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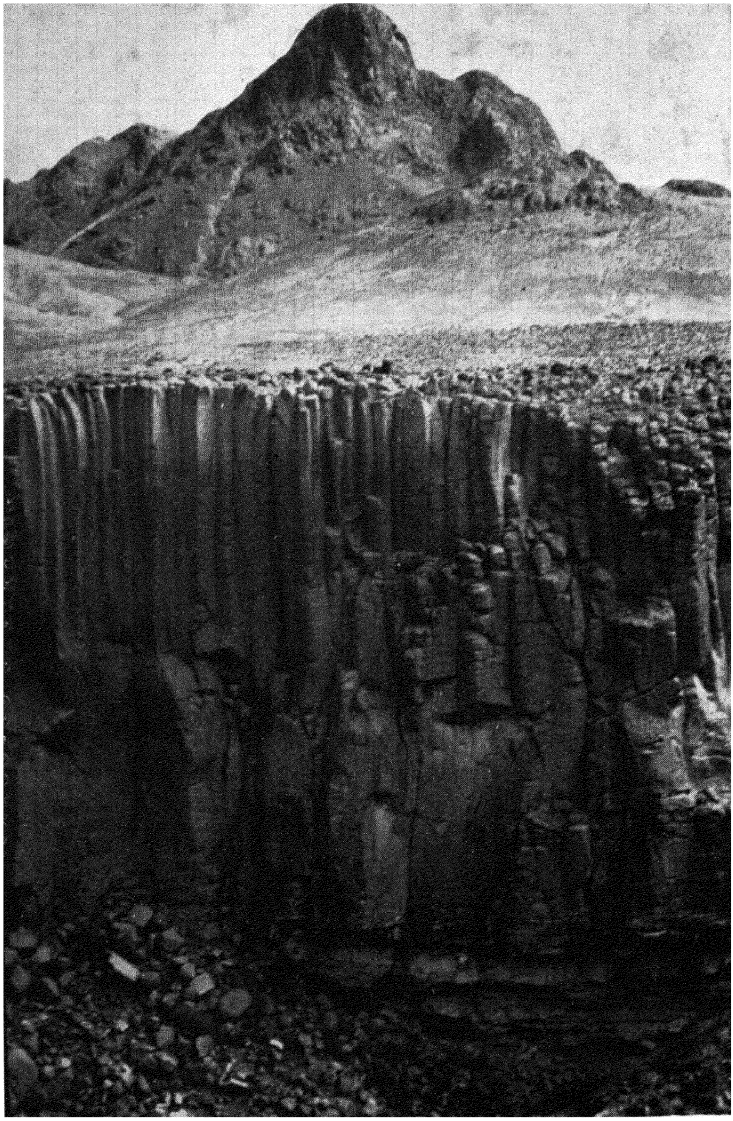
THE GEOLOGICAL DRAMA



G Termier

Frontispiece. Plateau lava-flow in the Atakor, Ahaggar, central Sahara. The prismatic character of the basalt is revealed in the cutting of a thalweg, while the ancient surface can be seen below the basalt-flow. In the background there is a volcanic plug of trachyphonolite

THE GEOLOGICAL DRAMA

The formation of the continents and the advance of life

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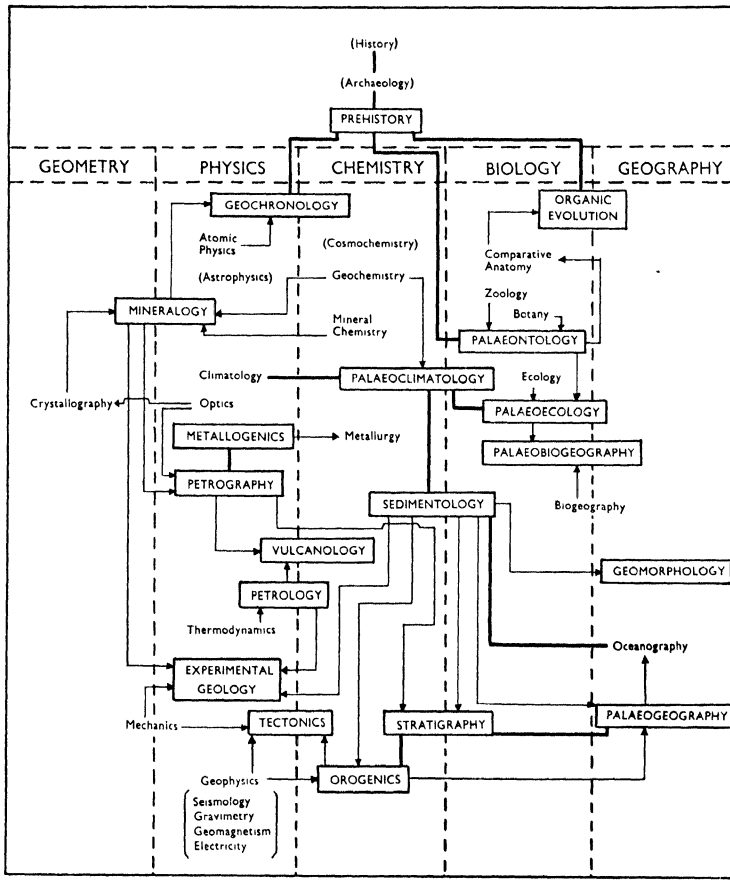


This diagram shows some of the complex relations between the various branches of science involved in the modern study of an inhabited world. The arrows indicate the direction in which one subject contributes to another, subjects connected by thick lines being mutually dependent. The manner in which all these subjects combine and overlap the old simple sciences of Geometry, Physics, Chemistry, Biology and Geography is shown by the divisions in broken lines, and it is clear that these old categories no longer denote separable subjects of study.

The table shows, for example, that the study of Mineral Chemistry and Crystallography contribute to Mineralogy, which is of value to Petrography, and this again joins Sedimentology in making the study of Orogenics possible, thus throwing light on Tectonics and Palaeogeography.

The study of the inhabited world, as a world, is thus a single vast subject, and the various 'sciences' involved are arbitrary but convenient labels for vaguely-defined aspects of it.

FOREWORD

During the last few decades the science of geology has developed in a number of different directions. These have been opened up, for the most part, by new material supplied by other sciences (such as those of physics, chemistry, astrophysics and biology), material presented either in the form of new techniques or embodied in the influences which stem from the results attained in these other branches of science.

In this book we have endeavoured, in the light of present-day knowledge, to describe the various phases and stages which succeeded each other during the development of life on this globe of ours. We have chosen this subject because it presents the great advantage of offering us, in their natural order, most of the geological phenomena which have appeared on the earth; that is to say the phenomena which are the objects of study in the fields of geodynamics, orogenetics and tectonics, sedimentology, stratigraphy, palaeogeography, petrography and palaeontology.

To the reader of this book we offer a considerable accumulation of data which have resulted from the researches we have conducted for a number of years past both into the documentation which many scientists in different countries and in various languages have provided, and also into the evidence which we ourselves have gathered in the field.

Not all the evidence we record has been incorporated into the accepted teaching of geology and we would stress that although the syntheses we have constructed and the generalizations we have made are all our own, these have been already

set forth, at any rate in part, in scientific and technical publications.

Among the views we advance we should like especially to draw attention to that which stresses the possibilities that now exist for integrating the data provided by petrology and palaeontology within the framework for geology in general. We hope that, by following this line of approach, we may be able to break away from what may be called the 'catalogue phase' of these two sciences of petrology and palaeontology.

In order to enable the reader to visualize the vast scope and the complex problems of geology today, we have thought it useful to set forth in a diagrammatic table the relations between the different branches of geology and those other sciences with which they link up. (*See* page 8.) The table, moreover, may possibly bring home to beginners the importance of not neglecting the sciences mentioned. We cannot insist too strongly upon the necessity for acquiring the various technical skills and for absorbing the specialized learning which are indispensable for any purpose in the realm of geological science. As we conceive it, geology is the most comprehensive of the sciences, and we shall try to demonstrate its universal significance in the following chapters.

But first we should like to draw especial attention to the concept of the orogen and the geosyncline. This concept has been—and indeed still is—somewhat called in question in France; but it has been defined by scientists of many different nationalities, and it does offer a plausible explanation of the transformations undergone by the lithosphere.

In fact, it is in this concept that we can observe the convergence of the data provided by the study of geophysics, of the petrography of the eruptive rocks, of sedimentology, of stratigraphy, of palaeogeography and of tectonics properly speaking. We shall see that the history of those peculiar regions which constitute the orogens has been singularly constant since the

dawn of the Pre-Cambrian Age. Moreover, this history records that coherent development which has been a principal characteristic of the evolution of the earth's crust.

One of the most pressing of geological problems is that of the classification of the eruptive rocks. During the past few years there has arisen a sharp difference of opinion between the 'magmatists' and the 'metasomatists'—with the latter gaining a distinct advantage over the former. Nevertheless, it must be conceded that but small progress is being made in petrology at the present time, although it seems clear to us that very fruitful results could be obtained by a closer co-operation between the petrologists and the general geologists.

We have, then, endeavoured to describe the complete sequence of phenomena which occurs during the evolution of an orogen, a sequence to which we have given the name of 'drama'.

Recent progress in geochemistry (which has developed into an independent science only during the last few years) is enabling us not only to understand much about the origins of rock-formation but also, in some measure, to see how a regular chemico-mineralogical succession of petrographic types is produced during the course of a 'drama'.

The study of tectonics has benefited greatly by the utilization of results obtained in the science of mechanics. Fifty years ago tectonics seemed to open up vast horizons, but not enough attention was paid to the nature of the materials, so that most of the sections were established upon the evidence of far too few observations. As a consequence, the science of tectonics has been one of those to be the most affected by changes in point of view. However, it has recently gained in precision and in reliability what it has lost in range and scope.

The reader should not be astonished if the dazzling views and theories of the 'mobilists' (such as Wegener and Argand) have not seemed to rest upon sufficiently convincing evidence

to provide a starting-point for the synthesis we have tried to present. Today, the attention of geologists is rather directed toward the mechanical behaviour of rocks. Therefore, the two chapters on flow-tectonics and on diapirism assume a significance which would have been unsuspected only twenty years ago.

Finally, we would mention that among the biological sciences ecology is now recognized as being of very great importance to stratigraphy, which in the past has too often been confined to the mere cataloguing of sedimentary strata. It is now possible to reconstitute both the conditions in which life evolved at a given epoch and the associations of living creatures existing during that epoch—and so on, through the ages.

We attempt in the following pages to reconcile the various points of view, and also to point out their consequences both in space (that is to say geographically) and in time (*i.e.*, during the evolution of the phenomena we have called 'dramas'). The Palaeogeographical researches whose conclusions we presented in an earlier work (1952) have led us to define the modes of formation of the geography of the present day. Since, moreover, we are of the opinion that the concept of the 'drama' enables us to co-ordinate and to group together the major geological phenomena, we are now developing the theme of this book for publication in a much fuller and more technical work.

INTRODUCTION

THE GEOLOGICAL SCALE

We would suggest that the reader never lose sight of the fact that all geological phenomena obey laws whose time-scale is very different from the one used for human history or even for geography. A geologist will feel quite justified in applying to slowly developing phenomena (whose duration must be measured in millions of years) dynamic terms which we are accustomed to use in describing what may be called almost instantaneous events. The man in the street sees a river sweep by, the geographer notes the flow of a glacier, the student of tectonics reconstitutes the movement of rock-sheets. In similar fashion, we recognize that the biological mutations obtained in a laboratory are on a scale very different from that of the mega-evolution of biological groups during the fossiliferous ages of the earth's history. We shall be led, later on, to speak of 'migrations' which can be detected only on the geological scale. The very nature of geological study requires that we should regard the majority of geological phenomena as having been of long duration (Plates XXIII and XXIV). Processes which were accomplished rapidly are not very likely to have left traces we can recognize today.

THE MEASURE OF TIME

In recent years several methods have been devised for measuring the real age (*i.e.*, the absolute age) of terrains and rocks. These

methods have been of the greatest importance in the progress made in geological research. As geology is essentially an historical science, it is obviously of great value to us to be able to determine the exact dates of events which have occurred during the course of terrestrial evolution. This is not the place to enter into a detailed account of these methods (most of which derive from nuclear physics) and we shall simply enumerate them and point out their special uses and limitations.

Let us remember, first of all, that most of the methods depend upon the ponderable relationship between a radioactive element and one of the products of its disintegration. As the rate of disintegration is constant the radioactive process has, not unjustly, been described as 'a clock that cannot go wrong'.

The *strontium* method is one of the most recent to have been perfected and it may be usefully employed in connection with the most ancient rocks. This method allows the calculation of the age of formations which are more than 3,000 million years old with an error of no more than ten per cent.

The *lead* methods (*uranium, thorium*)—which were the first to be devised—are suitable for less ancient rocks, that is to say for those which were formed between, say, the later Pre-Cambrian and the Tertiary epochs, the latter of which began some 70,000,000 years ago.

These computations of absolute age are furnished by data from the non-sedimentary rocks and especially the pegmatites (*see* page 59), formed in the depths of the lithosphere. The lead methods have also been extended to certain accessory minerals of granites which are strongly radioactive, the zircons, but here again the results refer only to the crystalline rocks.

The method of isotopic ratios (for instance those of strontium), as applied to the sulphates and carbonates, serves to indicate the age of the marine sediments from the Cambrian onwards to within about a million years.

The *radio-carbon* method is fundamentally different from

those mentioned above and depends upon the measurement of the quantities of a rather unstable isotype of carbon (C^{14}) which remain in organic substances after they have ceased to live. This 'radio-carbon' is produced by the action of cosmic rays upon the nitrogen of the upper atmosphere. As C^{14} has a relatively short life, the radio-carbon method can be applied only to substances of comparatively recent date. However, the method has been now so refined that datings of up to about 40,000 years ago can be determined.

It looks as though the history of the earth will be divided into two main types of datings: precise ones obtained by the foregoing methods, and the relative datings of sediments containing characteristic fossils determined according to the old traditions of stratigraphic geology. The relative datings are applicable to what we call the 'fossiliferous ages'—that is to say, those which succeeded the Cambrian.

The superposition of the two time-scales, the absolute and the relative, raises problems which were at one time embarrassingly difficult to solve, but we are becoming less and less hampered by the duality. True enough, we are not as yet in a position to date directly the most ancient sediments (the Pre-Cambrian) or to order them accurately, since they lack both radioactive minerals and fossils. However, we have taken notice of the geological positions of standard rocks, and by observing the succession of phenomena (which can generally be established) it has now become fairly easy to assign an undated formation between limits which are becoming progressively narrower.

A NOTE ON SOME ELEMENTARY CONCEPTS

Geological Chronology

We will not here enter into the details of the classifications employed in geology, but we may remark that we can

distinguish, successively, (i) the Pre-Cambrian ages, which occupied the first three thousand million years or so after the earth's crust was formed; and (ii) the fossiliferous ages, which comprise the last five hundred million years. With these classical geology (*i.e.*, stratigraphy) deals. (Plates XXIII and XXIV.)

The fossiliferous ages are divided into four eras: the Primary or Palaeozoic, the Secondary or Mesozoic, the Tertiary or Cainozoic, and the Quaternary. Each of these eras is subdivided into periods, to which corresponds a number of formations grouped together in 'systems'. In current language, however, the terms 'Cambrian', 'Triassic', 'Miocene', etc., refer both to the period and to the systems.

The Primary Era is composed of the following periods, which are now fairly well-defined by absolute datings in millions of years: Cambrian (–500 to –400), Ordovician (–400 to –350), Silurian (–350 to –320), Devonian (–320 to –280), Carboniferous (–280 to –220) and Permian (–220 to –200).

The Secondary Era comprises the Triassic (–200 to –175), the Jurassic (–175 to –140) and the Cretaceous (–140 to –70).

The Tertiary Era includes the Palaeocene (–70 to –60), the Eocene (–60 to –40), the Oligocene (–40 to –29), the Miocene (–29 to –12) and the Pliocene (–12 to –1).

The Quaternary Era comprises only the last million years.

The method we have mentioned above have enabled us to determine how long each fossiliferous period has lasted and even to estimate the duration and the rate of evolution of the organisms. The absolute measurements of age have, therefore, furnished much assistance towards the solving of the great problems of evolution.

Indeed, when we remember that the scale of absolute time-datings is rapidly attaining a considerable degree of accuracy (marked by the constancy of the unit employed, which, up to

now, is a period of one million years), we may confidently make certain observations regarding the relative scale (based on fossils) whose system of reference it has never been possible to unify.

This system of reference was based upon a computation of the rate of evolution from which we might estimate the time required to produce a 'transient' of any given species—that is to say, another and stable species or variety sufficiently different from the preceding species for us to regard the former as constituting a palaeontological zone, and (if possible) sufficiently widely distributed over the surface of the globe to enable correlations to be established.

Simpson[1] has well pointed out, and stressed, that the rate of evolution varies with the different zoological groups, both with the phyla and also with the epochs. Thus, the 'relative scale' from fossils is much more precise and delicate than the 'absolute scale' and more useful for the stratigraphic study of the sediments. Yet this 'fossil scale' presents two disadvantages. First, by no means all the sedimentary series (even later than the Pre-Cambrian) display fossils, the preservation of which is dependent partly upon general conditions and partly a matter of chance. Second, a scale based upon the evidence of the fossils cannot be referred to any fixed unit of time.

The Classification of the Eruptive Rocks

The present classification of the eruptive rocks is extremely complicated and, moreover, not very satisfactory. The non-specialist may confine his attention to the larger categories.

Rocks are called 'acid' when their percentage of SiO_2 is more than 65, 'intermediate' (or 'neutral') when the percentage varies between 65 and 52, and 'basic' when it is less than 52. Generally speaking, the acid rocks are lighter in colour and in

[1] G. G. Simpson: *Tempo and Mode in Evolution*. Columbia University Press, New York.

weight; their specific weight may be about 213 in the case of the ryolites. The basic rocks are darker in colour and more dense and in the peridotites the specific weight is as high as 4.

In a general way we may say that the minerals making up the eruptive rocks fall into two great classes.

(1) The 'white' elements, generally of a light colour and of relatively low density (2·5 to 2·7), *viz.*:

quartz (silica, SiO_2), the criterion by which the acidity of rocks is measured;

the *alkaline feldspars* (potash or soda);

the *plagioclase feldspars* (soda and lime), of which those containing lime belong to the basic rocks and are the most dense;

the *feldspathoids* (nepheline, leucite); these are closely related to the feldspars but have a lower percentage of silica;

muscovite, that is, white mica (potash).

(2) The 'dark' elements, of greater density (2·8 to 3·45, which are essentially ferro-magnesian: *biotite* (black mica), *amphiboles, pyroxenes, olivines.*

GRANITES—in the widest sense of the term—are light-coloured, granular in texture and relatively light in weight (specific weight from 2·59 to 2·73). They contain an excess of silica (SiO_2) in the form of free quartz and because of this are classed as acid rocks. They also contain feldspars and often a dark-coloured constituent as well, such as biotite, amphibole or (more rarely) pyroxene. The rhyolites are lavas and have a similar chemical composition to the granites.

SYENITES are granular rocks, but without quartz and generally with amphibole. Their feldspars are alkaline, that is to say that they contain potassium and sodium. The corresponding lavas are the trachytes.

The DIORITES and GABBROS are intermediate and basic rocks, respectively. They are crystallized to a considerable extent and contain lime-soda feldspars associated with amphiboles or pyroxenes. The lavas with a similar composition to the diorites are the ANDESITES, while those comparable to the gabbros are the BASALTS. Basalts are by far the most common of all volcanic rocks.

Both Syenites and gabbros may contain a considerable percentage of sodium which appears as the mineral *nepheline*. Those lavas which are of similar composition to the *nepheline-syenites* are the PHONOLITES. Those lavas which correspond to the *nepheline-gabbros* are the TEPHRITES. In certain lavas potassium dominates and occurs in the form of the mineral *leucite*.

The quality of feldspathoid may be greater than that of the feldspars and even replace the latter altogether (IJOLITES).

Lastly there are types which contain no 'white' elements, the *ultra-basic* rocks; in extreme cases these may be monomineral. These are classed as PERIDOTITES. They are rich in iron and are dense and dark in colour.

I

THE GEOLOGY OF CONTINENTS

IN THIS book we shall not deal with the much-debated question of the origin of the earth. Moreover, although theories derived from those advanced by Laplace (1749–1827) still find some advocates, in recent years we have been led, more and more, to conclude that our planet originated in a collection and conglomeration of cosmic dust, meteorites and asteroids.[1] There is no general consensus of opinion and consideration of such problems would take us far out of our way. We shall, therefore, begin our story of the earth not only after the formation of its crust (called the 'lithosphere' by geologists), but at a period when the temperature of the surface was more or less comparable with that prevailing today.

THE PRIMITIVE APPEARANCE OF THE EARTH'S CRUST

What was the general appearance of the earth's surface in those very remote ages? Geologists and geophysicists picture the earth as composed of some six concentric spheres which, in order from the periphery to the centre, are known as the atmosphere, the hydrosphere, the biosphere, the lithosphere, and the purely interior spheres, the shell and the nucleus. Direct observation affords us information concerning only the surface of the litho-

[1] H. C. Urey: *The Planets, their Origin and Development.* Yale University Press, 1952.

sphere, the upper portion of the hydrosphere, the lower portion of the atmosphere, and, lastly, the biosphere—that is to say, the regions in which we live. The greater part of our planet is therefore known to us only from geophysical observations, the results of which may be interpreted in various ways.

However, the reconstitution of the early conditions obtaining on the earth (which is the proper task of geologists) is based upon less hypothetical data derived from geophysics. It would seem that, at the present time, the lithosphere is composed of a thick layer of material similar to the lavas rich in iron, magnesium and calcium—in fact, of basalt, which is one of the commonest of all the rocks met with on the surface of the earth. On this thick layer there rests, in certain areas of the terrestrial surface, a thinner layer of lighter material having, generally speaking, the composition of granite. This is also one of the most widely distributed rocks.

To the basaltic layer is given the name of 'sima' (a combination of the first syllables of *si*licon and *ma*gnesium). The granitic layer is called the 'sial' (from the first syllables of *si*licon and *al*uminium). It has been demonstrated that the bottom of the greater part of the Pacific Ocean is of the composition of sima, and the same observation holds good, it would seem, for the Arctic Ocean, and perhaps for the western part of the Atlantic. In the vast sima-area of the Pacific it may be noted that, with the exception of the region of the Hawaii Islands, no earthquakes occur.

For many years geologists and geophysicists thought that they were justified in imagining a sialic layer forming a continuous sphere over the sima, and thence in concluding that the primitive crust of the earth was granitic in composition. It now seems, however, quite certain that such a granitic layer never existed, and that for several reasons. First of all, the area occupied by oceans with a floor of sima is much greater than that occupied by the continents. Now, it is established that the

continents have increased in area by means of a process which we shall describe later on, and that the most ancient land-areas are much richer in basaltic components than are more recent areas. This tends to show that such areas were formed in strongly simaic surroundings. We may also note that meteorites, taken as a whole, are always of sima-composition and that they contain nothing in the nature of granite. The meteorites, indeed, are made up of materials still poorer in silica than is basalt, and resemble the peridotites, rocks in which a ferromagnesian mineral, peridot or olivine, dominates. There is, then, every reason for supposing that the earth, like the meteorites (which are comparable to our shell and nucleus), is of a composition which is mainly sima.

It is certain that a hydrosphere appeared on this basaltic crust very early—indeed, as soon as the cooling of the earth allowed it. This is proved by the existence, even in sediments of greater age than three thousand million years, of detrital layers formed by the disintegration of rocks under the action of running water. It is possible that, during the course of the ages, this hydrosphere increased in volume[1] owing to additional water arising from the depths of the globe, but it seems more logical to conclude that, from the first, the hydrosphere contained approximately the same amount of water as it does today, although that water was distributed in a different fashion.

During the formation of the hydrosphere there was a precipitation of light elements (*e.g.*, chlorine, fluorine, boron, sulphur and phosphorus); it is, then, possible that the primitive waters of the earth had a *p*H less than 7 and that they attacked the earth's crust until the acids were neutralized by the bases which it contained, especially the alkaline metals and those of the alkaline earths, calcium, potassium and sodium, to mention but the more important of them.

[1] W. W. Rubet: *Geologic History of Sea-Water*. Bull. Geol. Soc. of America, Vol. CLXII, No. 9, 1951, pp. 1111–48.

If a comparison of the chronological results obtained shows the weakness and insufficiency of stratigraphical palaeontology, it is nevertheless necessary to employ the biological evidence in the elaboration of a geological clock. First of all, let us note that the succession of phenomena and events (which we shall call a 'drama' and which represents the unit of the structural evolution of the lithosphere) can, in a certain sense, be regarded as having been repeated in a fairly regular fashion throughout the course of time. It is not, however, a strictly cyclical phenomenon since there is never a complete return to the starting-point. Organic evolution, which is closely associated with the incessant unrest of the terrestrial crust, is, on the contrary, an absolutely irreversible process, and acts as a catch which prevents us from putting back the hands of our geological clock.

By its nature, then, the biosphere is opposed, at least in one respect, to the lithosphere. Though the peculiar property of life is most abundantly evident in organic structures, we must not lose sight of the fact that life began to appear during the geochemical evolution of sediments and rocks. Indeed, the advances made in their study have led geochemists to the realization that the relations between the isotopes of one and the same element may vary from those average figures which correspond to the primorial composition of the element in question. The most striking example of this phenomenon is afforded by the stable isotopes of carbon—C^{12} and C^{13}. The ratio C^{12}/C^{13}, which averages 89, is higher for the organic compounds and lower for the carbonates. Life, therefore, displays a tendency to concentrate natural carbon in the lighter isotope. In a similar manner, the relation between the isotopes S^{32}/S^{34} seems to increase steadily and regularly in the sediments during the course of ages. Thus, it might be possible to go back

:o an epoch when sedimentary sulphur had an isotopic composition close to that of the primitive condition.[1]

From this, it is deduced that the bacterial cycle of sulphur did not, until some 700 or 800 million years ago, begin to play the important part that it assumed later on. Furthermore, it may be noted that sedimentary sulphide of iron, that is *pyrites*, does not become very common in the sediments until the Ordovician period. After that time, *pyrites* is associated with special marine faunas, made up for the most part of young molluscs and generally characterized by their small size.

Indeed, the role of life in the early history of the earth was certainly considerable. There is, for instance, reason to think that during the consolidation of the earth's crust the atmosphere was devoid of free oxygen. This was produced, later on, by chlorophyll assimilation. On the other hand, the powerful ultra-violet rays of short-wave length coming from the sun, which are fatal to living things, were not then absorbed in the atmosphere, since the layer of ozone had not yet become sufficiently differentiated. The action of these rays must nevertheless have caused the appearance of various substances of organic type, notably hydrocarbons. Such a supposition is very strongly suggested by the existence of meteorites which contain hydrocarbons of a composition which is unknown on the surface of the earth.[2]

Life, then, must have appeared very timidly on the surface of our globe in places protected from the sun's rays, probably in regions that were several metres under the surface of the waters. Still, from its very beginning, life must have been chlorophyllic and have liberated oxygen. The existence of free oxygen in the atmosphere is proved by the presence in most of

[1] H. G. Thode, J. Macnamara and W. H. Fleming: *Sulphur Isotope Fractionation in Nature and Geological and Biological Time-Scale*. Geochim. et Cosmoch. Acta, III, 1953, pp. 235–43.

[2] *E.g.*, the Cold Bokevelt meteorite in South Africa. *Vide* G. Muller: *The Properties and Theory of Genesis of the Carbonaceous Complex within the Cold Bokevelt Meteorite*. Geochim. et Cosmoch, Acta, IV, 1953, pp. 1–10.

the Pre-Cambrian sediments (of even more than two thousand million years ago) of sedimentary iron ores of a rather special type. These occur in lenticular masses generally associated with ancient siliceous gels, so well bedded that they are called 'banded', and often, also, associated with deposits of *apatite*, that is to say, phosphate of lime. These three sorts of sediment are of the same type as those which, today, may be met with in certain lakes where they are due to bacterial action. Not only have these sediments constituted the greatest deposits of iron in the world (*e.g.*, those of Minnesota in the United States and also, perhaps, those of Swedish Lapland), but the banded iron ores of Pre-Cambrian ages also indicate that there was, at those epochs, a fairly considerable amount of free oxygen in the atmosphere.

The same epochs apparently also saw the formation of ozone by the action of short ultra-violet rays on oxygen, three atoms of oxygen forming a molecule of ozone. This atmospheric ozone constitutes a thin, uninterrupted screen only a few centimetres thick at a height which varies from about twelve to twenty-five miles. This screen arrests the very rays which generated it, and which had formerly prevented the existence of life.

The presence and the development of living things is also indicated by the formation of limestone. The primeval basalt must have served as the main substratum for primitive organisms. It is not, then, surprising that from these materials, combined with those of the hydrosphere and the atmosphere, there should have arisen the organic waste which formed the earliest known sediments of organic origin—that is to say, the iron ores we have mentioned above and the calcium and magnesium of the primordial limestones. The latter appear to be essentially associated with the secretions of Schizophytes, that is to say blue algae which are almost as simple in their organization as bacteria. Their cells have no nucleus and their chlorophyll

is diffused. *Collenia*, *Cryptozoon* and the Stromoliths afford examples.

We can say that, generally speaking, the part played by living things during the unfossiliferous Pre-Cambrian ages is indicated by their geochemical influence. To their action is due the formation of several different types of sediments: iron ores (Plate II), siliceous gels, phosphates of lime (transformed into apatites), limestones (Plate IV) and different minerals disseminated through the rocks (*e.g.*, graphite and pyrites).

During the fossiliferous ages life was subjected to new influences which provoked the appearance of more complicated organisms, the Metazoa and the Metaphytes. It was the fossiliferous ages which were those of organic evolution.

