of sinking, but these are but temporary expedients to

avoid immediate damage. The only effective long-term contribution that geology can make is the philosophical one of indicating that we cannot both retain our land undisturbed, and undermine it at the same time.

In Cheshire many acres that were green fields at the middle of the nineteenth century are already under water many feet deep; present-day areas of subsidence are shown in Fig. XV, 1. The general problem, however, was put into perspective by R. L. Sherlock in 1922, who remarked:

"The quantity of salt in Cheshire is so vast that it is likely to be some centuries before it is exhausted and the full subsidence [i.e. 600 ft. at Plumley] may never be felt. In that very distant future, however, there is a prospect of an area of some 200 square miles being reduced in altitude by an average amount of 100 ft., which would bring much of Cheshire below sea level. Even if the sea were to be kept out by embankments, the drainage water would form a large fresh-water lake parts of which might be, say, 400 ft. deep."

SOME OTHER MATTERS

Land valuation

Estimations of mineral reserves for land valuation purposes are directly dependent on geology. The recent nationalization of coal in Great Britain, for instance, has entailed compensation to former coal owners for loss of mineral rights. Determination of equitable sums follows on a geological appraisal of coal reserves both as regards a generalized estimate and as regards the tonnage reasonably to be credited to each parcel of land involved; indeed, that is the only possible satisfactory basis of negotiation. Valuations for other purposes—buying and selling, death duties, etc.—all need to take 'mineral rights' into consideration. So well known is the broad geology of Great Britain, however, that in this country little difficulty is normally experienced in arriving at reasonably satisfactory estimates.

Storage in caverns and mines

In very recent years the possibilities of storing liquids and gases in large underground caverns, either artificial or natural, and using the cavern walls as confining media, has been investigated with some success. This is a part of modern industrial development. Factors

that have to be taken very closely into consideration include geological structure, the position of a water-table if present, nature and porosity of rock, and fissured or unfissured character of the beds.

DAMAGE TO BUILDINGS BY BOMB EXPLOSIONS

Study of damage to foundations of buildings by bomb explosions

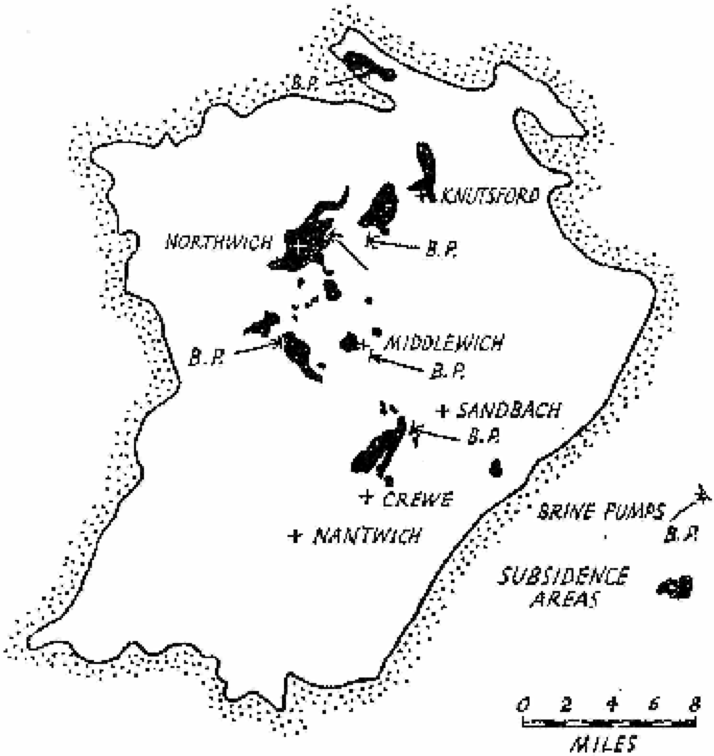


Fig. XV.—Areas of Subsidence in the salt areas of Cheshire. Land subsidence is there inseparable from the extraction of salt.

has been related to the fact that some strata are found to transmit shocks produced by explosion, others to absorb them. In one instance it is known that the explosion of an enemy bomb caused serious damage to a church four miles away, by shaking its foundations. In this case the strata were heavily charged with water, and accordingly transmitted much of the shock. The possibility of damage of this kind is fully recognized in official quarters, and the

geological structure of areas where it is proposed to explode large bombs, either for experiment or for bomb disposal, is normally determined previously to their detonation.

