Geology. — *"The Palaeothermal Problem in the Light of the Giant and Dwarf Theory of Stellar Evolution"*. By Prof. EUG. DUBOIS.

(Communicated at the meeting of May 30, 1925).

In all geographical formations with well characterized faunas or floras, starting with the Cambrium, these up to the upper division of the Tertiary give evidence of a hotter climate than at present, pliothermal conditions, at high geographical latitude. Though the distribution over the Earth was never perfectly uniform, it is not until the beginning of the Tertiary era, and then at first locally restricted, gradually more circumpolarly, that palaeontologic witnesses appear, testifying to gradual and progressing cooling, till at last in the Plistocene period evidence is found of the present distribution of heat.

Some of the surest palaeontological proofs of a hotter climate at high geographical latitude and more uniform distribution of heat over the Earth may be mentioned here, with a view to defining the palaeothermal problem.

In the Cambrian reef-building corals, which anthozoa now-a-days scarcely reach further than beyond the 28th degree of latitude at a single point, because they are physiologically-chemically restricted to hot seas, the secretion of lime being actually a function of the temperature, are met with up to $76^\circ\, {}^1/_2$ N. lat. in the New-Siberian Islands, and as far as beyond the Antarctic circle in Antarctica (Weddell-Sea).

Especially in the Upper Silurian formation coral reefs are known of all latitudes; in the extreme North, of the peninsula of Kanin, at 68° N. lat., and of the New-Siberian Islands and the Arctic-American Island of North-Devon, at 75° N. lat. The general hot climate throughout the period appears moreover from the cosmopolitan character of the faunas. In the Southern Hemisphere the Graptoliths in the South-Orkney Islands, found at 61° S. lat., bear witness to the same fact.

Also in the Devonian formation reef corals are found inside the Artic circle. The Upper Devonian floras of Ellesmere Land as well as of Bear Island at 78° N. lat. give evidence of the great uniformity of the vegetable world of the time. Likewise the marine Devonian fauna of the Falkland Islands and the Cape show the more uniform distribution of heat.

That the luxuriant Carboniferous flora, which is very uniformly of character over the whole Earth, must be considered as a lowland flora of a moist warm, i.e. tropical climate, appears beyond all doubt. In Spitsbergen reef corals are found in the Upper Carboniferous (chronologically equivalent to our coal-measures), and in the Lower Carboniferous of this group of islands and of Greenland, here even at 81° N. lat., the same flora as was widely spread at much lower latitude.

The Permo-Carboniferous Glossopteris flora of the Southern continents and India, which was found at 51° S. lat. as far as the Falkland islands, and in the Antarctic continent at 85° S. lat., i.e. five degrees from the pole, but also in Mongolia and China, and mixed with the northernhemispheric Permian flora, in Siberia and North Russia (at 61° N. lat.), had likewise the character of a flora of a hot and humid climate, as was recently set forth by GOTHAN [1]). This may also be derived from the fact that it occurs mixed with the Lepidodendron flora in South America and South Africa.

In the Triassic formation of Alaska the same fauna of reef-corals occurs at 60° N. lat. as in California at 41° $^1/_2$ N. lat., and in the Alps up to 45° N. lat.

Among the most reliable palaeontological evidences of a tropical climate are large forms of Reptiles. As cold-blooded animals the Reptiles are entirely dependent on the temperature of their surroundings as regards metabolism and consequently in all their functions. For this reason their life is minimum in our winter; in recent times only small forms, which can hibernate hidden, can exist at high geographical latitude. The general presence at high geographical latitudes of large Theromorpha in the Upper Carboniferous, the Permian and the Triassic formation, of large Dinosauria throughout the Mesozoic era, from the Triassic up to the upper Cretaceous formation, prove with perfect certainty that the climate there was without any winter, i.e. tropical.

In the Permian period there lived in Russia, at 61° N. lat., large Theromorpha (Pareiasaurus, Inostranzewia and others) which were closely related to South African forms, belonging to a widely-spread fauna found also in India, Europe and North America up to the Triassic period.

To a hot climate at high geographical latitude point also the large Stegocephalic Amphibia in the Triassic formation of Spitsbergen.

Already in the Triassic period there existed large forms of Dinosauria in North America up to at least 43° N. lat., in Europe up to at least 53° N. lat., in South Africa, India, Australia. Large Dinosauria also occur in the Jurassic formation of North America, Europe, South Africa. The time at which these landreptiles really flourished is, however, the Cretaceous period. From the beginning till the end of this period there existed the rich fauna of gigantic Dinosauria in North America and East Africa, in India, Central Asia, and Europe, as well as in South America and Australia. We know it of 51° N. lat. in Canada, of 70° N. lat. in Greenland, of 51° N. lat. in Belgium,, of 45° N. lat. in Mongolia, and of 39° S. lat. in North Patagonia. That of East Africa (Tendagu-

[1]) W. GOTHAN, Palaeobiologische Betrachtungen über die fossile Pflanzenwelt. Berlin 1924.

ru), at 10° S. lat., presents close resemblance to the famous fauna of the Como beds of North America. Compare Kentrurosaurus with Stegosaurus!.

The flora of the Jurassic is more uniform than that of any other period. On the east coast of Greenland, at 70° N. lat., it had the same tropical or sub-tropical character as in England at 54° N. lat., and of the species of Ferns, Equisetaceae and Cycadeae found in West Antarctica at 63° 15′ S. lat., at least as many occurred also in Europe as in India.

Also the angiospermian Cretaceous flora of the west coast of Greenland had a sub-tropical character at 70° $^1/_2$ N. lat.; it shows to be allied to the Dakota-flora of western North America known to beyond 56° N. lat., which for the greater part resembled the hot-temperate angiospermian Cretaceous flora of South Patagonia at 51° S. lat.