THE ELABORATION OF PRESENT-DAY GEOGRAPHY

If we glance at a map of the world we are at once struck by certain outstanding features, such as the huge extent of the Pacific Ocean, bordered with chains of islands dotted with volcanoes. Then there are the three continents, all of which terminate in southern triangular extremities. After that, we may note the fact that most of the land-masses are grouped in one hemisphere, having for its pole, according to some, Dumet Island, near the mouth of the Vilaine River in Brittany, or, according to others, a point in the Black Sea some 112 miles east of Constanza. Finally, we have the contrast between the North Pole, situated in an ocean, and the South Pole, around which extends the continent of Antarctica.

If we go back through the fossiliferous geological ages, these features may be considered, generally speaking, as having been permanent. We should add to them a broad belt more or less at the latitude of the northern tropical zone, which was for long occupied by a sea known as the Tethys, whose place today is,

roughly speaking, occupied chiefly by mountain-chains of Alpine system, among which are the Himalaya and the Antilles.

In fact, as long ago as 500 million years, the main lines of this geographical arrangement had already been elaborated by various changes and evolutions occurring in Pre-Cambrian ages. It is the sialic shields, or ancient platforms, which make up the essential components of the existing continents. As though to compensate for the erosion which has been continuously at work wearing down the exposed portions of the continents, the continental shields have been subjected to an almost constant vertical uplift; that is to say, to movements which are known as 'positive'.

These immense structural units (to whose elaboration we shall have occasion to refer later on) are the continental areas of stratigraphic geology, and they were increased, in quite regular fashion, by the addition of new segments during the fossiliferous ages.

If, then, we are justified in saying that the approximate shape of the shields has been almost permanent, we must, nevertheless, consider certain hypotheses which have been proposed to account for various associations and linkages between the fossiliferous strata laid down on the periphery of the continental shields. For instance, marine fossils belonging to comparable species occur in the Lower Devonian of both South Africa and South America. Since the two continental shields are today separated by the South Atlantic Ocean, and since, at present, the marine faunas of the South American and the South African coasts are not alike, we must ask ourselves how such an identity of faunas was established in Lower Devonian times.

Basing their theories upon the conformity which appears to exist between the eastern coast of South America and the western coast of Africa, A. Wegener and many other authors have thought that formerly the two continental shields were in contact and that a common sea bathed their southern shore-lines.

This hypothesis, which is known as that of the 'continental drift', has been also applied to all the southern continental shields—Madagascar, Arabia, the Indian sub-continent, Australia and Antarctica. E. Suess[1] gave the name of 'Gondwanaland' to the continent which was supposed to have been constituted by all these now scattered fragments. The name was taken from that of a continental formation in Hindustan, one which, long before Suess's time, had been recognized as extending almost uniformly over these various areas in Permian and Triassic ages. While most geologists are of the opinion that the various component parts of Gondwanaland became divided because of great subsidences, the partisans of the continental drift theory maintain that the various sections of Gondwanaland became detached from Africa, some moving east and others west, like icebergs of sial on an ocean of sima.

The continental drift theory has also been applied to North America, Greenland and Europe, on the one hand, and to Africa and Europe on the other.

Thus, although there are good reasons for concluding that the existing great continental shields have changed their geography but little since Pre-Cambrian times, the supporters of Wegener's hypothesis hold that the co-ordinates of the continents on the terrestrial globe have varied at times in a very marked degree. However, now that the results of geophysical research are assuming an ever more important place in the elaboration of geological theories, the continental drift hypothesis is being subjected to much destructive criticism. Indeed, there are cogent reasons for thinking that the crust of the earth is rigid for a depth of at least 450 miles, if we may judge from the way in which seismic waves are propagated. Therefore, any movement or drift of the very shallow sial crust on the solid sima appears to be difficult to admit.

Moreover, many of the correlations and resemblances

[1] E. Suess: *Das Antlitz der Erde.*

between continental blocks separated by great distances may be explained more simply by sea-currents and by their identical physico-chemical conditions. The arguments from climate which are invoked in favour of the Wegener hypothesis (such as, for instance, the geographical distribution of glaciers during the Upper Carboniferous) may well be explained by the geographical distribution of relief and by the general climate of the earth during the Upper Carboniferous.

The separation of the component parts of Gondwanaland (if indeed such a continent ever existed in the form in which it has been reconstructed) may be readily explained if we note that in any case these sections display numerous traces of fissuration. There may have existed between the sections connecting links which have subsided. Such a subsidence seems to have occurred in the case of Mozambique Land which, in Permian times, joined Madagascar to Southern Africa.

Finally, we may note that if the Wegener theory seems fairly plausible as regards South America and Africa, the hypothesis is manifestly inadequate in regard to Australia, for, to fit in with the theory, that continent would have had to have drifted very far indeed, whereas we have every reason to think that Australia's links, even from Cambrian times, have always been with the Far East.

To set against all this, almost the only fact which might seem to confirm the drift theory is the displacement of a small island—Sabine Island—off the north-eastern coast of Greenland, and even this displacement is considered, today, to be very doubtful.

There is another great problem to which we must refer at some length; that is the formation of the mountain chains, which lie on the marginal areas of the old continental shields, most of which are made up of relatively recent rocks. The circum-Pacific chain, on the one hand, and the Alpine chain, on the other, are among the most salient features in the present-

day geography of the earth. Two important geographical phenomena relating to these chains had been recognized before the end of the last century. Mountain-chains, generally speaking, arise on areas of deep sedimentation. Their foldings seem to be due, at least in part, to lateral or 'tangential' pressures. The mountain-chains, then, present a contrast to the main continental areas where sedimentation is not heavy and which are subjected to vertical movements.

IDENTITY OF EVOLUTION IN SHIELDS AND MOUNTAINS

We have just pointed out the contrast between the parts played by the continental areas, or sialic shields, and the mountain-chains. However, it can be proved that in the past there have been successions of mountain-chains which have been uplifted and then worn down, and that it is these that now constitute the continental shields. We shall show, also, that these shields (subjected to great erosion) play a role in the formation of new mountain-chains. In short, the problem we are now going to face is that of the elaboration of the sial of the continental masses and of other aspects of its behaviour.

At the present time, the continental shields are mainly composed of granite together with rocks whose origin (in great part sedimentary) is still more or less determinable and which present a gradual transition ending in typical granite. Such rocks are called 'metamorphic', that is to say 'transformed', and these, in addition to the granites, make up the crystalline rocks. There may be observed also among the metamorphic rocks, and in variable quantities, lavas of sima composition which have themselves been subjected to metamorphism.

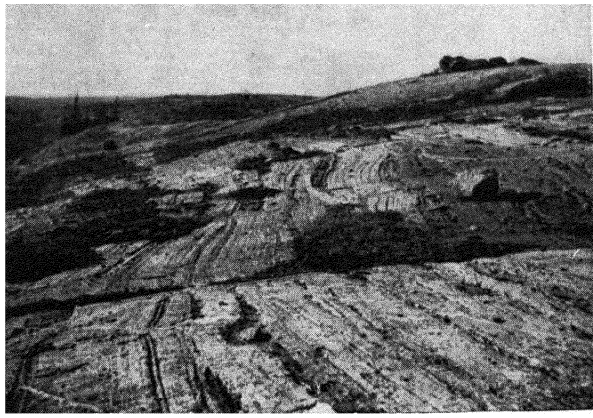
For long it was thought that the structure of the continental shields was uniform. It was believed that they were composed of several superposed sedimentary series whose metamorphism

declined from the bottom upwards. Each series would have been folded, then traversed by occurrences of granite, and finally worn down before the following series was laid down upon an immense peneplain.

The study of the Pre-Cambrian should, then, be undertaken by methods very different from those employed in the study of the fossiliferous strata. They should include the analysis of the degree of metamorphism of the sediments and examination of the great discordances or unconformities—that is to say, of the inclination of the sediments of a new series to the folded and eroded layers of the preceding series. But a more exact cartography, the study of tectonic complexity (that is, the abnormal superpositions which may occur in one and the same chain) and the increased means we now have for measuring absolute age, have all led us to revise the simple explanation formerly accepted.

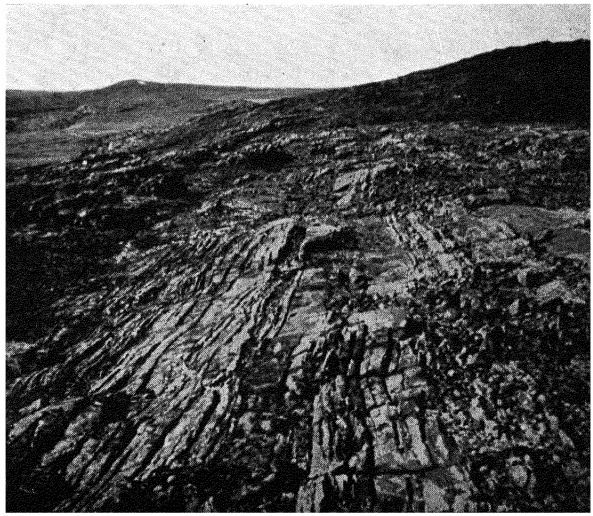
The Scandinavian geologists have recognized in their shield the presence of three, and perhaps four, different mountain-chains, differing from one another in age, in the direction of their foldings and in their geographical position. More recently, a similar change of viewpoint has occurred with regard to southern Africa and the Belgian Congo, peninsular India, the Canadian continental shield, and—quite a short time ago—Australia (Map 4).

We have, in fact, become possessed of a new Ariadne's thread that has led us to abandon many of the former syntheses. But the new clue has also directed us to a very important and significant discovery. The Pre-Cambrian shields were produced by an evolutionary process which is similar to that observable on the continents of the present day. Moreover, as far as we can see, the part of the existing continental areas was played (in the Pre-Cambrian formations) by areas formed still more anciently but in a similar manner—areas which are smaller than the shields and to which the name of 'nuclei' has been given. There



E. Aubert de la Rue

Plate I. Pre-Cambrian gneiss outcropping in the Koksoak Valley near Fort Chimo, south of Ungava Bay, Labrador. It consists of highly metamorphic sediments, now arranged vertically owing to folding. The sediments were deposited probably more than a thousand million years ago



E. Aubert de la Rue

Plate II. Quartzites with haematite of late Pre-Cambrian age, at Kayak Bay, south of Ungava peninsula, Labrador. These ancient silico-ferruginous strata were laid down in narrow basins on pre-existing gneisses (*see above*) which had been worn down to a pene-plain. Those zones which are richest in iron are extensively worked

G. Termier

Plate III. Pillow-lavas of labradorite (basalt without olivine) at the mouth of the Oued Arba, Algeria. The 'pillows' are clearly visible and the radial appearance of the cross-sections is clearly distinguishable. This outcrop was not caused by geosynclinal volcanism but by a later, geanticlinal, volcanic phase of the Algerian Neogene

are, generally, several of these nuclei in one and the same shield. From this we must conclude that the zones of influence in which the sial was formed became fused together and thus constituted a continental area.

Thus, if the same type of evolution that produced the increase in size of the nuclei also led to the proliferation of the shields (that is to say, to the differentiation of the sialic layer of the lithosphere) then we may conclude that the geography of the earth must have been completely different in Pre-Cambrian ages from what we have been accustomed to think. This is because of the practically permanent character it exhibits during the 500 million years of the fossiliferous ages.

A new sial, then, is derived in great measure from an earlier sial, more or less altered by the agents of erosion and then thrust down deep by subsidence. The main difference between the sial of the continents and that of the newer deposits is that the former constitutes a rigid block which reacts as a single mass to the movements of the earth's crust, whereas the latter is mobile and constitutes a flexible and plastic assemblage.

Again, the lavas which spread on the submarine bed of a geosyncline have a sima character. These are basalts, and since they flow on sea-bottoms they are subjected to the influence of the sea. Their general appearance is often that of great rounded masses of rock or 'pillows', and hence the name of 'pillow-lavas' given to such formations. (Plate III.) Each of these masses offers a texture and a chemico-mineralogical composition which varies from the centre to the surface. The pillow-lavas are rich in soda and in water, whose presence may be attributed to the direct action of sea-water on basaltic lava. Often enough, the sima lavas (called spilites) explode in the water, or are very rapidly attacked, and so give rise to green submarine tuffs, mixed with sedimentary elements. Such tuffs are known as 'greywacke'. Furthermore, by contact with these rocks the sea itself becomes richer in silica. Thus siliceous gels

are formed, especially through the action of organisms which utilize silica for the building up of their skeletons—the Radiolaria. To the silico-aluminous sediments of detrital origin is, then, added some of the sima, in the form of spilites and greywacke, often accompanied by the skeletons of Radiolaria.

2

GEOLOGICAL DRAMAS[1]

BEFORE we go any farther let us examine in some detail the elaboration of a sial segment which, as we have already seen, implies the formation of a mountain-chain.

The segment is almost always situated in the neighbourhood of an area of more ancient sial—a nucleus, shield or continent —and is thus on the fringe of the sima forming the primitive crust. The segment is thus established on two distinct types of material which differ from each other both by their density and by the mechanics of their behaviour. The segment is, first and foremost, a zone of weakness in the earth's crust. This weakness is manifested in three different ways: by ready subsidence, which may be caused by the weight of the sediments or perhaps independently of it; by fracturing, allowing of up-flows of lavas and vapours; and third, by a marked seismicity. Furthermore, owing to the vicinity of the continent, there accumulate in this zone products of the continent's dismantling—products which, after a relatively short journey by rivers and torrents, pile up as abundant deposits of detritus. Such a segment, situated on the edge of the continental sial and the sima, and the site of a great series of sedimentary deposits mingled with occurrences of lavas, develops into a basin or an area of subsidence called a 'geosyncline'.

[1] We suggest the word 'drama' instead of the phrase 'geological cycle' in order to designate the evolution of an orogen. The reason for our preference is of a technical nature and it is discussed in *Géologie et Pétrogénèse*. (Publication du Service de la Carte géologique de l'Algérie, nouvelle série, bulletin, No. 2, 1953.)

We would, however, point out that each of the features which mark a geosyncline may be met with, independently, in regions of the earth where there are no geosynclines. Subsidence, and even great depths of sediment, may, on the continental areas, give rise to basins which are not volcanic. The sagging and subsidence in these cases are due to vertical negative movements reacting simply to the upward pressures to which the shields are generally subjected. Subsidence may also occur in the ocean beds and produce great troughs which are too far removed from the continental surfaces to receive from them any appreciable amount of detrital sedimentation. Volcanism occurs in many fissures situated in the heart of continents or far out in the oceans. Seismicity is, as a rule, limited to the continental areas. Furthermore, it seems to be a fact that earthquakes with very deep origins (200 to 500 miles) occur only on the fringes. However, it must be admitted that such are to be observed only round the edges of the Pacific, whose girdle of islands is still, in part, geosynclinal.

The structural unit we have described above forms a region which is ready to undergo a process of evolution. This concerns the elaboration of its sial material, and involves a stage of mountain-range formation. For this reason, it is also called an 'orogen', a term which is applied to both the geosyncline and the mountain-chain which results from it. We may note that among the materials utilized in such a complex process, the detrital sediments of silico-aluminous composition figure very prominently; that is to say, they are sialic and are derived from the continent that has already been elaborated.

Let us now return to the history of the geosyncline. We shall see that, in the majority of cases, a geosyncline can be divided into a number of areas or zones. One of these is supported against the continental area (which we shall call the *foreland*), and although it has a tendency to subside and often receives outpourings of lavas, it enjoys some of the stability of

the shield against which it reposes. This zone is the *fore-trough*. To this a contrast is presented by a parallel or concentric zone, much more flexible and mobile (for it reposes essentially upon the ocean-bed). This is the *main-trough*. If we move from the main-trough towards the foreland, we shall see the features of the complex modified in a fairly progressive manner. In the main-trough the sediments are finer, the volcanism more intense. In the fore-trough, the sediments are coarser and the volcanism of variable intensity. Last, in the foreland—that is to say, outside the range of the geosyncline properly speaking—the sediments are much less thick (often calcareous in the basins) and there is practically no volcanism at all.

Naturally enough, in reality, things do not occur in such a schematically simple fashion. During the formation of a geosyncline there is sagging or subsidence of the continental peripheral areas, but fragments of these areas may survive at the point of junction between the two troughs, and more rarely in the troughs themselves. These great residual blocks display the same features as the foreland; that is to say, they are of sialic composition, they are rigid, and they are subjected to positive movements. Their area of alignment between the two troughs constitutes a zone of uplift between two areas of subsidence. Such an assemblage is called a 'geanticline'. On both sides the sediments are coarser and resemble those of the fore-trough.

REGIONAL METAMORPHISM

We have already defined metamorphism as the sum of those processes which convert sediments into crystalline rocks. Regional metamorphism (Plate I and Plate XXIII), which is the most common as well as the most extensive form of metamorphism, seems to be confined exclusively to the areas of the

geosynclines though it is not an essential feature of them. Such metamorphism may be entirely lacking, or it may even occur elsewhere, but the conducive conditions which prevail in the geosynclines are but rarely found together in other areas.

Indeed, the main factors or agents of regional metamorphism are: rise in temperature, increase in pressure, and (in many cases) interchange of chemical elements. Now, geosynclinal conditions are particularly favourable to such manifestations of energy. The very considerable weight of the sedimentary layers (several miles thick) gives rise to a pressure which mounts with every addition to the deposit. The very weight of the sediments drags them down to depths where (if we extrapolate the data derived from the geothermic grade measured in mine-shafts, that is to say an increase of approximately 3°C. for each 100 yards) there prevail very high temperatures (up to 300°C. at sixty miles below the zero reading).

However, the geothermic grade is probably much sharper than this in the geosynclines, where there is an intrusion of volcanic rocks and where vapours permeate. It is probable, indeed, that at a depth of sixty miles the temperature sometimes reaches 500° or even 600°C. As regards the chemical modifications produced, we may think of them as being determined by various processes, the two principal of which are (1) the occurrence of elements in a gaseous state which enables them to rise from the depths through the very numerous fissures in the geosynclines, and (2) migrations of elements provoked by conditions of temperature and pressure. This latter factor, indeed, inclines us to regard regional metamorphism as a superposition of zones of equilibrium, zones characterized by minerals whose stability is limited to any one or more of such zones.

For instance, there exist in sedimentary rocks and in certain lavas minerals like the micas and amphiboles, whose chemical composition includes water in the form of the hydroxyl radical

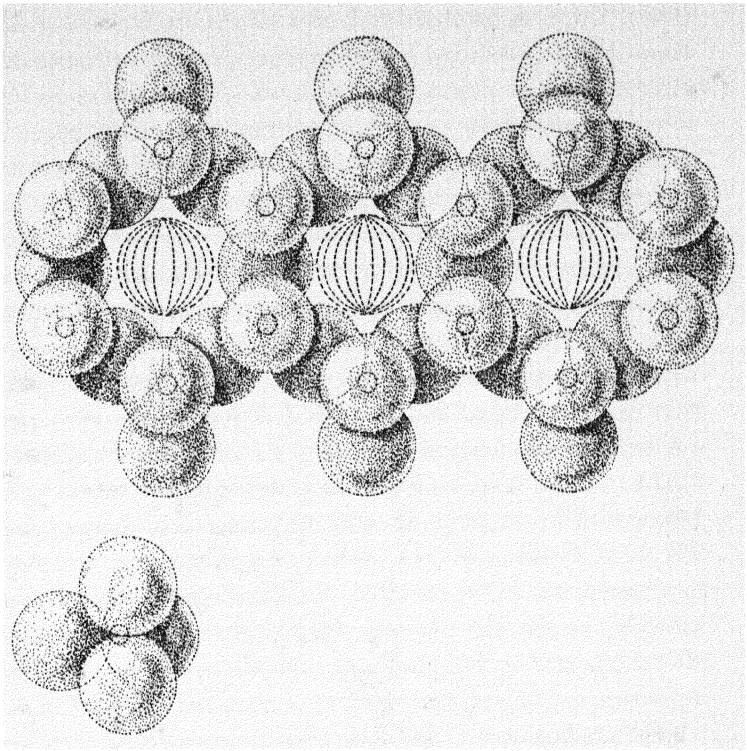


Figure 1. Fundamental atomic structure of an amphibole. The tetrahedrons of SiO_4 (*below*) are arranged in rings which form the links of chains in the centre of which are disposed the hydroxyl anions (*above*). Such chains are joined together by cations whose nature varies with the different species. (The radius of an oxygen anion is 1.4 Å, and that of a silicon cation, 0.42 Å)

(OH). Other minerals, such as gypsum, contain actual molecules of H_2O. Furthermore, the sediments laid down in aquatic surroundings are impregnated with water. We may conclude, then, that one of the main effects of regional metamorphism is the progressive elimination of this compound, first in the sediments and then in the minerals.

This water then creeps through the substance of the rocks, either as liquid (percolation) or in a state of vapour. The latter becomes supercritical (and acquires then a very marked power of solution) when the temperature exceeds 374°C. It is probable that this circulation takes place through the narrow spaces between the crystals and that, in this way, there is carried off in solution several of the component elements of the rocks.

In a similar way, other volatile substances are certainly displaced under the combined action of pressure and temperature. Of these, fluorine, chlorine, boron and sulphur are the most important. In this connection, we may remark that in the crystalline schists there is not to be found any of the salts produced by the evaporation of sea-water. Chlorides, fluorides and sulphates are, indeed, destroyed as soon as the effects of metamorphism begin to make themselves felt, and their acids are then liberated.

Water, possessing a greater or less power of dissolution, and the acids thus liberated in the rocks destroy such crystals as are not stable in their presence—for example, the garnet *pyrope* —and transform them into other minerals. Furthermore, the alkaline metals and those of the alkaline earths, freed after the loss of the acids, may also be displaced.

Before we go any further we must say a few words about the geological applications of the latest researches into structural mineralogy. Whether it be sial or sima, the lithosphere offers as its main constituent silica, known to everyone in the form of quartz or flint. To these minerals must be added some non-siliceous oxides, such as oxides of iron. If we wish to represent

the atomic arrangement of the crystalline system of the earth's crust, we may, as a first rough picture, consider the crust as an accumulation of oxygen ions. There are both anions (negatively charged ions) of large size, and—wedged amongst them—cations (with a positive charge equal though contrary to that of the anions) of much smaller dimensions. In the silicates, which form the commonest minerals, the small silicon cations are fixed in the middle of tetrahedra composed of a cluster of four oxygen ions. Such tetrahedra (SiO_4), linked together in various ways—either as a homogeneous whole (*i.e.*, silica SiO_2) or in droplets, chains, blades or networks in which they are joined together by cations—form the essential part of the framework of the lithosphere.

Now, each crystalline assemblage enjoys a certain latitude as far as its component elements are concerned. The silicates, in particular, form an isomorphic series of minerals having the same structure but in which the nature of the cations may vary widely, provided that they are of dimensions very nearly comparable with equivalent ionic rays. Even silicon may in this way be replaced by aluminium.

Among the most common of the cationic substitutions are those of iron or calcium by magnesium, and barium by potassium. The silicates of the crystalline rocks may be grouped into the following main series: olivines, garnets, pyroxenes, amphiboles (Fig. 1) and feldspars, to which may be added (among the igneous rocks) sphenes, apatites and feldspathoids. Among the oxides may be mentioned the large spinel group to which magnetite belongs. Anions and fluorine, which all have comparable dimensions, such as oxygen, the hydroxyl radical, may take each other's places.

If now we return to a consideration of the migrations provoked by the temperatures and pressures obtaining in regional metamorphism, we shall see that the law of isomorphic substitution—which has been briefly summarized above—allows

us to obtain an idea of what happens to the transformed elements. Just as in chemistry a strong acid displaces a weak acid, so also in metamorphism, a cation or an anion which may find itself in any given mineral in a zone of equilibrium where it can substitute itself for a less stable ion, must take the place of that ion. To these purely ionic reactions—which may be compared with the movements of pawns on a chess-board of three dimensions—is given the name of 'reactions in the solid state'. Of course we cannot, practically speaking, conduct experiments in the depths of the lithosphere, but chemists have reproduced, in the laboratory, comparable reactions, especially those relating to the apatite group.[1]

It must be said that there was, at first, a certain amount of scepticism of the concept of 'reactions in the solid state' as applied to petrogenesis. Indeed, this concept obliges us to admit that the cations at least are capable of spreading through the oxygen framework without being much hampered by the actual limits of the minerals themselves. However, it looks as though this explanation may be the only one able to account for the undoubted association of some minerals with given zones of equilibrium. Such associations can be explained in the case of rocks which have passed through a state of fusion, but not for sediments which have been progressively transformed into crystalline schists.

Finally, the diffusion of ions, initially caused by heat and pressure, occurs in various directions. Some of the ions are pulled downwards under the force of gravity, others resist this pull and manage to escape in the form of gas. Most of the ions, however, finally enter into new mineral combinations in which they displace other ions, and these, in their turn, seek—and eventually find—equilibrium.

Thus, the series of geosynclinal sediments end up by being

[1] G. Chaudron and R. Wallaey's *Synthèse des apatites par réaction dans l'état solide.* (Coll. Intern. C.N.R.S. Réactions dans l'état solide, Paris, Oct. 1948, pp. 103–5.)

converted into superposed metamorphic zones. If, for a preliminary estimate, we consider only the silico-aluminous rocks, such as clay, the zones will be seen to follow upon one another in the following manner: first of all, there will be about three miles of sediments situated beneath the surface. These, to all intents and purposes, remain unmodified apart from the change from uncompressed, water-charged submarine deposits into coherent rocks, by compaction and hardening. Argillaceous rocks, under pressure, then become modified into laminated shales and slates. In the next subjacent zone (or *epizone*) the rocks begin to lose their water and to become charged with silicate flakes of the mica type (sericites and muscovites) or chlorites. Such rocks are not always re-crystallized to such an extent that they lose all traces of fossils.

Under the epizone, in the *mesozone*, the shales and slates lose still more water and become mica-schists, in which white mica (muscovite) is first developed, with black mica (or biotite) becoming increasingly associated with it. Deeper down still, in the *catazone*, all the water escapes from minerals containing hydroxyl groups and feldspars are formed which convert the mica-schists into gneisses. The foliaceous structure which characterizes all these crystalline schists finally disappears and there is a gradual transition downwards, under a thickness of from 12 to 15 miles of strata, to a granite formed in place and known as 'anatexic' granite.

The final stage, then, of regional metamorphism (the so-called 'ultrametamorphism') is the formation of a rock of sialic type.

Just a few words about other rocks which are subjected to conditions of regional metamorphism. These rocks are, for the most part, sima lavas intercalated between sedimentary strata. At first, their composition is only slightly modified but their appearance becomes that of a schist. The minerals which are successively developed in such rocks are epidotes, then

amphiboles and garnets, after which the amphiboles lose their hydroxyl groups and are transformed into pyroxenes. Last, the rocks become feldspathic gneisses, more basic than the gneisses of silico-aluminous origin, and enclosed within the anatexic granite in the form of enclaves darker in colour and with a dioritic composition, or with one intermediate between granite and diorite ('granodiorite') (*See* Plate XIX). Thus, it is not surprising that anatexic granites should frequently be gneissic and heterogeneous and also that their density should be relatively great (2·73).

Geosynclinal sediments may also include limestones produced, most generally, by the action of living organisms (Plates IV and V). When these limestones are subjected to regional metamorphism they produce materials readily comparable with those which issue from basic lavas. Since, as we have seen, the substance itself of the limestones appears to have been borrowed directly from the sima, we are justified in speaking of a 'sima-calcareous pair'.

More uncommon sediments, generally of organic origin—such as deposits of iron, manganese or phosphate of lime—present more diversified products of metamorphism (Plate II).

THE BEHAVIOUR OF THE BASE[1]

During the evolution of a geosyncline, the base does not always remain inactive. Its rigidity and its tendency towards uplift are not enough to prevent it from being, in part at least, carried down (with its sediments) to depths where it may be subjected once again to metamorphism and anatexis. Such depths as these form part of the domain of the *Infrastructure*.[2] We should, however, note that the base probably plays a part which may

[1] *Socle* in the French version.—ED.

[2] G. E. Wegmann: *Ueber einige Fragen der Tiefentektonik*. Geol. Rundschau, XXVI, No. 6, 1935, p. 448.

be likened to that of a screen for metamorphism. This may be deduced from the transformation of the sediments of the fore-trough which lie on the base, but it is a transformation much less marked than that of the main-trough though it is possible that the sediments do not descend to like depths in the two cases.

Again, the fragments of the base which are situated at the boundary of the two troughs are rigid and stable, thus differing from the material of the two troughs, and make up the geanticline. When they have been subjected to sufficient down-thrust they are also affected by this new metamorphism, while frictions develop on their walls in consequence of movements in oppsite directions undergone by the troughs and by the fragments.

Such phenomena are, no doubt, the cause of the volcanism and the marked seismicity of geanticlinal zones. This volcanism, indeed, differs from the sima volcanism (such as is to be observed in the central Pacific or, again, in the main trough of a geosyncline) by the explosive nature of its manifestations and by the composition of its lavas among the most common of which are andesites, rocks of a chemical composition intermediate between that of the basalts and the granites. This is the type of volcanism which is to be found today on the periphery of the Pacific and in those volcanoes which belong to the so-called 'belt of fire'.

MOVEMENTS IN AN OROGEN

The occurrence of geanticlinal volcanism often coincides with the first orogenic movements which precede the uplift of mountains. As there may be several different zones dotted over the base, so several geanticlinal phases may take place.

It may also be noted that the theatre of the first disturbance is often that of the vast area represented by the foreland, which is subjected to apparently vertical movements.[1] The preliminary phases are localized in the crystalline base of the geanticline (as in the Alps and the Carpathians) and also in the foreland (*e.g.*, Trysil movements on the margin of the Scandinavian mountains). The deformations of the base, or deep folds, which affect much greater masses than do the deformations of the orogens, are due either to vertical movements confined, as we have seen, to continents (and called, for this reason, 'epeirogenic' movements) or, as Argand thinks[2] to tangential movements with a great radius of curvature. The effects are severe when this radius becomes comparable with that of the earth.

