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Movements of the Earth's Surface Crust, II.

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IN a recent paper appearing in this Journal (June, 1923) I dealt with a theory of the source of the surface changes experienced by the Earth over Geological time. In this present paper I propose to supplement the references to (*a*) the conditions of equilibrium leading to transgressional seas, and (*b*) the distribution of temperature in the continental crust.

Transgressional Seas.

In my former paper (*loc. cit.*) the development during inter-revolutionary times of a sub-oceanic crust was referred to. The conclusion was reached that such a crust might attain a thickness of some 15 miles (24 kilometres) in 25 million years.

Now the development of such a crust must have the effect of securing to the ocean a basal support extending nearly as far downwards into the substratum as the average basal level of the continental layer.

In order to arrive at this level we have to decide upon the most probable depth of the continental layer. Seismology has led to estimates between 30 and 35 kilometres. I shall take 32 k. If, now, we add the mean continental elevation (700 m.) to the mean depth of the ocean (4400 m.) and subtract from 32 k., we find the submergence of the continents in the substratum to be 27 k. The surface of the ocean floor is taken as the upper surface of the substratum. The base of the sub-oceanic crust is 24 kilometres below this level.

Now when fusion of the magma becomes widespread and its voluminal expansion lifts both ocean and continents together, there can be no general differential vertical movements due to loss of buoyancy, save in so far as the continental base may project into the magma below the general basal level of the sub-oceanic crust. This, on our present reckoning, will be only some 3 kilometres. It may be nil. But on the other hand, the deeply projecting compensations will experience the effects due to the lessening density of the magma. They will grow heavier, as it were; the former isostatic equilibrium will be disturbed; and, locally, the continents will sink or sag downwards.

This effect will mainly take place where great mountain ranges and raised plateaux exist at the surface. Such transgressional flooding as affected the North American Continent during Laramide times would owe its initiatory development to this source. Similarly the earlier enlargement of the Mediterranean would be associated with the older mountain ranges then existing. In short, it is to such effects that we must ultimately ascribe the phenomenon of mountains begetting mountains. For such hollows must collect the débris of the millions of years which follow.

As the period of revolution approaches, the ocean floor begins to melt away and commingle with the general magma. Increasing circulation, both lateral and vertical, assails it with hot and, possibly, superheated currents. As it dwindles the continents become more and more exposed to the molten lava, and, as they had attained their former elevation relatively to the ocean at a period when the lava was at its maximum density, they must now experience as a whole the effects of the diminished buoyancy and begin to sink relatively to the ocean level. The ocean cannot experience this effect, but its floor may buckle or subside. To such movements the diminished rigidity of the suboceanic crust would contribute and, subsequently, the lateral compression to which it would be subjected; as referred to in my first paper. The deeps near continental margins are probable testimony to such compressional stresses. We possess unassailable evidence of vertical movements of the ocean floor even within recent times.

It is evident that with such a complexity of factors and without any sure knowledge of the amount and downward extent of the density change of the substratum, estimates of the differential vertical movements finally reached cannot be of value. It seems certain, however, as stated in my former paper, that the movements must be adequate to account for such estimates of the depths of transgressional seas as Geologists have been able to arrive at.

We possess, indeed, an indication of the prevailing relative densities of the submerged continental materials and the sustaining magma which is of special interest.

If it be accepted that the continental emergence is about 5000 m. and its submergence 27,000 m. then the ratio of the density of the average submerged continental materials to that of the magma must be as 27 : 32 or as 2·53 : 3·0. A correction for the buoyant effects of the ocean will bring the ratio to about 2·65 : 3·0; which is in satisfactory agreement with the fundamental assumption that the continents do in fact, float on a substratum of basaltic magma.

In order to illustrate what has been said, let us consider the case of the continent of Africa. The mean height of that continent is stated to be 732 m. over sea level. The great plateau extending over its southern, central and eastern regions, possesses a mean altitude of 1332 metres. It, therefore, rises 600 m. over the general continental surface. If the density ratio of continental crust and magma is 2·6 to 3·0 we find that a compensating protuberance must extend nearly 4 kilometres into the magma to fulfil the condition that equal mass must underlie equal areas.