Disease prevention

It has been mentioned above that, regarded simply from the viewpoint of rock-getting, science would seem to be in the debt of the quarrying industry. The balance has been redressed, however, by such items as petrological work on dust from coal mines and other materials. This has played a vital part in the elucidation of the causes of lung diseases of various kinds that affect many industrial workers in the quarrying and mining industries, and has led to the discovery of preventive measures that are now enforceable by law in most countries of the world. It has reduced human suffering and loss caused by these diseases to a fraction of what it was a century ago. Insurance companies generally take advantage of this information in estimating premiums for workmen's compensation insurance cover in relation to quarrying and mining.

Utilization of volcanic heat

In recent years the possibilities of using the vast heat energy stored up in the deeper crustal layers of the earth has been investigated. Whether as a general development it will be possible to do so, and if so whether it will be economic, is a matter for the future. At certain volcanic spots, however, in New Zealand, Italy and elsewhere, where vulcanicity takes the form of geysers, steam vents and hot springs, harnessing this energy is not only possible, but is being actively carried out.

One of the most interesting cases is in Italy where at Larderello in Tuscany steam vents and hot lakes have been known for many centuries; they were mentioned by Lucretius Carus in the first century B.C. A scientific study—indeed it may justly be said a geological study—of them was made as early as 1769. Yet it is only during the immediate past and present decades that they have been utilized to any great degree. A prerequisite to this was a detailed geological appreciation of the probable cause of the generation of the steam, and of the nature and structure of the strata. This seems to indicate as the source a magma beneath rocks not older than Permian. Upon this appreciation has been based a plan of controlled boring; each borehole being in effect a new vent. The deepest is nearly 3,000 ft. deep. The uprising steam has a pressure up to 530 lb. per square in. Brought under control in these boreholes, it

P. Askew

A. The A, B and C layers of a podsol, near Canterbury. The indicating scale is one yard long

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B. A Geologists' Association field meeting of 1913

G. P. Abraham

A. Land forms of Derwentwater, produced by glacial action followed by river action. Lake Derwentwater is gradually becoming silted up

Central Office of Information

B. Raised marine platform, Reskijeage Cliffs, near Newlyn, Cornwall

provides sufficient power to drive generators that supply one-fifteenth of the whole of the electric requirements of Italy. These steam vents provide an interesting geochemical problem for the steam contains a very high percentage of boron, which has become a valuable by-product of the primarily electrical generating plant. It is an interesting, though perhaps here irrelevant, point that this very modern application of geology was rendered possible through American aid to Italy following the 1939–45 War.

As is the case of oil drilling, the Larderello developments are very largely controlled by a geological staff.

EARLY MAN

The advent of even the most primitive race of man is but a thing of yesterday in the scale of geological time. Geological interest in early man is more or less confined to the Old Stone Age or Palaeolithic races, who lived during the earlier part of the Pleistocene period; later interest then progressively moves through archaeology into history.

The study of such of early man's skeletal remains as have been found is perhaps more a matter of anthropology than of geology. In common with the bones of land mammals generally, his remains disintegrate completely in a matter of a few hundred years at the most and the chances of preservation are so extremely remote as to be almost non-existent. So rare, in fact, are fossilized human bones and so great is their corresponding anthropological and geological interest, that the notorious forged specimens known as the Piltdown Skull stimulated more than 300 scientific papers before the fraud was exposed. The geologist has been compensated for the paucity of fossil skeletal material by the preservation in Pleistocene drift deposits of vast numbers of stone tools made and used by these early men. They have a widespread appeal in the geological world, both non-professional and professional.

