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GENERATION OF MAGMA BY FRICTIONAL HEAT.

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ABSTRACT. Indications that the crust of the earth is strong and thick into depths of 700 kilometers or more, together with evidence that abundant igneous rocks correspond in composition to shallow earth layers, require an appeal to magma sources other than the subcrustal weak shell of isostasy which is commonly accepted as an inherited and potential source. A hypothesis is offered to explain the origin of magmas within the crust by appealing to mechanical sources of heat. The failure of a thick crust, brought about by thermal contraction of the earth, is considered to be effected by a piecemeal operation involving different parts separately during a long period of time, rather than by a brief and final collapse embracing the entire structure. Elastic downwarping of the crust to form geosynclinal depressions is followed by a long process of failure of the lower and major part along one or several underthrust fault planes. This failure provides a plausible explanation of plutonic earthquakes. The outer shell of the crust is the last part to fail. Owing to its greater compressibility it is not compelled to yield until after deeper layers have been relieved of the horizontal compressive stress. This manner of failure prescribes the slipping of large areas of thick crustal shells over and under each other with a development of enormous quantities of frictional heat. Magmas are accordingly created in more or less continuous sheets along nearly horizontal fault planes beneath wide regions. Thermal expansion leads to elevation of these regions, so that, when the outer crustal layer fails, a "head" exists above the sheet of magma derived in the failure. Regional subsidence drives the magma forcefully into regions of lower "head" and in this process additional mechanical heat for magma generation is supplied by friction in the highly viscous magma. Applications of the hypothesis to explain major deformations near the surface are indicated.

INTRODUCTION.

THE uncertainty that surrounds the fundamental problems of the earth's crust is apparent in discussions of the relations between intrusion and deformation, of the causes of diversity of igneous rocks, and of the sources of magma. These igneous problems are related and a solution of one would likely clear up the others. Local structures sometimes suggest that intrusion causes deformation. Elsewhere relations indicate that deformation accommodated a passive entry for magma. Neither interpretation is significant because in both instances effects are too remote from ultimate causes to decide them. Similar difficulties confront attempts to account for the compositional diversity of igneous rocks. Notwithstanding plenty of local though trivial signs of both differentiation and assimilation, these signs are so remote from ultimate sources that the variety and nature of parental magmas are highly conjectural. Plainly the third problem, that of the sources of magma, is the most fundamental and its solution might throw light on the others. Here the wide range of views emphasizes the incompatibility of assumptions used by different authorities.

A body of magma is either inherited or is created locally. A persistent view that a relatively thin crust overlies a layer of potential magma has lent support to the concept of inheritance. The assumed weak shell of isostatic theory has been accepted in many quarters as more or less definite proof of this view and as an indication that all magmas come from subcrustal regions. The same concept, coupled with the evidence for compositional zoning in the earth, suggested further that parental magmas, coming as they do from the one subcrustal layer, are all of one or closely similar composition. Hence arose the compelling need of magmatic differentiation in explanation of rock diversification, a process which implies that there is no primary granitic magma but that the prevailing masses of continental rock are wholesale differentiates of basic magmas supplied by the subcrustal weak shell. The difficulties surrounding this explanation of the origin of granite batholiths are enough in themselves to warrant a thorough search of the possibilities for securing a source of granite magma within the crust.

That inherited reservoirs of magma exist in the crust seems incredible, and especially in those shallow layers where granitic compositions are supposed to prevail. Accordingly, all possible means for local liquefaction in the crust should be examined. For example, the view is recurrent in geological literature that the granitic cores of mountains may have resulted from magmas generated by the mechanical heat of crushing and friction. The chief objection to this view comes from the evidence that these magmas are not products of fusion in place but have migrated into the folded region. The quantity of available mechanical heat seems to be adequate and an attempt will be made in the following pages to overcome objections.

Other suggestions have been made to account for a local generation of magma, notably radioactive heat and heat from chemical reaction. The former has not been substantiated. Moreover, radioactivity would tend to eliminate itself as an active breeder of magma during the long igneous history of the earth. Regarding thermal effects from chemical reaction, it is difficult to imagine important chemical activities within the strong and relatively cool rocks of the crust.

