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GEOLOGY

An Introduction to Earth-History

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OXFORD UNIVERSITY PRESS
LONDON NEW YORK TORONTO

First published in 1949 and reprinted in 1953

Printed in Great Britain by
Butler & Tanner Ltd., Frome and London

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CHAPTER I

THE SEARCH FOR THE METHOD

Geology is Earth-History. The history of the earth is clearly a matter of the greatest interest and importance to all of us who live upon its surface—of interest because we should like to understand the environment in which we find ourselves, of importance because some of the events are recorded in materials such as coal, oil and ores upon which our civilization is founded. Earth-history is dealt with in the science of geology, that branch of knowledge which is concerned with piecing together the records that the earth herself provides of her own stupendous drama—a drama that has now run for some two thousand million years. The common opinion was, and possibly still is, that the earth was made exactly as it is at this moment; it thus has no history. This opinion was that of the learned also so long as they confined themselves to speculations unchecked by any contacts with the common earth. But as soon as men went and saw what the earth was made of, hammered at the rocks in quarry and mine and so studied the records on the spot instead of speculating about them in the cabinet, ideas of a succession of events in the making of the earth began to germinate; the earth might have a history after all. The records are the rocks and we have first to inquire how they came to be read.

Fossils and the Forerunner. Since the earliest times it has been observed that many of the rocks contain objects with the shapes of shells and bones of animals or the leaves and seeds of plants. These objects are called fossils and we now know that they are exactly what they appear to be—namely, the remains of animals and plants preserved in the rocks. But this interpretation of fossils was by no means evident to classical and medieval scholars. For many centuries, fossils excited their curiosity and stimulated their imagination, so that countless fantastic explanations of them were put forward. They were accounted the work of spirits, good or bad, or the results of radiations from the sun or stars, or simply rather questionable jokes by the Mineral Kingdom in imitation of forms properly belonging to the plant and animal realms. Some commentators saw in them the apprentice work of the Creator, who rejected these early efforts when, with improving skill, He had become proficient enough to make the present forms of life. Others considered it not unfitting that Nature should express herself in rocks in the shapes of plants and animals and, as late as the seventeenth century, Plot was inclined to view these objects as the result of some quality in the earth which produced fossils as ornaments for the hidden parts of the globe just as flowers ornament the visible parts. Even in the nineteenth century a learned divine of Oxford maintained that the devil had placed fossils in the rocks to deceive and perplex mankind.

The true explanation of fossils, with the realiza-

tion of many of the consequences that followed from it, was suggested by some few of the old writers, but it was the Forerunner in arts and science, Leonardo da Vinci of Florence, the brightest ornament of Renaissance learning, who placed it beyond all reasonable controversy. A great part of Italy is made of rocks containing an abundance of fossil shells not greatly different from many that exist in present-day seas. During his engineering operations, da Vinci had inspected many excavations in fossil-bearing rocks and from his observations had drawn a series of correct conclusions: the fossils were the remains of marine organisms which had lived during the formation of the rocks in which they are now found; they indicated therefore that the sea had once covered North Italy, that on the floor of this sea the shells had been entombed and that afterwards the deposit enclosing them had been raised up above sea-level to make the Italian land. To quote from Edward MacCurdy's translation from da Vinci's *Notebooks*, 'above the plains of Italy where now birds fly in flocks, fishes were wont to wander in large shoals; sufficient for us is the testimony of things produced in the salt waters and now found in the high mountains far from the sea'.

The style of da Vinci's observations and deductions is of fundamental importance for the study of earth-history, and we may well illustrate his method in a little more detail. He had made himself familiar with the processes going on in the beds of rivers and along the shores of the sea, so that he was able to envisage the entombment of marine

organisms within the successive layers of mud falling on the sea-floor from the load brought down to the sea by the turbid rivers. Successive inundations gave rise to a number of layers of mud and, when these have emerged from the sea to make dry land, they become compacted into successive layers of stone in which the entombed shells are found as fossils. This must be the true explanation of fossils and their true significance, and da Vinci proceeds to show that other explanations are untenable. The influence of the stars cannot have produced the shells in the rocks of the mountains, because young and old shells are found together, each showing their growth-lines, some broken and some whole, and with many kinds occurring in one layer. Nor can they be due to the Flood, since they are often found in pairs as they grew, whereas the violent waters of a deluge would have separated them and broken them. Da Vinci uses a delightful argument to reinforce this conclusion: cockle shells are found in the rocks of Lombardy two hundred and fifty miles from the sea, the cockle lives near the shore and moves exceedingly slowly—how could it have travelled all these miles in the forty days of the Flood? Fossils are clearly the remains of things that once lived, for he could 'count on the shells of cockles and snails the number of the months and years of their lives, just as one can on the horns of bulls' and he noted for example that 'between the various layers of the stone are still to be found the tracks of the worms which crawled upon them when it was not yet dry'.

Four hundred years and more ago da Vinci had solved the problem of the fossils. He had done this, moreover, in the correct manner, by detailed examination of his material in the rocks, by the contemplation of processes in action to-day which threw light on the way rocks were made long ago, and by the consideration and rejection of alternative explanations. Further, having decided what fossils were, he had no hesitation in deciding what his particular samples meant—the stone containing them had been formed on the floor of a sea and had then been raised into land so that where now were the Italian mountains had once been the sea. The rocks he had examined thus recorded an event that had occurred in the past, but even the genius of the Forerunner could not make the next step. This depended upon the realization that there was a succession of rocks recording a succession of events. This realization could follow only from knowledge of an extensive area, and centuries were to elapse before the time-significance of the rocks was clearly demonstrated.

Light from Thuringia. The greatest advances towards this end were made in Thuringia about the middle of the eighteenth century. The two aspects of Thuringian geology which contributed to these illustrate the twofold quality of the science from which it draws its strength. First, the Thuringian scene presents aesthetic contrasts that entice inquiry; and second, the exploitation of valuable minerals in the Thuringian rocks keeps that inquiry within practical bounds, for, in such a setting,

speculations become tested at any time by the cold facts revealed by mining operations.

To the north of the Thuringian plain rises the mountain knot of the Harz, to the south the great spur of the Thuringer Wald thrusts out across middle Germany from the Bohemian highlands. The fundamental contrast between plain and mountain is enhanced by many lesser differences, by the style of the agriculture, the nature of the vegetation, the density of settlement, and even by the topics of the legends. The reason for the contrast was revealed to the pioneers—the nature and arrangement of the rocks were different in the two scenes. In the mountains, the rocks were harder and tougher, they appeared to be arranged in no particular way, they were clearly broken and upheaved and buttressed by adventitious masses of granite; they had given rise to a kind of scenery suggestive of an older and even hostile world. On the plains where men could live in comfort appeared the kinder and more familiar stones of everyday life, the pleasantly coloured sandstones and limestones, in layers decently placed in uniformity and order. Layer succeeded layer and the mining of one layer containing copper demonstrated that even thin layers had a wide extension. The chaos of the mountains contrasted with the regularity of the plains.

The explanation of these differences in the fabric of Thuringia as records of two different episodes in the history of that part of the earth resulted from the detailed observations of two eighteenth-century

naturalists, Johann Gottlob Lehmann and Christian Füchsel. Lehmann (d. 1767) showed that in the cores of the mountains were found the most ancient records presented by the disturbed and upturned rocks, often massive and devoid of fossils, dating he supposed from the time of the creation of the world. These were the Primary Mountains. Along their flanks were arranged the flattish layers of fossil-bearing rocks that made the Thuringian plain; these familiar sandstones and limestones were clearly laid down through the action of water and Lehmann suggested that the sand and mud making them had been washed off the Primary Mountains during the Flood, carried to the depressions and spread out there in layers which hardened into stone as the waters receded. These layers, clearly younger than the Primary Mountains and derived from them, were thus made of second-hand material and eminences formed of them could appropriately be called Secondary Mountains. Lehmann demonstrated in the Secondary Mountains of Thuringia no fewer than thirty successive layers of different bands of rock lying in regular order against the cores of the Primary Mountains. This was a very great achievement and it is worth while to study two of Lehmann's diagrams—'sections' the geologist calls them—given in Figure 1; it is clear from these that however wide of the mark he may have been in his actual dating, he realized that there was a succession of events in the history of the earth recorded in the succession of the rocks.

Füchsel (d. 1773) independently produced results similar to those of Lehmann and, besides continuing the succession of the rocks of the Secondary

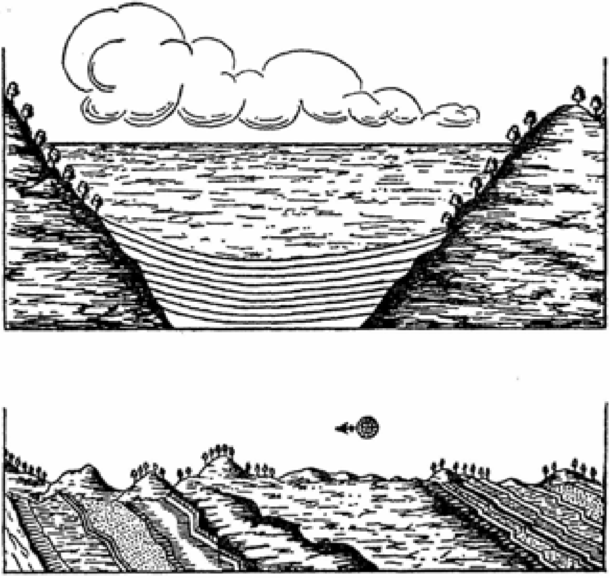


Fig. 1. Primary and Secondary Mountains (above) and the Succession of Beds in the Secondary Mountains (below), according to Lehmann. (Based on Plate XI, *Birth and Development of the Geological Sciences*, F. D. Adams, 1938, which is from Lehmann, *Essai d'une Histoire Naturelle de la Terre*, Paris, 1759)

Mountains, made two outstanding contributions that were destined to develop into fundamental principles of geological science. First, he showed

that many layers of these rocks were characterized by their own particular kinds of fossil organisms. He realized that in unravelling earth-history invaluable help would be forthcoming from this circumstance—layers may be matched or differentiated by inspection of the organic remains found in them. Second, Füchsel developed the practice of da Vinci in studying the processes of rock-formation in action at the present day and applying the knowledge thus gained to interpret the old rocks as records of similar processes operating in the past. This is a very celebrated doctrine of modern geology and one fundamental for the study of earth-history.

Füchsel's chief work was written in Latin and he used a word *stratum*, to mean a layer or bed of rock, that has become a keyword in geology. He applied it especially to the layers of sandstone, limestone, and similar rocks that made up the succession of the Secondary Mountains, and all these beds came to be grouped together as the *stratified rocks*. We have seen that these were obviously made by the deposition of sediment such as clay and sand from water, and nowadays the terms sedimentary and stratified are practically synonymous. This introduces the first of the great groups of rocks—the *sedimentary rocks*, formed for the most part by the deposition of materials from a moving medium at the earth's surface under normal conditions of temperature and pressure. Lehmann's figures thus exhibit a succession of sedimentary, stratified, or bedded rocks.

Werner the Neptunist. Lehmann and Füchsel recognized a sequence of events, beginning with the formation and upheaval of the mountain-rocks, followed by the deposition of the fossiliferous sediments in flattish beds of wide extent. These were conclusions of a fundamental nature, but by ill chance they were ignored, buried or forgotten. Instead of the sound developments from this sure beginning, there appeared the dogmas of Abraham Werner (1749–1817) in which the nucleus of truth with regard to succession was encrusted with many fanciful speculations.

In spite of this, Werner, who was Professor at the School of Mines at Freiberg in Saxony, did many great services to geology, both directly and indirectly. He aroused immense enthusiasm in his students, who went forth to teach his doctrine to all the nations; in many cases, however, they found evidence in the rocks that their beloved master was unquestionably wrong, and the greater of them, men like von Buch and d'Auboisson, played a leading part in demolishing the Wernerian or *Neptunist* Theory, as it came to be called. This doctrine was briefly this. At an early stage in its history, the earth possessed a very irregular nucleus completely covered by an ocean of a remarkable kind, since its waters contained, in solution or suspension, all the material required to make the crust. The first layer to be deposited on the nucleus formed the well-known rock granite, and this was followed by a variety of other rocks made up of aggregates of crystals—the rocks we now call crystalline. These

chemical precipitates, as Werner thought them to be, covered the whole globe and were given the appropriate name of the *Primitive Rocks*; they were massive rocks devoid of fossils. The next layers to be laid down were the *Transition Rocks*, in part chemical precipitates and in part made up of the debris of the older rocks. During their deposition, the primitive ocean was slowly subsiding and mountain-tops of Primitive Rocks emerging from the waters. Some of the layers of the Transition Rocks thus extended over the whole of the earth's surface but others only partially covered it. Typical of these rocks were the slates, and only occasionally were fossils found in them. The steep inclination of the layers of Primitive and Transition Rocks observed in the present mountains was due either to precipitation on the orginal steep slopes of the earth's nucleus or else to the slumping-down of uncompacted masses of the precipitates. After Transition times, the ocean continued to shrink and another set of layers, dominantly made of material worn off the older rocks, was deposited in gently inclined beds around the ridges of Transition Rocks. This new set included such rocks as the common sandstones, limestones, seams of coal, beds of salt, and so on, and they correspond to those that make the Secondary Mountains of Lehmann and Füchsel. Many of them are rich in fossils; Werner called them the *Floetz Rocks*, from a German word meaning bed. The last group to be laid down was the *Alluvial Deposits*—loose gravels, sands, and clays formed by the

decay of the older rocks and occupying the lower ground.

It will be noted that in the Wernerian scheme, the universal ocean gradually shrank; the difficulty presented by this disappearing ocean was met by permitting the waters to retire into the earth's interior or to be whisked away into space through the attraction of a passing star—a proposal of a very modern cast. Whatever difficulties remained, it was clear, as Werner said, that 'our earth is a child of time and has been built up gradually'. As our summary shows, Werner held and taught the fundamental notion of an orderly succession of rocks as records of earth-history, however astray he may have gone in interpreting these records. The essential of the Neptunist position was the formation of all rocks by precipitation or deposition from a universal ocean. We may look into the subsequent fate of this belief.

The rocks on which the Neptunist theory was wrecked were those called volcanic. Active volcanoes could be observed to erupt lavas which, when cooled down and solidified, gave a fine-grained blackish stone, the famous rock *basalt*. Rocks apparently identical with basalt occurred in all the earlier formed groups of Werner's system, either as layers or as vertical walls or dykes appearing to cut up through the adjacent rocks. It would seem reasonable to regard all these very similar rocks as having been formed in much the same manner, one which can be seen in operation at present-day volcanoes. But Werner acted against

reason and maintained that volcanic rocks were really unimportant and quite late features of the crust. He held that the basalt occurring as layers or dykes in the older rocks was so closely associated with other rocks, such as sandstones and limestones that had clearly been deposited from the primitive ocean, that it must just as clearly be a chemical precipitate from this same ocean. Sometimes these precipitates filled fissures and thus appeared as dykes or walls of basalt.

Go and See. Already in these few pages it has emerged many times that geological theories can only be tested by evidence supplied by the rocks themselves exposed in the field. It is fitting that Nicolas Desmarest (1725–1815), author of that most excellent of geological counsels *go and see*, should take his own advice and produce field evidence that went far to solve the problem of the basalts. Desmarest, who might be regarded as an eighteenth-century one-man Department of Scientific and Industrial Research for France, spent several years in examining the volcanic district of the Auvergne in Central France. He visited, too, many regions of active volcanoes and pondered over the origin of basalt for a dozen years before he published his results in the seventeen-seventies. He showed that columnar basalt (similar to that making the Giant's Causeway in Antrim and Staffa in the West of Scotland) occurred in intimate association with rocks unquestionably volcanic; he traced a columnar basalt in the Auvergne to its source in an ancient volcano and he deduced that

basalts, in other parts of the world as well as in France, were of volcanic origin and not, as the Neptunists vainly thought, chemical precipitates from a primitive ocean.

Two origins of basalt were thus before the geological world—to the Wernerians it was a chemical precipitate, to Desmarest and a number of field-geologists it was a volcanic product. The strife was between the Neptunists on the one hand and the Vulcanists on the other. It is meet that the greatest of Werner's students, Leopold von Buch (1774–1853), should become blessed with the truth in this matter as in other doctrines of the Wernerian faith. Von Buch left Freiberg filled with zeal for his teacher's cause. He first examined certain German basalts, found them interbedded with sedimentary layers, and was accordingly strengthened in his Wernerian opinion. Next he studied the Italian volcanic districts and his faith, though at times shaken by what he saw, still survived; he states that he can scarcely believe his own eyes and that here nature actually seems to contradict herself. But the Auvergne proved the beginning of his downfall. He admitted the reality of its ancient volcanoes and that among the products of these were basalts, but still he clung for some time to the Wernerian origin of the German basalts. He next extended his observations to many classic areas of ancient and modern volcanoes, the Atlantic Islands, Italy again, Iceland, and Scotland, and saw for himself that volcanoes were not rare and exceptional features of the crust, as Werner taught, and

that among their commonest products was basalt. Wernerism, when subjected to the critical test of field-observation, had failed. Its failure was demonstrated not only by Werner's favourite student, von Buch, but by many another honest Wernerian, d'Auboisson and von Humbolt among them.

Von Buch did not confine his observations to volcanoes, whether active or extinct, and early in the eighteenth century he spent two years in Norway, where his Wernerism received another shock. In the Oslo district, he found that granite, as we have seen the most primitive of Werner's Primitive Rocks and formed by precipitation from the primitive ocean before life had begun on the earth, was here clearly of a later date than certain fossil-bearing limestones of no great antiquity. Further, the granite had baked the limestone and had obviously forced its way into it in threads and veins. From direct observation, the pupil of Werner was compelled to admit that granite could not be a chemical precipitate but must result from the crystallization of molten rock-substance. The whole edifice of Wernerism had now collapsed for von Buch. 'Go and see' had triumphed, as it always will.

The Founder of Modern Geology. These conclusions of von Buch were not new; they had been made, together with many of equal importance for geology, some twenty years before by James Hutton (1726–97) of Edinburgh, apprentice lawyer, non-practising medical man, successful farmer, natural historian of the highest genius. Hutton,

rightly regarded as the founder of modern geology, established the correct method for the reading of earth-history—a true interpretation will follow not from speculation but from observation. In Hutton's own words:

> No powers are to be employed that are not natural to the globe, no action to be admitted of except those of which we know the principle, and no extraordinary events to be alleged in order to explain a common appearance. The powers of nature are not to be employed in order to destroy the very object of those powers; we are not to make nature act in violation to that order which we actually observe, and in subversion of that end which is to be perceived in the system of created things. . . . Chaos and confusion are not to be introduced into the order of nature, because certain things appear to our practical views as being in some disorder. Nor are we to proceed in feigning causes when those seem insufficient which occur in our experience.

Hutton's condensed account of his views appeared in 1788 in the first volume of the *Transactions* of the Royal Society of Edinburgh, and an expanded version was published in two volumes in 1795 as *The Theory of the Earth*. One single work can rarely have had so revolutionary an effect on thought. Hutton's literary style is said by the experts to be bad, and perhaps on this account his *Theory of the Earth* occupies the same place in a geologist's library as Marx's *Das Kapital* does in an economist's. We examine certain aspects of Hutton's genius.

Hutton derived the crystalline rocks such as granite and basalt—the typical chemical precipitates of the Wernerian school—from the hot nucleus of the earth. He demonstrated in the field that these rocks formed veins and dykes which had clearly been intruded into the surrounding rocks. They could only have originated by the consolidation of molten rock material and were the *igneous* or fire-formed rocks. Here, in the igneous rocks, is the second of the great groups of rocks that make the earth's crust. As usual, observation triumphed over speculation so soon as the rocks themselves were allowed to tell their story. For all reasonable men the origin of basalt and granite was settled once for all.

In his appeal to the present to furnish the key to understanding the past, Hutton developed the great principle of uniformity or *uniformitarianism* which, when fully expounded by Sir Charles Lyell (1797–1875), led to many fruitful advances in geological science. We have noted the beginnings of this principle in the methods of da Vinci and of Füchsel. The geologist is primarily interested in past events but he can interpret the records of these only by the consideration of processes at work at the present day and accessible to his observation. Rocks are being made to-day in the same ways as they were made hundreds of millions of years ago. If we understand how the deposits of modern deltas, for example, are being formed, we have a better chance of recognizing and interpreting the records of ancient deltaic accumulations; if we

observe what happens at active volcanic orifices we are better equipped to study the records of ancient volcanicity. Hutton, applying this principle that the present is the key to the past, interpreted the common stratified rocks, such as sandstones and limestones, as compacted sediments worn from the land and deposited in the sea.

Hutton clearly saw that such sedimentary rocks were originally laid down in flat beds but some of them are now found turned up on end, folded and contorted. In some places, these upturned beds are seen to be covered by an obviously younger set lying flatly across them. A drawing of a section showing this and one described and discussed by Hutton is given in Figure 2. Hutton interpreted this relation (the technical term for it is *unconformity*) as indicating a 'succession of former worlds'. The older set of rocks had been quietly accumulated for a long time and had then undergone a revolutionary disturbance during which they had been folded and upheaved. The agents of erosion and decay, such as the wind, running water and ice, acting upon them, had worn them down and formed from their debris the younger beds resting upon them. Under Hutton's hand, the Primary and Secondary Mountains of Lehmann had come alive and had been interpreted in terms of action; a chapter in earth-history had been read. Many observers before Hutton had appreciated the reality of earth-sculpture by river and rain, frost and glacier, but no one had realized before him the universality in time and space of erosion

and decay of rocks or had traced the effects of individual agents with so sure a touch. Again, the patient observer of detail, contemplating the 'small increments of change', was able to visualize vast sequences of events in the history of the earth. It

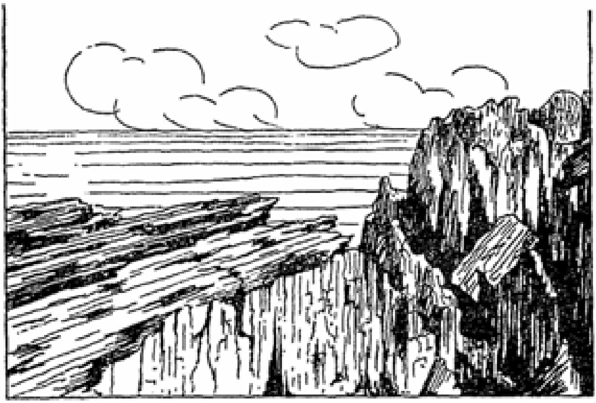


Fig. 2. Hutton's Unconformity, Berwickshire Coast, Scotland. Vertical Silurian beds are covered unconformably by flat-lying Old Red Sandstone beds and indicate a 'succession of former worlds'

is fair to recall that Desmarest had shown in 1775 that three epochs of volcanicity could be distinguished in the Auvergne by the degree of erosion and removal their products had undergone. The youngest had been scarcely touched by the agents of decay; the older had been strongly attacked and for a great part removed, leaving only small caps

on isolated hills; the third were so old that they lay beneath a considerable thickness of sediments. The ordinary processes of erosion, working exceedingly slowly but for vast periods of time, could carve out great valleys and remove enormous volumes of rock.

In Hutton's *Theory*, the internal heat of the earth was of prime importance. It was responsible for the upheaval and dislocation of the bedded rocks during the revolutionary periods of earth-history. With it was to be connected the formation of the igneous rocks such as basalt and granite. The consolidation of the original loose materials of the bedded rocks was a consequence of its action. But this was not all that resulted from internal heat. Hutton wrestled with the problems presented by a third group of rocks, additional to the sedimentary and igneous groups already noted. This third group now has the name *metamorphic*, a term meaning 'transformed' and introduced by Lyell in 1833. Hutton observed that many of these rocks had a bedded arrangement and therefore must have been formed in the same way as other bedded rocks, by the deposition of materials in the sea. They are now, however, clearly changed from their original condition, their stratification is distorted, their loose materials consolidated and their composition altered. These changes are the result, according to Hutton, of the more powerful action of the 'subterranean heat and expanding power'. Lyell considered that the transformation resulting in the metamorphic rocks was closely connected

with igneous activity—an opinion, as we have seen, foreshadowed by Hutton.

Three Styles of Record. By the middle of the nineteenth century, therefore, three great classes of rocks had been established. These were formed in different ways and supplied evidence for three different kinds of episodes in the making of the earth. We give the modern names and definitions of the three groups: *first*, the sedimentary or bedded or stratified rocks formed by the deposition of material from a medium at the earth's surface under normal surface conditions; *second*, the igneous rocks formed by the consolidation of molten rock-substance; and *third*, the metamorphic rocks formed by the modification of previously existing rocks of whatever kind. With the discovery that thin slices of minerals and rocks could be prepared for examination under the microscope, a very great deal had come to be known about the nature and origin of the materials making the crust.

Time and William Smith. We have been concerned with time in a broad way throughout the previous pages. We have seen that though geologists might, and usually did, differ radically on a great variety of questions, all held to the principle that the rocks recorded a succession of events. But whilst this is true, there was still little realization of the continuity and immensity of the record—this realization came only with detailed study of fossils themselves and of where and in what rocks they were found.

There had, of course, been precursors in the

interpretation of the succession of the rocks, especially in the centres of learning in Western Europe not far distant from exposures of rocks abounding in fossils. For example, many Italian observers had early noted the association of certain assemblages of fossil shells with certain limestones in the Apennines. In our own country, Robert Hooke (1635–1703), Curator of Experiments to the Royal Society, had recognized the true nature of fossils and their significance in earth-history. By 1800, the foundations of historical geology, or *stratigraphy*, were firmly laid by the labours of a group of French savants studying at their ease in the Paris region, and by one man, but the greatest of them all, William Smith, working at his job of civil engineer throughout the length and breadth of England.

In the favourable setting of the Paris basin, French stratigraphy progressed along sound lines, for there the successive beds are arranged in a simple manner, are well exposed and are rich in fossil remains not unlike living animals and plants. In the early years of the nineteenth century, the partnership of Cuvier (1769–1832) the biologist and Brongniart (1770–1847) the geologist was abundantly fruitful. They demonstrated that the Paris basin was made of a great series of deposits laid down in a definite order and traceable by their rock-characters and their fossil contents over wide areas. This great succession revealed, by the nature of the rocks themselves and especially by the type of fossil plant or animal contained in them, the

conditions of their making—in shallow sea, muddy estuary, salt lagoon or freshwater lake. The geography of a particular time in the past had been delineated and another chapter in earth-history had been read.

Meanwhile, similar conclusions reinforced by generalizations of a high order had been reached in England. As early as 1760, John Michell had described the order and nature of the main divisions of the bedded rocks of the country and had given a clue to the interpretation of the geological structure of this part of the crust. Later, William Smith (1769–1839), the Father of English Geology—surely no father of anything English could be better named—laboriously collected the detailed observations which enabled him to establish the fundamental principles of stratigraphy, principles applicable not only to the homely rocks of England but to those known and yet to be known of the whole world.

Smith's life and work provide material for much reflection. He was born of Oxfordshire yeoman stock, orphaned at an early age and self-taught apart from the rudiments acquired in the village school. He worked hard in his profession of land surveyor all his life and was never for long blessed even with necessary means. Compared with his contemporaries, he appeared ill-equipped for eminence in geological science, and indeed he reached it almost by accident. In a quarter of a century of perambulations through England, Smith acquired a profound knowledge of the details of

CHAPTER 2

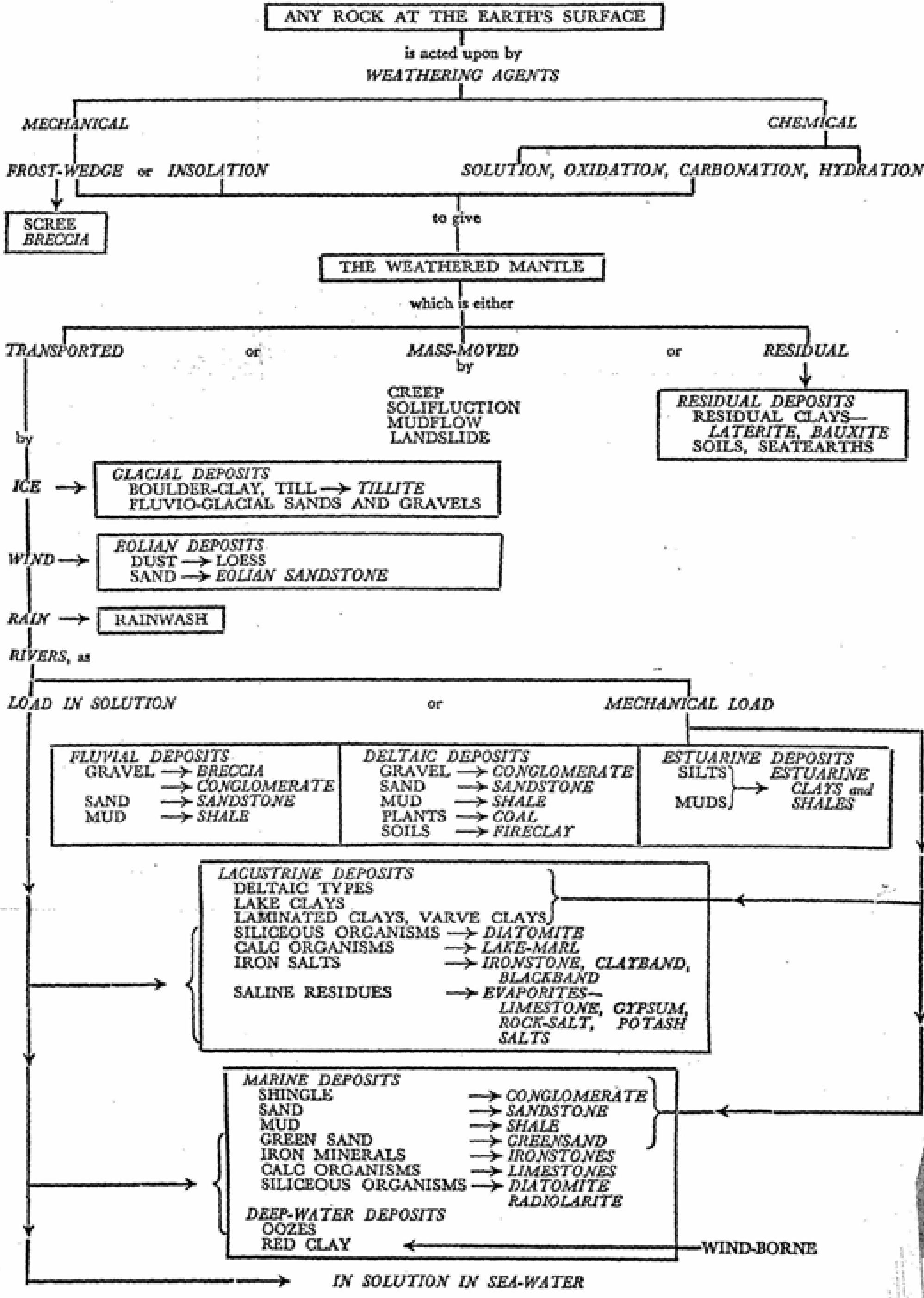
THE SEDIMENTARY ROCKS AS HISTORICAL DOCUMENTS

In the foregoing chapter the development of ideas concerning the sedimentary rocks, their origin and interpretation, has been summarized. It will be recalled that the sedimentary rocks are laid down on the earth's surface at ordinary temperatures from some kind of moving medium. They occur in layers or beds or strata. They can be arranged in an age-sequence and their individual beds are characterized by special assemblages of fossils, the remains of the organisms that lived during their deposition. The study of the sedimentary rocks in space and time is called stratigraphy, that of their fossil contents is palaeontology.

In this present chapter we are concerned with two inquiries. *First*, we consider the sedimentary rocks as revealing the environments in which they were formed; and, *second*, we consider the succession of these rocks as revealing a sequence of environments. In this sequence of sedimentation-environments we trace the course of earth-history.

In the interpretation of these rocks, Hutton's key has to be used. 'No powers are to be employed that are not natural to the globe, no action to be admitted of except those of which we know the principle, and no extraordinary events to be alleged

FLOW-SHEET OF SEDIMENTARY ROCK PRODUCTION



in order to explain a common appearance.' We are thus to employ the method of uniformitarianism, we have to use the present to interpret the past. This is supremely sound counsel, but it has its difficulties and we examine some of them later.

Making the Sediments. We have now to present the processes of making the sediments so as to display the origins of their derivatives, the sedimentary rocks. For this purpose it is best to consider the different fates of material, worn from the land, as it passes to its final resting place in the sea. The manufacturer or mining engineer often makes a chart showing the various stages in the manufacture of his goods or the production of his high-grade metal from the crude ore. Such a *Flow-sheet for sedimentary rock production* is shown on the folder facing this page and the stages in the process are now elaborated.

Weathering. The rocks at the surface of the earth are not in harmony with their surroundings. They have been formed under physical conditions for the most part markedly different from those of their present environments and, though their constituent minerals seem as lasting as time, they are really undergoing a slow chemical and mechanical decay. From the original rocks, with the composition and textural relationships of their mineral components proper to the environments in which they were formed, now arise new minerals and new arrangements more in keeping with the conditions of the earth's surface. These surface conditions are exceedingly variable and complex; we have an index

of some of them in the weather and the geologist accordingly talks of weathering and weathering agents, meaning by the latter the forces of mechanical and chemical decay acting at the earth's surface.

Weathering of the surface rocks is essential for life, since the formation of the soil mantle is one of its consequences. The nature and pattern of the soil belts of the world are controlled by the kind of surface rock and the style of weathering to which it has been exposed. Weathering on the moon is absent or at least peculiar and the lunar surface supports no life.

The surface rocks are slowly disintegrated or decomposed. Water freezing in their pores exerts pressures which break them into angular pieces which accumulate in heaps at the foot of steep slopes. These debris piles are screes and a cemented scree forms one variety of the rock named breccia. Violent changes of temperature, setting up complex strains, disintegrate the surface rocks, especially for example in desert regions. Chemical decay results from the action of surface waters which have acquired oxygen and carbon dioxide from the air and organic acids from the ground. Slow but inexorable operations of solution, oxidation, carbonation, and hydration are set in motion and these, inseparably associated with mechanical break-up, lead to the formation of an irregular weathered mantle over the surface rocks. Different combinations of weathering processes will be dominant in the different climatic belts, as a moment's reflection will show.

Much of the material making the weathered mantle is transported by ice, wind, rain, or river. What remains forms the residual clays such as laterite, rich in iron hydroxide, or bauxite, rich in aluminium hydroxide, or the more common residue, the soils. Ancient soils of a special character are the seatearths found beneath coal seams. Some of the weathered mantle, lubricated by water, creeps and slumps down the slopes—processes called mass-movement. It is that portion of the mantle, however, which is more actively transported that is of great interest to us as it provides the sediments from which the common sedimentary rocks are derived.

Ice Transport. The first, but not the most important, agent of transport is *ice*. Glaciers and ice-sheets, moving out from the regions of snow-accumulation, scrape away the weathered mantle and erode the solid rocks over which they pass. Frost-wedged material is showered on to the surface of the glaciers and adds to their load. When the mass of ice melts or retreats, the glacial deposits revealed consist of angular or subangular blocks of rock mixed up with finest ground-down rock-powder—the whole is unsorted and not chemically decayed. Modern glacial deposits of this kind have the expressive name of boulder-clay; a dialect term for them is till, and ancient consolidated boulder-clays are called tillites. Most bodies of ice are not excessively cold and streams run on and in and under the ice. These streams sort out some of the ground-down rock-material, transport it and de-

posit it as seams of sand and gravel in the boulder-clay. In front of the melting ice, the meltwaters deposit great spreads of fluvio-glacial sands and gravels, sometimes in hummocky or ridge-form as illustrated in the kames and eskers of Ireland, Scandinavia, and elsewhere.