Coral reefs of the Jurassic period are known in Europe up to 52° N. lat., in North America to 38° N. lat., and in South America to 40° S. lat. Those of the Cretaceous formation reach 47° $^1/_2$ N. lat. in Europe.

Important indications of a formerly hot climate are also given by fossil Palms. The general boundary lines of the present palm zone do not extend further than 38° N. lat. and 32° S. lat.; only a single palm species in the Pacific islands is found as far as 45° distant from the equator. The Middle Eocene flora of South England at 51° N. lat. contains a number of palm species. This flora presented on the whole, according to GARDNER, the appearance of the forests in the Malay Archipelago and tropical South America. The Middle Eocene flora of North America at the same latitude gives evidence of a much less hot climate than there. It contains but few palms, a deviation of the same nature as in the present temperatures of those places. At present the average temperature there in North America is in January 15° C. and in July 6° lower than in South England. The Eocene nummulites, which bear witness to the presence of hot sea-water, reached Zeeland in Holland, South England and even Bremen (53° N. lat.). The Eocene marine flora of Alaska (at about ten degrees higher latitude) was, indeed, only subtropical. In the Oligocene period coral reefs lay off the north and the south borders of the Alps, and as late as the Lower Miocene the tree flora of Europe contains some palm species by the side of a diminished number of other tropical forms to beyond 50° N. lat.

On the Pacific coast of North America, from Oregon northwards, only a cool-temperate climate prevailed in Miocene times. This difference in temperature between North America and Europe compared with the Arctic regions, which is constantly met with, corresponds to the present distribution of heat, and unless a consequence of a more America-ward position of the North Pole, it might be caused, just as at present, by hot North Atlantic ocean currents, which, undoubtedly, had preponderating influence in the Pliocene period.

The Arctic Tertiary floras, famous by the work of HEER, and now almost universally placed in the Eocene, have already long been considered of great significance for the palaeothermal problem. The most northern finding places are Grinnell land at 81° 45′ N. lat. and Spitzbergen at 78° 56′ N. lat. The richest finding-place lies on the west coast of Greenland, at 70° N. lat. Such floras of from uniformly temperate to a hot-temperate climatic character are now-a-days found 20 to 30 degrees more south. An equally mild climate as that of Greenland at 70° N. lat. must have been that in which existed the Eocene flora of Alaska between 55° and 62° N. lat. On the other hand, judging from the fossil flora, the Miocene climate of Japan, at about 33° N. lat., was slightly cooler than its present climate. But this seems to be compatible with a circumpolar hot condition, when by strengthening of the hot North Atlantic ocean-currents, the Arctic lowlands, especially in winter, were favoured, and Japan, in consequence of a more pronounced monsoon climate, in winter, was in a less favourable condition as regards heat.

In the Southern Hemisphere the fossil flora of Coronel in Chili, which is Lower Miocene or older according to Berry, bears the character at 37° S. lat. of a tropical rain-wood flora. At present the temperature is there on an average 15° C. in January and 10° C. in July. The Eocene flora of the northern island of New Zealand, at about the same latitude, is described as only temperately-subtropical. The present temperature is there almost 20° C. in January and 10° in July. The formerly more favourable thermal condition on the coast of Chili than in New Zealand may probably be explained by the at the time less cold polar current along this coast, as a necessary consequence of a general pliothermal condition. The so-called Fagus flora of the region round the Strait of Magellan, between 51° and 53°$^1/_2$ S. lat., which was hesitatingly placed in the Lower Miocene by DUSÉN, suggests a formerly hot-temperate, and in opposition to the present, a humid climate. In our times it is much cooler there, the average temperatures being 10° C. in January and 5° C. in July. Of the highest southern latitude is the fossil flora of Seymour-island in West Antarctica, at 64°15′ S. a place now buried under ice, which flora was placed in the Tertiary by DUSÉN. It gives evidence of a subtropical climate. These South-American and Antarctic floras are considered as Plistocene by IRMSCHER [1]) in connection with the hypothetical place of the pole according to WEGENER. The subtropical Seymour flora then remains, however, at at least 50° S. lat. WEGENER himself places it at 45° S. lat. in the Upper Tertiary. If the indeed not sharp, but at any rate older estimations of the geological age of these floras by BERRY and DUSÉN are accepted, they fit into the frame of the Tertiary floras of the Northern Hemisphere, which bear witness to a hotter condition throughout the

1) E. IRMSCHER, Pflanzenverbreitung und Entwicklung der Kontinente. Hamburg 1922

Boreal Earth, with temperatures diminishing from the beginning to the end of the Tertiary era. Disturbances in the zonic climate system, as in Europe through hot ocean-currents, in Japan through the monsoon-climate could locally retard or accelerate the, on the whole gradual, cooling, in the former case cause the temperatures even to rise above the earlier ones, in the latter case cause them to fall below the present ones. To the latter the Miocene glacial deposits in Alaska seem also to testify.

Of the orders of Reptiles extant after the Mesozoic era large forms are now-a-days found only in hot climates, at low geographical latitude. In the Tertiary of Europe Crocodiles and large Tortoises — not seldom of genera identical with those living at present — and also large Snakes are met with at high latitude. Thus Tomistoma, the Malay Gavial, up to 48°10′ N. lat. in the Miocene of Lower Austria, a gigantic Testudo as far as $42^{\circ 1}/_{2}$ N. lat. in the Pliocene of South France, large Pythonides in the Eocene of England, Belgium, France, Switzerland. In North America, on the other hand, Alligator is found only 5 degrees more northern than at present, in the Lower Pliocene of Nebraska, a little above 40° N. lat.