A serious dilemma is faced in the search for magma sources. On the one hand the view that there is an inherited zone of magma or near-magma beneath the crust is precarious in the light of the evidences that the crust is strong as a whole into depths of several hundred kilometers. On the other, while compositional evidence points to a relatively shallow source for most magmas, no plausible means for generating magma in the outer and cooler parts of a thick and strong crust have been substantiated. It is the purpose of the present paper to suggest such means, but conflicting assumptions must be examined first with a view to obtaining a decisive picture of controlling conditions in the earth.

CRUCIAL EVIDENCES BEARING ON THE SOURCE AND ORIGIN OF MAGMA.

The most abundant igneous rocks of both ancient and modern formation are granites and allied types of continental masses, and members of the basalt-gabbro clan which seem to dominate in oceanic regions. Broad geologic evidences and more precise geophysical data indicate that these most abundant rocks correspond in composition to the outermost shells of the earth comprising a thickness variously estimated at a few tens of kilometers. More basic intrusives, typified by peridotite and presumably from deeper regions, are relatively minor constituents of the visible parts of the crust. Compositional evidence accordingly suggests a correspondingly shallow source of most parental magma. Hence, to conclude that magmas come from inherited sources, it is necessary to assume either an unbelievably thin crust or a derivation of granitic rocks by differentiation from more basic magmas originating in deeper levels. Geophysical evidence, however, seems to decree that there is no weak shell or zone of potential magma to supply material for the abundant intrusives of the outer lithosphere, and accordingly that search must be made for means of creating magma in the shallow regions of the granitic and basaltic layers.

In view of the known effect of volume compression on the strength of rocks, thermal evidence seems to be definitely opposed to the isostatic assumption of a weak shell supporting a relatively thin crust, but suggests rather that strength persists into depths of hundreds of kilometers. Jeffreys' estimate[1] of the distribution of temperatures in depth leads to the conclusion that in general rocks are well below their fusion points into depths of 400 and perhaps 500 kilometers. After a later examination of additional data the same writer drew the following conclusions concerning the possibilities of inherited magma existing in a thick crust:

"Nothing in the new results encourages the hope that fusion temperatures are a normal feature at any depth within the crust. The approximate reproduction of the ultimate steady temperature given in 'The Earth' shows that the vertical distribution of temperatures shown on p. 154 needs little change as far as the present data are concerned. This is really not a defect. For though volcanoes exist, a generally fused layer would lead to absence of ocean tides and to a perfection of isostasy that certainly contradicts the facts. It still appears that volcanoes are a special phenomenon and their explanation cannot be found in the average temperature distribution with depth."[2]

These conclusions, derived from the thermal history and thermal state of the earth, are confirmed by deductions from low thermal gradients measured in several mines. The lowest gradient is the logical one to project for indications of temperatures at greater depths, and it seems to defy being reconciled to the existence of a continuous shell hot enough to be weak at depths less than several hundred kilometers.[3]

Seismological data confirm the thermal evidence that the crust is thick and strong. Deep-focus earthquakes give the most definite affirmation. These are recorded in all levels down to 700 kilometers or more. Seismologists[4] now generally agree

[1] Jeffreys, Harold: 1929, "The Earth," Cambridge Univ. Press, p. 154.

[2] Jeffreys, Harold: 1941, "The Thermal State of the Earth," Amer. Jour. Sci., Vol. 239, pp. 825-35.

[3] DeLury, J. S.: 1933, "The Strength of the Earth," Jour. Geol., Vol. XLI, pp. 748-56; 1936, "Geologic Deductions from a Thermal Equation," *ibid*, Vol. XLIV, pp. 479-95.

