DEPARTMENT OF THE INTERIOR
UNITED STATES GEOLOGICAL SURVEY
GEORGE OTIS SMITH, DIRECTOR

PROFESSIONAL PAPER 85—C

INTERPRETATION OF ANOMALIES OF GRAVITY

BY

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Published December 18, 1913

PART C OF PROFESSIONAL PAPER 85, "CONTRIBUTIONS TO GENERAL GEOLOGY, 1913"

WASHINGTON
GOVERNMENT PRINTING OFFICE
1913

CONTENTS.

ILLUSTRATIONS.

INTERPRETATION OF ANOMALIES OF GRAVITY.

By Grove Karl Gilbert.

THE ANOMALIES.

A by-product of the adjustment of primary triangulation for the United States was the determination of the deflection of the vertical at 765 stations.[1] In discussing these deflections Hayford introduced the hypothesis of isostatic compensation, with the result that the deflections were "thereby reduced to less than one-tenth of the mean values which they would have if no isostatic compensation existed." [2] The particular form given to the hypothesis was this: At some depth below the horizon of sea level, called the *depth of compensation*, the stresses due to gravity are uniform. Each unit vertical column above the horizon of compensation contains the same mass,[3] the product of the length of the column by its mean density being the same in all places, or the variation of length associated with topographic relief being compensated by reciprocal variation of mean density. In the adjustment of the deflections of the vertical various assumptions were made as to the depth at which compensation is complete, and the depth yielding the best adjustment was found to be 122 kilometers.

Hayford and Bowie, in discussing the determinations of gravity at stations in the United States, used the same hypothesis of isostatic adjustment and adopted from Hayford's earlier work the estimate of 122 kilometers as the depth of compensation. For each of 124 stations at which the intensity of gravity had been measured they computed the attractive influence not merely of the elements of the neighboring topography, but of the topographic elements of the entire earth, and the whole computation was made subject to the isostatic hypothesis. The attractive influence thus deduced was added (algebraically) to the value of gravity appropriate to the latitude and altitude of the station, giving a theoretic or computed value, which was then compared with the value obtained by observation. The difference—observed minus computed—is called the local anomaly of gravity. The mean of the 124 anomalies is 0.020 dyne. This is approximately one-fourth as large as the mean of anomalies obtained without the introduction of the isostatic hypothesis.

The success of the hypothesis in reducing anomalies of the vertical and anomalies of gravity is held—properly, as I think—to show that isostatic adjustment in the earth's crust is nearly perfect. Taking the outstanding or residual anomalies as measures of the approximation to

[1] The papers to which the present article refers are as follows:

Hayford, J. F., The figure of the earth and isostasy from measurements in the United States, U. S. Coast and Geodetic Survey, Washington, 1909; Supplementary investigation in 1909 of the figure of the earth and isostasy, U. S. Coast and Geodetic Survey, Washington, 1910; The relations of isostasy to geodesy, geophysics, and geology, Science, new ser., vol. 33, pp. 199-209, 1911.

Hayford, J. F., and Bowie, William, The effect of topography and isostatic compensation upon the intensity of gravity, U. S. Coast and Geodetic Survey Special Pub. No. 10, Washington, 1912.

Bowie, William, Effect of topography and isostatic compensation upon the intensity of gravity, U. S. Coast and Geodetic Survey Special Pub. No. 12, Washington, 1912; Some relations between gravity anomalies and the geologic formation[s] in the United States, Am. Jour. Sci., 4th ser., vol. 33, pp. 237-240, 1912.

Spencer, J. W., Relationship between terrestrial gravity and observed earth movements of eastern America, Am. Jour. Sci., 4th ser., vol. 35, pp. 561-573, 1913.

[2] Figure of the earth and isostasy, p. 175.