Wind Transport. The *wind* is everywhere an active transporting agent, but especially where material mechanically weathered is not bound together by a mat of vegetation. In deserts, the fine dust particles are easily blown about; great devastation has been wrought in the farm lands of the Middle West (the 'Dust Bowl') by removal by wind of the fine soil laid bare by the plough. Under suitable conditions wind-blown dust accumulates to considerable thickness, as is seen in the enormous loess deposits of China which are made of fine dust blown from the Gobi desert. More typical wind-borne or *eolian* deposits are made of larger particles—sand, usually composed of the obdurate and common mineral quartz, silica. Sand grains, trundled along by the wind, accumulate as sand dunes; the character of the particles, such as their rounding, frosting, and sorting, and the arrangement of the separate layers of sand in a kind of tip-heap structure, are typical of such wind-borne deposits. By processes of several kinds these loose sands may be converted into the hard rock, sandstone; if it can be shown that an ancient sandstone is of eolian origin, it can properly be called an eolian sandstone.

Water Transport. Moving water is the chief transporter of the weathered mantle. Rain running

down a slope carries the finer particles to the bottom to accumulate as rainwash. Soon, however, the action of the moving water becomes concentrated in stream beds. Armed with sand and stones, the river rasps away at its bed, the sides of the bed slump in and the river acquires a load of material which it transports. As an example of the scale, it may be stated that the Mississippi carries to the sea a load of two million tons or more a day. A river's load consists of two parts, one in solution and the other in suspension or rolled along. The load in solution is carried onwards to a lake or the sea and we examine what happens to it there later. The amount of the mechanical load a river can carry depends on the velocity of the water; as soon as the velocity is lowered some of the load is laid down. Along the river itself layers of gravel sand and mud are formed—the fluvial deposits. Consolidated river gravels provide another variety of breccia if the pebbles are angular, or the rock conglomerate if they are rounded; the fluvial sands when cemented or consolidated make another type of sandstone and the muds one kind of the rock known as shale.

Delta Sediments. Where the river runs into a lake or the sea, the velocity of its water is rapidly checked and most of its mechanical load is thrown down as the gravels, sands, and muds of the deltas. Subsidence appears to occur frequently in the large deltas, and inroads of the lake or sea result so that layers of freshwater or marine character—as shown by their contained organisms—may be formed as

intercalations in terrestrial deposits. Consolidated deltaic deposits provide further varieties of conglomerate sandstone and shale, derived from the coarse, medium, and fine grades brought down by the stream. The ill-drained surfaces of the large deltas, intersected by innumerable distributaries, are usually occupied by swamps in which vegetable matter may accumulate to a considerable thickness. Layers of such plant debris may be modified to produce the many varieties of coal; below many of the coal seams are found fireclays which in some cases represent the old swamp soils impoverished in alkalis and other plant foods which have been extracted by the plants providing the raw materials for the coal seams.

Lake Sediments. Some of the river's load may find a resting-place in lakes. These are only temporary features of the scene and are doomed to be filled up with lake or lacustrine deposits. In the lake, the velocity of the water is checked and the mechanical load is deposited; the coarser materials form the deltas pushing out from the mouths of the rivers, the finer materials, often impalpable muds, slowly settle down over the lake-floor. These lake clays are often laminated by very thin layers of slightly different colour, texture, or composition, and in some cases these laminations are records of seasonal events; a record of a complete year is known as a varve, from the Swedish word *varv*, a complete turn or circle. If, then, we could count a series of these varves lying one above the other we should have a measure of the time taken for their deposition. This

has been done for certain varves formed in connexion with the melting of the ice-sheets which recently, geologically speaking, covered much of Northern Europe and America. The record covers a period of some 25,000 years.

Other varieties of lacustrine deposits obtain their material from the load in solution. The remains of lake organisms may accumulate in sufficient quantity to make continuous beds; siliceous organisms such as diatoms give rise to layers rich in their remains and thus form the rock diatomite; molluscan shells made of calcium carbonate contribute to the formation of lake-marl and are helped by lime-secreting organisms such as algae. Iron salts may be deposited on the lake-floor in nodules or thin bands and give rise to certain kinds of iron ore.

Evaporites. A special set of lake deposits of great interest and importance is laid down in lakes which have no outlets. In such lakes, the load in solution cannot pass through and may become so concentrated as to be precipitated in the form of layers of salts known as the saline residues or evaporites. Depending upon the nature of the rocks in the drainage basin from which the rivers derived their load, salt lakes with waters rich in sodium chloride, sodium sulphate, alkali carbonates, borax, and other soluble salts may be formed. Most of the great salt lakes of the present and the past show, however, by the composition of their waters or of their deposits that their waters were originally sea-water. Bodies of sea-water become shut off from the sea and gigantic natural evaporating basins are

formed in which the solution is gradually evaporated to dryness. In a general way, the salts are precipitated in the reverse order of their solubility, the least soluble first, the most soluble last. The evaporation to dryness of an enclosed body of salt water would leave its record, therefore, as a series of layers of different evaporites—at the bottom a layer of limestone made of calcite, next a layer of gypsum, calcium sulphate, then a layer of rock-salt, sodium chloride, and finally a layer of bittern salts, the very soluble sulphates and chlorides of magnesium and potassium. The interest of the saline residues to us, looking at rocks as historical documents, is that their presence in ancient assemblages of rocks indicates a desert environment at that particular place at a certain time in geological history.

Marine Sediments. We may now follow the river load into the sea. In the estuaries, silts and muds, black with organic matter and finely divided iron compounds, are deposited and, when consolidated, form yet other varieties of clay and shale. In the open sea, sediments of great interest are being laid down which are the analogues of the most important of the sedimentary rocks—the common fossiliferous marine rocks which to-day make great parts of the land-masses. The raw materials for the marine deposits are provided by the river-load, by the wearing down of the coasts, or by transport by ice or wind. The solid materials are in a very general way sorted out into belts parallel to the coasts. Along the shores are formed accumulations

of shingle which, on consolidation, would give the rock conglomerate. The present continents are bordered by smooth submarine plains extending seawards for seventy miles or more. The shallow seas covering these continental shelves are places of vigorous activity; sediments of many kinds are being made there and life is varied and abundant. It is probable that the majority of the ancient marine rocks were formed in shallow seas.

Inshore the medium grained sands are laid down and show by such characters as ripple-marks that they are formed in no great depth of water; pieces of marine shells are common in them. When such sands are consolidated, usually by cementation of some kind, they provide the common marine sandstones. Some marine sands are rich in the green mineral, glauconite, a hydrated silicate of iron and potassium, and these greensands or glauconitic sandstones are common among the marine rocks. Flocculation of iron compounds brought in by the rivers leads to the deposition of other iron-bearing minerals. When sufficiently pure these deposits are destined to form ironstones. In quieter waters or in the deeper waters towards the outer margin of the continental shelves, the finest land-derived material is deposited as mud which, dewatered and compacted, gives the clays and shales of marine origin.

The countless organisms that live in the sea make their shells, skeletons, and other hard structures from the substances dissolved in the sea-water. Most marine creatures utilize calcium carbonate,

and in warm seas in which little land-derived material is deposited their remains may accumulate as shells, shell fragments, shell sand, and dust. Worked upon by cementation processes, these calcareous deposits are converted into the many varieties of limestone. In the tropical seas of to-day, corals and algae are building up coral reefs by the accumulation of their calcareous hard parts; similar action in the past is indicated by the occurrence among the sedimentary rocks of reef-limestones. Other limestones are formed by the consolidation of calcium carbonate precipitated from sea-water and many of the oolitic limestones, made up of spherical grains of calcite, have been made in this way. Marine organisms that build their hard parts of silica, such as diatoms and radiolaria, may sometimes accumulate on the sea-floor in sufficient quantity to form siliceous deposits of diatomite or radiolarite.

Beyond the continental shelves and slopes, the present ocean floor sinks to profound depths and is free from river-borne land-derived material. The deep-water sediments, formed at depths greater than 2,000 fathoms or so, must consist therefore of the remains of organisms leavened with wind-borne material, chiefly volcanic dust. The contributing organisms are the foraminifera and pteropoda, with calcareous skeletons, and the diatoms and radiolaria, with siliceous ones. The deposits are called oozes—an expressive word that exactly fits their physical character. Since calcium carbonate is more soluble in sea-water than is silica, the cal-

careous oozes do not reach such great depths as the siliceous oozes. When the water is deep enough even the siliceous skeletons dissolve before reaching the sea-bottom, so that the deepest part of the oceans is floored by a deposit of decayed water-logged pumice and wind-borne volcanic dust known as Red Clay. This remarkable deposit accumulates with such extreme slowness that certain of its ingredients—meteoritic dust, whales' earbones, and sharks' teeth (some of extinct species)—which can clearly have been contributed only at relatively rare intervals are found in very considerable quantities.

The Pattern of Present-Day Sedimentation. Our survey of the manner of formation of modern sediments and their derivatives, the sedimentary rocks, is now completed. Reference back to the 'flow-sheet' facing p. 27 will enable the common sedimentary rocks to be related to a certain process of manufacture or to a fairly restricted choice of processes. These processes depend upon their environments and we may now view the present environment of sedimentation as a whole.

The pattern of the many environments of sedimentation of to-day is controlled by the pre ent arrangement of lands and seas and their climate and relief, so that the physiography (or what used to be called the geography) of the present determines where and what sediments are made. It would be a fairly simple matter to make a map showing the distribution of the different kinds of present-day sediments, and such a map would not

differ much from a composite of physical and climatic charts. It would indicate, for example, where eolian deposits were being formed, where shallow marine deposits, where estuarine deposits and so forth, and these regions would naturally be related to the present deserts, shallow seas, and estuaries. The geologist uses a term *facies* to denote the total characters of a rock—its composition, texture, structure, fossil contents, and all its other qualities. These characters depend upon how and where the rock was made, so we can speak of an eolian facies, shallow-water marine facies, estuarine facies, and so forth, meaning that the rocks in question bear in themselves the hallmarks of having been formed by wind action, or in a shallow sea or in an estuary. Our map of modern sediments is thus a map of the facies of to-day.

The facies to be shown on our map would be developed from the 'flow-sheet' facing p. 27. The major division would be between the land facies and the marine facies, and in each division subdivisions could be made for any special end. The land facies would comprise the eolian, glacial, fluvial, and lacustrine, the marine facies the shallow water, deeper water, and abyssal. To complete the picture there are the very important facies developed on the hinge, as it were, of land and sea; they are the deltaic, estuarine, and shore facies. When these ten facies have been delimited, we should have an excellent picture of the sedimention of the present time.

Some finicky person might require a demons-

tration of the fact that all the sediments dealt with were 'of the present time'. This would be established by tracing the several facies into each other —by showing for example that a modern deltaic sand gave place one way into a fluviatile sand and another way into a marine sand and this into a marine mud. If the evidence of transition was not acceptable to the critic, we might try to establish the contemporaneity of all to-day's sediments by finding in all of them remains of the most widespread organism of to-day, namely man. Pieces of Spitfires or, more happily, of Messerschmidts, might be found enclosed in all facies of modern sediments and would be just as reliable a guide as the best fossils: to-morrow they will be fossils. This process of establishing the contemporaneity of deposits or facies is called *correlation* and on both large and small scales is the chief preoccupation of the geologist concerned with sediments or sedimentary rocks.

Patterns of the Past are Earth-History. It is admitted, then, that the facies pattern of to-day could be established; the basic work has in fact been done already by the cartographer and meteorologist. To-day's pattern, however, is slightly different from yesterday's, and the pattern of to-morrow will be slightly different from to-day's since the processes of weathering, erosion, transport, and deposition work continuously, even though their action is exceedingly slow. The shallow sea, for instance, is daily becoming shallower by the day's deposit and the shallow-sea facies is changing into

a shallower-sea facies. The facies pattern of to-day gives a record of to-day's events in the history of the earth. The whole history of the earth will be recorded by a sequence of innumerable facies patterns joined up, as it were, into a continuous film. Just as the sediments forming now give a record of the present so the sediments formed previously give a record of the past. These ancient sediments are the sedimentary rocks. By investigating these, the geologist deciphers as many of the former facies patterns as his knowledge permits. He applies the doctrine of uniformitarianism to the sedimentary rocks and, from their facies, he attempts to reconstruct the environments of past sedimentation for innumerable instants of time in the history of the earth.

The geologist could perform this his supreme task with great satisfaction if he knew all about the past and all about the present and if he were sure that processes in the past had always gone on like similar processes at the present. These provisos are by no means fulfilled. To begin with, it is difficult to investigate many very important processes of modern sedimentation, as, for example, those in the deeper parts of the sea—yet marine sediments have always predominated throughout earth-history. Further, as we see immediately, few rocks of the crust have preserved without change the characters they possessed as raw sediments; the change sediment to sedimentary rock is in most cases a real change and may lead to the partial obliteration of the original diagnostic features. Again, the pro-

cess of metamorphism may completely destroy the original nature of any rock. Besides, ancient sediments can never be revealed in their entirety but must be more or less concealed beneath younger accumulations. Lastly, it is likely that the present is, geologically, abnormal in that it is a sample of geological time which is only typical of a small percentage of the whole; reasons for this opinion are given later. At present, the continents probably stand higher than at any previous time in the history of the earth and certain geological processes are accordingly different in their rate, if in nothing else. The earth has proceeded with its physical evolution during its existence and past physical controls may not be exactly like their analogues of to-day. Organic evolution, too, has been a continuous process and the earth's flora and fauna have changed with time. For example, the spread of the grasses, a geologically recent event, must have led to a marked change in the extent and nature of earth-sculpture and the consequent erosional and depositional operations. All these criticisms, and many more, are doubtless justified. It is certain that uniformitarianism is not perfectly true for all time. Nevertheless, there is no other key and we must do our best (and it is really a very good best) with this one. While remaining always humble and watchful, we should find comfort in the likelihood that the wind has for a very long time blown as it does now, that rivers have run as they run now, that ancient waves were much like modern waves, and that a sand grain, for example,

fell through water when nothing alive had been created to see it, just as it falls through water in front of the ciné-camera. We must cling to uniformitarianism so long as our conscience permits.

The Records may be Obscured. It has been mentioned that the sedimentary rocks, as they are now exposed making the earth's crust, are in most cases different from the newly formed sediments from which they are derived. This difference results from a variety of operations. Pressure, as for example that of overlying beds, may lead to hardening and compaction of the raw materials by the welding together of the constituent particles or by the expulsion of water. Marine rocks are free from salt, though marine sediments are deposited in salt-water. Solutions of various origins moving through the porous materials of the crust set in motion great changes. From them, cementing materials may be deposited in the pores, and a loose incoherent sediment such as sand converted into a hard rock such as sandstone. Concentrations of particular substances result in the formation of concretions such as those of flint in chalk. Chemical reactions and replacements may be so complete as to modify profoundly the sediment acted upon. Recrystallization is brought about especially easily in rocks made of the more soluble minerals; an accumulation of shell fragments, made of the relatively soluble mineral calcite, calcium carbonate, may be recrystallized into a coarse mosaic of calcite grains from which all trace of shell fragments has disappeared. Compaction, cementation, replacement,

and recrystallization may thus disguise to varying degrees the original nature of the sediments from which the rocks as we now view them were derived. Time by itself does not make a sediment into a rock —some of the most ancient sediments are still incoherent accumulations—but a selection of these special processes is necessary. The technical name for these processes of rock-making is *diagenesis*.

The application of the principle of uniformitarianism to the sedimentary rocks may thus be greatly hindered by diagenesis. It may be made impossible by those more profound changes, referred to in the previous chapter, produced in rocks by the operation of metamorphism. Diagenesis works at temperatures and pressures not much unlike those of the earth's surface, whereas metamorphism involves high temperatures and strong pressures and, on many occasions, vast quantities of powerful fluxes and reagents. All this means that sedimentary rocks subjected to metamorphism may lose such original sedimentary characters as may have survived diagenesis. We should render homage to the sapient Hutton who, in spite of these difficulties, recognized bedded rocks among the metamorphic group. The metamorphic rocks are very widespread in the earth's crust and many of them are of great antiquity. These early pages of earth-history will always be difficult to decipher and will often be illegible.

Though diagenesis and metamorphism may reduce the evidence of a rock's origin and our own ignorance limit our interpretation of what remains

visible, still we can apply the key of uniformitarianism with success sufficiently often to make the doctrine our fundamental principle in the reading of history in the sedimentary rocks.

Additional difficulties in the reconstruction of the environments of past sedimentation result from disturbance of the earth's crust during the violent revolutionary periods of earth-history which we examine in a later page. As a consequence of these, the original order of the sedimentary rocks may be upset or gaps produced in their succession. In spite of all these difficulties, the interpretation of the sedimentary rocks as historical documents has given a surprisingly certain and complete record.

The Records in Space and Time. This record may be examined in two ways, as regards place and as regards time. The changes in the facies of one time as they are followed from place to place yield a picture of the geography of that time, and *palaeogeographical maps* are made exhibiting the distribution of lands and seas, mountains, deserts, lakes, and other physical features existing during the formation of the facies of any particular time. On the other hand, at any one place, a sequence of facies is provided by the succession of the sedimentary rocks present at that place. A sequence of facies therefore gives a record of the changes of the geography and fauna of any particular place, and these changes over the whole globe constitute earth-history. These two aspects of facies changes may be broadly generalized as follows: horizontal

changes of the facies of one time reveal the geography of that time; vertical changes of the facies of one place reveal the changes in the geography of that place. We may now develop and illustrate these two concepts.

Space. Perhaps the most famous group of rocks in Britain is the Old Red Sandstone, known to many either from the classic descriptions of Scottish scenes by Hugh Miller or from the equally classic description by Bret Harte of the conduct of scientific debate on the Stanislaw on the other side of the Atlantic when, it will be recalled, the proceedings interested a participant no more after 'a chunk of Old Red Sandstone caught him in the abdomen'. The British Old Red Sandstone consists of a great accumulation of red sandstones, breccias, and conglomerates with intercalations of flagstones and shales which contain fossil fish. These fish are very remarkable in that some of them possessed internal breathing organs like lungs; they can be compared with the present-day lung-fish of Australia which can live through periods of drought by burying itself in moist mud. Apart from remains of primitive plants, few other fossils are found in the typical Old Red Sandstone. From the detailed examination of the nature and relationships of the sediments, especially the coarser varieties, and of the fossils—that is, from the facies of the Old Red Sandstone—it can be concluded that it was deposited on a land under semi-arid conditions. Torrential floods sweeping out from the mountains of the time spread debris

in great sheets over the intervening hollows, some of which were occupied by transient lakes in which lived the lung-fish and his contemporaries and along whose shores grew the primitive land plants. This Old Red Sandstone land must have resembled parts of Central Persia of to-day.

This land-facies of the Old Red Sandstone is well developed in Scotland and it is represented to the south in Herefordshire by the red rocks of that county. Rocks of the same age in North Devon on the other side of the Bristol Channel show significant differences: a few bands are of Old Red Sandstone facies but most of the deposits of the time in this position are clearly of marine origin—they are coarse sandstones, shales, and thin limestones with marine fossils. Here is clearly a mixture due to oscillations of the sea-margin of a land-facies of Old Red Sandstone type and a marine facies, which is called the Devonian type. In South Devon, the marine facies alone is found and the Devonian rocks were deposited in a cleaner and possibly deeper sea than those farther north, since they now consist of shales and thick organic limestones. This marine facies of the Devonian can be traced over wide expanses of Southern Europe and indicates a Devonian Mediterranean. Detailed investigation of the facies changes in subdivisions of the Devonian rocks in Western Europe throws further light on the distribution of land and sea during the deposition of this group of rocks. In Figure 3 is presented a reconstruction of the geography of the time during which the lower parts

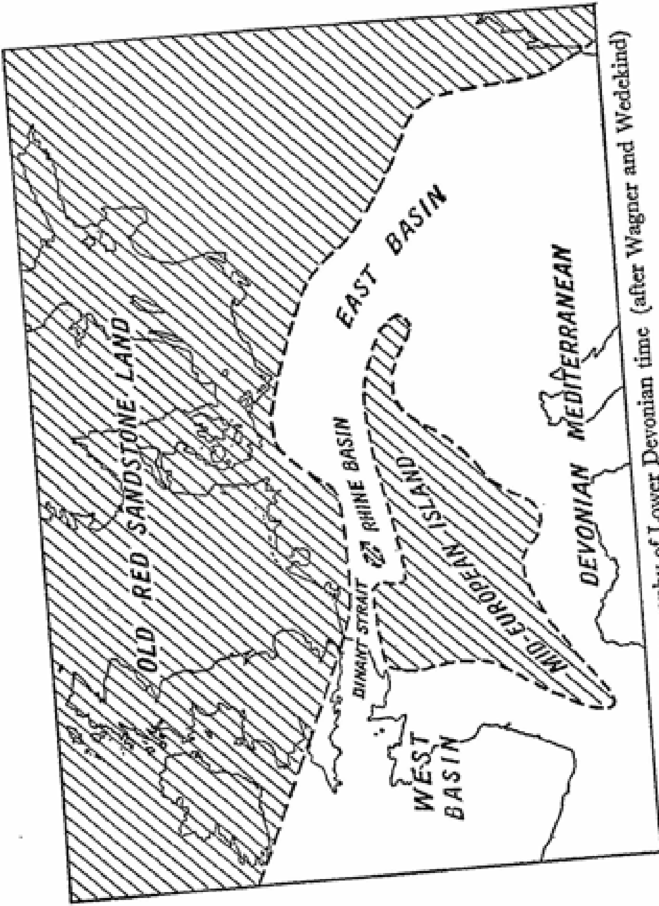


Fig. 3. Palaeogeography of Lower Devonian time (after Wagner and Wedekind)

of the Devonian rocks were formed. This is an example of a palaeogeographical map and is based, as we have seen, upon the changes of facies of one group of rocks formed at one time as it is traced from place to place; the rocks have revealed the geography of their time. Two points immediately arise for discussion.

The first point is concerned with the establishment of contemporaneity of the deposits, that is, with their correlation, to use the technical term. This is attempted in several ways. So far as exposures permit, the different facies are traced into one another directly; assemblages of fossils of one kind or another are matched up; the beds next younger and those next older are traced and correlated and it is concluded that what is in between these upper and lower boundaries is Devonian or Old Red Sandstone. The second point arises from this last remark: the time taken for the formation of the Devonian rocks as a whole can be reckoned in a way we deal with later in this chapter, and is suggested to be 40 million years; we have previously decided that the facies-patterns are changing daily; a palaeogeographical map labelled Devonian or even Lower Devonian can therefore bear only a superficial resemblance to a present-day geographical map—the time units dealt with are of different orders, 40 million years and one day. This criticism is of course completely justified and a geologist expert in Devonian stratigraphy would be the first to admit it. With the advance of detailed knowledge of the Devonian rocks, or of

any other rocks, it is hoped to deal with the facies changes in smaller and smaller sets of rocks and so to produce palaeogeographical maps averaging out the geography of smaller and smaller units of time. The ideal would be the correlation of facies changes indicated by the product of one act of sedimentation throughout its area of action. The attainment of this ideal is still far in the future, but for some subdivisions of the stratigraphical record dealt with in palaeogeographical maps the time interval has been cut to a small fraction of that of the example used here. We may now leave the consideration of horizontal changes of facies of one time to deal with the significance of the vertical changes of facies at one place.

Time. The development of the idea that there might be an ordered succession in the sedimentary rocks has been summarized in the preceding chapter. These ideas culminated in the fundamental generalizations of William Smith. Vertical changes of facies are recorded by vertical changes of rocks; at once Smith's 'law of superposition' is used in interpretation—the rock originally at the bottom of the series is the oldest and is succeeded upwards by successively younger beds. So soon as the sedimentary rocks are viewed as deposits then the law of superposition is obvious. At any one place, then, it can be established by patient piecing together of the evidence afforded by the field exposures that the sedimentary rocks occur in a definite sequence; in the absence of proof to the contrary, it is established that this sequence is the

original order of deposition, so that the changes of facies vertically can be read off in the changes of the rocks and interpreted as changes in geography of the place. Two significant types of changes have been registered time and again in geological history by the sedimentary rocks and must be examined and understood before other examples are considered.

The first type is the record of the advance of the sea over the land leading to the deepening of the sea at any particular place: this phenomenon is called a *marine transgression*; the retreat of the sea from the land is a *regression*. We may deduce how these two movements of the sea-level are revealed in the succession of the rocks. Consider a transgression first. The record at any one place might begin with beach deposits made up of pebbles of older rocks and constituting the rock conglomerate. As the transgression developed, shallow water deposits are laid down on the beach deposits and could be represented in the rock-succession by sandstones, often ripple-marked or glauconitic. The sea continuing to spread, deeper-water deposits are formed on top of the shallow water ones, so that the sandstones are found passing upwards into shales, consolidated deeper-water muds. The record (Fig. 4) of the transgression is provided by the succession conglomerate: sandstone: shale—a witness to beach: shallow-water: deeper-water at that particular place. Now consider the regression. The deep sea is replaced by a shallower sea and finally by land. Deep-water sediments are suc-

ceeded by shallow-water ones, these by estuarine or beach deposits and the episode may close, when emergence is complete, by the formation of deposits in lakes, rivers, deserts, or other environments on the new land. The record (Fig. 4) of the regression might be given by the succession—marine shale: marine sandstone: estuarine shale:

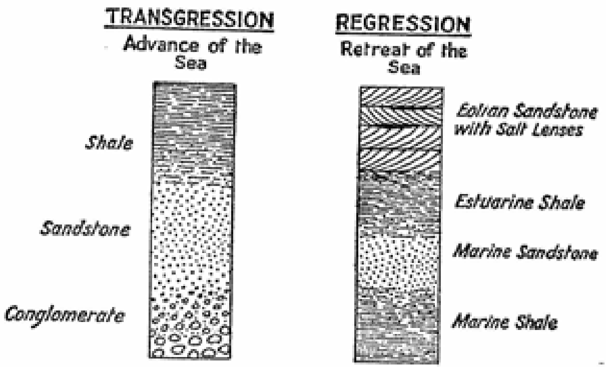


Fig. 4. The Succession of the Rocks recording a Transgression and a Regression

eolian sandstone with salt beds and marls. These deductions and examples are clearly over-simplified. As will be readily admitted, complications may arise through a variety of causes as, for instance, halts or even reversals in the progress of the movement and changes in the relief of the contributary lands. When we study later on certain episodes in geological history in detail we shall employ the simple rules we have just been following. Now we

consider certain other aspects of the consequences of the advance and retreat of the seas.

The Transgression. As a transgression proceeds, the sea comes to cover more and more of the land-areas, and the successive areas of sedimentation are accordingly enlarged. The later members of transgressive rock-series, therefore, have a greater extension than the earlier, and any one bed may *overlap* (to use the technical term) the bed below. The overlapping beds may rest *unconformably* upon the rocks which made the land surface over which the sea has advanced. These relations may be made clear by a consideration of the geological consequences of sinking England or Eire or Germany or whatever country one would like to see sunk. The land masses, as will be shown later, are made up of rocks which have been disturbed to greater or lesser degrees during the revolutionary periods of earth-history: the beds of sedimentary rocks may have been folded so that they no longer have their original horizontal attitude: all the rocks of the land-masses have, moreover, been subjected to those agents of weathering and erosion whose work we have already examined, and great portions of them carried to the sea. Sedimentation on the floors of the shallow epicontinental seas may continue without interruption during a transgression, so that the records are complete and the rock-succession is a *concordant* one. As soon as the transgressive sea begins to cover the land, however, its sediments are deposited on the deformed and eroded rocks of the land-areas, part of the record

is missing, and the newer rocks rest *discordantly* or *unconformably* upon the old rocks of the land. From the overlapping relation of the successive beds the direction in which the sea was advancing can be deduced.

We may display their relationship, and prepare for others which come up for discussion immediately, by trying to represent what might be the arrangement of the sediments deposited in the sea if it were to advance northwards from Brighton across the Weald to beyond London. The *section*,

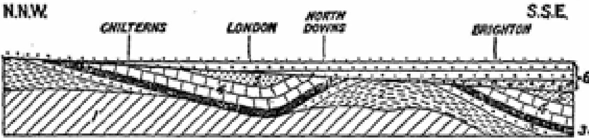


Fig. 5. A Hypothetical Transgression from Brighton northwards

1, Palaeozoic. 2–4, Cretaceous. 5, Tertiary (Eocene, etc.). 6, New Transgressive series.

as the geologist calls it, given in Figure 5, demonstrates the ascertained fact that the Weald and the London area are made of a series of sedimentary beds which have been gently folded into an arch and a basin. Permit the agents of erosion to plane off the rocks into a more or less level surface, sloping gently southwards, across which the sea advances northwards from Brighton. In this transgressive sea might be deposited a series of overlapping deposits, conformable on the site of the Channel, unconformable on the old rocks farther north. Similar relationships are found time and

again in the great pile of sedimentary rocks and they record the same events as our proposed Brighton transgression. In fact, what is possibly the greatest of all transgressions in earth-history, one dignified by the name of the Cenomanian transgression, is revealed in the rocks making the Weald and labelled Cretaceous in Figure 5. You are by now equipped to read the fifty or so million years of earth-history recorded by these Cretaceous rocks. Let us proceed.

A Great Inundation. The Cretaceous rocks of the Weald rest upon a group of beds of limestone, calcareous sandstones, shales, and gypsum, in the main of terrestrial facies and deposited upon a land-mass. The earliest Cretaceous rocks give evidence of their deposition in a Wealden lake; these *Wealden* beds are clays and sandstones with freshwater fossils. They are succeeded by the *Greensand*, a marine glauconitic sandstone—the Wealden lake had been drowned by the rising sea. Next follows the *Gault*, a marine clay, and then the characteristic Cretaceous rock, the *Chalk*, a marine limestone. The transgressive nature of the Cretaceous sea is revealed by the progressive extension of the area of deposition of its sediments, an extension evident even in so small an area as South-east England. Thus, deep borings in London show that the Gault is the earliest Cretaceous rock to be deposited there—the Greensand sea had not advanced so far north, and not till Gault times did the ridge of old rocks beneath London become submerged. This extension of the Cretaceous sea

was not confined to South-east England but is recorded from all over the world. It is this world-wide advance of the sea over the lands that provides the interest and importance of the Cenomanian transgression and we may now briefly consider this remarkable event in earth-history.

In the British area, marine sediments of Upper Cretaceous age were deposited over a very much wider area than the Lower Cretaceous. They overlap the older rocks of this group and, farther afield, are found lying on rocks of a much greater antiquity. Outlying beds of Chalk and associated sediments occur in Northern Ireland and in the Western Highlands of Scotland. The deduction is warranted that the transgressive seas of the Upper Cretaceous spread over most of the British Isles, though, admittedly, stretches of ancient rocks remained as islands in the waters. From the British region, this shallow sea extended over great areas of Southern Europe as vast bays and gulfs penetrating between lands of old rocks such as the Ardennes, the central plateau of France, Bohemia, the Balkans, and other projecting relics. Denmark and Southern Sweden were inundated and the northern coastline of this vastly expanded Mediterranean ran from Scania across Russia and beyond the Caspian into the Himalayan region. To the south, the sea swept into the heart of the African land-mass and Upper Cretaceous marine sands were deposited in what is now the Sahara. Farther to the east, Syria, Irak, and Iran were covered and the sea extended by way of the Himalayan region

and Burma to the Indian Ocean. Important, but less spectacular, marine invasions are recorded by the Upper Cretaceous rocks of East Africa and Madagascar, of Peninsular India and the East Indies, of Australia, Japan, and Eastern Siberia.

A similar story of the drowning of great expanses of the land areas beneath the waters of the Upper Cretaceous sea is revealed by the rocks of this age in the Americas. By the time of the maximum transgression, the shallow sea had made not only broad incursions over what are now the coastal areas of the Atlantic and Gulf states, but had spread as a wide strait from Mexico to the Arctic over the site of the present Rockies (see Fig. 26). Similarly, in South America, the position of the Andes was occupied by the Upper Cretaceous sea and less extensive marine invasions occurred on the Southern American land-mass.

At this time, then, the shallow seas of the Cenomanian transgression had advanced across vast expanses of the lands of all parts of the globe. The movement of the shoreline was a worldwide event —a fact that must control speculation as to its cause and to the cause of such movements in general. There is no general agreement on this question, the diversity of opinion arising from different estimates of the strictness of the contemporaneity of the movement in different parts of the globe and of its universality, steadiness, and regularity. Attraction of the masses of the waters by the continents or movements of the water as a consequence of changes in the velocity of the

earth's rotation are ruled out as explanations by the known distribution of the transgressive seas of various times. Slight movements of land-masses up or down would give rise to great regressions or transgressions, and some geologists, impressed by the tilted elevated shorelines of Scandinavia, favour some such mechanism. Others call upon movements of the ocean floor, either as an aftermath or as a precursor of a revolutionary episode. Subsidence results in a regression, elevation in a transgression. An influential school relates the transgression to the accumulation of sediments upon the ocean floor so that the waters overflow on to the lands. It is not a confession of defeat to propose that these and other causes, working sometimes together and sometimes against one another, may supply the complex conditions for advances and retreats of the seas. Such occur, whether we believe we have explained them or not.

The Regression. We may now consider certain aspects of regressions. We have already noted that the succession of rocks recording a retreat of the sea may end with land deposits. As soon as the land emerges from the sea there is a chance of a break in the record of sedimentation. There may be no deposition at a particular place so that certain pages of geological history were never written there. The new land is more likely to be subjected to erosion and some of the rocks making it removed so that certain pages of history, though written there, have been destroyed. The sediments laid down in a later transgression will rest, as we have

already seen, *unconformably* on the older rocks and there is a *break* in the succession of strata.

An example of such a break in the record of sedimentation is revealed by the relation in South-east England between the Cretaceous rocks and those labelled Eocene displayed in Figure 5. Eocene time in this region was characterized by an advance of the sea from the east during which the Eocene rocks—the most famous of them is the London Clay, that haven of safety for the bombed-out—were deposited in succession farther and farther to the west. Detailed investigation shows that the base of the Eocene beds is not in contact everywhere with the same bed of the Chalk below. In different places the Eocene rocks rest on different subdivisions—or zones, to use the technical name—as determined by their characteristic fossil contents. From this, geological history after the Cenomanian transgression can now be read: the chalk beds deposited during this transgression must have been warped into a series of gentle flexures and the upper parts of this removed by denudation before the advance of the Eocene sea. The extended history for South-east England is accordingly Cenomanian transgression, deposition of the Chalk, then regression, slight folding and erosion, and then the Eocene transgression.

The flexuring of the Chalk just considered is only on a gentle scale and the discordance between Eocene and Cretaceous rocks is revealed only after careful work. Transgressions following the major revolutionary periods of earth-history provide

much more spectacular displays, for, as we see later, during these periods the rocks have been subjected to violent disturbances of folding, contortion, and fracturing. Transgressive beds deposited upon the bevelled folds and fractures of such a basement may complete the evidence for breaks of worldwide significance. An unconformity of this spectacular type enabled Hutton to draw his noble conclusion concerning a 'succession of former worlds' and in Figure 2 has been given a drawing of the unconformity used by him.

The Problem of Permanence. From the foregoing, the impression has been obtained of the constant interchange during geological time of land and sea over great areas of the crust. Mountains have taken the place of seas, and seas have invaded the worn-down once mountainous lands. For the most part, the facies of the marine rocks now found in the land-masses clearly indicate that the transgressive seas were shallow. The invasion by shallow seas of low lands is a fact reasonably admitted by all. What is a subject of vigorous debate, as it has been for a century, is whether the really deep parts of the ocean floor have ever been raised to make land or the land sunk to make ocean deeps. Are the earth's major features permanent or not?

As we have seen, the deposits forming to-day on the floors of the deepest ocean have a characteristic and peculiar facies. The Red Clay and any rock made from it would provide marine rocks of so striking a type that they would be readily recognized and interpreted. Such abyssal deposits have

not been identified as taking part in the structure of the continents. It is true that at certain localities in the East and West Indies rocks of seemingly abyssal facies are found, but these areas are exceedingly unstable at the present time and local upheavals of even deep parts of the ocean floor may be admitted as possible. The virtual absence of abyssal rocks from the pile of sediments making the continents, indicates to many geologists that the ocean deeps have never been raised up to make land. The argument collapses if it is substantiated, as is suggested by some, that the Red Clay and associated deposits are peculiar to present-day sedimentation and were not formed at all in the past.