[4] Stechschulte, V. C.: 1936, "Geological Implications of Deep-Focus Earthquakes," Amer. Geophys. Union, pp. 81-83. Macelwane, J. B.: 1936, "Problems and Progress on the Geologico-Seismological Frontier," Science, Vol. 83, pp. 193-8. Gutenberg, B., and Richter, C. F.: 1939, "Evidence from Deep-Focus Earthquakes," Internal Constitution of the Earth, Chap. XI.

that the causes of these plutonic quakes are probably the same as for those of shallow origin. If so, rocks in general have great strength into depths greater than 700 kilometers. Strength in these great depths seems to imply either that even the lowest estimates of temperature in these regions are too high, or that compression dominates heat in deciding strength in these levels.

Notwithstanding these more direct thermal and seismological evidences that the crust is thick and strong, many hypotheses accept the limitations placed by the isostatic assumption of a relatively shallow shell of weakness. The writer has discussed elsewhere the evidences on which this assumption is built and reached the conclusion that they do not compel acceptance.[5] Without the shell of weakness in shallow levels no source seems to be permitted for permanent or inherited bodies of magma, hence search must be made for the means of local liquefaction. The compositions of abundant intrusives further suggest that these means operate in the outermost shells of the earth.

There seem to be definite possibilities for the local generation of important quantities of mechanical heat in the crust. The outer lithosphere is always suffering adjustments which imply the movement of large masses against the resistance of others. This, in turn, requires the generation of heat from friction. However, deformational processes are usually so slow that heat generated in this manner might be dissipated too rapidly by conduction to permit melting. This, more than any absence of important frictional heat, probably accounts for the lack of signs of true melting along fault planes near the surface. Other things being equal, such signs are expected more as depth increases, since insulation and higher temperatures are both consequences of deep burial and would facilitate melting. Furthermore, it is not unlikely that the occurrence of an important igneous mass formed from melting along a fault plane would be interpreted as a post-deformational intrusive. The same interpretation would be still more likely if the liquefied rock were forced to migrate into new positions.

In the following attempt at a solution of the problem of magma sources the writer accepts the view, as dictated by the preferred evidences, that a crust with a thickness of at least 700 kilometers has strength enough to resist large stress dif-

[5] 1942, "Compression Creep of Rubber and Rock," Jour. Geol., Vol. L, pp. 189-99.

ference during long geologic intervals. Material below the crust, owing to higher temperature, may be relatively weak and incapable of resisting stress difference of the same magnitude. Accordingly, the problem must be faced of accounting for the persistent development of magmas in outer levels where thermal and other evidences seem to decree a general lack of inherited magma.

Movements in the lithosphere are regarded as being caused primarily by thermal distortion. Failure of the crust in the thermal contraction theory will be treated as a protracted and piecemeal operation, involving the horizontal movement of enormous layers of rock over other masses. Frictional heat derived in these movements will probably generate thin layers of magma under wide regions. Following the initial formation of magma in sheets, further generation is expected from additional frictional heat derived from the energy of regional subsidence of over-riding crustal layers. The key to the present attempt to explain magma origin was provided by a recognition of the importance of compression creep in solids.

COMPRESSION CREEP INVOLVED WITH CRUSTAL FAILURE.

The movements commonly indicated by earthquakes now taking place along different parts of a widely extended fault plane indicate not only the continuous development of deforming stress in the strong crust, but also by their slowness the operation of compression creep. This operation requires only a fraction of the force needed to effect simultaneous movement along all parts of the fault. In a recent paper[6] the writer described compression creep and pointed out some of its bearings on geological processes. A quotation from this source will serve as a definition:

"A compressible solid may overcome resistance to its bodily movement by a piecemeal operation if the mass involved has dimensions permitting sufficient linear compression. Because resistance, such as friction, may be overcome locally and in successive stages, a small fraction of the force needed for an immediate effect will, given enough time, bring about the same bodily movement. This slow kind of movement against outside resistance, named 'compression creep,' suggests the view that the rate of geological deformation is correlated better with small forces operating through long time, than with mighty forces in critical periods."

[6] "Compression Creep of Rubber and Rock," loc. cit.

Measured by ordinary standards major deformation is a slow process even in the critical periods of geology. Slowness of deformation suggests control of the operation by compression creep. Accordingly, it seems that the crust of the earth may fail piecemeal in a long period of time when subjected to a stress difference small in comparison with the one required to produce instantaneous failure.

