Regions of Compression.[1]

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I.

IT is usual to contrast the horizontal forces acting on the earth's crust with those that are vertical and to regard the latter as more fundamental and important. This attitude is apt to be misleading, although it rests on a foundation of fact, if it be true, as is generally believed, that most horizontal forces are ultimately to be attributed to the contraction on cooling of the earth's interior, which lets down the crust so that it has to accommodate itself to an area less extensive than that which it previously occupied.

The discovery, however, of the release of energy in the course of the atomic degradation of uranium and thorium and their products caused a reconsideration of the question. It is true that the amount of radioactive materials diminishes as the basicity of the rock increases, and there is every reason to believe that the deeper rocks are more basic than those nearer the surface, but it is contended that, even if this be allowed for, the energy given out by them in their disintegration, converted into heat, would cause a rise instead of a fall in the earth's temperature. Prof. John Joly believes that this has in the past led to catastrophic developments characterised by great outpourings of lava. But, although the whole of the energy given out by radioactive elements, when isolated, is converted into heat, it is probable that a considerable proportion of the energy liberated by such elements, when they occur as rock-constituents, is used up in effecting physical, chemical, or atomic changes in the surrounding minerals.

That much of the radioactive energy set free in the disintegration of radium and thorium is absorbed in other ways than in raising the temperature of the rocks is clearly shown by the formation in certain circumstances of 'pleochroic haloes' round radioactive minerals. This occurs especially in the case of zircon embedded in biotite mica. Such a halo is a sphere with a radius of about 30 microns, and has a minute zircon at the centre. It is of a darker and a deeper brown and far more pleochroic than the rest of the mica. The difference is usually assumed to be the result of ionisation by the radiations from uranium and thorium contained in the zircon. The possibility of atomic changes under the influence of the α rays must, however, not be ignored.

The formation of the haloes must involve a considerable absorption of energy, the magnitude of which will be realised when it is remembered that the mass of the halo may be some 15,000 times that of the zircon at its centre, and more than 300,000 times that of the uranium and thorium to which the halo owes its existence. Nor is it probable that this absorption is confined to the pleochroic haloes.

It is, therefore, doubtful whether there is any considerable excess of radioactive energy available for raising the temperature of the earth.

The zone in which appreciable cooling takes place must extend over only a small fraction of the earth's radius, and the question arises whether the contraction from cooling in this zone is sufficient to account for the folding that we know to have taken place.

Dr. H. Jeffreys estimates that the actual crumpling and overthrusting observed in the principal mountain-chains of the earth has resulted in a decrease in the area of its surface of 2,000,000 square kilometres. At the same time, he calculates that the cooling that is taking place in the earth's interior will, on the basis of the observed coefficient of expansion of the rocks of the earth's crust, result in a decrease in the area of the surface amounting to rather more than 4,000,000 square kilometres.

Now, the folding of the mountain ranges included in this calculation by no means represents the whole of the folding to which the earth's crust has been subjected. Many folded areas are no longer mountainous. They are the sites of ancient ranges which have since been planed down.

It is, therefore, probable that the contraction to which the folds and overthrusts bear witness exceeds that which Dr. Jeffreys believes to have resulted from the cooling of the earth's interior. There is, however, little doubt that far greater contraction has taken place.

The sedimentary and the acid igneous rocks of the continents, which constitute the sial, are apparently underlain, at a depth variously estimated at from 100 to 15 km. by the sima: that is to say, basic and ultrabasic crystalline rocks, or magmas of similar composition, except that they contain water and other volatile constituents.

Dr. Jeffreys bases his calculations of the amount of contraction on the coefficient of expansion of specimens of crystallised rocks which have, of course, lost most of the volatile constituents that they possessed when in the state of uncrystallised magma. Yet, judging from the amounts given off in the course of volcanic eruptions, such as those of Hawaii, volatile substances must form an important proportion of even a basic magma, which will accordingly have a much higher coefficient of expansion than the crystallised rock.

