Climatic Changes during Geological Times.

By C. E. P. BROOKS.

I. GLACIAL AND GENIAL PERIODS.

AFTER the primary discovery of geologists that the various strata of rocks exposed at the earth's surface could be arranged in chronological order, and that when so arranged they represented a sequence covering a very long period of time, the most striking result of their investigations has concerned the great variations of climate which all parts of the earth's surface have passed through. Coral reefs have extended into the British Isles and central Europe, and evergreens have flourished beyond the Arctic Circle. At the other extreme, large areas now enjoying a temperate or even tropical climate were covered by thick ice-sheets.

The evidence for all these changes is now so abundant that the general facts can no longer be questioned, though there are still differences in the interpretation of details. Thanks to this patient accumulation of evidence, we are now well acquainted with the climatic history of most parts of the earth's surface. Only the very oldest strata, the Archæan, composed of gneisses and similar rocks, are so altered that they give practically no information as to the climate prevailing when they were formed. At one time they were believed to be remnants of the earth's original crust, born in fire, but although the uranium-lead and thorium-lead ratios show that, according to the usual method of computation, some of these rocks are so much as 1600 million years old, the astronomical calculations summed up by Harold Jeffreys point to the age of the solar system as being very much greater still. Hence it is very improbable that any parts of the original crust of the earth still remain accessible.

The sedimentary rocks formed in the succeeding Proterozoic era are in many localities sufficiently unaltered to indicate the conditions under which they were laid down. During the greater part of this era the prevailing deposits were sandstones, such as the thick Torridonian Sandstone of Scotland, and limestones, but in many widely separated areas glacial deposits have been found—near Adelaide in Australia, in the Himalayas, South Africa, the United States, the head of the Yang-tse River in China, and perhaps also in Scotland and the Varangerfjord in Norway. The glacial phenomena at the latter site are very fine; they may be of any age from Proterozoic to Permian, but are most probably Lower or Middle Cambrian. The succession of events is best shown in Australia, where ancient boulder-clays or 'tillites' have been found on two horizons separated by 9000 feet of conformable strata. The later of these two tillites occurs probably just below the base of the lower Cambrian. Two glacial horizons, one probably just pre-Cambrian and the other much older, have also been recognised in South Africa, and possibly in the United States and India.

The Palæozoic was thus ushered in by an ice-age, but by the Middle Cambrian all traces of glaciation, with the possible exception of the Norwegian, seem to have disappeared, and by the Upper Cambrian at least mild climates had developed in all parts of the world. The temperature was not the same in all latitudes; for example, the Archæocyathinæ, which are fully developed in Australia, are dwarfed and crippled in the Antarctic, but the zonal differences were less than at present. The Ordovician period was one of prolonged warmth; in the Silurian this general warmth continued, and corals spread into all latitudes, though in the Arctic only isolated dwarfed forms occur. The Silurian also gives us some evidence of the development of desert climates, while in south-east Alaska, and possibly in Tasmania, there are traces of ice action. In the Lower Devonian the faunal zones became more accentuated, and there is evidence of ice action at Table Mountain in South Africa and probably also in the Falkland Islands. In the Upper Devonian, however, the general warmth appears to have returned, and in the Old Red Sandstone extending from England to the Baltic States we have evidence of a widespread arid region, which Walther compares with the interior of Australia or with the Trans-Caspian desert. The prevailing warmth continued into the Lower and Middle Carboniferous, when thick coral reefs were formed in middle latitudes and a cosmopolitan flora spread over the greater part of the land surfaces, but in the Upper Carboniferous the ice-sheets returned over very wide areas.