Now if the density of the substratum changes 10 per cent. a downward movement of the plateau region of 400 m. must occur to restore isostatic equilibrium. The force so originating will be supplemented by similar isostatic forces due to such compensations as may exist beneath the Atlas ranges and the Abyssinian region. The effects of the vertical stresses may be to depress the continent—possibly tilting it—so that transgressional waters will invade its low-lying regions. Thus the desert regions to the north-east, now at an altitude of about 300 metres over sea-level, would be flooded. Again they might possibly give rise to rifting of the continent in such direction as would most relieve the stresses. It seems probable that this is the sort of effect which must usher in a revolution.

One outcome of the foregoing views is the recognition of the fact, that cyclical changes of stress must, from the earliest times, have affected the earth's surface crust. During the period of advancing liquefaction the outer crust, as a whole, must experience stresses of tensile character. For the earth's surface is then increasing in area. When the climax of revolution is attained there must be a period of relaxation and recovery. Following this the shrinking of the substratum inaugurates a period of compressive stresses. This is the orogenic period as explained in my last paper. These stresses also die out and a long period of comparative repose attends the slow accumulation of radioactive heat in the substratum.

These cyclical changes of stress must have profoundly modified the surface features of the earth. They are the inevitable outcome of the existence of the substratum and the presence of radioactive elements throughout the materials of the earth's surface.

The Distribution of Temperature in the Continental Crust.

It follows from the principles of isostasy that the thickness of the continental crust must vary considerably; extending downwards inversely as the greater surface features extend upwards. Taking the average density of the submerged continental materials as 2·6 and that of the substratum as 3·0 (*ante*), the compensations must extend downwards 6·5 times the elevation above the mean level of the raised surface features.

For the radioactivity of the continental crust we have a certain choice of data according as we take it to be of acid or of intermediate character. I shall assume that it possesses a radioactivity as if it were compounded of equal amounts of acid and intermediate rocks. This will be found to involve the development of $0{\cdot}27 \times 10^{-12}$ calorie per gram per second *. If the density be 2·6 this becomes $0{\cdot}70 \times 10^{-12}$ cal. per sec. per c.c.

I shall first consider the question of the distribution of temperature in the average continental layer. In my last paper (*loc. cit.* p. 1174) I gave a computation showing that for a crust of 24 kilometres thickness, the steady output of radioactive heat must equal that indicated by the surface gradient. This is, however, defective not only in under-estimating the thickness of the continental layer but in under-estimating the heat flow indicated by the assumed surface gradient. It is, therefore, necessary to consider the question afresh.

If we adhere to our former estimate of continental thickness, *i. e.*, 32 k. and take the average conductivity as 4×10^{-3} the basal temperature is found to be closely 900° C. (Strutt, Proc. R. S. 77 A). This, in the first place, is a sufficient approximation to the temperature of the substratum to meet the real point at issue:—that escape of heat through the continental stratum cannot take place to any considerable

* Phil. Mag. Oct. 1912 & April 1915, also June 1923.

extent. With a temperature difference of only 250° the leakage would be small and would be closed by the growth of a thin basaltic crust congealed on the continental base. In point of fact had we assumed a continental thickness of 35 k. (which would have sufficiently satisfied the views of seismologists) and 'acid' radioactivity (also permissible), the calculated basal temperature would have come out as 1225°. The value selected above for the conductivity is the mean for granites, 'whinstones,' micaschists, and 'traps' as cited by Everett (C.G.S. System of Units).

We have now to consider how far this result may agree with gradients as observed in bore-holes, etc. over the continental surface. The heat coming to the surface originates in two ways. One part is generated by the radioactivity of the continental layer; the other ascends from beneath. The first is readily calculable (on data already cited) as 224×10^{-8} cal. per sec. per sq. cm. The second is 31×10^{-8} cal. per sec. per sq. cm. The total is $2{\cdot}55 \times 10^{-6}$ cal.

Thermal gradients, as all know, are very various—ranging from 26 to over 54 metres per degree centigrade. They steepen with depth so that in a distance downwards of 1000 metres they may steepen from 49 m. to 29 m.* This fact, which is of general occurrence, shows that either some loss of sensible heat takes place or that, approaching the surface, the conductivity increases—as, for instance, due to presence of water.