A progressive improvement in design and construction of stone tools from stones that are not shaped tools at all but were used in their natural shape for various purposes, to most delicately worked implements, is to be expected on *a priori* grounds. During the past three-quarters of a century many thousands of flint implements of many kinds have been collected, and such a progression in form is in fact discernible.

The application of geological principles to the examination of these implements and their natural locations led to the establishment of a number of 'cultures', and although little is known of the

physical features of the men who made them, much has been deduced concerning their habits.

At the beginning of the sequence of forms is a kind of no-man's-land. Stones (in Britain and much of Europe most flints) that may or may not have received a little artificial trimming are known to those that believe them to show human workmanship as 'Eoliths'. That there are no certain criteria by which to judge them is unavoidable from the very nature of their presumed origin.

Some of the most primitive types of implement were fabricated by shaping a pebble or block of stone by chipping pieces off it. Among these are flattish ovate hand axes, and rather more elaborate pointed hand axes. It does not follow that a crude implement is necessarily an earlier form than a well-made one. Crudity in shape and workmanship of one form compared with another may depend on the skills of the respective makers, on the purposes for which the tools were made, and on the period of manufacture. Yet, even taking these facts into account, the sequence of cultures is well established.

A revolutionary improvement in technique arose when some palaeolithic genius discovered that flakes from stones could be generally much more effective than was a core-type implement. The later palaeolithic implements therefore are of flake type. They merge into a variety of highly finished tools of both stone and bone made by Middle Stone Age, or Mesolithic, men, and from those into New Stone Age or Neolithic types.

Not only has a sequence of palaeolithic 'cultures' been established, but by correlating observations on implements, on the deposits in which they were found, and on the mutual relationship of the various deposits, it has been found that palaeolithic implements may be used as zone fossils, as it were. By their means many various implement-bearing drifts of Pleistocene age have been geologically dated, and much light has been thrown on the sequence of geological developments of the immediate past that shaped the land-forms of today.

CHAPTER XVI

Geology for the Amateur

FOR a variety of causes amateur geologists are relatively few when compared with those who are interested in other sciences. Numbers of people take up botany, others acquire close acquaintance with birds, butterflies and moths. Chemistry and physics, though perhaps rarely amateur studies, are more widely appreciated than is geology, since in many guises they make an unmistakably direct impact on us.

Geology makes no such obvious and general impression. A widespread vagueness exists as to its real import and it comes to be thought of as something of a mystery, though as one that 'must be very interesting'. Yet potentially it is more than adequate to provide an absorbing interest for the non-professional.

One of the main reasons for this general position, in Great Britain at least, and also in some other countries, is that it is decidedly rare to find geology included as a school subject, although cultural considerations would seem to require that some instruction at least should be given. The omission is to be regretted, yet it must be admitted that good reasons can be advanced against its inclusion. Two of these although of doubtful validity are that it would be one more subject to take a place in an already crowded, and perhaps overcrowded, curriculum; and that at the present time there are very few members of school staffs indeed who are competent to teach even the rudiments of the science. But neither of these objections is basic; were it to become necessary both would be overcome in a matter of a few years.

The first real difficulty lies in the very comprehensiveness of

geology. A balanced programme of teaching would require that all four of the main branches outlined in Chapter II—physical geology, historical geology, palaeontology and petrology and mineralogy—received their meed of attention. Yet instruction in these depends on previous instruction in some other subjects. Palaeontology requires biology as a preliminary, or as a subject to be taken *pari passu* with it. Petrology and mineralogy need a grounding in chemistry and physics. Historical geology and stratigraphy introduce the none-too-easily grasped subject of physical geology. All three have a specialized jargon. There remains physical geology itself. This is almost coincident with physical geography as understood in schools today and to that extent physical geology is already taught.