It would seem, then, that epeirogenic movements have some influence upon orogenic movements. This may be so, but it is only a hypothesis. Perhaps we might go still farther and say that the former movements provoke the latter, and in so doing attribute to one and the same cause what we have distinguished as vertical and tangential movements.

Indeed, it seems true that the type of movement varies with that of the material involved. The base, which is rigid, rises or sinks as a block, and when the thrusts exerted upon it are unequal it tends to break up and form depressed compartments, or troughs, and uplifted compartments or horsts. These are the conditions of *fracture tectonics*. The sediments deposited on either the foreland or in the orogens, as long as they remain unchanged, keep a general character of plasticity. The limestones and lavas, however, which are the most rigid elements in the sediments, are liable to undergo slightly different reactions under the stress of mechanical action. Taken as a whole, these sediments may be regarded as forming what is known as a flexible cover. Their original plasticity (which is apparent from the form and shape

[1] P. Fallot: *Correlations orogéniques des chaînes marocaines*. C.R. Acad. Sc. Vol. CCXII, pp. 556–8, 648–50, 708–10, 995–7.

[2] Argand: *La Tectonique de l'Asie*. C. R. XIII. Congr. Geol. Internat. 1922.

of the folding) lasts for a far greater period of time than would allow of human observation.[1] We may, indeed, say that during the millions of years that it takes for a mountain-chain to be erected, the sediments are in a fluid state. The main factor (beyond movements of the base or deep folding) for producing *flow tectonics* appears, then, to be simply gravity, by which are communicated to the materials the differences of level produced by epeirogenic uplift and depression.

These movements of flow, which may be encouraged by the continued deposit of sediments, are stimulated by deep-seated movements and are, moreover, facilitated by the existence of plastic layers which form sliding surfaces. The Apennines (Map 3, p. 84) seem, certainly, to have been formed by the sliding movement of certain argillaceous beds (*scaglia* clays). In the Alps, rocks of but little cohesion, such as *flysch*, may have begun to slip after having been raised to great heights and then inclined at a sufficiently steep slope. The Triassic clays and saliferous strata represent the most plastic and lubricant levels we know of. Their condition is due, in part, to the phenomenon of defloculation—that is, the return to a dispersed state of the micelles of a colloidal gel. Such a series occurs in several Alpine regions. It is easy to understand, therefore, that it played an important part in the formation of several nappes.

There is, nowadays, a tendency to contrast the tectonics of the base with the tectonics of the cover, rather than to distinguish between vertical and tangential movements.

If, now, we turn to consider the very deep zones, that is to say, the infrastructure, we find that their plasticity is increased by the temperature and the high pressures there obtaining. These favour homogenization to a point where the original structure of the sediments disappears. The materials made up

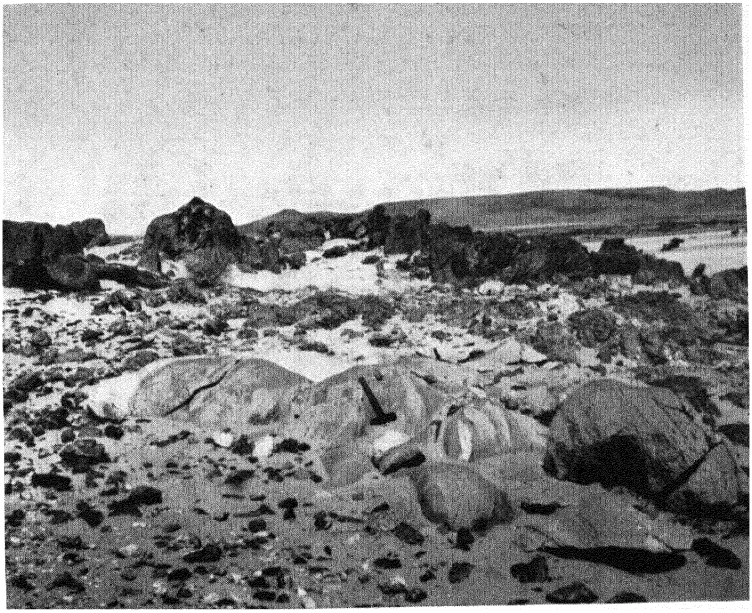
[1] *Vide*: M. Gigoux: *La tectonique d'écoulement par gravité et la structure des Alpes*: Bull. Soc. Geol. France, 5th series, Vol. XVIII, 1948, pp. 739–61.

of granites (and even of rocks of the catazone) can undergo *rheomorphization* (*i.e.*, take on a more or less fluid state) and then make their way into fissures and thus give rise to veins, loads and apophyses. But for any fissure to be produced, we must assume that movements have first occurred. At these great depths, where the base loses its rigid and stable character, it does not seem very likely that vertical movements are alone responsible for the uprising of the eruptive rocks. We are rather tempted to assume that there must occur tangential movements capable of enucleating plastic or more or less fluid masses, such movements being possibly due to a contraction of the orogenic axis occasioned by a contraction of the earth.

But, however this may be, the occurrence of movements in the highly metamorphic infrastructure has, as a consequence, a tendency for the sial to increase its domain in a vertical direction.

MIGMATIZATION

After the formation of anatexic granite by ultra-metamorphism, the upward thrust of the sial is evidenced by an extrusion of light matter towards the surface. This is, in character, essentially quartzo-feldspathic and penetrates into the crystalline schists in the form of anastomosed or parallel small veins (Plate VIII), even as isolated crystals. This process of emission is arrested at variable heights in the complex of metamorphic zones within which the light matter constitutes mixed rocks or migmatites. In any one of these rocks there may be distinguished two component parts, the matrix formed of crystalline schists, and the adventitious material made up of quartzo-feldspathic components. How this material is incorporated into the mass of crystalline schist is not certain. The proximity of the granite suggests injections of liquid matter from this rock, but judging

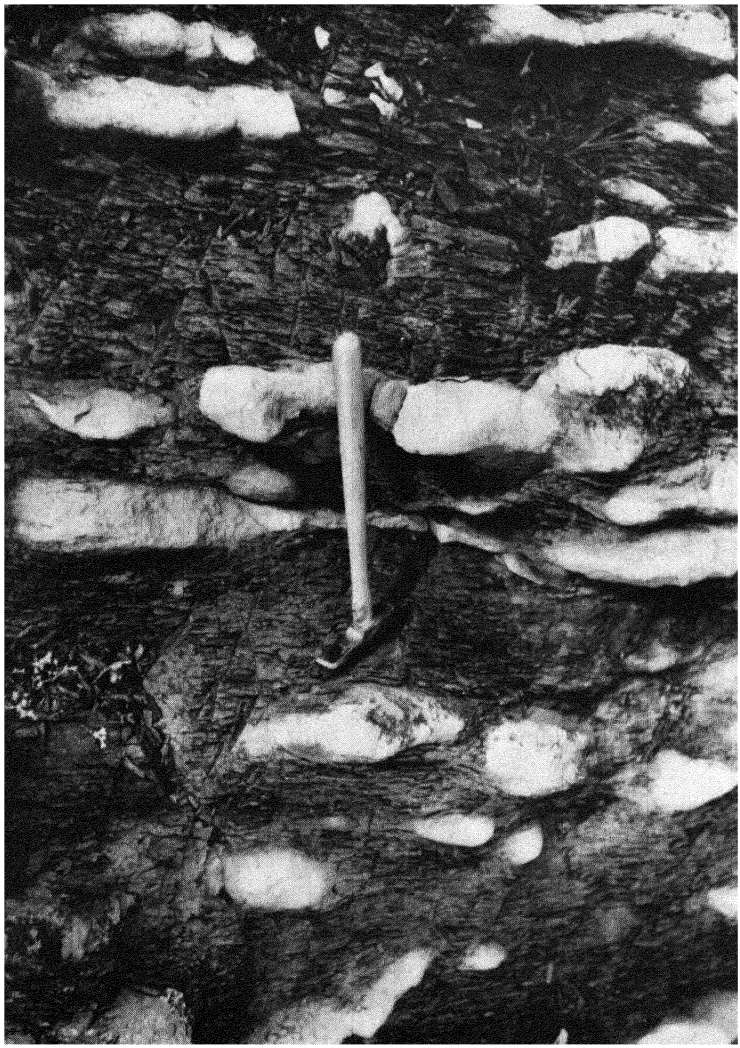


G. Termier

Plate IV. Outcrop of Pre-Cambrian migmatitic gneiss (Suggarian) near Tamanrasset, Ahaggar, central Sahara. In the foreground can be seen a lenticle of light-grey cipolin marble which is an ancient limestone that has been recrystallized by metamorphism. The gneisses and the cipolins represent two sedimentary facies which have been subjected to regional metamorphism. On the horizon, behind the Tamanrasset Plain, can be seen great volcanic table-mountains ('plateau volcanism')

G. Termier

Plate v. Detail of Pre-Cambrian gneiss at Rognstrand, northern Norway. These are amphibole-gneisses containing lenses of garnet-rock. Comparing this photograph with that opposite, we are strongly inclined to think that the original rocks from which these gneisses were derived were shales with calcareous nodules, certainly different in composition from those of Ashgill (*opposite*) but displaying nevertheless a similar type of sedimentation



G. Termier

Plate VI. Detail of the sedimentation in the Upper Ordovician (Ashgill) of Rauholmen, Oslo Fjord, Norway. The shales alternate with lines of fossiliferous limestone nodules

G. Termier

Plate VII. 'Horse-tooth' granite, Margeride, Allier Gorges, France, the intrusion of which occurred after the pre-Stephanian folding in the Massif Central. The rock is a porphyritic granite, the large white crystals of which are of microperthitic orthoclase

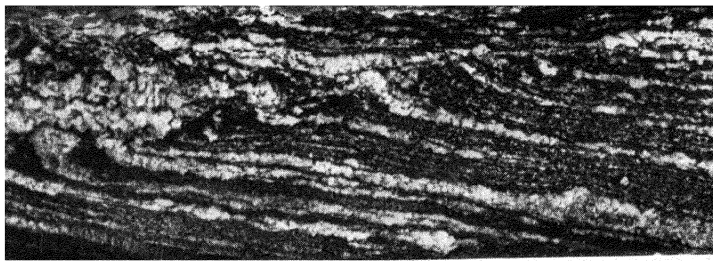


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Plate VIII. Detail of a *lit-par-lit* injection gneiss from the Pre-Cambrian (Suggarian) of Tamanrasset, Ahaggar, central Sahara. The photograph brings out clearly the dark schistose layers and the quartzo-feldspathic beds which separate them. The latter, which present bulges in the form of 'eyes', seem to have issued from the zones to the left of the photograph

from the disposition of the different sorts of migmatites, one is inclined to conclude that the most deeply situated of these receive the quartzo-feldspathic elements by diffusion. We may remark that these elements come from granite, but that they do not contain the dark and heavy components. The quartzo-feldspathic contribution, then, is the result of a selective process, since the elements which are displaced (the lightest in both colour and weight) are more easily made mobile than the others. We may, then, consider migmatites as the products of a metamorphism augmented by additions; that is to say, of *metasomatism*. The external envelope of the migmatites in the crystalline schists constitutes what is known as the *migmatitic front*.

BASIC FRONTS, SERPENTINE BELTS AND ZONES OF POSITIVE ANOMALY

The study of regional metamorphism resulting in granitization shows us that at certain levels in the lower regions of the catazone the crystalline schists are enriched with minerals containing calcium, iron and magnesium (known collectively as the *cafemic* elements), such as cordierite, garnets, amphiboles, pyroxenes and biotite. To such a zone has been given the name of the *basic front*. The most reasonable hypothesis to account for this phenomenon is that these cafemic elements are eliminated under the influence of ultrametamorphism, probably in the form of ions, so that the granite gains in purity. The facts we have just described, however, seem to be in contradiction with the tendency of ferro-magnesian elements to move downwards under the influence of gravity. Therefore, all the extrapolations of, and deductions from, the concept of the basic front must be subjected to a very close critical scrutiny.

We may now leave the domain of metamorphism, properly

speaking, and return to the sima volcanism of the geosynclines (ophiolitic volcanism). As we have seen, such volcanism occurs especially in zones of thick sedimentation where regional metamorphism takes place. Right at the beginning of the uplift of a mountain-chain (and often indeed both before and after the uplift) there occurs the placing in position, under a cover, of great masses of basic rocks. These are, indeed, of a composition comparable with that of basalt, but since they have not reached the surface they have cooled more slowly and have taken on a so-called 'granular' texture. Such rocks are generally gabbros (or coarse-grained basalts) but sometimes they contain such quantities of particular minerals that they are given special names—peridotites, pyroxenites, hornblendites, etc.—and comprise the group of ultrabasic rocks. Many of them have been altered during orogenetic movements into masses of a hydrated mineral known as serpentine. Such basaltic blocks (which are by no means all of equal age) are, however, to be found approximately aligned along the axis of the mountain-chain in formation, and they constitute what is called a *serpentine belt.*

The origin of these serpentine belts is very little understood, though they provide in each mountain-chain a mineralized zone containing either such metals as chromium, platinum or nickel, or useful minerals like talc. Their position in the main trough (rich in sima lavas) would lead us to associate them with ophiolitic volcanism and to consider each complex as a source from which lava flows. However, the formation of these belts is often later than such extrusions of lava and, moreover, the distribution of the belts is more localized than that of the lavas. For these reasons the theory has been advanced that the belts are linked with the basic front, the existence of which, as we have just seen, is due to the displacement of heavy elements either laterally or upwards, contrary to the law of gravity. Now, the ultrabasic masses of blocks remain always in disequilibrium

(positive gravimetric anomaly)[1]; the components of the serpentine belts constitute, therefore, areas of positive anomaly. The Cortland ultrabasic complex, a portion of the serpentine belt in the Appalachians, has been the subject of extensive study in this sense.[2]

In this connection we may remark that there exist gravimetrical anomalies in the orogenic zones. Along the main axes of the East Indies and along those of the Antilles (which, among the regions of present-day geography, exhibit conditions that are closest to those of the geosynclines) there have been observed both a zone of positive anomaly and one of negative anomaly. Moreover, negative anomaly is not infrequently found in chains of the more recent mountains, especially in areas where sial predominates. Thus, it would seem that we are justified in thinking that in an orogen the serpentine belt corresponds to a zone of positive anomaly.

A NOTE ON DIAPIRS

The upward thrust of sial is perhaps 'touched off' by tangential movements, nevertheless, one of its principal causes appears to be a certain sort of vertical movement to which the name of *diapirism* has been given.

The term *diapir* has been coined to designate structures which are common where a layer rich in *evaporites*, such as salt

[1] 'That condition of equilibrium to which a planetary body tends whether it is homogeneous or not' (Dutton, 1889) is called *isotasy*. Now, as the earth is heterogeneous, the relief of its surface (mountains) corresponds to the zones of lesser gravitational pull (negative anomalies) and the hollows of the earth's surface (oceans and troughs) to zones of increased gravitational pull (positive anomalies). Thus, very probably, the intensity of the gravitational field is uniform at a level of constant depth, called the *compensation surface*, so that 'the mass situated above two equal areas of this surface is always the same' (J. Coulomb). It is estimated that the mean depth of the compensation surface is about 18 miles.

[2] N. C. Steeland and G. P. Woolard: *Gravity and Magnetic Investigation of the Structure of the Cortland Complex, New York*. Geol. Soc. Amer. Bull., Vol. LXIII, No. 11, 1952, pp. 1075–1104.

and gypsum, is found beneath a thickness of sediments of normal type, such as clays, marls, schists, sandstones and limestones. The evaporites, being of less density than the neighbouring rocks, show a tendency to rise, and this is apparent even in unfolded areas when the saline mass attains a certain volume. Thus is formed a salt-dome whose upward thrust ends by bursting through the overlying sedimentary rocks (Plate x). Moreover, in mountainous regions, the pressures exerted by folding favour diapirism and, indeed, enable it to occur with smaller volumes of salt. In these cases, the diapir assumes the form of a sheet. The phenomenon of diapirism (which is due to differences in density) is encouraged by the plasticity of salt, which is, generally speaking, comparable with that of ice.

THE PLACING OF GRANITES

In the heart of more basic rocks, the sial, less heavy and rendered plastic by the high temperatures prevailing at great depths, behaves in much the same manner as salt; that is to say, it tends to rise. Most of the granites which outcrop at the surface are not anatexic, or formed *in situ* at the base of a complete succession making up a regional metamorphism. They have been *emplaced* in the highest zones, after having forced their way up through the migmatic mass (Plate ix).

We have seen that the serpentine belt corresponds approximately with the area of maximum deformation of the orogen, and thus to a zone of positive anomaly. Such conditions are eminently favourable for granitic diapirism. Within the anatexic granite, there becomes manifest a more homogeneous material, which, still granodioritic in character, is distinctly less heavy than the basic and ultrabasic rocks of the serpentine belt, and even than the anatexic granite. This individualization or differentiation is effected by means of which we have no certain

knowledge, but probably in several different ways, such as by diffusion in a solid, liquid or viscous state, or the concentration of gaseous phases. The upward movement of this lighter material coincides with the first real foldings of the geosyncline; that is to say, with the actual birth of the mountain-chain. Therefore, the material is called *synorogenetic granite*. Such granites constitute deep, elongated masses or blocks which follow the axis of the folds.

After this first folding, which affected a new and still plastic material, the latter hardens and becomes brittle and later movements of the chain gradually assume the characteristics of fracture tectonics, at least as regards structural details and those of the general subsidences and uplifts. The granites continue to rise. Indeed, on the site of earlier massifs or blocks, a still purer material is differentiated, one lighter in weight, rich in potassic feldspars and pink or red in colour. This forces its way through the earlier granites, rises higher than they and cuts through the folds. Since this material is later in date than the orogeny, it is called *post-tectonic* granite. Because it pierces the different layers with irresistible force and often presents a circular contour or outline it is also called *circumscribed granite* (Plates IX and XII).

After this, the diapir uprise of the granites approaches its limit. The density of the later granites is, indeed, not markedly different from that of the sediments they have to encounter. The density of pure limestone is about 2·7, that of argillaceous limestones 2·5, and that of dolomitic limestones reaches 2·9, while that of typical granite is, on an average, 2·67, though it may vary between 2·59 and 2·73.

But those granites which have risen highest present new peculiarities. They are composed of lighter and more volatile materials, which were concentrated at very great depths or borrowed from the rocks traversed and partly digested, as may occur with fluorine, boron and the alkaline metals, water vapour and carbon dioxide. These granites are, moreover, in an

increasingly marked state of thermal disequilibrium with the rocks that enclose them. As the temperature is not sufficiently high to provoke metamorphism, this disequilibrium manifests itself principally by diminishing exchanges between the granite masses and their surroundings. The intrusive block becomes practically a closed system in which the volatile components create conditions that foster fusion. The granite passes insensibly into less crystalline rocks (microgranites) and lavas (rhyolites). The accumulation of gaseous elements, produced while the fracture tectonics continue, causes explosions whose expansion provides an outlet for those lavas which have arrived near the surface. The effects of such explosions may be seen in concentric fractures from whose centre there radiate other fractions; some of the former are often filled with a light granitic material which thus forms a kind of annular wall, more or less complete —a formation to which the name of *ring-dyke* has been given.

EXCHANGES OF MATTER DURING THE DRAMAS

We have seen that zones of equilibrium in regional metamorphism can be established only because of certain ionic 'migrations'. The placing of the different granites by upward thrusts through the mass of subjacent rocks induces further exchanges and further states of disequilibrium, at least so long as the granites remain in the zones of metamorphism. It is, therefore, the geochemical phase of a drama that we must now examine. Since this phase is conditioned as much by the nature of the sediments as by that of the granites, and since, also, this geochemical phase appears to form a rather regular succession, we must again consider and examine the chemical nature of the sediments deposited in an orogen.

The initial products of a continental dismantlement are, speaking generally, arkoses; that is to say, feldspathic sand-

stones which present a composition rather close to that of the different granites. In particular, after the final formation of a mountain-chain, these arkoses form the first members of a detrital series, of more or less small grain, to which the name of *molasse* is given (Plate XXVII). On the edge of an area which is, to all intents and purposes, abraded right down—and often indeed over a very considerable extent of country—there are deposited lagoon sediments which are composed, very largely, of evaporites like salt and gypsum. To such deposits are added lavas, to which we shall have occasion to refer again under the name of 'plateau lavas', of basic, alkaline and acid types. It is important to bear in mind that the site of an orogen is, in part, that of the ruins of a more ancient chain, for this assemblage of arkoses, molasses, evaporites and lavas (on to which the geosynclinal sediments and ophiolitic lavas are laid down) is one of the first areas to undergo regional metamorphism.

We have already seen that evaporites are not stable in conditions of regional metamorphism, and that spilites are lavas especially rich in lime and soda. Now, one of the elements most in evidence during the initial phases of a drama is, in fact, *sodium*, often accompanied by calcium. The feldspars of the synorogenic granites and of the associated crystalline schists are often albite (soda) and oligoclase (soda-lime). To describe these geochemical phenomena which accompany the uprise of the first granites in a drama, the expression *albite front* is often employed.

We have noted that the later granites which are post-orogenic often contain microcline feldspar. They are also rich in *potash* which is present both in the microcline and in the micas, including biotite. We may, therefore, conclude that, among the alkaline elements, potassium rises more easily than sodium.

It is in the granites, and especially the circumscribed granites taken as a whole, that we may observe the commencement of

fluorine and boron condensation. Chlorine, however, does not appear in any great quantity; it is found associated especially with hydroxyl in the system of the amphiboles. Fluorine is an essential constituent of fluor and topaz. Boron also is present in the greatest quantity when tourmaline is abundant. According to the classical view those anions which (in common with water and the alkalis) are called 'mineralizers' and which are chemically active, come from granite at great depths. In reality, however, there is every reason to think that these are, for the most part, exuded from the sediments containing them when these sediments are attacked chemically. In any case, this latter view is undoubtedly well founded in the case of boron, which is present in greater quantities in fine-grained, silico-aluminous, marine sediments than in granites.[1]

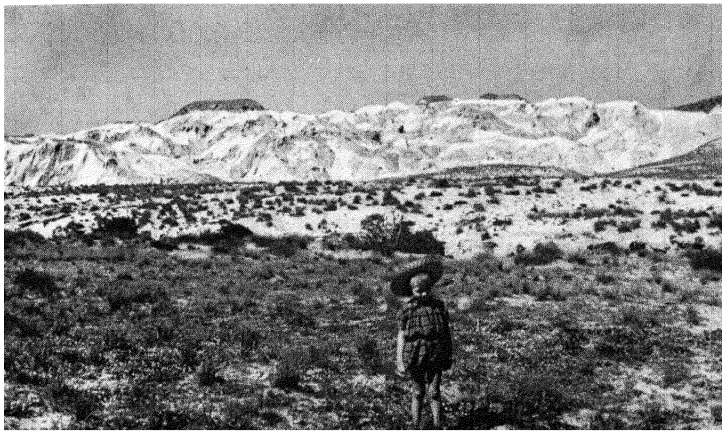
In the alkaline granites, which are the last to be emplaced, fluorine presents its greatest degree of concentration and, when associated with calcium, produces fluor; when associated with other metals it gives the rarer fluorides and silicates. We can, in this case, talk of a *fluorine front.*

From the geochemical point of view the drama may be regarded as a succession of 'fronts', each characterized by a particular element. The various elements can be enumerated thus: (1) sodium, (2) potassium, (3) boron, (4) fluorine. These various elements seem to be furnished to a great extent by detrital and continental sedimentation on the one hand, and by marine sedimentation on the other. Finally, we should not neglect the volcanic flows whose composition is very different and whose weight and volume (often very considerable) may furnish, in fairly large quantities, chemical components for the process of metasomatism.

[1] S. Landergren: *Contribution to the Geochemistry of Boron.* Arkic f. Kemi., Min., och Geol., Vol. XIX A, Nos. 25 and 26, 1945.

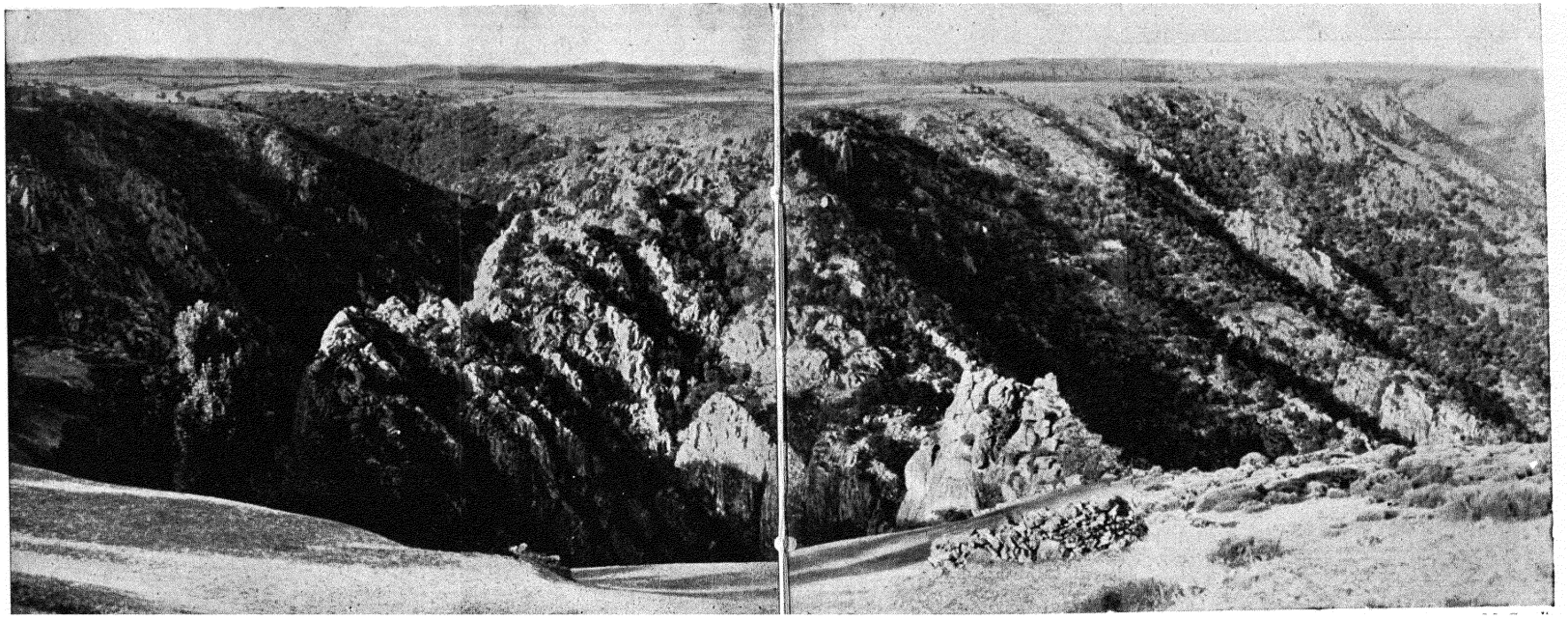
M Casalis

Plate IX. Post-tectonic granite (Pharusian) forming a serrated ridge directed from east to west, at In Eker, central Sahara. The granite cuts through the dark beds of schistose rhyolites that follow a north-south direction. Note the dome-shaped outline of this type of granite mass, an outline that is accentuated by erosion. The uplift of this kind of granite is thought to be due to diapirism of a kind analogous to that of salt, but effected at much higher temperatures and over a far longer period of time



G Termier

Plate X. Salt-dome at Hadjer-el-Mellah, north of Djelfa, Algeria. This 'mountain of salt' rises from among darker rocks, fragments of which appear on its top. The foreground scenery is typical of the Algerian high plateaux. We may note that as salt is a highly soluble substance, its rapid erosion must be compensated by the continuous uplift that is still going on



M. Casalis

Plate XI. The Gorges of the Chassezac Below the horizontal peneplain of Triassic age, which marks the site of the worn-down Hercynian mountain-chain, we can see the granites and granulites of Mt. Lozère, which are of Carboniferous age and equivalent to the Margeride granite. These granites have been cut by numerous faults, the largest of which is that of Villefort, which forms the axis of a dislocation running in a north-south direction for more than ten kilometres between the rocks on either side The photograph shows several fractures parallel with the main fault. The first ruptures were produced during the phase of 'fracture tectonics' which ended the Hercynian drama, but these ruptures left cracks along which renewed movement took place during Tertiary times. The fracturing of the Massif Central dates from the end of the Hercynian orogeny. It may be noted that a great fault is very rarely an isolated phenomenon and that, in most cases, there are multiple fractures of the kind exhibited so clearly in this photograph

M Casalis

Plate XII. Granites at Intoumine, Ahaggar. In the foreground the most recent granite (Pharusian) is in the form of a dome or cupola due to its peculiar structure, which is emphasized by the mode of erosion. In the background, more ancient granite (Suggarian) is intersected by the Pharusian granite. The Suggarian granite is migmatitic and more resistant to erosion

Now that we have placed in time the principal petrogenetic materials of the drama and of their granitization, we may return to a study of the geanticline, which is largely composed of those fragments of the base that are subject to up-thrust. The material which composes a geanticline is fundamentally of a sialic nature and it receives a much smaller contribution of sediments (which are also generally more calcareous) than do the troughs of the geosyncline. However, during the paroxysm of orogenesis the frictions developed and the movements described by a geanticline lead to contacts with the more recent, but nevertheless indurated, materials of the new mountain-chain. At the same time, basic rocks insinuate themselves through fissures, or they may be formed on the spot as a result of added metamorphosing material. No more than this is needed to induce either a new diapirism of the sial rocks of this base, or an afflux of lighter components which become diffused along the great ruptures. Often, when this happens, the matter composing the base is stimulated to new activity, or is—as we say—reactivated. In such a manner were produced the strings of tonalite, adamellite, and monzonite at the junction of the Alps and the Dinaric Alps, and no doubt also the banatites of the Carpathians and the granular rocks of the massifs in the Tertiary formations of Algeria.