A survey of the old sedimentary rocks reveals that they are dominantly of shallow-water type. Unless we assume violent fluctuations in the amount of water in the ocean, it seems reasonable to believe that deeps to contain the oceanic water have been in existence for a great length of time. If oceanic deeps are thought to be raised up, other oceanic deeps have to be made to receive the water. When in later chapters we consider the constitution of the earth's crust, we find, *first*, that columns of the crust of the same cross-section are in balance (in *isostatic equilibrium* is the technical term), and, *second*, that the continental masses are comparable to rafts of lighter material buoyed up or floating in a continuous denser layer which underlies the continents and floors the oceans (see Fig. 16). In a crust made in this way, the replacement of

oceanic deep by a land-mass would clearly be a chemical and physical operation of gigantic magnitude requiring forces of enormous power and producing worldwide results of a patently revolutionary character.

Many geologists therefore prefer to believe that the sites of the deep oceans were established early in the earth's history, but even those who are of this opinion are obliged to contemplate the crossing of the deep oceans by a variety of land-connexions—*land-bridges*—at intervals throughout geological time. The distribution of plants and animals, both modern and ancient, is responsible for this amendment. There are, for instance, certain remarkable correspondences in the faunas of various ages on the two sides of the Atlantic. On many occasions, the arrangement of the facies on what are now the two shores has been alike. We have, for example, the surprising fact that a group of ancient sedimentary rocks in the North-west Highlands of Scotland bears little resemblance either in lithology or fossil-contents to rocks of the same age deposited in Wales, but is very like a group found in the Eastern United States. Such examples could be multiplied and when reinforced by the study of the migrations and relationships of fossil plants and animals lead to the proposal that land-bridges are necessary. Along such bridges or along their shores the animals could move to give these cross-Atlantic similarities. The mechanical difficulties of sinking such land-bridges are considered to be very much less than in raising an

abyssal floor and especially when the notion of the stepping-stones of an archipelago is substituted for that of the continuous bridge.

A standard opinion, then, is that the permanence of the greater features of the earth is beyond debate. For a great part of geological time, continents and oceans have had more or less the same general shapes and positions as they have now. Their outlines have been trimmed and moderately modified only. Admittedly there have been formed at various times rather unstable zones where subsidence and upheaval have undoubtedly occurred, but such zones are *sui generis*, neither true deep ocean nor true continent. We can postpone the consideration of these labile belts of the crust till we deal with the revolutions that illustrate their fates and content ourselves with restating the standard opinion favouring permanence of ocean deep and continental mass.

During the last few decades, however, standard opinion has been assailed from an unexpected quarter. In this period, the development of what is known as the theory of *continental drift* has queried the whole basis of permanence. As we shall examine this theory in a little detail in later pages, we need do no more than introduce it and indicate its implications now. The possibility of the light continental rafts floating upon a denser continuous substratum has been mentioned in an earlier paragraph. On the theory of continental drift, it is proposed that these rafts can move, take up new arrangements and change their positions relative

to the poles. At one time all the now separated continental fragments were collected into one great land-mass, so that the major features of the earth were simply one ocean and one continent. The continental mass was broken and the fragments have drifted apart and taken up their present positions (see Fig. 18). The Atlantic is the much enlarged fissure produced by the Americas drifting away westwards from the Old World land-masses. If continental drift has occurred, the arrangement of ocean deeps and continents is changing continuously and the earth's major features are by no means permanent.

This brief discussion of the problem of permanence has raised a variety of topics in earth-history, some of which we consider later. It serves to illustrate the character of many geological questions. In investigation of the materials of the crust the exact methods of physics and chemistry are employed where they are appropriate, but in the study of earth-history there comes a time when these methods cannot be used. The geologist then considers a complex tangle of different styles of evidence and endeavours to draw reasonable conclusions from it. His methods are geological and, in all geological problems, are superior to those proper to any other science.

Dividing the Record. We now leave these stirring topics for the more sober one of the division of the record of the earth's history into manageable portions. Geological history, like human history, is a continuous narrative, and in both there must

be an element of artificiality in their subdivision. The accessions of most kings have not disturbed the current of human history and such ripples as they have produced have been felt over a restricted compass; it is possible for example that even 1066 is a date without special significance in the story of eleventh-century China. Likewise, many geological events important in the record of one of the Western European countries where the subdivisions were first made may have left little trace in America or Australia. The stupendous span of earth-history must, however, be broken up in some way even though the pieces may require trimming before they fit all regions of the crust.

In the previous chapter we noted the beginnings of a division in the record in the work of Lehmann, Füchsel, Werner, and others. Terms such as Primitive, Transition, Floetz, and the like came to acquire an age-significance in addition to their original lithological import. But it was the genius of Hutton that provided the fundamental advance. His interpretation of the unconformable relations between the rock-groups of the Berwickshire coast as indicating a 'succession of former worlds', meant in terms of earth-history that a revolutionary period separated two lengthy periods of sedimentation. The earlier of these periods was the *Primary*, the later the *Secondary*, in the old usage of these terms. A third division, younger than the Secondary and styled the *Tertiary*, was erected by the French geologists early in the nineteenth century to indicate the time of deposition of the

rocks of the Paris area which succeeded the Chalk. Soon the fossiliferous rocks came to be accommodated in three groups called Primary, Secondary, and Tertiary, though the limits were not the old ones. This grouping acquired stability when the life characteristic of the three groups was compared and contrasted. It was found that the oldest group contained fairly simple shells and the earliest kind of fishes; that in the middle group pride of place was taken by the reptiles; and that the latest group was characterized by mammals. The general aspect of the life of the three main *eras* was so distinct that catastrophic extinctions and new creations were envisaged. The obviously profound changes in the style of the earth's inhabitants appeared to coincide with the revolutionary, unconformity-making, episodes and as a consequence the tripartite classification of the fossiliferous rocks became so firmly established that it is the one still employed, though many of its foundations have since been shown to be insecure. Soon a second set of three names, reflecting the differences in the organic world during the three great eras, was proposed: Palaeozoic (Ancient Life) for Primary; Mesozoic (Middle Life) for Secondary; and Cenozoic (Recent Life) for Tertiary. Present-day usage is Palaeozoic, Mesozoic, and Tertiary—a usage indicating either a robust, even though illogical, spirit of independence among geologists, or else (what is more likely) a consequence of their inability to spell Cenozoic (Caenozoic, Cainozoic, Kainozoic) at all consistently. The three main divisions of time

recorded by the fossiliferous rocks are thus the Palaeozoic, the Mesozoic, and the Tertiary eras. We may now examine more closely some general questions arising from this subdivision.

Though admittedly the life of the three eras was different, there can be no question of sudden extinction and replacement of faunas. There has been a continuous evolution of organic beings, and the impression of breaks in this orderly succession results from the quickened rate of evolution during the revolutionary periods of earth-history. Extraordinary movements of land and sea then tried the inhabitants, modifications adapted to the new and rigorous environments had to be rapid to be successful, and a new creation seemed suddenly to replace the old. But somewhere or other the evolutionary sequence was complete.

As we have seen, the break in sedimentation registered by an unconformity may be of so striking a character that it was naturally used, when correctly interpreted, in the partition of earth-history. But this kind of break can be only of local importance, since we cannot conceive of the revolutions that give rise to it affecting at one time the whole crust of the earth. The gap in the history represented by the unconformity must be bridged somewhere. In spite of its defects, however, the stratigraphical break was used, and still is, as a basis of division in the rock-succession.

The break is but one result of disturbance in the earth's crust and other consequences may provide less restricted criteria for our subdivision. During

the revolutionary disturbances, the land-masses become broader and higher—a condition recorded by a regressive series of rocks. Material is now removed by erosion from the raised land-masses to the sea-basins, with the result that the waters spill over on to the lowered land—a condition recorded by a transgressive series of rocks. The oceans are connected, so that changes in sea-level must be worldwide. Here, then, appears to be an ideal method of subdividing our record: a standard unit of geological history should be that of one transgression and one regression. These movements of sea-level profoundly effect the course of organic development. Restriction of the seas, extension of the seas, changes in marine currents, in temperatures and in the arrangements and connexions of the minor seas, provide critical conditions for life. As a consequence, successive faunas may be developed with significant characteristics depending upon the changing marine environments of their formation. Accordingly, both the lithology and the fossils of the rocks assist in the employment of transgressive or regressive series in the classification of geological time. Unfortunately, worldwide movements of the sea-level are most likely not such simple events as we have just supposed. It is probable that a great transgression, for example, is a very lengthy affair, proceeding in some cases in a jerky fashion and complicated by independent movements of the land-masses. In spite of these defects, major movements of sea-level are clearly of great importance in earth-history and are to be

used where possible in dividing geological time. Inspection of the old established divisions shows that some are ideal—transgression plus regression —others have two or more such flows and ebbs, and others only a portion of either. We must make the best of things.

We have already noted the necessity of a continuous evolution of organisms during the formation of the fossiliferous rocks and have examined the possibility of a relationship between this organic evolution and the progress of physical events. It follows that there should be a succession of faunas or floras each characteristic of a more or less well-defined period in earth-history—a conclusion established empirically, as we have seen, by William Smith. It is along these lines of biological change with time that a satisfactory classification of the rock-record is to be reached. To this end, it is clearly necessary to deal with marine rocks deposited in deeper waters, since sediments laid on land or in the shallower seas may supply only an incomplete record. Standard continuous sequences of such rocks have to be established and their fossil contents at innumerable horizons investigated, so that these portions of the geological record are *zoned*. Zoning is the splitting up of the series of rocks into small subdivisions characterized by a certain fossil or fauna; it is possible because of the complexity of organic evolution. Nowhere, of course, can the whole colossal thickness of the sedimentary rocks be found piled up in succession into one continuous column.

The sequence has to be laboriously assembled piecemeal by detailed correlation of various sets of beds from place to place until the complete *stratigraphical column*, as it is called, is built up. The fundamental work is the zoning; different parts of the stratigraphical column have now been zoned with differing degrees of refinement and zoning still goes on. The types of zoning employed for rock-series of various ages are illustrated in later pages. It is sufficient to realize now that detailed investigation of the fossil contents of the sedimentary rocks leads on the one hand to their matching or correlation and on the other to their differentiation into their age-groups.

After these counsels of perfection, it is chastening to find that the actual subdivisions of the stratigraphical column in everyday use are a very mixed assemblage, built up in a variety of ways. Many of the phenomena employed are local—the rocks, or their fossils, or their unconformable relations seen in restricted areas of Western Europe. But in spite of the seemingly haphazard nature of the collection, the subdivisions have for the most part attained a stable worldwide application. We have already noted the division of geological time recorded by the fossiliferous rocks into the three eras Palaeozoic, Mesozoic, and Tertiary; the next subdivision of time is the *period*, recorded by a set of rocks known as the *system*. It is the geological systems that we have had in mind in most of the previous remarks. Our first classification of the sedimentary rocks as records of earth-history is

presented in Table 1 on p. 71, and we may now introduce the nomenclature of the systems shown there to illustrate the variety of their sources.

Let us begin near the bottom of Table 1 with the period named Cambrian. The rocks deposited during this period contain the oldest fossils so far discovered, apart from a few disputed and problematical forms found in still older beds. The oldest fauna of the Cambrian rocks is characterized by a particular genus of a group of animals, now extinct, known as trilobites (see Fig. 20); the genus in question has been given the name *Olenellus*. The purpose of this preamble is to define a lower limit of the Cambrian rocks, and this limit is taken to be the beds containing the *Olenellus* fauna. Whilst the *Olenellus* beds are the oldest fossiliferous rocks they are by no means the oldest rocks. They are found to lie unconformably on a great assemblage of still older rocks which might reveal, if we could decipher it, a history perhaps three times as long as that read from the Cambrian and all the succeeding fossiliferous rocks. This complex series of rocks older than the *Olenellus* beds has received a variety of names and has been subjected to a variety of classifications mainly of doubtful validity; in this book, we propose to call them all by the simple and excellent term *Pre-Cambrian*—excellent because it expresses the demonstrable fact that these rocks are older than the Cambrian. The base of the stratigraphical column, then, is made of the Pre-Cambrian.

This is a convenient opportunity to note in

TABLE I

FIRST STATEMENT OF EARTH-HISTORY

		Geological Period	*Duration (in million years)*	*Age*
		Pleistocene	1	
TERTIARY	Neogene	PLIOCENE	14	
				15
		MIOCENE	20	
				35
	Palaeogene	OLIGOCENE	15	
				50
		EOCENE	20	
				70
MESOZOIC		CRETACEOUS	50	
				120
		JURASSIC	30	
				150
		TRIASSIC	40	
				190
PALAEOZOIC	Newer	PERMIAN	30	
				220
		CARBONIFEROUS	60	
				280
		DEVONIAN (Old Red Sandstone)	40	
				320
	Older	SILURIAN	30	
				350
		ORDOVICIAN	50	
				400
		CAMBRIAN	100	
				500
PRE-CAMBRIAN				at least 1,750

parenthesis a usage of such words as Cambrian, Devonian, and the other divisional names which may have puzzled the reader. It is the practice of geologists to use these words both as adjectives and as nouns. We talk of the Cambrian System, the Cambrian Period, or a Cambrian rock or fossil; we also talk of the distribution of the Cambrian, the facies of the Cambrian, or the fauna of the Cambrian. This is a very convenient practice and does no harm.

Inspection of the column of Table 1 shows a set of three periods, *Cambrian*, *Ordovician*, and *Silurian*, which together make the older part of the Palaeozoic era. Rocks of these three systems are well developed in Wales and the Welsh borders, where they were investigated over a century ago by Murchison and Sedgwick. The Cambrian is named after North Wales, where Sedgwick first studied rocks of this age; the Ordovician and Silurian are so called from the countries of two Celtic tribes, the Ordovices and the Silures, in which rocks of these systems are displayed in classic sections.

Following the Silurian, comes the *Devonian* period. In an earlier page we have used the rocks of this system to display a notable contrast in facies in the British area and the employment of facies-differences in the construction of palaeogeographical maps. The name of this period is Devonian, derived from the locality where the marine facies of rocks of this age was studied by the early masters. The non-marine facies in Britain is that of the Old Red Sandstone, a descriptive name implying that

there is a new red sandstone as well. The Devonian is succeeded by the *Carboniferous* (coal-bearing), another descriptive name recording the occurrence of beds of coal amongst the sediments of this system. In Britain, the Carboniferous rocks are followed by a series in which red sandstones are abundant, and an excellent name for this series is the *New Red Sandstone*, contrasting with the Old Red Sandstone beneath the coal-bearing rocks. The name New Red Sandstone is, however, less suitable for the rocks of this age found in other places, since it has reference to continental rocks, whereas, as we have seen, the most suitable stratigraphical divisions are based upon marine successions. The marine equivalents of the lower part of the New Red Sandstone of this country were studied a century ago by Murchison in the province of Perm in Russia and the name *Permian* for the period was introduced. The upper part of the New Red Sandstone is divisible in Germany into three and was accordingly called the *Trias*, a title now used for the period, despite the local and continental character of the German rocks. The division between the great Palaeozoic and Mesozoic eras is made between the Permian and Trias which, as we have just seen, are linked in Britain as the New Red Sandstone. This statement illustrates the difficulties that have resulted from the fact that the early fundamental work on the statigraphical column and its subdivisions was done in North-west Europe where certain of the systems are of non-marine facies.

The Mesozoic era consists of the Triassic, Jurassic, and Cretaceous periods. We have already noted the origin of the name of the first of these. *Jurassic* is derived from the Jura Mountains where rocks of this age are well displayed. In England, events during the Jurassic period are recorded by the clays and limestones of a belt of country running from the Dorset coast through Somerset, the Cotswolds, and the Midlands to the Cleveland Hills in Yorkshire. These rocks, occurring in well-individualized layers and abounding in fossils, supplied the material for William Smith's fundamental laws of stratigraphy: they are his 'slices of bread and butter' and many of his names of Jurassic rocks have reached worldwide application. The third system, completing the Mesozoic, is the *Cretaceous*, so named because its most prominent bed in North-west Europe is the white chalk, *creta* being the Latin for chalk.

Passing to the Tertiary era, we have a group of names ending in *-cene*—*Eocene*, *Oligocene*, *Miocene*, *Pliocene*; these names mean 'dawn of the recent', 'little recent', 'less recent' and 'more recent', and were instituted by Lyell on the basis of the percentage of shells belonging to still-living species that were found in the rocks of the several systems. The development of knowledge concerning the faunas of these beds and a different concept of what an ideal system should contain have rendered this basis largely without meaning. The divisions are naturally now based upon the actual faunas occurring in the rocks. It is found useful to group these

relatively short stretches of geological time or relatively thin successions of rocks into two—*Palaeogene* to include Eocene and Oligocene, and *Neogene* to include the Miocene and Pliocene. By this grouping a nearer approach is made to the ideal geological period, a record of a transgression and regression.

We have now arrived near the top of the stratigraphical column and have sampled the heterogeneous collection of names used for time or rock divisions. In spite of this heterogeneity, the classification works. Geologists would be very unwilling to substitute for it a brand-new logically consistent nomenclature; they prefer what they have and its very blemishes are felt to record the painful stages of its natural evolution. Of course, a classification largely based upon local and, on occasion, anomalous occurrences in North-western Europe is found to creak in some parts when applied to other regions of the globe. In some countries it is felt necessary to recast part of the column. Thus, in the United States, the Carboniferous period is divided into two, the earlier called Mississippian and the later Pennsylvanian. On the Continent, the name Ordovician is not much used; the Ordovician is called Lower Silurian and our Silurian is called Upper Silurian. These are matters about which the reader of this book need not worry; we shall obtain a satisfactory picture of earth-history whatever subdivisions we use.

There now remains the very top of the stratigraphical column to consider. The latest stretch

of geological time is characterized by two events: a widely extended glaciation, and the development of man. These events are considered by some to be sufficiently remarkable to require a separate period and even a separate era in the nomenclature of earth-history. Accordingly, another *-cene* name, *Pleistocene* (meaning *most recent*) has been coined to represent this time. By some authorities the Pleistocene is added to the Tertiary to make the great division of the Cenozoic (or however it is spelled), by others it is made the beginning of a new era, the Quaternary. Admittedly, glaciation is a remarkable event in the history of the earth and man is a remarkable animal, but the recent glaciation is not a unique happening and man's advent on the stage of earth-history is, from the geological viewpoint, exceedingly recent and trivial. We propose in our Table simply to place Pleistocene at the top of the column and leave it at that.

There may seem far too many names of one kind and another used in the division of geological time, but it should be remembered that this time is immensely long. By comparison, the very much shorter period of human history as described in the books is similarly burdened, or embellished, with many names. There is no need for the reader to memorize the geological names—they will be acquired by use—and accordingly we give in Table I our first statement on earth-history. It is not a very full statement and in later chapters many additional details of several kinds will be added. There is in Table I, however, one remarkable detail

which requires a demonstration immediately, and that is the assignment of ages in definite millions of years to the various geological periods. We look into this matter now.

Geological Time in Years. In an earlier page, the interpretation of certain laminated clays, the varved clays, as records of the deposits of successive years, has been mentioned. By the use of such annual layers, the events of some 25,000 years have been studied during the retreat of the ice of the Pleistocene glaciation. Certain banded sedimentary rocks of early Tertiary age occurring in the Western States and interpreted as varves are considered to record some few million years. But these are small and disconnected fragments of earth-history and it is unlikely that the whole gigantic span will ever be dated in terms of years by these methods. We have to search for phenomena which have persisted throughout geological time, even though the division of the scale is less fine.

We have seen that the rocks making the surface of the earth are continuously being removed to the sea, there either to build up the sedimentary rocks or to contribute to the amount of the substances dissolved in the sea-water. Proposals have been put forward for the utilization of the rates and results of these processes in estimating geological time; one of the earliest of these proposals was advanced by Halley the astronomer in 1715. They are concerned either with the rate of sedimentation or of the addition of salt to the sea-water. If we knew the volume of the whole of the sedimentary

rocks and also the amount of the mechanical load carried to the sea by the rivers in a year, we could estimate how long it had taken to form the pile of sediments. Similarly, if we could measure the amount of sodium in the sea and the amount annually delivered by the rivers, we could make a calculation to show how long it had taken the sea to obtain its salt. Some of the measurements required can be made with a fair degree of accuracy but, on a great number of counts, these hour-glass methods are thoroughly discredited. Many objections can be raised, but only one, and that the most serious, need be stated here. Though geological processes have possibly worked in much the same way throughout geological history, they have certainly not worked at the same rate. Earth-history, as we have seen, is a record of immense periods of quiet when the land-masses were low and erosion was slight, interrupted by short periods of revolutionary unrest when the land-masses were raised up and erosion was accelerated. The present is such a time of geological revolution, with the continents probably showing a more developed relief than ever before in the history of the earth, with extremes of climate never reached before and with processes of erosion working at abnormally rapid rates. Accordingly, measurements of any erosive process, however accurate they may be for the present time, are abnormal for the greater part of geological time. An hour-glass in which the sand runs through at an inconstant rate is a poor time-measurer. We must search for some change which

proceeds at an unvarying speed. Such a change is provided by *radioactive decay*.

The elements uranium and thorium are the subjects of a series of transformations brought about by the emission of various particles or rays and resulting in the production of Radium G in the case of uranium and Thorium D in the case of thorium. At the same time, eight atoms of helium are formed from one of uranium and six from one of thorium. Radium G is chemically identical with the kind of lead having an atomic weight of 206 and Thorium D with the kind of lead having an atomic weight of 208. Ordinary common lead, not formed by radioactive decay, is a mixture of many kinds of lead and has the atomic weight of 207·21. Lead from a uranium or thorium parent can thus be recognized. So soon, therefore, as a uranium or thorium mineral is formed, radioactive decay begins, the mineral starts to 'wear-out' and the stable products, helium and lead, to accumulate. Under favourable conditions, all the helium and lead so formed may be preserved and their quantities measured. The rates of these changes can be measured or calculated; for example, the amount of lead with an atomic weight of 206 formed in a year by the radioactive decay of a million grams of uranium is now $\frac{1}{7600}$ gram. Nothing we can do seems to be able to change the rate of these transformations. Neither very high nor very low temperatures, nor tremendous pressures, nor the most powerful magnetic fields, nor a great variety of chemical environments affect the rate. Here seems

to be provided a constant change, contrasting markedly with the violently inconstant changes proposed for the geological hour-glass. There are, of course, a number of corrections and adjustments to be made, but the results based on both the helium and the lead determinations are so consistent among themselves and with one another as to inspire confidence in them.

It is important to realize what it is whose age is being obtained; it is a uranium or thorium mineral when the lead determination is used or a fine-grained igneous rock when the helium is determined. These minerals or rocks still have to be fitted by methods of geological observation into the stratigraphical column and their *geological* age decided. The field-relations of a uranium mineral, for example, to the rocks in which it occurs may indicate that it came into existence as such during early Cambrian times; its age, when determined, gives an age for the Lower Cambrian rocks. Sufficient age-data of this kind are now available to permit the drawing-up of a stratigraphical column in a *time-scale*, with the relative duration of each geological period represented by appropriate lengths of the column. This has been done in Table 1. The oldest mineral so far investigated has the great age of nearly 2,000 million years; the oldest fossiliferous rocks, the Oldest Cambrian, are about 500 million years old. From these figures we obtain an idea of the immensity of Pre-Cambrian time, a time at least thrice as long as that recorded in the great pile of fossiliferous sedimen-

tary rocks. We begin to realize, too, that the earth herself is of a very respectable antiquity. The question as to how old she is as a planet is the business of the astronomers; let us be satisfied for our part with the 2,000 million years.

CHAPTER 3

INTERVENTIONS FROM THE DEPTHS

The Igneous Rocks. We have seen that early in the nineteenth century three classes of rocks had become well established, the sedimentary, igneous, and metamorphic. The igneous rocks were those formed by the consolidation of molten rock-substance and they got their name from the observed fact that samples of this molten material were seen to be poured out from volcanoes, regarded as 'burning mountains', often shrouded in 'smoke' and providing other appearances of 'Fire' (*ignis*). We know now that volcanoes are not 'burning', that their 'smoke' is largely steam, and that no process of combustion goes on in their eruption. In spite of this, we can still use the term igneous if it is properly defined, and we cannot do better than accept the definition given in the *Encyclopaedia Britannica*, especially as this introduces another fundamental term. The definition runs:

all igneous rocks have consolidated from a state of liquidity, the liquid that finally consolidates as rock being technically referred to as magma. Rock-magma is a complex silicate solution carrying gases, the most important of which is water.

We obtain a sample of an igneous rock and acquire an insight into its production when we

examine the consolidation of a lava issuing to-day from an active volcano. As soon as it was recognized by uniformitarian arguments that such rocks were formed by the freezing of molten rock material, it became clear that this must have come from deeper levels in the crust or had been made in such deep levels and later revealed by erosion. Hutton remarked that 'a volcano should be considered as a spiracle to the *subterranean* furnace, in order to prevent the unnecessary elevation of land, and fatal effects of earthquakes'. The lava of the volcano poured out on the earth's surface and other portions of magma frozen and consolidated before it could reach the volcanic orifice obviously came from below. It is with these decided interventions from the depths that we have to deal first in this chapter.

The Volcanic Rocks. It happens that at this present time a vigorous discussion is going on among geologists concerning the origins of many of the rocks hitherto accepted as fulfilling the requirements of the igneous definition just quoted. It will be best, for reasons that develop later, to consider now only those rocks that unquestionably satisfy the requirements. The crux of the definition is the consolidation from molten rock-material, *magma*; no magma, no igneous rock, is a fair statement of a reasonable position. Let us see a little more about magma.

Magma is completely fluid. It is seen to issue from volcanic orifices as lava. From the behaviour of volcanic eruptions and from the nature of the

rocks formed by the consolidation of lavas, magma must have both non-volatile and volatile constituents. The non-volatile components appear in the rocks as the common silicate minerals; the volatiles give rise to the clouds of steam and other gases so prominent in eruptions. The igneous rocks resulting from the consolidation of present-day lavas can be matched with others formed at many epochs in the past. Uniformitarianism teaches us that it is reasonable to interpret these ancient rocks as the products of ancient volcanic eruptions—they are old igneous rocks of *extrusive* type. Further, in the crater walls of many volcanic piles, there can be observed dykes, veins, and sheets of rock, exactly like that derived from consolidating lavas, which can reasonably be interpreted as due to injection and solidification of magma before it could reach the earth's surface. These modern *intrusive* igneous rocks can be matched by similar rocks of varied geological ages. There are clearly a great many ancient and modern rocks which fulfil the definition and are unquestionably igneous. Prominent among these are the basalts and most of them are extruded on the earth's surface.

This group of undoubted igneous rocks, closely associated with volcanic activity, may be separately dealt with as the *Volcanic rocks*. We now have to acquire a little knowledge of them so that their significance in the history of the earth can be properly assessed.

A great many of the Volcanic rocks can be seen at the moment of their birth in active volcanoes

where magma, poured out as flows of lava, solidifies as it cools and can later be studied chemically and microscopically. Certain varieties of lava are viscous and, on cooling, produce in many cases natural glasses which, when chemically analysed, are found to have about 70 per cent of silica, silicon dioxide, in their composition. Other lavas are more fluid and when solidified appear stony, rather than glassy, due to the crystallization of a variety of minerals, mostly silicates, from the magma as it cooled down. A very common stony Volcanic rock is our old friend basalt; the average amount of silica in basalts is found to be about 49 per cent. The geologist calls volcanic rocks rich in silica *acid* igneous rocks, and those poorer in silica, such as basalt, *basic* igneous rocks. The acid and basic Volcanic rocks solidifying to-day around the orifices of active volcanoes can be compared with rocks of similar types formed, as shown by their relationships to the associated sedimentary rocks, in the past by the consolidation of lavas erupted from ancient volcanoes of many dates. With these truly effusive Volcanic rocks, poured out upon the earth's surface of their time, it is reasonable to consider the intrusive sheets and dykes, mostly of basic character, which are simply lava or magma that has solidified before it could reach the surface. It is necessary to repeat this point, since the Volcanic rocks, as the term is used in this book, include more than the surface lavas of the orthodox classification—our Volcanic rocks are all those related to volcanic activity.

Hundreds of Volcanic rocks, ancient and modern have been chemically analysed and their compositions are found to vary between somewhat restricted limits, ranging as regards silica percentage from about 73 per cent in the most acid types down to about 45 per cent in the most basic. A chemical analysis of a rock is a lengthy business requiring the services of a skilled chemist, but the geologist can, however, obtain a great deal of information on the chemical composition of rocks by observing their mineral composition, since in general the minerals present express the nature of the magma from which the rocks were formed. An acid magma rich in silica will give rise to a rock rich in minerals which have a high silica percentage, and a basic rock will be characterized by minerals with lower silica percentages.

As has already been mentioned, silica-rich acid magmas are viscous and readily cool to natural glasses, but such minerals as are able to gather their atoms into their proper lattice arrangement before solidification overtakes them are commonly quartz (silica, 100 per cent) and silicates of alkalies and alumina known as alkali-felspars (silica, 64–69 per cent); examples of acid Volcanic rocks are those known as rhyolite, obsidian, and pitchstone, the last two being entirely glassy forms. Less acid Volcanic rocks are represented by trachyte (silica about 62 per cent) which lacks free quartz as a component. Still less acid are the andesites with a silica percentage of about 59 and having as a common component another variety of felspar, a

soda-lime felspar or plagioclase, with less silica (58 per cent) than the felspars characteristic of the acid rocks. It is the basic rocks that are the most important and significant of the Volcanic rocks and we may now examine this group a little more closely.

Basalt. Basalt, a subject (as we have seen) in the debate between the Neptunists and the Vulcanists a century and a half ago, is the commonest of the basic igneous rocks and is worth a short technical description. Its name was already ancient when it was applied by Agricola (d. 1555) to certain German rocks. Most basalts are dark rocks with so fine a grain that their constituent minerals are usually not determinable by the unaided eye. They are heavy rocks, with a specific gravity of 2·98 and a silica-content of 49 per cent on the average. A thin slice of ordinary basalt examined under the microscope shows nearly half the rock to be made of a species of the mineral group of the plagioclase felspars which is relatively poor in silica (SiO_2 = 53 per cent) and rich in lime—it is a lime-plagioclase; the next commonest mineral is an alumino-silicate of iron, magnesium, and calcium known as augite (SiO_2 = 47 per cent) and this is often accompanied by the iron-magnesium silicate, olivine or peridot (SiO_2 = 40 per cent) and an iron oxide such as the mineral magnetite. An average mineral composition of basalt has been given by Holmes as: felspar 46·2, augite 36·9, olivine 7·6, iron ores 6·5, other minerals 2·8 per cent. The minerals are so arranged that the rock is made up

of an irregular framework of laths of felspar with the interstices filled in with the iron-magnesium minerals, augite and olivine. The arrangement of minerals in a rock is called its texture. A thin slice of a basalt as it appears under the microscope is shown in Figure 6, A, and from this the mineral composition and texture—as seen in one plane—

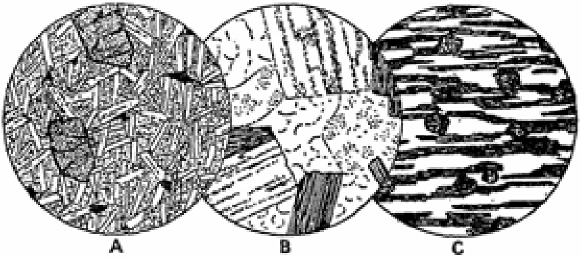


Fig. 6. Thin Sections of Basalt (A), Granite (B), Mica-schist (C). The basalt consists of large crystals of olivine in a finer base of felspar laths and pyroxene grains; the granite consists of dark mica, rectangular plagioclase felspar, cloudy orthoclase and clear quartz; the mica-schist shows oriented flakes of mica, with quartz between, and a few grains of garnet

can be seen. These details, many of them probably very dull, are felt to be worth giving, since basalt is one of the most important rocks in the make-up of the crust and in the elucidation of its history.

Some basalts have a little glass in their composition, due to sudden chilling of the magma before crystallization had been completed. In other varieties, disengagement of the volatile constituents as the pressure on the magma was lessened resulted

in the production of gas-cavities in the solidifying rock which have often become filled with later minerals, giving a kind of basalt known as *amygdaloidal* (Greek, *amygdalos*, an almond). In Hawaii, basaltic lava poured into the sea consolidates in pillow-shaped masses and similar *pillow-lavas* have recorded a similar event at many times in the history of the earth.

Basalt, as befits the commonest Volcanic rock, has been formed since time began. It can be observed to-day welling calmly out from the *central* vents of Mauna Loa in Hawaii where investigation shows that the whole island, rising to some 30,000 feet above the general level of the adjacent sea-floor and having a base over seventy miles across, has been built up into the great shield-volcano it is by successive thin flows of fluid basaltic magma. Many other central volcanoes erupt basaltic lava and similar volcanoes have done the same in the past. Gigantic as the Hawaian basalt accumulations are, however, they are dwarfed when compared with other basaltic piles. Thus, areas approaching a quarter of a million square miles *each* of basaltic lavas with aggregate thicknesses of thousands of feet are exposed in the Deccan of India, in Oregon, and in the Parana region of South America; almost as gigantic are many accumulations elsewhere, while it is probable that in early Tertiary times a basaltic lava-field stretched from Antrim through the Hebrides and the Faroes to Iceland and Greenland. Such volumes of magma can hardly have come out

from central orifices, however numerous, and a clue to their possible mechanism is provided by the observations on an eruption that occurred in 1783 at Laki in Iceland. Here, three cubic miles of basaltic lava were seen to be poured out from a *fissure* twenty miles long. It is suggested that such *fissure-eruptions* may produce the volumes of lava required for the basalt fields, a suggestion supported by the occurrence of multitudes of dykes which could act as feeders found in the regions stripped of basalt lavas by erosion, as in Parana. Central and fissure eruptions may not be altogether unconnected, since central vents appear sometimes to be arranged in a linear pattern as is the case in the Tertiary volcanoes of the West of Scotland and Northern Ireland. The eruption of great quantities of basaltic magma is an event that has taken place at many times in earth-history; the possibility that it may be connected with the formation of rents in the crust is clearly one of great significance in this history.

A portion of the basaltic magma concerned in eruption fails to reach the surface and becomes solidified, as we have seen, in the form of intrusive bodies such as dykes and sills. This portion, though it has consolidated at depths great or small, gives rise to rocks which can logically be considered only with the extrusive basalts and the volcanic rocks in general. The chemical and mineralogical compositions of these intrusive basic rocks are the same as those of the basalts. Such differences as they show are textural and arise from the different

environments of their consolidation. They naturally cool slowly so that the glass of basalts is not found in them. Two varieties may be mentioned here. The smaller dykes and sheets are commonly made of the type of basic rock known as *dolerite* or *diabase*, characterized by a texture called ophitic in which many laths of felspar are enclosed in a single plate of augite. Larger bodies are made of the rock *gabbro*—according to C. E. Montague, speaking as a mountaineer, the best of all God's stones; the gabbros are coarse-grained rocks with a texture controlled by the mutual interference of crystals of felspar and pyroxene during their growth.

The inference has already been made that many of the dykes or vertical walls of dolerite found near the extrusive basalt fields may have served as feeders of magma to the surface. The shapes of such vertical bodies are clearly controlled by tension acting tangentially at that particular part of the crust. It is unlikely that a tension will be relieved by a single fissure but rather by a multitude of parallel fissures. In accordance with this expectation, we find dykes often forming a *swarm*, made up of countless individuals with similar trends. A dyke-swarm indicates tension and consequent elongation in the part of the crust in which it occurs. Sheets of dolerite or gabbro often lie more or less horizontally and their emplacement has overcome a radial pressure. Along the margins of the basic intrusions there is usually little evidence of reaction between the magma and its walls; the igneous rock is finer in grain where it chilled

against the cold wall-rock, and the latter often shows signs of heating-up resulting in a certain degree of mineralogical and textural reconstruction which is technically known as *thermal* or *contact* metamorphism. This kind of metamorphism is local and restricted, and must be distinguished from that which has produced the metamorphic rocks in general.