In the Miocene of Central France (Allier) a Parrot was found of the present tropical African genus Psittacus.

Anthropoid Apes are found in the Miocene and earliest Pliocene of Europe. The best-known are the large Dryopithecus and the small Pliopithecus. Dryopithecus was found in the south and the south-east regions of France up to $45^{\circ 1}/_{2}$ N. lat., also in Spain, on the southside of the Pyrenees at 42°20′ N. lat., in Upper-Swabia at 48° N. lat. and with Pliohylobates in Rhine-Hessen at 49°40′ N. lat. Pliopithecus is known from south, south-east and central France up to 48° N. lat., from northern Switzerland ad $47^{\circ 1}/_{2}$ N. lat., from Upper-Swabia at $48^{\circ 1}/_{2}$ N. lat., from Styria at $47^{\circ 1}/_{2}$ N. lat., and from Silesia (Oppeln) at 50°40′ N. lat. As all present-day Anthropoid Apes are confined to the tropical rain-wood zone, the small forms (the Hylobatides) are met with only at a latitude 25 ° degrees lower in Burma, and the large forms in Sumatra, Borneo, and in Africa are found only to 5 degrees distant from the equator, it may be assumed that the Miocene and Old Pliocene climatic condition in the regions of Europe agreed with that in the present tropical rain-wood zone. Certainly the occurrence of a number of large Anthropoid Apes, among others Dryopithecus-species, in the Siwalik beds of the same time, to 33° N. lat., point to a climatic condition as is now-a-days to be found only at a few degrees' distance from the equator. The same may be said of the South African Australopithecus, which was found at a distance from the equator 23 degrees larger than the Gorilla and Chimpanzee of these times, to which this fossil, probably Lower Plistocene Anthropoid Ape is certainly closely allied.

Homunculus, an Ape of the family of the Cebidae, which family is now-a-days confined to the tropical rain-wood zone of America, was found in the Upper Miocene of Patagonia, at 50° S. lat., hence its testimony goes to prove the same.

Of the family of the Cynopithecidae only a single species hardly reaches, under particularly favourable circumstances (in Japan), the 41st degree of latitude, but in the Lower Plistocene (or Upper Pliocene) of Europe representatives of this family are found in different places of higher geographical latitude (in South France, Hungary, Wurtemberg, England). The most northern finding-places are the Heppenloch at Kirchheim in Wurtemberg, at 48 40′ N. lat., and the Cromer Forest-Bed, at 52° 1/2 N. lat. In those times Hippopotamus in Europe was found to beyond the 50th degree of latitude (Cromer, Tegelen), 20 degrees more to the north than it lived in historical times (in the Nile delta and the Jordan valley).

In the same way the Lower Interglacial fauna and flora of Tegelen, which may be referred to the upper Pliocene, at 51° 20′ N. lat., and the rich Megalonyx-fauna, which is met with in the Lowest-, Pliocene or Aftonian Interglacial of North America, to 41° N. lat., testify to warm-temperate, humid climates.

After this time it has never been considerably hotter anywhere at higher geographical latitude, than at present. It had generally become so much cooler here that with slight intermittant fall of the temperature, which also manifests itself in earlier formations, glacial periods could now begin to interchange with interglacial times. Before the Upper Pliocene, unless it be in the Miocene of Alaska and possibly Northeast Siberia, no traces of such an alternation of glacial and interglacial periods with comparatively small differences of temperature, are found, evidently because then it was still too hot on our planet for this.

To this short enumeration of some of the surest palaeontological proofs of a formerly warmer climate at high geographical latitude a geological testimony may be added, i.e. the occurrence in old formations of such products of weathering as laterite and beauxite. The Plistocene or older laterite in the Kalahari of South Africa, probably also the laterite of West Australia, the Cretaceous beauxite of South France, the Pliocene of the Vogelsberg in Germany and the Eocene of Antrim in Ireland testify, like the beauxite of Alabama in North America, to a former tropical climate.

Of equally great significance in the palaeothermal problem as the palaeontological proofs of former hotter conditions at high geographical latitude are the geological proofs of former cold conditions at comparatively low geographical latitude, the palaeozoic and proterozoic ground moraines or tillites. We know most about the Permo-Carboniferous "Ice Age", the glaciation of South Africa, India, Australia, and South America which took place at the transition of the Carboniferous in the Permian period. This glaciation has been proved with as much certainty — especially through polished and striated rocks under the tillites which, shown by MOLENGRAAFF in South Africa for the first time with certainty, have now been found everywhere — as the Plistocene glaciation of Europe and North America, South America, Australia, Tasmania and New-Zealand. In some places viz. in New South Wales and West Australia, in North India and South West Africa, glacial deposits were formed in the sea by floating ice.

In South Africa the traces of this Permo-Carboniferous "Ice Age" are found from 33° 1/2 S. lat., in Cape Colony, to 8° S. lat., in Katanga [1]; in India from 20° N. lat., in Central India, to 32° 1/2 N. lat., in the Salt Range; in Australia from 21° S. lat., in Queensland, to 43° S. lat., in Tasmania; in South America from 23° S. lat., in Brazil, to 52° S. lat., in the Falkland Islands.

The great prevalence of its ground-moraines does *not* distinguish the Permo-Carboniferous glaciation from the Plistocene, for this extended in the Cordilleras of South and Central America over 70 degrees of latitude and in fact over all the continents at the same time. But in contrast to the Plistocene the Permo-Carboniferous glaciation seems to have no *bipolar character*, for in the Northern Hemisphere unmistakable and extensive Permo-Carboniferous traces of ice have not been found except at comparatively low latitude, only in and near India. At any rate the extension in the Northern Hemisphere was comparatively restricted. Nor is a shift of the pole conceivable with the present situation of the continents, through which bipolarity of the known Permo-Carboniferous ice-traces would be obtained. Besides the general direction of the movement of the ice-sheets in South Africa is towards the South pole, in Australia and India away from the pole, hence at least partly *independent* also of the South pole, even if its position had been different.