A second great difficulty is that geology, if it is to have any real meaning to children, must be regarded essentially as an out-of-doors subject. Schools in urban areas would find this an obstacle not easily surmounted. While rural areas would offer ample open country for study, in many the geology might be far too complex for elementary needs.

Finally it may well be that syntheses of other subjects necessary to the formal study of geology would tend to overtax the powers of juniors, and might only be suitable for those who had already reached the level of the General Certificate of Education examination as taken in Great Britain.

The above points are, of course, debatable, but if their validity be accepted it would be a justifiable conclusion that in the present circumstances geology is not a really suitable school subject, but is one that is more fittingly introduced at the university undergraduate stage. It would then follow that matters are best left as they are now, for such schools as wish to take it, and for school scientific societies to foster those who show a natural liking for the subject.

If this summary of the position, apparently defeatist from the point of view of the geologist, be accepted, the question arises as to how the average person who has not had the advantage of an early start in a school scientific society could gain sufficient background to take up some section of geology as a hobby.

A number of excellent books have been written, but many people would find them difficult to use without guidance. Further, to repeat a point made above, an outdoor approach is a *sine quâ non*. Fortunately a number of associations exist whose members have an interest either wholly or partly in geology. These provide just those facilities that are necessary. In Britain the Geologists' Association,

with headquarters in London and with branches in the provinces, is essentially amateur in its outlook and its primary object is to hold field meetings both in various parts of Britain and in countries abroad. Some of these are half-day and day trips, others last as long as a fortnight or three weeks. These field meetings are reinforced by lectures and papers given indoors. The Geologists' Association possesses a 'self-help' atmosphere in which the veriest tyro and the trained professional go arm-in-arm, as it were. It has been responsible for introducing many hundreds to geology who have later become enthusiastic followers of the subject. Plate XIB is an interesting photograph of a G.A. field meeting of 1913. There are many other societies that arrange geological field meetings and lectures, such as the Liverpool Geological Society, the Yorkshire Geological Society, the Woolhope Field Club, the Bristol Naturalists' Society, the Cotteswold Naturalists' Field Club, the Dorset Natural History and Archaeological Society. In all cases subscriptions are very modest.

Many museums both in London and the provinces possess geological exhibits, but for the most part they tend to be unsuited to an introductory use. People living in London, however, have the advantage of the Geological Museum at South Kensington referred to above (p. 95), where numerous exhibits are on view with the express object of creating initial interest. Most museums are in a position to put anyone interested in touch with one or another of the various societies. The wide scope of geology however impels many of its adherents, amateur and professional alike, to specialize in one branch or another. Accordingly a brief analysis of the potentialities of the several sections, in so far as they may appeal to the amateur, is given here.

GEOMORPHOLOGY: THE STUDY OF LAND-FORMS

Since the landscape of any area is dependent for many of its characteristics upon local geology, perhaps the branch of geological study that promises to be most attractive to the amateur is the development of scenery. So much is this the case that many people respond with the comment "I wish I knew more about it" when a geological analysis of a particular scene is made for them.

To use the word 'scenery' in a geological context is natural and it has been employed both in numerous geological text-books and more popular works. Yet it is particularly necessary to be clear as to what is really involved. The definition of scenery, as given in the

Shorter Oxford Dictionary is that it is 'the general appearance of a place and its natural features recorded from the picturesque point of view; the aggregate of picturesque features in a landscape'.

This wholly acceptable definition implies that scenery is a resultant of vegetation, colour of soil, light (which depends on such things as time of day, season of year and cloud effects), and the actual form of the land. Geology embraces land-forms only, and is therefore but one of the contributory factors. In recent years this has been recognized by the introduction of the word 'geomorphology' into both geological and geographical literature. Though seemingly a piece of scientific jargon, this word conveys precisely the restricted idea required. It is with land-forms, rather than with the broader conception of scenery, that geology is mainly concerned.

