No. XVIII.—RADIOACTIVITY AND EARTH MOVEMENTS. By ARTHUR HOLMES, PROFESSOR OF GEOLOGY, THE UNIVERSITY, DURHAM.

I.—TECTONIC HYPOTHESES.

Both external and internal geological processes are controlled by gravity and the earth's bodily movements. The circulations of matter which constitute the external processes are maintained by energy derived from the sun, whereas the internal processes derive much of their energy from the earth's internal heat, the latter being partly an inheritance, and partly an income supplied by atomic disintegration. Hypotheses relating to the physical causes of earth movements must take all the relevant factors into consideration as fully as the data permit. At present there is a plethora of hypotheses in the field, some of which are mutually contradictory. Much of this confusion is a result of lack of data, and is temporarily unavoidable; on the other hand a good deal is unnecessary, and has been introduced by exaggerating the effects of certain factors while ignoring those of others. The most remarkable example of a neglected source of geological energy is the heat generated by the radioactive elements. Outside the British Isles there has been little recognition of the importance of this factor, and it is therefore hardly a matter for surprise that hypotheses in which it is ignored should prove to be inadequate.

Among the forces to which appeal has been made are the following (21):—

Gravitational:

Cosmic Stresses set up by

(*a*) Tides due to the sun and moon.
(*b*) Precession of the equinoxes.

Terrestrial

(*c*) Attraction between continents.
(*d*) *Pohlflucht* force.

Stresses set up by

(*e*) Departures from isostatic equilibrium.
(*f*) Departures from hydrostatic pressure in the crust.
(*g*) Condensation due to re-adjustments of the material of the earth.

Thermal:

Stresses set up by

(*h*) Contraction due to change of state and cooling by conduction.
(*i*) Expansion due to heating-up of the earth's interior.
(*j*) Contraction (*h*) and expansion (*i*) alternating in time (Joly's hypothesis of thermal cycles).
(*k*) Convection currents in the substratum (the hypothesis developed in this paper).

(*a*) Tidal stresses, due mainly to the frictional drag of shallow seas against the crust, retard the earth's rotation. This involves a bodily contraction of the earth and an approach towards a spherical form (65, p. 293). Schaffer has recently developed the geological consequences (91). Lee, however, adopts the opposite view that, despite this effect, the earth's rotation has been periodically accelerated as a result of gravitational condensation (79). Taylor appeals to tidal forces as the chief cause of Tertiary mountain building and continental drift. He requires, however, that the earth should have captured the moon towards the close of Cretaceous time (99, p. 158). Wegener regards a westerly drift of the continents, due to bodily tidal friction, as a possible factor in his far-reaching hypothesis of continental drift (108). As shown by Jeffreys (65, p. 322) and Lambert (75) the actual force is negligible. It would have to be ten thousand million times as powerful as it now is to produce the effects ascribed to it, and moreover, if it were, it would stop the earth's rotation altogether in about a year. We may therefore conclude that *the dominant forces involved in crustal movements must arise within the earth itself.* Joly requires a westerly tidal drift of the whole crust over the substratum (66) and this again is considered by Jeffreys to be inadequate to produce the required effects in the time available (61).

(*b*) Precessional forces have been referred to by Wegener and others, but they are clearly of little importance (59).

(*c*) See 59, p. 418.

(*d*) The *pohlflucht* force tends to move the continents towards the equator. It is a differential gravitational force resulting from the ellipticity of the earth. Jeffreys finds that its maximum value, in middle latitudes, is about 5,000 dynes per sq. cm. (59). This force has been appealed to as a cause for continental drift, but it is hopelessly inadequate at the present day, and with the present viscosity of the substratum it is equally incapable of moving the crust over the interior in any reasonable time (59).

But in the early stages of the earth's history, for example when the moon separated, the viscosity must have been very much lower and the crust should then have reached the stable position determined by a symmetrical distribution of the continents about the equator. Since the continents are not so distributed at the present day, *some other force must have operated in opposition to the* pohlflucht *to move them into the positions they now occupy.*

(*e*) Departures from isostasy, brought about by denudation and deposition and the resulting underlying thermal changes, are thought by Bowie to provide horizontal stresses adequate to account for the folding and overthrust structures of mountain systems (12). This hypothesis is both inadequate and internally inconsistent. Staub appeals to isostasy to generate currents in the substratum directed away from the roots of mountain systems previously compressed by approaching continents. The currents then drag the continents apart again, leaving a geosyncline between (96). This is like trying to lift oneself by one's own boot laces.

(*f*) Gutenberg has recently advocated deviations of the earth's crust from hydrostatic pressure as an important source of tectonic energy (37). Jeffreys requires rock-flowage in the crust to account for the fact that mountain ranges have been lowered and even submerged before the cover of sedimentary rocks had been removed by denudation. He suggests that the excess of pressure due to the weight of the mountains leads to plastic outflow of matter from the intermediate layer (see p. 568) with a compensating inflow in the lower layer (65, p. 295). The development of bordering geosynclines such as the Indo-Gangetic "trough" is inconsistent with this hypothesis. Daly has suggested for discussion a hypothesis of continental creep due to the sliding of sial blocks on a lubricating zone of glassy basalt (23). A bulging of the polar and equatorial regions with a depression between, towards which the continents migrate, is pre-supposed. No explanation is offered for the initiation of so unstable a deformation of the globe.

(*g*) The effects of gravitational condensation in a heterogeneous earth were fully explored by T. C. Chamberlin (18), but these are of interest only to those who accept the Planetesimal hypothesis. A discussion of the tectonic consequences, with experimental illustrations of general interest, has been provided by R. T. Chamberlin (17). Keith considers that the chief cause of orogenesis is to be found in the thrust against the continents due to the downward pull of gravity on the floors of adjacent oceans, combined with batholithic intrusion actuated by the resulting pressure on reservoirs of magma already in the crust (71 and 72).

Differential rock flowage is involved in many of the hypotheses mentioned, and this is made the fundamental consideration in a hypothesis of mountain building developed by Andrews (7). In this case, however, the flowage is not from ocean to continent, but results in a dynamic progression of folded belts from the interiors of the continents outwards. It is not clear to what forces the rock flowage is to be attributed. Convection currents in the substratum would adequately provide the necessary mechanism. As early as 1875, Suess deduced from his Alpine studies that "a mass movement, more or less horizontal and progressive, should be the cause underlying the formation of our mountain systems." His conception of the process was inevitably cloudy, but he accepted earth shrinkage, referred in part to the cooling of the crust, as a factor of prime importance.

This introduces us to the suite of hypotheses in which thermal processes play the leading part. The earlier attempts, antedating the discovery of radioactivity, need not be discussed. Those developed since are of four chief kinds; they may all be tested by comparing their consequences with the geological behaviour of the earth's crust.

(*h*) In 1915 I adopted the traditional hypothesis of a steadily cooling earth, and assumed that the effects of radioactivity were limited to slowing down the rate of cooling. Instead of calculating the age of the earth from the present thermal state of the crust, as Kelvin had done, I took the age as a known datum and assumed that radioactivity fell away exponentially with depth, so that the present average gradient could be reached after 1,600 million years of cooling. With a known distribution of radioactivity, it was then possible to calculate the present downward variation of temperature (44 and 45). The work has since been repeated by Jeffreys (65) and Adams (1).

The consequences of this hypothesis (which reconciles all the more obvious thermal data quite satisfactorily) have been very thoroughly explored by Jeffreys (65). In 1925, however, I abandoned the hypothesis because of its failure to account for the leading phenomena of geological history (47). The objections are:

(1) Its inconsistency with the prevalence of vulcanism of the plateau-basalt type. Jeffreys now suggests that the necessary rise of temperature in his basaltic layer may be due to the reaction of chemically active gases derived from the underlying layers (65, p. 298). This is a quite unacceptable extension of Day's brilliant work on volcanic activity (24).

(2) Its quantitative inadequacy to provide the contraction necessary to produce folded and overthrust mountain structures. The calculated reduction of area is only about one sixth of the amount calling for explanation (50).

(3) The distribution of orogenic periods in time is systematically different from that deduced from the hypothesis (50). By admitting deep-seated cooling by convection, Jeffreys now provides more nearly uniform intervals between successive orogenic periods (65, p. 292), but only at the expense of discrepancy (2) which becomes still greater.

(4) The improbability that compression dispersed through

a layer 150 km. thick could produce relatively superficial nappe structures like those of the Alps.

(5) The failure of the hypothesis to account for marine transgressions, and particularly for the development of geosynclines (50).

(6) The fact that under the hypothesis continental drift is manifestly impossible. It is of no service to say, as Jeffreys does (65, p. 305), that continental drift is " out of the question." See p. 584.

(7) No geochemical reasons are offered for the fundamental supposition that the substratum is so poor in the radioactive elements that its heat output can be ignored.

(*i*) In the remaining hypotheses this unnatural limitation of radioactivity to the crust is rejected. The geochemical and physical evidence, as we shall see, is certainly in favour of a slightly radioactive substratum and this implies the production of an excess of heat over and above that conducted to the surface. In flat contradiction to the contraction hypothesis, Lindemann considers the earth to be expanding as a result of the continuous internal accumulation of radio-thermal energy (80 and 87). However, this idea is geologically untenable. Many processes would intervene to permit the escape of excess heat and cumulative expansion would not occur so long as these continued to operate. Moreover, if the earth began as a fluid body it is obvious that it must have contracted from its initial volume until it reached a state of approximate or fluctuating equilibrium, in which case one of the two following hypotheses would apply.

(*j*) In Joly's well-known hypothesis of thermal cycles an alternating accumulation and discharge of heat is visualised (66). Accumulation leads to fusion of the substratum (regarded as of basaltic composition); crustal extension; volcanic activity; and marine transgressions. Westerly tidal drift of the crust slowly draws the ocean floors over the magma zone, and discharge of heat is brought about by thinning of the oceanic crust. Solidification sets in by crystallisation and the sinking of blocks, accompanied by crustal compression and marine recessions.

As the period of Joly's cycles seemed to be inconsistent with the duration of geological time as estimated from lead-ratios, I suggested in 1925 the possibility of longer periods referred to similar cycles arising in a substratum of peridotitic composition, the radioactivity of which was regarded as being much less than that of the " basaltic " layer above it (48). This conception has been further developed by Krige with special reference to the currents which would be set up between the hotter sub-continental and the cooler sub-oceanic regions (74). These modifications of Joly's original scheme do not, however, remove the physical difficulties in the way of its acceptance.