It is further in contrast to the Plistocene glaciation that most traces of the Permo-Carboniferous ice age occur at comparatively low latitude; even the marine glacial deposits are found at only about 33°, in India north of the equator and in Australia south of the equator, and at 27° S. also in South Africa.

Still in another respect does the Permo-Carboniferous glaciation greatly differ from the Plistocene, i.e. in this that the climatic character of the fossil flora immediately under and above the tillite and where two successive ground-moraines are found, in New South Wales, also that of the interglacial flora, presents more or less a tropical hot, not only temperate or at most hot temperate

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[1]) It has not been established beyond doubt that the tillite of Katanga is equivalent to the Dwyka tillite, possibly it is older. There is still less certainty about the age of the tillite found by KOERT in Togo, at 7° N. lat. That discovered by BALL and SHALER in the upper river basin of the Kongo, between 3° and 5° S. lat. is without doubt Triassic. Possibly some of the tillites found at very low latitude are the ground-moraines of local old glaciers. (Cf. E. HENNIG in: Geologische Rundschau, Band VI, p. 154, (Leipzig 1915)].

character. Evidently the glaciation in the Permo-Carboniferous period cannot have been the consequence of a few degrees' lowering of the general temperature, as in the Plistocene period.

From the fact that everywhere the Glossopteris flora appears after the Permo-Carboniferous glaciation, while in Australia and South Africa the Carboniferous Lepidodendron flora preceded this glacial period, it was, indeed, inferred that the new flora arose under the influence of the cold, and being adapted to cold, replaced the thermophile Lepidodendron flora. But this view must be relinquished now that the Glossopteris flora has been found in South Africa also under, even in the Dwyka tillite, and immediately above this Permo-Carboniferous ground-moraine, just as immediately above the Orleans tillite of South America (Brazil), a mixed Glossopteris-Lepidodendron flora. A fact of the same significance is the mixture of the Glossopteris flora with the flora of the Siberian and North Russian Upper Permian testifying to heat, together with which flora large Theromorphous reptiles lived. Nor have traces of ice been found there anywhere. Besides the plants of the Glossopteris flora are partly huge trees, partly large-leaved herbs; with GOTHAN it may be assumed that this flora physiognomically certainly did not present any differences worth mentioning from the Permo-Carboniferous flora of the Northern Hemisphere. Hence the Glossopteris flora did evidently not arise under the influence of glacial cold; on the contrary, it required heat, like the Lepidodendron flora.

But while these latter lowland floras existed under high temperatures, the immense ice-masses which transported the material of the Permo-Carboniferous tillites, were accumulated in the mountains.

There have been found convincing proofs of some glacial periods older than the Permo-Carboniferous one. In South Africa the existence of a lower Devonian tillite at Griquatown at 29° S.lat., and of a Silurian or Cambrian (perhaps even Algonkian) tillite at Clanwilliam at 32° S.lat., and at Capetown at 34° S.lat., established by ROGERS and others. According to HOLTEDAHL the tillite discovered by REUSCH at 70° N.lat. on the Varangerfjord, in the most northern part of Norway, is Lower Silurian and was probably supplied by a local glacier. The Arctic seas of the whole Silurian period were, however, undoubtedly hot. Upper Algonkian tillites have been found in China on the Jangtsekiang at 31° N.lat. by BAILEY WILLIS, and in South Australia at Adelaide at 35° S.lat. by HOWCHIN. The very extensive tillites in the Canadian province of Ontario between 46° and 50° N.lat. discovered by COLEMAN are dated in the Middle Algonkian period. Still perhaps somewhat doubtful is the Permo-Carboniferous glaciation discovered by WEIDMAN in Oklahoma at about 34° $^1/_2$ N. lat. Also the Permo-Carboniferous tillite of Boston at $^1/_2$ 42' N.lat., described by SAYLES.

Of a more local character is probably the Triassic tillite discovered by BALL and SHALER in Central Africa, between 3° and 5° S.lat.

On the ground of all this evidence it may be assumed that during the Proterozoic and Palaeozoic eras, which judging from the lead-content of uranium minerals may be estimated at from three to four times the whole later geological time, at least now and then the conditions were present for extensive accumulation of ice in the mountains, which conditions were absent thereafter. In view of the space of time they occupy, these events constitute a very important side of our problem, which might make us inclined to consider the condition in that long space of time as "normal" and miothermal (less hot), just as the present and Plistocene condition, in contrast to the Mesozoic-Tertiary "abnormal" and pliothermal (hotter) interval, in which no extensive glacial traces were found. We might also think of such very long pliothermal times as the latter, occupying from a fourth to a third of the whole space of time, in the Proterozoic and Palerozoic eras, interglacial periods of the highest order, which have alternated with the glacial periods proper. Judging from the best documented of these latter, the Permo-Carboniferous glacial period, pliothermal conditions were, however, present also then even in the neighbourhood of the ice. The circumstances that have led to ice accumulation in the Permo-Carboniferous period must at all events had been entirely different from those in the Plistocene-period. This renders it impracticable to continue the line from those earliest climatic conditions to the present times.