[3] Mass is the term employed by Hayford, and his usage has been followed in the present paper. In strictness weight is the quantity with which isostasy is concerned, and the substitution of mass for weight in the analyses involves the assumption that gravity is uniform from top to bottom of the zone of compensation. It is, in fact, about 1 per cent greater at the depth of 122 kilometers than at the surface. The numerical errors possibly entailed by the substitution are negligible.

perfect adjustment, the authors state that the mean anomaly in the vertical corresponds to the mass of a rock layer 250 feet thick, and the mean anomaly in gravity to a rock layer 630 feet thick.[1]

Each measurement of the intensity of gravity is of course affected by an error. The corresponding computed intensity is also affected by an error. Their difference, the anomaly, is the algebraic sum of the two errors. The average error of the observed values of gravity is demonstrably small, so that the anomalies differ little from the errors of the computed values. The error of a computed value is not all from a single source. Part of it comes from the data used, such as the altitude, the mean density of the surface rock, and especially the configuration of the surrounding topography; another part comes from the methods of computation, which were somewhat shortened for the sake of economy; and a third part comes from assumptions connected with the specific hypothesis of isostatic compensation. The authors cited discuss these classes of error with care and reach the conclusion that all are small in comparison with those arising from the assumptions.[2] An attempt to interpret the anomalies may therefore properly include the consideration of their relations to various assumptions.

INTERPRETATION BY IMPERFECT ISOSTATIC ADJUSTMENT.

The explicit general assumption as to compensation is that the excess of mass in any crustal column due to its projection above sea level is exactly compensated by defect in density uniformly distributed from the surface to a depth of 122 kilometers; and that defect of mass in any unit column beneath the ocean is similarly compensated by excess of density (with due allowance for the mass of the overlying water). This general assumption includes the more specific assumptions (1) that the compensation is perfect, (2) that the compensatory defect or excess is uniformly distributed through the column, (3) that the depth of compensation, 122 kilometers, is not subject to variation from place to place. To these may be added an implicit assumption of which there will be occasion to speak on a later page. The inexactness of the three assumptions is explicitly and fully recognized by the authors cited,[3] but their discussion gives prominence only to the inexactness of the first. In a general way they interpret the anomalies as due to uncompensated local excesses or defects of mass in the crustal layer, or, in other words, to imperfection of isostatic adjustment. The present paper will consider the possibilities of interpretation connected with the other specific assumptions.

INTERPRETATION BY VERTICAL HETEROGENEITY OF CRUST.

In place of the assumption that the vertical distribution of compensatory density difference is uniform, let us assume that it is subject to the same variation as is the assumed horizontal distribution of compensatory density difference. In each case the compensatory element of density is but a small fraction of the entire density.

The topographic relief most intimately associated with the gravity stations is that of the United States. The mean altitude of the United States, as given by the authors, is 2,500 feet, or 762 meters; and the compensatory correction to density for $+762$ meters is $-\frac{762\times 2.67}{122,000}=-0.0167$. The compensatory correction for neighboring oceanic topography is positive, and its average is coordinate in amount. The value 0.0167 may serve as a rough estimate of the average departure in density which was assumed in computing corrections for topography. An alternative estimate may be based on the topographic relief of the entire globe. Again, using the level of the ocean surface as a horizon of reference, making due allowance for the partial compensation given by the mass of the water, and combining positive and negative corrections irrespective of sign, we have 0.0381 as the resulting value of the average departure in density. Neither mode of estimation is entirely satisfactory, but together they

[1] This figure applies to 122 instead of 124 anomalies. By omitting two aberrant anomalies the mean is reduced from 0.020 to 0.018. See Special Pub. No. 12, p. 23.

[2] Special Pub. No. 10, pp. 88-94.

[3] Idem, p. 11.

yield an order of magnitude; and an intermediate value, 0.025, will be accepted as sufficiently precise for the present purpose. In order to discuss the effect of a vertical variation of density coordinate in amount with the postulated horizontal variation, it will be assumed that the average deviation of the density of any large portion of the crustal column from its normal is 0.025.

In the diagram, figure 7, vertical distance represents depth below the earth's surface, A corresponding to the surface and B to the level of compensation, 122 kilometers below. Horizontal distances, measured from AB as origin, represent density. The line CD arbitrarily represents the normal curve of density in relation to depth. The nature of the curve within the zone of compensation is unknown, and its form has no importance in the present connection. The shaded area CE expresses the assumption that in a particular locality the upper half of the zone is characterized by a uniform defect of density, and the shaded area DF expresses the assumption that in the same locality the lower half of the zone is characterized by an excess of density of the same amount. The widths of the areas correspond by scale to departures of 0.025. The introduction of these departures in density does not affect the total mass of the unit column, but it does affect the intensity of gravity at the top of the column. The tract of deficiency being nearer to the surface than the tract of excess, the loss of attraction exceeds the gain and there is a net reduction of the intensity of gravity.