This ice-age is generally termed the 'Permo-Carboniferous,' because when its remains were first discovered they were believed to fall mainly at the junction of these two periods. It now appears that the ice reached its greatest development in the Upper Carboniferous, when the ice-covered area was probably greater than at any other time in the earth's history. The most remarkable feature of this glaciation is the distribution of the ice-sheets—a large part of Australia, South Africa, India, eastern South America from southern Brazil to the Falkland Islands. This immense area, much of which is now within the tropics, was covered, not by local valley glaciers, but by immense regional ice-sheets. The striæ indicate that the ice moved southwards in Africa, but northwards in India, *i.e.* away from the equator, but in Australia the centre of dispersal lay to the south-west of Tasmania. Farther north there are some rather doubtful glacial deposits in Europe—Germany, France and Holland—and a large amount of quite definite evidence of glaciation in North America, where the glaciers appear to have attained a considerable size and to have reached the sea. The most interesting glacial deposits in North America, the 'varve' clays associated with the Squantum tillites, will be referred to later. No Carboniferous glacial deposits have yet been discovered in the Antarctic.

Apparently contemporaneous with the ice-sheets was the rich flora of the Coal Measures in North America, Europe and Asia, which developed from the cosmopolitan flora of the Middle Carboniferous, but in Australia, India and South Africa a new flora of hardier appearance developed above the glacial deposits—the Glossopteris flora.

In the Upper Permian the climate again became generally warm and dry, and this initiated a long period of genial climate which persisted with only minor interruptions throughout the Mesozoic and the greater part of the Tertiary. There was floating ice in the English chalk seas and in Australia in the Cretaceous, and Alpine glaciation in the Antarctic and in the San Juan Mountains of Colorado in the Eocene, and perhaps in the Italian Alps in the Miocene, but the general impression given by the Jurassic coral reefs of Europe and the Upper Eocene Arctic flora is one of slight differences of temperature between different latitudes and warm ocean currents penetrating into the neighbourhood of the poles.

During the Pliocene the temperature began to fall rapidly, and it is probable that quite early in this period the Antarctic ice reached the sea, while a boreal fauna developed in the Arctic Ocean which spread out into the Atlantic, and early in the Quaternary penetrated into the Mediterranean. During the latter period glaciers formed on the mountain ranges in all parts of the world, developing into great ice-sheets in the north temperate zone, where there were four main advances of the ice—the well-known Gunz, Mindel, Riss and Wurm stages of Penck and Brückner's classification. Since the maximum of the Wurm there have been several minor oscillations, passing gradually into the present climate.

The outstanding features of this history are the alternation of glacial and genial periods and the association of glaciation with mountain-building, of warmth with periods of rest. The Lower Proterozoic glaciation was associated with great outpourings of lava, the Late Proterozoic-Early Cambrian glaciation coincided with a period of disturbance, the Upper Carboniferous glaciation followed the Hercynian folding, and the Quaternary glaciation followed the culmination of the Alpine folding. Minor periods of unrest, such as those of the Silurian or Cretaceous, were followed by minor deteriorations of climate. This orogenic-climatic cycle becomes more obvious when the dates are considered. The Quaternary glaciation was an affair of yesterday. The radio-active clock (according to the usual basis of calculation) gives the age of the Upper Carboniferous as 260 million years, and the base of the Cambrian as 500 million years. The interval between the two Proterozoic glaciations has not been defined exactly, but a reasonable estimate would be 200-300 million years. Thus each cycle of the geological seasons seems to have run its course in about 250 million years, giving a regular sequence which has been termed the "rhythm of geological time."

Before the causes of this grand climatic cycle can be discussed, however, the possibility has to be considered that the fluctuations were more apparent than real. In any region, such as Europe, the climatic sequence can be expressed in terms of variations of apparent latitude. This obvious fact has led to several theories of 'pole-wandering' and 'continental drift'—Simroth, Kreichgauer, and finally, the very complete and far-reaching theory of A. Wegener.[1] Wegener's work seems at first sight unassailable. The earth's surface is at present divided into a number of climatic belts—an equatorial rain-forest belt, two sub-tropical dry belts, two temperate rain belts, and finally two polar glacial caps. Now consider the climatic variations of western Europe. In the Upper Carboniferous there are the coal-measures—apparently the remains of an equatorial rain forest. In the Triassic there are desert sandstones—remains of the sub-tropical dry belt. During succeeding geological periods Europe passed successively through the warm temperate and the cold temperate belts until in the Quaternary it entered the polar glacial cap. Now go back to the Upper Carboniferous. If regions now in latitude 50° N. were on the equator, the south pole must have lain in some point now in 40° S. While Europe was much warmer than it is now, a large part of the southern hemisphere must have been much colder, and in fact a large part of the southern hemisphere now enjoying warm temperate or sub-tropical climates was then glaciated.