But still many geologists see no essential difference between the Permo-Carboniferous and the Plistocene glaciation. Both events are considered to be caused by an extension of a niveous polar climate on to the rainy region of a temperate zone, in consequence of an only slight temporary lowering of the temperatures during a miothermal condition already existing over the whole Earth. WILHELM RAMSAY [1]) and others have rendered it plausible that miothermal times are periods of vigorous mountain formation, in which extensive parts of the Earth's crust are raised to a considerable height, which then cause the mean temperature on the Earth to fall through stronger loss of heat by radiation, lively vertical circulation in the atmosphere and increased condensation of water vapour. Such a miothermal period is the time in which we live. Anorogenetic periods, as the whole Mesozoic era, with lower and levelled continents and mountains, were, on the contrary, pliothermal times. Then glacial deposits were formed nowhere, not even at high latitude.

However the variations of the assumed conditions of heat on the Earth and those of its relief do not always run parallel. The climatic mechanism described by W. RAMSAY can, evidently, be suppressed by more powerful factors than an elevated or low relief of the Earth. In an "anorogenitic phase" the Lower Silurian tillite on the Varangerfjord was deposited, the Lower Devonian in South Africa, the Triassic in

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1) WILHELM RAMSAY, Orogenesis und Klima. Helsingfors 1910.

Central Africa. On the other hand the orogenetic Tertiary period was not miothermal, and it is inconceivable that millions of years of orogenesis were required for the development of the Plistocene miothermal effect. Besides, if there is a foundation of truth in the contraction theory, which is too much neglected at present, the relation between orogenesis and climate may possible be opposite to what RAMSAY and others suppose it to be, and the long Mesozoic anorogenetic phase may be the result of the universally ackowledged pliothermal condition of that time.

Apart from the "generally hotter or less hot conditions" on the Earth, we have apparently only to do with another localisation of the same climatic types as those existing at present. In fact the characteristics of these are absent in none of the geological formations considered here, — with the exception of glacial deposits in the Jurassic, the Cretaceous, and the greater part of the Tertiary periods. Besides the characteristics of a hot climate at high latitude and of accumulation of ice at comparatively low latitude, also those of the dry regions are found in the different formations; deposits of rock-salt, gypsum, desert sand, far from the places were they are found in recent times. They are all geographically distributed quite differently from the present distribution.

Was this distribution in every geological formation, not quite irregular, after all, and possibly *analogous* to the present distribution of the types of climate?

A priori it seems that the answer to this question can only be affirmative. In virtue of the spheroidal shape of the Earth the heat received from the Sun by any point of its surface must always have been function of the geographical latitude. Hence not even in the hottest geological period can a perfectly uniform climate have prevailed over the whole Earth. There must always have existed a system of *climatic zones* analogous to the present one with anomalies of a corresponding nature as in the present climatic system, which are to be attributed to the distribution of water and land, the height of the land, and the presence of meridional mountain-chains. In this the Sun, practically the only source of heat of the Earth's surface, is assumed to be *invariable*. To account for the constantly modified localisation of the climate types it is then natural to assume displacement of the equator and the poles during the whole geological past. Under for the rest equal telluric circumstances, as considered by RAMSAY, and taken in general, the climatic zones must have been distinguished from each other then in the same degree and the irregularities of the zonic system must have been comparatively as small as they are at present.

W. KÖPPEN and A. WEGENER [1]) see the climatic conditions of the geological past from this point of view, considering them in the light of WEGENER's hypothesis of the continental drift. On the maps of the

[1]) W. KÖPPEN and A. WEGENER, Die Klimate der geologischen Vorzeit. Berlin 1924.

world giving the different geological formations constructed by WEGENER, are indicated in the first place the two dry climatic zones, necessarily to be expected at about 30° then northern and southern latitude, from the deposits of rock-salt, gypsum, and desert sand, and between them the large circle of the equator is traced, along which the coal is situated of the equatorial rainy zone. Outside the dry regions are found the rainy regions of the temperate zone equally characterized by coal deposits. The ground-moraines of a niveous polar climate are often absent. A glacial period can certainly, in KÖPPEN and WEGENER's opinion, be suppressed by extensive transgressions in the polar region. It may, however, be stated, that for a continent as Antarctica with the earlier annexes the required extensive covering with water is always improbable. Besides they assume the polar climate to have been comparatively mild during the Mesozoic and Eocene time. This, like other "disturbances" in the climatic system of their maps is chiefly ascribed by them to the varying distribution of land and water, and the ocean- and air-currents dependent on them. They now see the situation of these climatic zones, which have been thus empirically determined, change from formation to formation. The poles have, therefore, shifted, though only within certain narrow limits, and the continents have drifted. Hence the history of the climate of a place is very nearly the history of its position with regard to the pole and the equator.

KÖPPEN and WEGENER consider that in this way they have shown systems of climatic zones, in main lines equal to the present system and with irregularities of the same nature, for all formations from the Carboniferous to the Plistocene. For the Quaternary period the shift of the poles accounts for the Ice Age, but they ascribe the alternation of glacial and interglacial periods to the secular variations of the eccentricity, the perihelium, and the obliqueness of the Earth's orbit, with which the solar radiation received by the Earth varies and in consequence the summer heat.

They consider the Sun itself as a source of heat constant throughout the whole geological past up to the present time. Already on account of an earlier greater "solar constant" their explanation of the varying distribution of the climatic types would call for a modification, in as much as disproportionately more heat than at present was transported from low to high latitudes with the then greater atmospheric circulation and sea currents. But when besides the greater energy of solar radiation had another spectrum maximum, the heat received by the Earth might have been distributed more uniformly or less uniformly over its surface than at present on account of the different behaviour of the atmosphere and the hydrosphere of our planet towards solar radiation of different wave length. Then also the difference of temperature between high and low might have been smaller or greater, and the "disturbances" might in general have been comparatively smaller or more important than at present. Moreover with very considerable apparent size of the Sun, the heat directly received at any place of the Earth will, according to BLANDET's hypothesis, have been less dependent on the geographical latitude.