The causes of the stress differences that lead to crustal failure are none too clear, but heat seems to be the most probable and certainly the greatest source of energy available for earth movements. Appeal will be made accordingly to thermal distortion. This may arise from such things as unsymmetrical distribution of heat sources like radioactivity, and inequalities of heat conduction, but the most commonly accepted and obvious cause lies in thermal contraction of the earth as a whole. The principle of compression creep will now be applied to the problem of the failure of a thick crust in the thermal contraction theory.

FAILURE OF THE CRUST IN THE THERMAL CONTRACTION THEORY.

If the earth loses sufficient heat, contraction leads to the building up of enough horizontal compressive stress to cause failure in the crust. It is customary to assume that during a few hundred million years this compressive stress is slowly built up and that the crust fails as a whole in a relatively brief and critical period of deformation at which time the stress is largely relieved. The writer offers a contrary view that crustal failure is a very protracted process which involves much of the time usually regarded as being antecedent to failure. The possibility that the crust fails as a unit is more credible if it is assumed to be only a few tens of kilometers thick, but even here it is doubtful. With a thick crust, one 700 kilometers or more thick as the writer accepts, failure as a unit is incredible and could be admitted only on the assumption of incompressibility.

Another commonly held part of the thermal contraction theory is that contraction of the interior and a growing horizontal compression in outer layers lead to a surface of no strain between. The writer offers the contrary opinion that except with an incredibly thin crust compression dominates so completely any conceivable thermal effects in determining volume that a wide surface of no strain is impossible. Volume compression is characteristic of all parts of the earth except in shallow levels where deformation may lead to local tension.

Measurements[7] show that granitic rocks are more compressible than those of gabbro composition which are supposed to prevail in a lower shell. Similarly, gabbro is more compressible than olivine-rich rocks which probably assume dominance in still deeper levels. The same measurements further establish what is expected on theoretical grounds, namely, that rocks become less compressible with increasing compression. Taken together these evidences point to an important and continuous decrease of compressibility from the surface downward. Seismological data on the elastic properties of rocks in various depths give confirmation. It is gathered from B. Gutenberg's estimates[8] of the variation of elastic constants in depth, that the outer granitic layers have several times the linear compressibility of material near the 700-kilometer level. With this difference in linear compressibility from top to bottom and with other things equal, the crust would be expected to fail first in lower levels from the horizontal compression built up by thermal contraction. However, other controlling factors are not equal. For example, strength probably increases into great depths and may do so in a degree that would offset differential compressibility in deciding the manner of failure. Again, temperature changes may be a considerable factor in determining the linear compression of various layers, owing to their influence on volume. Exact appraisal of all controlling factors in failure is impossible, but it seems very improbable that these will ever be so nicely balanced that the entire crust will fail as a unit. Other and perhaps the decisive factors suggest that the lower crustal layers fail first and that the greater and lower part of the crust fails inward before a relatively shallow outer shell is seriously taxed by the horizontal compressive stress.

Loss of heat from subcrustal regions, that is to say below depths of 700 kilometers or thereabout, leads to reduced volume compression in those regions and to concurrent horizontal compression in the crust. The force of gravity now acts to

[7] Adams, L. H.: 1939, "Elastic Properties of Materials of the Earth's Crust," Internal Constitution of the Earth, Chap. IV.

[8] 1939, "The Elastic Constants in the Interior of the Earth," Internal Constitution of the Earth, Chap. XIV.

"shorten" the crust. The first effect expected is an elastic downwarping of susceptible parts of the crust, an effect which is essentially the same as that viewed in the dimpling of a hollow rubber ball when inside compression is reduced by partial deflation. This dimpling would be impossible in the crust if rocks were incompressible but in the long circumference of the earth there is a degree of compressibility that permits a reasonable comparison with the rubber ball. The areas of downwarping would likely be determined largely by crustal thinness, though other factors might contribute. The various geosynclinal depressions of geologic history may well be initiated by and reflect this elastic downwarping which is expected as the first effect of thermal distortion. The existence of geosynclines may be determined accordingly by the same influences that later lead to crustal failure. If so, support is given to a view to be developed later that crustal disturbances from thermal contraction occupy a large part of the long period involved in the building up of horizontal compression to the time of its final release. An initiation of geosynclines in this manner would also support the view that the relations between their locations and those of final folding are decided in an early stage by common causes.