Dr. Jeffreys calculates, however, that the sima is crystalline down to a depth of more than 600 kilometres. This is because he takes the crystallisation point of a basaltic magma under atmospheric pressure at 1200° C. and that of a peridotite at 1400° C. These, however, are the temperatures at which the crystallised rocks that have lost their volatile constituents can be remelted. We know from the observations of T. A. Jagger that the basaltic magma at Kilauea, which retains some, though by no means all, of its volatile constituents, remains fluid at 750° C. It is true that he assumes that the magma was supercooled, but there is no evidence of this. There can be no doubt that the crystallisation point of a basalt- or even a peridotite-magma retaining its volatile constituents would be considerably less than that at which the crystallised rock can be remelted.

It is also assumed by Dr. Jeffreys that the crystallisation point is raised by 3° C. for every additional kilometre of depth, on account of the increase of pressure. This is a fair estimate of the rate of increase of the crystallisation temperature with increase of pressure

[1] From the presidential address delivered to the Geological Society of London on February 19, 1926. A large portion of the address in which illustrations are drawn from the Hercynian, Wealden, and Alpine folding, and all references, are here omitted.

near the surface; but P. W. Bridgeman has shown that the rate of increase diminishes rapidly as the pressure increases.

Allowing, then, for the fact that the temperature of crystallisation of a basaltic magma at the surface is much less than that assumed by Dr. Jeffreys, and for the lower rate of increase of the temperature of crystallisation with increasing pressures at great depths, there seems every reason to believe that a considerable portion of the cooling zone is in a non-crystalline condition, that it still contains a large proportion of volatile constituents, and that it has therefore presumably a higher coefficient of expansion than solid basalt. Nor would the substitution of a peridotite-magma, which Dr. A. Holmes believes to underlie the basalt-magma at a depth of 45 km., make any important difference.

It must be remembered, however, that, on one hand, the coefficient of expansion of all substances shows a marked increase with increased temperature, and, on the other, it diminishes with increase of pressure.

Unfortunately, we are without precise information as to the physical properties of magmas and still less as to the variations of these properties with changes of temperature and pressure. There is no insuperable obstacle to the determination of these data at temperatures and pressures up to those found at depths of about 35 miles (say, 56 km.), and they may reasonably be extended to considerably greater depths by extrapolation. In the meantime many of the problems that present themselves in geophysical research cannot be solved with any approach to certainty. It is earnestly to be hoped that a serious attempt to obtain the necessary data will be made.

There is another important consideration. In some part at least of the zone of cooling, amorphous magmatic material is passing into the crystalline state, not only as a result of the loss of heat, but also in places on account of the loss of volatile constituents. The process of crystallisation is accompanied by very considerable contraction in the case of all or nearly all silicates and mixtures of silicates, a contraction equivalent to that resulting from cooling through hundreds of degrees, whether in the amorphous or in the crystalline state.

Dr. J. A. Douglas has experimented on the increase in volume when crystalline rocks are melted and allowed to cool rapidly so as to consolidate without crystallising. The following were the results obtained with basic crystalline rocks, the composition of which approximated to that of the sima:

Name and locality of rock.	Sp.g. before melting.	Sp.g. of glass.	Percentage of defect of volume in the crystalline state compared with that of the glass.
Gabbro (Carrock Fell)	2·940	2·791	5·07
Olivine-dolerite (Clee Hills)	2·889	2·775	3·95
Dolerite (Rowley Rag)	2·800	2·640	5·71
Dolerite (Whin Sill)	2·925	2·800	4·27
Average			4·75

The fourth column must represent the contraction which a glass of the same composition as the rock would undergo in crystallising. This contraction may be compared with that which would have taken place as a result of simple cooling in the crystalline state.