Under certain states of evolution of the Sun, in which it possibly may have been in the geological past, the climatic zonic system may, therefore, have been less pronounced, and there may have been disturbances of more importance than at present. If the Sun's radiation itself has changed during the Earth's past, the history of the climate of a place is *not* chiefly the history of its situation with respect to the equator and the pole, plants and animals of a hot climate may have lived at comparatively short distance from a former pole and also from highlands covered with ice, and ice may have been accumulated at comparatively low latitude, isolated, and without polar connection.

Actually the following floras and faunas testifying to a hot climate existed at high latitudes on KÖPPEN and WEGENER's maps, also when there was ice at those places:

The prae-, inter-, and postglacial Permo-Carboniferous flora in South Africa at 70° to 80° S. lat., in Australia at 70° S. lat., in South America, in the Falkland-Islands, and in the Antarctic continent between 60° and 70° S. (Gangamopteris was also found *in* the Dwyka tillite).

The Permian large Theromorphous reptiles: Pareiasaurus, Dicynodon and others in South Africa at 55° to 60° S. lat. (Their nearest relations lived at 30° N. lat. in Northern Russia, like other Theromorpha: Dimetrodon, Naosaurus and others in Texas. The fresh-water reptile Mesosaurus, which is indeed only 70 cm. long, is found immediately on the Dwyka tillite).

The Triassic reef corals in California and Oregon near and beyond 60° N. lat. to Alaska at 75° N. lat. [1]).

The Triassic large Theromorpha: Cynognathus and others in South Africa at 60° S.

The Lower Jurassic large Dinosauria in South Africa at 60° S. lat.

The Jurassic flora in West Antarctica at 68° S. lat.

The large Dinosauria of the Lower Cretaceous Tendaguru fauna in East Africa at 53° S. lat. [2]) and the closely allied Como fauna of the same time, and also the Upper Cretaceous large Dinosauria in North America at about 45° to 50° N. lat.

The Upper or Middle Cretaceous large Dinosauria in North Patagonia at 60° to 70° S. lat.

The Under Cretaceous flora of Uitenhage in South Africa at 67° S. lat. and the Upper Cretaceous flora in South Patagonia at about 65° S. lat.

The Eocene hot-temperate leaf-tree flora in Alaska at 60° to 70° N. lat.

The probably Tertiary hot-temperate Fagus flora of the region about

[1]) In KÖPPEN and WEGENER's text p. 63, Triassic coral reefs in Oregon erroneously at "fast 40°".

[2]) In KÖPPEN and WEGENER's text p. 92 "damals 35° S.," propably printer's error.

the Strait of Magellan at 60° to 70° S. lat. (if however Plistocene at only about 30° S. lat.) and the probably Tertiary subtropical flora in Seymour island at 70° to 75° S. lat. (if Plistocene yet higher than 50° S. lat.).

The Eocene nummulites in the northern part of Madagascar to 67° S. lat. on the west coast.

The Miocene and Lower Pliocene Anthropoid Apes in Europe: Dryopithecus and Pliohylobates to about 37° N. and Pliopithecus to about 38° N.

The Upper Miocene Santa-Cruz fauna in Patagonia with Homunculus and Nesodon and others at at least 50° S. lat.

The Pliocene (or Lower Plistocene?) marine warm-water fauna of Nome in Alaska at at least 67° N. lat.

The Upper Pliocene (= Lower Plistocene) flora and fauna of Tegelen at 57° N. lat. and the simultaneous fauna of Cromer at 59° N. lat.

The Upper Pliocene (= Lower Plistocene) Megalonyx fauna in North America to 65° N. lat.

This palaeontological evidence, which might easily be added to, may suffice to prove that the shift of the poles and the drift of continents alone are not sufficient to solve the palaeontological problem. KÖPPEN and WEGENER acknowledge this for the Mesozoic and Eocene periods, but it applies equally well to the Palaeozoic and the Neogene period.

At comparatively low latitudes of KÖPPEN and WEGENER's maps ice is actually found accumulated outside polar connection. The Triassic tillite discovered in Central Africa between 3° and 5° S. lat. lies, on their map, at 38° S. lat., i.e. at a greater distance from the Triassic pole and too much isolated to have arisen through polar cold climate. The same thing holds for the Boston- and Oklahoma tillites, which however perhaps somewhat dubious, lie at about 15° N. lat. and 22° N. lat. with regard to the Permo-Carboniferous north pole. Nor do the directions of movement of the Permo-Carboniferous ice-sheets in South Africa, which are independent of the hypothetical Permo-Carboniferous (and the present) south pole, testify to polar glaciation. If circumpolarly glacial, the Upper Algonkian tillites on the Jangtsekiang would require much greater displacement of the pole than KÖPPEN en WEGENER assume from the present to the Carboniferous period. From the Cretaceous to the Carboniferous period, this point always was under or close to the equator of their maps.

However meritorious in details, the hypothesis of the shift of the poles and the drift of the continents, therefore, leaves the palaeothermal problem at bottom for the greater part unsolved. As further all the other attempts at telluric explanations have proved inadequate, as far as the essential part of the problem is concerned, the solution apparently must be found in the changes indicated above, of the quantity and the quality of the energy radiated by the Sun, in its evolution, to our planet, during the geological time. The successive genesis of the geological formations and the development of the vegetable and the animal world on the Earth must then have kept pace with this evolution.