In one and the same mountain-chain we can, then, distinguish two formations of granites, though these may be of the same age: the new granites deriving from anatexic granite in the main trough, and reactivated granites deriving from the base and associated with great rifts or faults. In Morocco, the Tichkas massif (Plates XV and XIX) situated on the Pre-Cambrian foreland of the Maghreb orogen, has a metasomatic origin comparable with that of the second of the above two classes of granites.

A difference of thermic and chemical potential is established by the emplacement of a granite mass (whatever its origin) in rocks which have been little if at all transformed in the upper zones of the lithosphere. From such a difference in potential a peculiar kind of metamorphism known as contact metamorphism results.

Such metamorphism is produced, essentially, by the proximity of heat which so raises the temperature of the sedimentary rocks that they develop phyllitic minerals and silicates of alumina, especially andalusite. In the sediments, the rise in temperature induces the same phenomena of loss of water as in regional metamorphism. Nevertheless, as the action of a granite mass is not only rather less great, but also—and this is more important—shorter in duration, than the action of regional metamorphism, the effects of contact metamorphism are much weaker and less extensive; indeed, the aureole they form around the granite mass does not exceed a few hundred yards in width. In theory, it would seem that all the minerals of regional metamorphism should occur in these restricted aureoles, arranged in more or less the same order. However, certain of them such as the garnet pyrope and the amphibole anthophyllite, which are not stable in the presence of an excess of water vapour, undergo decomposition. Furthermore, disthene (kyanite) is very common in regions of high pressure but is not met with in contact metamorphism.

Water and other mineralizing agents, such as boron, which may occur in the sediments themselves and become concentrated there by diffusion, as well as those elements which come from granites, such as those of the feldspars, induce the formation of various minerals in this metamorphism of the highest regions of the lithosphere.

We have seen that the anatexic granites form around them a ring or aureole of migmatites composed, essentially, of light quartzo-feldspathic material. It is not impossible that certain masses of diapric granite may also present fringes of migmatite, but in the upper zones of the orogen the quartzo-feldspathic material is almost exclusively located in the granite pegmatites. These are worth our attention for several reasons. They concentrate rare minerals of the granite series, especially radioactive substances, the rare earths and the compounds of tantalum, lithium and strontium, and these may be present in veins of quartz with cassiterite and wolfram. The high percentage of radioactive substances in the pegmatites has made these latter a favourite material for a determination of absolute age. Pegmatites, moreover, have provided the largest crystals in the world; some of the prisms of spondumene exceed fourteen yards in length, while some sheets of mica have a diameter of as much as three and a quarter yards.

It was for long thought that pegmatites were derived directly from granites (by magmatic differentiation) and were always associated with them. It has now been realized that a certain number of pegmatites have no connection at all with granite masses, and that the former (no doubt through the agency of faults) are formed *in situ* within certain rocks; such as beds of quartzites or limestones, or in blocks of eruptive rocks, *i.e.*, rocks which they have in part replaced, the composition of their minerals depending upon the surroundings in which they are produced.

Another peculiar feature of the pegmatites is their evolution. They by no means remain unchanged from the time of their first formation, but exhibit migrations of matter (ionic, gaseous, or hydrothermal) which modify their mineralogical

equilibrium, their primary minerals being replaced by others, which, in their turn, may also be destroyed or replaced.

These rocks (which, however, are not the only ones to behave in this fashion) display further peculiar associations which may be considered either as syncrystallizations or as actual transpirations or exudations from one mineral to another (exsolution)—or, yet again, as due to partial substitutions. Such is the case with 'graphic pegmatite', which consists of continuously crystalline orthoclase feldspar enclosing in its substance wedge-shaped fragments of quartz. On a polished surface these appear as isolated bodies embedded in a matrix which is, to all intents and purposes, a single crystal. A similar phenomenon may be seen in perthite, in which a crystal of microcline feldspar is striped with albite. We shall return later on to the subject of perthite.

SOME ACCIDENTS IN THE DRAMA

We have seen that the drama, its granites and corollary phenomena, develop in a relatively simple manner, and that in normal cases the development is almost predictable. However, in certain regions where many orogens have occurred, there may be observed complications or 'accidental' phenomena—accidental, at least, so far as their situation is concerned—and these cause rather different evolutionary processes from the normal. We give below descriptions of two of these accidental types, that of the charnockites and that of the perthitized granites.

Charnockites

The charnockites were for long regarded as aberrant and susceptible of no classification. They are rocks whose composition varies continuously from that of granite to that of the

gabbros and is characterized by the presence of hypersthenic pyroxene, (Mg. Fe) SiO_3, with (in the most acid types) quartz made opalescent and bluish in colour by the presence of rutile, and also containing orthoclase, garnet and graphite. Rocks of this type are common in India in the mountain chain of the Eastern Ghats. Since the tomb of Charnock, the founder of Calcutta, was made of this material, his name was given to it. Most of the charnockites are of Pre-Cambrian age, but they may occur in all the shields. They also probably exist in the majority of the orogens composing these ancient blocks.

It is now possible, thanks to the numerous and detailed researches which have been conducted into their nature, to form a general idea both of the charnockites and of their composition. We may conclude, indeed, that the charnockites constitute a certain type of mixed rocks differing from the migmatites in both composition and origin. The primary material is, generally speaking, a gneiss of sedimentary and eruptive origin, or a migmatite, and therefore belongs to the deep parts of the metamorphic zones. The gneisses have been cut through by veins of basic rocks (more or less resembling basalt) which seem to have taken up their position after the first phase of the uplift of a mountain-chain. It is this assemblage of gneisses and basic rocks that becomes transformed into charnockites. These retain approximately the relative positions of the gneisses and veins of basic rocks, as well as exhibiting a marked schistosity, but they also acquire catazone characteristics and even those of ultrametamorphism, with a possibility of mobilization. The minerals composing the charnockites undergo a special kind of selection which differs from that in the metasomatisms we have already dealt with. Most of the minerals with a hydroxyl group disappear; the amphiboles as well as the micas are transformed into hypersthene; furthermore the olivines (which are anhydrous) seem finally

to undergo the same fate. We can, then, refer primarily to a metasomatism through loss of water, or 'dry metasomatism'. Moreover, it would appear that exchanges by ionic diffusion are produced between the basic rocks (which become basic charnockites) and the gneisses which give rise to acid charnockites. The former supply magnesium to the latter and receive silica from them.

What is the source of energy that is responsible for the formation of the charnockites? It would appear that during the uplift of a mountain-chain the rocks which produce the charnockites are raised with the rest, and that it is during this rise that they are traversed by basic veins which, at the surface, may appear as lava flows. But before the tectonic phases occur movements of subsidence take place in most of the orogens, these subsidences being locally marked by marine invasions. Thus it is easy to see that in some cases real collapse may be produced, and that a part of the gneiss is suddenly thrust down into catazonal regions sufficiently deep for the production in them of ultrametamorphic types of rock.

Perthitized Granites

In the last tectonic phases, and even later than the movements properly associated with the mountain-chain, large fractures, often transverse to the direction of the folds, give rise to faulted and crushed areas. Large-scale sagging sometimes produces conditions of regional metamorphism in these zones, although they are less marked than those in the catazone. When gneisses, granites and even charnockites have been reduced to a mass of crushed constituents (called a *mylonite*; that is, a microbreccia of non-rigid composition), they present optimum conditions for undergoing thorough metasomatism. Fissures and intergranular spaces having become very numerous, the surface exposed to attack is, therefore, considerably increased. At least in the case of those granites which originally contained

lime-soda feldspars this metasomatism results in the production of perthite, that is to say crystals of microcline striped with albite.

THE TECTONICS OF THE DRAMA

We have described above the more important cases of petrogenesis which occur during the uplift of a mountain-chain. We must now consider the final sequence of effects when the chain has become incorporated into a continent.

Let us, first of all, examine the way in which folding is produced at certain phases of the drama. We have already drawn a distinction between the various types of materials, both plastic and solid, which are the primary constituents of the base, the infrastructure and the cover. However, an imaginary observer who might, from a helicopter, follow events taking place over a period of millions of years, could see only those tectonic movements which occur in the superficial layers—that is to say, in the cover—for the movements of the base or of the infrastructure would remain hidden until the deformations resulting from them were revealed during the dismantling of the mountain-chain.

If, then, without taking into account the evolution of the rock masses which occur deep down in the earth, we regard only the progress of the foldings, we are at once struck by their unstable character. This is due to two main causes; there is first, the activities of erosion (which may in a few million years abolish all relief that is not maintained by continued rejuvenation) and second, the transference undergone by the zones of folding during the course of ages.

The newer and more plastic their material, the less able are the foldings to endure. Thus, generally speaking, nothing much remains of the embryonic cordilleras produced during geanticlinal stages. The materials of which they are formed are

sediments of little coherence. Both under the sea's level and above it, they are inclined to flow from one height to another, and to form recumbent folds and overthrusts. However, in most cases, such cordilleras leave, as identifiable traces, only the unconformities and identifiable levels produced by their destruction.

In this connection, we may add a few words about the special physical aspects of the sediments in a developing orogeny. Generally speaking, all these sediments are known by the name of *flysch*, although they are far from presenting uniform characteristics. In a geosyncline that is only subsiding, flysch is composed of an extremely monotonous alternation which may still be found today in those parts of the trough which have remained in a static state. But at the level of the cordilleras the flysch represents the sediments of rough seas and is made up of ungraded components which have not been rolled and which include muds, sands, breccias and conglomerates, as well as huge blocks such as are produced by the collapse of cliffs ('Wildflysch').

The real mountains of a young chain are formed on the site of the troughs by an inversion of the relief of the geosyncline. These mountains are generally composed of fairly simple folds, of the sort called 'Appalachian' since the orogenic zone of the Appalachian mountains in North America is celebrated for the fine examples it displays. Such mountains are of materials which are solid enough to resist erosion fairly well. Erosion, however, does occur and gives rise to a coarse detritus which may be regarded as either the first molasses or the last flysches. However, the basins and the inland seas which communicate more or less freely with the open ocean still remain the most favoured sites for the deposit of materials with a tendency to subside, and for temporary transgressions which, in some cases, may occupy the whole region of the chain.

The last tectonic phases are evidenced by fracture-phenomena, and these phases are the most violent for they reflect a

Laboratoire de Géographie Physique

Plate XIII. The San Andreas fault, California. This fault, on which San Francisco is situated, is still active (hence its name of the 'living fault'). Movements along this fault caused the earthquake which destroyed the city in 1906

Plate XIV. Fault known as the *Bordière occidentale* of the Limagne, between Clermont-Ferrand and Volvic, Puy-de-Dôme Department, France: air photograph. This fault, which is really a group of parallel fractures about thirty miles long and some three miles wide, was moving in Oligocene times (probably in the Stampian) and was one of those that brought about the collapse of the trough of the central Limagne. Borings at Beaulieu, near Clermont-Ferrand, gave a value of about 5,000 feet for the total vertical throw of this group of step-faults

Photo from l'Institut Géographique National

comparatively sudden isostatic adjustment of the chain. Rifts, together with uplifts and subsidences, are produced even in the material of the cover, which has often been hardened by folding or by the calcareous layers deposited in the last troughs. But at this stage all movement is accentuated. In the areas of the flysches and the molasses (detrital rocks whose accumulation is continuous) the new movements of the cover occasion differences in level favourable for the development of flow tectonics on top of the fracture tectonics. Thus are provoked great slides (*'charriages'*) especially when the materials lend themselves readily to such movements. These are the most considerable and the most durable since, after them, the formation of the chain is practically complete. These slides, accompanied by disjunctions, often exert on the foreland an influence as severe as, if not more severe than, on the orogen itself. In this connection, we may mention the Jura Mountains and the Laramide zone of the Rocky Mountains, chains of the cover formed on the foreland of the Alps in the former instance, and on that of the North American Sierra Nevada in the latter.

Last, the completed mountain-chain may be regarded as resembling a pack of cards resting obliquely on the edge of a table which is itself covered with a cloth that the cards crumple a little. Each card in the pack covers the next one. The table is the foreland and the cards are the longitudinal zones of the orogen. We say that each of the component parts overlaps the next, the whole being pushed in the direction of the foreland. The usual construction of a mountain-chain is thus as follows:

The ridges of the fore-trough come straddling horizontally across the folds of the cover of the foreland and then cross the ancient crystalline components of the geanticline. In some places these remain undisturbed but in others they are to some degree carried along with the sediments. Then the whole is capped by the thick series of the main trough, with its regional metamorphism, its (possible) serpentine belt and its anatexic,

synorogenic and postorogenic granites. This complexity of superposition indicates clearly the definite and final stratification of the tectonic phases. As we have already noted for the geosynclinal phases, the tectonic phases spread out like waves from the geanticlinal base and the foreland as far as the main trough.

To sum up in a few words the succession of dislocations occurring in an orogen; we may say that all the deformations which result from subsidence begin in the main trough and that all those due to uplift have their origin either in the foreland or in the fragments of the geanticlinal base. The elaboration of a mountain-chain appears, then, as an interference between waves of subsidence (whose movements resemble those of the ocean) and waves of uplift (which are linked with continental movements). Orogens therefore appear as the result of the nature and disposition of the boundaries between the blocks of sial and the great stretches of sima, boundaries where the tendency of the continents to rise and that of the oceans to subside produces a 'continental flexure'—a *zone où l'enveloppe des continents et du fond des océans change de sens de courbure.*[1]

[1] J. Boucart: *Géographie du fond des mers*, Payot, Paris, 1949, p. 74.

3

THE FRACTURING OF CONTINENTS

WE HAVE just given a detailed description of the evolution and development of an orogen; that is to say, of one of the components which, by progressive assemblage, build up a continent. However, as soon as it is completed an orogen is at once exposed to erosion and becomes covered with molasses. If it were not frequently rejuvenated by epeirogenic movements (like the rest of a continent) it would become a vast peneplain, almost devoid of relief and subject to invasion by the sea, as was a large part of North Africa during the Middle Cretaceous. We have already noted that only a portion of an orogen is utilized by its successor, yet, possibly under the influence of the same movements that cause the formation of a mountain-chain, the continent becomes fissured. This fracturing occurs in ways which we shall attempt to define by choosing some well-known examples. (Plates XI, XIII, XIV, XXII, and Fig. 2.)

THE GREAT AFRICAN RIFTS

If we examine a map, even a small-scale map, of Africa, we notice that there exists a remarkable number of alignments which are marked by lakes, rivers and volcanoes. The largest of the alignments (which is, indeed, twofold) runs approximately from south to north and includes most of the great lakes of

eastern Africa. It is formed by a sunken trough and is bordered by fault zones which begin at Beira on the Mozambique Channel and reach, by way of the Dead Sea, as far north as Syria. That is to say, this great trough gashes the surface of the Old World like an open wound nearly four thousand miles long. To this long trough, and to others like it, the name of 'rift-valley' is given. The great African Rift Valley is of comparatively recent date (see Map 1, page 69). It commenced with abundant outpourings of lava which covered the whole region at the close of Upper Cretaceous times. These were

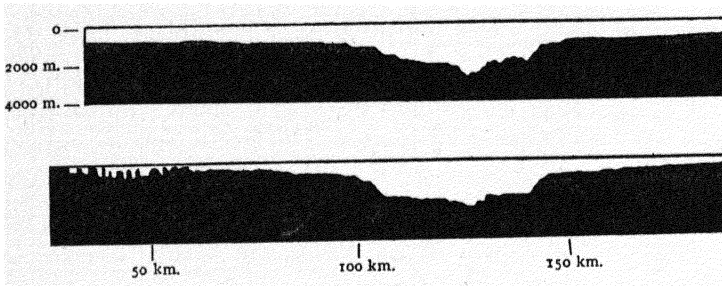
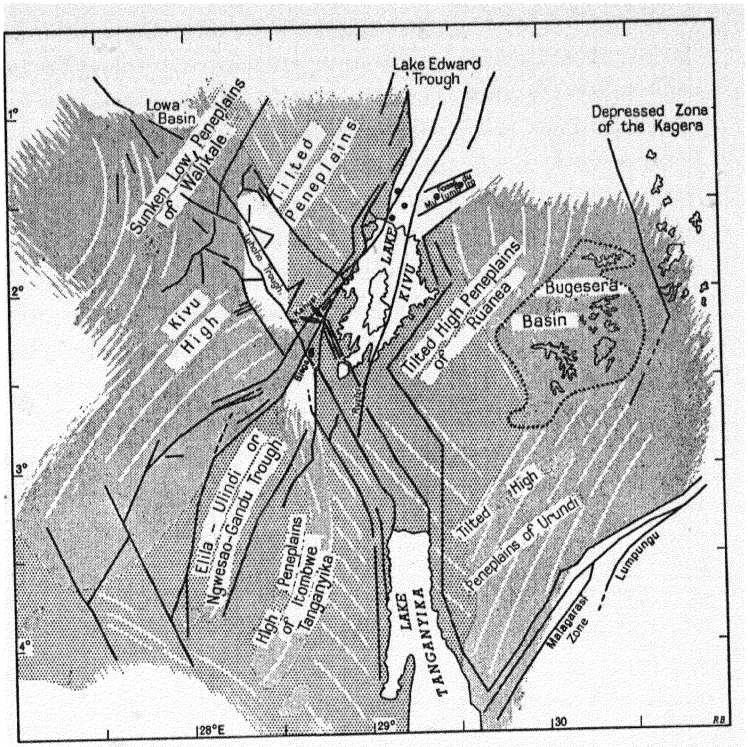


Figure 2. Two sections across the Red Sea, prepared by J. Y. Cousteau, W. Nesteroff and H. Tazieff by means of an ultrasonic sounding apparatus. The first section approximately follows parallel 20° N. and runs eastwards as far as longitude 40° E. The second section, directed east-north-east, is to the south of the first. These profiles are interesting as showing the appearance of a trough of subsidence (Graben). Reef formations can be observed on the lower cross-section

especially marked during the Eocene Period. Then occurred a series of subsidences, one after the other, as we may see from the ancient deposits left by the Great Lakes whose history was exposed during the Quaternary Era. They were accompanied by the birth of volcanoes, some of which date from before the latest faultings, as they may be perched overhanging the perpendicular cliffs, or even cut through by them; others, again, were formed after the faults and are dotted along lines parallel with them. Kilimanjaro, the highest peak on the African



Map 1. The Western Rift-Valley of East Africa, Kivu-Ruanda-Urundi region. *Grey:* the crystalline Pre-Cambrian foundation. *White:* the direction of the Pre-Cambrian folds. *Black lines:* faults and fractures. *Black dots:* Recent volcanism

continent (19,340 feet), belongs to the volcanic phase occurring during the formation of the great East African rifts. The volcanic action has, moreover, continued to the present day.

Other lines of eruptive phenomena, running more or less from north to south, seem to mark out other fractures parallel with the preceding ones, and are approximately of the same age. There is, then, no doubt that Africa, the continent in which occur the most ancient rocks we know of on this earth, is undergoing fracturing. The initial fissuring dates back, indeed, to a very remote past. A huge trough (likewise directed from north to south) cuts through the Ahaggar from one end to the other and it dates back to the Pre-Cambrian. In South Africa there is a great flexure or fold-fault filled with volcanic rocks. This forms the Lebombo range. It is contemporary with the Carboniferous foldings of the Cape and its volcanism is of Liassic age. If these phenomena of rifting foretell the end of a continent, we can see, however, that, in all probability, Africa will not split apart for several tens of millions of years yet. We need not, then, worry much about this eventuality: our other preoccupations are enough for Mankind today.

GRANITIZED FLEXURES

In the heart of the old granitic continental masses, such as China and Indo-China (as well as South Africa, as we have just seen), there are fractured regions which are peculiar in that they contain both old basic lavas and more recent granites. The example offered by the hills to the west of Pekin is particularly striking. In this area there may be seen faults which border a sunken area of the ancient base. Along these faults and flexures (in a wide sense of the term), and in other parts of the area, a granite of Jurassic age has been intruded and this has even produced eruptions of rhyolites at the surface. The collapse of the

trough between sial walls of unequal altitude has, moreover, provoked slipping of the sedimentary cover of Carboniferous and Permo-Triassic age, a movement which is still attested by features of the topographical relief.[1] There seems, then, to be no doubt that the granites emplaced in this way are granites which have been (by the action of fracture tectonics) reactivated in a manner more or less comparable with that which we have already described in connection with the granitization of the base.

SEAS WITHIN THE ISLAND ARCS

After the erection of mountain-chains on the edge of continents, or '*chaines liminaires*' (E. Argand), it would appear that the tensions produced by orogenic movements sometimes produce a certain type of subsidence by which the sinuous chain becomes detached from its foreland. A number of different theories has been advanced to account for such dislocations, and of these Argand's is the best known. Argand thinks that the festoons of islands on the western side of the Pacific are 'stragglers' detached from the mainland of Asia by the profound resistance of the sima and the distension of the sial during the presumed drift of Asia towards the west.

However, if this view finds some support in the example of the Sea of Japan (which is today 9,800 feet deep, whereas at the beginning of the Tertiary its site linked the Japanese arc to the Asiatic continent), it must necessarily apply equally well to more ancient seas, such as the Barents and Kara seas in the north of Europe, which were produced in one and the same way at the end of the Caldonian orogeny, and which have ever since then left the comparable loose festoon of islands of Svalbard (Bear Island and Spitsbergen) and Novaya-Zemlya. In this

[1] P. Teihard de Chardin: *Remarques sur les flexures continentales de Chine*: B.S.G.F. 5th series, Vol. XVI, 1946, pp. 497–502.

case, then, the subsidence would be evidence of a drift of Europe towards the south—a drift, moreover, that is postulated by Argand (independently of the facts just mentioned above) to account for the origin of the Alpine chain.

However, some authorities suppose that the same chains of Pacific islands, with their enclosed seas, are evidence of the contraction of the earth, displaying figures inherent in the geometry of the contraction, for the 'festoons' are disposed along a great circle of the terrestrial globe.[1] According to this hypothesis, the arcs of Caledonian age might be component parts of another geometrical figure due to a contraction effected in more ancient times still.

We would here stress only the fact that the site of these subsidences has always been occupied by more ancient masses making up the foreland of the island chains which have been formed over and upon them. Such masses resemble the nuclei which, as we have seen, are the original components of the Pre-Cambrian shields. For this reason, the enclosed seas of the sort we have just described are sometimes called 'nuclear basins'.

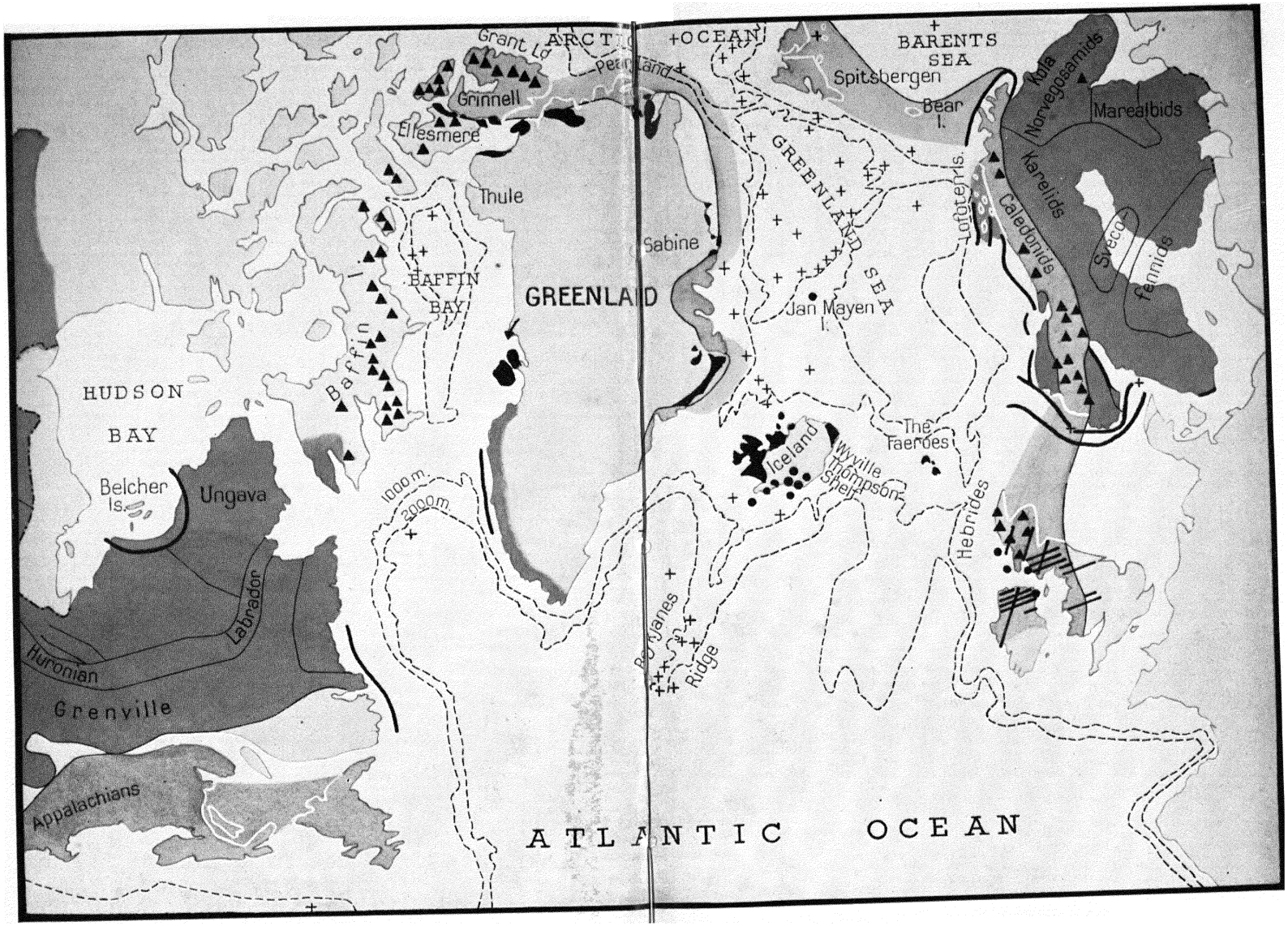
PLATEAU BASALTS

After the termination of the dramas, and at various periods during the history of a continent, there occur volcanic phases of a type very different from those which occur during orogenesis. Through the fissures that split the base and the cover of a continental area there are emitted lavas which are essentially of basaltic composition, very much like those occurring in the central Pacific and particularly in the Hawaii Islands. These are olivine basalts, very fluid, which have, so to speak, seeped upwards through fissures in the sial without forming debris-cones.

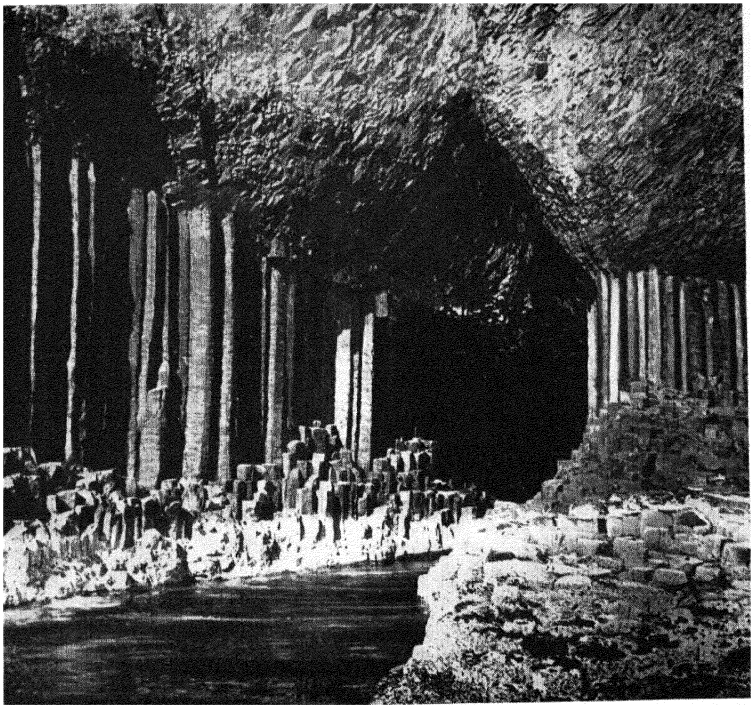
[1] A. E. Scheidegger: *Examination of the Physics of Theories of Orogenesis.* Bull. Geo. Soc. America. Vol. LXIV, No. 2, 1953, pp. 127–150.

G. Termier

Plate XV. Veins of basic lava intersecting fluted limestones of the Lower Cambrian. These veins stand out on the weather-worn surface of the limestone and are made up of lavas which rose through intersecting fissures. Grano-dioritic massif of Tichka, the southern face of the Djebel Aftas, Morocco



Map 2. The Thulean Province (North Atlantic). Note the relative positions of the ancient land areas in the various regions, as well as the absence of recent geosynclines. The latest orogenic movements were Caledonian (Ireland, Scotland, the Scandinavian mountains, Svalbard, western Greenland). Recent vulcanism and present-day seismicity are highly developed at the northern extremity of the mid-Atlantic ridge. It is instructive to compare this map of a region marked by subsidences with Map 3 (subsidence of the Tyrrhenis) and with Maps 4 and 5 (which depict regions in the course of orogenic evolution).
Dark grey: Pre-Cambrian terrains. *Medium grey:* Palaeozoic dramas (Caledonian). *Light grey:* existing outlines of continents. *Black lines:* faults. *Dashes:* isobaths for 3,300 feet and 6,600 feet. *Crosses:* seismic centres. *Triangles:* zones of rejuvenation. *Black circles and black patches:* volcanism in the Thulean province



W Shepherd

Plate XVI. 'Organ-pipe' (columnar) basalt, Fingal's Cave, Staffa, Scotland. This basalt-flow forms part of the extrusions of the Thulean province

The term 'fissure' is applied to this type of volcanicity. These lavas may cover areas of thousands of square miles, pile up to thicknesses of thousands of feet, and overlie preceding formations. These, however, we may often observe owing to recent erosion undergone by the lavas. They fill fissures which often occur in parallel lines, and, when these have become exposed, in the course of time, exhibit what we might call 'fossilized' areas of faulting and constitute 'swarms of dykes'. (Plate XV.) Such lavas also work their way in between the beds of sedimentary strata and form sills. It almost always happens that on recent basaltic plateaux there also appears a more explosive sort of volcanism, giving rise to craters and cones, features which may, in their turn, be submerged beneath new masses of lava. (*Frontispiece.*)

Although these basaltic plateaux often occupy but relatively small areas of the whole extent of any given country (such as the *cheires* of the French Central Massif), yet they sometimes cover vast regions, as in South Africa (where the eruptions were in Liassic times), or as in the Ethiopian regions, farther north in Africa, which were formed at the end of the Cretaceous and the beginning of the Tertiary.