Jeffreys has vigorously assailed the hypothesis of thermal cycles on the grounds that alternation of the fluid and crystalline states could not occur, since the substratum would remain permanently fluid on the postulated conditions; and that tidal drift of the crust over the substratum could not occur at the required rate (61). MacCarthy has pointed out that rapid loss of heat through the ocean floors would involve abnormal heating of ocean water (83). Lotze has attacked both Joly's scheme and my proposed modifications by confronting them with the complexities of earth history (81 and 82). It must be admitted that there is no evidence of world-wide compression alternating in time with world-wide tension. Compression of the crust, even in subsiding areas of long-continued sedimentation, seems always to have been in progress somewhere or other. Tensional phenomena, when they occur, are contemporaneous with compressional phenomena elsewhere. Thus the sudden opening of the Uralian geosyncline took place at the close of the Silurian while the Caledonian belt was being strongly folded.

Though his mechanism for bringing about the loss of excess heat is unsatisfactory, Joly has boldly faced the situation that arises if an excess of heat is generated in the substratum, and he has clearly realised that some form of crustal drift is absolutely necessary to permit the discharge of such heat.

(*k*) From the above discussion it will be realised that the substratum should still be in a " fluid " or glassy state. One of the objects of this paper is to discuss a mechanism for discharging the excess heat, involving circulation of the material of the substratum by convection currents, and continental drift operated by such currents. Tidal friction may co-operate to a slight extent, but is not essential. The possibility that currents might be set up by differential radioactive heating was recognised by Bull in 1921 (14), though in 1927 he considered that little evidence could be adduced in its support (15, p. 155). Ampferer has postulated *unterströmungen* in the substratum to explain crustal movements (5), and Schwinner considers the currents to be due to convection (94). Kraus also finds it necessary to adopt magmatic currents to explain the evolution of geosynclines, orogenic belts and continents (73). Born has pointed out that, although such hypotheses thoroughly meet the geological requirements, they suffer from the defects that they demand extensive movements in the substratum and require a source of energy that has not been made intelligible (38, p. 124). But one need not look far for an adequate source of energy. It is to be found in the radioactive elements. To the distribution of these we now turn, first considering the nature of the substratum and the overlying crust.

II.—THE NATURE OF THE CRUST AND SUBSTRATUM.

In recent years the comparative study of the seismograms of near earthquakes has thrown new light on the structure of the continental crust. The recognition of the Pg, P* and P waves and the corresponding S waves indicates that three distinct layers, known respectively as upper, intermediate and lower, are concerned in their propagation (65, Chap. VI). The velocities of waves of the P and S types are given by the formulæ

$$Vp = \frac{13.13}{\sqrt{10^6 \beta d}} \text{ and } Vs = \frac{7.37}{\sqrt{10^6 \beta d}}$$

where β is the compressibility and d is the density of the material through which the waves are propagated. Thus, we have

$$\beta d \times 10^6 = 96.8/Vp.Vs$$

which can be calculated for each of the layers. Adams and Williamson (4) and Adams and Gibson (2 and 3) have determined β for a representative series of rocks and minerals at various pressures up to 12,000 megabars. From the data for minerals the compressibility of a rock can be calculated by adding together the products of volume percentage of each mineral by its compressibility. Some representative results are compiled in the following tables.

Layer	Vp	Vs	βd x 10^6
Upper	5.4—5.6	3.2—3.3	5.60—5.24
Intermediate ..	6.3	3.7	4.15
(Top of) Lower ..	7.7—7.8	4.25—4.35	2.95—2.85

See Jeffreys (62); Gutenberg (38); and Terada and Miyabe (100).

Rock	Pressure (megabars)	d	β x 10^6	βd x 10^6
Granite	2,000	2.61	2.11	5.51
Granodiorite ..	,,	2.69	1.82	4.90
Diorite	,,	2.74	1.61	4.41
Diorite	7,000	2.76	1.53	4.22
Tachylyte ..	,,	2.87	1.45	4.16
Amphibolite ..	,,	2.90	1.30	3.77
Gabbro	,,	3.06	1.16	3.55
Peridotite ..	10,000	3.44	0.91	3.13
Dunite	,,	3.32	0.79	2.62
Eclogite	,,	3.50	0.80	2.80

The *Upper Layer* has been generally identified with granite, but petrological evidence indicates that the range of rocks of the sial suite is from granite to diorite, and that granodiorite is nearer the average composition than granite. Moreover, the properties of the layer are complicated by the presence of a sedimentary and schistose cover of very variable thickness, and by widely distributed intrusions of basic rocks. The observed value of βd is higher than that calculated from the data for the rocks known to be present, and this difference must not be overlooked in the attempt to identify the materials of the underlying layers. Another point of importance is that the deeper parts of the upper layer, wherever exposed to observation, are found to exhibit structures due to flowage, the characteristic types being gneisses and amphibolites. It is therefore to be anticipated that the intermediate layer will also be characterised by fluxion structures.

The thickness of the upper layer is found by Jeffreys to be about 10 km. in the neighbourhood of Great Britain and the adjoining parts of Europe, rising to 12 km. when the Alpine region is included (62). Gutenberg (38) and the Japanese seismologists find rather higher values (86).

The *Intermediate Layer* has given rise to much discussion. Jeffreys cautiously favours an identification with tachylyte (glassy basalt), but this is unacceptable on geological grounds. I suggested diorite or quartz-diorite as a more reasonable alternative (52). Wagner has recently attacked the problem in the light of the evidence provided by the xenoliths of the South African kimberlite pipes (104). He concludes that the upper layer is underlain by a shell composed predominantly of amphibolites accompanied by gabbros and basic granulites. The βd value for amphibolite, 3.77×10^{-6}, is a little lower than that found from seismic evidence, 4.15×10^{-6}, but, as we have seen, this difference is favourable to the identification rather than otherwise. If, as seems probable from the diamond-pipe evidence, the amphibolite layer passes down into granulite, the intermediate layer should provide seismic evidence of a double character. Mr. R. Stoneley has informed me that he has recently detected a hitherto unrecognised wave between P* and P. This discovery is consistent with the existence of a granulite layer, and affords a remarkable confirmation of Wagner's reading of the geological evidence.

Diorites and quartz-diorites are likely to be

(*a*) differentiation products of granodioritic magmas;

(*b*) products of reaction between granitic magmas and sediments in the hearts of mountain systems; or

(*c*) hybrid rocks due to interaction between basaltic magmas and granitic rocks or magmas.

They are essentially sialic rocks, and if we admit their presence in the upper layer, as we must, there is no longer any reason to postulate their abundance in the intermediate layer. As a working hypothesis the latter will here be regarded as amphibolite, probably passing downwards into granulite, both facies being subject to local transformation into eclogite under appropriate dynamic conditions (25).

The thickness of the intermediate layer is found by Jeffreys to range from 20 to 25 km. Other observers confirm these figures or favour a slightly greater thickness.

The *Lower Layer* may be eclogite or some form of peridotite, identifications that are supported by Wagner's discussion of the kimberlite xenoliths. Geochemical and petrological evidence and the analogy with meteorites suggest that the lower layer is most likely to be of peridotitic composition, while the thermal evidence favours the view that the material is in a glassy rather than a crystalline state. Unfortunately the values of βd for glassy peridotite under different pressures have not yet been determined. Such material would be very difficult to prepare in blocks suitable for investigation. It is probable, however, that at high pressures the relatively higher values of β and lower values of d characteristic of glassy materials will closely approach those of the equivalent crystalline materials. If the crust passes down into a glassy substratum the temperature of the lower surface of the crust will be that of the melting point of the material occurring there. Thus it is probable that the top of the lower layer may be crystalline. Seismic evidence would give no indication of the change unless the downward variation of βd became discontinuous in the zone of change of state. The known variation of βd is a continuous increase to a depth of 2,900 km., the increase being in accordance with the change of pressure and not necessarily requiring any further change of composition. It should be noticed that the seismic evidence does not prove, as is commonly assumed, that the lower layer is crystalline, but only that it is highly rigid. It is also highly viscous and is therefore mechanically indistinguishable from a solid. It may nevertheless be "fluid" in the sense of lacking strength and crystalline structure.

The term *crust* is used for the upper and intermediate layers and any part of the lower layer that is crystalline, while the term *substratum* is adopted for the underlying thermally "fluid" or glassy part of the lower layer.

As pointed out over half a century ago by F. J. Evans (28, p. 27) the variations of the earth's magnetism suggest a change of state in passing from the crust to the substratum. More recently Chapman has drawn attention to this neglected source of information about the earth's interior. He states that at a depth of some 300 km. the value of the electrical resistivity is about 3×10^{12} e.m. units, whereas for the crystalline rocks of the crust the value is 10^{15}—10^{16} and rises with temperature (19). Not only does the great difference indicate a change of state, but, as Chapman remarks, "despite the mechanical stability of the earth, fairly rapid changes are proceeding within it," suggesting that "the interior is much more mobile than the outer layers."

Turning now to the oceanic part of the crust, we have little information except that its properties are consistent with its identification as gabbro or amphibolite (65, p. 115). For the Pacific floor the group-velocity of Love waves with a period of about 20 secs. is 3.8 km./sec. or more, as compared with 3.2 km./sec. for the Eurasian crust. The respective velocities of Sg (which should be about the same as these particular group-velocities) are 3.8 and 3.9 for amphibolite and gabbro, and 3.1 and 3.3 for granite and granodiorite. Other seismic evidence (41), as well as petrological and isostatic considerations, supports this identification, and we may therefore regard the Pacific crust as being like that of the continents, but with gabbro passing down into amphibolite in place of the sialic upper layer. In the floor of the Atlantic, and to a less extent in that of the Indian Ocean, there appear to be patches of sial lying above the "gabbro-amphibolite" layer. The thickness of the oceanic crust is probably of the same order as that of the continents; thermal considerations suggest that the former is likely to be thicker than the latter. The lower layer of the oceanic areas cannot be distinguished from that lying beneath the continents. The substratum thus appears to be a continuous shell bounded above by the crust and below by the metallic core. The core extends from 2,900 km. to the centre and its nature is reasonably well established by many converging lines of evidence.

III.—THE RADIO-THERMAL ENERGY GENERATED IN ROCKS.

Since Kelvin's method of dealing with the problem of the earth's thermal history was shown to be invalid by Lord Rayleigh's discovery of the widespread distribution of the radioactive elements in rocks (98), various attempts have been made to tackle the problem afresh. Although numerically the actual proportions of the radio-elements (other than potassium) are exceedingly small, yet owing to the fact that their disintegration is accompanied by the liberation of heat, their presence is of an importance that cannot be overemphasized. The total annual heat outputs are as follow (56):

Uranium family	$7,900 \times 10^{-4}$ cals./gm. U.
Thorium family	$2,300 \times 10^{-4}$ cals./gm. Th.
Potassium	1.24×10^{-4} cals./gm. K.
Rubidium	2.38×10^{-4} cals./gm. Rb.