According to the giant and dwarf theory of stellar evolution drawn up by HENRY NORRIS RUSSELL in 1914, the principle of which had already been acknowledged by EJNAR HERTZSPRUNG in 1905, who also introduced the names of "giants" and "dwarfs", our Sun at first was in the state of a giant star of great dimensions but slight density, of rising temperature and with a maximum of the energy of radiation and colour shifting from red to yellow and further in the spectrum. After a certain maximum of temperature and certain smallest wave-length of maximum energy of radiation in the spectrum had been reached, the Sun entered the phase of a shrunken but dense dwarf star of descending temperature. The maximum of the energy of radiation in the spectrum and the colour now shifted in the opposite direction, towards the red, so that our yellow dwarf sun has passed its present temperature and spectral stage already once, viz. as a giant star. In the giant stage the dimensions gradually diminished, but at the same time the temperature rose so that the total intensity of radiation remained the same throughout this whole phase. In the dwarf stage, on the other hand, the Sun became smaller with descending temperature, so that the total intensity of radiation steadily diminished.

The highest temperature reached in the giant phase and the smallest wave-length of the maximum of radiation in the spectrum reached corresponding to it, depends on the mass of the star. The maximum temperature is comparetively low in a scarcely middle-sized star like the Sun, and the displacement of the maximum energy of radiation in the spectrum from the red, has been comparatively small. At present the Sun is in the condition of a yellow dwarf star, in the middle of the *G*-class of the Harvard-classification, and its effective temperature is about 5900° abs. The temperature maximum at the transition from the giant- to the dwarf phase was calculated at 6600° abs. by EDDINGTON (1922). It may have been still less high. At such a maximum temperature the Sun as giant star has probably never reached the stage of the *F*-class. With the Harvard classes *A* and *B* following in the ascending series of the temperatures, this belongs already to the First class, of the "White Stars", according to the earlier classification of SECCHI. During its giant phase the Sun first belonged to the *M*-class, corresponding to the Third class, of the "Red Stars" of SECCHI, then to the reddish yellow *K*-stars, which with the *G*-stars constitute the Second class, of the "Yellow Stars" in the earlier classification, and to all the transitions between the *M*- and the *K*-stage and between the *K*- and the *G*-stage, till the highest point of the giant phase above the *G*-stage was reached. According to WIEN's law a displacement of the maximum of energy in the spectrum to a wave-length about 0.9 times the value from about 570 $\mu\mu$ in the yellow to 510 $\mu\mu$ in the green corresponds to a change of temperature from 5900° ot 6600° , and according to STEFAN's radiation law a total intensity of radiation almost one and a half times the value [1]). But these are probably extremes. If the maximum of the temperature in the Sun's evolution curve lay close above the *G*-points, the total intensity of radiation in the giant phase was not much greater than in the present condition of the Sun, and the spectral radiation has changed only little since the highest temperature had been reached.

The views about the sources of the stellar energy of radiation and the cause of the change of the giant phase into the dwarf phase, hence about the internal nature of stellar evolution, have undergone important modifications and extension since the new theory was drawn up, especially of late years, through the work of EDDINGTON, JEANS and others, and chiefly in connection with the results of modern physics. These views themselves are still in a state of evolution, but to all probability the conception of the course of stellar evolution, which we owe to HERTZSPRUNG and RUSSELL, will remain unaffected.

For the Sun's evolution ages are calculated hundreds of times greater than the geological past considered here. It seems, therefore, to be entirely inadmissible to connect this evolution with the palaeothermal events discussed in this communication. But in the calculations of the Sun's age there is still so much uncertainty, chiefly on account of insufficient knowledge of the internal nature of stellar evolution, that the possibility at least remains that the whole or a large part of the giant phase of the Sun and the part of its dwarf phase passed through up to now, coincide with the geological time [2]). This possibility becomes probability when we consider the palaeothermal problem in the light of the giant and dwarf theory.

If it is an established fact that the Sun was still a giant star comparatively shortly ago, it must have passed the greater part of its past as a reddish yellow giant star of the *M*- and *K*-classes. The total radiation was then greater, just as in the whole giant stage, but not very much greater than the present radiation, but the maximum of energy lay in or near the red, and on the whole the radiation was of greater wavelength than at present. Besides the volume was really gigantic, especially in the *M*-stage, and the apparent size very considerable.

The long time of the Sun's past as much less hot red or reddish giant star, or at least a large part of it, may be considered in connection

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[1]) According to the same law about 35° C. (against 3° C. now) is found for the Earth's mean effective temperature under the hottest sun, ceteris paribus. The calculated temperature at the surface of the Earth would have been still higher. The real temperatures must have remained far below this on account of the much greater albedo.

[2]) Cf. the end of J. H. JEANS's article: On the Masses, Luminosities, and Surface-Temperatures of the Stars. Monthly Notices R. Astron. Soc. Vol. 85, January 1925, p. 211.

with the long Protero- and Palaeozoic time, in which "Ice Ages" occurred more than once. Then the Earth received, indeed, more solar radiation than at present, but of lower temperature, and also of another quality as regards its relation to the atmosphere and the hydrosphere. It should be remembered that the atmosphere acts in two ways on the solar radiation that passed through it. First through its water-vapour and carbonic acid it absorbs all the solar radiation and also the dark radiation emitted again by the heated Earth at certain places in the red part of the spectrum and far beyond it : *selective absorption*. Secondly it absorbs more or less of the energy of the whole radiation, on account of internal reflections at the air-molecules and other small particles which scatter them in all directions. This makes the atmosphere itself source of light and heat, the great significance of which has only been realised quite recently. The "diffuse daylight" and "the blue shy light is at the same time radiation of heat. Lord RAYLEIGH has shown that *this diffuse reflection* is in inverse ratio to the fourth power of the wave-length; hence it is slight for red and yellow, great for blue and violet rays. Also in water the short-wave rays undergo strong dispersion, and return to the atmosphere for the greater part, the red and ultra-red rays, on the other hand, are absorbed. Thus the energy of radiation of short wave-length is chiefly communicated to the high atmospheric layers, those of great wave-length, on the contrary, to the lower atmospheric layers, which are rich in water-vapour and carbonic acid, and to the hydrosphere.