The expected initial effect of thermal contraction on the crust, namely elastic downwarping, leads to a lessening of the area of the crust, since the crustal arch is flattened across wide geosynclinal belts, and hence to an increase in the horizontal compressive stress. The time required for ultimate failure is accordingly shortened. With further thermal losses and accompanying downwarping the time comes when the crust must fail. It has been indicated already that general factors suggest that the thick crust will not fail as a unit, but successively in its different parts as these are affected by the controls over failure. Next to be examined are the particular conditions set up by thermal contraction, which may determine the manner and place of initial failure.

Reduction of cubic compression in subcrustal regions leads to a lessening of the support for the lowest and relatively incompressible layers of the crust, which are expected to fail before shallower layers of more compressible material. Other and local conditions might contribute to determine the place of initial failure. For example, elastic downwarping might cause a local and pronounced increase of horizontal compression. This would suggest a possible correlation of the sites of geosynclines and those of initial crustal failure. Again, the place of failure might be associated with unevenness in thickness of the crust. Thermal considerations support the view that the crust is thicker under ocean basins than under continents.[9] This being so, and with the reduced pressure in subcrustal regions, ideal conditions are offered for the intervention of failure by compression creep. Unevenness in the bottom of the crust would influence the location of the place of first failure brought about by differential compressibility perhaps long before the strength of overlying layers is taxed. Failure of the crust may begin accordingly shortly after the initiation of geosynclinal depressions and long before the final failure as viewed in shallow deformation.

A low-angle underthrust fault displacement is started in the bottom of the crust. A favorable place for failure is provided by proximity to a belt of elastic downwarping and to a region where the thicker oceanic crust gives way horizontally to the thinner sub-continental crust. Reduced volume compression in subcrust and consequent lessening of lateral support for the downward bulge of the sub-oceanic crust would provide conditions that favor the "slicing" off of the bulge through the operation of compression creep. A fault plane starts to form near the flank of the bulge and slowly extends at a low angle to embrace a wide belt of the lower crust. The lower part of the oceanic crust is slowly underthrust into the subcrustal region of reduced compression. The amount of linear compression in the underthrusting layer will probably require a movement of a kilometer or more along much of the fault plane, which may be gradually extended thousands of kilometers horizontally. Plutonic earthquakes will accompany the movement and heat from friction will be developed in enormous quantities. Heat would cause liquefaction along the fault plane if movement were rapid enough. On the other hand, if movement were sufficiently slow, no melting would result, but the similar quantity of heat developed would lead to thermal expansion of rocks above and below the fault plane.

When the horizontal compressive stress is released from the bottom shell, this layer becomes a part of the subcrust in the sense that it joins the region governed by volume rather than linear compression. Owing to the vagueness of quantitative

[9] Jeffreys, H.: 1935, "Earthquakes and Mountains," p. 164.

data the writer sees no means of approaching an estimate of the thickness of the shell involved in the initial failure. It may be a thick shell representing a large fraction of the crustal thickness or it may be a relatively thin shell. If the latter, it seems likely that the bulk of the crust will be involved in a succession of failures of a number of layers from the bottom outward. Each failure would be accompanied by plutonic earthquakes and important heat generation. Whatever the manner of failure, the sum of expected effects is that the relatively incompressible bulk of the crust accommodates itself to horizontal compression by underthrust faulting. Moreover, this compressive stress is largely released before the more compressible outer shell of rocks has its strength seriously taxed by the same compression.