The geothermal effects of potassium are of the same order as those of the more strongly radioactive families, because of the great abundance of potassium in rocks. The output from rubidium, however, can be ignored because of the rarity of this element.

In the following table the average contents of the radioactive elements in rocks have been compiled, and from these data and the heat outputs cited above, the total generation of heat in average rock-types is calculated.

Heat Production per annum in Rocks, etc.

Types of Material	U $\times 10^6$	Th $\times 10^6$	K $\times 10^2$	Total Heat Production (Calories per annum)	
				per 10^6 gm.	per 10^6 cc.
Granites ..	9.0	20.0	3.4	15.9	42.2
Granodiorites ..	7.7	18.0	2.5	13.3	36.4
Diorites ..	4.0	6.0	1.7	6.7	19.0
Central Basalts:					
Continental .	3.5	9.1	1.9	7.2	20.9
Oceanic ..	3.6	7.1	1.8	6.7	19.5
Plateau Basalts	2.2	5.0	0.8	3.9	11.4
Gabbros ..	2.4	5.1	0.7	3.9	11.7
Eclogites ..	1.0	1.8	0.4	1.7	5.8
Peridotites ..	1.5	3.3	0.8	2.9	9.4
Dunites ..	1.4	3.4	0.03	1.9	6.6
Meteorites:					
Stony ..	1.7	0.9*	0.16	1.8	5.8
Stone-iron ..	1.0	n.d.	—	—	—
Iron	0.07	n.d.	n.d.	—	—

It is important to make sure that practically all the energy liberated by atomic disintegration does, in fact, appear as heat, for Evans has suggested that " it is probable that a considerable proportion of the energy liberated . . . . . is used up in effecting physical, chemical or atomic changes in the surrounding minerals " (27, p. lx). If this view were correct, we should expect the heat generated by radium in a glass container and determined experimentally, to be much less than the heat equivalent calculated

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* This is a single determination by Joly (*Phil. Mag.* (6), 18, 1909, page 142) and may not be representative.

from the energies of the rays emitted. Yet, despite the intense colouration of the glass, the calculated and observed heat outputs agree almost exactly. The total heat from one gram of radium and its short-lived daughter elements was observed by Meyer and Hess to be 137 cals./hour. The calculated output is 137.14. We may therefore safely conclude with Rayleigh (70, p. 55) and Lawson (78) that the evidence decides conclusively against the suggestion of Evans.

It is also important to know whether there is any possibility of inhibition of heat output when the radio-elements are deeply buried in the earth. All experimental work directed to test this, involving temperatures up to 2,500°C., very high pressures, and bombardment by every kind of ray, has failed to affect the progress of disintegration in any appreciable way. The quantum theory provides the explanation. To disturb the interior of the atomic nucleus—the seat of the instability that leads to decay—temperatures of the order 3,000 million degrees and correspondingly high pressures would be theoretically necessary. There is clearly no reason to suppose that any of the conditions obtaining within the earth could influence the rates of atomic disintegration.

It follows that to ignore the ceaseless outpouring of energy that is everywhere occuring in terrestrial materials would be as wrong as to ignore the effects of gravitation.

IV.—THE DECREASE OF RADIOACTIVITY WITH DEPTH.

We must next compare the heat-output of the rocks with that lost from the continents by conduction to the surface and radiation into space. The average amount of heat so lost from each sq. cm. per second is given by the product of the average thermal conductivity of rocks (0.006) and the average temperature gradient (0.00032° C. per cm.). The loss per year (3.15×10^7 secs.) is therefore

$$0.006 \times 0.00032 \times 3.15 \times 10^7 = 60 \text{ calories/sq. cm.}$$

Evidently this could be made good by the radio-thermal energy generated within a thickness of 14 km. of granite; 16.5 km. of granodiorite; 52 km. of plateau basalt or gabbro; or 60 km. of peridotite. It may therefore be inferred that the earth's radioactivity is strongly concentrated towards the surface.

The facts of distribution and the geochemical behaviour of the elements in question are definitely in accord with this inference (43, 49, 89). However we may combine the thermal data on p. 571 with the seismic and petrological evidence bearing on the structure of the crust it seems certain that an outer shell of the earth less than 60 km. thick must generate sufficient heat to make good the loss from the surface. The distribution of radioactivity favoured by Jeffreys, and limited to allow the interior of the earth to cool, corresponds with a layer of granite 11 km. thick underlain by a basaltic layer 22 km. thick. There is then no excess of radioactivity left over for the interior. The temperatures of the basaltic layer are about 300° C. at the top and 650° C. at the base (65, p. 297). Clearly these are too low to permit vulcanism of the plateau-basalt type. If basalt magma comes from a greater depth, the distribution of radioactivity necessarily involves the production of an excess of heat, and igneous activity becomes the mechanism by which part of the excess is enabled to escape. But in this case the original restrictions imposed by the hypothesis of limited radioactivity have been fatally exceeded. The substratum becomes permanently " fluid " in the thermal sense and the earth cannot cool down in the manner postulated (47).

Jeffreys has shown that if the limited amounts of the radio-elements admitted to be present in the crust were uniformly distributed through the 2,900 km. shell, then the material below a depth of some 50 km. could never have solidified. Convection would then proceed in the substratum until the radio-elements became strongly concentrated towards the surface. He writes, " the transfer would only stop when the temperature gradient at all depths had become so low as to permit solidification. This implies that the concentration would ultimately be almost complete " (65, p. 146). I can see no reason for supposing that the freeing of the substratum from the radio-elements can yet have become as complete as Jeffreys requires. All the experience of geochemistry is strongly opposed to such a hypothetical possibility. No process of magmatic differentiation is known that could bring it about. It is likely that the material of the upper layer, together with the oceans and the atmosphere, was differentiated from the general body of the earth while the latter was still a relatively mobile fluid. The process of " gaseous transfer " so implied would be very effective in leading to a marked concentration of the radio-elements in the first-formed crust. But the known radioactivity of basalts and peridotites of widely different ages shows that the suggested process was far from removing all the radio-elements from the substratum. Yet clearly, if we admit only a slight radioactivity in the substratum there must be generated within it an excess of heat which would maintain fluidity.

Let us suppose, to illustrate the effects of slight radioactivity, that the heat output within the substratum is only 1/700 of that of plateau basalt. On geochemical grounds it is difficult to see how this can be anything but an underestimate. The volume of the substratum (60 km. to 2,900 km.) is 88.75×10^{10} cu. km., and the total heat generated per year on the assumed figure is 142.5×10^{17} calories. This is equivalent to the cooling of 62 cu. km. of basaltic magma from 1,000° C. to a crystalline rock at 300° C. Obviously, to get rid of this quantity of heat some process much more drastic than ordinary volcanic activity would be called for. The volume of lava in the 1929 eruption of Vesuvius was only 12×10^{-3} cu. km. The annual loss of heat from all volcanic sources has been estimated at 6×10^{17} calories (82, p. 83).

For the accumulated heat of 200 million years to escape through the sites of the oceans it would be necessary for one third of the whole of the ocean floors (taken at 60 km. thick) to be engulfed and heated up to 1,000° C., and replaced by magma which cooled down to form new ocean floors at 300° C. A process competent to bring about this result on the scale indicated would be some form of continental drift involving the sinking of old ocean floors in front of the advancing continents and the formation of new ocean floors behind them.

We may therefore conclude that

(*a*) if the crust of the earth makes good the loss of heat by conduction to the surface, and

(*b*) if the substratum has only 1/700 of the heat-generating capacity of plateau basalt; then

(*c*) the substratum cannot yet have cooled sufficiently to have crystallised, but must still be in the stage of convective circulation, and

(*d*) to avoid permanent heating-up, some process such as continental drift is necessary to make possible the discharge of heat.

V.—CONVECTION CURRENTS IN THE SUBSTRATUM.

THE CONDITIONS FOR CONVECTIVE CIRCULATION.

In the simple case of an extensive layer of uniformly heated viscous liquid, with rigid conducting surfaces above and below, the conditions leading to convection currents are fairly well understood. There is stability until a certain critical temperature gradient is reached, depending upon the compressibility, conductivity, and viscosity of the fluid. As the critical gradient is exceeded, the uniformly stratified distribution of material becomes unstable, and in the attempt to restore stability a system of complementary currents begins to develop, ascending in some places and descending in others. The disturbances are at first chaotic, but of all the possible systems of movement some tend to persist and to increase steadily with time at the expense of others. This leads gradually to the survival of local centres from which vertical currents ascend. Towards the top the currents spread out in all directions from each centre until they interfere with one another, turn downwards, and form sheet-like return currents. Thus irregular polyonal prisms come to be enclosed by the downward currents. Under ideally uniform conditions the polygons would ultimately become hexagonal and the diameter of the hexagons would be three or four times the depth of the convective layer (60).

In the earth the critical gradient appears to be about 3° C. per km. So long as this is exceeded convection must go on, provided that the material has no strength, and that the viscosity is not too high.

Jeffreys has shown that the viscosity of the substratum cannot by itself prevent convection (63). To stop convection in a layer nearly 2,900 km. thick, the viscosity would need to be of the order 10^{26} c.g.s. From the 14 monthly variation of latitude the mean viscosity is found to exceed 5×10^{20} (59, p. 424). The actual value is certainly not much higher than this. Since the beginning of the last withdrawal of the European and North American ice-sheets, the time T elapsed is nearly 20,000 years, or 6×10^{11} secs. Important upward movements, referred to the relief of load consequent upon the melting of the ice, have occurred over areas of a linear extent L of the order 1,000 km. or 10^8 cm. The thickness H of the substratum involved in the isostatic adjustments is between 30 and 3,000 km. (3×10^6 and 3×10^8

cm.). The relation between these factors and the viscosity V is given by $3 VL^2 = g H^3T$, g being nearly 1,000. With these data we find V lies between 5×10^{17} and 5×10^{23}. Even the maximum value is well below the limiting value 10^{26}.

At high temperatures the strength of materials rapidly diminishes and, as the fusion point is approached, it disappears. It is therefore to be expected that the substratum should be devoid of strength. Geologically, the abundant evidence pointing to regional isostatic compensation within a depth of 60 km. or less is the best indication that this expectation is realised. Jeffreys, however, infers from the fact that the equator of the geoid is not exactly circular that deep-seated stress-differences must be resisted by the substratum, and that the latter must therefore have at least a little strength (65, p. 222). The viscosity would then be infinite until this was overcome. The bulge of the equator corresponds to an excess of material about the longitude of Central Africa. Such an upward bulge of Africa is undoubtedly genuine, but it has developed since the Cretaceous from a state of almost perfect peneplanation (55 and 107). Thus Central Africa has been affected—and still is—by a process which has actively uplifted the region faster than isostasy could restore equilibrium. It is well-known that isostasy is most disturbed where recent movements have been most active; perfect adjustment implies relatively static conditions. So far from proving the existence of deep-seated strength, the development of the bulge proves that some dynamic process is operating in the substratum sufficiently actively to maintain a slight departure in advance of complete compensation.

