flood, mentioned by Florus as the cause of the migration of the Cimbri and the Teutones. The occurrence of the remains of a boat in the 20-foot beach on the Clyde points to one of these movements at least having been much later than the diluvial movement which destroyed the Mammoth and its companions. Perhaps the deposition of this beach was coincident with the so-called Cimbric flood.

These are questions, however, which the future must settle; what we are now chiefly constrained to urge is, that the raised beaches which have been supposed to index immense movements of the earth's crust, up and down, are capable of a much more moderate and much more plausible explanation, namely, that they are necklaces put about the land by the amorous sea in one of its more ardent moments, and correspond to the line of wreckage in the fields after an inundation.

VI.—THE CORRUGATION OF THE EARTH'S SURFACE AND VOLCANIC PHENOMENA.¹

By ARTHUR VAUGHAN, B.A., B.Sc.

IT is important, in the first place, to discuss those facts concerning the Earth which must be taken into account in any attempt to deal satisfactorily with the problem before us.

To a depth of about 80 feet in Temperate regions, the earth has its temperature determined by the seasons; being warmed in summer and cooled in winter. Below this average depth the temperature remains constant throughout the year, and shows a steady increase as we go downwards. By observations made in deep borings, it is found that this increase is at the rate of about 1° F. for every 60 feet, and that this law holds true throughout a descent of several hundred feet; but that the rate of increase diminishes at considerable depths. This increase in temperature with distance from the surface points unmistakably to a large store of heat in the interior of the earth, and the increase in the rate at which temperature diminishes, as we approach the surface, agrees with what we should expect to happen if a large heated mass were allowed to cool; the nearer the surface the greater would be the rate of loss of heat, and consequently the more rapid the diminution of temperature.

The next important point to be considered is that, however the rocks near the surface may differ in composition, they are all distinguished by being divided up into larger or smaller portions by joints, bedding-plane, etc. The actual amount of separation caused by this means varies very much with different rocks; but in so far as it exists must necessarily allow of closer approximation if the rocks ever become subjected to great pressure. That this jointing is sufficient to allow of seasonal expansion is obvious, notwithstanding the fact that the difference between summer and winter temperature in continental regions is often extreme. Again, this division into smaller portions by jointing, etc., remains true at all

¹ The author wishes it to be stated that this article was sent in on March 31st, 1894, but has not appeared earlier for want of space.—EDIT. GEOL. MAG.

depths to which observation has been carried; so that this property may be roughly said to define what is meant by the crust.

Let us now carefully consider what would be the effect of allowing a large heated mass to cool. We will first take the simplest case, namely, a sphere of homogeneous material. Considering the mass as made up of consecutive concentric shells, the outermost shell, on account of its greater exposure and closer proximity to the cooling influences, will cool faster than the next inner; but, since cooling necessarily produces contraction, and since the amount of contraction is dependent on the loss of temperature, the external shell will contract faster than that underlying it. It obviously follows that the outer shell exerts a squeezing force upon the interior, and, by compressing the mass into a smaller volume, increases its density. The interior in its turn prevents the outer shell from contracting to the full extent proper to its loss of temperature, and thus sets up a state of strain in the outer shell. Thus, progressively, each shell, by contracting upon the next inner one, increases the density of the interior, and is itself at the same time thrown into a state of strain.

A familiar illustration of this process is the brittleness induced in most metals by rapid cooling, and to minimize this state of strain recourse is had to the process of annealing. This reasoning seems to apply with equal force to the case of the earth. Each shell, as it contracts from loss of heat, compresses the included mass and increases its density; continued contraction of shell upon shell produces cumulative results in the same direction.

From this very effect also the amount of contraction will increase; for it is found that the coefficient of expansion of any material increases with its density. This, perhaps, affords an explanation of the fact that, whilst the specific gravity of the surface rocks averages about 2.5, that of the whole globe reaches 5.5.

It may, perhaps, be diffidently suggested that in a molten mass there would be a tendency to lessen the effect of differential contraction by a rearrangement of material in such a way that each successively smaller shell should have a greater coefficient of expansion to recompense it for a smaller loss of temperature.

Further, the effect of gravity upon such a molten mass would be to cause the accumulation of the heavier material towards the centre.

These two causes—the effect of gravitation on a molten mass and the subsequent effects of contraction—must be looked to as furnishing a probable cause of increased density in the interior.

To the compressing force of contraction we must also look for an explanation of the fact, established by astronomy, that the whole globe is solid. For, judging by the increase of temperature towards the centre, the rocks of the interior must be far above their melting point, and can only be prevented from melting by subjection to great pressure.