Eventually the more compressible outer shell of the earth must succumb to the great horizontal stress induced by thermal contraction. When it yields it will act as a unit and its various parts will migrate differentially over deeper rocks which have lost most of the horizontal compression. The common estimate from data on the strength and compressibility of abundant rocks is that the crust suffers a circumferential shortening of 40 to 50 kilometers before failure is required.[10] Other factors may reduce this estimate. However, the linear compression in the outer shell is of a magnitude to require that when failure ensues, movements of the outer shell toward the places of failure will be through distances of at least a few kilometers. The thickness of this outer shell is problematic and is probably variable in time and place. The initial failure is expected to be near the surface along a low-angle overthrust fault. The first movement will be relatively rapid. Later movements, controlled by compression creep, will be slower. The overthrust fault plane will be gradually extended and will become more and more horizontal. Eventually it will reach the bottom of the compressed outer shell, along which it is expected to grow horizontally until the compressive stress is largely relieved from the entire shell. Wide regions are accordingly involved. The frictional heat developed in the forced sliding of a thick sheet of outer crust over a now static lower crust is looked on as a probable means of producing magma in shallow levels. An attempt is made in

[10] Jeffreys, H.: 1935, "Earthquakes and Mountains," p. 145.

Fig. 1 to give diagrammatic expression of the mechanism which has been described.

GENERATION OF MAGMA FROM FRICTIONAL HEAT.

Failure of the outer shell of the crust in the manner described implies the movement through several kilometers of enormous masses of unknown but considerable thickness which cover areas equal to a large fraction of the earth's surface. Heat must be developed in enormous quantities along a nearly horizontal fault plane. P. G. Nutting[11] provides a formula for the estimation of heat generated in overcoming friction

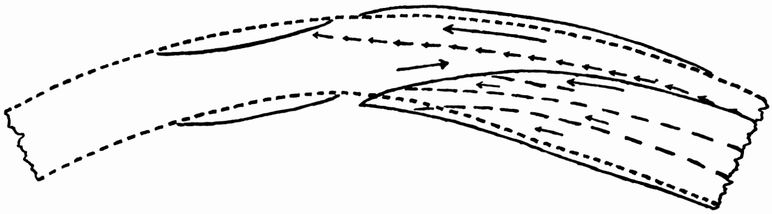

Fig. 1. Section of the earth's crust about 6,000 kilometers long and from 600 to 800 kilometers thick. The thinner continental crust to the left shows elastic downwarping in the change from the broken to the solid lines. A continuation of the broken lines into the region to the right depicts the thicker sub-oceanic crust before deformation. The underthrust portion of the major and deeper part of the crust is surrounded by solid lines. The same total effect might be produced by a number of underthrust slices suggested by the broken lines in the same portion. The later overthrust of the outer and lesser part of the crust is indicated by the long arrow. The underlying row of arrows marks the bottom of this overthrust slice, and at the same time shows the horizon in which magma is expected to be formed from frictional heat. Change in elevation at the surface, brought about by thermal expansion and perhaps by crustal thickening due to underthrusting, is suggested by the change from the broken to the solid line over the region to the right. The scales of downwarping, of thermal expansion and of the thickness of the outer, overthrust layer are exaggerated.

between rock surfaces. Following his data, a rock layer thick enough to exert a pressure of 1,000 pounds per square inch, when displaced a distance of 1 centimeter horizontally over a similar rock surface, develops 0.33 calorie for each square centimeter of the frictional surface, or enough heat to raise the temperature of a layer of ordinary rock 1 centimeter thick 0.8 degrees C. If this formula were applicable for the horizontal displacement through 1 kilometer of an outer shell 60 kilo-

[11] 1929, "Deformation and Temperature," Jour. Wash. Acad. Sci., Vol. 19, pp. 109-15.

meters thick, a rough calculation would show the generation of enough heat to warm and melt a thickness of more than 200 meters of common rock. This result is valuable for showing the potentialities of frictional heat in great earth movements, but the formula does not apply after melting is started. Other equations for determining mechanical heat would then be necessary, such as those used for viscous or plastic flow.