In like manner, in North America, the 'Keweena basalts' (which occur in spectacular outcrops on the peninsula of this name that juts out into Lake Superior from its southern shores date from towards the end of Pre-Cambrian times, and were probably preceded by older emissions in other parts of the Canadian shield. But there are some which are more recent, as, for instance, those occurring on the site of the Laramide chains.

It is, however, probable that in peninsular India (where the so-called 'traps' in the Deccan occupy an immense area—120,000 square miles—and attain, in places, a thickness of 10,000 feet) and in Greenland, we find the greatest thickness and extent of plateau basalts. We shall see later that the basalts of Greenland belong to a vast assemblage, called the 'Thulean

province' which is characterized by comparable successions of lavas of identical age. These cover Iceland, the north of Ireland, Part of Scotland and Spitsbergen. In the area of this assemblage are two sites famed in art and literature: the Giants' Causeway and Fingal's Cave. (Plate XVI and Map 2, between pages 72–3.)

We have dwelt a good deal on the plateau basalts because they draw our attention to a phenomenon which has not, perhaps, received all the attention it deserves. There can be little doubt that Greenland has sagged under the stupendous weight of its volcanic formations. As these basalts are spread over fractured areas, we may well ask whether, during the later stages, the weight of the basalts and the tendency towards subsidence do not combine to cause great slices of continents to be swallowed up in the depths and subject them to invasion by the sea. We shall see later on that such a hypothesis seems to be supported by a number of facts. Indeed, if such processes did occur, then we are led to suppose that for large portions of the continental shields there may be a sort of return to the sima bottom. A similar consideration also arises in connection with each new orogen, since the bottom of the foreland is often covered with plateau lavas during its evolution.

There exist ultrabasic rocks which occur as extrusions through the fissures, and such rocks seem to provide a certain amount of evidence in favour of the views set out above. (Plate XVII.)

PETROGENETIC EVOLUTION OF THE CONTINENTS

We have sketched out, in its main lines, the general evolution of the continents. But now, as for the most deeply situated zones of the orogens, we may inquire what are the interactions between the autochthonous rocks and the new occurrences. Let us, first of all, see what are the factors we have to consider.

The most important are of a mechanical nature, and they are associated with the deep flues that form the major fractures and to a subsidiary extent with the less profound fractures in the continental chains—rents due to posthumous movements of ancient orogens as well as to reactions produced by the erection of new mountain-chains. To these mechanical factors must be added by no means negligible physical agents, such as temperature and pressure, though we are now considering regions comparatively near the surface of the lithosphere. The temperature, which is high in the region of the lava occurrences, does not cause in the immediately neighbouring rocks more than the comparatively slight effects of baking, with a tendency for the sediments (hardly, if at all, modified) to flow and infiltrate into the fissures. In these regions, pressure may be set up by friction between the different component materials, or it may be comparable with that which is produced during the superficial foldings. Such an orientated pressure is a 'stress': that is to say, it is capable of producing a certain schistosity (in one way or another) in relation to the sedimentary bed, and is thus able to disrupt it, but such a stress is very unlikely of itself to cause the appearance of new minerals. The zones of crushing, where rocks are transformed into mylonites (microbreccias with a fluxion texture: *see* Plate XVIII) and other rocks termed cataclastic, also do not enclose any minerals peculiar to them.

The fractures, then, play the part of channels of approach—indeed, of avenues of ascent—which allow the mineralizing agents access to the places where they do their work, namely, to those rocks fit to receive them and in which they constitute fronts. We may see the origin of these mineralizing agents in the materials traversed, whether these be granites, gneisses or sediments. In the case we are considering, however, the processions of migrating substances do not, generally speaking, accompany the upward movement of the granites but rather that of the basalts.

However, to be quite correct, we should here mention once again the reactivated, and even the 'posthumous' granites, belonging to the group of alkaline granites and rhyolites which appear in the final stages of granitization. They are rocks which may continue to settle into place long after the tectonic close of a drama.

We may note, also, the establishment in regions for long deprived of any orogeny of fronts which are potassic or fluoric and strongly radioactive, and these induce, in ancient sedimentary or metamorphic rocks, the appearance of microcline feldspar which often assumes an ovoid form. In this way were produced the *rapakivis*, curious rocks met with in Finland and Sweden, and to be found also in other regions. These rocks present the mineralogical composition of granite but considerably resemble, in their origin, the mixed rocks formed by metasomatism.

However, although it continues to be subjected to the constant influence of the sial, the later petrogenesis of the continents has basalt as its principal agent. This lava, in origin similar to that found in the depths of the oceans, may have to traverse a thickness of from 60,000 to 80,000 metres of sial along fractures which are generally narrow but which may broaden out in some places.

In the most profound depths (and also above them) the basalt exercises an abrasive action on the walls of the passages and they sometimes collapse into it (this is called 'magmatic stoping') so that the rock may sometimes contain portions of sial in the form of inclusions. At the average temperature of the basalt (which is from 1,000° to 12,000°C.) there is bound to be established between these inclusions and the basalt, and even between the basalt and the walls of the passages, exchanges by fusion, by dissolution, or by ionic diffusion. Little by little, the basalt becomes altered or *contaminated*; that is to say, instead of remaining a simple olivine basalt, it takes on a peculiar composition and gives rise to exceptional rocks

containing rare minerals. Thus (to the rather puerile satisfaction of the petrologists) it affords an excuse for the establishment of a great number of new names.

The most common final phases of the plateau series are still, however, basalts, though enriched with alkaline components. As long as their content of silica remains fairly low such formations do not become acid rocks. Their alkalinity is evident in the presence of less limy plagioclases, of feldspathoids closely resembling these, but less rich in silica, or even of potash feldspars. The feldspathoid is nepheline or leucite according to whether it is soda or potash which predominates. Leucite, however, is rare, while effusive rocks with nepheline (such as the phonolites) are very common (Plate xx). We should emphasize that in the lavas containing feldspathoids, the basaltic origin is often indicated by the presence of olivine. If the assimilation of sial is still more pronounced the basalt is transformed into andesite (which is rather uncommon among the plateau rocks) and then, finally, into rhyolite, generally rich in potash. When this latter rock is present in considerable quantities, it is not unlikely that it, also, derives from mobilization of the granitic material.

Apart from the sima matter we must also take into account masses which are properly sial, and their covers. We shall then see that the cessation of tectonic activity appears to be of little importance as far as the geochemical fronts are concerned, since the predominating mineralizing agents remain the same. Thus the assumption that the main sources of these agents lie in the sediments is confirmed.

GRANULAR ROCKS WITH NEPHELINE

Nepheline syenites and nepheline gabbros are met with on continental areas. The main varieties of these rocks are more

often associated with basalts than with nephelinic lavas such as phonolites, but they are also found in association with alkaline fluorous granites comparable with the last granites of the drama.

As these granites are often deposited after the tectonic phases, and since the symptomatic minerals they contain (such as the amphibole riebeckite and the pyroxene aegyrine) are those characteristic of the nepheline syenites, it is fair to assume a relationship between the two petrographic groups. On the other hand, it has often been observed that granular nephelinic rock-types are associated with limestones, and the latter, lacking silica, favour the stability of the feldspathoids.

In Norway, in the rift valley formed at the end of the Primary Era which is now the Oslo Fjord, the nepheline syenites may be seen in the heart of the plateau lavas, which cover ancient sediments that are in part calcareous. (Plate XXI.)

Moreover, we would seem to be justified in assuming a purely metasomatic origin for a number of massifs of nepheline syenite. This may well be the case with the curious formation in Alnö (an island off the coast of the central Swedish province of Medelpad) which occurs in Pre-Cambrian migmatites. Here, chemical transformations seem to have affected a zone which is partially crushed, and (by the action of the temperature and of water driven out from those rocks nearest to the conduction vent) to have given rise progressively to alkaline minerals which bestow a specific character upon mixed rocks, *fenites*, nepheline syenites and gabbros.[1] Dehydration takes places in the central portion of the complex and this results in the hydration of the periphery. The fractures themselves are disposed concentrically around the focus of explosion and are filled with olivine-bearing lavas, not unlike basalt but rich in biotite mica and especially in the carbonates of either lime or magnesium. These

[1] H. von Eckermann: *The Alkaline District of Alnö Island.* Sveriges Geol. Undersökn, Vol. XXXVI, 1948.

aberrant types of rock (which make up the family of the alnöites) are obviously 'contaminated' by limestones, and develop first into true veins of carbonites, poor in silicate minerals, and then into a central mass composed of crystallized calcite and apatite together with various minerals of the nepheline syenites. To these calcareous types, so closely associated with eruptive masses, has been given the name of *carbonatites*. Although their metasomatic origin seems undoubted, they behave quite in the manner of eruptive rocks.

THE CRYSTALLINE ROCKS OF THE CONTINENTAL MOUNTAIN-CHAINS

We have noted above that metasomatism is not arrested by the termination of the tectonic dislocations and, also, that the fluorine front and the alkaline front continue to influence the continental areas. It is not, then, surprising that metasomatic action (exercised through fissures and fractures) may occur in continental mountain-chains which arise from the cover of non-marine basins, outside the orogens. One of the most interesting examples would appear to be that of the Pyrenees, a chain which underwent definite geosynclinal conditions during the Primary Era (when the area formed the southern portion of the main trough of the Hercynian orogen) but which, during the Alpine orogeny, seems to have been a continental chain rejuvenated by deep folding originating in the base. During the Jurassic Period, masses of ultrabasic rocks (known as *lherzolites*) were introduced into the limestones, and these ultrabasic rocks do not seem to be directly connected with the Permo-Triassic lavas, but to have been formed by metamorphism of the dolomitic limestones. Moreover, in this same orographic zone we may observe, in the sedimentary rocks, the crystallization of a rather peculiar mineral—*dipyre*—which is a chlorinated

alumino-silicate of lime and soda. Metasomatizing agents, probably in the form of fumaroles, enriched with chlorine and soda during their passage through rock-salt of Triassic age, seem to be responsible for these crystallizations.[1]

In the great Bushveld complex of South Africa metasomatism by an emanation of the same type transformed a great thickness of sediments of varied composition into rocks which for long were considered to be of magmatic origin.[2]

[1] M. Longchambon: *Contribution á l'ètude du métamorphisme des terrains secondaires dans les Pyrénées orientales et arriégéoises.* Bull. Serv. Carte Geol. France, Vol. XXI, No. 131.

[2] S. Van Biljon: *The Transformation of the Upper Part of the Pretoria Series in the Bushveld Igneous Complex.* Trans. Geol. Soc. South Africa, Vol. LII, 1949–50, pp. 1–176.

4

CONTINENTAL ASSEMBLAGES

IN THE foregoing chapter we have reviewed the various ways in which continental areas increase in size and also break up. We may now consider the general behaviour of such areas. There is, indeed, no theory to invalidate the idea that, if any continental area is susceptible of extending its borders, then there will come a moment when it encounters the zone of expansion of one of its neighbours. It is not necessary to postulate, as is often done, movements as of a whole block, drifting movements by which one continent may be pushed against another, in order to explain that there takes place a confrontation between them or what might be termed a struggle for position.

In fact, in such circumstances the dispositions may vary. We have only to consider the present state of the continents to realize that some of their borders (as for instance those of southern Africa, of eastern America and of western Australia) are not fringed with existing geosynclines. Indeed, these are ancient coasts on the edge of Pre-Cambrian shields or very old mountain-chains. We may well suppose that such coasts have undergone subsidences and many phases of degradation, but also that, at the present time, these areas are not increasing in size. On the other hand, the periphery of the Pacific Ocean, especially of its western side, offers a succession of insular festoons which are, nowadays, in full evolutionary development.

If we now consider one of the youngest of mountain-chains, that of the Alps, which, in the broadest sense of the term, stretches obliquely across almost the whole of the Old World (and occupies the site of the Tethys), we shall find in this vast orographic area an example of the evolution of two antagonistic continental margins, that of Europe and Asia to the north, and that of Africa, Arabia and India to the south. The mountain-chain is composed of a double mountainous band which is almost unbroken. The northern component consists of most of the Alps proper, the Carpathians, the Balkans, the Caucasus, the mountain ranges of northern Turkey and northern Iran and, finally, the Hindu Kush. The southern band consists of the Betic–Riff–Kabylian chains of southern Spain and North Africa, the Dinaric Alps, the mountains of southern Turkey and of southern Iran, and ends in the Himalayas. These two main bands are completed by rejuvenated subsidiary ranges and by foldings of the cover.

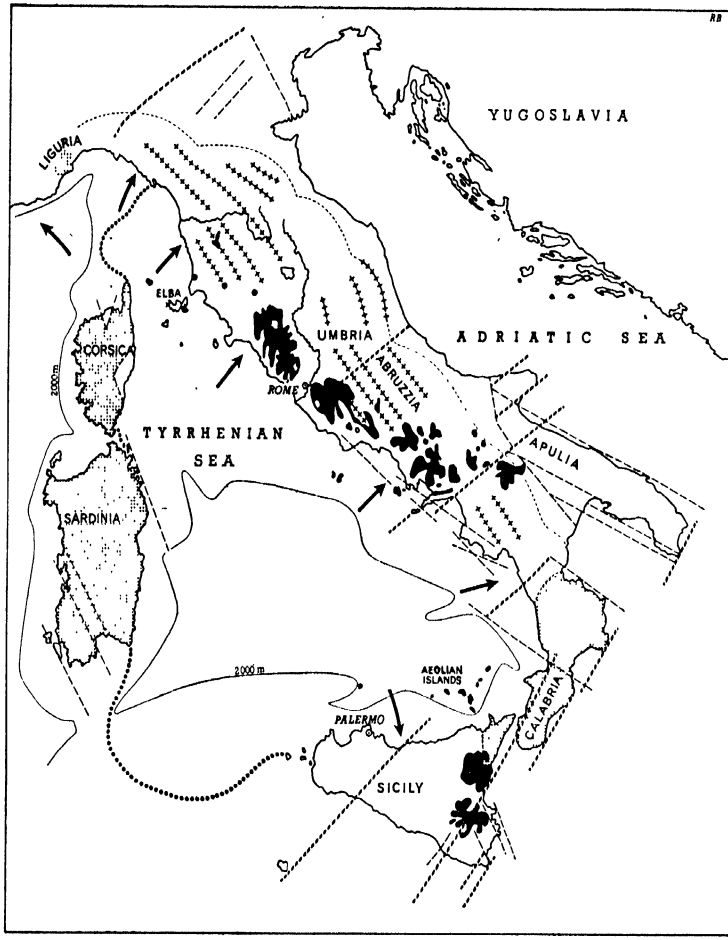
In fact, the Alpine orographic regions have succeeded more ancient orogens of at least Primary age. These are, to the north, the Hercynian chain in Europe, continued eastwards as far as Central Asia; and, to the south, the Maghreb chain, formed by the Moroccan Meseta and its prolongation in the Algerian Sahel. But what is especially interesting is that of these ancient orogenic zones there remain fragments, some of which seem to have formed parts of a chain of Hercynian age, while others appear to be parts of nuclei of Pre-Cambrian age. To these fragments the name of *intermediate massifs* has been given. As a matter of fact, these fragments are disposed, in an irregular alignment, between the northern and the southern Alpine mountain-chains, and constitute the Iberian Meseta (or Hesperic massif), Corsica, Sardinia, the Elbas and the Calabrian

massif, Mount Rhodope in the Balkans, the base of the Hungarian plain, the massifs of the Turkish intermediate zone,and the central massif of Iran.

For a clear understanding of the Alpine dramas some study of these ancient 'nuclei' seems important, for, not only are the folds disposed around them, but also they partook of the properties of the sial and so displayed a tendency towards uplift which provoked outflowings from their plastic covering. Moreover, during the final adjustment of the chain, these ancient blocks showed a tendency to split and to subside, and, in so doing, they gave rise, no doubt, to a part of what have been called the *Mediterranean ovals* whose whole assemblage constitutes the existing Mediterranean Sea. These 'ovals' are zones, more or less elliptical in shape, and are still bordered by centres of seismic disturbance and by volcanoes which emit lavas. These are generally of basaltic origin but are contaminated and often of a feldspathoid and potash character (*e.g.*, lavas containing leucite of the Mediterranean type, like those of Vesuvius). The ovals include the western Mediterranean, the Tyrrhenian, Adriatic and Aegean Seas.

One of the most interesting examples of such subsided blocks, and moreover one which has been the best reconstituted by geologists, is that which occupied the site of the Tyrrhenian Sea, and which for this reason has been named *Tyrrhenis*. (Map 3, page 84.)

The subsidence of Tyrrhenis (whose borders are marked by the Italian volcanoes of Latium) dates from the end of the Tertiary Era. The chain of the Apennines was moulded around this area of subsistence; they follow the outline of the block and continue right down into Sicily. These mountains (which despite the presence of ophiolotic volcanism and of metamorphism in the series of their sediments, present also the character of a chain of the cover) spread out in successive waves—both in time and in space—from the edge of Tyrrhenis towards the



Map 3. The Tyrrhenian Province. This map presents, in a schematized form, the structure of the Apennines (due to flow tectonics) and shows the approximate site of the sunken area of Tyrrhenis (one of the Mediterranean 'ovals') together with the positions of the principal recent volcanoes

east.[1] This vanished Tyrrhenis, then, which no Homer ever saw, has left a durable legacy. First of all its uplift gave an impulse to the formation of the Apennines; secondly, its collapse produced great faults along whose edge the Italian volcanoes stand like sentinels guarding a tomb.

The antagonism which existed between the continental evolution of Eurasia and that of Indo-Africa (as indicated by the Alpine chains) provides us, in particular, with evidence that ancient nuclei (enveloped in one of the two orogens or between the two) have played an important role in the evolution of the mountain-chain and finally broke up during the last phases. So we must admit that in what we now call Europe there are preserved portions of Africa (*e.g.*, all the Dinaric and Alpino-Dinaric chains), just as India and the Himalayas, though soldered on to Asia, are really pieces of the vanished Gondwanaland.

PHANTOM CONTINENTS

The above remarks concerning the fracturing of continents and the history of Tyrrhenis may suffice as an introduction to the consideration of the problem of what we may call 'phantom continents'—that is to say, those great land-masses that have been conceived (though in differing ways) by both poets and geologists. So as not to anticipate questions which we shall come to later on, we shall confine ourselves, in this section, to the structural domain only, but we shall approach the problem from another point of view in the concluding portion of this book, which is devoted to the migrations of living organisms and to the question of continental bridges.

Of all the phantom continents the most celebrated is Atlantis, a legendary land situated 'beyond the Pillars of Hercules' (that is, westwards from the Strait of Gibraltar),

[1] G. Merla: *Geologia dell'Appennino settentrionale*. Bull. Soc. Geol. Ital., LXX 1951–2. Also, L. Trevisan: *L'Elba orientale e la sua tettonica di scivolamento per gravità*. Mem. 1st. Geol. Univ. Padova, XVI, 1950.

whose subsidence and disappearance are said to have taken place in proto-historic times. We may say at once that none of the geological evidence we at present possess affords any evidence at all for the existence of such a region, or for its having subsided so recently. Man—whose appearance, even if we count the first bipeds of Homined type, does not seem to date farther back than about a million years—could not possibly have known or have seen the land area we are about to consider.

We have referred (in connection with the plateau basalts) to a huge continent, consisting of the lands of the North Atlantic, the *Thulean Province* (Map 2, between pages 72 and 73). If we look backwards in time, we see that the component parts of this province underwent a common evolution from the beginning of the fossiliferous periods, and, moreover, that the region in question is discontinuously surrounded today by the Caledonian orogens. These comprise the Caledonian chain proper, which starts in Ireland and constitutes most of Scotland and the northern parts of England, the Scandinavian mountains and Svalbard to the east, and the mountain-ranges of East Greenland to the west. After the formation of the Caledonian chain its component parts shared a common history during the Devonian, which was the age of those molasses deposits known as Old Red Sandstone. Extending from the Caledonian area—on the one side into northern Europe and on the other into North America—the Old Red Sandstone seems to have spread over a huge North Atlantic continent which is usually called (for Devonian times) the 'Old Red Sandstone continent'. There, then, is our Thulean province.

Let us go back farther in time and see if we cannot find on the site of this province (which is today, of course, mostly sea) some traces of continental sima. Such have not been found in Iceland or in the volcanic islands of the North Atlantic, but towards the edge of the European Caledonian orogen (and away from its main zone and serving, so to speak as a western

foreland) we may discover some few precious landmarks of authentic Pre-Cambrian age. In Great Britain we have the Outer Hebrides and the north-west Highlands of Scotland, on the western shores of Norway the Bergen massif, and, farther north still, the Faroë Islands. On the eastern coasts of Greenland no Pre-Cambrian vestiges have been observed, but it may be noted that, as far as we can see, the alignment of the Greenland orogen does not appear to have conformed to the eastern foreland. In fact, there can be distinguished in Greenland a western metamorphic zone, joined to the continent and disappearing under the ice-cap, and to the east of this zone a geanticline and a fore-trough which suggest that the foreland was situated still farther to the east—that is to say, on an area now covered by the North Atlantic.[1]

Since Greenland was the area that served, in more senses than one, as the starting-point for Wegener's theories, we cannot dismiss out of hand the possibility of a 'drift' which might have dislocated the various fragments of the Thulean province. Several different solutions based upon the assumption of a drift have been proposed for this jig-saw puzzle. However, Wegener's theories—like many others founded upon a scientific assumption—must be accepted entirely or not at all, and rejected *in toto* if the premises appear to be devoid of solid foundation. On the other hand, the conception of large-scale subsidences—suggested by the formidable Thulean basaltic plateaux—is based on real facts. The relief of the bed of the North Atlantic Ocean, southwards from the Arctic Ocean, comprised two areas which have depths of more than 6,500 feet: the Baffin Sea between Baffin Land and Greenland, and the Scandian Sea between Greenland and Scandinavia (with its prolongation, Spitsbergen). Now, both these seas have shores which have been raised by recent epeirogenic movements.

[1] We would refer readers to the copious literature published over a period of more than twenty-five years by L. Koch and his collaborators in *Meddelser om Grönland* at Copenhagen.

Baffin Land (which is Pre-Cambrian) and the Scandinavian mountains (which are of Caledonian age) owe their altitude to such rejuvenation. A coastal fault seems, moreover, to run along the western coast of Norway.[1] We are thus led to conclude that the subsidence mentioned above was counterbalanced by this uplift. The Scandian and Baffin Seas thus assume great interest as probably representing the sides of sunken continents. Moreover, we should remember that these regions include the main centres of seismic disturbance in the Northern Atlantic.

THE MID-ATLANTIC RIDGE

If we trace towards the south the seismic zone of the Scandian Sea we encounter Iceland, a large island of predominantly volcanic formation, which is continued under the ocean as a ridge or crest bristling with volcanoes and of great seismic activity—the Reykjanes ridge. A sinuous line, dotted with volcanic islands and sometimes forked, may be recognized without difficulty along the median area of the Atlantic Ocean; it conforms more or less to the pattern of that ocean's coasts, and is so situated that it commands abysses on either side, although it itself runs below the surface at depths ranging from 3,000 to 6,000 feet. All the lavas emitted by the volcanoes along this crest or ridge are, both in their nature and their structure, close to basalts and also to nephelinic lavas. Hence the lavas of this type are called *Atlantic* lavas. We may justifiably compare them with many of the plateau lavas and especially with those of the African continent. Indeed, we should emphasize a certain link or liaison between this Atlantic type of volcanism and that of the west coast of Africa, and point out that the island of St. Helena seems to be situated at the intersection of the volcanic line of the Cameroons and the mid-Atlantic ridge.

[1] O. Holtedahl: *On the oblique Uplift of some Northern Lands.* Norsk Geogr. Tidsskrift, XIV, 1–4, pp. 132–139.

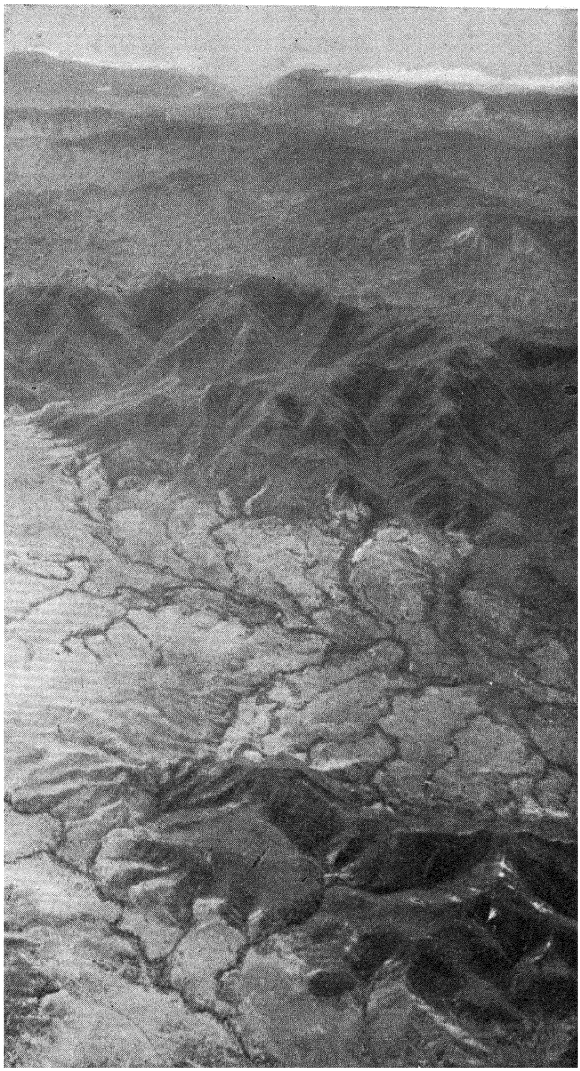


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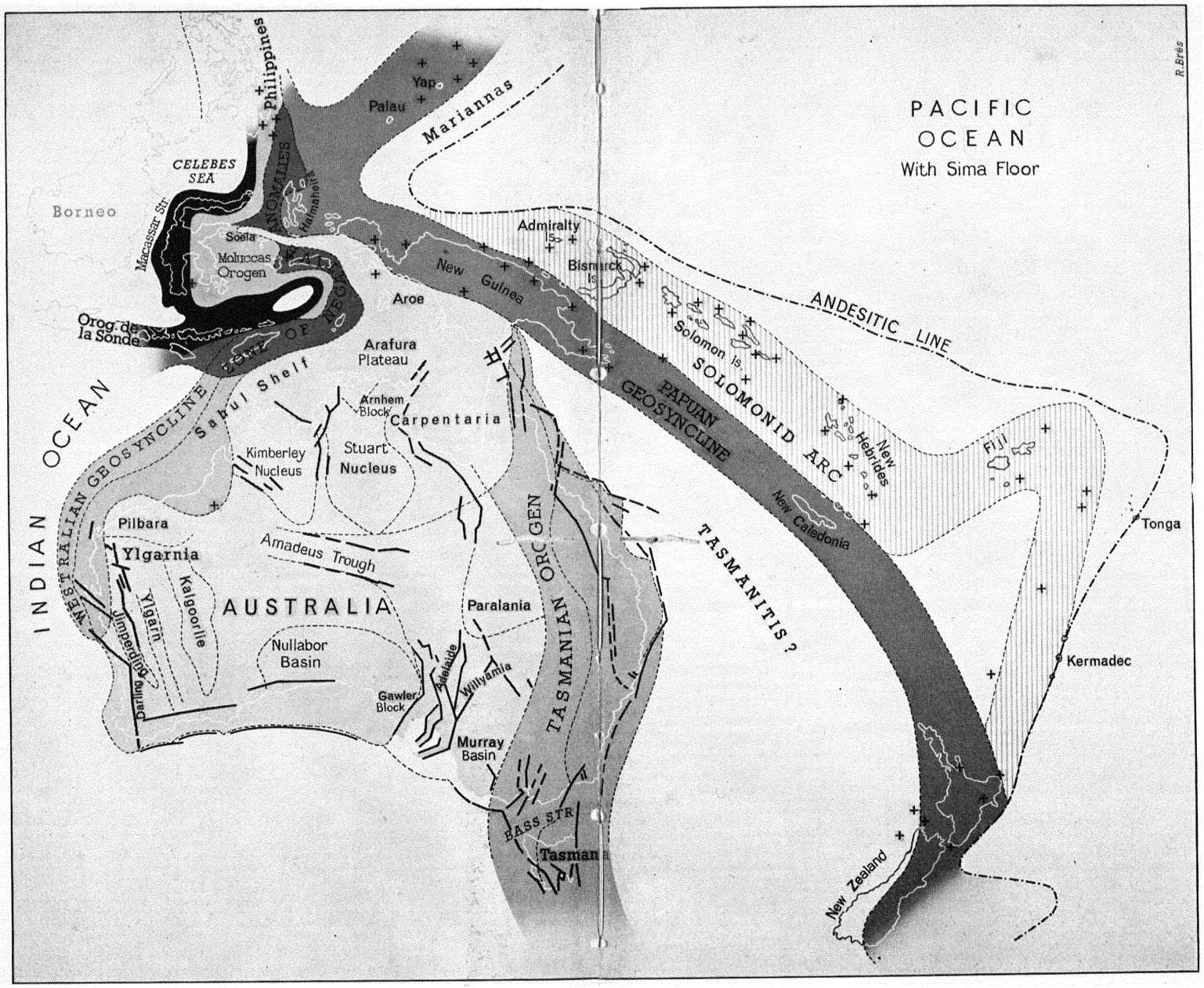
Plate XVII. Peridotite massifs in the Ouaco region, New Caledonia. The peridotite massifs, dark in colour and standing out in relief, lie upon a substratum of basalts, tuffs, greywackes and cherts. The whole assemblage, later in date than the main New Caledonian orogeny (which is probably Cretaceous), seems to be related to submarine fissure extrusions. The basalts and associated rocks are of Eocene age, while the peridotites, formed later than the movements at the end of the Eocene, were probably extruded beneath the sea during the Oligocene



Map 4. Australasia, showing the expansion of Australia towards the east. Pre-Cambrian nuclei (*see* page 32) were joined on to the western part of the continent, then the geosynclines developed successively from west to east. These were the Tasmanian orogen (Palaeozoic), the Papuan geosyncline (Mesozoic), and the Solomons Arc (which seems to be still active).
Crosses: areas of recent earthquakes

G. Termier

Plate XVIII. Mylonites to the west of Tamanrasset, central Sahara. An extensive crushed zone of Lower Pharusian age (Pre-Cambrian). The rocks affected have taken on a schistose appearance. Erosion has also cut them into little ridges

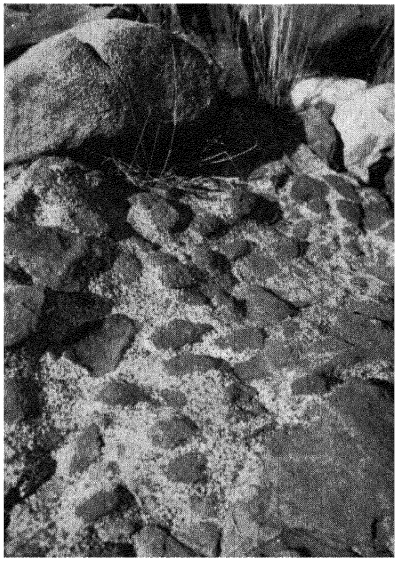


Plate XIX. Granitic gneiss with numerous inclusions of grey gneiss, a type of metasomatic granite. The inclusions (harder than the surrounding rock) stand out because of erosion. From the grano-dioritic massif of Tichka, on the southern slope of the Djebel Toutke, High Atlas, Morocco

G Termier

Thus, from its origin in the north of the ocean to its most southern isles the ridge in question is associated with fractures both by its connections and by its lavas; furthermore, it is dotted with seismic centres. The whole arrangement is sometimes interpreted as being that of a nascent orogenic area. According to this hypothesis an orogen may thus arise as the result of continental subsidences and so on a sima of recent date. In these circumstances, the Atlantic would appear as one of the first great modifications of the earth's surface to have been produced since the beginning of fossiliferous times. Moreover, this modification would have followed on and have been provoked by the closing of the Tethys by the Alpine orogeny.