According to Prof. F. D. Adams, the cooling at a depth of 50 km. has been from about 1450° C. to 950° C. If, like Dr. Jeffreys, we adopt Fizeau's formula for the variation of the volume of rocks, with temperature, namely, $V_t = V_0(1 + et + e't^2)$, where V_0 is the volume at 0° C., V_t that at t° C., $e = 7 \times 10^{-6}$, and $e' = 2{\cdot}4 \times 10^{-8}$, we find that a cubic centimetre of basic rock at 0° C. will have a volume of 1·0606 c.c. at 1450° C., and 1·0283 at 950°. The contraction in cooling from the former to the latter temperature would accordingly amount to 3·05 per cent. of the volume at the higher temperature, about 62 per cent. of the contraction in crystallisation from a melt without volatile constituents. At a depth of 100 km. the cooling is estimated to have been from about 1770° C. to about 1290° C., corresponding to a decrease in volume from 1·08756 c.c. to 1·04897 c.c., a decrease of 3·55 per cent. At 200 km. the cooling is estimated to have been from about 2200° C. to 1900° C. with a decrease from 1·1316 c.c. to 1·0994 c.c., equal to 2·84 per cent. It is evident, therefore, that the contraction on crystallisation would, even apart from the presence of volatile constituents, be much greater than from the simple cooling of crystalline material.

The steam and other volatile substances, however, are eliminated on crystallisation; consequently, the decrease in volume will be far greater than that on crystallisation from a magma without volatile constituents. The volatile constituents may afterwards occupy for a time cavities, large or small, in the consolidated rock or elsewhere in the earth's crust; but by far the greater part will sooner or later escape into the atmosphere, with a corresponding decrease of bulk of the solid earth as a whole.[2] The expulsion of volcanic materials will naturally have a similar effect.

Contraction will also occur on a change of crystalline state from lighter to denser minerals of similar composition, and not improbably on a transformation of elements into others of less atomic volume. Both these changes may be determined by the heavy pressure of the earth's interior. It is, however, probable that most of such possible changes took place early in the world's history. It is only where the pressure has for some special reason been increased or where directed pressure (shearing stress) has intervened, that such changes may be expected to have occurred during the geological time of which we have any record in the rocks.

There is, nevertheless, one change in the terrestrial conditions which will result in a general and progressive increase in pressure, and thus cause an equally general contraction. The acceleration of the moon's position in the heavens is usually considered to be in great part attributable to the slowing down of the earth's rotation. This will result in a decrease in the centrifugal force, with a consequent increase of pressure in the interior of the earth and a corresponding contraction in its volume. These effects have been calculated by R. Stonely, who arrives at the conclusion that "diminishing rotation is a much less potent cause of the elevation of mountain-ranges than is cooling, but that it is sufficiently important to be considered as a large correction to the cooling theory."

[2] The latent heat evolved on crystallisation and changes in crystal structure must delay the processes of cooling and crystallisation, while that absorbed on the expansion of volatile constituents will accelerate them.

As I showed in my previous address, there are at least two opposing influences tending to modify the length of the day: the progressive contraction of the earth accelerating the angular velocity, and the tidal friction producing a contrary effect. At present, the latter seems to be more powerful; but it is possible that in the past the reverse has been the case, especially in the early stages of the earth's existence.

All the processes which have been considered will result in direct primary movement downwards towards the centre of the earth; but, on account of the fundamentally homogeneous character of the earth's material at deep levels (shown by the close similarity of the transmission of earthquake waves in different areas), the subsidence from this cause must everywhere be nearly the same, and will rarely result directly in appreciable *differential* vertical movements of the earth's crust.

There are, on the other hand, processes by which the surface of the earth's crust may locally be permanently extended. This can happen in regions of tension in two different ways. In the first place, temporary rifts, often of considerable size, may be filled by igneous magmas which afterwards consolidate, and by broken material from the sides and the neighbourhood. In the next place, movements of extension occur along the planes of normal faults. When, later, a period of compression supervenes, such movements will not be reversed unless the hade, the deviation from the vertical, is very great, that is to say, well over 45°; otherwise, the pressure at right angles to the fault-plane will increase the friction so much that movement will be impossible. The surface of the crust may also be increased by hydration, especially in the case of igneous rocks. These extensions of the earth's crust must in the long run tend to produce effects in the way of folding and thrusting similar to those resulting from the contraction of the interior.