It must be doubted whether superincumbent pressure can have any great effect; for, were the whole globe composed of concentric homogeneous ellipsoidal shells, each such shell of gravitating matter must be necessarily self-supportive, and could only exert pressure upon the interior by undergoing contraction.

So far we have reasoned as if the whole globe were made up of homogeneous shells. But the crust is composed, and has been so throughout all geological time of which we have any accurate knowledge, of rocks differing greatly in their capabilities of expansion and contraction; and further the greater part of the crust has its temperature determined by earth-heat, or in other words possesses heat which it must be gradually losing. It is consequently important to obtain some idea of what would occur during the cooling of a large heated mass, where outer shells were composed of materials with different coefficients of expansion.

The first effect, caused by the cooling of the outermost shell, will be to produce a pressure upon the interior; but the strain thus set up in the outer shell will be gradually relieved by the splitting permitted between materials of different powers of contraction.

Thus the outermost shell will consist of a great number of slightly disjointed portions. This process will be continued throughout the cooling of the outer heterogeneous shells. When the interior, supposed homogeneous, begins to contract, the disjointed parts of the outer shell will be brought closer together to accommodate themselves to a smaller area—a movement of which they will always be capable without the formation of folds or rucks, since the loss of temperature is necessarily greater the nearer the surface.

Applying this reasoning to the contraction of the crust of the earth, it seems probable that jointing must ensue in the manner described above in all such rocks as have heat to lose. We do not, however, maintain that this is the only way in which such splitting can be brought about, for, no doubt, the shrinking from loss of moisture has always been a very effective cause.

We will now attempt to obtain some estimate of the amount of jointing necessary in order that the outer shells may follow a contracting interior. Let us assume a shell at the depth of a few miles to have its temperature diminished 10° , and further, let us suppose that this contraction is unresisted by a more slowly contracting interior.

For the purposes of actual calculation let us suppose the material of which the shell is composed to have a coefficient of linear contraction equal to .00001174 (this is the coefficient of sandstone, which is intermediate between the coefficients for cast and wrought iron, and is greater than that for marble). From these data the contraction of one mile is found to be 7.2 inches. This, then, is the amount by which one mile length of the next overlying layer must be able to contract to avoid rucking up.

Putting this statement into another form; every yard of shell just overlying the contracting interior must be capable of shrinking $\frac{1}{16}$ of an inch to avoid rucking. The amount required at the surface will not appreciably exceed the above amount; for, if we imagine contraction to take place at a depth of five miles, the required amount of shrinking in each yard of arc at the surface will be approximately $\frac{3}{8} \times \frac{1}{16}$ of an inch.

It would seem that there could be no difficulty in assuming sufficient separation space in all known rocks to allow of this extent of approximation. But the case is in reality much stronger than appears in the above figures, for we have assumed no contraction to go on in any of the overlying rocks, whereas contraction must be in progress in all those rocks whose constant temperature exceeds the mean average surface temperature, and this at a faster rate than in the underlying interior, with the result that the separation spaces throughout the overlying shells are being increased so as to allow of additional approximation.

There would seem, then, no difficulty in accepting the idea that the crust will in general follow the contracting interior and not be thrown into folds, but will accommodate itself to a smaller area by the closer approximation of its component parts.

More space has been spent in considering this point than would perhaps seem necessary; but the theory has very generally been accepted that corrugations are caused by the shrinking away of a contracting nucleus from a consolidated non-contracting crust.¹

It will be well, consequently, to examine what amount of corrugation could be produced on the supposition that the crust is non-contracting and incapable of accommodating itself to a smaller area. The interior is imagined to shrink away, but, by the action of gravity, the heavier areas of the heterogeneous crust are retained in contact with the shrinking nucleus. It follows, on the hypothesis of an incompressible crust, that the intermediate portions will be thrown into folds.

Employing the same data as before, and further assuming that the two areas, which, owing to the effects of gravity, sink with the contracting nucleus, are 1000 miles apart, we find by an easy calculation that the greatest possible height to which the under surface of the intermediate portions of the crust could rise is less than 5000 feet.

This is on the assumption that the crust is bent into two planes meeting above the middle point of the contracting arc. Again, since we cannot suppose the contracting nucleus to lie many miles beneath the surface, this maximum elevation will not be sensibly increased at the surface itself. It is very important to point out the favourable exaggeration involved in the data employed in the above calculation.

In the first place, owing to resistance from within, no shell could contract to its full extent; secondly, a fall of 10° would represent an enormous loss of heat in the interior; again, it is improbable that the two areas which sink with the nucleus could be so far apart; and lastly, that the crust should be thrown into the form supposed is utterly impossible, and at variance with the structure of all known mountain systems.