PRE-CAMBRIAN AND RECENT OROGENS

The foregoing considerations induce us to retrace our steps a little and to attempt to make a few comparisons. However, from lack of sufficient data, such comparisons can unfortunately hardly be much more than simple outline sketches.

We have seen that the scheme of continental evolution may be reduced to a type-drama which can be recognized both in the Pre-Cambrian shields and in recent mountain-chains. However, we have confined our enumeration of what are called the 'permanent features' of the earth's crust to the fossiliferous ages and have not sought to trace these features in Pre-Cambrian times. Furthermore, we have had to limit the duration of the Tethys, since this feature disappeared, practically speaking, in the mid-Tertiary Era when it was replaced by the Alpine mountain-chains.

This limitation of our enquiry seems to us to be fully justified if we consider the facts which relate to the direction of the ancient mountain-chains and to that of the recent fractures. Here are a few examples: while the direction of the Pre-

Cambrian foldings in western Africa is predominantly from north to south, the direction of the Maghreb orogen (Primary Era) and of the Kabyle orogen (Secondary and Tertiary Era) is distinctly from east to west. We may, however, note that the fractures and the volcanism of Africa display, on the whole, submeridional directions, as do also those of the Atlantic regions. In the same way, if we consider the Karelid (Karelian) chains of the Scandinavian Pre-Cambrian, we see that their direction, more or less from north to south, is opposed to the east-west line of the Tethyan Chains (Hercynian and Alpine). We may, therefore, conclude that the Tethys did not exist, even in a rudimentary state, in Pre-Cambrian ages, and that a continental connection may even have existed between the Scandinavian shield and that of Africa on the site of the Tethys. The intermediary blocks (particularly the Hesperic massif and Sardinia) might contain fragments of this connection, which was eventually swallowed up, little by little, into the depths of the Tethys Sea.

Another instance, just as illuminating, is that of the Far East. The ancient chains of Korea, Manchuria and of southern China were directed, if not absolutely from east to west, at least fairly obliquely, to the meridian during Pre-Cambrian and Palaeozoic times. The Permo-triassic and Cretaceous chains of the Pacific coasts (which form the island festoons of today) are sub-meridional, and the Jurassic granitized flexures in China display various different bearings but none are the same as those of the Pacific coast chains. Moreover, true intermediary massifs exist in the coastal areas, such as those of Shantung, southern Korea, and Fukien in eastern China. To these we may add also the central plateau of Indo-China. From these facts we may conclude that the insular chains of the Pacific Ocean's western coasts present a disposition that is relatively recent and was unknown in Pre-Cambrian times.

In peninsular India the east-north-east direction of the

Satpura range (aged 955, plus or minus 40, millions of years) intersects the more ancient direction of the Dharwarian chain.

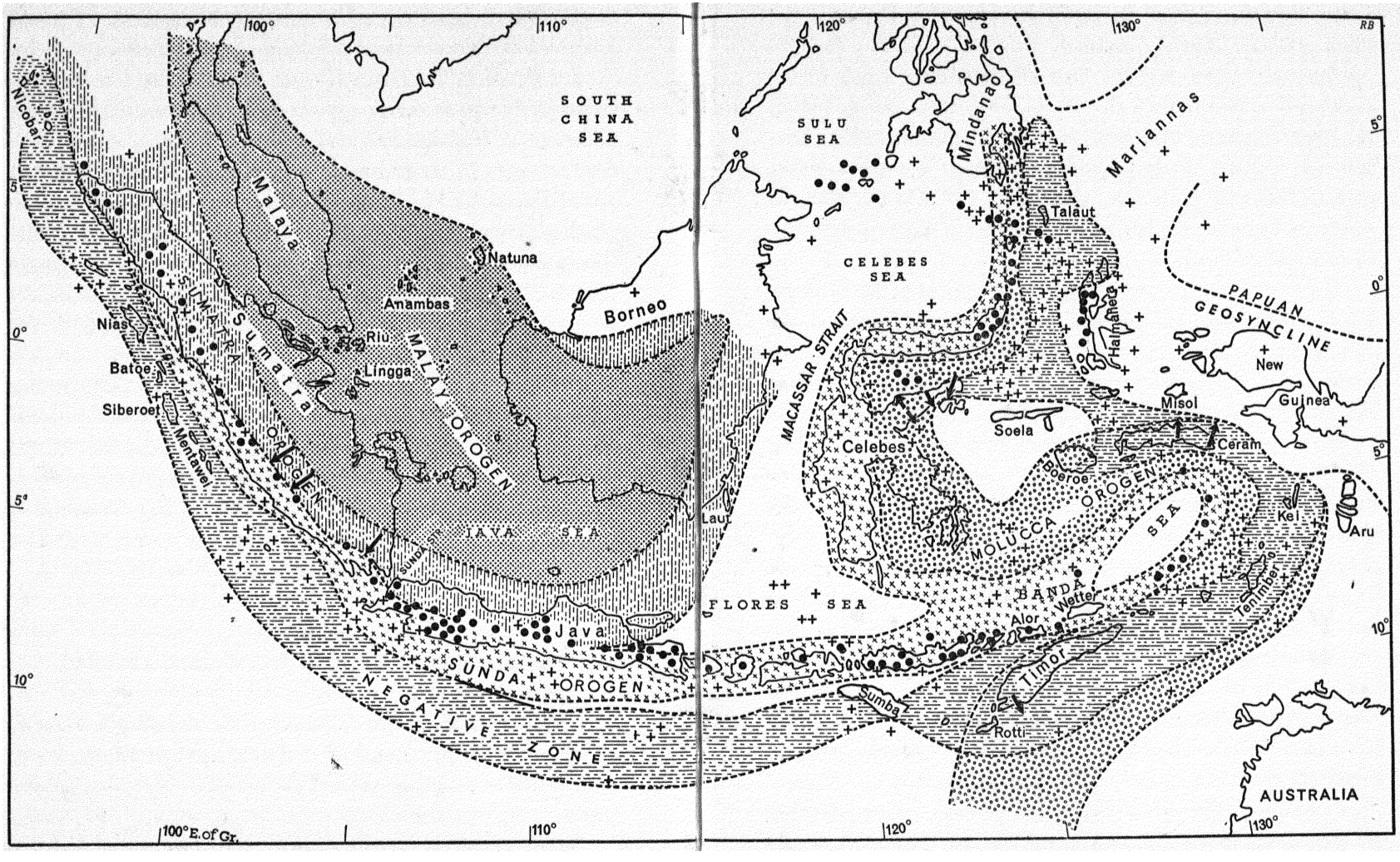
On the other hand, the lay-out of the western mountain-chains of North America appears to have started in the same direction at least by the end of Pre-Cambrian times. The deposits in the Grand Canyon of Colorado (Plates XXIII and XXIV) form part of a huge assemblage called the Beltian geosyncline, which already displayed the same orientation as the Rocky Mountains, the Sierra Nevada and the Coastal Ranges (chains of various ages but more or less parallel to each other) which at the present time make up the main features of the relief of the western portion of North America.

We may deduce from these few comparisons that the idea of geographical 'permanence' is only of limited and comparative validity in the scale of geological time. The face of the earth has no doubt presented aspects which have been rejuvenated several times, and rejuvenated totally, during the course of that long history which has been unrolled over a period of more than three thousand million years.

THE ESTABLISHMENT OF A 'PERMANENT FEATURE'

If we seek for some factor common to the enduring features of terrestrial geography, we shall find it in a phenomenon easy to guess—that of the coalescence of the nuclei or of the continental shields.

We have seen that two continents, or two nuclei, situated close to one another, end up by being in contact. Then they become joined or 'soldered' together by an area which is sensitive and mobile because it is in a state of disequilibrium. The evolution of this area may be more or less complex: it may be a double orogen (the Alpine chains), a simple orogen (the Urals and probably the Caledonian chain of Europe), or an orogen



Map 5. Map of the East Indies showing the orogens of the Asiatic province, those of the Australian province, and their junction. In the western part of the map we see the Malayan orogen as a southward extension of the Shan plateau, which is situated to the west of the Indo-Chinese shield. The Malayan orogenesis is continued in those of Sumatra and the Sunda Islands, which similarly prolong the Burmese orogen. These are all Asiatic units. In the eastern part of the map we see the orogen of the Moluccas, which is a prolongation of the Westralian geosyncline (*see* Map 4). It may be noted that the Sunda orogen, as well as the zone of negative gravimetric anomalies, envelops the two groups of orogens, and furthermore, that the Papuan geosyncline and the Solomons Arc (Map 4) effect a junction with the arcs of the Philippines and the Marianna Islands. *Arrows:* directions of thrust. *Crosses:* sites of the main seismic centres. *Black dots:* positions of existing volcanoes

confined to the foreland (an example of which is known in the Flinders Range, central Australia).

Once the 'soldering' has been effected, those edges of the continents which remain free retain, in general, the power of orogenic evolution and will undergo anastomosis. This anastomosis appears, generally speaking, to result in a harmonizing of their orogenic evolutions; that is, the two continental areas display a concordance between the orogenic phases occurring in each one of them.

Let us take just one more glance at the chains of the Western Pacific, since these are the best known. We shall see that the Asiatic continent was made up, at the time of the formation of these chains, of several eastern Pre-Cambrian shields—that of Kolyma-Jukagir in the north, that of Mongolia and Manchuria farther south, and, lastly, that of China proper. The first recognizable festoon, on the fringes of Mongolia, consists of the Sikhota-Alin chain (north of Vladivostok), which is continued in the south-east to the western Japanese ranges (the Akyioshi), and is thus linked to the mountains of northern Indo-China. It is interesting to note that these chains (which appear to confirm the joining of the Mongolian shield to that of China) were all formed during Triassic times, the main orogeny of each one of these ranges being a little more recent than that of its homologue situated immediately to the north. Thus, the Sikhota-Alin range is of Lower Triassic age, that of Japan Middle Triassic, and that of Indo-China Upper Triassic.

Later on, in Cretaceous and Tertiary times, a new complex of mountain-chains (situated to the east of those mentioned above) concluded the annexation to the Asiatic realm of two new shields, that of Indo-China, Thailand and the East Indies (Map 5, pages 92–3), on the one hand, and Australasia (Map 4, between pages 88 and 89) on the other.

5

THE EARTH'S SURFACE IN PREHISTORIC TIMES

THE FIRST TRACES OF LIFE

As we remarked at the beginning of this book, the evolution of living creatures does not seem to have begun much before the onset of the Cambrian Period. During the preceding periods, for hundreds of millions of years, living things were represented by bacteria and the lowliest sort of *algae*. Moreover, these hardly evolved at all. Their organization was very rudimentary and life was, to all intents and purposes, a series of physico-chemical processes. We might say that these primitive organisms represent a geochemical phase which occurred at the same time as the formation of certain sediments, such as limestones.

At any rate, no traces of any metazoa, or metaphyte, worthy of the name, has been recovered from an undoubtedly Pre-Cambrian source. In saying this we do not, of course, imply that no meta-organisms existed before the Cambrian Period but only that no trace of any such meta-organisms (which the palaeontologists recognize as undoubted) has been found in Pre-Cambrian unmetamorphosed sedimentary formations. In fact, the limestones were almost always formed from 'blue algae' and these are rather destructive of other organisms. The most common rocks are of detrital origin and of flysch and molasses type. Such are rather rapidly formed as sediments in

either running or still water. Moreover, even in fossiliferous times the flysches constituted very poor preservative media since, while they are being deposited, oxygen circulates freely in them. Thus conditions are set up favourable to dissolution, to oxidation, and to the destruction of organic matter. The molasses, on the other hand, are generally to be found on the surface of the continental masses where Life, as we shall see, did not appear until much later on. The reducing conditions most favourable to fossilization seem to have been but very rarely present in Pre-Cambrian times. At this point we recall the considerations we have already set forth regarding both the geochemical cycle and the isotopic composition of sulphur. Thus, if there were meta-organisms in Pre-Cambrian ages, they are unknown to us either because they were not fossilized or because they were destroyed by metamorphism. In any case, such living matter, if it existed, could neither have been very highly organized nor very abundant on the surface of the globe.

If, now, we turn our attention to the dawn of fossiliferous time—that is to say, to the Infra-Cambrian—the absence of fossils (other than those of the blue algae limestones) may appear surprising if we reflect that from the beginning of the Cambrian there existed a relatively rich marine fauna. In an attempt to explain and to understand the reasons for this contrast, let us endeavour to reconstruct a picture of the world as it may have appeared between seven and five hundred million years ago.

THE FACE OF THE EARTH IN INFRA-CAMBRIAN TIMES

The main fact that dominates the geography of this period is that the Pre-Cambrian shields (which later were to play the part of the continents) had then almost entirely emerged from the waters, and that they were covered with molasse deposits

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Plate x x. Trachyphonolite dome of the Essa, Atakor, Ahaggar, central Sahara, quaternary volcanism imposed upon the Pre-Cambrian massif of the Ahaggar. In the background are the peaks of the northern ridge of the Tidhemayene

G. Termier

Plate XXI. Nepheline syenite ('ditroite' of Brogger) at Siktes, Langesund, in the south-west of Oslo Fjord, intersected by a vein of nepheline-syenite pegmatite. The dark-coloured minerals are aegyrine pyroxene and mica-biotite (lepidomelane); the light-coloured minerals disposed in parallelopipeds are microcline-microperthite feldspars and nepheline

of later date than the last orogenies, with abundant plateau lavas, and, finally, with glaciers (*see* Plates XXII and XXIX). It was, indeed, an epoch during which the extension of the continents reached a maximum; it was a glacial epoch, and it was also one of deserts. On the present-day continents, partially marine Infra-Cambrian rocks are found only in the orogenic belts where these rocks heralded the Palaeozoic dramas. For example, they are found around the Arctic Sea, in the Caledonian orogens, in the Armorican part of the Hercynian orogen and in the Beltic Chain of North America. Over these vast areas the most common fossils are always Schizophytes, which often produced very large masses of limestone. In addition, there are a certain number of Protista of the Hystrichosphera group which, in the sileceous banded rocks, play the part that was assumed later by the Radiolaria in those red, green or black jaspers called *radiolarites*.

It is interesting to note that on the Esthonian and Russian coasts of the Baltic Sea the waters advanced and deposited clay formations. Since those remote times, this region has not passed through the phases of a drama, and has not even been subjected to folding, so that the argillaceous material, not having suffered any transformation, has retained its pristine plasticity. In the blue clays of Leningrad and Reval there are some small, conical shells, *Volborthella*, which have been considered by some, though doubtfully, to be molluscs more or less related to the Cephalopods.

During the Infra-Cambrian the continents, being, of course, devoid of vegetation, must have been subjected to an erosion far more intense than anything we may observe today. On the surface of the continents there formed enormous temporary lakes, filled at irregular intervals with rain-water, like the lakes now existing in South Australia. The Infra-Cambrian lakes, like the Australian lakes, also sheltered great masses or 'cakes' of blue algae.

TRANSGRESSIONS AND REGRESSIONS ON THE CONTINENTAL AREAS

In the first chapters of this book we considered the formation and elaboration of the continents, and in so doing, were led to study the orogens. Occasionally, however, we have mentioned basins and cover-deposits on these continents, though we have not gone into any detailed description of these phenomena. Indeed, as far as we can see from rocks of this nature in the Pre-Cambrian and the Infra-Cambrian, the sediments deposited upon the continents appear (even in the subsidence troughs) to be of detrital origin and of molasse type, and sometimes lacustrine; no undoubtedly marine formation has ever been recognized. Of course, the absence of fossils makes it difficult as a rule to determine the conditions under which any series was deposited. However, it is worth while remarking that the blue algae which are sometimes found in geanticlinal formations (which bear some resemblance to those of the continents) are organisms which today live in still waters of no great depth; that is to say, in lagoons and lakes.

To this group seems to have belonged the earliest organism whose existence we know of with certainty. It is the *Corycium enigmaticum* that flourished more than a thousand million years ago and whose remains are found in Finland, embedded in the argillaceous sediments of a mollasse series formed during the uprise of the great Scandinavian chain of the Svecofennids.

Thus, what we know of the Pre-Cambrian continents suggests that they have been almost constantly above the level of the seas. The Leningrad and Reval clays, then, bear witness to an entirely new phenomenon, that of the invasion of a continental area by marine waters. In fact, side by side with the orogens which, as we have seen, continued to develop during

fossileferous times, the great geological events of these epochs are the movements of the seas over and upon the continental areas—that is to say, *transgressions* (which are gains by the sea) and *regressions* (which are gains by the land).

We can mention but a few of the various hypotheses which have been put forward in explanation of the beginning of this series of marine invasions and retreats. They include an increase in the volume of water of the oceans, the restriction of their beds and the expansion of the continents. We know, indeed, that the continental shields were increased in size by the orogens which arose on their edges. We may, then, be inclined to think that the seas, for long contained within the limits of their original beds, were led to overflow on to the continental margins when the margins themselves began to encroach upon the domain of the oceans. We can place the period of this encroachment in the Infra-Cambrian. This phenomenon opened a new and important chapter in the evolution of the earth's surface, and, indeed, in that of the lithosphere, for thenceforth marine sedimentation was to become of preponderant importance, and the petrogenetic role of life was to assume an increased significance.

However, the study of geology through the ages allows us to observe that the shiftings of the shore-lines are not continuous phenomena but take place in fits and starts. At any given point the transgressions alternate very irregularly with the regressions. Attempts have been made to explain this alternation. 'Laws' have been evoked which, of necessity, rest upon hypotheses relating to the cause of these movements.

Movements of the earth's crust which are capable of producing marine transgressions have (because of their origins) been classed as *epeirogenic*. These we have already dealt with; they are vertical movements, linked with the deep foldings of the continental masses. As such, they are related to the orogenic phases, so that there is some relation between the transgressions

of marine waters on to the continents and the dramas in the orogens.

Eustatic movements are changes in the level of the oceans, and these may have been caused either by the elevation or subsidence of the sea-beds, or by an increase or decrease in the volume of the water—for example, by the melting of the ice-caps and glaciers at the end of a glacial epoch. The rise in the level of the oceans, owing to the melting of the last great masses of the ice-caps of the Quaternary Era, has been estimated to have been not less than six hundred feet. However, the quantity of water represented by such a rise in level must have been first withdrawn from the oceans during the glacial phases. Since there are traces both of great ice-caps and of a first marine transgression in the Infra-Cambrian, we are tempted to think that the principal role in determining the rhythm of transgressions was played by epeirogenic movements.

PULSATIONS

The ebb and flow of the seas away from and on to the continents suggest that there must exist some sort of tidal phenomenon, whose movements, however, are much slower than those of the daily tides we all know today. Moreover, the relation (which we cannot clearly define) between these advances and retreats and the epeirogenic movements leads us to conclude that the variations of terrestrial geography have obeyed comparatively regular pulsations.

E. Haug[1] was the first to suggest that the alternation of transgressions and regressions on the geosynclinals coincided with an inverse movement on the continental areas, each phase of the alternation having been, practically speaking, common to the whole globe. Later on, it came to be thought that a

[1] E. Haug: *Traité de Géologie*. Paris, 3rd impression, 1921–27.

more or less regular succession of very long-lasting transgressions and of short regressions was more in accordance with the evidence.

Scientists of the German School[1] have established for the world as a whole what seems to be an almost regular series of orogenic phases from the Cambrian to the present day. If there really exists a rhythm of pulsation for the earth, then these phases would act, so to speak, as a metronome. Such a conception, which forms the theme of Umbgrove's book,[2] has been correlated by that author with the transgressions. However, little by little, objections have appeared which tend to invalidate such a hypothesis. The first of these objections is this: it is very difficult to determine, in terms of time, the exact limits of any orogenic phase. We cannot, indeed, make use of any absolute measurements of age in this connection, for the simple reason that the measurements that we can effect present a margin of error that is greater than that admissible for the relatively precise dating we need. Moreover, secondary phases often occur between the main ones, and that, indeed, to such an extent that we may ask ourselves whether orogeny is not really a continuous process whose apparent discontinuity is suggested only by the existence of certain physical features. All the same, it remains true that there seem to have existed periods of discontinuity, several of which were synchronized for the whole surface of our planet.

We may now examine these 'universal phases' a little more closely and, in order to clarify our ideas, let us select one which has been recognized as the most widely spread—namely, the *Taconic phase*, so-called from the mountain-chain of that name in the north of the Appalachians. It is a geanticline of Pre-Cambrian age, granitized, folded and thrust at the end of the Ordovician and the beginning of the Silurian Periods. It

[1] W. Grabau: *The Rhythm of the Ages*. Peking, 1940. H. Stille: *Grundfragen der vergleichenden Tektonik*, 1924.

[2] Umbgrove: *The Pulse of the Earth*. The Hague, 1947.

has been thought that this phase can also be recognized in the Cordilleras of the Andes, especially in Argentina, but in that region there are no Silurian sedimentary deposits. In the Caledonian orogen of Europe (and this is particularly well marked in Wales) the Ekné phase—which is of like age with the Taconic—is much less important than the Trondhjem orogeny, which is of more ancient date. In the Hercynian orogen several movements have also been equated with those of the Taconic, both in the Ardennes and the Montagne Noire. But, if in both cases we are concerned with a deformation of the base, it is by no means certain that these two phases have been accurately synchronized, since uplift occurred in the Montagne Noire before the end of this period. However, we may remember that the Ordovician lasted some fifty million years.

In Svalbard and in eastern Greenland the principal orogeny took place in upper Ordovician times. Similar examples could be cited, and in abundance, from all over the world, and not for this phase only but also for all the other orogenic phases of any considerable importance. In reality, we must conclude that the so-called 'universal phases' can be considered as such only if we remember that they are but approximately synchronous and that the term 'synchronism' does not have the same meaning in all the different orogens.

Sometimes (as is the case for the Triassic mountain-chains of the western Pacific) the phases seem to have been staggered in a regular fashion, just as though an orogenic wave had been propagated southwards (*see* p. 94). In other instances, the phases appear to be related to a single series of movements in a given continent, but there to have made their influence felt in diverse ways according to the various developments of the dramas there taking place. Furthermore, many of the orogenic phases are not world-wide phenomena.

As regards the relationship which appears to exist between orogenic phases and marine transgressions, it would seem that

we (who must remain but superficial observers) should not lose sight of the fact that a phase sufficiently powerful to set in motion the uplift of a mountain-chain would itself provoke a regression of the waters of the ocean, and this regression may be theoretically compensated by a marine overflow in another region. However, such a correspondence or link between a marine regression and an orogeny is perceptible only if we are dealing with a permanent mountain-chain—the result of several phases whose effects have been cumulative. Thus the Taconic Cordilleras—partly destroyed and then covered over by the Silurian seas—were subject only to temporary regressions except, as we have seen, in the extreme north, where they built up a real mountain-chain as early as this period. However, later on, in the Devonian, and after all the Caledonian mountain-chains had emerged, the northern and circum-Atlantic regions underwent an important regression. Furthermore, in these instances we can speak only of the regressions, for we cannot with certainty establish whether the related transgressions (which we might reasonably expect to have occurred) really occurred.

If we consider orogenic movements as a whole we shall be inclined to enquire whether geosynclinal subsidences would not, by a play of symmetry, provoke transgressions over marginal areas. Stratigraphical research allows us to ascertain that a geosyncline begins modestly enough and that the waters invade the area and then gain the adjoining lands sufficiently extensively to receive sedimentary deposits from the neighbouring continental mountain-chains. But beyond and above these considerations, it is certainly true that platforms no longer subjected to orogenic evolution are subjected to transgressions (as was the case, for instance, with western Africa during the Middle Cretaceous) and that mountainous zones are, as we have seen, situated next to the areas of subsidence which cause the formation of new seas.

Moreover, in addition to the scalar factors (*i.e.*, those of

the surfaces covered and of the volume of water displaced) in marine transgressions and regressions, we must also take into account the vectorial factors (*i.e.*, the directions assumed by the transgressions). We shall thus come to the conclusion that during the course of several million—and sometimes of several tens of millions—of years, the seas were subjected to great displacements and that these represent the axes of the main advances of the marine invasions.

We should, nevertheless, bear in mind that shifts and changes of this sort must not be confused with the measurable flow of currents which can today be observed in all oceans. The displacements referred to above represent a definite statistical result, but though we can measure their effects after the event, from the biological point of view they did not exercise their influence upon a single generation of swimming or floating organisms. The sea gained on the land very slowly—perhaps less than an inch a year. No doubt this reference to the human scale of computation does allow us to understand the rhythm of sedimentation (Plate XXV) and the alternation (often monotonous and sometimes of very considerable thicknesses) of various sorts of sediments with their special faunas. Marked variations in any given direction appear only progressively in such a series. There are advances and there are retreats which indicate the great length of duration of the phenomena. In fact, if we regard only the details and not the general effect, we shall perceive that the influence of the transgressions may not only be discontinuous but also, at times, reversed.

In order to treat this whole question from as many points of view as possible, we shall return to it again after we have considered some other ideas and concepts.

Let us now, for a moment, leave geology and enter the domain proper to biology and ecology.

It is matter of constant observation for the farmer, the hunter and the fisherman, as well as for the naturalist, that we cannot grow any sort of plant in any sort of place. Moreover we do not expect to find any given kind of animal in every place. We all have some sort of idea as to the environment favourable for the existence of a particular organism. Broadly speaking, each one of us divides the world, first of all, into two great sections—that of the continental environments and that of the marine environments. Then we proceed to smaller subdivisions. We know, for instance, that different climates do not support the same plants or the same animals. The northern tundra is a very different place from the tropical jungle. Again, the strange appearance and odd characteristics of deep-sea fishes arouse our curiosity.

The different means of subsistence also afford us information about the links that bind organisms to their environment. Carnivorous animals need food that is, for the most part, the flesh of herbivorous animals, while these latter need plants upon which to feed. Plants are the reservoirs of energy for the whole biosphere and they, in their turn, must have the energy furnished by light, which is captured by means of chlorophyll and transformed by photosynthesis.

During fossiliferous times there have been many different climates prevailing on the earth, many different environments, and many different assemblages of organisms. We must endeavour to reconstruct these assemblages if we would learn more about the phenomena which have occurred on the face of our earth.

When we spoke of Pre-Cambrian sediments (often rendered unrecognizable by metamorphism) we stressed the great importance of research into their origins. The presence of such and such a mineral of a certain chemical composition, and (for less altered rocks) the form and the arrangement of the constituent grains, allow us to gain an approximate idea of this origin. Progress in the study of sedimentology is helping more and more in the reconstruction of this primitive material. Even when there are no fossils it is sometimes possible to recognize the action of living matter. However, we are likely to remain very uncertain with regard to the former climates which prevailed in the different zones of the earth's surface.

When we get to fossiliferous times, the increasingly visible traces of organisms in the geological formations make research a good deal easier and we are able to study the rocks in conjunction with the fauna and flora which they contain. To such an assemblage the name of *facies* is given (Plate XXVI).