There are other forces operating on the earth's crust, besides those due to the excess of the area of the crust over that of the surface of the interior, that must tend to produce horizontal movements.

In the first place, a slowing-down in the earth's rotation will be accompanied by a consequent change in the form of the solid earth, which on a large scale adjusts itself to the forces operating on it, but of course not so rapidly as do the aqueous and gaseous envelopes, though geologically the time required is relatively short.

Such a reduction of the rate of rotation of the earth will result in a decrease in the equatorial diameter and in an increase in the polar diameter, involving a movement in the substance of the earth. This will consist in a flow, at all levels, from the equatorial plane towards the poles, combined with a slight downward movement near the equator and a slight upward movement near the poles. The circumference at the equator will contract, but one must not expect contraction which is common to the surface and to all depths to have the same effect as a contraction affecting a portion of the interior, and not the exterior; and, as a matter of fact, there are no north-and-south folded mountains that can reasonably be considered to have been formed in this way. The crust at the equator would, therefore, seem not to have been folded from this cause, but to have been distorted horizontally—being contracted east and west, and extended laterally northwards and southwards. This will add to the effect of the simultaneous decrease in the meridional periphery of the earth, and a strong north-and-south compression in intermediate latitudes will result which cannot be relieved by lateral extension, except to some extent in high latitudes where there will be a small but appreciable expansion of the earth's surface.

It is, therefore, not surprising that in low to intermediate latitudes the compressive forces in the earth's crust arising from causes already discussed are intensified in a north-and-south direction so as to favour the formation of east-and-west folding.

Somewhat analogous effects would result from a change in the position of the poles relatively to the configuration of the earth's crust. This would probably be a result of the shifting of the earth's crust relatively to the core, rather than of a change of the axis of rotation of the earth as a whole from one position to another in its mass. Tidal action may result in an east-to-west movement of the earth's crust, but this alone would not directly affect the position of the pole relatively to the features of the earth's surface. But, if there were a locality such as that of a deeply-rooted mountain-mass where the cohesion between the earth's crust and the core was greater than elsewhere, there would be a tendency for the crust to rotate round it, and this would bring new tracts under the poles. There would then be a drifting-away of the continental masses from the new position of the pole on the earth's crust and towards the new position of the equator; this might appreciably affect the configuration of the earth's surface.

It has been suggested that the centre of gravity of the earth's interior does not exactly coincide with its centre of form, so that there is a point on the earth's surface where the force of gravitation is at a maximum, and towards which both the ocean waters and the continental masses tend to move. If this be the case, and the crust of the earth shifts relatively to the interior, the point of maximum gravitation will occupy a new position on the earth's crust, and the drift will be directed towards the latter.

There seems reason to believe that in late Palæozoic times the principal land-masses were united in one great continental mass collected round Africa as a centre, and that they have since drifted away eastwards, southwards, and westwards towards the centre of the Pacific. This would be only what one would expect if the points with the maximum force of gravitation were in Devonian and Carboniferous times in Central Africa, and in Tertiary and Quaternary times in the centre of the Pacific. But, although the forces, developed directly or indirectly as a result of tidal retardation and the resultant relative movement of the earth's interior and crust, must be taken into serious consideration, and may from time to time exercise decisive influence on the structure and configuration of the earth's crust, it is only the horizontal forces resulting from the contraction of the earth's interior, assisted by expansion of its crust in local and temporary regions of tension in the manner already explained, that are sufficiently powerful to account for the development of the folds and thrusts of the present mountain-chains and those that existed in former geological periods.

(*To be continued.*)