In further support of the inference that the substratum has no strength we can appeal to the secular variation of the earth's magnetism, which, as already pointed out, implies relative mobility of the interior. The only theory which provides for the maintenance of the earth's magnetism, and which is not contradicted by other observed facts, has been proposed by Larmor (76); it involves the circulation of the material within the earth by a system of currents symmetrical about the axis and the magnetic equator (19).

Granting the physical possibility of convection within the substratum, the effect of radioactivity would be to steepen the gradient over the critical gradient and so increase the rate of circulation until the new heat could be carried off as fast as it was generated. With the differentiation and crystallisation of the crustal materials, the interior would be able to discharge the excess heat only in so far as the crust could be fused or broken through from below. Both processes are described in the sections that follow.

The mode of circulation of the material of the substratum can be deduced from general principles. It will depend mainly

(*a*) on the varying thickness of the substratum from equator to poles;

(*b*) on the varying thickness and radioactive content of the crustal cover; and

(*c*) on the rotation of the earth; upward moving currents will be deflected westwards and downward currents eastwards; in the northern hemisphere horizontal movements will turn towards the right and in the southern towards the left; such deflections, however, are likely to be very slight, and they will not be further discussed at present.

The Planetary Circulation.

Considering the first of these we may infer by analogy with the atmosphere a circulation like that of the planetary system of winds. Within the earth the ellipticity of successive shells of increasing density gradually decreases with depth. Thus a considerable part of the difference between the polar and equatorial radii will be concentrated in the substratum. The equatorial thickness being greater than that beneath the poles, and the distribution of radioactivity being independent of latitude, the equatorial temperature gradient will be steeper than that towards the poles. Thus the general circulation from this cause should be as shown in Fig. 1.

As the equatorial ascending currents approach the base of the crust, they divide; half turning north and half south. As a result of the powerful drag thus imposed on the lower part of the crust the latter will flow with the currents but with a lower velocity, each level moving less rapidly than its underlying neighbour. The upper levels will tend to give way by fissuring or faulting as in the case of a glacier or ice-sheet. Thus the ultimate effect on continental blocks originally over the equator will be to drag them apart, leaving a depressed geosynclinal or oceanic belt along the equator. We have already seen that the early operation of the *Pohlflucht* force should have left the continents distributed symmetrically about the equator. The long history of the Tethys girdling the continental half of the earth between Gondwanaland and Laurasia is a clear indication of the operation of some opposing force tending to pull the continents apart. In the planetary circulation we have a first clue to its nature. The closing up of the Tethys is referred to the subsequent action of the sub-continental circulations.

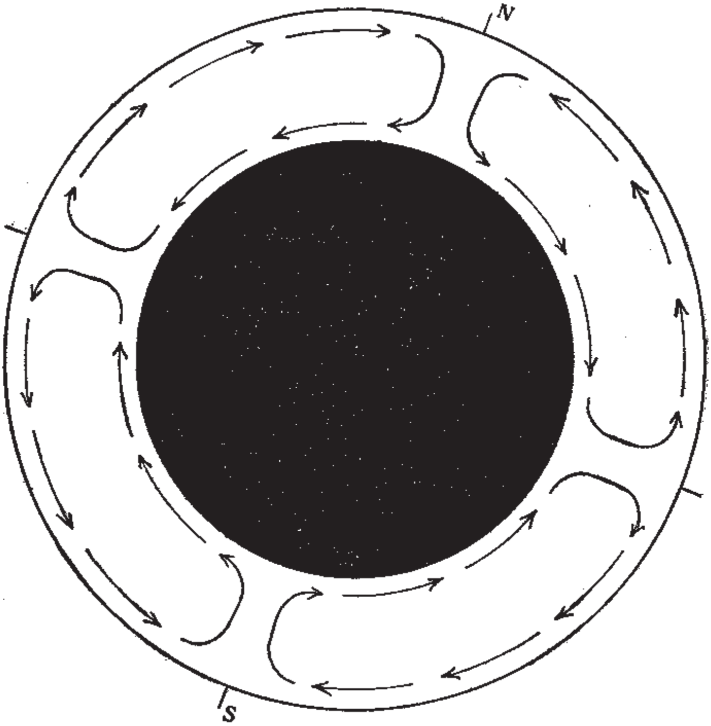

Fig. 1.[1]

THE SUB-CONTINENTAL CIRCULATION.

Superimposed upon the general planetary circulation there must be cyclonic and anticyclonic systems set up by the effects of regions of greater and less radioactivity in the overlying crust. Chief of these are the monsoon-like currents due to the distribution of continental blocks and ocean floors. Such evidence as we have, suggests that the radioactivity of continental rocks is

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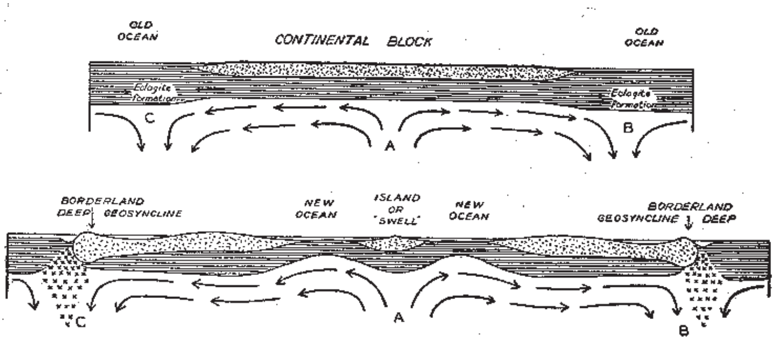
[1] For descriptions of figures see pp. 605-606.

generally greater than that of oceanic rocks. Thus, although the temperature at the base of the crust will be everywhere nearly the same, the continental crust should be thinner than the old or normal oceanic crust, and thus beneath the continents the temperature should be higher than at the same level beneath the oceans. The circulation due to this unequal heating of the substratum would be a system of ascending currents somewhere within a continental region, spreading out at the top in all directions towards the cooler peripheral regions. The downward currents would become strongest beyond the continental edges where weaker currents from the oceanic regions would be encountered (Fig. 2).



Figs. 2 and 3.

In the simplest case the drag on the base of the continental crust would be radially outwards, but in reality the circulation would necessarily be more complex. Ascending currents would not generally be localised about a single centre, but rather about several centres and along previously thickened belts such as those of mountain ranges. In the peripheral regions, however, the currents would be everywhere directed towards the oceans.

In Fig. 3 an attempt has been made to represent the effects on a continental profile under ideally simple conditions. Where the ascending currents turn over, the opposing shears and the resulting flowage in the crust would produce a stretched region or a disruptive basin which would subside between the main blocks. If the latter could be carried apart on the backs of the currents, the intervening geosyncline would develop into a new oceanic region. The formation of a new ocean floor would involve the discharge of a great deal of excess heat. It will be shown later that the new crust will be more nearly basaltic in composition and more richly radioactive than the normal material of the substratum (p. 583).

We must next consider what will happen at the continental margins, or generally, where two currents meet and turn downwards. The crust above the zone of contact will be thrown into powerful compression and the amphibolite layer will tend to be thickened by accumulation of material flowing in from two directions. The observed effects of dynamic metamorphism at high temperature and differential pressure on such material lead us to expect that recrystallisation into the high-pressure facies, *eclogite*, will here take place on a large scale (25). The change of density from 2.9 or 3.0 to 3.4 or more, combined with the simultaneous operation of isostasy would lead to marked subsidence. Sinking of blocks of eclogite would also be facilitated by stoping promoted by the tongues of basaltic magma that would inevitably be present. Such foundering would effectually speed up the downward current for two reasons: the greater density of the sinking blocks, and the cooling of the substratum material in their vicinity.

Other possible consequences of eclogite formation will be suggested later; meanwhile we may notice that it provides a mechanism for " engineering " continental drift, and at the same time for discharging some of the excess heat generated in the substratum. Each part of the continental block would be enabled to move forward, partly by the fracturing and foundering of the belt of ocean floor weighed down with eclogite immediately in front, and partly by over-riding the ocean floor along thrust planes lubricated by magmatic injections from below.

The hypothesis of eclogite formation is supported by the fact that it provides a reasonable explanation of oceanic deeps. It is consistent with their depths, as judged from the requirements of isostasy, and with their occurrence in front of the active orogenic arcs bordering the Pacific on the Asiatic and Australasiatic side (53). That oceanic deeps are under compression is the opinion of Meinesz. He sees in downward flexure under stress a reason for the local defects of gravity revealed over deeps by his gravity surveys of the oceans. Evidence of the foundering of blocks is from the nature of the case not easy to find, but it may be forthcoming from the occurrence of deep earthquakes (arising from 100 km. or more) off the coast of

Japan (86), and by the signs of volcanic activity that have been detected in the floor of the Tuscarara Deep.

The upper or sialic layer of the continental margin will also be thickened by the differential flowage of its levels towards the obstructing ocean floor. Here thickening of the crust and mountain building will occur, and the mountain roots, unable to sink, will begin to fuse and give rise to igneous activity of the Circum-Pacific type with basalt-andesite-rhyolite volcanoes. It has frequently been pointed out that, if the material of the ocean floor is weaker than that of the advancing continent, then mountain building will not take place; while if it is stronger, continental advance becomes impossible. With the mechanism here suggested this *impasse* does not arise. Mountain building occurs as a result of rock-flowage set in operation by the underlying current; it will generally occur provided that the horizontal component of flowage is greater from behind than in front. Deep-seated outflow of sial beyond its former margin appears to be involved in the great and geologically rapid uplifts indicated by the presence of abyssal deposits in the outer sedimentary zone of many island arcs (42). The forelands move like an ice-sheet, the upper levels being carried forward as a dead weight devoid of orogenic energy other than that which is derived from the active substratum below.