In terms of ecological biology, a facies corresponds more or less with a biotype; that is, any given environment with its associated flora and fauna. But when we come to deal with an ancient biotype we may remember that it may have suffered modifications. First of all, there may be importations (owing to sea-currents and other factors) of organisms which did not actually live in the biotype. Then, there may be modifications due to the disappearance of living creatures (such as soft-bodied animals) which do not lend themselves to fossilization and which consequently leave no trace of their existence. Lastly, there may be modifications due to alteration caused by currents, wave-action or erosion. Such alterations may (for us who are very late-comers as observers) change considerably the whole assemblage constituting a facies.

Nevertheless, if we proceed with prudence and care we can obtain a very fair idea of the various biotypes which have succeeded one another on the surface of the globe.

We may note that one of the most significant results to be gained from such a study is the conviction that biotypes evolve just as do the organisms which inhabit them. We may say, in fact, that the various environments have been progressively colonized by living creatures. This progression of biotypes has been, on the one hand, a function of acquired physiological adjustments and, on the other, of the existence of favourable environments.

CONTINENTAL AND MARINE ENVIRONMENTS

We have already referred to the absence of meta-organisms on dry land during the Pre-Cambrian epochs. The only traces of what may have been living creatures are to be met with in lake deposits in the biochemical form of secretions or excretions which may be attributed to bacteria or to blue algae.

This lack of life on the continents continued for a period of more than two hundred million years. It is not, indeed, until towards the end of the Ordovician Period, or even, more probably, until well into the Silurian, that life began to appear on the dry land. The physiological factors necessary before this colonization of the land could take place were the separation of the organism's interior medium from its exterior environment (that is to say, the isolation of the circulatory system from the surrounding air or water), and the development of organs capable of absorbing oxygen directly from the air. Favoured as they were by peculiarly propitious circumstances (due to the formation of great continental masses) several groups of animals and plants which had acquired the indispensable faculties set out, at about the same time, to

conquer the land during the Silurian and—even more vigorously—in the Devonian Periods.

Before that time we may say that it was the seas alone that sheltered all the meta-organisms. In the immense domain of the seas we can today recognize several zones, distinguished chiefly by the depth of their waters. We may point out in this connection that the dominant factor is not the negative altitude (*i.e.* the depth) and the consequently increasing pressure, although that may attain a very high figure, for the majority of marine animals possess an internal system which is in more or less free communication with the water. The amount of pressure, indeed, is of relatively little importance. What is of grave importance to marine organisms is that the sun's rays do not penetrate down much farther than six hundred feet.

Now, in the case of green plants there is an essential connection between light and life—the connection of chlorophyll assimilation. Herbivorous animals are strictly limited to an area in which green plants can flourish, so that at the present time the most populated part of the seas is the zone which does not exceed a depth of six hundred feet. This is the so-called *neritic* zone and it happens to coincide, more or less, with the submarine shelf that borders the continents. Where the shelf ends the edge of the land masses drops down steeply towards the abyss of the oceans. This shelf is known as the *continental shelf.* If we base our calculations on what we know of the comparative anatomy of marine animals, we may conclude that the majority of animals whose fossils belong to remote ages must have lived in the neritic zone.

This zone and the coast-line proper are, in our days, linked by an intermediate area, the *inter-tidal* zone or the zone of the tides' ebb and flow. In this area, which is regularly swept by the waves, the land often becomes dry but is as often covered again by the sea. This is the zone in which the blue algae which we have so often mentioned are abundant. If, as seems likely,

this zone was one of the first to be colonized and was—and still is—populated by vegetation of such a low type, it must be borne in mind that conditions in this zone are harsh and rude. The intensity of the light is almost as strong as on dry land, and the ultra-violet rays (which are soon attenuated under the surface of the sea) are also of great intensity. Moreover, in the inter-coastal areas the surf has free play and rolls living creatures about as though they were pebbles. In fact, the inter-coastal zone constitutes an environment that is 'hard to live in', and it must have formed a school for those organisms which were learning to adapt themselves to life on dry land.

If we disregard the numerous floating micro-organisms (*i.e.* plankton—either Protista, or small animals and plants, or eggs and larvae) and also the highly organised animals which are good swimmers (nekton), almost the whole of marine life is concentrated on the bottom of the sea. The bed of the sea is, indeed, rich in foodstuffs composed of bacteria and Protista, on which live many of the creatures which sift the mud or particles in suspension. This zone is the *benthos*, and it is inhabited by such creatures and also of the animals whose prey they are.

If we go back to that stage of plant evolution which is in evidence at the beginning of fossiliferous times, and which is characterized by very small schizophytes, essentially bacteria, we shall not be surprised to note that the animals of the same epoch were microphagous organisms—that is to say, they were well adapted to feeding upon very minute particles.

LIFE IN THE CAMBRIAN PERIOD

Of the various sediments formed by the erosion of the Infra-Cambrian continents, the finest were muds favourable for the life of Protista. These muds, which have long since become

clays or slates, formed the most populated sea-floors. On the other hand, the coarse and fine sands (later transformed into sandstones and arkoses, were still sterile. The calcareous muds (partially secreted and partly built up by bacteria) were also colonized by other organisms. All life in Cambrian times occurred within these limits.

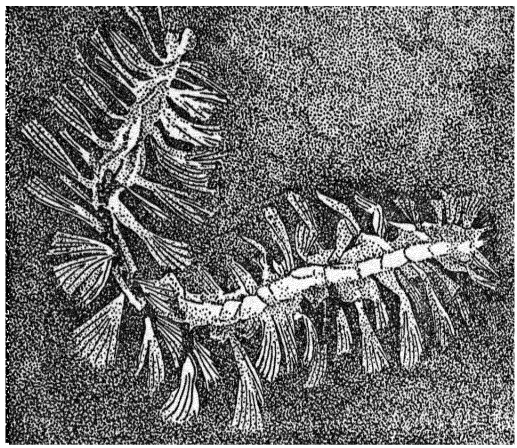


Figure 3. *Canadia setigera* Walcott, a Polychaete (annelid) preserved in the Middle Cambrian formations of Burgess Pass, British Columbia. Note the parapodia with their tufts of bristles

In the Lower Cambrian, the main lines of invertebrates appeared in rather rudimentary forms. There were Sponges, Coelenterates, Worms (Fig. 3), Onychophora, Crustaceans, Brachiopods, Echinoderms, and perhaps even a Prochordate, to which must be added a profusion of extinct Arthropods, namely the Tribolites and Pre-Merostomata. The majority of these forms (except the Coelenterata and the Holothuria, which seem to have lived in the seas, and the Sponges, which sought out the limestone formations) are animals which lived on the sea-bed, right in the mud, which is in a reducing environment.

Such conditions were so favourable for fossilization that, paradoxically enough, the invertebrates of the Cambrian Period are among the best known to us of the whole fauna of the Primary Epoch. In this connection, we may note particularly the Mount Stephen fauna of British Columbia. There, in the fore-trough of the Cordilleran geosyncline, a great number of worms and Arthropods are to be found and these have been preserved by siliceous impregnation in the most minute anatomical detail.

The faunas from the calcareous environments are strikingly different from those of the muds. They are essentially those of reefs which had already been formed (instead of the masses of *Collenia*), and they include organic structures whose geological duration was relatively short. These are forms which seem to be related to the calcareous sponges, or perhaps even the siliceous sponges, but whose regular structure recalls to some extent that of the Coelenterata. They are referred to as the *Archaeocyathines* and, in southern Australia, where they occur in abundance, they are familiarly known as 'Archaeos'.

The distribution of *Archaeocyathines* affords very interesting ecological indications. They lived mostly in Lower Cambrian times and, at that epoch, they were spread over the whole world. This fact leads us to think that marine conditions were then more or less uniform all over the globe.

If we ignore those traces of glaciation which may be found in the Pre-Cambrian, and especially in the Infra-Cambrian, we may regard the 'Archaeos' as giving us the first biological evidence of climatic conditions. Nevertheless, the interpretation of the 'Archaeo' evidence is not, perhaps, quite as simple as the earlier observers thought, for we can find no definite homologues between these organisms (which are closely related to the sponges) and the polyps of the coral seas. However, the calcareous platforms on which the 'Archaeos' are found, have, in themselves, a physico-chemical significance. The temperature of sea-water has a direct influence upon its power of dissolving

salts, and, therefore, of providing salts to those animals which use them for forming their skeletons. The vast and widespread reef-formations thus incline us to think that the Lower Cambrian seas were warm. One should add, however, that strictly speaking the term 'reef' does not apply exactly to biotypes with *Archaeocyathines*, and in their case it might be better to employ the word 'bioherm'. For further discussion on this subject we would refer readers to the pages we devote to the question in our *Histoire géologique de la biosphère*.[1]

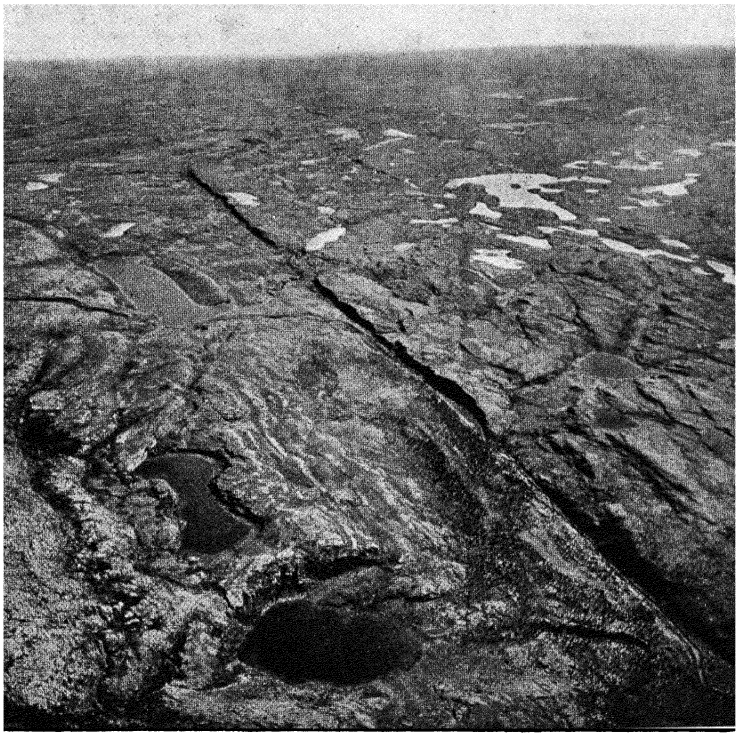
If we now consider the groups of Trilobites, we shall see that their distribution seems to indicate an undoubted line of communication between the Asiatic faunas and those of North Africa. Thus, we may state that, as early as the Lower Cambrian, a Tethys already existed.

If the two sets of facts stated above are compared, we come to the conclusion that there existed, contemporaneously, a tropical-equatorial marine belt, and also a uniformly warm temperature in the seas of the globe up to rather high latitudes.

Nevertheless, we should not lose sight of the fact that in Lower Cambrian times we are not so very far removed from the original, initial transgression, and that the Cambrian seas (apart from such permanent oceans as the Pacific, the Arctic and probably part of the Atlantic) were still more or less confined to those areas which constituted the theatre of the preliminary stages of the Palaeozoic geosynclines.

In Middle Cambrian times, the geography was still not very different from that of the Lower Cambrian. However, an examination of the faunal assemblages does not lead us to draw the same conclusions as for the Lower Cambrian. The 'Archaeos' are much less numerous, so that we are justified in thinking that the seas of this epoch were less uniformly warm. Moreover, we find that the groups of Trilobites had changed, for there had been some organic evolution, and their distribu-

[1] Published by Masson, Paris, 1932.



Royal Canadian Air Force

Plate XXII. Fault in the Canadian shield at Hornby Bay, to the north-east of Great Bear Lake. This fracture separates a sub-horizontal and probably Infra-Cambrian formation (composed of grits, quartizites and conglomerates) on the right, from rocks which are a little older, but slightly metamorphosed and belonging to the Upper Pre-Cambrian, on the left. The Quaternary glaciers, after their retreat, dotted this barren landscape, which is situated somewhat to the north of the Arctic Circle, with lakes. It is very probable that the fault was formed not long after the formation of the Infra-Cambrian deposits, whose thickness not far away (at Coronation Gulf) seems to be as great as 50,000 feet

P–

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Plate XXIII The Grand Canyon of Colorado, U S A. This V-shaped gorge has been cut through the Pre-Cambrian 'Vishnu' mica-schists, which were formed by regional metamorphism. These rocks were once folded into a mountain-chain which was subsequently worn down to the peneplain shown at P. This level marks the upper surface of the Pre-Cambrian formations, the short cliff above it belonging to fossiliferous times

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Plate XXIV. A more extensive view of the Grand Canyon, the stepped cliffs of which offer one of the most famous natural sections in the world. About 700,000,000 years ago the peneplain indicated in the Plate opposite became covered with grits and conglomerates of Infra-Cambrian age, representing the southern edge of a great sagging area known as the 'Beltian Trough'. Then came the deposits of Cambrian sands, about 500,000,000 years ago, and the other Palaeozoic formations (Devonian, Carboniferous Permian)

G Termier

Plate XXV. Rhythmic sedimentation (Lower Ordovician). Alternation of limestones containing Trilbotes (*Megalaspis*) with shales containing Graptolites (*Didymograptus*). Gzeitungholmen, Oslo Fjord

tion shows the establishment of a number of different *provinces* (Atlantic, Pacific, and so forth) which hardly communicated with one another, although these provinces were often separated by relatively narrow barriers such as that represented today by the Green Mountains, in the Appalachians. Resemblances between the different Trilobite faunas would seem to indicate that communications were easiest around the periphery of the Arctic Sea, along the orogens of the Caledonian belt in that region.

DISPLACEMENTS OF FAUNAS[1]

The complexity of the ecological provinces which are today distributed over the face of the globe has given rise to a new biological science, 'biogeography', which is divided into the two branches, zoögeography and phytogeography. Palaeobiogeography is the counterpart of this science in the geological sphere.

The two examples we have given of the distribution of living creatures during Lower and Mid-Cambrian times indicate that this distribution varies much from one epoch to another. It seems that the biogeography of the earth in any geological age may be modified at least as rapidly as its geomorphology. We are thus led to enquire what are the reasons for the appearance, the disappearance and the displacement of marine animals and plants.

[1] The concept of *migration* as understood by biologists (*i.e.*, seasonal movements undertaken by individuals or groups of individuals at certain periods of their existence) should not be confused with the concept of *geological migration*, as defined and described by E. Haug in his *Traité de Géologie* (1921–1927). This is easily distinguished from biological migration by its time scale, and it refers to displacements of fauna resulting from the changes in geographical and physiographical conditions which occur over long lapses of geological time—sometimes several millions of years. The shifting of one or of several zones is sometimes discernible between, say, the appearance of the same species in America and North Africa (*see* H. and G. Termier: *Affinités des faunes Nord-Africaines au cours de l'ère primère*. Revue Scientifique, No. 3308, 1950, pp. 209–216).

For an adult organism, that is wedded to a certain biotype, to quit this biotype, several circumstances must occur simultaneously. First of all, the organism must be ill at ease, either because of physico-chemical changes (such as the lowering or the rising of the temperature), or because the organism has no more living-room, owing to proliferation of other organisms—or, again, because there has been an invasion of the biotype by animals which are more robust and aggressive. Of course, it goes without saying that an organism must be physically able to leave its biotype (Plate XXVIII). This, for instance, is impossible for creatures which are fixed and which must live and die in the same place.

In order for a living creature to instal itself in a new habitat, the general conditions must be favourable and it must not find its new home already occupied by rivals. Indeed, the new habitat must be empty as far as concerns animals which have the same needs and habits as the immigrants; that is, unless it happens that the immigrating animal is far superior physiologically to those it may encounter in the new ground. Finally, the immigrant must be able to discover the favourable site and location.

Except in a few cases, the spontaneous migration of adult organisms is accompanied by very great difficulties unless they move into areas immediately adjacent to those they leave. Thus, it is easy to understand why, from Mid-Cambrian ages, the 'Archaeos' almost completely disappear. In some Siberian areas, where the 'Archaeos' held out longer, they had to face competition from the calcareous blue algae. At first this competition was not very fierce (as long as general conditions in the seas remained favourable for the 'Archaeos') but, in the long run, the schizophytes gained a complete victory owing to their incomparable vitality.

Migrations which colonize the seas must take place in particular ways, and, since adult organisms do not generally possess

the requisite properties, it is logical to think that it was the larvae which played by far the most important role in such migrations.

Larval forms of the dwellers in the ocean depths hardly ever present the definite characters of the adult forms. In most groups there are larvae which descend at once to the sea-bed, but there are also some forms which, before doing so, form part of the plankton carried along by sea-currents, and which may thus accomplish journeys of considerable length.

The larvae vary a good deal in type and character from one group to another, but it may be generally assumed that pelgaic larvae are much commoner in warm than in cold seas. Consequently the possibilities of migrations are much increased by a rise in the temperature of the waters.

This point allows us to explain the almost world-wide distribution of *Archaeocyathines* in the Lower Cambrian seas. These were warm seas where the larval life of the 'Archaeos' could be of a long enough duration for them to be carried by the sea-currents for great distances in any directions.

Since the Tethys already existed in the Lower Cambrian, there is some reason for thinking that this sea already possessed the characteristics of the tropical-equatorial zone which it retained during the greater part of the fossiliferous ages. Among the reasons we have for assuming this state of things, one of the most interesting is that presented by the distribution of traces of glaciation during the Infra-Cambrian. These traces are to be found both in the continents of the northern and the southern hemispheres, but not, it would seem, in regions situated in the latitudes covered by the Tethys. We may, therefore, be justified in supposing that the seas which transported the larvae of the 'Archaeos' were subject to movements resulting in vast superficial sheets of warm water flowing principally from the warm Tethys towards the still cold polar regions. The presence of these calcareous organisms in Antarctica and in Canada (among

other regions) seems to present an argument in favour of this point of view.

During the Middle Cambrian, the Trilobite faunas in particular show that there then existed provinces which communicated with each other along the periphery of the Arctic. The Trilobites were not fixed to any one spot and certain of the genera must have been fairly good swimmers, but most of the adult forms lived in close connection with the sea-bed. On the other hand, the larvae certainly led a pelagic existence of variable duration as do those of the crustaceans of the present day. The migrations of the Trilobites, although not universal, are quite clearly traceable on the northern, arctic route; they force us to conclude, first of all, that these seas were not cold (although they may not have been as warm as the waters of the original Tethys), and second, that the main surface currents flowed from the arctic regions towards the south. It would thus appear that warm waters derived from the Tethys warmed the arctic areas and probably caused the ice-caps to disappear, and that, once a thermic equilibrium had been established, the currents from the south ceased to flow northwards and thus the supply of warm waters was cut off. Nevertheless, the circum-arctic seas were still sufficiently warm to allow fairly long pelagic life to the larvae of the invertebrates. The ocean currents, counterparts of those in the preceding epoch, changed their directions and thus carried these faunas far south to a milder climate.

TRANSGRESSIONS AND DISPLACEMENTS OF TETHYAN FAUNAS: ARCTIC INFLUENCES DURING FOSSILIFEROUS TIMES

We have dwelt for several reasons upon what we have been able to learn about events in Lower and Middle Cambrian times. These ages are the earliest in which we can observe organic evolution taking place. Again, the events of these ages allow us to make deductions from a number of plain biological facts. The *Archaeocyathine* facies and the Trilobite facies were clear and distinct to an extent for which we cannot easily find an equivalent later on. Lastly, the seas were only beginning to invade the continental areas, so we do not have to make allowance for events occurring in previous epochs, events which, although past, might leave enduring consequences. It may be added that, without being a period of orogenic calm (there has never been such on the earth), this part of the Cambrian saw the rise of no great mountain-chains.

These phenomena, which we have presented in a very schematic manner, and to which we give the names of *transgressions*, of *displacements of Tethyan fauna*, and of arctic influences, seem also to have recurred on several different occasions (we estimate nine) during the course of the fossiliferous ages.[1]

During the Tethyan trangressions the Tethys itself occupied a very wide area and spread its waters far beyond the orogens which had formed its borders. These periods of trangression were ages of warm climate for the earth as a whole. Most probably there was, at those times, a melting of the polar ice-caps, and, consequently, a greater volume of water in the oceans which were thus able to spread in shallow sheets over the continental areas.

[1] H. and G. Termier: *La Paléobiologie, fil conducteur de l'Histoire de la Terre*. Rev. Scient. 3315: Jan.–Feb. 1952, pp. 31–48.

Typical warm-sea animals, which, generally speaking, secrete and build up a robust skeleton formed of carbonate of lime, began to invade regions hitherto denied to them and there to construct reefs (Plate XXVI). In such creatures, which, like many of the polyps, became rapidly adapted to the reef facies, the vast amount of space available induced great vital activity during which new types emerged. The main stages of Coelenterat evolution, for instance, coincided exactly with the Tethyan transgressions. Together with these animals, certain creatures from other facies adapted themselves progressively to the conditions prevailing in the reefs. Among these latter were all sorts of molluscs, echinoderms and crustaceans which, in course of time, acquired a thick, calcareous envelope, and which, as they found an abundant supply of food where they settled, became heavier and more sedentary.

After the continents had become populated with various floras and faunas, the periods of Tethyan transgressions (which were ages of marine expansion) were not very favourable to the further development of terrestrial life. However, the transgressions provoked warm damp climates which might be broadly compared with those prevailing during the wet monsoon season on the coasts of the Far East at the present day. The spread of terrestrial forms especially sensitive to this sort of climate allowed also of an almost world-wide distribution of certain favoured plants, such as the ferns. But after the Tethyan transgression was over the climate on the continents became harsher, though the seas remained lukewarm owing to the high specific heat of water.

We can observe a progressive diminution of the reefs during the period of arctic influences. One of the best known examples of this is to be found during later Jurassic times in the reefs of the Jura. Simultaneously with the spread of arctic influences the waters of the Tethys shrank back to their original bed while no doubt ice accumulated little by little at the poles. The most

favoured marine organisms were those which presented the least amount of specialization for any given facies.

Just as the Tethyan transgressions were accompanied by warm currents which carried the equatorial faunas towards the poles, so the arctic transgressions were accompanied by tepid currents taking the faunas in the opposite direction. We are probably justified in thinking that from the time of these transgressions ice-caps began once more to form at the poles. The Senonian Chalk seas appear to have had about the same temperatures as the present-day Atlantic Ocean in similar latitudes.[1] The oceans, then, would have lost water, locked up in the form of ice. Thus it was that the arctic transgressions prepared the way for the regressions.

THE PROGRESS OF LIFE ON THE SURFACE OF THE EARTH

Since the Infra-Cambrian (a period of continental stability before the emerged lands had become populated with living things) several epochs of marine regression and of flooding of land surfaces have occurred. Generally speaking, these epochs followed, fairly regularly, a complex of events consisting of a Tethyan transgression and an Arctic transgression. Furthermore, they were sometimes marked by the upheaval of mountain-chains and always coincided with a maximum of climatic differentiation. In fact, there was a simultaneous occurrence of extensive glaciation and vast desert areas. The locking up of huge quantities of water in the form of polar ice was accompanied by a marine regression and by the desiccation of many lagoons, giving rise to the formation of deposits of salt, gypsum and dolomite.

In such times, before the continental platforms had become

[1] H. C. Urey, H. A. L. Lowenstam, C. R. Epstein and McKinney: *Measurement of Paleotemperatures and Temperatures of the Upper Cretaceous of England, Denmark and the South-Eastern United States*. Bull. Geol. Soc. Amer., Vol. LXII, No. 4, pp. 399–416.

the theatre of great marine invasions (as in the Upper Cambrian at the time we are considering), there occurred an almost complete retreat of the Tethyan waters, at least in the region of the present Mediterranean. A retreat of a similar kind may possibly have taken place also at the end of the Primary Period (that is during the Permian), but at that time the site of the Mediterranean area did not completely emerge. Around the shores of the Pacific ocean (and to a less extent elsewhere) we often find traces of the sea's advances during these periods of Tethyan regression, but such inundations are hardly comparable in extent with those of the Tethyan transgressions. We can, however, state that the great epochs of Tethyan regressions were also the ages of circum-Pacific transgressions which were due, in part at least, to the time-lag between the various uplifts of mountain-chains in different parts of the world.

THE FIRST LIVING CREATURES TO BECOME ADAPTED TO DRY LAND CONDITIONS

There were, then, periods during which the continents were well above sea-level, but during the Cambrian, and even during most of the Ordovician, there existed no animal or plant with a physical structure enabling it to survive and to evolve in the atmosphere.

Nevertheless, among the marine faunas, and even among some of the less highly organized forms, there were some which possessed an internal medium isolated from the exterior. Such animals support, better than others, variations in the salinity of the waters. Some of these organisms, indeed, contrived to live in lagoons which were supersaturated with salt, owing to the sun's radiation, while others existed in estuaries where the salt waters of the sea mingled with the fresh waters brought down from the dry land.

It is in Ordovician sediments of estuarine type that the earliest fragments of vertebrate animals have been found. There is only one step from life in water of variable salinity to existence in fresh water. This step was taken in the Silurian Period (perhaps even in the Ordovician) by two great groups of animals: (1) the Vertebrates, the whole of whose evolution until the Devonian took place on the continents in lakes and rivers, and (2) the Arthropods. Among the latter the Merostomata, allied to the Trilobites, became slowly specialized for a fresh-water existence and gave rise to several groups: Gigantostraca, ancestors of the giant carnivores of Devonian times; Xiphosura, which returned to live in the coastal regions of the seas; and the Scorpions, whose first representatives were possibly marine (although the specimens collected on the island of Gotland do not allow us to affirm this categorically) but which, after the Silurian Period, were undoubtedly terrestrial animals breathing air.

Aerial respiration was a very difficult faculty to acquire. The apprenticeship, so to speak, must have often been served in the intertidal zone. This was true especially for the gastropod mulluscs, of which several ancient types, such as Pleurotomaria and the Bellerophontidae, although still provided with a pallial cavity sheltering several gills present a peculiar vascularization of the ceiling of the cavity. This might well be called a 'lung', by comparison with that of such Pulmonates as the landsnails (*Helix, Bulimus,* etc.), and was perhaps used as such. Among the Arthropoids air respiration seems often to have been acquired in a less complicated fashion, either because their gills were still able to function in damp air (as is the case with certain crabs), or because tegumentary folds began to appear beside the gills and presently supplemented them by forming tracheae. This may be observed in certain Myriapods.

With the Vertebrates, the transition to aerial respiration was facilitated by the existence on the Devonian continents (on

which were laid down the molasses of the Old Red Sandstone) of seasonal lakes into whose muddy beds burrowed fish that were thus enabled to survive during the dry season, just as the Dipnoans (descended from some of these Devonian fish) do at the present day. Many fish which live in fresh water or in the sea possess an appendage in the form of a sac in the pharyngeal region, whose physiological function is not very evident. This is called a *swim-bladder*. Among the Dipnoans a real lung seems to have evolved from this organ.

Nevertheless, no animals could have made much progress towards the conquest of the continents had not the plants also undergone a sufficiently rapid evolution.

In the seas of the Lower Palaeozoic, green, red and brown algae developed very considerably. We know, however, that no extant representative of these organisms is capable of surviving long out of water. We may, then, suppose that their ancestors adapted themselves to fresh waters in a similar way to that followed by animals. However, vascular plants living in the open air and breathing through their stomata appear only at the end of the Silurian Period. These vascular plants were types that flourished in marshes. They possess a thallus and although they resemble algae they are also related to the mosses. They are herbaceous but do not yet exhibit one of the most important characters for the biochemical role of plants, the increase of the green surface responsible for photosynthesis. Indeed, leaves do not begin to assume importance before the second half of the Devonian Period. First appeared simple ferns (*e.g.*, *Archaeopteris*), and then followed rapidly all the other ferns, the Lycopodiales, the Equisetaceae, the primitive Conifers and the Cordaitales, of which the assemblage made up the lush and luxuriant biotype of the Carboniferous forests whence we derive our coal.

We can say, then, that real continental biotypes were established during the Devonian, but the dry land was not as

intensely populated by plants and animals as it is today. Life had appeared on the land and had taken up its position, so to speak, but modestly, with no exuberance. Still, though life on the continents was confined to fresh waters, lakes, marshes and their immediate neighbourhoods, nevertheless the painful pilgrimage up from the sea through the estuaries had been accomplished.

It was not until Upper Devonian times that Vertebrates began to venture out of their aquatic surroundings. At Mount Celsius (Ymer Island), in the folded and uplifted fore-trough of the Greenland geosyncline, the first stegocephalous Amphibian

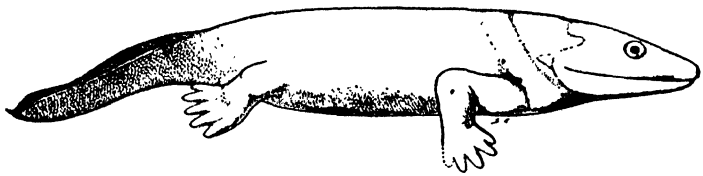

Figure 4. A reconstruction of *Ichthyostega* sp. (*After* E. Jarvik)

—*Ichthyostega*—was discovered. Its tail was still much like that of the Crossopterygian fish, but *Ichthyostega* (Fig. 4) walked upon four feet.[1] The Ichthyostegids were, indeed, still fish in their possession of a real dorsal fin (supported by radial and dermal bones), in their independent peroperculum, in their vestigial suboperculum, in their developed neural endocranium and in their parasphenoid. Nevertheless, they were amphibians in their limbs and in the position of their external nostrils, a position, moreover, which is very peculiar and suffices to class these creatures in a very definite group.

We thus have in *Ichthyostega* a transitional form, one of those which enable us to verify the conclusions drawn from comparative anatomy.

[1] E. Jarvik: *On the fish-like tail in the Ichthyostegid Stegocephalians*. Meddell. om Grönland, Vol. CXIV, No. 12, 1952.

