Regions of Tension and Continental Drift.[1]

By Dr. J. W. EVANS, F.R.S.

IN many areas the earth's crust has been subjected to compression manifesting itself in folding, cleavage, thrust-faults, and certain types of igneous activity. Such compression may prevail over an extensive region, or may be of a purely local character. In the former case, it is usually attributed to the progressive contraction of the earth's interior, although this has been disputed by some authorities. In the latter, it is merely an incident in the development of more extended structures. The results of compression have long been studied, but comparatively little attention has been given to the occurrence of tension in areas where it has left evidence of its existence in the form of joints, normal or slip-faults, occasionally replaced by monoclinal folds, dykes, and other characteristic igneous phenomena.

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The distribution and direction of the jointing, the slip-faulting, and the dykes of western Europe of post-Hercynian date, are all due to tension, producing stretching, fracture, and separation, and together they imply relative movement, or drift, in the rocks with which they are associated.

The most prevalent strike of these fractures in the British Isles and western France is from north-north-west to south-south-east, implying a drift from east-north-east to west-south-west, or *vice versa*. However, in the Devon-Cornwall peninsula there appears to be a general downward slip to the south-west, modified later, it would seem, by a movement towards the north-west. In Skye the faults posterior to the igneous activity seem to show a similar change in the direction of the tension. In the north-west of Connaught, of Ulster, and of Sutherland the faults appear to strike as a rule north-east and south-west, implying the presence of a drift to the north-west, but in western Ulster, and in Mayo, this appears to have been preceded by an earlier tension directed towards the south-west or south-south-west, indicated by the north-west and south-east or west-north-west and east-south-east basic dykes.

Closely connected with the drift of the surface-blocks must be the stretching of the presumably plastic zone beneath. Indeed, it would seem that it is this stretching or slow flow which is the immediate cause of the minor fissuring of the crustal rocks. The blocks which are thus formed are then so disposed relatively to one another as to cover, so far as possible, the extended space. This may happen in two ways:

In the south-western peninsula of England and other localities the fault-fractures had originally considerable hade, usually directed to the region of weakness, and the extension took place by the downward slip of the block on the upper side of each fault.

In Skye and elsewhere the hade of the fissures seems originally to have been practically vertical; but the blocks between the faults were afterwards inclined, so that the beds which were formerly nearly horizontal now dip in a direction opposite to the faults. In this case the covering of the extended area is effected by the tilting of the blocks. It is probable that in such cases the underlying magma has, it is suggested, flowed in the direction of the hade of the faults.

The volcanic activity in the west of Scotland and in the north-east of Ireland commenced, on the evidence of plant-remains, early in the Eocene, and may have continued for a great portion of that period. The faulting which has been described must have been of still later date. It is indeed impossible to fix any limit to the continuance of the tension. How far it was present in Mesozoic times we cannot say with certainty, but it apparently had a beginning in the Permian.

The drift towards the west (south-west or north-west) in western Europe seems to have been widespread, though greater in some regions than in others, but everywhere east-and-west distances appear to have been increased.

We are not in a position to estimate the total amount of this extension. It could only be calculated if we knew the width of each joint, the hade of each fault-plane, the direction and amount of the movement in it, and the thickness of each dyke. It does not, however, seem likely that the total relative change of distance between Central Europe and western Ireland has exceeded, say, 6 to 12 miles (10 or 20 km.) since Triassic times.

The true significance of this drift becomes evident on examination of a depth-chart of the North Atlantic. It is at once seen that the approximately north-west and south-east strike of different forms of fracture that is so prevalent in the British Isles and western France is related to the ocean-deep of which the north-eastern boundary runs roughly south-east and north-west, parallel to the French coast of the Bay of Biscay, out into the open Atlantic; and that the north-east and south-west strike which is found in the north-west is apparently similarly related to the edge of the trough that extends from south-west to north-east beyond the Hebrides. The drifts to the south-west and north-west seem to be towards these abysmal regions of deep water, the crustal blocks being carried forward by the flow of the plastic region beneath. The formation or widening of these deeps cannot have greatly preceded the drift towards them, which seems to have culminated in Tertiary times. From what has been stated, there would seem to be reason to suppose that the development of the oceanic deep on the north-west of the British Isles was of a later date than that on the south-west.