PRINCIPLES OF GEOMORPHOLOGY

Fundamental principles of land-form development may be compared in some respects with those of sculpture and carving. A sculptor uses chisels of various kinds to obtain different effects. The 'chisels' employed by nature are those agents of erosion outlined on pp. 22–25, namely, rain, rivers, frost, ice, wind and the sea. But in both sculpture and carving the 'grain' of the material is also important. This includes alternations of harder and softer layers, variations in their thickness, and the pattern of arrangement.

On those kinds of wood that possess little grain, or on a block of Portland freestone or Carrara marble (types of materials that are texturally more or less homogeneous throughout) the artist may work his will. A strongly grained wood or a slate or phyllite imposes limitations. In the former Geological Museum at Jermyn Street, London, an intricately carved Chinese screen worked in slate was exhibited. Its most notable feature was the skilful way in which the carver had utilized in his design certain colour bands and harder layers present in the slate. In a way this screen was the expression of a fifty-fifty collaboration between nature on the one hand and the Chinese carver on the other. The broad design was already inherent in the block of stone; the carver developed it and added his own detail. So it is with earth sculpture; the basic design is inherent in the strata; the several erosional agents develop it according to their powers.

The basic principles of the study of land-form development are few and simple; briefly they are:

(1) Most land-forms are produced by the erosion of the land surface.
(2) Soft rocks are more easily removed than are hard rocks.
(3) The local arrangement of strata strongly influences the local pattern of scenery.
(4) Each agent of erosion is capable of producing its own characteristic effect on strata of the same kind and arrangement.
(5) Vertical movements of land area relatively to sea level give rise to special features, particularly around coastal regions.
(6) During the temporary periods of sojourn in the course of its transportation to the sea, débris produced by erosion may be built up into its own characteristic land-forms.

It will be immediately apparent that, to comprehend the development of even the simplest land-forms, some background of geological knowledge is required. This need not necessarily be extensive. An appreciation of the first three of the above points may be all that is necessary to interpret the broad 'grain' of a tract of country; that is, the general directions in which local strata tend to run. The North and South Downs, the Cotswolds and the striking 'edges' of Derbyshire mark the 'grain' of the country around them. They are hills of simple structure, each of which owes its form to the presence of a hard rock formation dipping at a low angle in one direction and overlying a softer one. Mountainous districts normally provide land-forms of greater complexity. Those of the Derwentwater district of Cumberland, of which Plate XIIA is a photograph, are the outcome of glacial action that cut a U-shaped valley and gave rise to a lake, and of river action that, among other things, is now active in filling the lake in.

Examples of land-forms

The inherent interest that land-forms may provide was well brought out by an exhibit on view in 1954 in the Geological Museum at South Kensington. This comprised a series of some forty pictures drawn by well-known artists, and published as advertisement posters by British Railways. Every picture brought out some strong natural scenic feature and each feature was directly susceptible of a geological explanation. It is unlikely, perhaps, that in every case the artist was conscious of the geological nature of the land-forms that he had portrayed; the probabilities are the reverse. Yet each picture possessed an added interest beyond the purely

aesthetic, once the underlying geological causes of the land-forms came to be understood.

A picture of the South Downs of Sussex indicated a gently moulded contour. Land shapes of this kind are directly associated with the soft chalk limestone as it reacts to erosion by rain and rivers under a temperate climate. Another picture, of Cleeve Hill and Nottingham Hill in the Cotswolds, emphasized hill-forms associated with harder, well-jointed limestones, and a lowland outline normal to soft-clay formations, also carved with these same agents of rain and rivers.

A drawing of the Cuillin Hills of Skye reproduced their rugged nature. This is a reflex of the type of rock of which they are comprised (a gabbro), as it was sculptured by the harsh tools of glaciation; the Cuillins still retain their form as a legacy from the glacial period.