It is clear that the natural fixation of broken rock particles began with plants taking root on dry land. The erosion, which had hitherto continued without restriction from the time of the first upheaval of a mountain-chain, began to be checked. Sediments, often of detrital origin, began to be reduced to a finer consistency. Gradually, as life developed progressively, the organically formed rocks came to form a considerable part of the sediments. At the same time, the continental soils which, with their humic acids, were comparable with the marine muds and slimes began to be of importance in the geochemical evolution of the earth's surface.

THE PROGRESS OF LIFE FROM THE CARBONIFEROUS TO THE TRIASSIC

What we may call the 'great continental epoch' which followed (though tardily) on that of the Old Red Sandstone began at the end of the Carboniferous, continued during the Permian and extended partly into the Triassic (Plate XXVII). Amphibians, Insects and Arachnids show very considerable development, while the Vascular Cryptogams, which made up the great coal forests and which appeared as early as the Devonian, gave scope for the evolution of new types. These groups left the marshes (where they had enjoyed their heyday at the time of the warm coal forests) and almost simultaneously acquired structures towards the end of the Permian and during the Triassic which gave them the means of transmitting life with a 'time-lag'. In the plants, seeds, furnished with protective envelopes and reserves of sustenance, replaced directly developing ovules. The embryonic additions to the reptiles' eggs—new-

comers among the vertebrates—allowed of the embryo's preservation from the beginning of its existence. Lastly, towards the end of this long period of emergence, there appeared insects with complete metamorphosis.

This sum-total of acquisitions indicated a novel possibility—that of the safeguarding of the germ-cells (or even of young animals) so that they might survive without much harm an unfavourable period, such as a cold winter or a dry season. The existence of seasons, in our sense of the term, is proved by the annulations or growth-rings in the wood of the earliest conifers.

DELIMITATION OF LAND PROVINCES

During this same epoch, which begins at the end of the Carboniferous and ends sooner or later in the Permian or Triassic, we find the first evidence of the formation of 'provinces' differentiated from one another by their assemblages of plants. The Euramerican province exhibited Lycopods (*Lepidodendron*), Calamites, Seed-Ferns (*Pecopteris, Callipteris*) and Conifers; the Angarian province *Schizoneura* but no Conifers; the Gondwanian province the Glossopterids; and the Cathaysian province (with a corresponding province in the North American mountains of Colorado) ferns of a type similar to those which flourish today in the monsoon lands. Palaeogeographers have devoted much study to the situation and position of these provinces. They are, in fact, first and foremost climatic areas, since some of the elements of the Gondwanian flora penetrated not only into the Angarian assemblages but also into some parts of Europe, while, as we have noted above, the Cathaysian flora of the Far East is present also in North America.

With regard to the Gondwanian province, it would seem that the Tethys had isolated it from the northern continents until the Permian Period, as is indicated by the distribution of

the tetrapod Vertebrates. Indeed, in the light of our present knowledge, it looks as though these animals underwent the very early phases of their evolution in the Laurasiatic regions, especially in various parts of the North Atlantic continent, and, later on, in Russia and Asia. However, it would appear that during the Upper Permian an uplift occurring along a north-south axis raised the Iranian areas and, for a time, bisected the Tethys in this region. At all events, during this epoch reptiles made their appearance in South Africa.

The above-mentioned provinces, as we have described them, hardly survived through the Triassic Period. As early as the Permian in America, and during the Triassic in Eurasia, desert conditions invaded the continents. The floras which had flourished in the coal-marshes were permanently destroyed. However, since they were more robust, Conifers of the family *Araucariaceae* (trees which, today, are especially characteristic of Australia) managed to strike root in the red sands and to prepare for their future vigorous development. During the Triassic, also, there was some attempt made by the Lycopods to adapt themselves to a desert facies, but this *Pleuromeia* was not the direct forerunner of any later line.

REGRESSIONS AND THE APPEARANCE OF MONSTERS

While the continents increased in area over the surface of the earth, the oceans, more restricted in area than those of today, were bordered by sea which underwent intense evaporation. Those Invertebrates which developed in these seas were subjected to the influence of an abnormally high salinity, to which they reacted in a variety of ways. In the cold and temperate regions of northern Europe the creatures inhabiting these lagoons suffered from the temperatures and decreased in size as witness the dwarf fauna of Zechstein (the Upper Permian of

Germany). On the other hand, in the tropical conditions prevailing over the area (then rather discontinuous) of the Tethys, the Invertebrates of all groups gave rise to strange forms which, for the most part, died out without leaving descendants. Thus, as early as the Upper Carboniferous there appeared Brachiopods looking like corals (*e.g.*, *Richthofenia*, which has a conical shell encumbered with calcareous deposits), and other Brachiopods (namely *Leptodus*) with extensively fretted shells. In the Lower Permian of Timor there are crinoids which underwent atrophy of their arms. The Triassic fauna of Saint Cassian (in the Austrian Alps) also shows a tendency towards dwarfishness, and displays curious forms, such as the Tiarechinid echinoids, which are unlike any other sea-urchin before or since.

THE BIOLOGICAL CONDITIONS IN THE SEAS AT THE DAWN OF SECONDARY TIMES

From the beginning of fossiliferous times (and the commencement of organic evolution) there elapsed a vast epoch of rather more than 300,000,000 years before the Primary Era came to a close. During that time almost all the main groups of living organisms which we know today, had made their appearance, and many of these had also accomplished the essential phases of their evolution. This holds good, from Cambrian times, for the Sponges, the Trilobites (which became extinct during the Permian) and the Brachiopods; from Ordovician times for the Bryozoa, the Pterobranchia and the Echinoderms; from the Devonian for Fish and the Vascular Cryptogams; from the Carboniferous for Amphibians; and from the Permian for Reptiles and Conifers.

However, during the harsh Permo-Triassic ages there took place a drastic process of selection among the great accumulation of different organic forms. The creatures inhabiting the

coralline seas and the open sea (especially when the internal medium of these animals communicated directly with the external) were particularly hard hit. Most of the Corals, the Echinoderms, almost all the Bryozoa, the Brachiopods and the Cephalopods waned and, finally, were reduced to insignificance. Such as survived were the more simple types, able to subsist almost anywhere and to live in almost the worst conditions obtaining. Thus, among the Madrepores (a humble family of small, solitary Corals that flourished in Carboniferous times) the Plerophyllids were practically the only forms to survive; it is these which were the ancestors of the modern Hexacorals. A similar fate was suffered by the Goniatites, of which a small number of genera gave rise to the Ammonites of the Secondary Era.

On the other hand, organisms with well isolated internal media and consequent independence of variations in salinity triumphed over all obstacles, either without any appreciable change of form, as in the Cnidaria, or with notable benefit, as in the calcareous Algae, the Lamellibranchia and the Gastropoda. These last, moreover, had evolved regularly during the Primary Era and had acquired a number of structural improvements. In particular, the primitive Aspidobranchia (which suffered from the poor drainage of the pallial cavity and which, for this reason, seemed condemned to live for ever upon rocky sea-beds) acquired a better drainage system in the Pectinibranchia with a single gill, and thereby became fit to prosper on muddy sea-bottoms; thus great possibilities of considerable development were opened to them.

By the end of the Ordovician, submarine vegetation, especially Algae, seems to have been sufficiently developed on sea-beds consisting of fine sand or muds to constitute cover and even shelter for young animals, and to provide areas analogous to the spawning-grounds of the present-day marine prairies. It was from the end of the Ordovician, and with increasing

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Plate XXVI. Stromatopore reef in the Mjosa Limestone facies of the Ashgillian (Upper Ordovician) which outcrops at Bergvika on the edge of Helgoya Island in Lake Mjøsen, Norway. The polishing action of erosion has exposed the 'corals', the colonies of which appear here in cross-sections in the form of a 'gendarme's hat'. This reef is one of the most ancient in the world. The illustration may be compared with that of Plate VI, which represents a non-reef facies of the Ashgillian, also in Norway

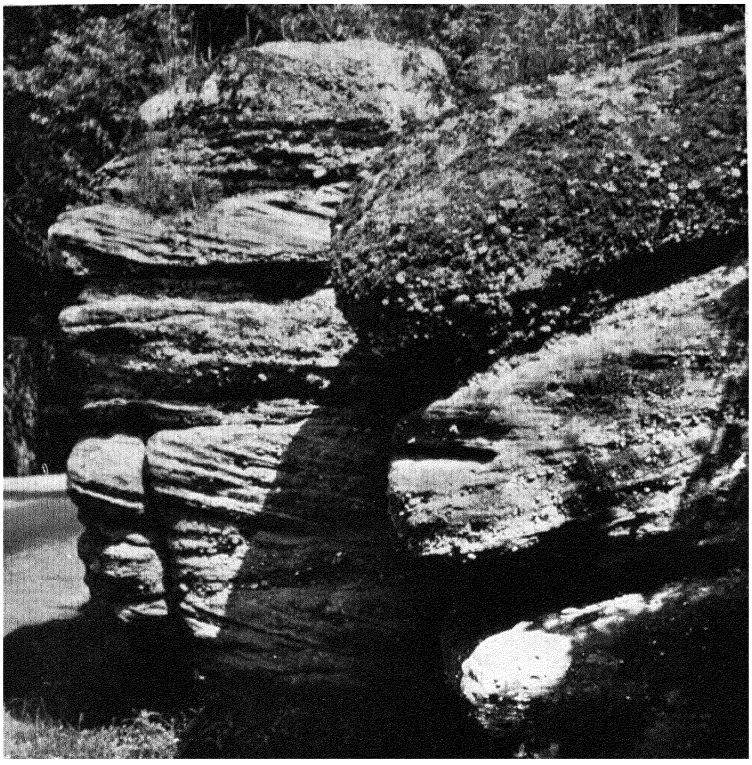

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Plate XXVII. Coarse grits of Triassic age (Bunter Sandstone) with cross-bedding, at Mont Sainte Odile, Vosges, France. A continental deposit formed from erosion of the Hercynian chain. The formation is, in fact, a molasse

frequency as the Primary Era progressed, that we encounter faunal assemblages made up of individuals of small dimensions whose shells have usually been transformed into iron pyrites, owing to the reducing conditions prevailing on these sea-beds. Among these dwarf faunas may be recognized Gastropods, Lamellibranchs, Trilobites and Cephalopods. In particular the last-named, which were swimming animals, are always found in an immature state. These assemblages, which became installed on the low coasts of shallow seas, were to prosper and multiply from the commencement of the Liassic transgression, and were the melting-pot out of which the Ammonites were to come.

In the warmer seas, it was calcareous Algae of all sorts that were to be most prevalent. They were to create a new reef-biotype in which, from Triassic times, the first hexacoral Polyps were to appear, and to which all the then existing types of Invertebrates were to adapt themselves.

TRENDS OF EVOLUTION DURING THE SECONDARY ERA

The Tethyan transgression, which started in the Trias and became more widespread in the Lias, and especially in the Middle Jurassic, sufficed to re-populate the seas with a new and more homogeneous fauna.

The formation of an assemblage of marine Invertebrates of modern type resulted from a number of events beginning in the Upper Jurassic. First came the Arctic transgression, and this was followed by the regression at the end of the Jurassic and the beginning of the Lower Cretaceous. Then came the Tethyan transgression of the Middle Cretaceous and, finally, the Arctic transgression which superseded it during the Senonian (Upper Cretaceous).

These ages were marked by the elaboration of all the Hexacorals, the prodigiously rich development of the Ammonites, the appearance of all the existing families of dysodont, heterodont and desmodont Lamellibranchia. To these must be added groups now extinct, such as the reef-forming Rudists. The Gastropods manifested a tendency to develop in the direction of the Opisthobranchs, and showed yet another tendency towards the highly specialized carnivorous forms. They have representatives in practically all the facies and, little by little, they spread to the deep seas.

During the Secondary Era the land faunas and floras evolved regularly, their progress being marked by two great forward spurts, for which the two main continental periods served as spring-boards.

From Triassic times, the reptiles began to branch out into numerous and varied types. Some evolved towards the reptilian groups we know today, while others evolved towards extinct types such as the Dinosaurs, whose gigantic size and great diversity of forms made them the dominating animals during the whole of the Secondary Era. Others, again, were the forerunners of two new sorts of creatures which were for long to remain of little importance and hide modestly in the background; these were the birds and the mammals. Homothermism, a characteristic of warm-blooded animals, no doubt appeared during the Triassic, associated with other improvements such as the differentiation of the hair and of the teeth; it was a step towards the mammalian type, though it is also met with later on in other very different phyla, where we get the feathers and wings of birds.[1]

[1] On the physiological significance of homothermism as a factor in freedom of movement, one may consult with advantage H. Laborit's *Résistance et soumission en physio-biologie* (Masson et Cie, Paris), which deals with what is known as 'artificial hibernation'. The therapeutic treatment which goes by this name (and which has been successfully developed by Laborit) was suggested by the concept of the phenomena of 'defence' closely connected with the problem of the phylogenetic significance of homostastic regulation.

The continents exposed at the end of the Upper Jurassic and the Lower Cretaceous were the domain of gigantic reptiles which, as they appeared after a long and moist period of marine transgression, inherited from it a number of amphibious types such as *Diplodocus* (Fig. 5) and *Brontosaurus*. Reconstructions have made us familiar with their huge, heavy bodies, their pillar-like limbs, their tiny heads at the ends of very long necks. The seas, on the other hand, were peopled with types such as the Ichthyosaurs and the Plesiosaurs. During these ages the plants, which had also been undergoing constant evolution, gave rise ultimately to the Angiosperms, that is, the true flowering-plants.

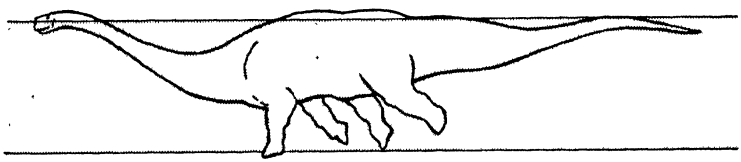


Figure 5. A reconstruction of a great amphibious Sauropod reptile (*e.g.*, *Diplodocus* or *Brontosaurus*) as it must have appeared in its aquatic habitat

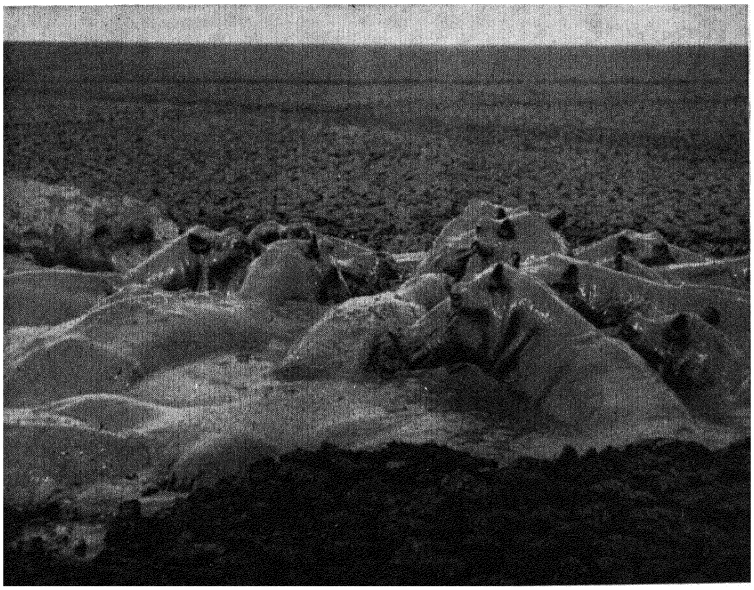
The latest spurt of evolution on dry land took place during the Secondary Era on savannas, prairies, steppes and maybe also in deserts. The amphibious reptiles gradually waned and finally disappeared altogether, while swift-moving, running reptiles multiplied in the arid biotypes. The gigantic forms were more adversely affected by seasonal variations of climate than were the other reptilian types, since both their huge dimensions and the decreasing amount of animal and plant food available made them ever more vulnerable to their enemies. The Dinosaurs had disappeared by the end of the Danian. It is true that some of their physical characters (*e.g.*, gigantism, and various hypertelic conditions—that is to say, the exaggeration of any given feature under the action of disturbances, often of

glandular origin, as is the case with the horns of the Cervidae) are characteristic of types undergoing degeneration, but it seems that the aridity of the climate was also a factor in hastening the destruction of the Dinosaurs (Plate XXVIII). The biotypes that were the richest in Dinosaurs were those of the marshy, alluvial plains, such as those which covered the Cordillera region of North America before the upheaval of the Laramide mountain-chains. Furthermore, the cooler conditions which prevailed during the great regressions were unfavourable to the existence of gigantic animals whose bodies possessed no system of thermal regulation, so that, finally, there survived only such reptilian types as have remained to the present day.

On the other hand, the Mammals and Birds, whose homothermic system was already fairly effective, found almost virgin expanses on which they were not slow to spread and where they prospered.

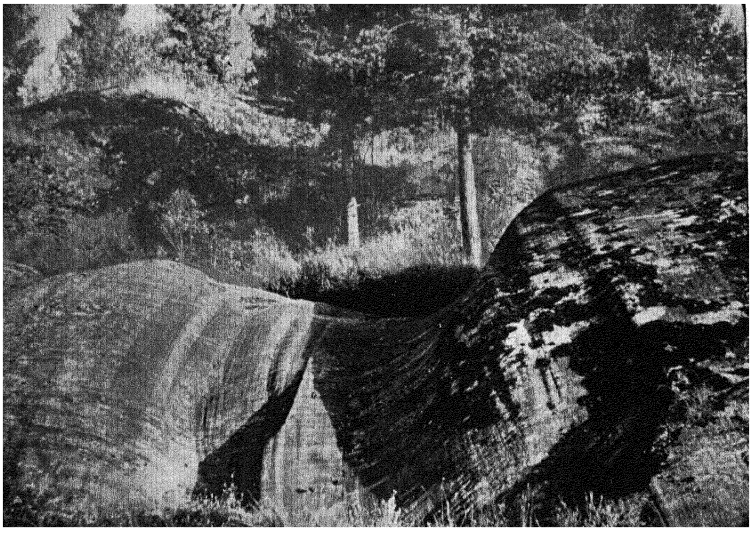
THE PROBLEM OF CONTINENTAL BRIDGES

Up to now we have referred only incidentally to the ways in which land organisms spread. It is, indeed, difficult to follow in any detail the various vicissitudes of such movements during geological periods. However, we have seen that tetrapod Vertebrates invaded the Gondwanian lands from the north during the Upper Permian, probably utilizing new routes which had recently emerged. We must, however, be more circumspect when it comes to a consideration of the migrations of plants, for seeds or spores are light enough in weight to be swept up by the winds and carried great distances. It is probably to such occurrences that we may attribute the vegetation of the atolls which are scattered over the Pacific Ocean. Also, the birds, when they had developed considerable powers of flight, were capable of transporting accidentally seeds, insects and even



Rapho

Plate XXVIII. Herd of hippopotami dying of hunger and exhaustion from the effects of the 1950 drought, which caused the evaporation of four-metres depth of water from the marshy lake of Rukua (Tanganyika) and kept the animals half immersed in the mud. These large mammals either could not, or did not know how to, ward off the catastrophe by moving away in time to a wetter region, and they all perished. This picture compels us to consider that the aridity which became marked in Danian times may have been a determining cause of the disappearance of the Dinosaurs



G. Termier

Plate XXIX. Ice-smoothed Pre-Cambrian gneiss, polished and scored by the great Quaternary ice-sheet, at Rognstrand, southern Norway. Northern Europe and North America (*see* Plate XXII) were covered by ice-sheets on four separate occasions during the last million years. The immense areas covered were, practically speaking, denuded of all forms of higher organisms. After the last glaciation life reappeared in the deserted regions but, in Europe, with an impoverished flora

fresh-water molluscs, either stuck to their feet or caught in their feathers.

During the Tertiary Era, the nearest to us in time, the mammalian colonization of all the continents allows us to come to closer grips with the problems of migration. It is, indeed, now well established that several complete faunal assemblages of Mammals successively invaded very large areas of the earth's surface. Since it is not very reasonable to hold that animals of the same genus appeared simultaneously, yet independently, in continents far removed from one another, and since it is (to say the least) rather exceptional for large land mammals to cross the seas, either by swimming or with the aid of natural rafts (though this is possible across narrow straits), we are led to envisage the existence of continental bridges.

In fact, the concept of transgressions and regressions, even of those which occurred on a comparatively small scale during the Tertiary, enables us to reconstruct fairly easily some of these land bridges. The best known is certainly that of Central America which, in two different geological ages, provided a passage between North and South America.

Central America was until the Eocene Period a part of the Caribbean Continent. It next experienced the uplift of a mountain-chain in the northern Antilles and of another in the southern Antilles, the latter of which was linked up with the Caribbean Chain of Venezuela. Then, towards the end of the Eocene and at the beginning of the Oligocene, a local Tethyan transgression severed the two Americas. Thus, while the mammalian faunas in other continents constantly intermingled and evolved in an almost uniform fashion, in South America (starting from similar forms, but quite independently) there took place an evolution which might be called 'nonconformist', since it gave rise to types that appear strange, and even aberrant, to zoologists who are familiar with the present-day descendants in other continents of the Tertiary mammals. Each biotype

existed and each type of animal evolved. There are, among the Notungulata, for instance, types resembling hares, horses, camels or rhinoceros, and among the marsupials imperfect mammals which have survived in South America—as in Australia—to our day, because competition was there less fierce than elsewhere; there are also carnivorous types.

At the beginning of the Quaternary an uplift re-established the continental bridge of Central America by which came invasions of more powerful types of animals evolved and originating in other continents, and coming down from—or actually having been differentiated in—North America. In South America most of the autochthonous animals declined in numbers, or disappeared, easily overcome and supplanted by alien forms even better adapted for life in South American conditions than were the types which originated there.

In contrast to the former isolation of South America there was almost certainly a link between North America and Europe and Asia in Tertiary times. The Bering Strait, still a very shallow sea, must be considered as the most likely area of communication between North America and Asia, but we must admit that there was possibly, at least from time to time, a direct passage-way between Europe and North America.

So we once more meet with our phantom continent of the Thulean Province (Map 2, between pages 72 and 73) which, at any rate during the Eocene, might well have formed the link between the two great land areas. However, we must remember that after the Oligocene (when the subsidences must have become permanent) direct communications between Europe and North America seems to have been difficult, since great mammalian groups (such as the Artiodactyls) remain characteristic of the Old World and not of the New.

It is not, however, fanciful to think that for some time the Caledonian orogenic zone, more or less rejuvenated, allowed of a procession of mammals being established all round the

globe, pretty near to the line of the Arctic Circle. The name of *Arctica* has been given to this belt, which is composed of island chains, of land bridges long since vanished and of portions of existing continents.[1]

A GENERAL VIEW OF BIOGEOGRAPHICAL EVOLUTION

We have sketched out the main lines of the more striking phases of organic evolution as they appear in the light of geological phenomena. All that we know about this evolution does not (except in the case of very simple organisms such as the Schizophytes and the Protista) relate to a genealogy occuping more than five hundred million years—that is to say, a period of less than one-seventh of the earth's history. Moreover, we must admit that many forms—more than one of which has had time to disappear entirely—were fully elaborated by the end of the Primary Era, two hundred million years ago.

The close connection which has existed between the marine transgressions and regressions (a connection we have sought to stress throughout this book) demonstrates to what a great extent organisms are dependent upon their environment. When we compare the biological features (which have been so often defined according to violently opposing theories, such as 'complex organism × environment', 'pre-adaptation', and 'empty space') with the geological phenomena to which the various facies are due, the former take on a new significance—the only one that agrees with the facts of evolution.

The expression 'complex organism × environment', as it has been defined by E. Rabaud (in *Transformisme et adaptation*, Flammarion, Paris, 1942), represents a synthesis of the components of a palaeobiological facies reconstituted with the aid

[1] A. J. Eardley: *Structural Geology of North America*. Harper's Geoscience Series, New York, 1951.

of biostratigraphy. The so-called 'pre-adaptation' of organisms is a concept which applies to certain comparatively unimportant organic characters which do not seem (at first) to have had any precise significance and which for long remained accessory but conferred upon the creatures possessing them the means of acquiring a new type of physiology in a new environment. As to the concept of 'empty space',[1] this assumes its full significance when a great and far-reaching biological phenomenon has entirely changed the conditions of environment and thus has produced novel biotypes which are attractive to, and at the disposal of, certain organisms.

By the end of the Tertiary, the major portion of the earth's surface had been occupied; that is to say, it had been gradually conquered by the biosphere. Then a new phenomenon appeared—one very important indeed for us, but one which seems also to have been very important for the history of the earth—the appearance of Man.

If we consider the possibilities offered by our planet, we can theoretically imagine several successive evolutions each ending in total destruction. The fossiliferous ages (from the Lower Cambrian) do not cover a period of more than five hundred million years, yet this has been long enough for the evolution of all the species from the first Trilobites to Man. But we know now that the age of the earth must be at least three thousand five hundred million years, a period seven times greater than that which has elapsed from the Cambrian to the present day. There is no doubt that, at the beginning of the earth's history, both the composition of the atmosphere and the nature of the climates were not very favourable to the appearance of life, though it is probable that amelioration of these conditions took place comparatively quickly.

Have such suppositions, based only upon what appears to be logical reasoning, any chance of being verified? Surely not,

[1] L. Cuénot: *L'Evolution biologique*. Masson, Paris, 1951.

if we take into account the data—far from complete, though certainly sufficient—offered by geological research. As we have emphasized in the last chapters of this book, organic evolution is closely and intimately linked with the physico-chemical conditions prevailing in the seas and on the lands, and with their inter-reactions. But the marine transgressions and regressions—which have exercised a direct influence upon both climates and biotypes—do not seem to have begun before the Infra-Cambrian. In these circumstances, the organic evolution appears as a marvellous adventure, but also as a unique adventure, at least as far as our planet is concerned.

6

THE POSITION OF MAN IN THE HISTORY OF THE GLOBE

IT SEEMS clear enough that the first appearance of Man in the biosphere was as unostentatious as that of all those other animals which, later on were to have remarkable descendants. If we push back our search as far as possible, we must admit that the lemurs in the Eocene and the monkeys in the Oligocene (of Egypt) seem to have occupied only a very modest place in their chosen biotypes. About a million years ago or more, there existed in South Africa a group of Primates less specialized than the existing anthropoids and including forms, the *Australopithecinae*, which some scientists consider as representing a type similar to that which was ancestral to the Hominidae.

Some six hundred thousand years ago there existed in the Far East (and especially in Java and China) types which were more like us and which were tool-makers, although they had still not evolved very far towards the human form. Of these the best known are the *Pithecanthropus* of Java and China. From that time the Hominidae began to spread in Asia and to reach Europe.

Early Man soon learned how to kindle fire and to fashion implements. These gave him superiority over other creatures in procuring his subsistence and in physical contests. Man enjoyed a great advantage over all other living creatures both by the development of his brain and also by his unspecialized

hands. But we may note that until about 100,000 years ago Man did not venture out of the warm and temperate regions.

The great geological peculiarity of the Quaternary lay in its being a period of regression which favoured the development of land biotypes, and also encouraged marked climatic differentiation. Four successive glaciations, in various parts of the world, both covered and wore down the continental areas (Plate XXIX), and thrust towards the tropical zone the belt of steppes and savannas whose place was taken by tundras and glaciers. The warm floras and faunas, more and more impoverished at each glaciation, regained ground, however, during the interglacial periods, and the Hominids followed in their wake.

During the fourth Glaciation (known as the Würm or Vistula), Man did not emigrate to warmer climes for he had become able to clothe himself and to keep himself warm. Indeed, he had attained almost the same stage of evolution as we enjoy at the present day. Different races of men adapted themselves, more or less successfully, to various extremes of climate.

Gradually, by increasing his means of subsistence and the area of his conquests, Man 'discovered' all the different zones of the biosphere and colonized practically all the land biotypes. Today, men like ourselves inhabit the Sahara in Africa just as they do Verkhoyansk in Siberia or the northern Canadian wilderness. We cannot, of course, say that men really flourish in such uncongenial surroundings, but they are able to live and even to work in them.

Thus, human evolution must be considered from quite a different point of view from that of the rest of organic evolution, which, as we have seen, is determined in so rigid a fashion by the vicissitudes of physico-chemical conditions, themselves ordered by geological phenomena.

To designate the world in which Man lives and moves there

have been coined terms with a geophysical consonance, such as 'Noosphere' and 'Psychosphere'. But we may justifiably argue that Man, by his power of reasoning and his spirit of invention, has inaugurated a new phase in the realm of Life. Whereas in Pre-Cambrian ages life appears essentially as a geochemical process, and whereas during fossiliferous times life follows the irreversible path of evolution, with Man the history of life ascends to a higher plane. Evolution, we may say, has become a conscious process, and appears capable of acting upon itself.

From the material point of view Man must now be regarded as a *geological agent*. Not only does he delve into the earth in order to extract therefrom minerals, coal and oil, not only does he use for his own profit energy of geological origin (hydro-electric power, for instance), but he also modifies various aspects of terrestrial geography. The cutting of the Suez and Panama canals, the drainage of the polders and of the Pontine Marshes, the diversion of the course of the river Volga, are geological phenomena that are by no means negligible. Furthermore, by deforestation and by afforestation (such as that undertaken in the Landes department of France), Man increases or checks both the rate of, and the ravages caused by, erosion.

CONCLUSION

If we would sum up in a few words the geological history of the earth's crust, as we know it today, we might say that the great geological phenomena obey regular laws, most of which are represented by those sequences which we have called *dramas*.

On to this recurring framework of physico-chemical processes has been grafted the phenomenon of Life. Encouraged by the relative movements of the lands and the seas, which

seem to have begun at a more or less definite period in the world's history, Life has moulded Matter. Moreover Life has developed in its own special way, for it has progressed along the irreversible direction of organic evolution.

Finally, Evolution clearly jumped a gap with the appearance of Man, a creature capable of *thought*.

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