This gain in conductivity due to moisture is exhibited in experimental determinations. We find dry sandstone reading 0·0055 and damp sandstone from 0·0064 to 0·0085 (Everett, *loc. cit.*). The mean of these figures and a gradient of 30 m. would account for a heat flow of $2{\cdot}5 \times 10^{-6}$ cal. per sec. per sq. cm. The conductivity of the damp sandstone may be excessive, but as we have taken but little account of the rise of gradient downwards it is plain that the thermal conditions arising out of a crust uniformly radioactive and at its base maintained at a temperature in or about 1150°, is not discordant with the indications of surface gradients.

We shall now turn to the question of the thermal stability of the greater compensations. I shall take as an extreme case that of the Tibetan Plateau. Its average height over sea-level is stated to be 15,000 feet or 4575 m. Its height reckoned from the average continental surface level of 700 m.

* See Daly, Ann. J. Sc. May 1923.

is, therefore, 3875 m. Using the factor arising out of the density ratio as given above, *i. e.* 6·5, a compensation depth of 25,187 m. is obtained. Adding the continental depth and the height of the plateau, a total depth of 61 k. is arrived at.

What will be the distribution of temperature in so great a vertical depth of continental materials? The base is, say, at 1200°. The surface is at 0°. If the rise in temperature downwards exceeds at any level 1200° then there must be downward flow of heat. It is easy to see that this condition must come about. Hence there must be some level at which the direction of heat-flow changes, and this level must be that of maximum temperature. The equation connecting basal temperature with depth is $\theta = \frac{Q}{2k} D^2$, where Q is the heat generated in unit volume in unit time, k is the conductivity and D is depth. Accordingly the intersection of two parabolic curves, one displaced 1200° in the scale of temperature, may be used to determine the solution of problems of the present sort. We find that the level of maximum temperature is closely 42 k. from the surface and 19 k. from the base; the maximum temperature being 1500°.

From this we may infer that fusion must be nearly if not actually reached in this compensation. We might, of course, have chosen data which, while defensible, would give a lower internal temperature. But even as it stands it is doubtful if under the conditions of pressure actual fluidity would exist and not rather conditions of viscosity. Nor would a certain amount of fusion in such a case necessarily confer instability. For the fused interior would be on all sides shut in by a thick wall of stable material which, at least in periods succeeding revolution,—such as we now live in—must be but little hotter than the melting-point of the basalt and which being highly siliceous is, probably, mainly composed of quartz; the initial melting-point of which is 1600°.

However, even if in this particular case vertical forces could be transmitted through such a mass, it is certain that much deeper compensations would, on our data, be unstable. It is not improbable that herein we find a limit to isostatic compensation. It is stated that the Himalayas are only 80 per cent. compensated. Mountain elevation on the surface of the Globe would find limits from this cause. For observations appear to show that the rigidity of the crust is not able to carry the greater ranges without the support of compensations.

The whole matter is instructive. For the genesis of batholithic invasion from beneath, attending the rising mountain ranges,—which is one of the most striking and eloquent features of mountain structure—seems to find explanation in these simple calculations.

We may go even further. We saw above that the continental crust, taken at 35 k. thick, attains a radioactive basal temperature nearly the same as that of the substratum. Certain facts of petrological science possibly indicate that such a basal temperature would be greater than that of the magma. I refer to the evidence we possess that juvenile gases (notably water) contained in the abyssal magma might confer upon it a melting temperature somewhat lower than that which we observe in extravasated materials. If this be the case heat would flow downwards during the long era of general thermal accumulation throughout the substratum.

Now there must be a limit to such heat supplies to the magma ; for under the continental base there is no escape for the heat till general fluidity is reached and the inevitable tidal movements distribute the heat into suboceanic regions. The superheated materials gravitating upwards must therefore accumulate beneath the continents, and if the temperature rises sufficiently, the base of the continental layer must melt ; and when circulation and surface drift of the upper crust commence these melted materials must be carried from beneath the continents and float upwards around their margin.

These inferences seem to show that in the thermal conditions arising out of radioactive heating there arises a limit to continental thickness. Now this also controls the horizontal area of the continents, and, dependently, the area and depth of the ocean. For we see that if, originally, these lighter materials, rising like a scum to the surface of the magma, had been piled up deeper than they now are, either fortuitously or from forces originating in the rotational motion of the earth, they must inevitably have melted away beneath, until they attained their present thickness and surface extension.

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