The Loch Awe neighbourhood of Argyllshire possesses an attractive irregular hummocky topography. These hummocks were produced by glaciers. Some are elongated hillocks, composed of boulder clay laid down and shaped by ice. Others are humps that when viewed from one direction have a smooth outline, but when seen from the opposite have a harsh craggy appearance. These latter were carved out of hard 'solid' rocks. The smooth side faces the upstream direction of former ice movement. The great pressure of the glacier in its travel over the rocks smoothed away all irregularities. But on reaching the downstream end of the mass of rock the overriding ice plucked off large pieces, leaving a craggy outline. Rocks of this type are termed *roches moutonées* from their fancied resemblance, when seen from a distance, to sheep lying down. (The same idea of resting sheep lies behind the name of 'greywethers', given to some large isolated boulders in the south of England, although these are not of glacial origin.)

A view from Knockhill, north-east of Crieff, Perthshire, includes some rugged mountains in the distance and low-lying green slopes in the foreground. This remarkable change of scene is primarily a result of a tremendous geological fault known as the Highland Boundary Fault. This fault displaces strata a matter of several thousand feet vertically and brings a mass of very hard strata into juxtaposition with one of relatively soft beds. The latter have been eroded to a very much greater extent than the former.

As a final illustration, a picture of the Newquay district of Cornwall showed a series of distinctive flat-topped headlands. At one geological period these flat tops formed part of a wave-cut platform

of a sea bed. Subsequently the whole area was elevated several hundred feet above the sea, and still later the originally continuous flat plane has been cut by streams into separate blocks. A similar feature near Newlyn, also in Cornwall, is shown in Plate XIIB.

The above illustrations are of broad land-forms whose origins are relatively obvious. It would be misleading, however, were they to give an impression that geomorphology is an entirely simple matter, for many features can only be explained by invoking most complex geological processes. Every endeavour to trace the causes that have produced a particular item of scenery requires its sufficiency of geological knowledge, and, equally important, of good powers of observation. When the stage of broad generalizations is passed, there are progressively required closer acquaintance with stratigraphy and tectonics, a fuller understanding of the several 'carving tools', and a greater ability to note minute differences in the contour of the ground.

Numerous excellent books assist in the first two requirements; indeed an introductory book on physical geology—that is, one that describes the general habits of rivers, the behaviour (radically different from that of rivers) of glaciers, and the general ways in which anticlines, synclines, faults and other structures affect land-forms—becomes essential. But book knowledge of these things can only be used effectively if it is applied to observations made in person in the field. Many books clearly explain certain specific examples of geomorphology. In the nature of things these are models on which interpretations of other features may be based; they cannot be more. The permutations and combinations of changes in type of rock, geological structure and climatic conditions both of today, and of the past that still affect the present, are infinite, and land-forms are accordingly infinitely variable from place to place; that is part of their attraction.

The only pieces of apparatus required are a geological map and (if available) a geological description of an area, and no storage facilities for specimens are wanted. To those that have eyes to see, and who enjoy unravelling puzzles, geomorphology becomes a most rewarding spare-time occupation.

The field geologist often reverses the interpretive procedure of geomorphology. He observes the land-forms and uses them as part of his evidence for determining earth structure. The principle adopted is that every change in contour of the ground, however slight it may be, means something; this may be little, or it may be of great importance. One of the first things a field geologist who

finds himself in an unfamiliar area has to do is 'to get his eye in' to the local land-forms, major and minor. As he proceeds with his work he attaches to them the value that they deserve as field evidence of geological structure.

PALAEONTOLOGY

Fossil-collecting is a fairly common hobby among boys and girls of school age. Some young collectors, perhaps the majority, are mildly attracted by the (to them) unusual. These soon discover, however, that except in only a few strata, fossils are by no means common, and that to find them involves concentrated and lengthy searching. They find also that in those rocks that are prolific, such as some of shelly limestones of the Jurassic formations, the kinds of fossils are limited in number. The mildly interested collectors soon fall by the wayside.