The Volcanic rocks from acid to basic have now been introduced. Their countless varieties make a brave show in museum cabinets. The student of earth-history, however, must regard the Volcanic rocks in quite the reverse way from that in which a philatelist regards his stamps. The rare rocks are the least important in earth-history; it is certainly commonness that counts. When we survey the volumes of the different kinds of Volcanic rocks found in the crust, we find that the basic types are some fifty times as abundant as all the others put together. The typical Volcanic rocks are basalt and its intrusive representatives, so that the rhyolites, trachytes, and acid andesites are relatively rare. These are fundamental facts that a reasonable history of the earth has to consider.

A New View of the Rocks. We have hinted already that it appears to some geologists that the igneous group has been unwarrantably extended to include many rocks which cannot be shown to have consolidated from a magma and which, indeed, can be shown in some cases to have been formed in some other way. The most widespread and important

of these rocks whose igneous origin is questioned is the famous rock granite. No one has seen a magma or lava solidifying to give granite. Though admittedly granitic dykes and veins occur and granite may thus sometimes be an igneous rock, these are quite insignificant manifestations and the truly gigantic bodies of granite found in the crust cannot, as we see later, reasonably be interpreted as having consolidated from a magma. Granite is thus never formed at the surface; it comes into place or is made deep in the crust; it is a rock of the depths. In the writer's opinion, the processes by which metamorphic rocks are made are closely connected with the processes by which granite is made; the metamorphic rocks are intimately associated with the granitic rocks. This is no new idea but is really a return to Lyell's belief of a century ago. The writer proposes to unite these rocks of the depths, the granitic and the metamorphic, into one group with Lyell's old name, *Plutonic*. They contrast in every way with the dominantly basaltic rocks, certainly magmatic, mostly derived from lavas and forming the true igneous rocks, which we have already examined under the title of *Volcanic* rocks. For the writer, then, the terms igneous and metamorphic are useful only on restricted occasions; a classification of rocks into Neptunic or sedimentary, Volcanic, and Plutonic will be found, he believes, to suit the earth-machine as a whole much better than the customary classification. The technical reasons for this preference are beyond the scope of this little book; the reader must accept the

assurance that many phenomena of earth-history become more reasonable when rocks are viewed in the writer's way. In Figure 7 there is reproduced from one of the specialist publications a rather light-hearted cartoon displaying the new proposals which, in spite of its seeming levity, will be found to have points of serious import. We have dealt with the Neptunic or Sedimentary rocks of the cartoon in the previous chapter, and have acquired in this a little knowledge of the Volcanic rocks. We may now pass on to the Plutonic rocks and see what interventions from the depths they record.

The Plutonic Rocks. The Plutonic rocks comprise the granitic and metamorphic of the usual classifications. We deal with these two types in turn and show their relationships.

Granite. Every dweller in a city has seen and can now study most advantageously splendid specimens of a great variety of granites, for large polished slabs are available for inspection along the more opulent streets. They are usually light-coloured greyish or pinkish rocks clearly made of large mineral grains. In thin slices, they show their constituents to be quartz, felspar, and some other silicate such as mica and hornblende. Quartz has the composition silica, the felspars of the granitic rocks are potash-felspars (silicate of aluminium and potassium) and soda-lime felspars (silicate of aluminium, sodium, and calcium), the mica is white muscovite (silicate of aluminium and potassium) or dark biotite (silicate of aluminium, potassium, iron, and magnesium), and hornblende is an alumino-

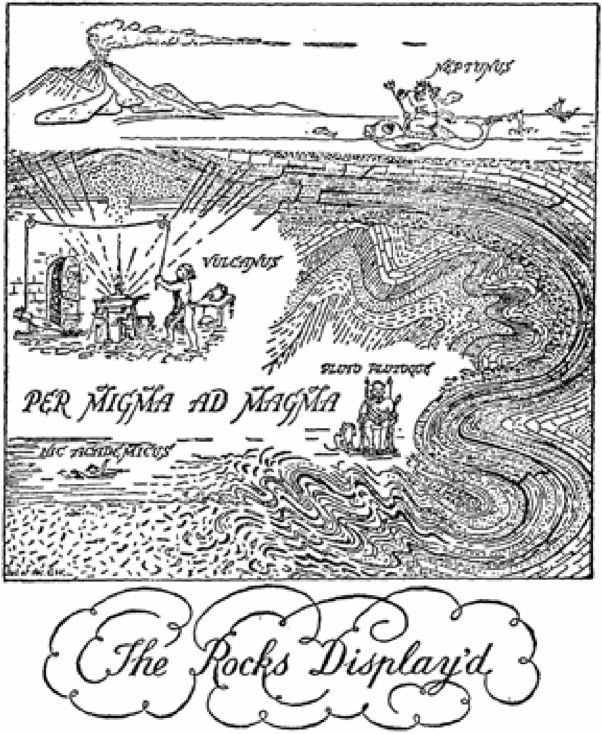


Fig. 7. *The Rocks Display'd*; a cartoon on the author's proposals concerning a new classification of rocks. (Reproduced by permission of the Council of the Geologists' Association from *Proc. Geol. Assoc.*, Vol. LV, Part 2, 1944)

silicate of calcium, iron, and magnesium. A typical granite is shown in the thin slice given in Figure 6, B. The mineral compositions of representative granitic rocks is exemplified by the following:

St. Austell Granite, Cornwall. Quartz 32·6%, potash-felspar 34·5%, soda-lime-felspar 19·2%, micas 9·2%, others 4·5%.

Vermilion Granite, Minnesota. Quartz 25%, potash-felspar 50%, soda-lime-felspar 20%, biotite 2%, others 3%.

Boulder Granodiorite, Montana. Quartz 23·7%, potash-felspar 19·9%, soda-lime-felspar 34·5%, biotite 4·2%, hornblende 15·3%, others 2·5%.

The silica percentage is about 70 in the varieties with little soda-lime felspar (granite proper) and about 65 in the granodiorites which have abundant soda-lime felspar. These dull details can now be forgotten, as their purpose is simply to show that granites are very different rocks from basalts. Their occurrence in the earth's crust is very different too, as we now proceed to show.

The Occurrence of Granite. Whatever their origin may be, the granite rocks are rocks of the depths, revealed to us by the removal of considerable thicknesses of overlying rocks by erosion. For the most part they are seen over great areas which are the surface expression of truly gigantic volumes. These bodies of granite are called *batholiths*, 'rocks of the depths'. Their size is illustrated by the British

Columbia batholith which is 1,500 miles long by about 100 miles wide, by the Patagonia batholith 800 miles long, by a Montana batholith with an area of 16,000 square miles, or by a Finnish batholith of 7,000 square miles. Batholiths are thus very big bodies indeed, and their size has to be considered in any theory of their formation. The top of a batholith can be studied by field-observations or explored by mining operations; the granite is found to be covered by an irregular domical roof of older rocks into which it has made its way. How, will be considered in a moment. Mining shows that the horizontal cross-sections of batholiths become larger as their depths become greater and that the walls are often steep. The existence of a floor to any batholith has not been demonstrated. The deeper the level of the crust, the more voluminous does granitic material become.

The Great Room-Problem. If these gigantic masses of granite are viewed in the orthodox manner as igneous rocks resulting from the consolidation of a granitic magma, then one of the many problems which has to be faced is that of what has happened to the equally gigantic masses of rock which were there before the granitic magma came into its position. This is the geologist's version of the general problem of how to dispose of the body. One proposal has been made to solve this room-problem by permitting the magma to dome up its roof or to get into position by some structural rearrangement of the adjacent portions of the crust. Another proposal suggests that the magma made its way up-

wards in the crust by wedging off blocks of its roof which then sank through the magma to beyond our reach—a process called *magmatic stoping* by analogy with the method of mining called overhand stoping. It must be confessed that many geologists simply shut their eyes to the fact that any room-problem exists in granitic emplacement. But a fundamental problem does exist and one that appears insoluble to the writer so long as the magmatic origin of granite is taken for granted and so long as the contents of the igneous rock pigeon-hole of the text-books are regarded as sacrosanct. Let us rid ourselves, if only for a moment, of the dogma that granites are magmatic igneous rocks and try to reorient our views.

Though without personal experience, we may assume that murderers find it much easier to dispose of very small bodies than of large full-size ones; similarly, if little or no rock were to be got out of the way in the emplacement of granitic batholiths then the room-problem would become very much simpler. A simpler explanation is not in itself more likely to be right than a complex one, but our simpler explanation has the advantage of accounting for what is perhaps the most remarkable quality of batholiths, namely, that the granitic rocks appear to have *replaced* the older rocks whose position they have occupied. The gigantic volumes of the older rocks that are replaced cannot have been pushed aside by an equally gigantic body of magma nor can they reasonably have sunk out of sight through the magma. Our simpler explanation is that no

gigantic volumes of rock have to be disposed of and no gigantic volumes of magma have to be emplaced, since the granite is made where we now find it by the rearrangement of material for the most part already there. This making of granitic rocks without a magma is called *granitization* and is a subject of hot debate among geologists at the present time. The writer holds that most granitic rocks are formed by granitization of earlier rocks and not by consolidation from a magma. The reasons for this belief are mostly beyond the scope of this book, so its presentation and consequences will appear perhaps very cut-and-dried. Anyone interested in following the debate more closely will find adequate references in the bibliography.

Granitization. In granitization it is suggested that fluids of some kind—it is the fashion to call them *emanations* at the present time—have come up from below and traversed the solid rocks by way of their pores or their bedding or other structural planes. As the emanations pass through the rocks they react with them and convert them more or less completely into granitic rocks composed mainly of quartz, alkali-felspars, and micas. If the rocks undergoing transformation are of extreme composition such as limestones or basic igneous rocks, for example, then the product of granitization may contain additional minerals such as hornblende and pyroxene or its felspar may be richer in lime; thus are provided bodies of the less common plutonic rocks of this origin such as those known to the systematist as syenite and diorite. The overwhelm-

ingly dominant granitization products are, however, granite and granodiorite.

The process of granitization can often be observed arrested at various stages in the large polished slabs generously provided by the bankers and brewers as exterior embellishments of their premises. In these slabs can be seen fragments of the older rocks in which granitic minerals such as felspar are beginning to appear and, with the continuance of this felspathization, a gradation into granite can be established. The reality of granitization has been demonstrated in a multitude of areas all over the world.

If batholiths are formed in this way, then their replacement appearance is to be expected, since the previously existing rock has been converted into granite on the spot. As we shall see in the next chapter, the sedimentary rocks in certain rather restricted belts have suffered violent disturbances after they were deposited. They have been crumpled, folded, and broken. In these belts the material of the deeper levels of the crust must be disturbed likewise, and that which rises to higher levels will find easier passage along the trend of these folded stretches. We are not surprised to discover, therefore, that the granite batholiths are found in these folded belts of the crust, that they are elongated along them and that their formation is closely associated with times of crustal disturbance. These are matters which will be more fully appreciated when the next chapter has been read.

We trust that the retentive reader is by this time

unable any longer to restrain his impatience at our disregard of the great discovery, hailed as such in an earlier page, of Hutton's that granite veins were igneous intrusions. We reply that there is no reason why granites should not be intrusive. A body of rock soaked with fluids could become mobile and be forced into higher levels of the crust where on complete solidification it would present intrusive relations to the adjacent rocks. Further, squeezing of a soaked mass would expel the liquid material from the sponge and inject it into its surroundings as igneous veins. Finally, it will be no tarnish on the bright fame of Hutton if it is found, as appears possible from certain recent work, that many granite veins are the result of the granitization of the solid rocks by emanations passing along restricted channels. It is reasonable to hold that granites igneous by definition are immeasurably subordinate to granites arising by granitization.

Migmatites. Such a process as granitization, in which we envisage the entry of fluids into an assemblage of solid rocks heterogeneous in composition, texture, and structure, will clearly result in most cases in heterogeneous products. Granites, in fact, are found when examined in large slabs to be likewise variable in all these qualities. In many, there are apparent granitic, half-granitic, and non-granitic portions representing stages reached in granitization. Around the margins of what appear to be more coherent bodies of granite these granitic and non-granitic mixtures are abundant. In certain areas such as Finland, the Pyrenees, the Highlands

of Scotland, and elsewhere, such mixed rocks or *migmatites* occur on a vast scale; they are clearly mixtures, as can be seen from Figure 8, whatever our opinion on the genesis of the granitic portion may be. Here we adopt the view that the formation of migmatites is closely connected and often

Fig. 8. Migmatite, a mixture of granitic material (light) and country-rock (dark) (after Sederholm)

identical with the granitization process. Many granites are the final term of migmatite-production.

The Metamorphic Rocks. It will be recalled that our Plutonic rocks comprised two groups, the granitic and metamorphic. With the introduction of the migmatites, we approach the many problems of the metamorphic rocks. We are not to consider

here two classes of rocks usually placed with the metamorphic; the first are those produced as a result of the heating by hot injected magma of its wall-rocks—these are the thermal or contact metamorphic rocks already referred to; the second class occurs adjacent to great dislocations in the crust along which the rocks are sheared and rolled out—this dislocation-metamorphism, like thermal metamorphism, is local and restricted and, sooner or later, both these kinds of rock-transformation will have to be removed by geologists from metamorphism proper and considered apart. What we deal with here are the results of changes in rocks which have affected vast segments of the crust—segments of the size of half Canada or the Peninsular part of India. If we wish to distinguish this metamorphism proper we cannot do better than use the excellent non-committal name of *regional metamorphism*.

Let us survey the metamorphic rocks. Since they are produced from any kind of previously existing rock, their bulk chemical compositions and therefore their mineral compositions are extremely varied. The minerals of the original rocks, consisting for the most part of weathering products or surface lava-flows, are not all stable under the conditions deep within the crust, and new assemblages of minerals are formed which are more in harmony with the temperatures, pressures, and concentrations of the new environments. Common minerals of the metamorphic rocks are quartz, alkali felspars, calcite, micas, hornblende, the green chlorites (silicates of aluminium, iron, and mag-

nesium), hydrated silicates of magnesium such as talc and serpentine, simple aluminium silicates such as andalusite, kyanite, and sillimanite, and many varieties of garnet (silicates of aluminium, lime, and magnesium). What assemblage of minerals is formed depends in the first place on the composition of the original rock, in the second on the physical controls of the new environment, and in the third on the nature and amount (if any) of material introduced into the system undergoing reconstruction. An example in illustration is given by three metamorphic derivatives of the basic igneous rock, dolerite: one is composed of chlorite, soda-felspar, and calcite, another of hornblende and soda-lime felspar, a third of pyroxene, garnet, and quartz—all three derivatives have the same chemical composition as the original dolerite and their differing mineral assemblages register differences in the physical controls of their metamorphism.

Certain of the minerals of the metamorphic rocks form platy or columnar crystals, common examples being the micas, chlorites, talc, and hornblende. In a number of metamorphic rocks these platy minerals are found to be arranged in parallel fashion so that planes of easy parting are produced. An extreme case is seen in the common rock slate, which splits into thin sheets parallel to the orientation of the minute plates of chlorite and mica which compose it; most slates are clay-rocks which have been subjected to considerable pressures under which the new-formed platy minerals have

arranged themselves in an ordered relation. In slates the new mineral plates are exceedingly small in size, but in a great variety of common metamorphic rocks large plates and prisms are formed which, arranged in parallel, produce the orientation texture known as *schistosity*. Rocks showing schistosity are the schists—mica-schists derived from clays and slates, chlorite-schists and hornblende-schists from basic igneous rocks, talc-schists from ultrabasic igneous rocks originally rich in olivine. The appearance in thin section of a mica-schist is shown in Figure 6, C.

Whether a metamorphic rock is schistose or not depends of course upon the presence of schistosity-making minerals; thus, quartz and calcite are not normally platy or columnar so that the quartzites, metamorphosed sandstones, and the marbles, metamorphosed limestones, are not normally schistose rocks.

Many coarse-grained metamorphic rocks possess a texture which Darwin designated *foliation*. Foliated rocks are made up of lenses, streaks, or discontinuous bands rich in particular minerals, and present a rough striped effect seen, for example, in rocks called gneisses. Many of the gneisses are clearly migmatites in which streaks of dark schistose material persist as relics in light-coloured portions. Gneisses of this origin provide a link between the granitic rocks on the one hand and the schists on the other. This unity is the basis of the writer's Plutonic group of rocks and may now be looked into.

The Unity of the Plutonic Rocks. In many parts of the world, transitions have been demonstrated from rocks in the earliest stage of metamorphism through higher grades into products of migmatization and granitization. A classic example of this kind of transition is provided by the metamorphic rocks of the Scottish Highlands in the counties of Angus, Kincardine, and Aberdeen. On the margin of the Highlands in the Edzell region, lowly metamorphosed clay-rocks are characterized by the mineral chlorite, a little farther to the north-west rocks of the same chemical composition have developed biotite, and this zone is succeeded by others first with the index mineral garnet, then kyanite, and finally sillimanite, as seen in the Deeside district of Aberdeenshire. A succession of zones of increasing metamorphism is here registered by the index minerals, developed in rocks of clay-composition, of chlorite, biotite, garnet, kyanite, and sillimanite. The sillimanite-bearing rocks occur as parts of a great migmatite-area. These are matters of observation however they are interpreted.

Our interpretation is this. In portions of the crust undergoing granitization there is obviously an influx of material which, whether it be considered to be magma, emanations, fluids, or anything else, is hot and energetic. Such material acts upon the solid rocks, converting part of them into granitic rock or granitic magma. If anything comes in, something has to move out and this expelled material, still hot and active, streams into the rocks around the migmatite core and facilitates there the

formation of the metamorphic rocks. By the entry of the granitizing fluids, therefore, a complex series of reactions and replacements is set going. Fronts, as we now call them, of diverse chemical and physical qualities move out from the granite core as ripples on a pond but, unlike the ripples, they leave a mark in the zonal arrangement of the metamorphic rocks about the core. On this interpretation, the granitic, migmatitic, and metamorphic rocks are reasonably united into one group, that of the depths—the Plutonic.

The Two Styles of Intervention. Looking at these interventions from the depths, we can now distinguish two fundamentally different classes of events recorded in them. The first results in the outpouring of gigantic volumes of magma as lavas dominantly of basic composition and probably arising along tensional fissures; this gives the Volcanic rocks. The second class of event is recorded deep within the crust by the production of granites, migmatites, and metamorphic rocks, especially in the folded and disturbed zones; these are the Plutonic rocks. The material for the Volcanic rocks visibly comes up from below to the surface, the Plutonic rocks are revealed only when a thick cover has been stripped from them by erosion. Both clearly come from the depths and our next task is to see what is known of these hidden regions of the earth.

Knowledge of the Depths. For the most part, the geologist makes his observations at the surface of the earth. A few bores have probed the crust for as

much as 16,000 feet, but these have afforded only tantalizing glimpses of the merest outer skin of the planet. During violent periods of folding and disturbance, deep portions of the crust may be raised to shallower levels and there become exposed by erosion, but even these samples probably came from depths no greater than four times that reached by the deepest boring. By direct observation, therefore, we can obtain information about only an outer film of trifling thickness. Fortunately, we can by inference make not unreasonable suggestions concerning deeper zones and, indeed, concerning the whole interior of the earth. These inferences are derived from two sources. First, earthquake shocks travelling through the globe supply physical data that indicate what substances are likely to make its innermost parts. Secondly, reasonable theories about the origin of the planet allow certain deductions to be made concerning the course of its subsequent evolution and lead to suggestions about its broader structure. We look into these interesting matters now.

Evidence from Earthquakes. Most of our knowledge of the nature of the earth's interior comes from the study of earthquakes. The rocks of the crust are subjected to strain which may become at some particular place more than they can stand. The rocks therefore snap and a jar is sent through the adjacent crust as an earthquake. The disturbance is transmitted by three kinds of waves, two travelling through the earth and the third and slowest along its surface. The waves passing through the

earth are of particular interest to us. The faster is propagated by vibrations of particles to-and-fro in the direction of the path of the wave and may be called the P or 'push' wave. In the slower wave, the particles vibrate at right angles to the direction of propagation and may be called the S or 'shake' wave; distortional waves of this kind cannot be transmitted by a liquid. The waves of a strong earthquake are recorded by a number of seismographs—pendulums of various kinds—stationed at different distances from the originating crustal fracture. From these records the times of arrival of the P and S waves at the seismograph stations are obtained and hence their speeds can be calculated. It is found that the speeds are greater the deeper the waves have travelled through the crust. The speed of earthquake waves, like that of any other waves, depends upon certain physical properties, the density, rigidity, and compressibility, of the material through which they pass. These quantities can be measured in the laboratory for all varieties of rocks and the speed of propagation of P or S for any rock compared with that of a certain zone of the earth. The laboratory determinations are made where possible at high temperatures and pressures, so that conditions deep in the earth are reproduced in some measure. In this way, suggestions are forthcoming on the constitution of the earth's interior. Two aspects of these concern us here.

The first suggestions concern the composition of the outer layers of the crust and the evidence for

them is supplied by what are known as near-earthquakes, since the fractures causing them are no great distance from the recording seismographs. When the records of P and S for these earthquakes are scrutinized, it is discovered that P is really made up of three separate pulses and S of three also. This can be interpreted as the result of the breaking-up of the original P and S waves into parts by refraction, so that each part travels in a different layer with a speed appropriate to the nature of the layer. In the *upper layer* the velocity of P is 5·4 km./sec. and of S 3·3 km./sec., values agreeing with those calculated for *granite*. Waves that have travelled in deeper layers have speeds of 6·0–7·2 for P and 3·5–4·0 for S in an *intermediate layer* and more than 7·8 for P and more than 4·4 for S in a *lower layer*. There is some difference of opinion in detail concerning what crustal rocks best fit these velocities. The lower layer is by many regarded as made up of something like the rock *peridotite*, an ultrabasic rock very rich in olivine, and the intermediate layer of *basalt* or *gabbro*. All agree on a general point most important for our present purpose, namely, that a granitic shell overlies a basaltic shell. The granitic shell is conveniently called the *sial* (from *si*lica and *al*umina) and the basic shell the *sima* (from *si*lica and *ma*gnesia). By methods which need not detain us, seismologists propose thicknesses of some 20 km. for the granitic layer and 30 or so for the basaltic layer. These thicknesses are most likely of the right order and their insignificance compared with the earth's diameter may be noted.

The second group of suggestions concerns the constitution of the innermost parts of the earth. From P and S records of earthquakes felt over great areas of the earth, it is known that their speeds increase fairly regularly down to a depth of about 2,900 km. (the equatorial diameter of the earth is 12,757 km.); it may reasonably be deduced that the peridotite layer, close-packed and compressed, continues to this depth. Waves that have passed through the central part of the earth, deeper than 2,900 km., exhibit very remarkable properties. In the first place, they travel more slowly than expected for their depth of penetration, and in the second place, the distortional S waves are not transmitted as such through the core, indicating that this is essentially liquid. Some observers consider that a change in the properties of the core can be observed at a certain depth. On the grounds of the high density (5·5) of the earth as a whole compared with that (3) of the average surface rock, of the physical properties of the proposed materials and of certain deductions from the most reasonable view of the earth's early history, it is suggested that the core consists centrally of iron and a little nickel (*nife*), with a shell of liquid sulphides around it.

The findings of seismology, then, provide the following succession of earth shells: an outer granitic shell, a basaltic shell, a peridotitic shell extending to a depth of something like 2,900 km., and centrally a liquid sulphide shell surrounding a liquid iron-nickel nucleus.

Let us return to the consideration of the granitic

and basaltic shells, the sial and the sima. Earthquake investigation shows that the sima is a continuous shell underlying both ocean and continent alike. On the other hand, the sial is discontinuous, being apparently absent from below the Pacific and thin and patchy in the Atlantic and Indian oceans. The continents are thus disconnected slabs of granitic sial, covered by a veneer of sediments, and resting upon a continuous layer of basaltic sima (see Fig. 16).

The Mechanisms of Intervention. We set out upon this survey of the results of seismology in order to find what the depths might be like from which came the interventions recorded in the Volcanic and Plutonic rocks. From what we have found it seems reasonable to connect the Volcanic rocks, overwhelmingly basic, with the basaltic sima, and the granitic generators of the Plutonic rocks with the granitic sial. When we attempt to explore these connexions we are compelled for the time being to advance a number of speculations, trusting that new methods of attack will eventually show which, if any, of them are correct.

Our first problem is to produce vast volumes of basaltic magma in the solid sima and deliver it quickly at the surface of the earth, there to form the Volcanic rocks. Daly has argued that the lower part of the basaltic sima is hot and glassy and is able to inject itself into fissures opened in the crust as a result of tension; so soon as it ascends, its viscosity decreases as the pressure decreases, and it shoots rapidly to the surface as basaltic magma,

urged up by the weight of the crustal column bearing on the glassy substratum. Minor quantities of the magma force their way between horizontal bedding planes of the adjacent rocks, to appear as sheets of dolerite and gabbro. The maximum elevation of modern volcanic cones can be calculated on Daly's theory, for a liquid column of basaltic magma about 4 km. high would balance the weight of the adjacent crustal column. Mauna Loa in Hawaii conforms with this expectation and so does Etna which, having apparently reached its maximum height, now erupts from its flanks. Daly's proposals have not proved acceptable to all geologists and alternatives involving radioactive heating, friction, gas-fluxing, heating by convection currents in the substratum, and so forth, have been advanced. But the discussion of these, though interesting, is beyond our scope here.

We have seen that subordinate amounts of the Volcanic rocks are not of basaltic character. These may have been produced either by the assimilation of small quantities of the wall-rock through which the basic magma passes, or by a process of crystal-fractionation whereby early-formed heavy crystals, poor in silica and rich in denser constituents such as iron (olivine for example), have been withdrawn from the magma by settling, leaving it more acid in character.

Some granites considered to be igneous are found closely associated in space and time with gabbro intrusions, and the suggestion has been advanced that this quota of granitic magma was

produced by fusion of the sial by the rise through it of basaltic magma from the substratum. Further, it is possible that respectable quantities of andesitic magma may result from liquefaction of the sial in special zones of disturbance. But both these complications may best be left to the specialist.

We have seen that the great batholithic granites arise in belts of the crust where the rocks have been violently folded and disturbed. It is reasonable to hold that in such belts the sial has been depressed so that partial or complete melting or activation of some kind is possible. These crustal disturbances initiate and localize granitization and the formation of granite and, as we see in the next chapter, they result from compression of the crust. We can state, as a preliminary conclusion to be tested later, that Volcanic rocks are associated with tension, Plutonic rocks with compression, though the closeness of the association in time is different in the two groups.

The Beginnings of the Earth. The study of earthquakes indicates that the earth has a shelled structure of sial, sima, and nife. In the preceding paragraphs it is suggested that the dominant interventions from the depths, the granitic Plutonic rocks and the basaltic Volcanic rocks, come from the sial and sima respectively. We may now appropriately examine the proposals concerning the origin of these shells so fundamentally important in the story of the earth. In this examination we have to deal with the very beginnings of the planet. This is a problem for the astronomers, but the geologist may rightly prefer one of their proposals to another

because it fits his geology the better. Let us adopt, then, the proposal that the planets were formed from the ancestral sun as the consequence of the near approach of another star. Just as the sun and moon raise tides on the earth, so the celestial visitor raised tides on the sun—tides so powerful that solar matter was pulled out free from the sun's body. As the star receded, this free matter, the raw material for the planets, was left revolving around the sun. We prefer that development of this *Tidal Theory* which considers that the filament drawn out from the sun was gaseous, rather than the older view that the ejected material was in the form of solid particles. The heated gases of the filament expanding into space are cooled and slowed down till gravitation takes control, the more refractory substances liquefy and begun to condense into the nuclei of the planets. As the temperature continues to fall liquefaction is completed. Even in the gaseous condition some density-stratification in the filament is to be expected and this becomes enhanced in the wholly liquid planet. It is reasonable to believe that by a combination of density-stratification in the gaseous, gaseous-liquid, and liquid states in which materials of varying refractoriness are concerned, aided by separation into more or less distinct liquid fractions as the melt cooled, there could be produced a shelled structure in the liquid earth. The materials arranged themselves in a general way according to their atomic volumes, those with the smallest in the innermost parts of the earth. Thus arose the iron core, the

metallic sulphide layer around it, and the silicate mantle outermost. That all this might be achieved in the entirely liquid earth is an opinion that can be subscribed to by the majority of geologists, but the next step in the evolution of the earth is one that rouses most violent debate. We are here faced with two of the grandest problems in geology, the first being the manner of formation of the sima and sial layers and the second being the concentration of the sial into the discontinuous continental masses.

Problems of Sial and Sima. We could lay the basis for a solution to both problems if we could invoke liquid immiscibility in the molten silicate shell whereby it splits into two liquid fractions, an outermost granitic overlying an inner basaltic. The first problem might be solved along these lines, and we could proceed to deal with the second by adopting Sir George Darwin's theory of the birth of the moon by the abstraction of a portion of the outermost shells of the primitive earth due to the attraction of the sun. Such a breaking-off of the lunar material requires a still liquid earth, while the density of the moon, 3·5, is appropriate to its derivation from such outer shells as proposed. By such an origin for the moon, part of the sial shell would be removed from the earth and the remainder would break up into gigantic continental fragments in the consequent adjustments. The Pacific Ocean, beneath which sial is lacking, might be the scar left when the lunar material departed.

Some of us would be happy to accept some such solution, but the experimental study of silicate

melts appears to be directly opposed to the separation of liquid fractions in such melts. It is true that Greig has shown that liquid immiscibility does occur at temperatures of about 1,700° C. in melts of silica with magnesia, lime, and iron, and the formation of liquid fractions in melts rich in alkalies or alumina at higher temperatures has not been proved to be impossible, though the physico-chemical experts regard it as unlikely. As Shand has observed, if the newly condensed shell of liquid silicates about the growing earth were indeed capable of developing two immiscible liquid phases, one richer in alkalies and the other richer in lime and magnesia, then the problem of the earth's granitic shell would be solved.

Laboratory work on silicate melts shows that in cooling melts of the appropriate composition the first mineral to crystallize is olivine, iron-magnesium silicate, with the specific gravity 3·3. These heavy crystals have been observed to sink through the residual liquid, now poorer in the constituents required to make olivine, and accumulate on the floor of the crucible. An analogous process is believed by many to have operated in the primitive silicate shell. Crystallization and sinking of olivine and augite led to the formation of a granitic layer, rich in alkalies, alumina, and silica, over a basaltic layer, rich in iron and magnesia. Opinion differs as to the amount of remelting that the olivine crystals would suffer as they sank into deeper and hotter levels, but there is a fairly general agreement that, by this mechanism, repeated again and again, the

separation of the silicate layer into sima and sial would be completed with their solidification, so that the earth would then be too strong to allow the moon's substance to be pulled out from it.

The Problem of the Discontinuous Sial. The second fundamental problem, the reason for the disconnected continental sial masses, is likewise a matter for diversity of opinion. Some consider that this discontinuity of the sial is a very primitive and original feature, brought about by convection currents in the liquid earth which moved and aggregated a granitic scum just as the scum on boiling jam is moved and aggregated. One of the many difficulties of such schemes is to produce, in the light of the observed course of crystallization in silicate melts, solid sial rafts in a molten sima substratum. Another view regards the sial as originally a continuous earth shell which has become broken into pieces and packed together into bundles during the early revolutionary periods of the earth's history. We have seen that even though Pre-Cambrian time is immensely long, at least three times as long as the whole of Cambrian and later time, yet there is still an earlier concealed history in the earth's crust. Possibly something like two thousand million years are concerned in this Pre-Cambrian and earlier history of the planet, and the proposal is advanced that during this immense time the sial has been buckled and folded into the discontinuous sial continents. On this view, it is the job of the geologists dealing with the old basement to unroll these folds and to show that there is

sufficient sial to cover decently the parts of the ocean now bare. It is sobering to remember that unless a packing of sialic material, however caused, had taken place, the waters would have covered the earth's surface; as we have already noted and as we examine in detail later, the sial continents stand high because they are light, the ocean basins are deep because their underlying material is heavy, and so the waters are drained off the continents.

The First Crust and the First Rains. Most geologists consider that the first crust—the Primeval Crust—of the earth is not visible to us. The oldest rocks of the crust are derived second-hand rocks capable, it is held, of being interpreted along uniformitarian lines. We may, however, speculate as to what the first solid surface of the earth might have been like. The consolidation of the crust had contributed vast quantities of steam and other gases to the primitive atmosphere which lay, heavy, torrid, and turbulent, over a surface possibly consisting of loose ashes and broken-up materials of volcanic origin. As the earth's temperature fell, water appeared for the first time on the earth and geological history began. The First Rains, on all counts, must have been a sudden event, a descent of vast quantities of hot and chemically potent water on a heated surface that had not known water before. Uniformitarianism would certainly not apply to this event and operations of a tremendous and catastrophic nature were set in motion. Incredible weathering and erosion would be performed by remarkable floods rolling down into the depressions and, most likely,

violently contrasting chemical precipitates would be deposited there. Though the oldest rocks do contain bands which might meet these expectations, they are mostly made up of normal uniformitarian types and we can fairly conclude that the first crust and the first deposits have been obliterated by subsequent geological operations of erosion folding and deposition. As we have said before, let us cling to uniformitarianism as long as possible.

Dating the Interventions. It is obvious from the foregoing pages that the interventions from the depths are remarkable events in earth-history and, as such, they have to be dated as closely as possible.

Lavas of the Volcanic group are found interbedded with sedimentary rocks whose age can be determined according to the methods of William Smith. Intrusive Volcanic or Plutonic rocks are clearly later than the youngest rock they penetrate or contact-metamorphose; an upper age limit may often be put by the discovery of pebbles of the intrusive rocks in conglomerates of known age or by the determination of the age of beds resting unconformably upon them. Close dating of great migmatitic and metamorphic complexes is often difficult since fossils may be absent or destroyed, transitions from non-metamorphic rocks unobtainable, and even the law of superposition unreliable. As an example, consider the metamorphic rocks of the Grampian Highlands of Scotland. These are covered unconformably by Old Red Sandstone, so are older than this period, but by how much is a matter for discussion; opinions differ on the ages

of both the rocks as sediments and of their metamorphism—to some geologists both these dates being Pre-Cambrian, to others the first Pre-Cambrian and the second Silurian, and to yet others both Lower Palaeozoic.

This relative uncertainty in the dating of many important Volcanic and Plutonic events makes their insertion in the chronological table of the Stratigraphical Column a matter of difficulty. On the whole, Volcanic and Plutonic chronology will be better dealt with after the revolutionary episodes in earth-history have been studied in the next chapter.

CHAPTER 4

THE REVOLUTIONARY EPISODES

AT MANY places in the foregoing, brief reference has been made to the two contrasting styles of earth-history: on the one hand the lengthy quiet periods when vast quantities of sediments were carried to the seas and the continents became lowered; and on the other hand, the short violent periods when the sediments were disturbed and the land-masses extended and elevated. We have now to examine in some detail the way in which these earth revolutions are recorded and how the record is read.

Original Conditions are found Disturbed. Any rock as we now observe it is the product of a vast series of operations which have never ceased since the earth began. Some of the changes require enormous time for their execution and we cannot see them at work; others are accomplished in an instant and leave a clear record. We can isolate any episode in the history of a rock and study what the rock was then like, and we can name this condition *original* with reference to subsequent happenings. In the case of the sedimentary rocks, their original condition so far as this present inquiry is concerned was characterized by their arrangement in flattish beds in a definite order with the older underlying the younger. The lavas of the Volcanic rocks had

a similar arrangement. The original condition of the intrusive Volcanic rocks is that in which they consolidated from the magma as dyke or sheet.