So long, however, as the continents remained in their present positions relative to each other, some parts of the southern glaciated region must fall in low latitudes no matter where the south pole is placed. Wegener gets over this difficulty in two ways. First, he considers that the relative positions of the continents have not remained the same. Continents are composed of masses of relatively light rock (sial), embedded in heavier rock (sima) which under long-continued pressure acts as a viscous fluid. Hence under the continuous action of any horizontally directed force the continents will drift through the sima. The east coast of America fits so neatly into the west coast of Europe and Africa that there is good warrant for believing that the two were formerly united and have recently drifted apart; there is some geological and biological evidence in support of this view. Similarly, though on less plausible grounds, Wegener effects a *rapprochement* of Africa, India, Australia and the Antarctic continent, the whole forming in Carboniferous times a compact continent or 'Pangæa,' centred near the south pole. But even this is not enough; parts of the glaciated area of Pangæa extended into temperate latitudes, and Wegener further supposes that the south pole described a wide curve through this primitive continent, so that different parts of the land area were glaciated at different times.

Wegener accounts for the long periods in which there is no evidence of ice action anywhere on the earth by supposing that during these periods the poles lay near the centres of extensive oceans, while during the glacial periods the poles lay near or over the land. In the Miocene the north pole is placed over Alaska, whence it moved eastwards across North America and Greenland to the neighbourhood of Spitsbergen. Thus the 'Quaternary' glaciation of America is older than that of Europe. The succession of glacial and interglacial periods is accounted for by Köppen [2] on astronomical grounds.

The whole work is wonderfully ingenious, and it has been accepted by many geologists. There are, however, a number of very serious objections to it. The forces which Wegener postulates to move the continents are twofold—a tidal force acting from east to west, which is indefinite but may be large, and a very small drift towards the equator which is common to all floating bodies. H. Jeffreys [3] considers that while the deeper layers of the sima are viscous, the surface layers are too rigid to allow these small forces to act. Joly's recent theory of the cyclic melting and solidifying of the sima [4] may provide an escape from this objection, and

[1] Wegener, Alfred, "The Origin of Continents and Oceans." Transl. by J. G. A. Skerl. London, 1924.

[2] Köppen, Wladimir, und Wegener, Alfred, "Die Klimate der geologischen Vorzeit." Berlin, 1924.

[3] Jeffreys, Harold, "The Earth; its Origin, History and Physical Constitution." Cambridge, 1924.

[4] Joly, John, "The Surface-history of the Earth." Oxford, 1925.

we may perhaps grant the possibility of east-west movement for which there is some geophysical evidence. But the "flight from the poles" is another matter, and in fact, according to Wegener's reconstructions, during a large part of geological time the main mass of land in the northern hemisphere was moving, not *from*, but *towards* the north pole. The evidence for these movements is entirely palæoclimatic, and needs to be very convincing to support such far-reaching deductions. Is it convincing? Leverett's comparative studies of European and North American glacial deposits do not bear out the assumption that the main part of the American glaciation is far older than the European. According to W. H. Dall the Miocene glaciation of Alaska is a myth, the main glaciation of that country having occurred in the Quaternary. The mild polar climates of the Upper Eocene cannot be accounted for by movements of the poles, since Berry has shown that a flora allied to the present temperate flora completely surrounded the north pole in high latitudes, forming a ring out of which it is impossible to bring the pole in any direction. The desert deposits of the Mesozoic are practically limited to the latitudes in which deserts are found at present. Wegener's reconstructions do not account at all for the climatic sequence in the Antarctic, as recently set out by Wright and Priestley.[5] There remains the Upper Carboniferous period.