It is, therefore, easy to see that where in the Protero- and Palaeozoic eras there were extensive highlands even at comparatively low latitudes, as there certainly were at the end of the latter period in the Southern Hemisphere, large ice-masses must have accumulated on the strongly radiating highlands in the badly heated upper air, more isolated also on mountains of the lowest latitude; we see the latter even as late as the Triassic period. The lowlands and the sea being well heated, there was strong vertical circulation in the atmosphere, consequently sufficient supply of water-vapour towards the highlands for accumulation of snow-ice. For the rest the niveous circuit is many thousands of times slower than the pluvial circuit, and large ice-sheets can already be formed with slight snowfall during thousands of years (examples of this are Antarctica and Greenland). In the lowlands and in the sea, which were hot to the highest latitudes on account of the strong currents, caused by the high "solar constant" and the strong absorption of the red radiation, hot-climate plants and animals could live, even near the ice-covered highlands. Possibly the considerable apparent size of the then giant sun also contributed to making the climate hot at high latitude.

As the different conditions of the Sun's development gradually passed into each other, just as the geological formations do, this long first period cannot be sharply defined in either way. Probably it was much longer than the whole period succeeding it, for the temperature rose to double its value in the giant phase from the *M*-stage to the *G*-stage, and after it to the highest point of the giant phase only still about a tenth. In this respect the Mesozoic period may probably be brought in connection with the *G*-giant stage to the maximum of the Sun's evolution. With an intensity of radiation or "solar constant" of the same value the distribution of energy over the spectrum was the same in the *G*-stage as at present. Further with maximum of energy shifted still more away from the red, the wave-lengths of the spectrum were on the whole at the highest temperature smaller than ever before or after. In this period the rays of short wave-lengths obtained more and more importance compared with the long-wave ones, ultimately even more than they have in the present condition of the Sun. The upper atmospheric layers were more heated at the time than before, and air masses charged with great quantities of entropy in equatorial regions and capable of radiation were now carried to high latitudes by the general circulation of the atmosphere operating especially powerfully in winter; they thus contributed greatly to the more uniform distribution of the heat over the earth, in the way as has been shown for the present time especially by EMBDEN. This mechanism must have been more powerful than at present on account of the greater "solar constant", in consequence of which a much more uniform climate must have prevailed over the whole Earth, at the same time the differences of temperature between high and low were much smaller than before, and in general the highlands could not become sufficiently cold for accumulation of ice.

But in the dwarf phase the temperature fell and the maximum of energy in the spectrum was displaced in the direction towards the greater wave-lengths. At the same time the total intensity of radiation, the "solar constant", decreased, and ultimately the present condition of a dwarf star which is in the middle of its *G*-stage, was reached. At this maximum of the giant phase a new epoch in the Sun's life does, therefore, really start. The effect of the low temperature on the intensity of radiation has no longer been cancelled since then by certain (insufficiently known) factors, which kept the intensity of radiation equal in the giant phase, and this while the heating of the upper atmospheric layers and the diminution of the want of uniformity in the distribution of the heat over the Earth caused by it, decreases. If this dwarf period is assumed to run parallel with the Neozoic period, it becomes comprehensible that climatic zones began to take definite form, and that at last the whole Earth got into a really miothermal condition with real general glacial periods.

When this view is held, great revolutions in the biosphere, the causes of which remain else perfectly unaccountable, are still more easily accounted for than in the light of the earlier views about the evolution of the Sun. Already shortly after the beginning of the Cretaceous period, i.e., according to the synchronism assumed, still before the turning-point in this evolution, the new epoch of the vegetable world sets in, in which the Angiospermal leaf trees predominate, which in contrast to the Mesozoic Gymnospermal flora, which was then for the greater part dying out, possess a very great total leaf-surface. This great revolution in the vegetable world may now be considered as an adaptation to the quantity of red radiation, which was then becoming minimum. For it is this radiation, to which the principal absorption band of the chlorophyl corresponds, that chiefly brings about the carbonic acid assimilation at the slight light intensity under which the leaf operates according to WIESNER's researches. It is also available already in the early morning and still late in the evening. The chlorophyl of this time is evidently the same green colouring matter as in the oldest carbonic-acid assimilating plants.

The greatest revolution in the animal world occurs somewhat later. The largest forms of the class of Reptiles, a number of orders, die out at the end of the Mesozoic era. This is accompanied at the beginning of the Neozoic era by the rapid and rich development of the class of Mammals, which was only represented by a few small, scarcely changing forms from the Triassic period to the end of the Cretaceous period. In fact the predominance in the animal world passes from the Reptiles to the Mammals. The Neozoic period is the Age of Mammals, as the Mesozoic period was the Age of Reptiles. It is natural to seek a connection between this revolution and the general diminution of heat in the high latitudes starting at the turning-point of the Sun's evolution. Large Reptiles, being animals entirely dependent on the heat of their surroundings, could no longer in general exist then at high latitude. Mammals, on the other hand are in a high degree independent of the temperature of their surroundings on account of their own heat. This class could, therefore, not but occupy the places in the biosphere left vacant by the extinct Reptiles, as we actually see in many convergent developments.

The new stellar evolution-theory thus throws a clear light on some of the most important problems met with in the investigation of the Earth's crust.

May the discussed, well established geological facts contribute to the further development of this theory!