The doctrine of the balance or "isostasy" of different areas of the earth's surface, which now seems to be firmly established, requires that the continents should be composed of lighter materials than the floor of the deep sea. The former consist mainly of granite (including the foliated granite more usually described as granitoid gneiss) and of sedimentary rocks which, though widespread at the surface, form only a comparatively small part of the whole. These are together conveniently referred to as sial. The ocean-beds must, on the other hand, be composed of heavier rocks made up of the silicates of iron, manganese, magnesium, and

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[1] From the presidential address delivered to the Geological Society of London at the anniversary meeting on February 20.

calcium—the sima of Suess. This conclusion is confirmed by the greater "magnetic permeability" of the ocean-floor compared with the continents, indicating in the former the presence of ferrous oxide.[2]

The distinction between sial and sima appears to be the result of a primeval magmatic differentiation of the outer zones of the earth into a lighter acid portion consisting mainly of silica with alumina, the alkalies, and much water and other volatile constituents—that is to say, the typical magma of acid rocks such as granites and rhyolites—and a heavier basic portion corresponding to the magmas of dolerites and basalts, passing doubtless below into that of the still more basic peridotites.

There seems to be no doubt that Suess was right in supposing that the sima extends everywhere below the sial of the continents. There is, however, considerable difference of opinion as to the thickness of the continental sial. Wegener[3] supposes it to be so much as 63 miles (100 km.). This is founded largely on Hayford's level of isostatic equilibrium or uniform density, which he placed at a depth of 71 miles (114 km.). It was afterwards reduced by Bowie to 60 miles (96 km.), which, however, appears to represent the depth of the sial forming the downward extending folds of the Rocky Mountains. Doubtless in the Himalayas it would be still greater, but in plains and plateaux the thickness may perhaps range from 9 to 40 miles (15 to 64 km.).[4] It would depend on the altitude of the land and on the density of the sial. Nor is the depth to which the sial extends necessarily the same as that of the depth of uniform density. In the older parts of the continental shields the latter is probably considerably less than the former.

The idea that ocean-depths are the result of foundering is wholly opposed to the doctrine of isostasy, for it implies that the rocks which form the floor of the oceans are of the same composition as those of the neighbouring continents.

The only alternative is to conclude that the continental masses of sial can, under the action of continuously applied external forces, slowly drift through the sima, and that they have thus moved apart and left the ocean-deeps between them.

The magma of the granite of the sial must, on account of the large amount of water and other volatile constituents that it contained, have cooled to a comparatively low temperature, say 600° C., before it crystallised. These constituents were, however, eliminated and lost, so that it would thereafter require a much higher temperature to melt or even soften the rock, and the sedimentary constituents of the sial would (as a rule) prove equally refractory.

The basic rocks that constitute the sima, especially if they are rich in iron, are on the other hand less affected by the loss of volatile constituents. We may therefore expect that, at a temperature corresponding to comparatively moderate depths, they would become to some extent plastic.

The principle of isostasy appears in fact to depend on the circumstance that, given sufficient time, by no means very long from the geological point of view, the sima acts as a whole as a fluid in which the sial floats, to use Airy's simile, like a log in water, or in Wegener's words, like ice-floes in the sea, although, it need scarcely be said, the viscosity of the sima (even at a fairly high temperature) is many thousands of times that of water. There is therefore nothing surprising in the blocks of sial making their way through the sima, accompanied, it may be, by crystallised sima adhering to their lower surfaces.