One further point in regard to this theory:—

Since the effect of the shrinking interior must be to draw closer together those portions of the crust which are in contact with it, the force between any two portions of the earth's crust must be one

¹ A discussion of the later theory of Mr. Mellard Reade is contained in Part II. of this paper.

of compression. Thus any relief, sought for by the breaking of the crust, can only be found in the pushing of one portion over the other; that is to say, in the production of reversed faults. Normal faults could find no place as consequences of such a system of earth movement.

To pass on now to give what we think to be a possible and adequate explanation—

Let us suppose that some large area on the earth's surface is at considerably less distance from the centre than the surrounding regions, and that furthermore the surface rocks in such an area are maintained at a very low temperature. It follows that under such an area the surfaces of equal temperature will be at once more numerous and more crowded than under the surrounding regions—more numerous because, the surface being kept at a lower mean temperature, the range of temperature from the interior to the surface is greater and more crowded because the distance from the centre to any point of our hypothetical area is less than in the surrounding areas. In this case the distance between two points in the same radius, having stated temperatures, will be less than in the regions surrounding the area. In consequence, the transference of heat from one point to the other will be greater; or in other words the loss of heat will be greatest under the depressed area. Thus beneath such an area contraction will proceed at a faster rate.

In this place we wish to point out, once for all, that we shall simply consider the effects of contraction upon the nucleus which we imagine to be practically homogeneous at equal distances from the centre. We shall further assume that the overlying crust, being formed of heterogeneous materials, will follow a sinking interior without any rucking, for the reasons given at length above. This distinction in geneity between crust and nucleus probably means no more than that the materials composing the originally homogeneous surface shells have been rearranged by agencies, with which we are not now concerned, to form a heterogeneous crust. It will further appear, on carefully considering the areas under discussion, that the thickness of the crust may be considered to be at least small.

From the faster contraction which we have shown must take place under such an area, two results necessarily follow. In the first place there will be a great strain upon the rocks bordering upon the depressed area, since the tendency of contraction must necessarily be to draw them closer together. The effect of this strain will necessarily be in the direction of lessening the rapidity of descent from the elevated to the depressed areas, and in this attempt pressure will be produced on the underlying rocks. Secondly, on account of this very resistance to contraction, any arc traced on the area, being in the form of a broad arch, whose centre is approximately the centre of the earth, will in attempting to contract bend inwards so as to lessen its curvature, and consequently shorten its length. In performing such a movement, the underlying

material will be, so to speak, squeezed out, and this will cause a real transfer from under the sinking area to beneath the surrounding regions. We may reasonably expect great compression, contortion, and plication to accompany such a movement. Such transference must cause real elevation of the surrounding regions in addition to the relative elevation due to depression of the sinking districts.

That this theory would be adequate to account for the present height of mountains seems very probable from the following considerations. The simple fact that a large area is depressed, and therefore the sea-level brought nearer the centre of the earth, implies the raising of the undepressed parts above it. Due to this cause, we obtain the same maximum height as was found possible under the theory referred to above.

In the second place, actual transfer of material from under the sinking area must add still more to the elevation caused by relative displacement.

Lastly, we have the important fact that the rate of contraction beneath such areas is far in excess of the average under neighbouring areas, and that this rate is maintained by the continual contraction of fresh portions of the heated interior, brought into contact with the cold outer layers by the squeezing out of intermediate material.

The material thus pressed out from under the contracting shell-caps and forced beneath the surrounding regions, will exert an additional strain upon the overlying crust, which, as explained above, has already been stretched by the contraction itself. In this process it is quite conceivable that great metamorphism will result from the movement under enormous pressure. But, so long as this pressure is unrelieved, no igneous rocks could possibly be generated; for, though no doubt the compression will raise the rocks upon which it acts to a temperature far above their melting point, any increase of volume which melting would imply will be strenuously resisted.

Two extreme cases must now be discussed:—

First: suppose the change from elevated to depressed areas to be spread over a large space and to be uniformly slow. In this case, the strain upon the overlying rocks will be spread over a very large area, and there will be no lines of special weakness. Here, then, we should not expect the crust to split right through at any point, but rather that it would suffer a uniform extension by the extension and development of local separation spaces, and in this way very gradually relieve the state of tension. This gradual relief from pressure might be sufficient to slowly melt the underlying materials, which, when first brought into the position contemplated, must have been under so great a pressure as to be raised above their melting point.

The slowness of the action would ensure the production of a holocrystalline igneous rock.

Secondly: suppose the change from elevated to depressed areas to be very rapid. Here we have special lines of weakness afforded by sudden bends, and the probability seems to be that at such points the crust would be unable to withstand the total strain and would split right through.