The effects of possible fusion and of differential flowage of the amphibolite layer remain to be considered. Since the outward transport of heat towards the periphery along any stream-line from the area where the currents ascend necessarily increases with the distance from that area, the currents will begin to fuse the base of the crystalline crust and a process of magmatic corrosion and transport will develop. This will become cumulative towards the periphery. At first the material undergoing fusion is likely to be peridotite, but sooner or later a point will be reached where partial fusion of amphibolite will occur. At the same time the lower layers of the amphibolite will be carried forward by rock-flowage more rapidly than those at higher levels. In part, the spilitic or basaltic magmas so generated may give rise to vulcanism above, but most of the magma should escape into the zone where the flowing amphibolite is being transformed into eclogite. There the magma will facilitate sinking of the eclogite blocks and lubricate the shear planes over which the continent advances. The place of the material removed from the amphibolite layer will be taken by the heavier material of the substratum, and, in accordance with isostasy, the region above will subside; that is to say it will become a geosyncline (50, p. 272). By the accumulation of sediments from the continent behind and the borderland or mountain arc in front, further subsidence of the geosyncline will occur. Thus the base of the crust will be kept hot, and may even grow hotter, and the process of geosyncline development will continue. It should be noticed that this region, though tending to subside, will nevertheless be under compression whenever rock-flowage in the underlying sial is more rapid than that in front. Thus folding may proceed concomitantly with subsidence and accumulation of sediments. This is well known to have occurred, but hitherto no explanation has been offered. Such geosynclines will be referred to as *interior* geosynclines. Those within the Asiatic island festoons are active examples. Compression associated with depression has been proved by recent geodetic measurements in the Kwansai District of Japan (100, p. 234).

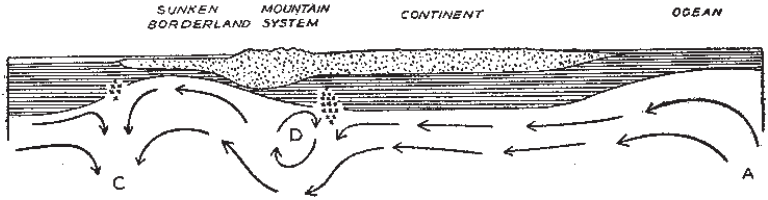


Fig. 4.

Sooner or later a time will come when the buried crustal material beneath the infilled geosyncline will become hotter and weaker than the material behind and in front. Moreover, the grip of the underlying current will have weakened as a result of the higher temperature and lowered viscosity. At this stage thickening of the geosynclinal belt due to compression will become more effective than thinning by magmatic corrosion; mountain building will have set in (Fig. 4). The long history of the Cordilleran geosyncline of Western America, and its subsequent orogenesis (92), supplies a spectacular example of the process theoretically deduced. The Mesozoic and Tertiary history of Alaska tells the same story of long-continued subsidence interrupted and ultimately overcome by the effects of compression (85).

Meanwhile the mountain roots will set up an accelerated transport of heat towards the continental edge, and the currents will thus move out far beyond the edge before beginning to descend. The borderland or mountain arc will then no longer be in the original zone where the horizontal component of rock-flowage is retarded against the belt of eclogite formation and deeps. Its lower levels will be stretched and thinned, and the area will subside as the interior geosyncline had previously done. Thus the disappearance of borderlands such as Cascadia—a phenomenon that has long been a puzzle to palæogeographers (92, p. 201)—may readily be understood. The hypothesis suggests that western America represents a more mature stage of development than eastern and south-eastern Asia.

To determine the velocities of the sub-continental currents under different circumstances is obviously highly desirable. Such rough estimates as I have attempted to make indicate a velocity of the order 5 cm. per year (50 km. per million years) as probable when the excess of temperature above that corresponding to the critical gradient is 10° C. On this conservative estimate the minimum period required to produce the Atlantic by continental drift would be some 100 million years.

The time taken for a block of eclogite to fuse completely is probably of the order 50 million years. Thus, sinking blocks should have nearly reached the bottom of the substratum before becoming entirely fluid, and streaks in the ascending currents should therefore be fed with magma much more nearly basaltic in composition than the general body of the substratum. The ascending currents will approach the surface in the region behind the advancing continent, and thus the new ocean floor is likely to receive the whole of the basaltic material available.

With ascending currents of such relatively light material, and descending currents made relatively dense by the presence in them of eclogite blocks, the whole circulation will be speeded up while continental drift is in progress. Moreover, the first effect of the formation of a new ocean floor will be in the same direction, since the crustal material previously there will be displaced by much hotter basic material. Later, however, the heat transported to the periphery of the continent and beyond will gradually prevent the formation of eclogite, and the zone of deeps will tend to migrate outwards and disappear. The magma representing what would otherwise have become eclogite will escape through the ocean floor in front of the edges of the sunk borderlands. The supply of sinking blocks having ceased, the current will slow down. At the same time the roots of the mountain system near the margin of the land will become the site of an opposing current (beginning as at D in Fig. 4), since there the heat output will have become greater than that of the continental crust behind. Moreover, as the new ocean floor cools, the ascending currents will fade out for lack of thermal sustenance. For a long time conditions will be chaotic, but gradually an entirely new convective system will evolve tending to close up the continents again. The approach of Africa and Europe across the site of the Tethys is the most striking example of this inevitable reversal of circulation brought about by the changing boundary conditions of an earlier system of currents.

VI.—SOME GEOLOGICAL CONSEQUENCES.

Continental Drift.

Turning now to the effects of a radial sub-continental system of convection currents as visualised in plan, it is easy to see that each great continental block—such as Laurasia or Gondwanaland as they were at the close of the Palæozoic—should tend to break up into smaller blocks. The latter will drift radially outwards, leaving disruptive basins behind and between, and having geosynclines and borderlands in front, represented later by mountain systems and sunk borderlands.

In the case of Gondwanaland the evidence of late Carboniferous glaciation is here accepted as a definite geological proof that such drifting has since taken place. As I have already briefly reviewed the whole problem in a recent paper (54), the ground need not here be gone over again. It is desirable, however, to direct attention to later discussions by Thomas (101), Walton (105) and Cotter (20), which indicate that in New South Wales, Rhodesia, South-West Africa and India, the glacial beds are all nearly contemporaneous and of probably late Carboniferous rather than early Permian age. Simpson has shown from the meteorological standpoint that glaciation of regions now in or near the tropics " could not possibly have been brought about by any rearrangement of land and water," and he is forced to conclude that " there has been a considerable shift of the continents relative to the poles and the climatic zones " (95, pp. 22

and 23). The deduction cannot be escaped that South Africa lay near the South Pole and, if verification be required, it is to be found in the distribution of Upper Carboniferous laterites recorded by Harrassowitz (39).

But, this being granted, we must envisage not only a radially outward drift of each great land mass towards the Pacific and the Tethys, but also a general drift, possibly involving the *whole* of the crust, with a northerly component on the African side sufficient to carry the South African region from the South Polar circle, and Britain from the tropics, to their present positions. This picture is rather different from Wegener's, but it is believed to be a reasonable statement of the movements that occurred. Here, then, we have a severe test of the convection hypothesis. Can it provide a northerly drift for the African hemisphere?

In Fig. 5 the combined effects of the two types of circulation so far considered are represented for the time at which the movements leading to our present geography began. A quantitative treatment is at present impracticable, but a roughly qualitative assessment is possible on the assumption that the sub-continental circulation becomes stronger than the planetary circulation. In Gondwanaland the chief ascending current would most probably develope near the Cape Mountains and their continuations. Thus the planetary circulation would be completely reversed beneath Gondwanaland. In Laurasia the chief ascending currents would be along the Appalachian—Caledonian belt, modified in Europe by the eastward divergence of the Hercynian ranges, and the planetary circulation would thereby be strengthened in the north but reversed in the south. The resultant forces (as represented in Fig. 5) would clearly be in the direction of rotating the whole crust towards the north on the land hemisphere and towards the south on the Pacific side.[1] The success of the hypothesis in providing a possible mechanism for this long-puzzling movement goes far to justify its tentative acceptance.

The hypothesis has other significant implications. It indicates that superimposed on the general crustal drift there would be a relative approach between Africa and Europe. This would be intensified by the resultant of the currents from the hot regions beneath the growing Indian and South Atlantic Oceans.

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[1] For the long-distance transmission of thrusts through the crust see Goldstein (31).

Although these currents would be directed towards the interior of Africa, and would thus place Africa under compression, the resultant would be a drive in a northerly direction. Here we have exactly the conditions postulated by Argand and other Alpine geologists as essential to account for the structure of the Alps.

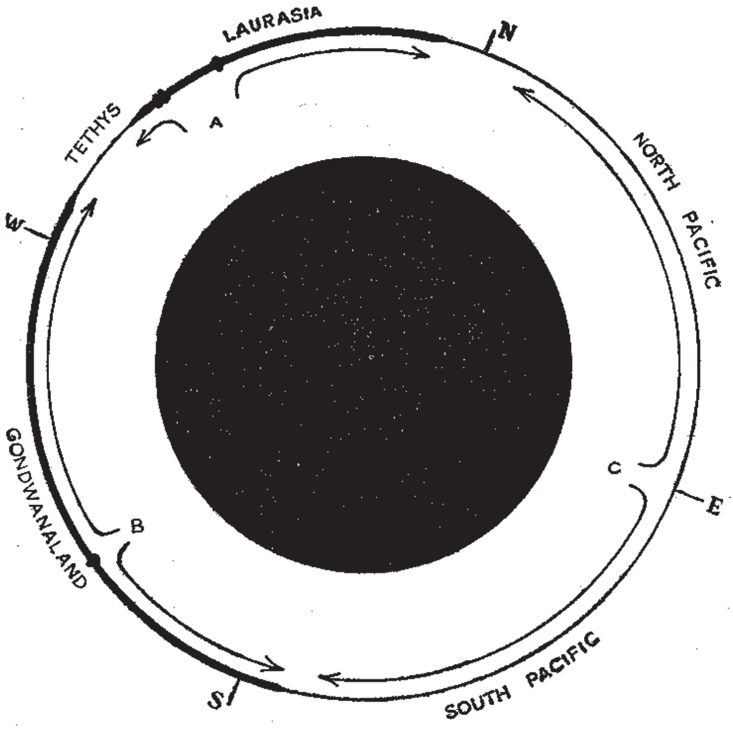

Fig. 5.

The northerly drift of India would seem incredible if it were not implied by the facts (*a*) that in the late Carboniferous India was glaciated from the south; (*b*) that it became an active site of laterite formation from the Eocene onwards; and (*c*) that the

Himalayas and Tibet, from being a depressed marine area have become the highest mountain-flanked plateau on the face of the earth. The very powerful drag that would be necessary to effect the movement and the enormous thickening of the crust to the north implies an unusually vigorous current. The latter can reasonably be referred to the growth of the Indian Ocean, for this would greatly intensify the currents that initiated its formation. As India pushed through the Tethys geosyncline, much of the underlying amphibolite layer would be recrystallised into eclogite and sunk. Only in this way could the great excess of heat that would otherwise have accumulated beneath Tibet have been discharged. Isostatic considerations suggest quite independently that the sial or upper layer of Tibet and the Himalayas must greatly exceed the normal thickness and that the amphibolite layer is likely to be very thin or represented by eclogite. The region is one that may be expected to become the seat of uprising currents that will lead in the future to earth movements and batholithic intrusion on a gigantic scale.