It is to the major fissures of the earth's crust, which are represented by the ocean-deeps, that we must look for the fundamental cause of igneous activity in regions of tension. As the fissure opens, the underlying sima magma will rise, in order to re-establish a condition of isostasy. This will be facilitated by the fact that the accompanying release of pressure will render the magma fluid, and at the same time cause it to expand. This expansion will be all the greater, on account of the volatile constituents in the magma. Its density will of course diminish correspondingly, and it will rise higher in the fissure than it would otherwise have done.

In the course of time, however, a large proportion of the volatile constituents will escape, crystallisation commence, and the density increase, so that the column will sink to a certain extent.[5]

Some idea of the depth from which the sima of ocean-deeps rises can be gathered from the temperature of igneous magmas. Dr. H. H. Thomas, from an examination of the metamorphism of the xenoliths in the Loch Scridain magma-reservoir, arrived at the conclusion that it was initiated at a temperature of nearly 1400° C.[6] This figure rests on experiments with dry metals, and must, he thinks, be reduced, if the presence of water under pressure be taken into account. Some heat may have been lost while the magma was rising, and during the course of its intrusion; but there may have been a slight accession of temperature from oxidation or radio-activity. We may, however, assume for purposes of illustration that the temperature in the original position of the magma was in the neighbourhood of 1400° C.

According to the calculations of Prof. L. H. Adams, which appear to rest on a sound basis,[7] this temperature would be ordinarily found at a depth of about 72 miles (115 km.). This actual figure is, at best, a conjectural estimate; but it would seem probable that some parts at least of the magma of igneous intrusions must come from a depth that cannot have been very much less. It would therefore seem that the formation of these major fissures presents the most probable means by which material from great depths has reached the neighbourhood of the surface, a conclusion which is of some importance in considering the source of the metalliferous ores.

Before the opening of a fissure, differentiation at such depths would be impossible, on account of the extreme viscosity of the magma under heavy pressure, but the release of pressure due to the opening of the fissure

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[2] A. Wegener: "The Origin of Continents and Oceans," 1924, pp. 32-33.

[3] *Ibid.* p. 37.

[4] H. S. Washington's estimate is from 15 to 20 km. (9 to 12½ miles), Journ. Washington Acad. Sci., vol. 14 (1924), p. 437.

[5] An incidental effect of the formation of rifts would be the lowering of the level of the sea. The area of the deeps lying below 15,000 feet (4573 metres) is about a third of that of the whole ocean. If, then, a tenth of these came into existence as rifts about the same time, in consequence of an average sinking of 7500 feet (2287 metres), the surface of the sea would be lowered by about 250 feet (76 metres). These figures are, of course, only intended to show that the effect would not be negligible.

[6] Q.J.G.S., vol. 78 (1922), pp. 250-54, and "Island of Mull," Mem. Geol. Surv., 1924, p. 278.

[7] Journ. Washington Acad. Sci., vol. 14 (1924), p. 468.

would result at once in an increase of fluidity. The first differentiation would be, in all probability, a repetition of the primordial process of differentiation into basic and acid magmas already mentioned, for the sima would appear to be capable of yielding another but smaller crop of an aqueous acid magma. This would be followed by further differentiation by crystallisation due to cooling as well as to loss of volatile constituents, with the result that ultimately a wide range of igneous rocks would be evolved.[8] Before, however, differentiation had advanced very far, a series of lateral intrusions from the major fissures would have commenced. The flow of the deep subcrustal sima towards the fissure would cause a temporary sinking of the adjoining crust, simultaneous with the rise of the magma in the fissure, with the result that, for a portion at least of the length of the column filling the fissure, the pressure of the magma would exceed that of the surrounding rock, so that intrusion would take place.