If we find these original arrangements disturbed in any way, we have a record of an event of some significance in earth-history. The very fact that we can study the ancient marine rocks as part of the present lands indicates a change in their original relations to sea-level. But such broad movements of relative depression or elevation of considerable segments of the crust are not to be our concern at this moment; we have dealt with some aspects of this matter in our consideration of transgressions and regressions. We now have to examine evidence of more violent, if more restricted, movements whereby the original arrangements have been more thoroughly upset. From an examination of the rocks themselves we decide that such movements result from forces—tensional, compressional, or gravitational—that have acted upon a particular portion of the crust, for, like other solid substances, the rocks have fractured under tension or have folded or fractured under compression. They have broken or bent. We must acquire a little knowledge of the anatomy of these crustal fractures and folds so that we can evaluate them as records of revolutionary events.

Fractures. We begin with certain kinds of fractures. We can distinguish two types, joints and faults. Fractures at which only a little movement, and that mostly at right angles to the fracture-plane, has taken place are *joints*; fractures with a

bigger movement, and that parallel to the fracture-plane, are *faults*.

Joints. All rocks, even the most carefully selected monoliths, are penetrated by multitudes of irregular cracks developed most probably as they are gradually disinterred by erosion and weathering and their environment changes. We do not include such more or less fortuitous fractures among the joints, which are regular planes along which the rocks affected may break with clean-cut surfaces. These joint-planes are often arranged in sets or systems so that one set of vertical parallel planes is crossed by another vertical set at about right angles. When such a system of two sets of joints is accompanied by a well-marked bedding, a cuboidal pattern of the parting planes of the rock is produced. An excellent and significant example of such a pattern is provided by a piece of ordinary coal. Pick a piece out of the coal-scuttle and have a look at it. It is not shapeless but has its own proper shape—the shape of a piece of coal—because it is bounded top and bottom by bedding-planes and front and back by one set of joint-planes and at the two ends by another set at about right angles to the first. The significant feature about the shape of a piece of coal is that jointing controls many important operations in the mining and utilization of coal. The directions of the joints in the seam will determine the lay-out of the mine, the number and perfection of the joints will decide the ease with which the coal is mined, what the average size of the blocks will be, how the coal will

behave in the crusher and washer, and for what industrial processes it will best be used. Jointing is no academic matter to the coal-miner or to anyone concerned with the excavation of rock. One of the most persistent excavators is nature herself, and the agents of chemical and mechanical weathering work most readily along these parting-planes in the rocks. Joint-planes become fissures by such weathering and their quality decides much of the detail of cliff and crag.

The majority of joints are the result of shearing of the rocks during crustal movements. Similar patterns of fracture are produced when some homogeneous material such as glass is subjected to torsion ; excellent though unwelcome examples of such patterns were provided when thick plate-glass windows in solid frames were fractured during the bombing of London. Investigation of joint-patterns forms part of the investigation of the *tectonics* of a region of the crust, tectonics meaning the structure considered in relation to the forces and movements that have operated in that region. Another and different class of joints results from tensional stresses during shrinking. Examples are provided by starch or mud as they dry out, and the roughly hexagonal columnar jointing seen in some sedimentary rocks may be of an analogous origin. Columnar jointing due to contraction is shown on the grandest scale by certain fine-grained basaltic rocks such as those making the Giant's Causeway in Ireland or Staffa in Scotland; the most stable contraction-pattern in a homo-

geneous medium cooling from a surface will clearly depend upon shrinkage towards centres arranged at the corners of equilateral triangles. Contraction-joints are mentioned here only because they are often spectacular—they are not directly connected with tectonic events in the crust.

Faults. As we have said, movement parallel to a fracture produces a *fault*. The displacement of the rocks on the two sides of the fault is naturally only relative. It may amount to thousands of feet in a vertical direction or to scores of miles in a horizontal direction. Alongside the fault, the rocks are often broken up so that they are more readily eroded; the depression of the Great Glen of Scotland lies in a belt of strong faulting. There are many classifications of faults, but here we select for our attention those in which the plane of fracture and dislocation stands steep. Of these, we consider three examples which have the names *normal fault*, *reverse fault* and *tear-fault*. The *normal fault* is that normally encountered in British coal-mining. Suppose in working a flat-lying coal-seam we encountered a fracture sloping downwards away from us along which displacement had carried the continuation of our coal-seam down to a deeper position. Such a fault is a normal fault, the fault-plane is inclined towards the downthrown side, the effect in that particular portion of the crust is an extension and the forces responsible for the dislocation are clearly tensional, acting tangentially to the earth's surface. The *reverse fault* is the reverse of the normal fault in that the fault-plane is in-

clined towards the upthrown side, the crust so faulted is shortened and the responsible forces are compressional. In the true *tear-faults*, the displacement is dominantly in a horizontal direction. Kennedy has recently shown that a displacement of some sixty-five miles is likely to have occurred along the tear-fault of the Great Glen of Scotland.

It is not to be expected that pressures, whether tensional or compressional, will be relieved by one single fracture and, accordingly, we find the crust traversed by a number of more or less parallel fractures forming a *fault-belt* or *fault-system*. Movements along faults may bring together rocks of entirely different resistances to erosion so that marked topographic diversity may result at the earth's surface. We instance the example of the Ochil Fault in the Midland Valley of Scotland which has brought softer Carboniferous sediments on the south against hard Old Red Sandstone lavas on the north; the great south-facing escarpment of the Ochil Hills has resulted. When we are dealing with a number of parallel faults of differing throws, a couple of characteristic topographic forms result which deserve consideration. Two parallel faults throwing away from one another may produce, with suitable rocks, an upstanding segment known as a *horst*; two parallel faults throwing towards one another produce a *trough* or *graben*. The horsts of the Vosges and the Black Forest flank the graben of the Rhine Valley as illustrated in the geological section of Figure 9. The Rhine valley north of Basle is a narrow seg-

ment 300 km. long but no more than 40 km. wide sunk down a kilometre or so.

The Rhine graben is thus no small structure but it becomes dwarfed alongside the colossal troughs encountered in the fracture belt of East Africa and neighbouring regions. These include the Great Rift Valleys made famous by Gregory. This network of fractures stretches from

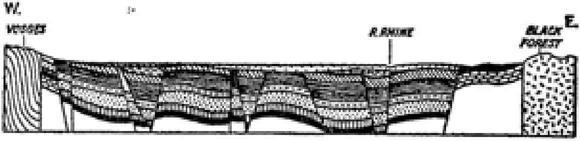


Fig. 9. The Rhine Graben: between a series of parallel fractures the Rhine valley has been dropped between the Vosges and the Black Forest

beyond the Zambezi 20° south of the equator northwards to Damascus 35° north of the line. It is thus the greatest single tectonic element in the architecture of the crust, extending over a sixth of the earth's circumference. In the depressions of the southern mosaic of fractures are situated the long, narrow, and deep lakes of East Africa—Lakes Nyassa, Tanganyika, Kivu, Edward, Albert, Rudolf, and many lesser. Farther north, the fractures cross Abyssinia to the Red Sea and Gulf of Aden, which are themselves gigantic drowned depressions collapsed between parallel fractures. At the north end of the Red Sea the rift valley continues as the Gulf of Suez, and a branch system forms the Gulf of Akaba, which continues north-

wards through Palestine to Syria. This last stretch is the most famous, for in its depression are the Jordan Valley with the Sea of Galilee and the Dead Sea; we realize the extraordinary nature of these structures when we remember that the floor of the Dead Sea is some 2,600 feet below the sea-level of the Mediterranean and its water-level some 1,292 feet below.

Opinion is divided as to whether the Great Rifts result from tension or compression. Some geologists regard the rift valleys as fallen keystones in a crustal arch undergoing extension by normal faulting, and consider that the zig-zag pattern of the fractures cannot be accounted for by compression. Others suggest that the faults bounding the depressions are steeply inclined reverse faults arising from compression. Bullard has found that the value of gravity is low beneath the rift valleys and we are therefore dealing not with fallen keystones but with light segments held down in position by the overriding wall-blocks. This discussion is beyond our present scope, but the Great Rifts remain as one of the grandest elements in the architecture of the crust.

Folds. Let us now consider the folds and associated fractures which result from compression. With a little manoeuvring we can imitate many of the structures seen in the folded belts of the crust by pressing our two hands on a heavy table-cloth covering a table and then bringing the hands closer together; the originally flat-lying table-cloth will be rucked up into folds of various kinds. As the

distance between our hands decreases, so the gentle and simple folds first formed become more pronounced and complex. The degree of folding records the amount of compression and shortening undergone by the cloth. Any small area of the cloth has lost its original horizontality and is now inclined with respect to the table-top. The analogous inclination in folded beds of the crust which, as we have seen, were originally flattish and more or less horizontal, is called the dip, defined as the steepest inclination of the bedding plane at any particular place. On geological maps, the dip of a bed at any exposure is recorded as an arrow pointing in the direction of the steepest slope and having alongside it a number indicating the inclination in degrees from the horizontal. A line at right angles to the dip is called the strike, a word related to stretch ; the strike gives as it were the stretch trend or extension in a horizontal plane of a tilted bed or of any elongated structure.

We shall probably soon tire of holding our hands still on the folded table-cloth so we may conveniently transfer our attention to a stack of corrugated iron where the folds are fixed and rigid. A single sheet is an affair of arches and troughs running its length, the stack, as can be seen at its ends, is an affair of the arches and troughs of many sheets nesting in one another. The technical terms used to describe similar structures in a stack of folded beds are anticline for arch and syncline for trough; in the anticline the beds on the two sides dip away from the crest of the arch, in the syncline

they dip towards the bottom of the trough. In nicely folded beds, as a glance at the stack of corrugated iron sheets would show, anticline and syncline alternate, a side or limb of an anticline passing into a limb of the succeeding syncline. Also, we could mark with chalk the top of each anticline and the bottom of each syncline and we would get a series of chalk-marks parallel with the length of the folds; similar lines in geological folds are called fold-axes—they give the strike of the folding. Axes drawn on the tops of one group of nested anticlines of an infinite number of corrugated sheets would join up into a plane, the axial plane, which bisects the series of folds; we could chalk the trace of this plane on the end of the stack. In this particular example, the axial plane stands upright, the two limbs are inclined away from it at equal angles and the fold is said to be a symmetrical one. We could reproduce symmetrical folds with our table-cloth but we should most likely find that many of the folds were not symmetrical, that one limb was steeper than the other and that the axial plane was inclined. The asymmetry of such folds and the inclination of the axial planes can be increased by suitable manipulation of the cloth until one limb of an anticline becomes inverted and tucked in below the other, giving an overfold. The overfolding may continue so that the axial plane becomes almost horizontal and the fold is then lying down—the technical term is recumbent; a good model of recumbent folds lying one on top of another is provided by the forms assumed by a towel

as it comes through a mangle. Meditation on these homely examples connected with table-cloths, mangles, and corrugated iron will fit us to appreciate the similar structures provided in the great fold-belts of the crust. We return to the overfolds in a moment.

In the crustal fold-belts, what is found to be folded are the beds of sedimentary rocks and lavas and the sheets of intrusive material—all originally formed in flat-lying and extensive layers. The original condition is disturbed and thus a revolutionary event in earth-history is recorded. The simplicity and regularity of the model folds of the sheet of corrugated iron are not repeated in nature. In the first place, natural fold-axes are not consistently horizontal nor necessarily straight lines. The inclination of a fold-axis is called its pitch; as a fold is followed in the direction of pitch, higher and higher elements of the structure are encountered, as can be realized by viewing a tilted pile of sheets of corrugated iron. Fold-axes are not for long straight lines. Though they may be horizontal, they may yet be curved and thus provide arcuate folds or arcs. If they are not horizontal, they may change their inclination along their length; a position on a fold-axis where the pitches are away from one another is a culmination, where they are towards each other is a depression. When we examine the fold-belt of the Alps we shall see the profound effects on the structure as a whole resulting from the operations of pitch, culmination and depression. A second diversity is produced in

natural folds by the fact that though individual folds are elongated they cannot go on for ever but sooner or later end, the folded beds passing gradually into unfolded beds.

Two other fold-structures may be mentioned here. These have the descriptive names of domes and basins, though usually they are not of circular plan but elongated in one direction. In the dome the beds dip away from the centre of the structure, in the basin they dip towards the centre.

Overfolds and Overthrusts. Now let us return to the overfolds. The capital letter S provides a suitable model—a push from the right has resulted in the formation of an overturned syncline, the bottom half of the S, and of an overturned anticline, the top half. The weak place in the structure represented is obviously the middle part, the middle limb the geologist calls it, connecting the lower limb of the overturned anticline with the upper limb of the overturned syncline. In the crustal overfolds, any particular bed becomes thinned in this middle limb both by extension of the bed and by migration of material into places of less pressure such as the arches and troughs of the adjacent folds. As the folding continues, the thinning of the middle limb may become so marked that the adjacent folds cannot hold together and fracture occurs along it. The S-structure parts along the middle limb, the top of the S moves to the left along a plane gently sloping to the right. Technically speaking, overthrusting has occurred and the plane of movement is an overthrust or

thrust-plane. In many of the fold-belts, great wedges of the crust have been moved forward along thrust-planes over the rocks below for scores of miles. Particularly clear examples are provided in the North-west Highlands of Scotland, as is shown in a later page. Along the great thrust-planes the rocks have been ground down and crushed into fine particles to form the kind of rock known as mylonite (Greek *mylē*=mill), so called because it has been through the mill, as it were. By overthrusting or by large-scale recumbent folding, such as occurs in the fold-belts, great masses of the rocks of the crust have been translated far from their original positions; these translated masses are known as nappes (i.e. sheets, compare *napkin*, a little sheet).

Fold-belts. Compression of the crust under the impulse of tangential forces thus leads to a contraction expressed in the folding and overthrusting of the beds or other original structures affected. Relief is not attained through one single fold or one single overthrust. We find, in fact, that many compressional structures are associated to make the fold-belts, long narrow welts of crustal disturbance. The Alps, the Atlas, the Himalayas, and other mountain-zones of to-day provide examples of such fold-belts. In addition to their folding, the fold-belts possess other rather remarkable characters which we consider later on.

In the preceding paragraphs we have acquired a knowledge of the anatomy and terminology of folds and overthrusts. We can make these dry

academic bones come alive by studying in outline the two disturbed zones of the crust already referred to, first the North-west Highlands of Scotland as a sample of overthrusting and second the Alps as a sample of folding and nappe formation.

Overthrusting in the North-west Highlands. In investigating the revolution that has affected the rock-groups of the western seaboard of the counties of Ross and Sutherland in the North-west Highlands of Scotland, it is first necessary to determine what the original relationships of the rocks were—original being used here in the sense previously defined as indicating the conditions before the episode in earth-history we are studying. In displaying these original relationships we have an opportunity of applying those principles of the historical study of the earth that have been set forth in earlier chapters. The oldest rock-group of the area is a series of Plutonic rocks—migmatites, gneisses, and schists—to which has been given the name *Lewisian.* The Lewisian has been determined to be the oldest rock because it underlies in its original position all other rocks of the region. It is covered unconformably by thick beds of red felspathic sandstone, the *Torridon Sandstone.* Its red colour, the unweathered nature of its felspar grains, the existence in it of wind-shaped pebbles—in short, its facies—indicate on uniformitarian lines that the Torridon Sandstone was deposited in a semi-arid continental environment. This is confirmed by examination of the surface of Lewisian on which it rests. Beneath the Torridon Sandstone

is revealed the oldest landscape in Europe, for the sandstones are seen to fill the valleys and to bury the peaks of a rugged mountainland carved out of the Lewisian by the ordinary agents of erosion in Torridon Sandstone times. The grandeur of his theme is brought home to the most utilitarian of geologists when he observes such sections as that along the roadside north of Loch Assynt where he can pick up dreikanter, etched by the winds of five hundred million years ago, from the desert floor of Lewisian, rotted in that same distant period. Such thrills arise in no other science and they can be had at no cost by professional and amateur alike. It is not to be wondered at that there was a time when professional geologists were paid low wages because they so obviously enjoyed their job. But let us return to the geological history of the North-west Highlands. The next episode in this is a marine transgression recorded by sedimentary rocks which, from their fossil contents, are of *Cambrian* age. These Cambrian beds rest unconformably on Torridonian and Lewisian, their plane of contact with these being smooth and clearly one of marine denudation. They record an advance of the sea over the Torridonian land by a series of beds beginning with sand, followed by mud and then grit and then shell-debris, and now represented by an upward succession of quartzite, shale, grit, and limestone. The original relationships of the rocks of the North-west Highlands were, therefore, as follows: at the bottom the Lewisian, covered unconformably by Torridon Sandstone which is suc-

ceeded unconformably by Cambrian sediments. These relationships are shown in the left-hand portion of Fig. 10. We have now established the original, pre-revolution condition of the rocks in this region and can pass on to examine the evidence for subsequent happenings.

This can best be done by first recording the observations that a geologist would make along what he would call a traverse over a particular stretch of the disturbed area and then by applying these observations to the North-west Highlands in general. As our sample traverse we select one which is bound to be made by any reader of this book fortunate enough to visit the North-west Highlands; it runs along the south side of Loch Glencoul five miles north of Inchnadamph in Western Sutherland, beginning at the roadside two miles south by east of Kylesku. Going eastwards from the road, the observer passes over outcrops of Lewisian, Torridonian, and Cambrian rocks with the characters and relationships already noted. He can satisfy himself, by extending his direct observations on the actual outcrops to the interpretation of the surrounding hill-scenery, that first a hilly land-surface of Lewisian has been buried beneath the Torridon Sandstone and second that the lowest Cambrian beds, quartzite, rest on a smooth plane of denudation carved out of Torridonian and Lewisian rocks. He has reaffirmed the original relationships of the three rock-groups, Lewisian the oldest, Torridonian the intermediate, and Cambrian the youngest. Continuing east-

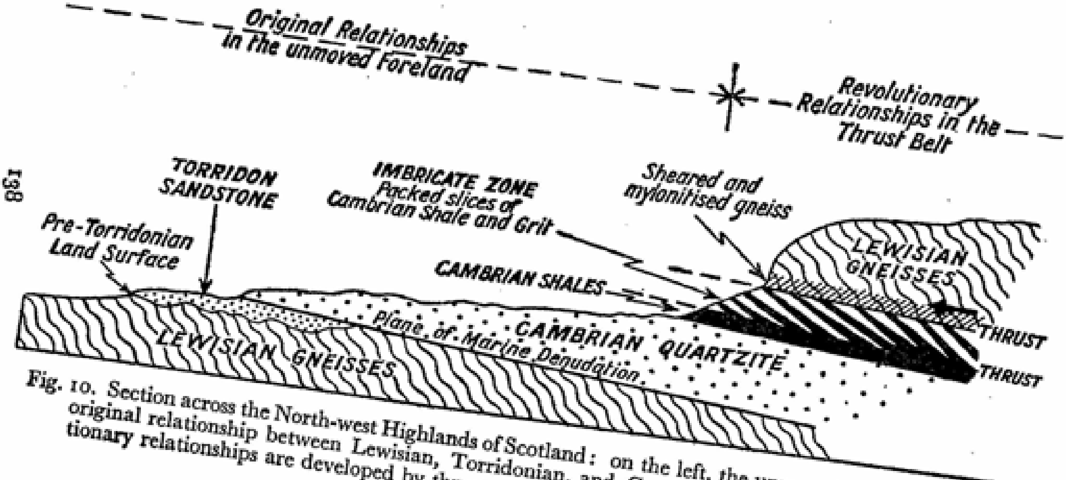


Fig. 10. Section across the North-west Highlands of Scotland: on the left, the unmoved foreland with the original relationship between Lewisian, Torridonian, and Cambrian rocks; on the right, revolutionary relationships are developed by thrust-movements

wards on his traverse, he finds the lowest Cambrian beds, the quartzites, covered by the next in the succession, the shale. Relationships are still original, but as he proceeds up the steep hillside towards the head of the loch he observes associations of the shale and the grit which are clearly not original. Instead of the original succession of shale and grit, he finds some shale and some grit repeated again and again, so that many small samples, as it were, of these beds make up a thickness of a hundred feet or more. It is clear that thin slices of these two beds have been packed together by movement along a number of small steepish thrust-planes so that they come to lie on one another like tiles on a roof. The technical name for this structure is imbricate, from the Latin *imbrex* = tile. Climbing up through this imbricate zone, our observer meets spectacular evidence of still more profound disturbance of the original relationships, for he finds the Cambrian rocks overlain by Lewisian, an entirely unnatural arrangement demanding for its production revolutionary happenings in the history of the earth. Detailed investigation of the junction between Cambrian and overlying Lewisian reveals that the rocks are there sheared and mylonitized. The evidence justifies the interpretation that a wedge of Lewisian has been thrust over the Cambrian beds which, beneath the plane of movement, have been packed together into a pile of imbricate slivers. The right-hand part of Figure 10 shows these structures, so we can now compare the original relationship of the left

part of the section with the revolutionary relationship of the right.

Violent disturbances similar to those now so evident at Loch Glencoul have been demonstrated in a belt of the North-west Highlands stretching from the north coast of Sutherland southwards for a hundred miles to Skye. West of the belt of disturbance the foreland of Lewisian, Torridonian, and Cambrian remains unmoved, in the belt great wedges of the crust have yielded under compression and have been moved along gently-sloping thrust-planes tens of miles towards the north-west, piling themselves on one another and dragging out the underlying Cambrian in imbricate slices. Inchnadamph in Sutherland is a place of pilgrimage for geologists since nowhere else is clean-cut over-thrusting so well displayed.

Folding in the Alps. The Alps, whose geological structure we are now to consider, is the most remarkable of all the folded regions of the crust. It is probable that its structure taken as a whole is not a fair sample of that of the ordinary fold-belt, but it is well worth studying for its own sake. Moreover, in spite of this possible abnormality, the Alps do supply the most spectacular examples of recumbent folds, nappes, and overthrusts which, on a minor scale perhaps, are found in other folded zones.

We have given the homely simile of the forms assumed by a towel coming through a mangle to illustrate a pile of recumbent folds lying on top of one another. We may use this model, without in

any way implying any analogous method of production, to begin the examination of the structure of the Alps. The pile of folds in the towel is elongated with the fold axes running parallel with the length of the pile and consists of fold upon fold, as shown by inspection of the ends of the pile; the lower folds—the lower tectonic elements, the geologist would call them—are covered by the higher tectonic elements, and the highest fold of all conceals those below it; we could unfold the towel, lay it flat and make some kind of estimate about how much it had been 'shortened' in making the pile of folds. Now transfer ourselves to the Alps. A century or more of geological investigations in Switzerland and Western Austria has led to the interpretation of the Alps as basically a pile of enormous recumbent folds, with their axes curving in a gigantic arc from the Riviera to Vienna; elaborations of this basic concept will appear as we go along. Erosion has bitten deep into the pile and great valleys have been excavated in the mountain belt so that as good a view of the crustal folds is provided as is given by the ends of our folded towel. Moreover, a considerably better view of the lengthwise development of the Alpine folds is obtained since, in the first place, many of the higher structures have been partially removed by erosion to reveal those below, and, in the second place, culminations of pitch bring up to observation portions of the lowest folds and depressions of pitch have preserved in their saddles many of the higher structures so that their relationships can be estab-

lished. We have spoken of higher and lower tectonic elements such as recumbent folds, nappes, and overthrust slices and, so far as their erosion is concerned, we can treat this succession of structures as we do a succession of beds. Thus, in the Alps, there are found relics detached by erosion from the rest of a nappe which correspond to the outliers of a bedded succession—these nappe outliers are called klippen (singular, klippe). Similarly, partial erosion of a higher nappe, often on a culmination,

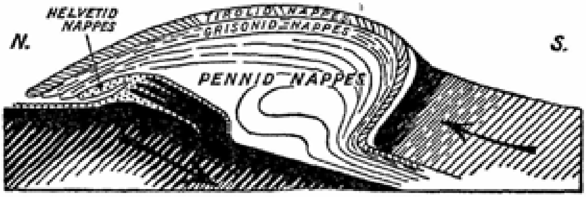


Fig. 11. The Four Nappe-groups of the Alps

reveals an inlier of a lower nappe; this inlier is known as a window, since through it can be viewed the lower tectonic elements framed by the higher.

Reduced to the simplest terms, the interpretation of the great fold-pile of the Alps is that it is made up of four great tectonic units each consisting of a group of nappes. Beginning with the lowest, these units are named in ascending order: Helvetid, Pennid, Grisonid, Tirolid. Their arrangement is indicated in a schematic way in Figure 11. In this figure, the super-imposed nappes are shown as complete folds not reduced by erosion. We obtain

the notion of the great masses of the highest tectonic units flopping-over towards the north, overriding and dragging out the lower units and even wrenching out wedges of the crystalline foundation. We can readily appreciate the shortening of this segment of the crust, a shortening activated by the approach of the two margins of the original area of sedimentation. We can unroll our folded towel; let us see how the Alpine folds unroll. In this operation, the Alpine geologists take advantage of the changes in facies as indicating changes in environment of sedimentation. They have determined that the sedimentary rocks making the Helvetid nappes were deposited on the continental shelf bordering a northern land, the Pennid materials in a deeper sea to the south, the Grisonid, Tyrolid, and Dinarid materials on the continental shelf of a southern land. Unrolling the pile of nappes as we did the folded towel, we can display the constituent sediments in their original undisturbed positions of formation. We arrive at the idea that the Alps have been made out of the sediments of a sea, *Tethys* we call it, lying between northern and southern lands. The operation of unrolling the nappes is indicated in Figure 12 with the results shown in the lower part. Conversely, the nappes can be re-made by folding the sediments of Tethys through the approach of the southern land to the northern. As the Swiss geologists put it: *Africa overrides Europe*.

Now, subject the complete and whole nappes of our diagrammic scheme to erosion, bearing in mind that the fold-axes are subject to undulations, that

they pitch and have culminations and depressions. We can readily see how, by a combination of adequate erosion and suitable structure, outlying relics of the higher tectonic units can be left scores of miles in advance of the remainder of their unit to give the klippen, and how stripping-off by erosion of the higher elements on culminations gives a window exposing a lower structural element or even a dragged-out wedge of the crystalline basement. We can best proceed with our study of the

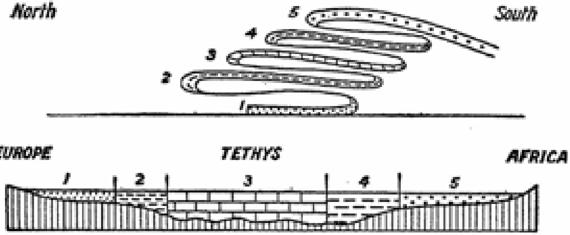


Fig. 12. Unrolling the Alpine Nappes

Alps by working through a section tied on to the actual ground, and for this purpose we cannot do better than take one drawn by the Swiss geologist Argand from Lausanne across the Alps to Lombardy; it is shown, on a very reduced scale, in Figure 13. We begin at Lausanne.

At Lausanne we are in the Swiss Plain between the Jura Mountains to the north and the Alps to the south. The Swiss Plain is the country of the *Molasse*, a series of sandstones and conglomerates of Oligocene and Miocene age, freshwater or

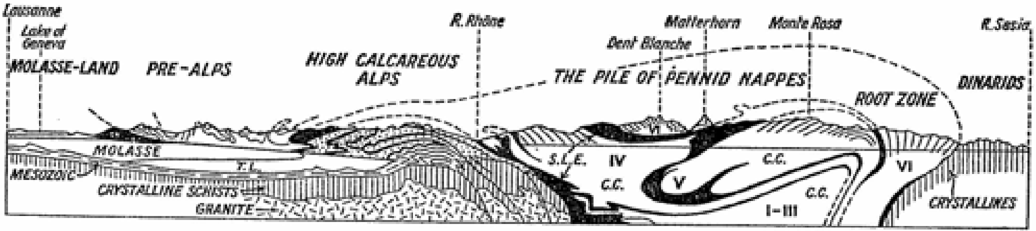


Fig. 13. Geological Section across the Alps from Lausanne to Lombardy (after Argand)

marine in origin and made up of debris eroded from the rising Alps. The older Molasse is involved in the Alpine movements and supports relics of overthrust nappes. Collet of Geneva has given the following motion picture of these events: 'the Alps travelling forward, and the pebbles going forward from the chain as it grows and then the chain riding over its own debris'. South-east beyond the Lake of Geneva is the complex and fascinating region of the *Pre-Alps* formed, it is thought, of relics, that is, klippen, and the fronts of folds belonging to the Helvetid, Pennid, and Grisonid groups which have been thrust over the Molasse. The highest structural fragments which make great klippen possess a facies quite unlike that of any native Swiss sediment; they are *exotic* and can best be matched with high tectonic elements of the Alpine edifice such as the Grisonids. They may represent all that remains in Switzerland of the great rock-sheets that once covered the Western Alps. Beyond the Pre-Alps rises the great mountain-wall of the *High Calcareous Alps*, composed of Helvetid nappes made out of Mesozoic sediments that were deposited upon the crystalline foundation. In this zone, great overthrusts of the Scottish type are produced by the splintering and dragging forward of the old foundation as a consequence of the passage over it of the enormous masses of the highest tectonic elements. On culminations, extensive areas of the foundation are revealed, as in the granitic and gneissose masses of the Aiguilles Rouges and Mont Blanc. South-east of these

massifs follows the gigantic pile of *Pennid* nappes, six great recumbent folds with such famous names as Simplon, Great St. Bernard, Monte Rosa, and Dent Blanche, and made of Mesozoic sediments of deep-water facies. The pyramid of the Matterhorn is a remnant, isolated by erosion, of the Dent Blanche nappe. South-east again of the Pennid folds is a narrow *root-zone* where the continuations of the Pennid and higher nappes plunge vertically down. Beyond, in the Dinarids, is the south-east side of the fold-belt with movements directed relatively to the south-east. Even from this condensed traverse, some idea of the style and complexity of the Alpine folds can be gathered.

Let us now transfer ourselves to the *foreland* of the Alpine arc and examine the structures of the Jura Mountains. Here, between the buttresses of the crystalline massifs of the Central Plateau of France and the horsts of the Rhineland, have surged forward the upper layers of Mesozoic rocks under the Alpine impulses to produce structures comparable to those of the rumpled table-cloth with which we began this examination of folding in general. The folded table-cloth slides along the table-top during folding, it is detached from the table. In the folded Jura this detachment—*décollement* (unglueing) is the technical word—takes place at a slippery salt-bed in the Middle Trias. Below this lubricating layer, the rest of the sediments covering the old foundation remain undisturbed by the Alpine storm; above it, the sediments fold into table-cloth folds, anticlines making hill-

ridges, synclines the valleys between, and no fold persisting far. A section, based upon one of Buxtorf's, illustrating this décollement in the Jura is given in Figure 14.

The Two Styles of Earth-movement. Now that we have been introduced to the morphology of folds and fractures and have studied a few examples, we are ready to consider more general topics concerning the architecture of the crust. It will have become evident that there are two fundamentally different styles of movement in the earth's crust. The *first style* we have been examining in this chapter. It is that which gives rise to the fold-belts of the crust in which evidences of shortening under tangential compression are clear and abundant. A belt is a long and narrow thing; the fold-belts are long and narrow too, so that relatively little of the total volume of crustal material is involved in them. The process of making the fold-belts is called *orogeny* (Greek *oros*, mountain). For reasons that we examine later, the fold-belts often form mountain-zones, but the term orogeny as used by the geologist refers to a style of geological structure and not to a topographic elevation. *Orogeny then is a violent short-lived revolutionary episode in earth-history, recorded in restricted fold-belts of the crust.*

The *second style* is *evolutionary*. We have studied its results in the transgressions and regressions recorded in the pile of sedimentary rocks. We have watched the ebb and flow of the waters over vast areas of the continents. Broad swells and depressions form in the crust by vertical movement of

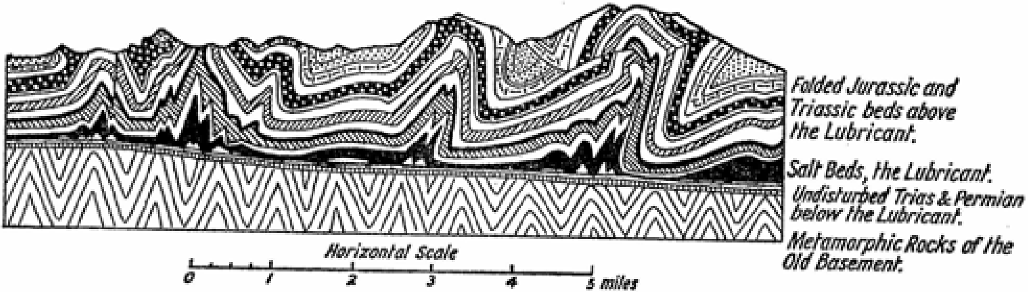


Fig. 14. Décollement (Unglueing) in the Jura: above the lubricating salt bed the beds have packed and folded and have become unstuck from the unmoved beds and basement below

great segments. In this style of movement we cannot lay our hand on a part of the crust and say 'here is a fold' or 'there is a fracture'; we are dealing with broad warpings. *These gentle long-lived evolutionary episodes in earth-history, recorded in the sedimentary successions over great expanses of the lands, are called epeirogenic*, from the Greek word *epeiros*, continent.

Orogeny and epeirogeny are thus two fundamentally different styles of earth-movement. Epeirogenic movement affecting great masses of continental size, or orogenic movement producing a fold-belt stretching thousands of miles, must clearly demand causes of corresponding orders of magnitude. They are worldwide movements requiring a worldwide mechanism for their making. We consider certain aspects of this problem later.

The Over-thick Geosynclinal Piles. We return to the examination of the orogenic belts to discuss one of their most remarkable characters. The sediments involved in the revolutionary events recorded in the fold-belts are many times thicker than the unfolded sediments of the same age. This fact was first demonstrated in the Appalachian fold-belt of the Eastern United States where the folded sedimentary rocks are some 40,000 feet in thickness, while the unfolded rocks on the flanks reach no more than a tenth of this. The fold-belts are long and narrow and the sediments in them are consistently over-thick (see Fig. 15). The raw materials of which the fold-belts are made were thus deposited in a long narrow trough to which Dana in 1873

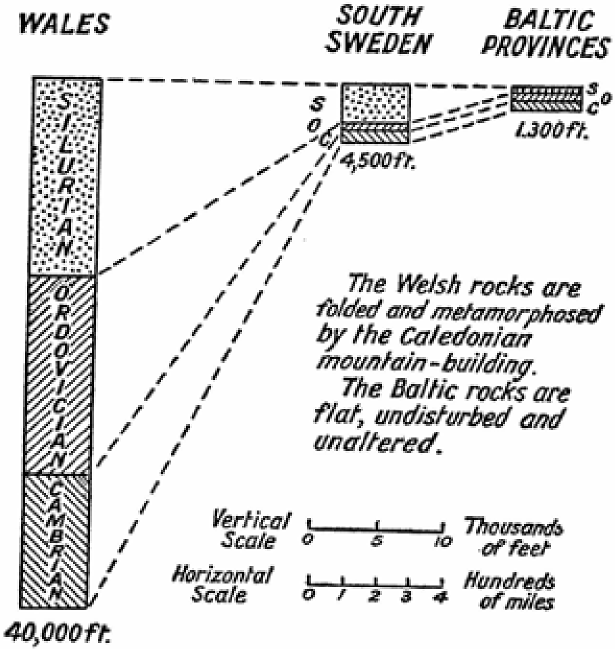


Fig. 15. The Over-thick Geosynclinal Pile: the contrast between the very thick Welsh deposits of Lower Palaeozoic age, which have been violently folded, and the thin Baltic deposits of the same age which are unfolded

gave the name *geosynclinal*, now *geosyncline*. The preliminary operation in the orogenic revolution is the formation of the geosyncline and its filling with sediments.