The position of Australia, and the unusual width of the depressed area that separates it from the Australasian arc, are consistent with the assumption that the currents from the Indian Ocean substratum were particularly vigorous. Australasia had not to meet the full resistance—thermal as well as mechanical—of a continental block like Asia, and so, as we find, it travelled even further away from its original site than India did.

Antarctica, on the other hand, was moved in the face of the southward currents of the South Pacific substratum and therefore was unable to drift so far away from the neighbourhood of Africa. Originally it probably lay on the Pacific side of the South Pole, but the general crustal drift already described (Fig. 5) carried it polewards.

No ocean has yet formed between Asia and Europe, although, as Argand has pointed out, the region from the Caspian and Aral Seas to the Obi basin is a relatively depressed one. Presumably the tendency to powerful currents was slight, corresponding to the fact that the Asiatic coast lands are in a much less advanced stage than those of North America. Moreover, the bodily thrusting of the northward extension of India beneath the Tibetan area may have created a thermal resistance which would prevent the normal development of currents beginning to move outwards from the Khirgiz Steppes.

PERIPHERAL MOUNTAIN SYSTEMS.

Taylor and du Toit have both drawn attention to the orogenic rings corresponding to the dispersive movements of Laurasia and Gondwanaland. In Figs. 6 and 7, I have represented these rings on a projection for which I am indebted to my former colleague, Prof. J. M. Holmes.

Laurasia is thought to have spread outwards towards the Pacific and the Tethys, and it is surrounded to-day by the orogenic ring of the West Indies, the Cordillera of North America, the Asiatic Island festoons and the northern side of the Alpine-Himalayan system. Within it lie the great disruptive basins of the Arctic and North Atlantic Oceans. The arrows in Fig. 6 indicate approximately the directions of continental movement implied by the structures of the ranges. For the Tethys-belt Argand's bold diagrams clearly illustrate the conception that ranges thrust over a foreland from a geosyncline imply an underthrust of the foreland in a direction having a component opposed to that of the surface overfolds and nappes (9). As in the case of compression of a plastic substance between the closing jaws of a vice, so here the energy is supplied by the movements of the forelands; and as the vice is actuated by an external source of energy, so here the forelands are carried forward by deep-seated rock-flowage maintained by currents in the substratum.[1]

Sub-continental flowage from Asia towards the Pacific may be inferred from the échelon structure of the island festoons. The remarkable analysis of the latter by Tokuda (102) and his Japanese colleagues (29), and his success in imitating the structures by simple experiments, have revealed the operation of active agents from the interior of the arcs, as originally surmised by Suess. In each case the maximum movement has been towards the middle of the arcs, becoming gradually less towards the more stable buttresses (Kamchatka, Yezo, Formosa, etc.) between successive arcs. This line of attack has been developed by Lee and applied to the tectonics of Asia as a whole (79, map p. 511). Outward movements have been deduced by Brouwer from his observations relating to the mountain building now in progress in the Banda arc (13). The forward flowage of sial is evidenced by the Tertiary charges of level in Java described by Martin (84, p. 14), and by the great and geologically rapid uplifts of the outer zones of many growing island arcs to which Hobbs has repeatedly directed attention (42).

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[1] For an experimental illustration of this type of process see Bull (16, pl. 10).

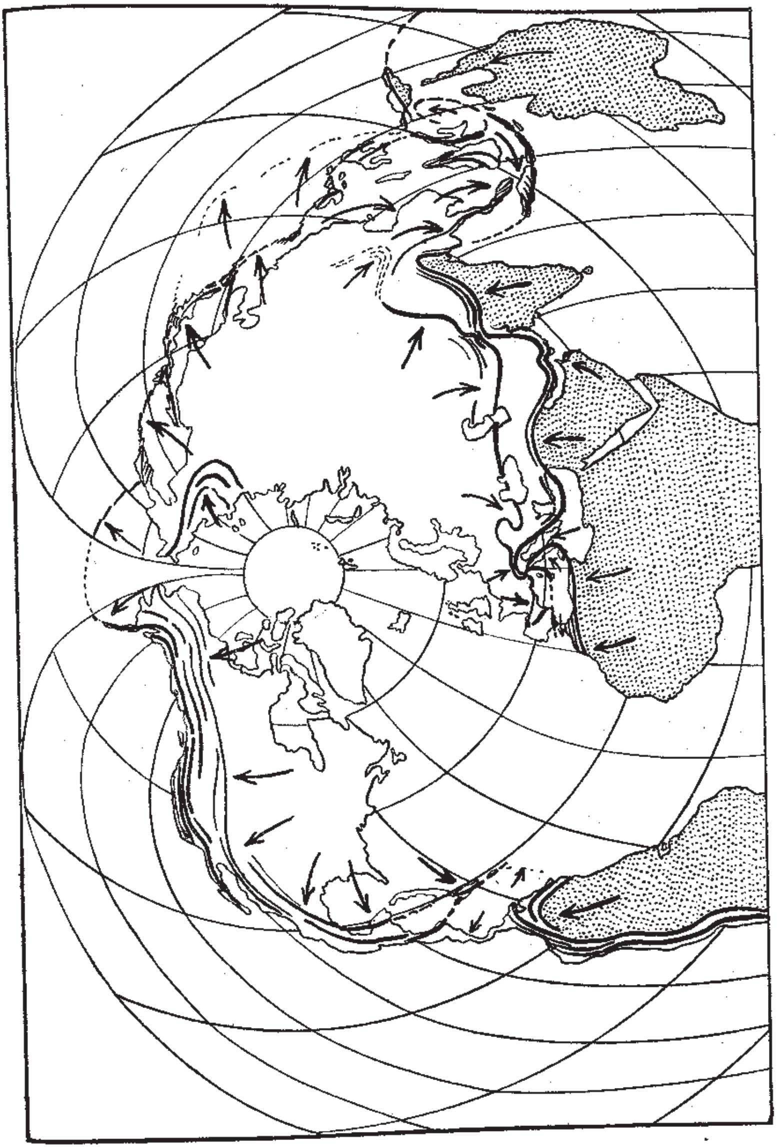

Fig. 6. *Scale:* 1 : 170 x 10^6.

E. C. Andrews has made a valuable comparative study of Australasia, China and Japan, and North America, and despite the fact that on the American side the structures are now closely telescoped, he has made it clear that there has been a marked outward growth of each of these terrains towards the Pacific. With advancing time, from the Pre-Cambrian onwards, the ore-deposits appear in zones successively nearer the present periphery, as if there had been an outward spread of material (6). The more complex Antillean region has recently been dealt with by Schuchert (93) and is referred to below.

In Gondwanaland the movements appear to have been at first radially outwards from the neighbourhood of southern Africa, and afterwards, as they developed, from the South Atlantic and Indian Oceans. Here we have the broken orogenic ring of the Venezuelan Andes and the South American Cordillera, the Antarctic Andes, the New Zealand and New Guinea mountains of the Australasian arc, the Himalayas, north of India, and the southern side of the Alpine system, north of Africa (Fig. 7). Observations in Peru (110) and Colombia (36, p. 164) have revealed thrusting from the Pacific and Antillean sides, indicating an outward movement for South America. Henderson has recently presented evidence for regarding the north-east trending crustal ridge, of which New Zealand is the highest part, as the upthrust edge of a gigantic crustal block with its frontal scarp overlooking the Tonga Deep (40). For New Guinea and Antarctica there is, as yet, little detailed evidence, but the mountains are just where they would be expected on the continental drift and convection current hypotheses here developed.

GEOSYNCLINES.

In 1927 I discussed the physical conditions under which geosynclines could be formed and concluded that " the only known causes competent to produce geosynclines in which the original floor has subsided to great depths are (*a*) migration of light magmas from the geosynclinal column into the bordering regions; and (*b*) thinning of the original *sial* layer by stretching; in each case accompanied by a compensating inflow of heavy material from greater depths " (50, p. 272). To these I added (*c*) increase of density due to metamorphism of the underlying material, as a subsidiary cause. The convection hypothesis provides a mechanism for each of these.

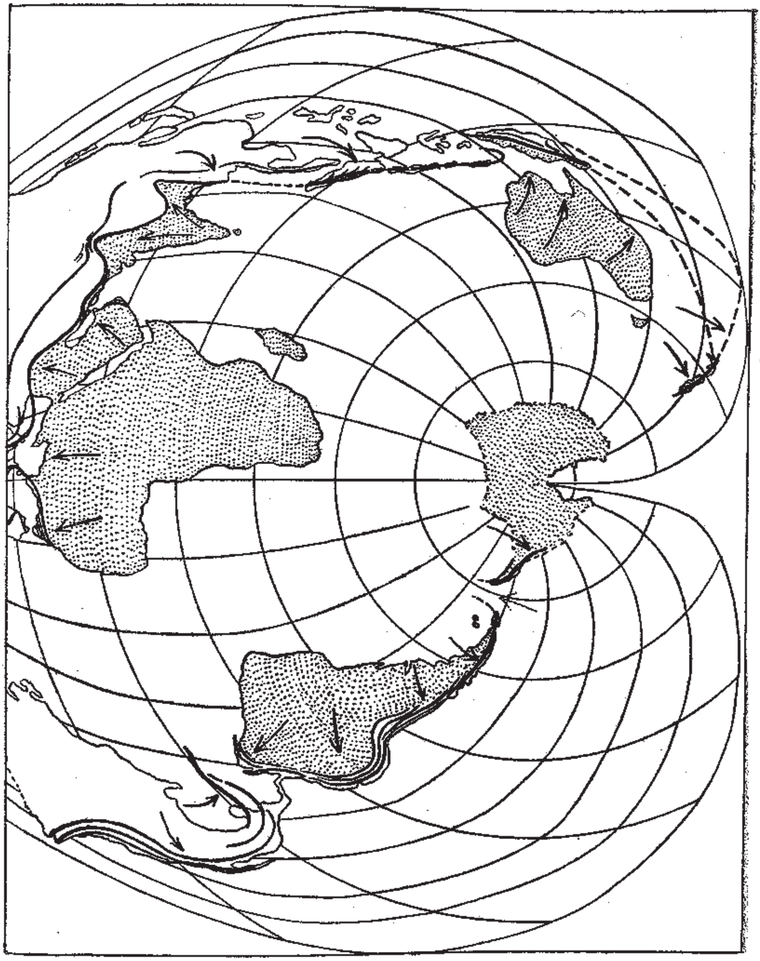

Fig. 7. *Scale:* 1 : 210×10^6.