As differentiation proceeded in the intruded magma, the progress of the segregated acid magma would be retarded by local viscidity, caused by the loss of a portion of the volatile constituents and by cooling at the surface of contact with the adjoining rock. This would not be the case with the ultra-basic and basic magmas below it (which would form by far the greater portion of the whole), as they contain less volatile constituents, and are less dependent on them for their fluidity. The ultra-basic and basic magmas would, therefore, progress more rapidly than the acid magma. In so doing they would let down the still fluid portion of the acid magma above them until the latter reached the level of their flow. Here it would be protected from loss of volatile constituents, and the temperature of the surrounding rock would by this time have become little less than that of the magma itself. The acid would therefore follow the basic magma in the channel of intrusion, a succession which corresponds very closely to the order of intrusion of plutonic magmas in the west of Scotland and at the Lizard.[9]

How far this lateral penetration will extend, and what form it will take, depend on the nature and structures of the rocks, and the earth-movements that may supervene. A magma may travel a considerable distance horizontally, or with a gentle inclination upwards—without any manifestation, other than the filling of fissures at right angles to the prevailing tension—until it meets with an obstacle, such as deeply-rooted mountain-folding, when it may form a tumefaction in the nature of a laccolith which will become a centre of igneous activity, and give rise to radiating and concentric structures as well as plutonic rock-masses, or it may well out in fissure-eruptions. Its progress and manifestations will be due partly to the hydraulic pressure to which it is subjected, and partly to the expansive force of its volatile constituents, and these will be assisted in some cases by faulting, bringing the magma into contact with rocks under less pressure, into which it will penetrate along joint- or fault-planes.

Of all these manifestations of igneous activity, it is the occurrence of parallel dykes that is usually the most widely extended, both in space and in time, and affords the most satisfactory evidence of the area throughout which a subterranean magma has spread—so far at least as it is accompanied by a prevalence of tensional conditions above it.

(*To be continued.*)

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[8] That the first stage of the differentiation of igneous rock is into an acid and basic magma is, to my mind, abundantly proved by Dr. W. A. Richardson and G. Sneesby's analysis of the frequency of igneous magmas of different silica percentages. This clearly shows two distinct peaks, one acid and the other basic, *Min. Mag.*, vol. 19 (1922), pp. 303-13.

[9] I have long advocated such an explanation of the order of intrusion of plutonic rocks in my lectures at the Imperial College of Science and Technology. I may add that the ultra-basic magma would move more rapidly than the basic: for, on account of the excess of the density of the basic magma over that of the adjoining rock, the maximum difference of pressure will occur below it.

The Nutrition of Cattle.

THE subject of the feeding of cattle assumes importance from the large part their products play in human dietaries. An accurate knowledge of their metabolism and nutritive requirements, apart from its intrinsic scientific interest, may lead both to more economical methods of feeding and at the same time to an improvement in the quality and quantity of the products, meat and milk, obtained from them. In this survey a brief account will be given of some recent work on the energy, protein and mineral requirements of these animals, with special reference to the production of milk in dairy cows.

The measurement of the energy requirement resolves itself into the problem of estimating the heat given out by the animal, since to maintain the body in equilibrium a similar amount of energy must be taken in in the food. The output of heat can be measured directly by placing the animal in a calorimeter, or chamber in which the heat emitted is measured by the amount absorbed by a current of cold water circulating through the chamber; the analysis of the ingoing and outgoing air at the same time will give the consumption of oxygen and output of carbon dioxide during the experimental period. The method requires the use of elaborate apparatus, so that in practice the indirect method of determination of the heat output is more frequently employed. In this the output of carbon dioxide and consumption of oxygen are determined over a short period, and from these data, together with the value of the respiratory quotient, *i.e.* the ratio of carbon dioxide produced to oxygen consumed, a value can be found for the heat production which is sufficiently accurate for most purposes. The respiratory quotient conveys information as to the types of foodstuffs which are being oxidised in the body, and this information is essential since the heat produced varies according to the type of foodstuff, protein, fat or carbohydrate utilised.

The problem of estimating the heat output in the case of cattle has been still further simplified by W. W. Braman (*J. Biol. Chem.*, 1924, vol. 60, p. 79): the only data required are the output of carbon dioxide and the amount of food taken. In a large number of experiments he has found that the ratio heat/carbon dioxide is highest in starvation and falls steadily with increase in the amount of food eaten, the heat production increasing more slowly than the carbon dioxide formed.