When we look into the nature of the sediments

in the abnormally thick geosynclinal piles, we find that their facies are such that the majority of them must have accumulated in no great depth of sea-water. Many of the sedimentary rocks encountered are coarse detrital accumulations laid down rapidly in shallow seas by the erosion of adjacent high lands. The problem at once arises: how can, say, 40,000 feet of shallow-water sediment accumulate in one pile? It is obvious that as a shallow trough was filled with shallow-water sediments, its floor slowly subsided so that the deposition of a great thickness of sediments of this one facies became possible. The geosynclines, therefore, are long narrow troughs whose floors are slowly subsiding. It was, and to some still is, an irresistible temptation to conclude that the weight of the sediments depresses the floor of the geosyncline; as a foot is added to the pile, the floor goes down a foot so that another foot can be added. For certain reasons connected with the equipoise of the crust—a topic we examine immediately—this mechanism is unlikely to operate. The successive beds of shallow-water facies accumulate to enormous thicknesses because the floor of the geosyncline is being continuously and slowly downwarped. Not the least of the many astounding features about the geosynclines is this correspondence between the amount of sediment eroded from the adjacent lands and the downwarping of the floor of the trough; events in the trough and on the flanks must be correlated.

Several proposals are before us concerning the cause of geosynclinal downwarping. One view sees

it in tension, another in compression. According to the first opinion, the crust is thinned by being elongated, and the thinned part sags to form the geosyncline. The second, and more plausible, opinion regards the downwarping as part of a buckling under compression, other parts being one or more flanking upwarps, whose erosion supplies the sediment to fill the trough. A third proposal invokes the help of convection currents below the crust; it is suggested that where such currents turn over and descend they may drag down the crust and so produce a geosynclinal depression. The discussion of these, and other, proposals is beyond our present purpose. However caused, the warps will be places of easier fracturing in the crust so that we are not surprised to find basic volcanic rocks, both intrusive and extrusive, intercalated among the sedimentary rocks of the geosynclinal piles.

The Fate of Geosynclines. Whatever may be the mechanism by which they are formed, the geosynclines—filled with a great thickness of partly unconsolidated sediment—will be zones of weakness in the crust when compression does act upon it or acts upon it more violently. *The crust gives along the geosynclines; their contents take up the shortening.* The over-thick pile is buckled, thrown into folds and overfolds, sliced into great nappes and overthrust wedges, and the structures of the orogenic belts arise. This splaying-out of the contents of the trough along its margins is reasonably interpreted as resulting from the approach of the flanks of the

geosyncline; the jaws of the vice come together so that what is between is squeezed. We have mentioned splaying-out, but from various considerations it is obvious that only part of the geosynclinal pile will buckle upwards; its deeper parts will buckle downwards and so come into hotter and more energetic zones of the crust. Further, the formation of the geosyncline and the subsequent orogenic disturbance are not without effect upon the sialic layer below. By the depression of this layer, granitic magma or granitizing emanations become activated and invade the lower portions of the folded structure. As we have noted in the previous chapter, the folding initiates and localizes the sites of granitization. The rocks of the depths—the granitic batholiths, the migmatites, and the metamorphic rocks—are naturally linked to the orogenic belts; folding and Plutonic rocks are manifestations of the same underlying cause. We now realize the profoundly different roles played by the Volcanic and Plutonic rocks in earth-history. When, in the next chapter, we display the pattern of this history we shall give examples of the accumulation of geosynclinal piles and of their subsequent fates.

The Crust is Balanced. It has been noted in an earlier page that though the term orogeny means, literally, mountain-building, the geologist uses it to denote the production of the structural complexities he sees in the fold-belts. But many of the fold-belts, especially the more modern, are mountain-belts in the geographical sense—they are

elevated zones of the crust. In inquiring into the reason why many fold-belts stand high, we touch upon what is the most fundamental property of the earth's crust, a property which is concerned in one way or another with all geological operations. We proceed to look into some aspects of the ideas grouped around this principle of *isostasy*.

This term isostasy is based upon a Greek word meaning in equipoise or balanced. The principle is that the earth's crust is in equipoise. Above a certain level in the crust—the *level of compensation*—calculated to be some 50–100 km. below sea-level, columns of the same sized cross-section have the same mass whatever their length. In other words, in such columns length multiplied by density is a constant value. The longer column, that which stands high, must therefore contain the greater amount of lighter material, and the longest column, such as the high mountain-ranges of to-day, must have most of the lighter material. We have seen this result foreshadowed in our account of the constitution of the crust as revealed by earthquake study. We saw there *first*, that the continental masses, made of light granitic sial, stood high, *second*, that the oceans were floored for the most part by heavy sima, and *third* that the Atlantic with a thin and patchy sialic covering is on the whole not so deep as the Pacific, which is probably bare of sialic material; the length of the continental, Atlantic, and Pacific columns is related to the densities of the materials making them.

The proposal that the mountainous columns are

made up of less dense material can be tested by plumb-bob observations. The astonishing fact was demonstrated long ago that mountains attract the plumb-bob to a very small amount and in some experiments have actually repulsed it. The mountains are hard and solid things which we know and can test; the extraordinary behaviour of the plumb-bob can only be related to some more deep-seated cause. It can be reasonably interpreted by postulating deep roots of light material extending beneath the visible mountains; the attraction of the heavier material flanking the light roots has worked against the attraction of the mountain mass. Along another line, the existence of a granitic sialic root beneath the Sierra Nevada has been deduced from the speeds of earthquake waves which have passed beneath that range. The mountainous eminences, the continental masses and the deep ocean floors agree as witnesses of isostatic adjustment. We can represent the relationships between the lengths of the crustal columns and their constitutions by the suggestions of Figure 16. The lighter sialic rafts are buoyed up in the denser sima. The floating body with a higher freeboard has a deeper draught, the log with most out of the water has most in it, and the high mountains have deep sialic roots.

In the making of the geologist's mountain-belt we have seen the packing and compression of the light sediments filling the geosyncline so that a thick pile of light material arises along the site of the trough. The sialic jaws of the depression have

come together and have aided in the formation of the deep root of light material beneath the mountain-belt. The column of light material rises to attain isostatic equilibrium and becomes a long and therefore high column, the geographer's mountain range.

Measurements show that isostatic adjustment in the crustal columns is almost perfect, a fact giving rise to interesting speculations. The lengths of the

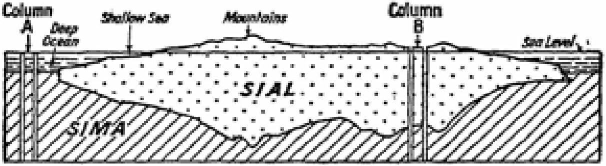


Fig. 16. Isostasy: balance in the crust; the mass in the short column A equals that in the long column B; the light sialic rafts of the continents are buoyed up in the denser sima

columns do not remain constant; material is eroded from the land and carried to the sea so that a load is taken from the continents and placed upon the sea floor. Isostatic equilibrium can be maintained by slow sub-crustal flow of deep dense material from regions of deposition to regions of denudation, a proposal requiring but little strength in the layer of the earth below the crust. We can contrast a strong crust, the lithosphere, with a weak sub-crust, the asthenosphere. But the lithosphere, though strong, sags under great and widely distributed

loads. For example, melting of the great ice-sheets of the Pleistocene period has led to the emergence of the glaciated lands as the weight of the ice which depressed them was taken off them—an emergence recorded in the existence of raised beaches, old shorelines, now many metres above the present sea-level.

Dating the Revolutions. Revolutionary disturbances, whether human or geological, are short-lived affairs separated by long periods of relative quiet. As we have said before, it happens that we are now living in the midst of a geological revolution and we shall examine orogeny in action in a later page. There have been many revolutionary episodes in the past and we have to inquire how these are dated and how they fit into the time-scheme of the geological column.

It is obvious that an earth-movement must be later than the youngest rock or structure affected by it. It may sometimes be difficult to fix a lower limit with any accuracy since it may not be possible either to date the disturbed rocks, on account perhaps of their lack of fossils, or to demonstrate that the rocks seen to be disturbed are in fact the youngest to be affected. Consider a folded copy of *The Times*; to-day's *Times* must have been folded to-day, a *Times* a year old could have been folded any time during the year, and a *Times* with its date removed would provide opportunity for much discussion as to when it was folded. So it is with the sheets recording earth-history. The upper time-limit of a crustal movement is obviously fixed by

the age of the oldest beds, which, undisturbed, overlie the folded rocks; this age may be determinable within varying limits. Some examples will help here; we may conveniently use rock-groups familiar to us from foregoing pages.

The folded Lewisian is unconformably covered by the unfolded Torridonian in the North-west Highlands of Scotland; we cannot on the geological evidence decide what was the interval of time between the folding of the Lewisian and the deposition of the Torridonian sandstones—the interval may be a few million years or the half of geological time. All the geologist is justified in saying is that the Lewisian rocks were folded in Pre-Torridonian times. In the same region, the basal Cambrian quartzite rests unconformably on the Torridon sandstone; the tilting of the Torridonian is earlier than the deposition of the lowest Cambrian beds and, failing discovery of fossils in the Torridonian, that is all that can be said about its date. The interval for the revolution can be more accurately delimited when the relevant rocks are fossiliferous sediments. A good example here is provided by Hutton's unconformity in Berwickshire (Fig. 2) which, as we have repeatedly remarked, revealed to him his 'succession of former worlds'. At Siccar Point on the Berwickshire coast, the basal beds of the Upper division of the Old Red Sandstone—determined to be such by the fossil fish they contain—rest upon the upturned edges of vertical Silurian rocks whose fossils indicate that they belong to the lowest division of that system; the Berwickshire

folding is therefore later than Lower Silurian and earlier than Upper Old Red Sandstone times.

We may intercalate here a revolution that we have not mentioned before. It is recorded by the unconformity below the Permian rocks in Yorkshire; here the folded uppermost Carboniferous rocks of the Yorkshire coalfield are covered by the unfolded basal beds of the Permian—we are justified in stating only that the folding is later than the youngest Carboniferous rocks *of Yorkshire* and earlier than the oldest Permian rocks *of Yorkshire*. There may be still younger Carboniferous rocks and still older Permian rocks elsewhere. For our last example of dating a movement we may take the warping of the Chalk in South-east England; here a group of sands called the Thanet Sands and belonging to the Lower Eocene rests upon various zones of the Chalk—the movement is later than the youngest zone of the Chalk encountered and earlier than the Thanet Sands.

In the small island of Britain, then, many earth-movements of differing styles and scales are recorded and these can be dated within very varying limits. A view of the geological history of the British area gives a picture of an alternation of short revolutionary episodes and long quiet periods. A picture of earth-history as a whole may not be a simple enlargement of the British picture but perhaps a composite of many overlapping pictures. This may arise from a number of causes, the chief possibly deriving from the very nature of the timing of geological events. The geologist uses no stop-

watch, and two events are contemporaneous to him when they fall within an interval of hundreds of thousands of years. Detailed analysis, such as that of Stille, the German geologist, reveals that very few fold-periods can be precisely dated. Many of the gaps in the stratigraphical column in which orogenies are now placed are exceedingly wide, so that by a very coarse correlation the succession of earth-movement becomes falsely simple in style. For the present and until more detailed correlations are possible, we must accept the oversimplified picture.

Where the duration of a fold-movement can be estimated, it is of the order of hundreds of thousands of years and contrasts with the vaster periods required for sedimentary accumulation. It remains true to say that earth-history is an affair of short storms and long calms; orogeny appears not to be, as some geologists have suggested, a continuous earth-process. It seems rather that the great revolutions consist of several episodes which in themselves may not have been strictly contemporaneous.

With the limitations suggested above, it appears that the more violent revolutions are recorded in widely separated areas of the crust. As an example, consider the episode of folding, known as the *Laramide*, which separated typical Cretaceous sedimentation from typical Eocene sedimentation. The type localities for its display are in the Rockies, but it is recognized in the Andes in South America and at many places along the great fold-belt that stretches from the Mediterranean to the East

Indies; north of the great complexities of this belt, we see it appearing as the minor warpings of the Chalk beneath the transgressive Eocene in France, Belgium, and England.

Orogenies, as we have seen, differ in scale, and one orogeny differs in scale in different regions of its development. Accordingly, many or few episodes can be inserted in a time-chart and can be grouped into major revolutions in various ways—all these different treatments depending upon the outlook and often on the nationality of the compiler. For our present purpose we can distinguish three major revolutions, each with minor phases, in the earth's history since Cambrian times. The first occurred during the later part of the Older Palaeozoic and, from its development in Scotland, is called the *Caledonian* orogeny; the second is late Younger Palaeozoic in date and has a variety of names, *Hercynian*, Variscan, Appalachian, and others; the third is the great *Alpine* orogeny, of late Mesozoic and Tertiary date.

During the vast stretches of Pre-Cambrian times, there were doubtless many gigantic revolutions whose records will provide puzzles for generations of geologists. The discussion of Pre-Cambrian orogeny is mainly beyond our present needs; we will deal with certain aspects of it in the next chapter and content ourselves now with this bald statement.

With the insertion of the main orogenic phases in our geological column we arrive at our Second Table of Earth-History.

TABLE II

SECOND STATEMENT OF EARTH-HISTORY

Geological Period	*Orogenic Episode*
Pleistocene	
PLIOCENE	
MIOCENE	MAIN ALPINE
OLIGOCENE	
EOCENE	
	LARAMIDE
CRETACEOUS	
	NEVADIAN
JURASSIC	
TRIASSIC	
PERMIAN	
	HERCYNIAN
CARBONIFEROUS	
DEVONIAN	
	CALEDONIAN
SILURIAN	
	TACONIC
ORDOVICIAN	
CAMBRIAN	
PRE-CAMBRIAN	CHARNIAN KILLARNEAN-KARELIAN LAURENTIAN-SVECOFENNID GREAT BEAR LAKE WHITE SEA MANITOBA

The Causes of Revolutions. We have now made acquaintance with the manner in which orogenic revolutions are recorded in the crust and how at intervals they have enlivened the calm unfolding of earth-history. We may best close this chapter by inquiring into the proposals put forward to account for the orogenic episodes. As was to be expected for so vast and nebulous a topic, these proposals are many and we can select only a few for examination. Our selection displays some of the more reasonable or more interesting—no duality being implied by these adjectives—of the speculations and propositions.

Red-hot lava is seen to come up from the bowels of the earth, temperatures in deep mines are higher than surface temperatures, the earth is considered to have a crust and in this crust the igneous or fire-formed rocks are abundant. All these and many more early observations and tenets of geology were in keeping with the view that the earth was a hot body cooling down and, if cooling, then contracting. The mountain-belts were clearly belts of compression where zones of the earth had contracted. It is no wonder that the classic and still favoured opinion on the cause of orogeny is the *Contraction Theory*. The contraction of the cooling earth gives rise first to the geosynclinal depression and then, growing in power, compresses the contents of the trough into the folds of the mountain-belts. The solid crust has to accommodate itself to a shrinking interior and can do so only by shortening itself. This shortening will occur in the

belts of weakness formed by the elongated geosynclinal depressions filled with unconsolidated sediments. The pattern of the Alpine orogenic belts appears to agree with that demanded by the theory. Further, in a contracting earth, stresses will begin to accumulate again after each orogenic relief until they overcome the strength of the crust; along these lines the periodicity of orogeny is to be explained. Finally, the worldwide distribution of the orogenic belts of one revolution requires a worldwide cause and here earth-contraction fulfils the requirements. The Contraction Theory has therefore much in its favour and, in a shifting world, is the sure anchor of the orthodox.

Criticisms of the Contraction Theory are nevertheless numerous and varied. Its fundamental postulate that the earth is cooling has been questioned, whilst many of its upholders admit that the amount, on any reasonable estimate, that the earth has cooled is insufficient to account for the actual crustal shortening seen in the fold-belts. From the mechanism of earth-contraction that is proposed, it is concluded that the orogenic episodes should be more widely spaced as the earth becomes older, but this is clearly not the case in fact. In spite of this, as Jeffreys has said, 'even if the contraction theory was given up, it would still be necessary to find a theory to account for the contraction' actually observed.

We can only inadequately glance in passing at two other theories of mountain-building. Daly suggests that the earth is warped by unequal con-

traction in the continental and oceanic segments so that the continental masses slide down inclines over the glassy substratum towards the oceanic depressions and thereby compress and buckle up the contents of the geosynclines located on the land-margins. Mellard Reade considered that with sufficient subsidence the sedimentary piles in the geosynclines would be so heated and expanded that they would rise upwards as folded mountain-belts; they could not find relief sideways on expansion and might rise so high that nappes slid down the flanks of the elevated mass. Both these theories can be subjected to fairly destructive criticisms.

In the early earth, convection currents must have operated, light hot material rising to the bottom of the crust, there spreading out, becoming cooler and heavier and then descending. With heating maintained by radioactive decay, it is reasonable to consider that subcrustal convection currents continue to move in the present earth. We may recall that sub-crustal currents of some kind are demanded in isostatic readjustments. The activity of *Convection Currents* in mountain-building has been advocated by Bull, Holmes, and others. It is proposed that these currents rasp along the bottom of the continental rafts and drag them along. Descending systems of slow currents pull down the geosynclinal trough, as previously mentioned, quicker currents increase the downwarping so that the sedimentary filling of the trough is compressed into the folds seen in the orogenic belts, which themselves rise into mountain ranges when the

currents slacken off again. The Convection Current Theory of orogeny is admittedly attractive, but until more is known of the earth's interior and until the localization of the current systems and the relation of the postulated systems to the pattern of the orogenic belts are more clearly elucidated by it, it must be judged as non-proven.

The Convection Current Theory has begun to move the continental sialic rafts sufficiently to compress the fold-belts. The *Theory of Continental Drift*, which we have already mentioned and which we now examine, freely moves the sialic rafts over the sima substratum like ice-floes over the sea. The continental masses have become mobile, the earth's primary features are no longer permanent, palaeogeographic maps are to be modified by almost another dimension; it is not to be wondered at that Continental Drift is capable of arousing violent and vituperative discussion when more than two geologists meet together.

A great body of geological and geophysical data, hypotheses, and speculation permits the conclusions that the discontinuous sialic continental fragments are buoyed up in a continuous simatic layer and that the sialic layer is thin under the Atlantic and absent under most of the Pacific. These conclusions may reasonably be accepted. When we examine the edges of the continental rafts we find some very remarkable differences. The Pacific edges are characterized by fold-belts and arcs running parallel with the ocean margins; the Atlantic edges, on the other hand, show fold-belts running

at an angle to the margins and presenting the appearance of being cut off sharp by the Atlantic coasts. The Theory of Continental Drift proposes to account for this, and a great deal more besides, by reuniting the now separated land-masses into one great continent which, at the beginning of the Mesozoic, broke into fragments which slowly drifted apart, westwards and towards the equator. The Atlantic is a much-widened fissure formed by the drifting of the Americas westwards from Europe and Africa; the fissure has cut across the orogenic trend-lines and the Atlantic type of coast has resulted. The prows or leading edges of the sialic rafts are buckled as they move through the sima and have thus given rise to the Pacific type of coast with the fold-belts running parallel with the ocean margins. The drift towards the equator has compressed the sedimentary contents of the great geosyncline of Tethys to make the Mediterranean fold-belt of the Alpine orogeny.

What geological considerations underlie these entertaining proposals? We select a few. First, however they are interpreted, there are undoubtedly very remarkable correspondences in the geology of the two sides of the Atlantic. Fold-belts of many ages, faunal provinces, facies regions, and similar geological individualities match up in a surprising way when the Americas are placed close to Europe-Africa. As one example, the Cambro-Ordovician rocks of the Eastern United States have a northern and a southern facies; identical northern and southern facies occur in rocks of the same age

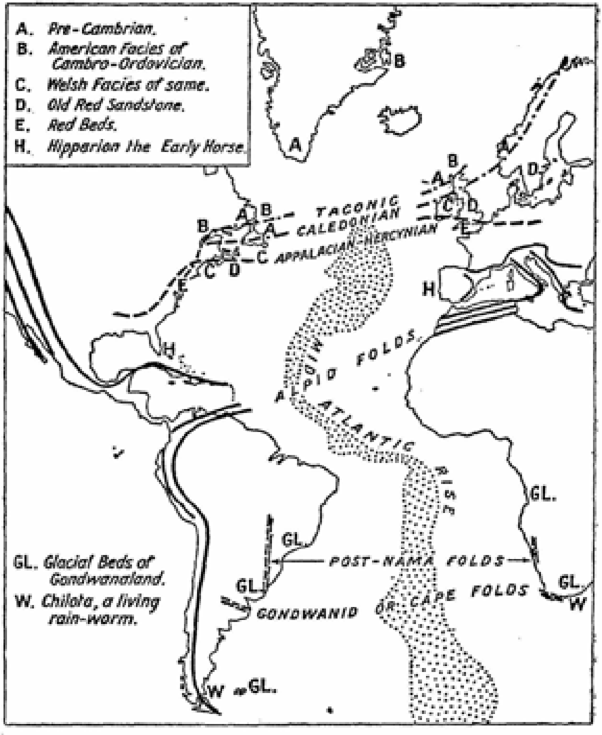


Fig. 17. A Selection of Cross-Atlantic geological Matchings (after Du Toit)

in Scotland and Wales. As another example, the Caledonian disturbances of Scotland appear to run ashore in Newfoundland and the Hercynian folds of Southern Ireland to connect with the Appalachian

folds of the same date in the Eastern States. The early Scottish pioneers landing in Eastern Canada recognized that typical Scottish rock, the Old Red Sandstone, and called their new country Nova Scotia. Fold-belts of various ages in South America match up with belts of corresponding ages in Africa. A selection of these cross-Atlantic matchings is given in Figure 17.

A second consideration is the detailed similarity in the rather peculiar geological history of South America, South Africa, Australia, and India—a similarity which has resulted in the notion of *Gondwanaland*, a great southern land-mass (see Fig. 25). In Permo-Carboniferous times this land-mass was subjected to intense glaciation and tillites are found on its detached portions, both north and south of the equator. Contemporaneous with this glaciation, tropical coal-swamps existed in the northern hemisphere. Such arrangements could be interpreted if the present fragments of Gondwana-land were collected in Permo-Carboniferous times around a south pole and had since drifted apart, as suggested in Figure 18. If the sialic rafts are permitted to move through the sima, their positions with respect to the earth's axis of rotation may become changed so that the problem of the occurrence of tropical facies in the present polar regions and polar facies in the present equatorial regions may be solved.

For many geologists and geophysicists, the theory of continental drift is wrecked by the absence of a motive force of sufficient power. No adequate cause

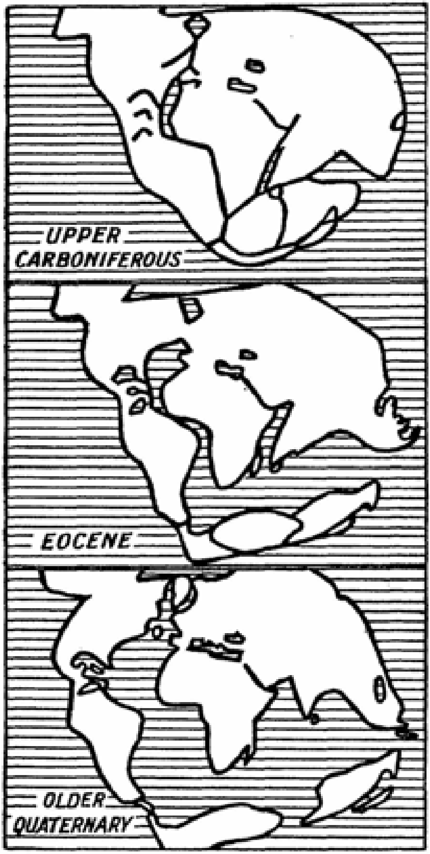


Fig. 18. The Drifting of the Continents (after Wegener)

for drifting is proposed. If, however, we decide *on geological grounds* that drift has occurred, we are not compelled to provide a mechanism. We are certain of the Pleistocene glaciation without being able to give its cause, and we are certain of transgressions and a host of geological events without knowing what occasioned them. There are, of course, numbers of grave criticisms of the Drift Theory. For example, so far as orogeny is concerned, we find the fold-belts made up of over-thick geosynclinal sediments and not of pushed-together sialic stuff. But geology would be much less attractive without this and similar speculations to enliven it.

CHAPTER 5

THE PATTERN OF EARTH-HISTORY

IN THE foregoing we have examined the strands which go to make the pattern of earth-history. We have learnt how to read the records of great movements of land and sea provided by the sedimentary rocks, how to interpret the evidence of volcanic and plutonic episodes, and how to unravel the complexities of the revolutionary epochs. We have now to weave the diverse strands into the unity which makes the past of our planet and, finally, in a spirit perhaps of reckless prophecy, to suggest what its geological future might be. From the multitudinous episodes thronging to be recorded, we can select only sufficient to preserve the continuity. Of these, a few can be viewed in some detail as illustrative of profound and significant turns in earth-history.

The Oldest Rock. What is perhaps the very oldest rock available for our inspection is a conglomerate from Manitoba and, from determinations by radioactive methods of the age of associated rocks, it is well over 1,750 million years old. It is a sedimentary rock, presumably formed in that far-off time by the ordinary processes of sedimentation. Our oldest record is thus one of an event that is being repeated to-day. We can perhaps push our history one stage farther back, for the conglomerate con-

tains pebbles of granite which witness to an earlier orogenic epoch, but beyond this is a geological blank. There is a tremendous lost period between the birth of the earth and the deposition of the Manitoban conglomerate. We have lost the first crust, we can only speculate on the nature of the first atmosphere, and the very remarkable sediments resulting from the first rains are lost to us. So soon as these rains fell, the geological history of the earth began. But our oldest accessible sediments are normal rocks and we do not know how great an interval separates them from the time of the first rains. Before the making of the Manitoban conglomerate, earth-history is an affair for the astronomer and geophysicist, but with its deposition the first decipherable page of the geological record was written and the geologist can begin his tale. But this beginning appears as no straightforward and fluent opening chapter but rather as a fortuitous collection of scraps of paragraphs and sentences. Let us look into the reasons for the obscurity of this early record.

Pre-Cambrian Obscurity. The lower limit of the Cambrian system has been placed at the beds containing the oldest undoubted and recognizable fossils—the *Olenellus* fauna—and their date has been given as about 500 million years ago. The Manitoban conglomerate is older than 1,750 million years; the Pre-Cambrian rocks registering the events between these two dates are almost entirely devoid of decent organic remains. The Cambrian and later rocks teem with varied fossils so that the

500 million years of their formation can be divided up into a multitude of life-zones, and the standard methods of stratigraphical correlation applied to them. The Pre-Cambrian rocks, formed during a period three times as long, holding only a few doubtful evidences of life, and occurring in disconnected outcrops, cannot be dealt with by the standard methods; correlation becomes a hazardous proceeding. The application to the Pre-Cambrian rocks of either of old William Smith's laws, the very bases of stratigraphy, is uncertain; where there is a chance that the rocks have been turned upside down the Law of Superposition is not reliable, and where there are no fossils the Law of Strata Identified by their Fossil Remains means nothing.

Though it naturally forms the basis of much of the correlation in the Pre-Cambrian, lithology is really no sure guide. Pre-Cambrian time is so vast that even rare phenomena such as widespread glaciation might be repeated half a dozen times, whilst more ordinary events have certainly recurred unceasingly. Without fossils, rocks of the same type, whatever their ages, may appear alike. Before the geologist correlates two Pre-Cambrian red sandstones, for example, he should pause and contemplate two detached specimens of Old Red and New Red Sandstones, known to be separated by 100 million years.

It is often said that metamorphism is the cause of the obscurity of the Pre-Cambrian record, but this statement is only partly true. Metamorphism

may have destroyed Pre-Cambrian fossils just as it has destroyed Tertiary fossils, but there are gigantic accumulations of Pre-Cambrian sediments completely unmetamorphosed and seemingly utterly devoid of organic remains. Admittedly, an old fossil has run more risk of being destroyed than a modern one, but we should not appeal to metamorphism either to wipe out fossils or to supply evidence of antiquity. Metamorphism cannot be used as a test of the age of rocks.

Local Sequences Best. In the geological history of the Pre-Cambrian, then, we must deal with very long and somewhat elastic time units, imperfectly correlated and delimited. It is customary, especially in America, to divide Pre-Cambrian time into two parts, an earlier called *Archeozoic* (primeval life), and a later called *Proterozoic* (earlier life). These names are not altogether happy choices since there is practically no life, either primeval or early, recorded in these rocks. This twofold classification of the Pre-Cambrian appears to be an extension of the local fact that in some countries a non-metamorphic series of rocks rests unconformably upon a metamorphic series; in Scotland, as we have seen, Torridon sandstones rest upon Lewisian gneisses. There is a danger of over-simplification of the Pre-Cambrian picture, of forcing all metamorphosed rocks into the older category and all unmetamorphosed into the younger. It seems better, till we know more, to deal with the Pre-Cambrian rocks *locally*, in local sequences. We study samples of these local sequences immediately,

but we have first to examine the validity of the methods by which they are built up.

Building-up the Local Sequence. Great advances have been made recently in the determination of the age-relationships of Pre-Cambrian sediments by the use of original sedimentation-characters such as current-bedding, graded bedding, ripple-mark, and others. The laminae of sediment involved in current-bedding often have their *tops* truncated before the deposition of the next layers, the *bottom* parts of graded beds are the coarsest, the cusps of symmetrical ripple-marks are originally *uppermost.* These characters are illustrated in Figure 19. They may be preserved even in highly metamorphosed beds and, by observations on their present attitude, they may with good fortune indicate the 'way-up' of the succession and help to compensate the Pre-Cambrian geologist for his inability to use William Smith's two laws. By these means, great inversions of the metamorphosed sedimentary rocks of the Grampian Highlands of Scotland have been demonstrated. Mining geologists, working, for example, in the Canadian mineral districts, use these criteria constantly. But, when all is said, only local stratigraphical sequences can be established with their aid. Correlations and determinations of relative ages in great regions have been attempted by other means.

Extending the Local Sequence. Among these other means, the recognition of granites of various ages in the Pre-Cambrian complexes has been applied. If it can be shown that a certain granite was being

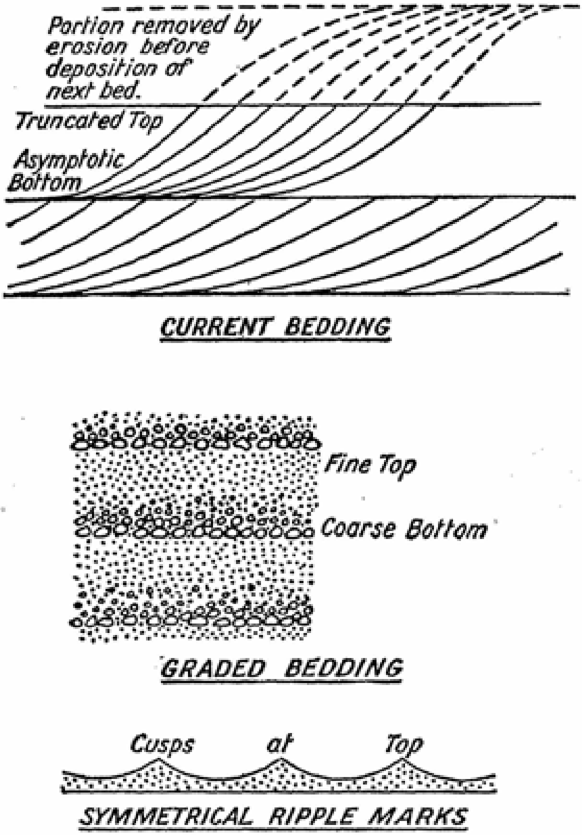


Fig. 19. The Way-up in the Sedimentary Rocks: current bedding, graded bedding, ripple-mark

eroded during the interval represented by a certain unconformity, then all rocks invaded by that granite are older than the unconformity. In Finland and in Canada, three separate unconformities divide the sequence and, between these erosion intervals, three separate granites came into position and are accordingly dated. If these granites can be distinguished and recognized over great areas, then a means of correlation is available. The validity of this method depends upon the determination of a given granite as belonging to a certain epoch of granitization. This, in the writer's opinion, may be a hazardous proceeding involving views about granite with which he has little sympathy.

We have mentioned unconformities in the Pre-Cambrian complexes. Many episodes of upheaval and degradation of great mountain-systems are to be expected in a time so extensive as the Pre-Cambrian. Investigation of the old rocks of Scandinavia, Canada and elsewhere, reveals three or more major revolutions. In any restricted area, the record of several cycles of sedimentation, orogeny, granitization, and erosion can be established with geological certainty, but correlation with the records of other areas is no simple matter. The magnitude of an unconformity, for example, may vary in different parts of the one region and different unconformities may be expressed over widely different expanses. There is an almost irresistable temptation to correlate major unconformities and make them a record of a single

world-wide orogeny. When we designate all Pre-Cambrian orogeny as Huronian or Charnian, as some do, we ignore a great succession of revolutions. This question of the sorting-out of the Pre-Cambrian orogenies will perhaps be settled by radioactivity determinations, a matter which has been dealt with by Holmes. In his invaluable synthesis of the 'waves of change which have pulsed through geological time' and have been recorded in the orogenic cycles, Holmes has summarized the radioactivity data bearing on the ages of the Pre-Cambrian revolutions. The cycles recorded in the chief Pre-Cambrian areas are disentangled by means of age-determinations of geologically dated rocks, and then these partial sequences are erected into a single sequence based upon these ages and applicable to the whole Pre-Cambrian of the world. By this, six dated orogenies appear: they are the following, their approximate dates being given in millions of years: Manitoba, 1,750; White Sea, 1,600; Great Bear Lake (Canada), 1,350; Laurentian (Canada), Svecofennid (S. Finland), 1,050; Killarnean (Canada), 750, and Karelian (Lapland), 850; Charnian (England), 600.

This line of attack on the problem of Pre-Cambrian correlation seems full of promise and may provide, with increasing knowledge, as sure a sequence for these ancient rocks as fossils have in the younger.

The Pre-Cambrian Shields. The Pre-Cambrian rocks form two distinct kinds of outcrop. In the first, and the less important for our present purpose,

they are brought up for our observation in the cores of the *later fold-belts*. We are more concerned here with the second type of occurrence, the great Pre-Cambrian *shields* in which millions of square miles of the earth's surface are made by these ancient complexes. These shields form the nuclei of the continents which appear to have been built up around them; between the shields the continental masses are covered by skins of younger rocks. The shields have been for long the great stable portions of the crust; their rocks have not been folded since late Pre-Cambrian times, and unfolded Cambrian beds rest upon them around their margins. The more important shields are the *Canadian* making two million square miles of eastern Canada, the *Baltic* forming most of Scandinavia and Finland, the *Siberian* providing the nucleus of Asia, a minor development in *Peninsular India*, the western half of *Australia*, the *African* making most of Africa south of the Sahara and including Arabia and Madagascar, and the great *South American* shields of Guiana to the north and Brazil and the Plate to the south of the Amazon. The small development in the Western Highlands and Hebrides of Scotland may be considered either as a fragment of another shield or as a portion of the Canadian shield, according to the reader's opinion of Continental Drift. We can only glance at a few aspects of the geological history recorded in these immense masses.

Parts of the shields are geologically well known, since Pre-Cambrian rocks supply the bulk of the metalliferous ores, especially those of iron, copper,

nickel, gold, and silver. In parenthesis, we may remark that whoever implements Article IV of the Atlantic Charter, providing for equal access to raw materials, would best prepare himself for his task by a short study of the Pre-Cambrian. The shields provide evidence of the two contrasting styles of earth-history, the quiet accumulation of great piles of sediments and lavas and the violent disturbance and granitization of these piles in the short orogenic spasms. The record is best known in Finland and Canada.