Others find a real attraction in one aspect or another of fossils. In point of fact many palaeontologists of today, both amateur and professional, have continued and expanded their schooldays' activities. Palaeontology, however, tends strongly towards specialization, and interest may ultimately centre around a single biological group on the one hand, or on the other, around acquiring from a single bed as complete a collection as possible of fossils of different genera and species. Amateur palaeontologists have a potential of conferring great benefits on geological science. One of the most outstanding examples is that of Charles Lapworth (1842–1920), who, starting his life as an amateur, became Professor of Geology at Birmingham, and is amongst the ranks of the most eminent geologists of all time. Again, the late E. S. Cobbold, working in the Welsh borderlands, contributed an immense amount to our knowledge of Lower Palaeozoic stratigraphy. W. Tutcher became a world authority on Lower and Middle Jurassic fossils. B. Pope Bartlett, a country doctor in Dorset, worked for twenty-five years during the early part of the century on a single bed little more than 9 in. thick, but widespread over Wiltshire and Dorset. He discovered much of stratigraphical interest concerning the Upper Greensand and Lower Chalk. A. W. Rowe, another doctor, by studying the fossils of the Chalk of the Kent Coast, established a zonal sequence that has been assimilated into the internationally accepted zonal scheme for the Chalk formation. A. Wrigley, in more recent years, by collecting from the London Clay, shed light on its fauna, and conditions of deposition. All these built up large and varied collections of perfect shell-forms that, in addition to having

great scientific value, were a joy to see purely from the standpoint of aesthetics when displayed in their cabinets. Many of the important fossil collections in our museums have been made by amateurs, for collecting often necessitates long and continuous residence in the same district in order to be regularly on the spot.

Palaeontology, as distinct from merely collecting fossils as 'formed shells', demands both patience and manual dexterity. Perfect specimens of fossils such as those on view in our museums are but rarely come by without being 'developed'. For one perfect specimen found in the field, many broken ones are obtained. Even the perfect ones usually have much country rock or 'matrix' adhering to them. Its removal, whether the rock be hard or soft, generally needs considerable skill, in attaining which many good fossils are spoilt. A certain amount of apparatus and a convenient place to work are necessary to develop fossils, which is definitely not a job for the drawing-room. Some biological knowledge is required to ensure that specimens are not damaged through ignorance of their structure and, at a more advanced stage of work, to enable recognition to be made of some possible fossil structure that may not hitherto have been discovered. But initial biological knowledge need not be profound; deeper insight follows automatically with deepening interest. Difficulties of housing accommodation for the fossils may prove an unfortunate and progressive deterrent to collecting, for specimens require individual protection to prevent their deterioration, which can be rapid if they rub against each other even if they are in hard rocks; and fossils from soft rocks are usually very fragile. A collection therefore soon assumes considerable bulk. Micropalaeontology, dealing as it does with minute fossils, avoids the troubles of storage space, but necessitates the use of a good microscope. It is a branch of palaeontology likely to appeal to members of a microscope club.

Petrology and Mineralogy

Petrology, whether amateur or professional, is also a specialist study. It does little to satisfy a collecting instinct, for a collection of rock specimens, however much it may appeal to the specialist, has none of the aesthetic appeal that is possessed by a group of colourful and shapely minerals or of carefully developed fossil shells. One of its main interests lies in identifying the constituent minerals of the rocks and in deducing their modes of origin by examination of thin slices under the microscope. A microscope especially built for petrological work is essential, as are also facilities for making thin slices,

although this last need no longer be a deterrent since slices are made at reasonable cost by professional lapidaries.

The scientific definition of a mineral as given on p. 34 has to be accepted in a consideration of mineralogy. As a hobby mineralogy largely resolves itself into collecting and identifying minerals (most of which are crystals) from their macroscopic characteristics.