The rate of the horizontal displacement of the outer crustal layer has a decisive influence in determining the amount of heat available for magma generation. Rapid movement would cause a sudden generation of magma and then only heat from friction in viscous flow would be available. In the same rapid movement the latter source becomes increasingly small with the decreasing viscosity following rise of temperature. If movement were slow enough, on the other hand, frictional heat would be removed by conduction and magma generation prevented. That movement may be too slow to allow frictional heat to overwhelm losses by conduction is shown by the absence of magma in extensive overthrust fault planes in shallow levels. However, projection of these same places into distant and deeper regions might well spell magma generation. Deformation is slow, even in critical periods, so that the thermal insulation provided by burial to depths of a few tens of kilometers becomes an important factor.

With the failure of the outer shell local movement near the place of failure is expected to be relatively rapid. Magma will form and resistance to compression creep accordingly will be lessened in more distant areas, so that the fault plane is extended and the sheet of magma expands more or less in pace. Various conditions surround different parts of the fault plane. In one place melting may be resulting from solid friction. In another heat may be generated in viscous flow or even in plastic flow of highly heated material. Except locally and during brief periods it seems unlikely that viscosity will be so low that considerable heat will not be produced in viscous flow. Slow movement favors the formation of much highly viscous material rather than of small quantities of superheated liquid. Moreover, viscosity is known to increase enormously under confining pressures expected at depths of a few tens of kilometers. A displacement effected through flow in highly viscous material will probably produce a large fraction of the heat expected when the movement is effected against solid friction. It appears accordingly that there are great potentialities for magma generation along deep fault planes.

With the establishment of a widespread sheet of magma beneath the creeping outer shell of the crust, fresh possibilities arise for the creation of further important quantities of magma from the heat of friction. It was indicated in earlier pages that the heat generated along the widely extended underthrust fault or faults is expected to cause notable thermal expansion of the thick crust both above and below the levels of failure. It was suggested also that elevation of the surface might result from thickening of the crust due to underthrusting. A rough estimate will show, however, that the thermal effect alone is probably sufficient to cause a surface elevation of a few hundred meters. This elevation implies the creation of a "head" above the level in which magma is later formed by creep of the outer crustal layer. A wide region, corresponding to a large fraction of the earth's area, if it has a "head" over surrounding regions and overlies a more or less continuous sheet of magma, will tend to subside and to drive the magma horizontally into surroundings with lower "head." The energy of subsidence is enormous and a small fraction of it converted into heat would account for the generation of great quantities of additional magma. The mechanical equivalent of heat from subsidence of a layer about 60 kilometers thick through a distance of 100 meters is roughly equal to the amount needed to melt a layer of rock 130 meters thick or to warm and melt a cool layer 80 meters thick. It is not implied that all this heat is available for melting. However, with the degree of viscosity expected at great depth and in company with slow movement a large fraction of this mechanical heat may well be expended in the generation of additional magma.[12]

SUMMARY OF HYPOTHESIS AND AN INDICATION OF ITS BEARINGS ON GEOLOGICAL PHENOMENA.

Thermal and seismological evidences of strength into depths of several hundred kilometers suggest not only a crust of corresponding thickness but that the earth is a cooling body as well. A cooling earth will suffer two kinds of thermal distortion. One of these leads to crustal failure and results from

[12] DeLury, J. S.: 1932, "Magmas from Subsidence," Amer. Jour. Sci., Vol. XXIII, pp. 357-68.

symmetrical cooling by more or less equal conduction along all radii and a consequent volume shrinkage. Another kind of distortion is possible from exceptional and local heat losses or gains which may be reflected at the surface by changes of elevation. Stresses caused by thermal contraction lead to failure and require the movements of large masses of the crust against others and the consequent generation of important quantities of frictional heat. In the manner of failure predicted for the crust, the outer layer of considerable thickness is displaced horizontally through a distance of several kilometers against the friction of underlying rock. The frictional heat developed in this displacement causes liquefaction and the formation of a widely disposed sheet of magma. Subsidence of the overlying layer leads to the generation of more frictional heat and an increased quantity of magma. A generation of magma in this manner in the shallower levels of the crust meets fairly the abundant compositional evidence that the largest masses of igneous rocks seem to come from magmas derived in these levels. There is accordingly no need to appeal to differentiation of deep and inherited sources of magma to account for the formation of the abundant granite batholiths.