The Finnish Record. As a result of the application of the doctrine of uniformitarianism, Sederholm the Finnish master and his successors have unravelled the tangled complexities of the old rocks of Finland and have demonstrated in them four cycles of sedimentation separated by orogeny, granitization, and erosion. Sediments of normal type have been demonstrated to make the oldest basement. Lavas flowed into the sea to make pillow-lavas in that far-off time as they do to-day in Hawaii. It is with reverence that the geologist visiting Finland sees metamorphosed varved clays, deposited in a glacial lake nearly 2,000 million years ago, covered by varved clays deposited half a million years ago during the Pleistocene glaciation. Modern work on the Finnish complexes indicates that certain of the orogenic phases produced fold-belts of Alpine style sited on geosynclinal depressions. In repeated episodes of granitization, the country-rocks have been converted into granites, migmatites, and profoundly metamorphosed rocks.

The last deposit of Pre-Cambrian time is a continental red sandstone, unfolded and unmetamorphosed, which was worn down into a level surface before the Cambrian transgression. This Jotnian sandstone recalls our Torridon sandstone in character, but, as we have said before, without fossils all coarse red felspathic sandstones are alike.

The Canadian Record. In the Canadian Shield (see Fig. 22) the sequence of events is best known in the Great Lakes area, where gigantic deposits of iron-ore have given stimulus to geological exploration. In this area, sediments and volcanic rocks of normal types amounting to tens of thousands of feet in thickness are interrupted by at least three great unconformities recording orogenic episodes of folding and granitization. The oldest rocks are the sediments and pillow-lavas of the *Keewatin* System whose formation was followed by the great mountain-building known as the *Laurentian*, dated by Holmes as 1,050 million years old; extensive granitization and migmatization profoundly changed the Keewatin sediments, giving rocks which were for long regarded as the first crust of the earth. The Laurentian mountains were then subjected to erosion and worn down; along their lowered flanks were deposited, perhaps as wide alluvial fans, the conglomerates and sandstones which give the *Timiskaming* System. Next followed the great *Algoman* revolution, when Timiskaming and all older rocks were folded and in places granitized. Though we are by no means finished with the story, we are beginning to realize the complexities

of Pre-Cambrian geology. The Americans place the boundary between Archeozoic and Proterozoic at the erosion interval that succeeded the Algoman mountain-building.

The younger or Proterozoic portion of the Great Lakes Pre-Cambrian begins with the *Huronian* System, a gigantic pile of sediments of many facies —conglomerates, quartzites, limestone, slates, and vast deposits of iron-ore. Huronian detail need not detain us, but we must consider one particular bed. This is known as the *Gowganda Conglomerate* and is clearly an ancient boulder-clay or tillite; with it are associated banded slates interpreted as varves. The old tillite rests upon a surface which shows glacial scratches and holds erratics whose provenance can be determined. Applying exactly the same methods as are used in the study of the modern Pleistocene glaciation in the same region, Canadian geologists have determined the directions of ice-movement during that remote event and have shown that some thousands of square miles were covered by the Gowganda ice-sheet. Here is uniformitarianism at its best. We return to Pre-Cambrian glaciation immediately but have now to finish the Canadian record. This ends with the formation of the basic lavas and red sandstones of the *Keweenawan* series ; the sediments are of land facies and have been compared with the Scottish Torridonian and the Finnish Jotnian. In certain parts of the Canadian Shield, the last event in Pre-Cambrian time was a mountain-building movement known as the *Killarnean* orogeny in which

Keweenawan rocks were involved. These details are given to indicate the intricacy of the story that is revealed in the Canadian Shield which, though well-known in places, is still for the most part virgin ground.

Before leaving North America for more general topics, we have to introduce the *Belt* System, a gigantic accumulation 50,000 or more feet thick of sandstones, shales, and limestones, occurring in Montana, Idaho, and British Columbia. These beds were not violently folded but only gently warped and then eroded before the deposition of the Cambrian rocks. Though they are what the fossil-collector would call promising rocks likely to yield an abundance of fossils, only a few doubtful remains have been discovered in them after extensive and lengthy search; this is an interesting general matter that we look into in a later paragraph. We have first to discuss the Pre-Cambrian glaciation.

Glaciation in the Pre-Cambrian. The Gowganda Conglomerate is by no means the only Pre-Cambrian bed interpreted as a record of glaciation. Deposits regarded as Proterozoic tillites have been described from such widely separated localities as the Canadian Shield, Utah, the Flinders Range of Central Australia, the Yangtze valley in China, India, South Africa, Norway, and East Greenland. The temptation to erect a worldwide glacial period can be resisted by remembering the length of Proterozoic time, some 500 million years; in half that time, between the Permo-Carboniferous and now, there have been two first-class glaciations.

Proterozoic time is long enough to contain several widespread glaciations even though they are rare events. What we have to realize is that great ice-sheets have been formed time and again from a quite early period in geological history.

Pre-Cambrian Life. There remains to be considered the fascinating problem of life in the Pre-Cambrian. As has been mentioned, devoted search for a century has revealed only meagre traces of organisms in the Pre-Cambrian rocks. The varied life of the Cambrian seems to start with a bang and gives an impression of a large number of diversified forms suddenly appearing. This impression needs a little correction; Cambrian life is not highly organized but is still somewhat 'wormy' in type. Even the intricate-looking tribolites have a bilateral symmetry—they are 'worms with flaps on each side'. Many of the Lower Cambrian shells are thin horny structures. But still the Cambrian seas did support an abundance of creatures whereas the Proterozoic, in spite of its name, appears to have been almost barren. Apart from tracks, burrows, traces of supposed sponges and of possible radiolaria, the common organisms reported from the Proterozoic rocks are algae. Calcareous algal deposits appear to be widespread and abundant. We should not marvel too much at this—'lime-secretion' by algae seems to be almost a matter of inorganic precipitation. We have decided in previous pages *first* that the Proterozoic rocks appear to be suitable for the deposition and preservation of fossils, and *second* that metamorphism

cannot be held responsible for the destruction of Proterozoic organic remains.

While we are considering the question of Pre-Cambrian life as it should be recorded by fossils, there arises a connected inquiry. This is concerned with the occurrence of great thicknesses of sedimentary rocks in the Pre-Cambrian which normally demand life of one kind or another for their formation. Thus, beds of graphite, occurring exactly like coal-seams, are abundant in the Canadian Pre-Cambrian; there is much more carbon in these rocks than there is in all the coal seams of the Carboniferous. In Finland, a seam of anthracite (schungite), 2 metres thick, is found in the Pre-Cambrian rocks. In many Pre-Cambrian successions, black shales and slates are widespread and abundant. Admittedly, some graphite is of inorganic origin, but the circumstances of the ordinary Pre-Cambrian occurrences demand the existence of abundant plant and animal life at that time. But there are also enormous developments of limestone and dolomite throughout the Pre-Cambrian, and the manner of their production is an interesting inquiry since they show little indication of organic accumulation.

From what we have said in many previous pages, it is reasonable to propose that Pre-Cambrian organisms were mostly soft-bodied. Not till late in the period did they begin to encase themselves in calcareous shells or reinforce themselves with calcareous structures. By the Cambrian, their attempts had begun to succeed; a transitional

stage is marked by the chitinous horny structures requiring only a little lime. From the many proposals to account for this change over from soft-bodied to protected or reinforced types of life, we select two for comment.

Brooks suggested fifty years ago that the shores and bottoms of the shallow seas were first discovered and colonized by marine organisms just before the opening of the Cambrian ; in this new habitat, competition was intense and forms able to develop chitinous or calcareous shells and skeletons for their protection prevailed to give the Cambrian fossils. As a criticism of Brooks's proposal, we may suggest it is unlikely that the shores and shallow seas were ever vacant and tenantless; they must have been inhabited all the time life has been on the earth.

Daly has argued that the Pre-Cambrian oceans were free from lime so that no material was available for the building of calcareous shells and structures. Soft-bodied organisms, decaying in multitudes on the sea-floor, provided ammonium carbonate, which reacted with calcium salts dissolved in the sea-water to give insoluble calcium carbonate, which was precipitated. Thus no lime was left in the sea-water and the great thicknesses of limestone and dolomite found in the Pre-Cambrian were deposited; the remarkable sedimentary iron-ores, jaspers, and cherts were due to similar reactions. Daly suggests that lime became available, so that Cambrian organisms could build their shells of calcium carbonate, either by the

evolution of sea-bottom scavangers or by the delivery into the sea of great amounts of calcium salts. This latter event (and it seems to the writer the more likely) could be caused by the lengthy erosion of Pre-Cambrian mountainous lands on which were exposed great expanses of basic volcanic rocks and limestones—these, as we have seen, being common Pre-Cambrian rocks.

Whether or not the effect on the Pre-Cambrian seas was what Daly has proposed, a great period of erosion closes Pre-Cambrian history. The mountainous continents were worn down into gently undulating plains across which the transgressive seas of the Cambrian advanced. Let us examine these great inundations.

The Great Inundation of the Lower Palaeozoic. In the Lower Palaeozoic we have a well-documented chapter of earth-history, lasting some 175 million years and providing a typical example of the lengthy and quiet style of event. As we have seen, this great time is divided by the specialists into Cambrian, Ordovician, and Silurian, each with a number of smaller sections, but in this little book we require only sufficient detail for the continuity of the story. The fossils found in the Cambrian rocks are varied and abundant, so that accurate correlation is possible and rocks can be matched as records of time-intervals over the whole world. The Lower Palaeozoic as a whole is a story of great submergences and emergences, transgressions and regressions, with only local and exceptional earth-movements. These floods and ebbs must not be

considered as something like a Severn bore; they took tens of millions of years for their completion and we may best get the proper perspective by comparing the Lower Palaeozoic crustal warpings with the present rate of uplift of the Northern Baltic lands, about a centimetre a year. The keynote of Lower Palaeozoic history, then, is the gradual advance and retreat of the seas.

The lengthy erosion period at the end of the Pre-Cambrian had left the continents low. The *Cambrian record* begins with a great transgression, the sea flooding on to the low lands and continually expanding. As a result, the Cambrian rocks rest discordantly on the old foundation and the higher Cambrian beds are usually more extensive than those below. The sediments do not include much limestone; the succession begins with sandstones or quartzites, followed by shales and these by thin limestones. In certain elongated tracts, geosynclines were initiated in which continuous deposition of thick sediments took place. As an illustration of these, let us consider North America in Cambrian times; palaeogeographic studies show that two north-south geosynclines were established, one on the site of the eastern half of the present Cordillera and the other on the site of the present Appalachian Mountains in the Eastern States (see Fig. 24). In the Canadian Rockies, magnificent sections, 12,000 or more feet in thickness, of Cambrian rocks of the western geosyncline are exposed. The mountains bordering the western geosyncline on the west and the eastern on the east

provided vast amounts of coarse detritus to make the early Cambrian sediments, but later in the period they became lowered by erosion and contributed finer material in smaller quantities to the Cambrian seas, as witnessed by the general succession sandstones, shales, thin limestones. The quiet sedimentation of the Cambrian was undisturbed by volcanicity. It ended with a broad emergence.

Ordovician time saw the maximum extension of the seas. Half North America, for example, was covered and only the old Pre-Cambrian islands kept above the waters. Fluctuations of the sea-levels, successions of regional and local inundations and emergences, have been established by patient accumulation of data on facies changes and sequences. It is enough for us to see the general picture of quiet ebb and flow. But the Ordovician quiet was broken in many regions by first-class volcanic outbursts. In the Eastern United States, great ash-falls occurred during the middle of the period, whilst in Britain piles of lavas and thick beds of ash accumulated in many districts during Ordovician time. Volcanic rocks of this age make the craggy Borrowdale country of the Lake District, and similar resistant lavas are responsible for much of the bolder scenery of North Wales, on Snowdon, the Arenigs, Conway Mountain, and Cader Idris.

The Taconic Disturbance. In restricted and widely separated areas, the close of Ordovician time was marked by a disturbance dignified by the name of

the *Taconic Orogeny*, from its development in the Taconic Mountains of Massachusetts. The over-thick Cambrian and Ordovician sediments of the northern part of the Appalachian geosyncline were compressed and folded into a mountain-belt stretching from Newfoundland to New Jersey. This Taconic mountain-belt was levelled by erosion before the deposition of the Silurian beds which rest unconformably on the folded older rocks. Disturbance of the same age is recorded by the unconformable relationship of Silurian to folded Ordovician and older rocks in the Welsh Borderland. The Post-Cambrian movements in the North-west Highlands of Scotland may also be Taconic. By some geologists, the Taconic disturbance is regarded as an early spasm of the greater orogeny that closed the Lower Palaeozoic.

The Ending of the Lower Palaeozoic Geosyncline. Most of *Silurian* history continued the pattern of minor transgression and regression characteristic of the Lower Palaeozoic, but towards the end of the period less usual deposits heralded a change in the style of events. Normal Silurian sediments can be examined in Shropshire and the Welsh borders, but more spectacular displays are provided by the gorge and falls of Niagara. The lip of the great falls is made of resistant dolomites of Middle Silurian age which rest upon more easily eroded shales and sandstones of the lower part of the system in which the pool has been carved. The gorge is floored with Ordovician rocks on which the Silurian rests discordantly. The Niagara limestone

of adjacent regions of the United States and Canada affords many excellent examples of ancient coral reefs. Ill-bedded limestone composed of organic fragments bound together by coral sand and mud forms lenses or knolls sometimes a mile long and seventy or more feet high enclosed in normal thinly bedded limestone. This Niagara sea, presumably shallow, clear, and warm, extended into the present Arctic regions, for similar limestones are found in Greenland. In Shropshire small reefs occur in the Wenlock Limestone of middle Silurian age.

As already mentioned, the standard Lower Palaeozoic style of events began to change towards the end of Silurian time. The first abnormality we have to consider is the development in Upper Silurian times of arid conditions over a great region in the eastern United States. The coral seas of earlier time gave place to a great Dead Sea from whose intensely salt waters were precipitated lenses of salt. These lenses, interbedded with shales, occur over an area of some 10,000 square miles. In many places, beds of salt hundreds of feet thick are encountered, a thickness uncomfortably great to be derived from the evaporation of an enclosed basin of any reasonable depth. We must suppose either a thickening of this very mobile and temperamental rock by folding, or else a continuous replenishment of the waters being evaporated in the basin by accessions from outside—a mechanism seen in operation to-day in the Gulf of Ka'rabugas on the east shore of the Caspian.

In parts of Britain, the normal type of marine Silurian rocks is followed by a group, the *Downtonian*, which appears to represent a transition into the succeeding continental facies of the Old Red Sandstone. The Downtonian consists of yellow sandstone and shales with thin layers of *bone-beds*. These are made up largely of fragments of fishes and crustacea, and the manner of their formation has given rise to some discussion; one set of interpretations sees them as due to extinctions of the organisms through sudden changes of conditions or through earthquake shock, another regards them as products of an environment in which little land-derived detritus was forthcoming to dilute the organic contributions. Whatever the origin of the bone-beds may be, the Downtonian rocks record the change of conditions which brought the Lower Palaeozoic to an end. Before we examine the further progress of this change, we have to glance at the life of these early periods.

The Pattern of Lower Palaeozoic Life. We have already seen that the earliest faunas preserved for us in the Cambrian rocks were composed of abundant and varied types. These were all inhabitants of the sea. Life, apart from a few lowly forms of plants which clung desperately to the rocks of the shores, had not yet discovered the land which stood gaunt and bare, unprotected by a plant cover and therefore ravaged by every wind and rain. In the Cambrian seas, invertebrate animals of diverse groups swarmed and struggled. Some contrived experiments which succeeded for

a hundred million years or more but were then found wanting, some as far as we can see did nothing but exist and yet their descendants still exist. But some pioneers gained a slight advantage which, by continued development, has provided the highest forms of modern life.

The dominant types of Cambrian life were the brachiopods, with a bivalve shell, and the trilobites, less abundant being forms such as sponges, protozoa, worms, cystids, gasteropods, and others. The trilobites lasted till Carboniferous times but then went under, yet their remarkable experiment had succeeded throughout the Lower Palaeozoic. Drawings of some of those used in zoning the Cambrian rocks are illustrated in Figure 20. During Ordovician times, marine invertebrates continued to thrive and multiply. During this period, the remarkable group of organisms known as the graptolites flourished. These were minute colonial animals living in small cups arranged along rods attached to some kind of float or floating body (Fig. 20). Their evolution was rapid and their manner of life led to their wide dispersal, so that they are used for delicate correlation over immense areas; they are the zone-fossils of the Ordovician and Silurian rocks.

One of the most important events in the history of the earth occurred in later Ordovician time—an animal emerged with the beginnings of a backbone. A fast-moving organism had found that he could prevent his head from being driven back into his body by strutting himself with an internal

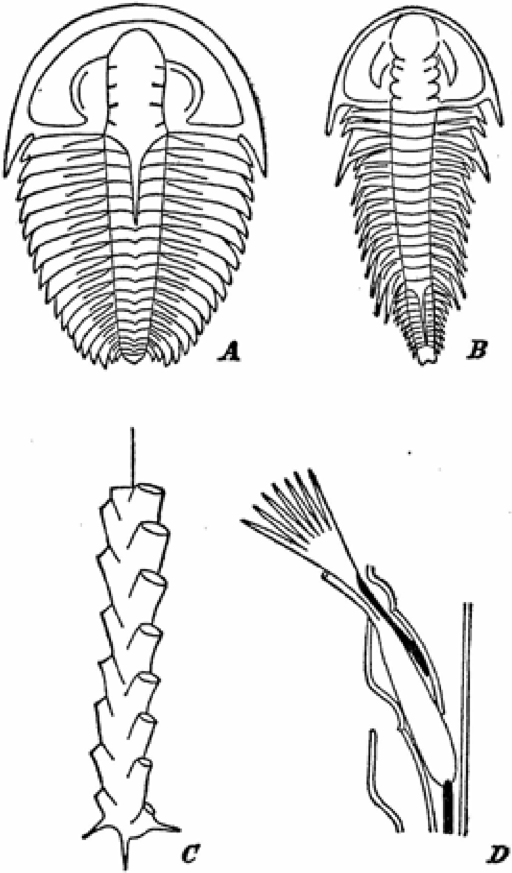


Fig. 20. Trilobites (A and B) and Graptolites (C and D); examples of Lower Palaeozoic organisms

longitudinal skeleton. The first of the fish had appeared and, with this beautiful device of a backbone, animals could now become larger and more complex. Man, preening himself in an airplane, should look back humbly at these distant ancestors, the *Ostracodermi* of the Ordovician. By the end of Silurian time, small fishes were abundant if primitive; their lower jaws were poorly developed and their type is now almost extinct. With the Silurian, too, we have the beginnings of life on the land, though it is represented only by fragments of land-plants and obscure scorpion-like beasts which were probably air-breathers and spent some of their time, at least, ashore.

The Caledonian Revolution. Let us continue with the geological record and examine the happenings in late Silurian time. If we trace the development of the whole pile of Lower Palaeozoic sediments from the Baltic area westwards into Britain, we disclose two significant facts: *first*, the Baltic sediments are very much thinner than the British, and *second*, they are unfolded and unmetamorphosed whilst the British rocks are violently folded and usually in the condition of slates (see Fig. 15, p. 151). As an illustration, the few hundred feet of the Cambrian Blue Clay of Leningrad is a record of the same length of time as thousands of feet of grits and slates in North Wales. It is clear that we are dealing with two contrasted facies, that of the stable area in the Baltic and that of the unstable or geosynclinal area in Britain. We may look at the history and fate of the British Lower Palaeozoic

geosyncline as an example of a characteristic series of events in earth-history.

Beginning with the deposits of the transgressive seas of the earliest Cambrian, a great pile of sedimentary rocks, in places nearly eight miles thick, accumulated during Lower Palaeozoic time in a belt elongated north-east and south-west lying between land-masses in the Scottish Highlands on the one hand and possibly in the Channel or Northern France on the other. Detailed investigations of the facies of this gigantic assemblage reveal a north-east and south-west alignment. The main major facies concerned are known as: the *graptolitic*, black shales deposited in the deeper parts of the sea; the *geosynclinal*, coarse detrital accumulations such as grits and conglomerates; the *volcanic*, the products of vast numbers of Ordovician volcanoes; the *shelly*, shallow-water or shore deposits characterized by brachiopods and trilobites. Facies studies have enabled reasonable palaeogeographical maps to be constructed for many intervals of Lower Palaeozoic time. The classic example of facies contrast is that eludicated by Lapworth in the Girvan and Moffat districts in the Southern Uplands of Scotland; at Moffat 290 feet of graptolitic black shales were deposited in the same time as 4,400 feet of grits, sandstones, and shales were formed at Girvan, some fifty miles distant. Sedimentation in the geosyncline was not continuous and was interrupted from time to time through buckling of the floor. We have seen one particular example of this in the Taconic disturbance at the

end of Ordovician time. But this and the lesser disturbances were only the precursors of the greater revolution that set in towards the close of the Silurian and ended the existence of the Lower Palaeozoic geosyncline. The heralds of this revolution were the abnormal deposits of the Downtonian. In the places of the deep seas were formed brackish lagoons and, as the revolution continued, the site of the geosyncline became a land-mass. The main phase of the *Caledonian orogeny* had occurred. The contents of the geosynclinal trough were folded and compressed, the finer-grained types were converted into slates, granites came into position. In Britain, the effects of the Caledonian orogeny are seen in the cleaved and folded Lower Palaeozoic rocks which make the Southern Uplands of Scotland, the core of the Lake District, North and Central Wales and South-east Ireland. The general trend of the structures is north-east to south-west. In the preceding chapter we have given details of the spectacular results of orogeny displayed in the thrust-zones of the North-west Highlands, where the displacements can be proved to be post-Ordovician in age, and thus could be reckoned with the Taconic disturbance.

The Caledonian geosyncline was not confined to Britain, but swept in a great arc through Scandinavia and Spitzbergen to Greenland. Along this arc arose the Caledonian mountains. In Scandinavia, we find the counterpart of the North-west Highland thrust-zones but there the direction of movement is towards the south-east. The two

margins of the geosyncline had given as the jaws came together (Fig. 21). Orogeny dated as Caledonian is known from all continents and this revolutionary period provided one of the major

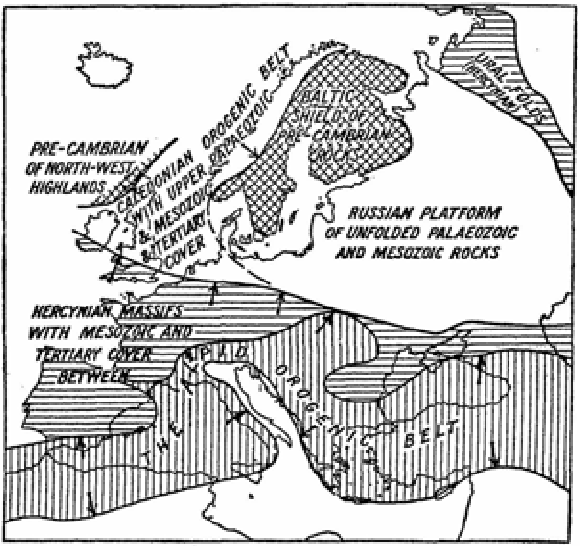


Fig. 21. The Geological Make-up of Europe

events in earth-history. We see more of it when we cross again to America.

The Consequences of the Caledonian Mountain-building. The consequences of the main phase of the Caledonian orogeny in North-east Europe are revealed in the striking contrasts in facies of the rocks

of the Devonian; we have used these contrasts in an earlier chapter to illustrate facies-variations and have given in Figure 3 a palaeogeographic map based upon them. Britain to the north of the present Bristol Channel together with Scandinavia and adjacent regions, for so long the scene of geosynclinal sedimentation, now became mountainous lands with a general grain running north-east and south-west. Along the flanks of the mountains and in the lakes occupying the depressions between them were deposited the breccias, conglomerates, sandstones, and shales of the Old Red Sandstone —the land facies of the Devonian. Relics of these deposits are seen in Herefordshire, around the Cheviot, in the Midland Valley of Scotland, and along the shores of the Moray Firth. The lower division of the Old Red Sandstone is made up partly of a great thickness of volcanic rocks, mostly andesitic lavas, and much of the hill scenery of the Lowlands arises from these resistant masses; the Pentlands, Ochils, Sidlaws, and the hills about Oban are examples. The Caledonian orogeny continued during Devonian times as witnessed by an unconformity below the upper division of the Old Red Sandstone.

Off the shores of the land upon which accumulated the Old Red Sandstone, there was deposited the Devonian littoral facies which we have already sampled in Devonshire. This facies extended in a general west-east direction from southernmost Ireland through Cornwall and Devon into Northern France. It is typically developed in the Ardennes

and is continued by many German massifs such as the Harz into Poland. The record begins with thick accumulations of shallow-water sediments and is continued by limestones, shales, and other deposits of deeper seas. Basic lavas helped to swell the pile. During Devonian time, the land margin oscillated so that, especially in its more northerly developments, this littoral facies shows intercalations of Old Red Sandstone type.

South of the littoral belt is the main, truly marine, facies of the Devonian, made up for the most part of limestones and shales. In this mediterranean region, sedimentation was continuous from Silurian through Devonian into late Carboniferous times, so that complexities resulting from the Caledonian mountain-building are absent. But, as we see later, it was this great geosynclinal pile that was violently affected by the next major orogeny, and its rocks, toughened and buttressed during this revolution, now make the mountainous massifs of Spain, Pyrenees, Central France, the Vosges, the Balkans, and North Africa (see Fig. 21). As a contrast, Devonian deposits are thin and flat over the great plains of Russia; eastwards in the Urals we have, however, another example of geosynclinal accumulation similar to that of the mediterranean region and, like it, violently affected by subsequent earth-movements.

Viewing Devonian events in Europe as a whole we observe the beginning of a northward transgression which, by Carboniferous times, had penetrated deep into the Old Red Sandstone lands.

Before we take up the consideration of this inundation we have to cross to America for a glance at Devonian happenings there. In Canada and the United States we can distinguish in a general way the two contrasted facies of Devonian rocks. In New Brunswick and Nova Scotia, a group of red conglomerates, sandstones, and shales recall, though imperfectly, the Scottish Old Red Sandstone; these rocks have yielded fossil fish comparable with those of the lowest and the uppermost divisions of the Scottish rocks. Elsewhere in North America, Devonian strata are marine; after their retreat at the close of the Silurian, the seas advanced, reoccupied the whole of the Lower Palaeozoic geosynclines and came to cover during the Devonian Period vast stretches of the continent. American geologists have however recognized an episode of unrest over part of their Devonian seas. The earth-movements known as the Acadian Disturbance began to affect the northern part of the Appalachian geosyncline at about the middle of the Devonian period and increased in intensity till its close. A mountain-belt arose in Eastern Canada and New England and the disturbance is recorded as far south as South Carolina. Volcanic and plutonic activity accompanied the orogeny. As a consequence of the Taconic and Acadian disturbances, the northern portion of the Appalachian geosyncline became permanently land. If we define Caledonian orogeny as that accomplished before the close of the Devonian period, then the Acadian disturbance can be reckoned as Caledonian. Along

the west coast of Newfoundland, in the estuary of the Saint Lawrence and south to New York, this Caledonian mountain-front shows overthrusting to the north-west similar to that of the Caledonian

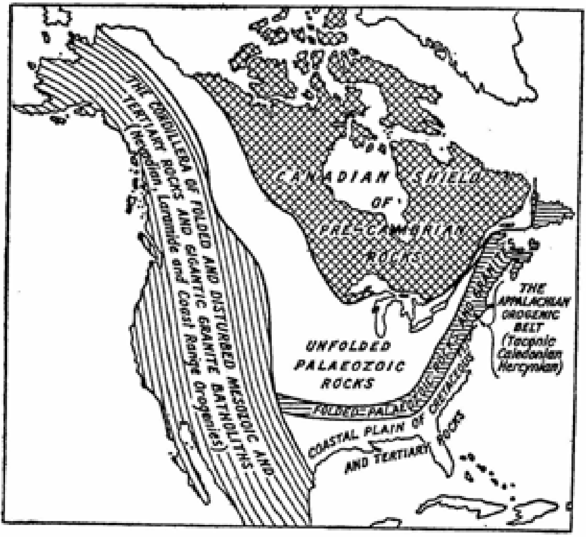


Fig. 22. The Geological Make-up of North America

front of the North-west Scottish Highlands (Fig. 22). The orogenic belt, truncated by the Atlantic in Scotland, has come ashore in Newfoundland to provide comfort for Wegener and his followers in Continental Drift.

Devonian Life. Devonian times were trying times for life, and biological changes occurred commen-

surate with the geographical changes. Graptolites and trilobites, successful during the quieter Lower Palaeozoic, could not stand the pace and declined or became extinct. The dominant forms were the fishes, descendants of that Middle Ordovician experimenter who had tried out the first backbone. The Devonian fishes were heavily-armoured primitive types, but were the forerunners in two developments of fundamental importance. The anatomy of the Devonian Crossopterygian fishes shows the beginning of the paired pattern of limbs which in time developed into that of the higher vertebrates, the amphibians, reptiles, and mammals. Further, primitive lungs were evolved and some of the fish spent some of their time out of the water. Our ancestors had landed. These amphibians did not, and have not yet, conquered the lands, because they have not been able to shake off old habits such as laying their eggs in water. But still the course was now set for the development of the highest vertebrate creatures. Invertebrate life continued to flourish in Devonian times, the corals, lamellibranchs and gasteropods becoming more important elements in the faunas. A simple ammonoid or coiled cephalopod appeared. Profound changes took place in the plants, and by the close of the period land plants were abundant and highly organized. The earliest land flora, one of a simple type, is beautifully preserved in the silicified peat-bed discovered by William Mackie at Rhynie in Aberdeenshire and reckoned to be of Middle Old Red Sandstone age. The occupation of the lands

by plants must have led to a change in the rates and styles of denudation; the bare inhospitable landscapes of earlier times were now clothed and protected.

A New Transgression. We have already noted the initiation in Devonian times of a transgression in Western Europe; the higher Devonian rocks of Belgium, for example, overlap the lower and extend farther to the north. In the Carboniferous period which we have now to consider, this transgression reached its maximum and ended with the period. The British Carboniferous rocks provide an excellent record of these events.

At the beginning of the Carboniferous period, a clean shallow sea invaded the Old Red Sandstone land on its southern fringe in South Wales and Southern England, and in it were deposited the lowest beds of the *Carboniferous Limestone.* With continuing advance, the same sort of sea came to cover the northern Midlands, where only the upper parts of the Carboniferous Limestone are found. Between these two provinces a low land, 'St. George's Land', stretched from the Irish Sea across Central Wales and the southern Midlands. The Carboniferous Limestone, though thick and extensive, is of shallow-water facies, with lagoonal muds, banks of shells, and other characters of this environment. As the rocks of Carboniferous Limestone age are followed northwards, their facies change; in Yorkshire, shales and sandstones are intercalated with limestones, and farther north in Northumberland and the Midland Valley of Scotland seams of

coal enter into the succession and limestones become thinner and rarer. It is clear that the clean seas of Derbyshire are giving place to muddy estuaries and deltaic flats bordering a northern land. To complete the picture of Carboniferous Limestone times, we may refer to the contemporaneous Culm facies of Devonshire, deepish-water marine muds, and to the outpouring of vast bodies of lava and the emplacement of other Volcanic

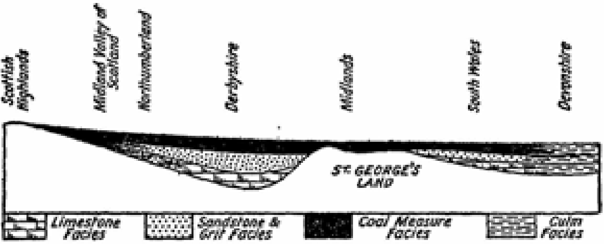


Fig. 23. Variations in the Facies of the Carboniferous Rocks of Great Britain

rocks in Southern Scotland. These facies variations are indicated in Figure 23.

From the characters of the deposits which succeeded those of Carboniferous Limestone time in Britain, it can be deduced that the land-masses to the north became elevated so that their rivers were rejuvenated and could transport great loads of coarse detritus into the Carboniferous seas. The shallow seas between St. George's Land and the northern highlands were invaded by vast deltaic fans recorded in the sandstones and shales of the

Millstone Grit. With the progress of Carboniferous time, the sea-basins were filled and great swamps spread out from Scotland till most of the British Carboniferous seas were blotted out. The time of the coal-swamps, of the deposition of the *Coal Measures*, had come. The records of these events can be seen in Figure 23.

The Coal Measure Rhythm. When we look into the make-up of the Coal Measures we find their thousands of feet of sediments to be made of innumerable repetitions of a small standard sequence. This begins with coal, followed by shale, sandy shale, sandstone, seatearth (fireclay or ganister), and then coal again. This sedimentary rhythm can be translated into action as follows: the coal seam represents a period of standstill when in the tropical swamps and forests vegetable matter could accumulate to a considerable thickness; following the standstill there came a rather rapid subsidence, the forests were drowned by the incoming water of lake or sea, and the filling-up of the resulting depressions is recorded in the succession of shale and sandstone; when they were filled so that swamps could be formed again, forest growths extracted their food from the swamp-soils and produced the seatearths below the coal-seams. Coal Measure history is thus made up of a great number of standstills and subsidences.

During the later Carboniferous, coal-swamp conditions spread over considerable areas of Northern France, Belgium, and Germany, while in Russia and the Mediterranean region truly marine facies

were maintained. In the North-west European area, the uppermost Carboniferous rocks are often red sandstones and marls, deposited in a semi-arid environment; such rocks are the herald of the next great event in geological history, the Hercynian orogeny. This had already been foreshadowed by movements during Carboniferous time. We examine its course and its effects on the building of Europe in a later page.

In the Eastern United States, the beginning of the Carboniferous saw the denudation of the Acadian lands and renewed filling of the Appalachian geosyncline with shallow-water sediments. Farther west, extensive floodings have left their record in thick limestones in the Mississippi region and the Americans call their lower Carboniferous rocks the Mississippian accordingly. The Carboniferous—Pennsylvanian to the Americans—was a time of fluctuating marine and continental conditions in the eastern States, with the eventual establishment of coal-swamps over vast deltas and alluvial plains. The days of the long-lived Appalachian geosyncline are numbered; we look into its fate when we examine the Hercynian orogeny.

Carboniferous Life. Before we do this we have to note the salient features of Carboniferous life. Invertebrates continued to develop, though there were changes in the relative importance of different groups. Goniatites, corals, brachiopods, and fresh-water 'mussels' are among those used for zoning the Carboniferous rocks. Trilobites declined, their exit being helped on by the activities of shell-

crushing fishes which abounded in the seas. The amphibians emerged in strength; they were awkward squat creatures with broad flat heads bearing three eyes, a character they had inherited from the Crossopterygian fishes; man, that proud animal, should remember he too has a third eye, though now vestigial. The first reptiles appeared and, though small and weak, were the ancestors of the gigantic lords of creation of the succeeding period. Insects of amazing variety and size flitted through the tropical jungles. In these there was a riot of strange trees and ferny undergrowth; chief among the trees were some with jointed stems similar to their lowly present-day descendants the horsetails, and others, the scale-trees, were giant club-mosses. This rank vegetable matter went to make the coal-seams, so that we warm ourselves to-day with the sunshine of 300 million years ago. With these more romantic themes ready to their hand, why do the poets still sing of love or war?

The Hercynian Revolution. Preparations for the great Hercynian orogeny of late Palaeozoic times had been long in the making. Since the Cambrian, the Appalachian trough had been filling with an immense accumulation of shallow-water geosynclinal sediments, in spite of occasional disturbances and minor upheavals. In Central Europe a similar geosynclinal pile had been formed south of the old Caledonian northlands, and in many other parts of the world these foundations for revolution had been laid. These belts of sedimentation-subsidence were the sites of violent earth-movements towards

the close of the Palaeozoic, and another of the testing times of earth-history had arrived. This late Palaeozoic orogeny has a variety of names which express its importance in the structure of the crust. We call it here the Hercynian orogeny after the Harz Mountains, but it is also known as the Armorican (Brittany), Variscan (*Varisca*, Voigtland, Saxony), Appalachian, Altaid, and so forth.