Type (*a*) is here referred to magmatic corrosion and flowage of the amphibolite layer; it has already been described as the "interior" type of geosyncline on page 582, where it was shown that it would commonly be developed under conditions of compression. Each continental block has, or has had, one or more examples of this type. Most familiar are the seas within the Asiatic festoons from the Behring Sea to the Java Sea and beyond to the Riverine tract of Burma. On a far greater scale are the depressed areas of the Coral and Tasman and Arafura Seas of Australasia. Antarctica has its representative in the Weddell and Ross Seas. The corresponding African feature is probably to be seen in the Eastern Mediterranean and the Adriatic, though here additional complexities have entered. The long-lived composite Cordilleran geosyncline of North America provides the greatest known example of geological history (92). The Gulf of Mexico is probably in part a geosyncline of similar origin. South America and Europe have also had their interior geosynclines, though now they are, for the most part, closed up or uplifted by subsequent compression.

Type (*b*) is that due to the distension of a continental block or the separation of two such blocks by diverging currents. The Tethys is the greatest example of the latter case, and the opening of the Uralian geosyncline in the Lower Devonian illustrates the former. Ocean basins evolve from the long continued operation of the process.

Type (*c*) is represented by a special kind of median area lying between opposed mountain systems bordering approaching forelands. The Caribbean Sea, the Western Mediterranean and the Banda Sea are examples. These are all in regions where sub-continental currents approach and throw the nearly sial-free crust into compression.

Still another type of geosyncline, also referable to (*c*) remains for consideration; the type that forms on the foreland side of a growing mountain system. There are many present-day examples: the Indo-Gangetic trough; the Persian Gulf and the Tigris-Euphrates valley tract; the Schotts depression south of the Atlas; the fore-Caucasian sunkland from the Caspian to the Sea of Azov (90); the Orinoco valley south of the Venezuelan Andes; and in part the Adriatic-Po valley depression and the Eastern Mediterranean. The latter area has already been mentioned as an interior geosyncline of type (*a*). It is a region of composite origin and its tectonics are correspondingly complex. The pure type is well represented by the Indo-Gangetic trough, and it differs from type (*a*) in developing during the compression of type (*a*); Grabau describes the phenomena as "the migration of geosynclines" (32). Whereas type (*a*) is due to the thinning of the amphibolite layer, the new bordering geosyncline forms as a result of the compression that transforms type (*a*) into a mountain system. As the amphibolite layer continues to flow towards the mountain roots it meets there an obstruction (above D in Fig. 8) and is transformed into eclogite. Thus the region bordering the mountains becomes depressed. Sediments accumulate and may in their turn become steeply folded. An excellent example is to be found in the Soan geosyncline (now folded) of Poonch State in Kashmir, recently described by Wadia (103). Here there is a continuous record of 20,000 feet of sediments ranging from the early Miocene to the middle Pliocene, indicating very marked subsidence during the time when the Himalayan folding was at its height.

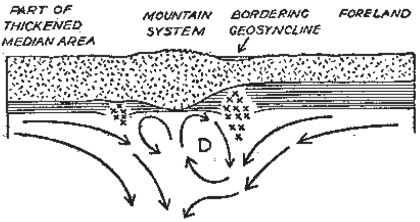

Fig. 8.

Thus it appears that convection currents, co-operating with eclogite formation in the appropriate belts, are competent to account for all the varieties of geosynclines that have been recognised.

MEDIAN AREAS.

As Kober has emphasized in the case of the Alps, two opposing mountain systems are commonly overturned away from each other with a more or less broad *zwischengebirge* or median area between. The median areas range from high plateaus like Tibet through regions such as Persia and the Pannonian basin to deep seas like the Western Mediterranean and the Caribbean Sea. The case of Tibet is a result of enormous thickening of sial (Fig. 8) due to the underthrust of India accompanied by the disappearance of most of the amphibolite layer. The Western Mediterranean and its analogues represent relics of the Tethys floor which had probably very little sial covering when the approach of the continents began. The intermediate examples mentioned above may possibly have been sial patches forming "swells" in the original Tethys. As the forelands approached, the zones of eclogite formation would also approach and unite beneath the sial patches. The colliding mountain arcs on either side of the median area would protect it from superficial compression, and hence it may even have subsided while the enclosing ranges were being pushed over their respective forelands. Such was the case in the Pannonian basin within the Carpathians (36, p. 160). Afterwards there might develop a thickening of the area (*plis de fond*) as a result of continued deep-seated inflow of amphibolite.

When median areas are compressed, the stream-lines of rock-flowage will tend to swerve round at right angles to their original directions wherever there is a lateral inferiority of resistance (Fig. 9). This should be particularly noticeable where approaching continents have an ocean on one or both sides, e.g. in the case of North and South America. The lateral stresses directed against the ocean floor will develop thrust planes increasing in steepness as the more rigid upper levels of the crust are fractured. In plan the thrust planes will be convex towards the oceans. Magmas will escape up the curved fractures and form volcanic belts or arcs of islands at the surface. In this way the Panama-Costa Rica land bridge and the volcanic arc of the Lesser Antilles can be readily explained. No difficulty stands in the way of the generation of magmas—basaltic, andesitic or rhyolitic—for median areas are destined by their position with regard to the advancing currents to become foci of heat concentration. The Persian and Pannonian median areas are partly girdled with Tertiary volcanoes. The peripheral volcanoes of the Caribbean have been already referred to. A similar arrangement of volcanic arcs is to be found around the Western Mediterranean (42) and the Banda Sea.

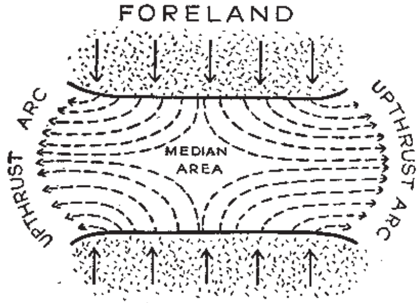

Fig. 9.

The sea enclosed by the Southern Antilles between Antarctica and Patagonia is not a true median area, since Antarctica and

South America have separated rather than approached. The island arc here is probably a lag effect due to a strung-out belt of sial having been dragged against part of the Pacific floor left between the two continental blocks as they advanced. Corresponding to this interpretation there are volcanoes and deeps on the eastern side where the substratum currents from the Atlantic and the Pacific meet squarely, but on the western side there is nothing corresponding to the Panama volcanic ridge of Central America since there is no pressure between Graham Land and Tierra del Fuego (57).

RIFT VALLEYS.

The convection hypothesis suggests the possibility that rift valleys are the surface expression of narrow elongated median areas of a very special type. A vast area of south and eastern Central Africa was reduced in pre-Tertiary times to a peneplain which has since been uplifted through hundreds and even thousands of feet. As Wayland infers: " this bulging suggests very deep-seated compression " (107). It has already been indicated that the northward drive of Africa was probably the resultant of substratum currents moving in from beneath the Indian and South Atlantic Oceans. A source of compression for the great *plis de fond* of High Africa is thus available. Wayland also points out that the site of Lake Victoria was formerly a watershed of domoid form, and he considers that the subsidence which led to the formation of the Lake depression was contemporaneous with the appearance of the nearly encircling rift valleys. The Victorian bulge may well have started a subsidiary system of currents as the sial layer thickened, and it is here suggested that the rift valleys lie over the belts of eclogite formed where the Victorian system of radial currents met the two sets of currents coming in from beneath the growing ocean floors (Fig. 10). To the south the latter would impinge directly, but to the north the Victorian currents would reinforce the northward drift so that the Western rift would die out, whereas the Eastern would continue. The currents would not be directly opposed. So long as they converged they would meet along a line, like the currents producing a line-squall in the atmosphere. Along this line eclogite would form from the amphibolite material flowing in. At the same time the tendency of the sial on either side to advance would lead to the development of curved thrust surfaces steepening towards the surface, as already visualised

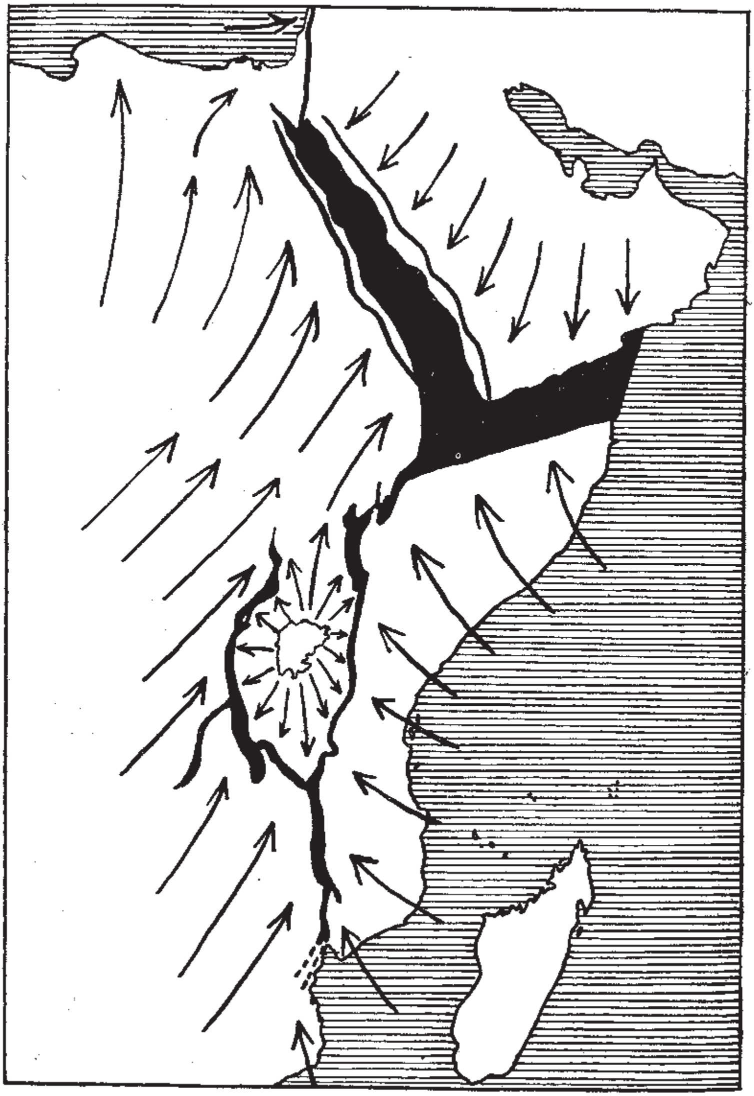

Fig. 10.

by Wayland (106). The crust would move forward and upward on these surfaces and would thus come to be tilted away from the zone where the fractures outcropped. Superimposed on this effect would be the subsidence due to eclogite formation, this being greatest in the middle and systematically less towards the sides. Figs. 11 and 12 illustrate the processes invoked and the structures produced. The mechanism is like that of cauldron subsidence, but elongated along a line instead of being centrally over a magma-chamber. Magma would, of course, be present, as always where heat-conveying currents approach. It would occupy spaces left by the sinking of blocks of eclogite, and its subsequent displacement and contraction on cooling would contribute to the many accessory phenomena associated with rift valleys. The subject is not one that can be discussed briefly to any further advantage, and a fuller discussion, including that of the very interesting petrological implications, must be reserved for another occasion.