The portion nearest the sinking area would thus be drawn away from the rest of the crust, which would be raised to a higher level by the pressure from below. In this way a normal fault, or succession of such faults, would be brought about.

Again, the sudden relief from great pressure caused by this means, when the underlying rocks are far above their melting point, would result in their sudden melting. The very high temperature at which this melting may be supposed to be produced will necessarily ensure very complete liquefaction, and aided partly by the pressure from below, and partly by the increase in volume due to melting itself, the molten material will be exuded through the clefts formed in the broken crust, to rise to the surface in a flow of lava. Further, the rupture of the crust would certainly cause an earthquake, and, as we have shown, it would be natural to expect depression or elevation to be a consequence. That earthquakes are often followed by such phenomena is well known.

Again, the greatest pressure being between the stretched crust and the upward forced interior, the depth at which earthquakes would be generated on this theory seems to accord well with observed results. It merely remains now to point out where such areas as we have considered exist, and to illustrate the effects of the theory by well-known examples. In the first place the earth is flattened at the Poles, so that each Pole is about thirteen miles nearer the centre than any point in the equator. Again, the Polar regions have, for vast ages, been covered by ice, so that the ground is constantly frozen far below the surface; also the change is very gradual from elevated to depressed areas.

We should expect then that the Polar regions themselves are sinking, but that the neighbouring regions are rising, and that this should be an effect spread over large areas. These facts seem to be in accord with the observations that whilst Greenland is found to be sinking, Norway is rising.

A suggestion may here be thrown out as to a possible explanation of the events supposed to have occurred during the Glacial epoch.

Before the Glacial period there is evidence that the British Isles, as a whole, were above sea-level; but that during the period subsidence took place and that, after its departure, the Islands again rose. This seems to be in entire agreement with what the above theory would require. During the period of great cold, lasting for an enormous time, the ground must have been frozen to great depths, as is proved by borings in Siberia, where the effects are still very obvious in frozen ground, extending to several hundred feet. In consequence rapid contraction must have taken place beneath the area, together with the transfer of material from below. These two causes combined must have drawn the area down to below the sea-level. On the termination of the period, the Polar regions must again have become the principal area of subsidence, resulting in the gradual upheaval of the neighbouring regions, as evidenced by the raised beaches of Norway and Scotland which characterized the post-Glacial period.

The second class of areas, which satisfy the conditions of our theory, are the deep ocean floors. Here we have depressed areas surrounded by more elevated regions; the surface layers being maintained at a very low temperature, as determined by recent soundings. These, in general, afford examples of the case in which the passage from elevated to depressed areas is rapid. We should therefore expect to find, along the borders of such areas, evidence of volcanic phenomena. It is sufficient to quote, as illustrative examples, the vast ring of volcanoes which surrounds the Pacific Ocean. It seems also specially worthy of notice that Japan is the scene of continually recurring earthquakes. Now it is on the borders of the Pacific in the neighbourhood of Japan that we find the most rapid passage from elevated to depressed areas, for here is the deepest depression in the whole ocean. In consequence, we have here a line of great weakness, and should expect earthquakes to be most frequent if in any way dependent upon the above explained cause. As a last point of agreement with the theory, we may notice Darwin's theory of Coral reefs as pointing to the comparatively rapid sinking of the deep sea floors.

In conclusion, a few words may be said upon the necessary consequences of the truth of this theory. It points unmistakably to the permanence of continental and deep sea areas, and would indicate that the tendency has always been to deepen and render narrower the ocean basins. Perhaps, also, it points to a continual tendency to render the globe more elliptical by increasing the flattening at the Poles. It would also necessarily follow that great elevations could only take place on the borders of deep oceans, or in proximity to regions of prolonged cold. Lastly, that volcanic phenomena may be expected to occur along the coast regions of great oceans.

It may be remarked, as a necessary deduction from the first of the above statements, that the crust covering the areas with which we have dealt must be extremely thin, and that, at the bottom of the deep sea basins, we should expect to find the nearest possible approach to the primitive crust.

It is, of course, not assumed that this theory is applicable to all cases of subsidence and elevation which, when local, are no doubt due to much less potent forces, such as denudation and deposition.

(To be continued.)

VII.—ON THE ALLEGED CONVERSION OF CHLORITE INTO BIOTITE BY CONTACT ACTION.

By Lieutenant-General C. A. McMAHON, F.G.S.

I HAVE to thank Dr. Callaway for the courtesy and good-humour with which he has received my criticisms on his paper in the December Number of the *GEOLOGICAL MAGAZINE*. Would that all controversial fencing were conducted with equally well-tipped foils.

My Roman soldiers, in particular, have been received with a kindness that reminds me of the friendly meetings of the British