In attempting to apply this hypothesis of crustal failure to an explanation of outstanding geologic events the many conflicts of view in the field of tectonics present themselves. Space permits only a brief indication of its possible application to some of the major tectonic problems.

In drawing Fig. 1 the writer had in mind the history of the Appalachian region. Downwarping without failure initiated the geosyncline, which during the Paleozoic era received a thick accumulation of sediments. An extensive borderland to the east, which supplied the bulk of these sediments, is related to the elevation caused by thermal expansion as shown in the Figure. When the outer layer of the crust failed, it moved against the weak sedimentary layers of the geosyncline and deformed them. With subsidence of the borderland great quantities of magma were generated to move horizontally and finally upward to form the batholithic core of the folded Appalachian mountains. This succession of events on the Atlantic side of North America is fairly typical of the processes by which the continental mass has been narrowed and thickened into a relatively high-standing continent. However, the movements which Asia has suffered in the later geologic eras have opposite effects. Apparently this continent is spreading outward. Accordingly, the mechanism of crustal failure is different under various regions. Other factors than those described in earlier pages and indicated in Fig. 1 may decide places of downwarping and whether movements will be toward continents or ocean basins. Again, a modification of the manner of failure described may govern in oceanic areas.

In most mountain systems there is good evidence that the thrust which leads to "shortening" comes mainly from one direction. The present hypothesis seems to offer a reasonable explanation of this phenomenon, which presents obvious difficulties in the opposing concept of a relatively thin crust collapsing as a unit. Perhaps the most serious criticism that has been levelled at the thermal contraction theory of crustal failure comes from the evidence that the amount of crustal "shortening" is too great to be explained by the theory. A related objection arises from the indications that important tensional effects, like normal faults, are produced more or less contemporaneously with compressional effects as viewed in folding and overthrusting. In other words, the crust is "lengthened" in some regions while being "shortened" in others. The writer's hypothesis offers definite possibilities for the removal of these difficulties.

Regional subsidence of an outer crustal layer creates magma and drives it forcefully into shallow mobile belts. Differential drag by the moving and viscous magma sheet may carry parts of the layer faster than others, leading to compressional effects in the mobile belt at the front and to contemporaneous tensional effects, such as stretching and normal faulting, in a wide region to the rear. The forceful intrusion of magma accordingly produces effects which may give an exaggerated impression of the amount of crustal "shortening."[13] Similar effects are produced by differential flow in continental ice sheets and by the migration of rock salt from beds to form salt domes.

The manner of failure indicated for the deeper part of the thick crust suggests an explanation of plutonic earthquakes. In fact, these quakes supply the best evidence as to the thickness of the crust. They are expected in all levels between those of "normal" depth down to 700 or more kilometers. It is further anticipated that the "sense" of direction of movement will be the same under wide regions and throughout long

[13] DeLury, J. S.: "Magmas from Subsidence," *loc. cit.*

periods of time. In general, shallow quakes above the same regions are expected to show movement in an opposite "sense."

Further possible applications of the hypothesis can be barely indicated at this time. For example, it suggests an explanation of diversification of igneous rocks by mixing processes rather than by differentiation. Intrusion is forceful in the main, though local effects may suggest that it is passive. The suggested correlation of deformation and intrusion agrees with the facts. The "sial" of continental masses is segregated by horizontally rather than vertically operating processes. Hence comes a plausible explanation of vast geographic changes and the baffling problem of past continental connections and separations. Adequate means are suggested for changes of elevation. A fairly even distribution of mass around the earth is expected, but there is also room for the creation of important gravity anomalies. Confusion is added to the already confused thermal problem of the earth, but may lead eventually to its clarification.

The writer has avoided any attempt at minute accuracy in estimates of distances of displacement, of quantities of heat, etc. Data are too inaccurate to permit the use of anything but round numbers. However, the hypothesis is regarded as being on a sound qualitative and a reasonable quantitative basis.

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