[5] British (*Terra Nova*) Antarctic Expedition, 1910–1913, "Glaciology," by C. S. Wright and R. E. Priestley. London, 1922.

Most meteorologists would say that the development of extensive ice-sheets reaching sea-level within the tropics is inconceivable, and that for the Upper Carboniferous Wegener's theory offers the only possible solution. The succession of glaciations in different continents following a moving pole is not tenable in the light of recent geological work, which seems to demonstrate the approximate synchronism of the glacial maximum in all countries, but this scarcely affects the main problem. A more serious objection is the Upper Carboniferous glaciation of North America, which Wegener's reconstruction places on the equator. Evidence has been found that in Oklahoma, Arkansas, Massachusetts, Nova Scotia and perhaps in other regions also, powerful glaciers reached the sea, and ice-bergs or heavy shore ice transported large boulders fifty miles or more from their original source. The best development is seen in the Squantum beds near Boston, where, in addition to thick tillites, there are seasonally banded clays which are similar in all respects to the 'varve' clays formed during the retreat of the Quaternary ice-sheets in Sweden, Finland and North America. The glacial nature of these beds appears to be incontrovertible, and the well-marked seasonal banding appears to be incompatible with their formation on the equator. Whether Wegener's theory is adopted or not, the climatological problem presented by ice reaching sea-level within the tropics still remains to be solved.

(*To be continued.*)

On the Rare Earths.

THE group of about sixteen elements the oxides of which are popularly known as 'rare earths' are characterised by an exceedingly close relationship in their chemical and physical properties—a relationship which, in its intimacy, is not paralleled by any other group of elements. In consequence of this fact, the task of isolating the individual members of the group has been one of quite exceptional difficulty. Until recent years, practically every reported discovery of a new element of the group was proved, by later searching investigation, to be not one element, but two or more. In addition to this difficulty has been that of distinguishing an alleged new element from some other previously discovered element, with the result that one and the same element was discovered over and over again, each discoverer giving it a separate name. Hence, the chemistry and the nomenclature of the rare earths were for many years in a state of almost hopeless confusion from which they have emerged only during the present century, and particularly in the last decade.

The history of the discovery of the rare earths goes back to 1794 when Gadolin discovered the yttrium earths, out of which a considerable number of separate elements have since been identified. By the discovery of ytterbium and cassiopeium (or lutecium) by Auer von Welsbach in 1906, it was thought that the whole of the rare earths had been discovered, and it was not until the development of the atomic number rule by Moseley that it was found that a space in the series, corresponding to an element with an atomic number of 61, was vacant. There is now fairly conclusive evidence that, after a great amount of work by various investigators, including an exhaustive and negative examination of rare earth fractions by Prandtl and Grimm extending over a year, this element has been definitely identified by the use of the X-ray spectrum. There is also good reason for supposing that with the discovery of illinium, the name given to the supposed new element, the whole of the rare earth elements have been found and identified.

The term 'rare' as applied to these elements is relevant only in the case of a small minority of them. Cerium, believed to be the most abundant, is considered to be little, if any, scarcer than nickel, and many of the others are far from being scarce, even if concentrations of them are not common. On the other hand, a few of the elements appear to be among the rarest known, and this appears to be particularly true of erbium, and the element 61, which has so long eluded the searchers for it and even yet has not been found in measurable quantity.

The primary occurrences of the rare earth minerals in Nature are confined mainly to pegmatite dykes or pegmatitic rocks, considered to have been formed during the last phases of crystallisation and differentiation of an intrusive magma, that is to say, to the phase following acid rock formation. But rare earth minerals are usually not present in important concentrations in the primary rock formations, and it is only by the denudation of the containing rocks and the natural concentration of the relatively heavy minerals set free that accumulations representing any appreciable quantity of the material are formed.

The main source of the rare earths, so far, has been