In general there is less scope for collecting minerals than fossils. Sedimentary strata only occasionally yield large crystals and the number of varieties is small. Crystals of calcite, known as dog-tooth spar, are locally common. Crystals of selenite are sometimes numerous in beds of clay. Large colourless and transparent selenite crystals, sometimes 4 or 5 in. long, are known popularly under such names as 'fossil water' or 'fossil ice'. Quartz crystals are also locally common, usually in veins associated with some ore-bodies. Another common mineral is iron pyrites, existing as 'fool's gold' in coal and in numerous formations as nodules of marcasite, and in other forms. Marcasite nodules that are commonly found in chalk are often commonly believed to be 'thunderbolts'. They are not meteorites, but it becomes most difficult to convince many people on this point.

While the list of minerals to be collected as large specimens from sedimentary strata is soon exhausted, the converse holds in the case of vein rocks that have either been metamorphosed by mineralizing gases or fluids or consist of substances that have crystallized directly from them. A great variety of beautiful crystals exists in these rocks. Many, however, are mostly inaccessible except in tin mines, copper mines and the like. In Great Britain the best known hunting-grounds for vein minerals are Cornwall, parts of Wales, Derbyshire and the Lake District. Fluorspar (Blue John spar of Derbyshire) is one of the most attractive of these minerals. Since specimens are normally unobtainable direct from mineral veins, tip-heaps of waste material from the mines may be fruitful sources of supply, although many of these have been so closely searched that chances of finding rare minerals are few.

Metamorphic rocks other than vein rocks also yield numerous minerals, instanced in particular by garnets. Gemstones also come under the subject of mineralogy but to make a collection of these is normally beyond the resources of the average man. Many crystals have an added interest to the collector when they are contained in a fragment of the country rock in which they occur in nature. In fact it is often in the association of a mineral with its surrounding rock that its geological interest actually lies.

The restricted collecting sources of minerals may to some extent be augmented by recourse to dealers in mineralogical specimens. Certain dealers in the past, however, regarded mineralogy from a somewhat different standpoint from that of amateur collectors. During the latter part of the nineteenth century mineralogy, or perhaps more correctly collecting minerals, was a fashionable hobby amongst some of the more wealthy section of the community in Great Britain. Many crystal specimens, particularly large and striking crystal aggregates, decorated their houses. During this period in particular the demand for specimens, particularly for those attached to a fragment of country rock and thereby related to their original surroundings, was greater than the supply. Many fakes were prepared for sale; individual crystals of various kinds, valueless in themselves, were cleverly stuck on to somewhat unlikely rocks and sold at correspondingly enhanced prices. Some very skilful fakes were recently discovered in a collection that had been bequeathed to the University Museum at Oxford. It is found that few of the adhesives and colouring matters that were used resist boiling water!

During the early part of the present century suggestions founded on a very slight basis were subtly put out in some seaside towns adjacent to those areas in Great Britain where rarer minerals would be expected to occur, that on sea beaches crystals of gem or near-gem quality were likely to be found as pebbles; and that these would repay cutting and polishing and mounting as jewels. Many pebbles were indeed collected—and for each of them the 'jewellers' substituted a synthetic stone made in Germany and worth a few pence only.

Historical Geology and Geological Mapping

To make a geological map of an area of open country is by far the best way of getting the most out of historical geology. In mapping, the surface arrangement of the several strata of a district are traced and their mutual relationships determined. This leads to the formulation of views on the probable progression of geographical events of past ages that led up to the present-day structures and land-forms. But geological mapping as a pastime has its limitations. Not every locality is suitable for amateur working; cities and towns obviously have no attractions. In open country it is not always easy to get permission from landowners to enter on their land, particularly where game is preserved or land is heavily cropped. In point of fact, however, most difficulties of access are usually overcome, once a landowner appreciates what one is doing. In country of simple

geological structure a reasonably good all-round geological knowledge is wanted, and complicated areas demand a first-class background. The rate of progress of work, as regards area covered, can only be slow. In country of relatively simple structure a fair rate for a professional surveyor doing detailed mapping, and working full time, is three square miles in a fortnight, and complex country may take considerably longer.

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