In Central Europe, the Hercynian revolution developed in several pulses during late Carboniferous and early Permian times, reaching its maximum violence at different times in different regions. During these disturbances, the contents of the geosyncline were cleaved, folded, and thrust against the buttresses of the Caledonian northlands, the packed sediments rose as mountain chains, and the roots of the folded belts were granitized and metamorphosed. The relics of the great Hercynian mountains still form massifs of upland and highland and contrast effectively with the gentler country made by the later sediments deposited between them (see Fig. 21). The Hercynian chains stretched from Ireland to the Donetz. We see their lowered heads in Co. Cork, in Devon and Cornwall, Brittany, the Central Plateau of France, the Ardennes, the mountain-masses of Upper Germany and Bohemia. As a sample of their tectonic style may be given the thrusting of great cakes of Devonian and Silurian strata over the Carboniferous in the Belgian coalfield. In the central zone of the Hercynian fold-belt, plutonic activity is revealed on a grand scale; we see a puny marginal mani-

festation in the granitic masses of Devon and Cornwall.

Hercynian Events in Britain and America. North of the violent disturbances of the main Hercynian fold-belt, the revolution is manifest in structures of a gentler kind. We may use Britain to display them. The Carboniferous sea-floors and deltaic swamps were elevated; portions of them, such as the Midland Valley of Scotland, moved between parallel fractures; other portions were broadly folded into basins and domes whose configurations were influenced by the old buried foundation with its Caledonian and earlier trends. The higher beds of the Carboniferous were eroded from the domes and uplifted parts but were protected in the basins and depressions; the *coal-basins* such as those of South Wales, the Midlands, Yorkshire, and Lancashire resulted. Erosion went too far in Ireland, where the widespread Carboniferous rocks consist almost entirely of the academically interesting but economically unimportant Carboniferous Limestone; this is Ireland's greatest injustice, whatever the politicians may say, and, to add to it, England received the greater share of the eroded material though the coal itself was destroyed. In the arid wastes of the elevated Hercynian land and in the shallow salt-lagoons and land-locked seas around it, there were deposited the red sandstones, breccias, salt-beds, dolomitic limestones and rocks of the desert-formed New Red Sandstone. These rocks lie unconformably above the folded Carboniferous and now conceal some of the coal-basins. During

their deposition, rocks of true marine facies were being formed in Eastern Russia and the Mediterranean region and supply the standard marine succession of the Permian and Triassic systems. The close similarity in the course of events in the Caledonian and Hercynian orogenies is evident. With the deposition of Triassic rocks in the Mediterranean region a new geosyncline was initiated, a geosyncline in preparation for the gigantic Alpine revolution of the Tertiary and to-day and so worthy of a special name of its own, Tethys.

We have already noted that disturbances and revolutions to be grouped with the Hercynian orogeny of Europe took place in North America and many other regions. The great sedimentation-trough of Palaeozoic geography, the Appalachian geosyncline which in its prime reached from Labrador to Mexico and whose history is summarized in Figure 24, was near its end. During Permian times it was compressed from the east and its sedimentary filling was buckled and thrust westwards, metamorphosed and granitized. The complex of folded ranges (see Fig. 22) which now make the eastern border of the continent was completed—we have sorted out its several components in the foregoing. During Permian times, too, practically the whole of North America was uplifted to make an arid land and continued so for the Triassic period. In these deserts, the brilliantly-coloured continental deposits were formed which to-day give much of the Western scenery its bizarre appearance. Only in small gulfs and embayments in the far west

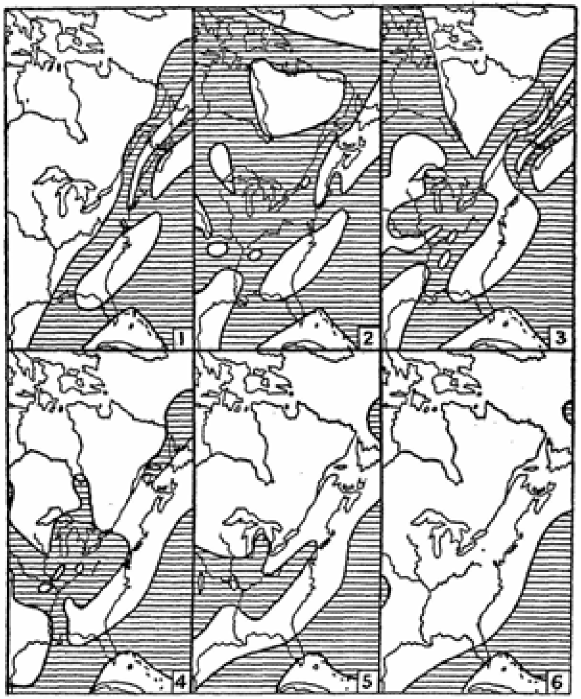


Fig. 24. History of the Appalachian Geosyncline: the distribution of land and sea at six times during the Palaeozoic. (Based upon the palaeogeographic reconstructions of C. Schuchert)

and south of the continent were marine rocks laid down.

A Testing Time for Life. Widespread aridity and, as we see later, widespread glaciation made the Permo-Triassic a critical time for life. Adapt or die became the law. The Coal Measures trees gave place to conifers. Trilobites became completely extinct. Among the invertebrates, the ammonites rose to pre-eminence. The Stegocephalian amphibia dominant in the Carboniferous continued to thrive, and though their end was near, they, as Huxley put it, 'pottered with much belly and little leg, like Falstaff in his old age'. Reptiles evolved rapidly with an abundance of forms, and some of them found their way back to the sea. In Triassic times a tiny insignificant creature, but a mammal and the herald of all the mammals, crept fearfully on to the scene.

Gondwanaland and its Glaciation. During the long interval from Upper Carboniferous to Jurassic, the geological history of Brazil, South and Central Africa, Madagascar, Peninsular India, and Australia was in all essentials identical. It is, moreover, a peculiar history recorded in continental sediments yielding a distinctive series of floras. It is reasonable to conclude that these widely separated lands are but fragments and relics of a great continental land-mass (see Fig. 25). This southern continent we know as Gondwanaland; we have already considered in an earlier page its bearing on the theory of Continental Drift. In the northern hemisphere the vast tropical swamps of the Carboniferous

gradually gave place to the arid deserts of the New Red Sandstone; on the southern land-mass of Gondwanaland the Carboniferous closed with the development of ice-sheets of continental dimensions, the Permian was a time of cold but was wet enough for the formation of coal-seams, and the Trias was a period of gradually increasing aridity. This climatic contrast between the northern and southern land-masses in Permo-Carboniferous times provides some

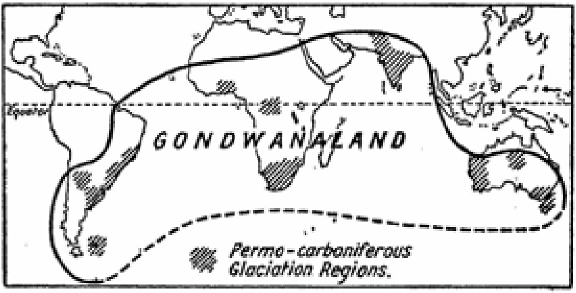


Fig. 25. Gondwanaland

of the most entertaining of geological discussions. We may glance at the relevant evidence from Gondwanaland.

In Peninsular India, depressions in the basement of Pre-Cambrian rocks are occupied by accumulations of continental facies known as the Gondwana Series. The lower part of this is made of beds of glacial origin, a tillite in places 600 metres thick, and banded varve-like clays. Associated beds have yielded fossil plants among which is a small hardy

fern-like plant called *Glossopteris*. The *Glossopteris* flora characteristic of Gondwana is unlike the contemporary floras of the northern hemisphere. The upper parts of the Gondwana Series are continental sandstones, shales, and coal-seams. In the Salt Range of the Punjab, tillites and fluvio-glacial sandstones are intercalated with marine beds which are dated as of uppermost Carboniferous or lowermost Permian age. If the tillites are of one glaciation, then the Indian ice-sheet was of considerable size, reaching across some fifteen degrees of latitude. In many parts of Australia and Tasmania, rocks with the *Glossopteris* flora include half a dozen or more thick beds of tillite, perhaps belonging to three glacial events; if the banded shales associated with certain of these tillites are true varves then they record the events of 4,000 years. South Africa provides in the Karroo System a magnificent series of Gondwana rocks. Its base is made by the Dwyka Conglomerate, a tillite up to 600 metres thick, which rests upon glaciated and moulded surfaces of the old basement. Marine intercalations supply evidence that the age of the lower beds of the Karroo is uppermost Carboniferous. These are succeeded by great thicknesses of shales, sandstones, and coals—a series providing remarkable collections of fossil reptiles proving them to be of Permian and Triassic ages. *Glossopteris* has been recorded northwards as far as Uganda and rocks like those of the Karroo are widespread in Madagascar. The ancient rocks of the Brazilian Shield and of Argentina and the Falkland Islands are covered over

extensive areas by continental rocks including tillites of Karroo facies: *Glossopteris* and the Karroo reptiles are abundant.

The evidence for widespread Permo-Carboniferous glaciation is thus of a high order of validity. It is of course likely that the glaciations recorded in the tillites of the Gondwana are not strictly contemporaneous and that great intervals of time separated, for example, the several glaciations of Australia. Even so, we have to admit a general refrigeration on land-masses now spread from 45° south to 30° north of the equator and from 70° west to 150° east of Greenwich. If the glaciations were more or less contemporaneous, the ice-sheet was astride the equator; if they were not contemporaneous, the ice-sheets were near the equator both to north and south. Further, in South Africa, the direction of ice-movement is southwards, away from the equator. These are very remarkable facts and, as we have already seen, have received remarkable explanations. The theory of Continental Drift has grouped the fragments of Gondwanaland around a south pole as one smaller continental mass capable of supporting an ice-sheet of reasonable size; later the land-mass broke up into fragments which have drifted apart to their present positions (Fig. 18). The sialic skin has shifted relative to the earth's axis of rotation, so that fragments with polar facies have reached and crossed the equator, just as the contemporaneous tropical beds of the northern hemisphere have moved into high latitudes.

The proposal of Continental Drift, whatever its own difficulties may be, is not faced with that of erecting (and then demolishing) innumerable land-bridges across the oceans along which the plants and animals of Gondwanaland could move. There are great resemblances in the land-fauna, especially in the reptiles, found in the Gondwana beds of South America and South Africa, and the *Glossopteris* flora is common to all fragments of the southern land-mass. There are now no traces of these sialic land-bridges in the simatic ocean-floors, and their removal is as great a problem as that of supplying the motive force for continental drift. However far-fetched may be the explanation any one of us may favour, we can all appreciate the colossal fact of Gondwanaland, its history and inhabitants, which calls for an explanation.

The Quiet of the Mesozoic. After the stormy events of the Hercynian orogeny we enter another of the quiet periods of transgression which intervene between the revolutionary episodes. At the close of Triassic times, the broad elements of the geography of Europe were two, the newly instituted geosynclinal sea of Tethys occupying the Alpine and Mediterranean regions and, north of it, an extensive low-lying desert land on which had been deposited the red sandstones, marls, and salt-beds of the Trias. Over the lowlands and between the stumps of the Hercynian mountains, advanced with pauses and spurts the transgressive seas of the Jurassic, in whose shallow waters accumulated the muds, shell-banks, coral-debris, swamp material,

and so forth that went to form the richly fossiliferous rocks with which William Smith, Oppel, and many another master were to build the foundations of stratigraphy. In their great basins of deposition between the Hercynian islands, these beds have remained almost undisturbed and completely non-metamorphic, unlike the deposits of the same age in the Alpine geosyncline. The Jurassic, a well-behaved system, closed with a retreat of the seas and an irregular warping. The succeeding Cretaceous system is likewise well-behaved—the Cretaceous seas advancing into the same basins, spreading extensively during the great Cenomanian transgression and then retreating to close the Mesozoic. These are the outlines of the story for Europe and we may now fill in a little detail. We shall find a rather more violent story in America.

The Jurassic Flow and Ebb. The record of the opening phase of the Jurassic transgression is an interesting one. It is given by a thin and persistent group of rocks called the *Rhaetic* which, though only a hundred or so feet thick in Britain, is found as far afield as the west and north of Scotland. The British Rhaetic consists of marls, shales, thin limestones, and bone-beds—these latter are made up of rolled fragments of vertebrates—fish, amphibia, and reptiles. The Rhaetic facies is best interpreted as formed in a shallow sea receiving only little sediment from a still arid and flat land. It provides the transition between the continental Trias and the truly marine Jurassic.

With the development of the transgression, the

clays and thin limestones of the lowest division of the Jurassic proper, the *Lias*, were deposited over wider areas. The Liassic sea was still a shallow one, lying off a northern land towards which its sediments become more sandy. Among these are bedded iron-ores deposited in shallow lagoons. The Lias is followed by the *Oolites*, variable clays, sands, and shelly limestones; in the south of England they are of marine facies, in the north they are represented by estuarine and deltaic deposits which include thin and poor coal-seams. Next followed the maximum extension of the Jurassic seas, when the *Oxford Clay* and associated beds were laid down. The Jurassic period closed with a partial regression associated with the uplift of a ridge across the southern Midlands and the London area; north of the ridge in Yorkshire the sea withdrew completely, while to the south of the ridge a shrinking sea gave place eventually to a fresh-water lake. The upper Jurassic rocks, the *Purbeck*, are here fresh-water limestones and terrestrial deposits showing among them fossil soils, and they pass upwards into lake deposits (the *Wealden*) usually grouped with the Cretaceous system.

The Cretaceous Flood. It will be convenient to deal briefly with Cretaceous events in North-west Europe before proceeding to America. We have already used the development of Cretaceous rocks in Britain to illustrate the record of a transgression. Drowning the Wealden lake in their stride, the Cretaceous seas advanced upon the central ridge,

joined up from north and south across it, and then expanded into the vast inundation of the Cenomanian transgression. We read this record, as we have seen, in the characters and extents of the members of the Cretaceous succession in southern England—lacustrine Weald clay, shallow-water marine Greensand and Gault clay, and the marine limestone, Chalk, of the great transgressive period; the higher the bed in the sequence, the greater is its extension.

The Chalk is the most famous of the Cretaceous rocks. Though in recent times we in England have thought much of the White Cliffs of Dover, even to the extent of singing about them, we must remember that the Chalk extends from Ireland by way of Denmark and Germany to South Russia, where it is thickest. Chalk consists of very fine-grained mud of calcium carbonate, many of the particles being tests of foraminifera, together with fragments of shells. Common among the foraminifera is the genus *Globigerina*, and the chalk was at one time compared with the Globigerina-ooze now forming on the deep ocean floors. Its deep-water origin is, however, questioned. Chalk was more probably deposited in a relatively shallow sea and owes its purity to the circumstance that the surrounding lands were hot deserts from which little material was washed in. Many features of the Chalk reinforce this opinion—the common occurrence of rounded, wind-borne, quartz grains, the existence in Scotland of partly eolian deposits of this age, the character of the organisms, and the presence of

certain chalk breccias that are of shallow-water origin. We see in the Chalk an example of the control exercised by the surrounding lands on the facies of a marine deposit.

Events in the American Cordillera. We may now consider Jurassic and Cretaceous events in North America. Throughout Palaeozoic history we have been concerned almost entirely with geosynclines and revolutions in the eastern States. Now we have to transfer ourselves to the western part of the continent to review the construction of the great Cordillera. In Western Canada and the States, the Jurassic opens with the advance of the sea in long narrow inlets from north and south along the present Rocky Mountain belt (see Fig. 26). On either side of a central rib, great thicknesses of sandstones and limestones were formed, reinforced by volcanic flows. The Jurassic closed with a violent disturbance, called the *Nevadian*, since the Sierra Nevada was then constructed. The contents of the eastern sedimentation inlets were folded by pressure driving towards the east, the sediments were metamorphosed and truly gigantic bodies of granodiorite emplaced. The first element of the Cordillera had been made (Fig. 26).

In Cretaceous times, the sea came again from north and south along the eastern flanks of the Nevadian mountains, overspread the Gulf states and, during the great submergence of the Upper Cretaceous, the two inlets joined to make a great geosynclinal sea from Alaska to the Gulf of Mexico. In this, a pile of sediments and lavas accumulated

till the episode of sedimentation ended with the shallowing of the geosynclinal trough and the formation of swamp and deltaic beds. At the close of the Cretaceous period the considerable *Laramide*

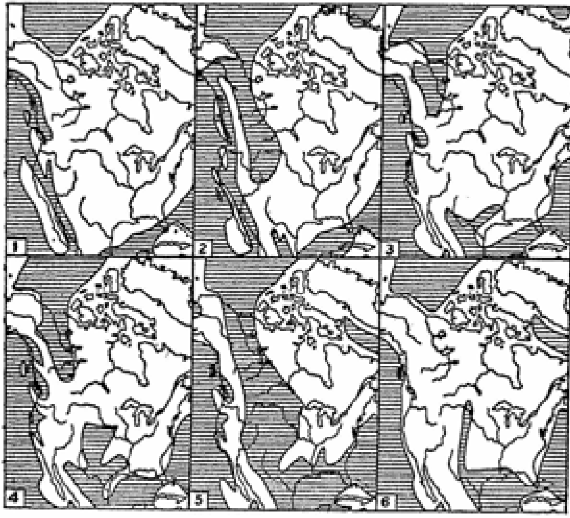


Fig. 26. History of the Cordilleran Geosyncline: the distribution of land and sea at six times during the Mesozoic. (Based upon the palaeogeographic reconstructions of C. Schuchert)

orogeny produced the second element of Cordilleran architecture, the Rockies themselves. The Cretaceous geosynclinal pile was arched, folded, and thrust from the west; plutonic activity, as usual, accompanied the revolution and segments of the

pile were metamorphosed and granitized. The great western Cordillera of both North and South America arose as a formidable mountain-belt in early Tertiary times: the western continent was receiving its present shape. The third element in the Cordillera was added in the late Tertiary as the result of disturbance along the Pacific border.

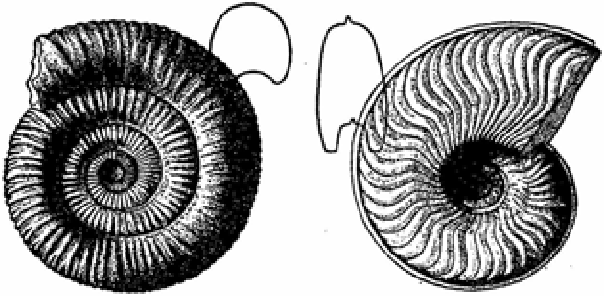


Fig. 27. Ammonites (reproduced by permission of H.M. Geological Survey)

Life of the Mesozoic Times. During the Jurassic and Cretaceous, many remarkable and mostly unsuccessful experiments were made in living creatures. It is true that no new types of invertebrates were evolved and the ammonites (Fig. 27), already present on the scene, were the dominant forms—their endless variety provides the material for the zoning of the Mesozoic rocks. Among the plants, true ferns became widespread and the conifers improved their position. Fish and the smaller amphibia flourished, true birds flew for the first

time, but the masters of the Mesozoic were the reptiles. These abounded in an astounding variety of form and size and they conquered all the habitats, land, sea, and air. Some of them were colossal, weighing perhaps between thirty and forty tons. But they were not brilliant animals, their brains perhaps amounting to a couple of ounces per ton of their weight and, though they tried many experiments in the way of bony armour, spikes, and knobs, they declined and mostly perished. In the midst of these fantastic perils, the small rat-like mammals managed to survive secure for the future in the possession of two qualities that were to make them rulers of the Tertiary world—their habit of nursing their young, and their warm blood.

The Tertiary. Post-Cretaceous time, dignified by the name of Tertiary, amounts as a whole to no more than some seventy million years. Since the chief centres of learning of Western Europe are situated on Tertiary sediments and since these sediments abound in fossils not very different from living forms, it is not to be wondered at that the Tertiary sedimentary record has been investigated in great detail, split into divisions and subdivisions based on the slightest movements of land or sea. Apart from a few special events, such as the development of man, the formation of modern geosynclines and a first-class glaciation, Tertiary history records its most exciting episodes not in the sedimentary rocks but by volcanicity and orogeny on the grandest scales. Accordingly, it will be fitting for us to dismiss in a few paragraphs the general

record of Tertiary sedimentation before we deal with the more spectacular happenings.

In Europe, the geography of Earlier Tertiary times, like that of many previous times, comprised two main elements; north of the old Hercynian stumps was a North Sea across South-east England, Northern France, Belgium, Denmark, and North Germany, and south of the massifs the Mediterranean Sea of Tethys continued, in spite of certain premonitory bucklings of its floor. The record of the northern sea is that of a transgression over the warped Chalk lands—we have detailed its course in England in an earlier page—and by Oligocene times a shallow lagoonal sea had extended itself over lower Germany and Poland and had penetrated between the Hercynian massifs. In Hampshire, the Oligocene strata include continental deposits and the Earlier Tertiary as a whole was brought to a close by the general uplift accompanying the climax of the Alpine orogeny in Miocene times. Outside Tethys, the orogeny reveals itself by the minor flexures which have produced the classic 'basins' of London, Hampshire, and Paris. Europe had now received almost its final impress except that Italy was still beneath the waters of a shrunken Tethys. The Later Tertiary in Europe is a record of minor transgression and regression—the Mediterranean Pliocene, for example, providing in Italy a beautifully complete sedimentary cycle. English Pliocene deposits are represented by the 'Crags' of East Anglia—shell-banks and sand spits along a distributary of an earlier and greater Rhine.

By the end of the Cretaceous, North America had assumed, by processes we have examined, almost its present outline and, during the Tertiary, it acquired its present relief through vast adjustments, mainly of faulting. Important terrestrial accumulations modified the surface and marine Tertiary sedimentation was confined to the Pacific border and to the Gulf States. Thick deposits in the former region were affected and are being affected by the last element of Cordilleran structure, the *Cascade* disturbance. In parts of the Gulf States—Louisiana in particular—Tertiary sedimentation is on so vast a scale that it is clear that we are witnessing the growth of a modern geosyncline; already about 30,000 feet of shallow-water deposits have accumulated.

The Mammals surmount the Tertiary Trials. We have already noted that the Tertiary was a time of profound unrest. Volcanic outbursts proceeded on a gigantic scale, the grandest mountain-belts of all time were erected, violent earthquakes rocked great segments of the crust, the continents were enlarged and came to stand higher with a more diversified relief than ever before, belts of extreme climatic differences were established and, to crown all, an ice-sheet overwhelmed millions of square miles. It is during this seventy million years of turmoil that the mammals have come to the fore. During the last few millions the highest mammal, man himself, has come to master the storm, if not himself. All these elements of unrest are still operating. Volcanoes are active in the great 'belt of fire',

earthquakes shake the world daily, and in certain zones we see orogeny in action. It is possible that many acute questions of European politics will be finally solved by the quiet and inexorable return of the ice-sheet. Man has certainly been reared in a hard school.

Tertiary Volcanoes. During the volcanic episodes, especially those of the early and middle parts of Tertiary time, colossal volumes of basaltic magma were delivered at the surface, most likely, as we have already argued, by way of fissures penetrating deep within the crust. The Deccan Traps of India, the Columbia lavas of the Western States, the Patagonia basalts and other piles of Tertiary lavas, covered hundreds of thousands of square miles with dominantly basaltic flows up to 10,000 feet in total thickness. Outpourings of basaltic and more acid magmas have continued to to-day along the zones of crustal instability as, for instance, around the Pacific rim and along the great African rifts.

In early Tertiary times, basaltic flows began to build up in the north Atlantic region a volcanic pile to which fresh additions are still being made in Iceland. Relics of this lava-field are seen in Antrim, the Western Isles of Scotland, the Faroes, Greenland, and Iceland. Whilst it is reasonable to account for this gigantic pile by outpouring from fissures, there were also in operation central volcanoes of astonishing complexity. Such centres are seen in Skye, Rum, Ardnamurchan, Mull, and Arran in Scotland, and in the Mourne Mountains

and Carlingford in Northern Ireland. By denudation at these centres there is revealed at different levels the intricate anatomy of great volcanoes. In Mull, for example, there is a bewildering succession of caldera-subsidences, intrusion of ring-shaped dykes and cone-shaped sheets, paroxysmal eruptions, quiet lava-outpourings, and deep-seated intrusions. The much-simplified section of Figure 28 gives an idea of Mull volcanic complexity.

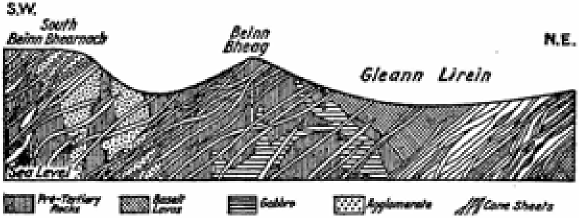


Fig. 28. The Complexity of the Mull Volcano of Tertiary Time. (Based upon Figure 35, p. 237, of the *Tertiary and Post-Tertiary Geology of Mull*. Mem. Geol. Survey, Scotland, 1924)

The Alpine Revolution. Let us now consider the Alpine orogeny. We have noted the birth in Triassic times of the Mediterranean geosyncline of Tethys and its development in later periods up to the Middle Tertiary. We have displayed in some detail the style of tectonic edifice that was erected in the Alpine portion of Tethys. Here in the Alps is orogeny in its most extreme form. Elsewhere along the course of Tethys the impulse is not so one-sided, the orogenic belt is broader and ex-

hibits a certain degree of bilateral symmetry. The Alpine fold-belt (Fig. 29) begins at the Straits of Gibraltar, with the Betic Cordillera of Southern Spain as its northern branch and the Atlas as its southern. The northern branch continues by way of the Balearics and the Pyrenees into the Maritime Alps, makes the great arcs of the Alps themselves, the Carpathians and the Balkan mountains, crosses the Crimea into the Caucasus and continues by the north Persian ranges into the high Himalayas. The southern branch passes from the Atlas into the Apennines and so into the tightly compressed Alpine arc, diverges to form the Dinarics, extends into Greece, crosses into the Taurus and beyond to the mountains of southern Persia and Oman, and bends north at the Indus through Baluchistan to join the northern stem in the Himalayas. From here, the Alpine belt is continued into Burma, Malaya, and the East Indies, diverging to make New Guinea and New Zealand on the one hand and Japan and the other Asiatic island festoons on the other. Outside the southern branch in various regions such as the Persian Gulf and the Indo-Gangetic plain, we see the formation of a new geosyncline, while in the East Indies we see orogeny in action. Observe the great arc of Sumatra, Java, Flores, and the other islands, with the smaller arc parallel to it off the south-west coast of Sumatra. Here is a region of marked crustal instability in which deep-sea deposits are uplifted, violent earthquakes are common, great volcanoes are active—the festoons are expressions of an embryonic moun-

tain-chain rising from the deep. Along a narrow strip in front of the main arc and including the minor arc there are great deficiencies in gravity, isostatic balance is completely upset, and clearly a light mountain-root is forming.

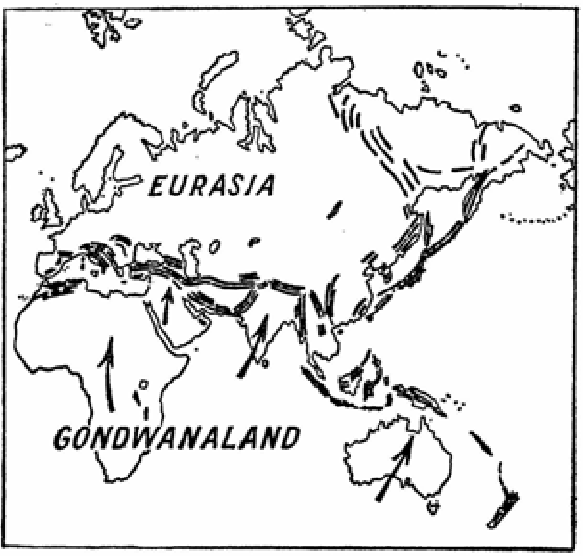


Fig. 29. The Alpid Fold-Belt in the Eastern Hemisphere

Viewing the Alpine belt as a whole (Fig. 29) we obtain a general picture of the approach of Gondwanaland towards Europe and Asia with the squeezing of the sedimentary filling of Tethys between them. We have now seen that the Alpine

orogeny in the wider sense is made up of Nevadian, Laramide, and Alpine phases, and is not yet finished. Through it have arisen the great mountain zones of to-day.

The Great Ice-age. The last episode in Tertiary history that we have to consider is the recent glaciation. The uppermost beds of the Pliocene in England, for example, indicate that conditions were changing from temperate to arctic; above them is a bed with arctic plants, the herald of still worse conditions, for it is itself covered by glacial deposits laid down by the Pleistocene ice-sheet. In Northern Europe, Scandinavia was the main centre of ice-dispersal and ice from there impinged on the British coast and competed with local ice nourished in the Highlands and on other high grounds. The ice covered some three million square miles in Northern Europe and another ice-sheet nearly twice as large occupied Canada and the northern States (Fig. 30). Alpine glaciers increased their size into piedmonts and in the Southern hemisphere, too, the general refrigeration was apparent.

The glaciation is not a single continuous process but was interrupted by a number of interglacial stages when the climatic conditions improved and the ice-fronts retreated. Interglacial stages are recorded in favourable circumstances in the stratigraphy of the glacial deposits—boulder-clays, for example, being separated by beds of a warmer facies, containing fossils of plants or animals of more temperate climates. The duration of the interglacial stages has been estimated by the degree of

weathering of the earlier boulder-clay below. Thus in the Alps, where four glacial stages have been demonstrated, the duration of the interglacial stages has been guessed (not an unfair word) as

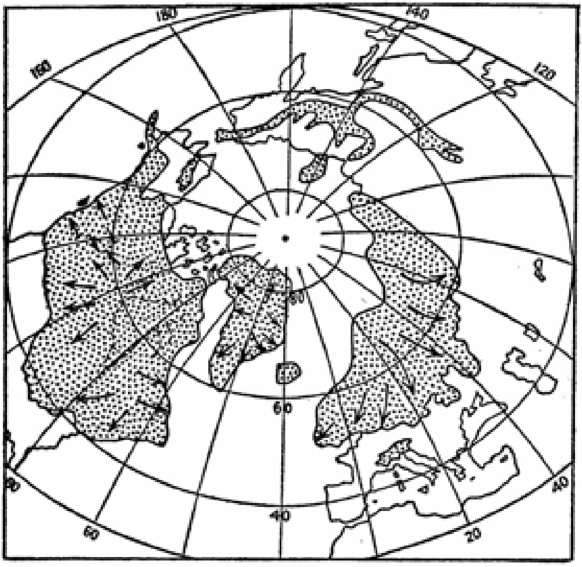


Fig. 30. The Pleistocene Glaciation in the Northern Hemisphere (after E. Antevs)

75,000, 300,000, and 75,000 years; the length of time that has elapsed since the last glacial stage up to the present time is estimated as 25,000 years.

The great ice-sheets blotted out the pre-glacial topography and spread as they retreated an

irregular blanket of drift upon it so that many features of present-day drainage-systems appear abnormal misfits. The weight of the great masses of ice depressed the land areas and their growth abstracted water from the seas, so that when they finally disappeared, readjustments from both causes led to a complicated post-glacial fluctuation in sea-levels, recorded in raised beaches and submerged forests. Since the glacial period, parts of Scandinavia where the load was heaviest have been elevated 250 metres, and we may recall that the movement is still going on at about one centimetre a year. The final retreat of the ice was followed in the glaciated areas by the establishment of tundras and steppes, leading to the present forest conditions —though man has made short work of most of the trees.

The cause of large-scale glaciation is not the concern of the geologist, but he can contribute to the discussion the geological fact that glaciations have been associated with continental elevation. Other suggested factors are changes in solar radiation, in the composition of the atmosphere, in the distribution of land and sea, and in the eccentricity of the earth's orbit. Let us be content in this little book to contemplate the grandeur of the fact of recurrent glaciation.

Life in the Tertiary. Tertiary life had a modern look from the start. The forests were essentially of modern aspect and, from the presence of grazing animals, grasses must have clothed the lands by mid-Tertiary time. Invertebrates had finished their

major evolution long before and some important groups, such as the ammonites, did not pass into the Tertiary. Toothless modern birds appeared. The reptiles, dominant in the Mesozoic, could not stand the Tertiary pace and their grotesque experiments of the Cretaceous failed and, as they failed, the lowly mammals swept into power. The Tertiary is the 'age of mammals'. The early forms were still mean-looking beasts with many of the attributes of, say, the modern hedgehog. But evolution was rapid and diverse. Developments went along four main lines—in size of body and of brain, and in specialization of teeth and of feet. Adaptation to varied environments resulted in the production of the abundance of modern types. The fossiliferous Tertiary rocks have supplied complete ancestral trees for many of our modern animals, such as horses, elephants, camels, and the marine mammals. It is man and his relatives whose ancestry is in most doubt. The older Primates, to which order man belongs, were probably derived from Cretaceous insectivores, something like a modern tree-shrew, and by way of early lemur-like forms provided the great apes from which man has sprung. Life in the trees demanded good sight and a proper estimation of distances, a good balance and well-developed grasping powers in the limbs. With the agility of body went a nimbleness of brain to co-ordinate the new functions, and by the Pliocene something like a man had appeared. The trying times of the ice-age converted this creature into a real man. With this emergency upon him, he

found the use of tools and of fire, and took shelter in caves and made himself more or less permanent habitations. His bones are exceedingly rare as fossils, but his implements are abundant in Pleistocene accumulations. These reveal an increasing degree of skill in working such intractable materials as flint and bone, and by the time the geologist hands over the story to the archaeologist, man has become an accomplished, if not a particularly attractive, being. His story then concerns the archaeologist and historian—we leave him to them.

The Pattern of Earth-History. We have travelled a long way since we first encountered the 1,750-million-year-old Manitoban conglomerate and have seen a strange series of events and a bewildering procession of life in our passage. From it all, the pattern of earth-history has emerged in cycles of geosynclinal quiet and orogenic unrest with volcanic and plutonic embellishments falling into their proper places. In that portion of the history which is relatively clear to us we have examined the records of the formation of Lower Palaeozoic, Upper Palaeozoic, and Mesozoic geosynclines, each followed by its appropriate orogeny, Caledonian, Hercynian, and Alpine. The revolutions resulted in abnormal conditions, high and wide continents, extremes of climates, growth of ice-sheets. Each of these testing times has seen a spurt in organic evolution, vertebrates triumphant over the difficulties of the Caledonian, the reptiles over the Hercynian, and the mammals and man over the Alpine.

What of the Future? Because of our lack of sufficiently detailed and worldwide knowledge, it is easily possible to over-simplify the record, but still the pattern seems to remain. Is the pattern clear enough to be used to foretell the geological future of the earth? Consider the physical environment first. If the Alpine revolution has finished, we may look forward to a quieter period when conditions may be less rigorous. We have seen, however, that the Alpine orogeny may be still continuing and it is possible that the abnormal events accompanying orogeny are by no means yet completed. The ice-sheets may yet return. Post-glacial time is a mere 25,000 years, while the previous interglacial stages lasted at least three times as long—we may be sunning ourselves in a fourth interglacial stage. On the other hand, if the glaciation is finished and a geosynclinal time is coming, the ice-sheets will be completely melted and the levels of the seas rise by some hundred feet. There is, however, no urgent need for the dweller in the Strand to put his name down for a flat on Hampstead Heath—geological events move slowly and this particular one may not happen at all.

We add a last word on the geological future of man. From the geological record it is observed that the dominant forms, evolved during the times of stress, prevailed for a hundred million years or so. Man, with his beautiful brain, is as distinct from the rest of the mammals as these were from the reptiles. At the widest estimate, man has dominated for a few million years and, if the pattern is correct, he

still has a long while to run. When he has learnt to control himself and his surroundings better—these including especially the gifts from the crust—there can be no supplanter. But perhaps the Mesozoic reptiles had the same idea about their situation and paid little heed to the rats of mammals gnawing at their tails.

. . . .

The tale is told. The geologist, 'standing on the earth as upon a footstool', looks at the past with wonder and turns to the future with hope. *In manu Domini sunt omnes fines terrae.*

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