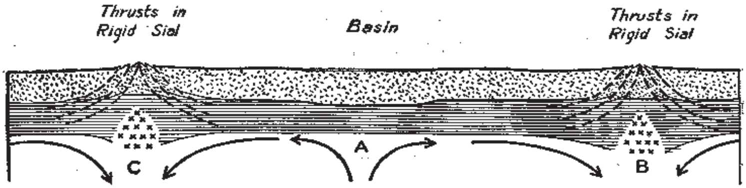

Fig. 11.

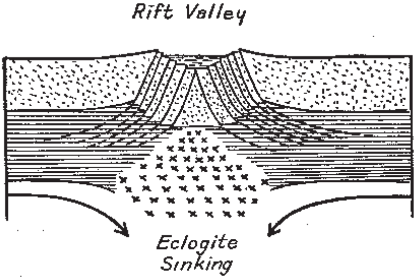

Fig. 12.

To explain the Gulf of Aden and the Red Sea on this hypothesis it seems necessary to assume that the older currents directed southwards from the Tethys did not die out beneath Arabia until after the newer Gondwanaland system had become active. It is noteworthy that the Red Sea had already formed when Arabia began to push against the geosyncline from which the Zagros Mountains were raised. After the first subsidence of the Red Sea and Gulf of Aden there would be a downward protrusion of the sial layer relative to the lower surface of the surrounding sial of Egypt, Arabia, etc. (as in Fig. 12). As the Gondwanaland currents drove back the weakening Tethys currents, much of this protrusion would be carried under Arabia by rock-flowage. Thus the Red Sea and the Gulf of Aden would continue to subside, and the plateau of Arabia would be produced by uplift consequent upon the addition of sial to its original sial layer. It must be clearly realised that the currents marked in Fig. 10 as flowing southwards from the Tethys region were later reversed. (See Figs. 6 and 7).

The whole problem of rift valleys is so difficult that it would be idle to pretend that anything more than a promising clue has been suggested. Examples such as the Dead Sea trough and the Rhine Graben may later fall into line, but at present speculations regarding their origin cannot be offered with any confidence.

CHANGES OF LEVEL OF LAND AND SEA.

In his recent Presidential Address on the Pacific Gregory writes, " The direct geological evidence is overwhelming, that large blocks of the earth's crust rise and fall for vertical amounts greater than the greatest depths in the oceans. If continental blocks cannot sink, much geological evidence becomes meaningless " (34, p. cxxxii). The convection-current hypothesis provides adequate processes to account for the great changes of level that have taken place. The replacement of the amphibolite layer by heavier peridotitic material could provide up to 3 or 4 km. of subsidence. Sunk borderlands, such as those off North America (92), Peru (97), the South Coast of Java (84) and the North Coast of New Guinea (111), may all be referred to the action of this process. The disappearance of other continental areas, like the old Atlantic lands, may be readily accounted for by continental drift and the gradual development of new ocean floors. Still greater depths require the substitution of eclogite or peridotite for the gabbro-amphibolite material of the ocean floor. Great vertical uplifts are brought about by the thickening of the sial layer as in Tibet and Arabia, or by the outward flow of sial from the continental crust to the outer zones of peripheral island festoons. Similarly, mountain roots may be carried laterally away from their place of origin, resulting in lowering of the mountains and uplift of the regions in front. Obviously, with the four kinds of material, sial, amphibolite or gabbro, eclogite, and peridotite, combined with all the phenomena of convection, rock-flowage, fusion and crystallisation, the possibilities of changes of level and lateral movements are sufficiently varied to meet all the valid requirements of geological history.

The explanation of marine transgressions offered by Joly's hypothesis of thermal cycles has been generally regarded as one of its most attractive features. Under the convection hypothesis the conditions for marine transgressions are less regular and of less embarrassing amplitude (48, p. 536). While continental drift is in progress the old ocean floors immediately in front are sinking, and the heavy blocks of eclogite follow a path that carries them beneath the advancing continents. Thus the latter will sink a little, rising later as the sunken blocks gradually fuse. Behind the continents the material of the new and growing ocean floor is at first hot and expanded as compared with its later condition after cooling. This implies a relative rise of the ocean floors while they are hot, and consequent spilling over of the water above. The combined effect of these two processes will be marked transgression while continental drift is active. Recessions should follow as the drifting gradually slows down. The actual events since the close of the Palæozoic match the deduction in a general way. With many fluctuations the transgressions reached their maximum in the middle Cretaceous, falling away with the late Cretaceous mountain building, expanding again during the Eocene, and finally withdrawing as Recent time was approached. There are many reasons for fluctuations: geosyncline development, mountain building, sinking of borderlands, and rising and falling of median areas all produce marked local changes and smaller world-wide reactions. Sedimentation implies a displacement of water. Movements of continents towards the equator retard the earth's rotation and lead to the spreading of seas in high latitudes with recession in low latitudes. Conversely, if continents drift polewards the opposite effects are produced. These consequences are due to the immediate response of the water surface to changes of rotation, and are reversed as the geoid slowly accomodates itself. The accumulation of ice-sheets lowers the sea level and melting of the ice raises it. Isostatic adjustments imply minor modifications. Clearly the interplay of possibilities is very varied, and the analysis of the actual facts is not likely to lead to sound conclusions until the study of world stratigraphy has advanced far beyond its present beginnings.

VII.—CONCLUSION.

It is not to be expected that the first presentation of a far-reaching hypothesis and its manifold applications can be wholly free from errors. The workings of the inner earth reveal themselves only indirectly, and their actual nature in space and time is certain to be far more complex than can be visualised. Nevertheless, the preliminary survey that has here been given seems to show that the convection-current hypothesis goes far to account for

(*a*) the leading features of continental drift since the close of the Palæozoic;
(*b*) mountain building and island festoons;
(*c*) oceanic deeps;
(*d*) the initiation and development of geosynclines of various types under both compression and tension;
(*e*) the growth and disappearance of borderlands;
(*f*) the varied characters of median areas;
(*g*) rift valleys;
(*h*) the distribution of earthquakes;
(*i*) igneous activity and the distribution of volcanoes;
(*j*) marine transgressions and recessions; and
(*k*) possibly the maintenance of the earth's magnetism.

So far the treatment has been almost entirely qualitative and therefore it inevitably stands in need of criticism and quantitative revision. The hydrodynamics of the substratum and its behaviour as a heat engine need to be attacked on sound physical lines. The capacity of substratum currents to promote magmatic corrosion, transport and crystallisation, and to produce migrating sub-crustal wave forms, calls for detailed treatment. The full bearings of the hypothesis on petrogenesis have yet to be investigated. Meanwhile its general geological success seems to justify its tentative adoption as a working hypothesis of unusual promise.

This paper is based on a lecture delivered before the Society on 12 Jan. 1928 and summarised in the Geological Magazine (51). Advantage has been taken of the delay in writing up the material to incorporate references to papers which have appeared since the date of the lecture.

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DESCRIPTION OF FIGURES.

Fig. 1, p. 578.—Planetary circulation of the substratum (crustal effects being ignored).

Substratum, white. Metallic core, black.

Fig. 2, p. 579.—Sub-continental circulation.

Upper or sial layer, dotted. Intermediate layer (amphibolite, gabbro, etc.) line-shaded. Substratum, unshaded.

Fig. 3, p. 579.—Distension of the continent on each side of A leaving an island or "swell" in the "dead" area above A. Above B and C eclogite formation results from the crystallisation of the material of the intermediate layer, and oceanic deeps are produced. The front part of the sial is thickened and a borderland results. Behind this, one effect of the heat transport from A to B or from A to C is the development in each case of a geosyncline.

Fig. 4, p. 582.—The geosyncline has been compressed into a mountain system above D where a new system of currents begins. The outward current towards C is strengthened and the borderland is stretched out and becomes a sunk-land. The opposing current at D leads to the formation of a bordering geosyncline as shown in Fig. 8.

Fig. 5, p. 586.—Convection currents (Triassic time), illustrating the dominance of the clockwise direction and the resulting northerly drift of the land hemisphere.

A. Ascending currents controlled by the Hercynian and Caledonian thickening of the crust. (In North America these two belts more nearly coincide than in the diagram).

B. Ascending currents controlled by the Cape Foldings, previously formed during the growth of the Tethys.

C. Ascending currents of the planetary circulation beneath the Pacific.

Fig. 6, p. 589.—Orogenic "ring" and continental movements of Laurasia. (The adjoining blocks of Gondwanaland are dotted).

Fig. 7, p. 591.—Orogenic "ring" and continental movements of Gondwanaland (dotted).

Fig. 8, p. 593.—Illustrating the formation of a bordering geosyncline (e.g. Indo-Gangetic trough) between a mountain system (e.g. Himalayas) and its foreland (e.g. Peninsula India).

Fig. 9, p. 594.—Stream-lines of rock-flowage in the lower crustal levels of a median area between two approaching continental blocks: to illustrate the formation of upthrust arcs, generally surmounted by volcanic islands, convex in plan towards lateral areas relatively deficient in resistance.

Fig. 10, p. 596.—The rift valleys of Africa (after Gregory, 35) with hypothetical substratum currents indicated by arrows. The currents beneath Arabia are to be regarded as a survival of the Tethys system which was later reversed by the growing activity of the Gondwanaland system. The Arabian part thus represents an earlier period than the rest of the diagram.

Fig. 11, p. 597.—Hypothetical section across the Victorian area of the African bulge. Subsidiary currents due to the latter ascend at A and produce the Lake basin above. Descending currents at B and C are responsible for stresses that produce thrust planes above (broken lines) and eclogite below (crosses), thus localising the sites of the Eastern and Western Rifts.

Fig. 12, p. 597.—Illustrating the formation of a rift valley by subsidence of the sial over the belt of eclogite formation. It should be noted that in Figs. 11 and 12 the opposing currents have generally a northerly component not representable in the plane of the diagrams.