To obtain numerical results it is necessary to assume horizontal as well as vertical dimensions for the bodies of rock affected by abnormality of density, and computations are facilitated by giving each ideal body the form of a right cylinder, the one resting on the other. The radius of the cylinders is assumed as 61 kilometers (one-half of the depth of the level of compensation); the assumed defect in density for the upper cylinder and the assumed excess for the lower are each 0.025; and the station on which their influence is computed is assumed to be at the center of the upper face of the upper cylinder. The computed influence [1] of the defect in density on gravity at the station is -0.0375 dyne; that of the excess is $+0.0115$ dyne; and their algebraic sum is -0.026 dyne. If the excess of density is in the upper body and the defect in the lower, the effect on surface gravity is $+0.026$ dyne. These quantities are to be compared with the mean anomaly for the system of gravity stations, which is 0.020 dyne.

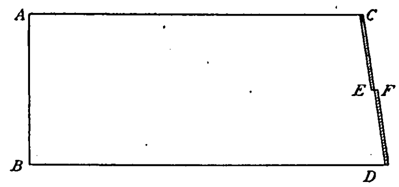


FIGURE 7.—Hypothetic relation of density anomalies to densities and to depths.

Thus it appears that the same moderate assumptions as to variation of density which Hayford and Bowie apply to horizontal relations in discussing isostatic compensation yield, if applied to vertical relations, departures in gravity intensity of the same order of magnitude as the outstanding anomalies found after making allowance for isostatic compensation. From this I infer that the anomalies may be in part due to irregularities in the vertical distribution of densities, or that such irregularities are competent, alike in the nature of their influence and in its possible amount, to cause such anomalies of gravity as have been discovered.

INTERPRETATION BY VARIATION OF DEPTH OF COMPENSATION.

Let us now consider the effect of removing the restrictive assumption which makes the depth of compensation uniform at all points. In Hayford's discussion of deflections of the vertical separate computations are made for ten divisions of the United States, and the results of these computations lead to the conclusion "that while there are indications that the depth of compensation is greater in the eastern and central portions of the United States than in the western portion, the evidence is not strong enough to prove that there is a real difference in depth of compensation in the different regions;" [2] but the authors of the papers on gravity use only the assumption of uniformity. In view of the recognized heterogeneity of crustal material it appears to me both possible and probable that the depth at which material is sufficiently mobile to effect isostatic adjustment is subject not only to regional but to highly localized

[1] Computed by means of a formula given by Hayford and Bowie in Special Pub. No. 10, p. 17. [2] Figure of the earth and isostasy, p. 143.

variation. To obtain an idea of the quantitative relations between local variation of the depth of compensation and resulting variation of gravity, I have postulated a circular tract having a radius of 61 kilometers and having such topographic relief that the compensatory density, for a depth of 122 kilometers, is -0.025. Then I have introduced various changes in the postulated depth of compensation, with corresponding changes in the compensatory density, and computed the effect on local gravity. The change in intensity of gravity corresponding to 40 per cent increase in the depth of compensation is -0.0161 dyne; the change corresponding to 40 per cent decrease is $+0.0125$ dyne. These quantities are to be compared with the mean anomaly of gravity, 0.020 dyne. The resulting figures would be somewhat but not greatly different if the computations were applied to an area several times larger.

The general fact appears to be that local variations of the depth of compensation are competent to cause anomalies of gravity, but that very large variations would be necessary to produce such anomalies as have been observed. To explain in this way the greatest of the anomalies it would be necessary to assume that the zone of compensation is many times as deep at some places as at others. While such a condition may not be impossible, the geodetic results indicate that it is highly improbable; and I am disposed to regard variation in depth of compensation as decidedly less available in interpreting anomalies than variation in the vertical distribution of densities.

GEOLOGIC RELATIONS OF ANOMALIES.

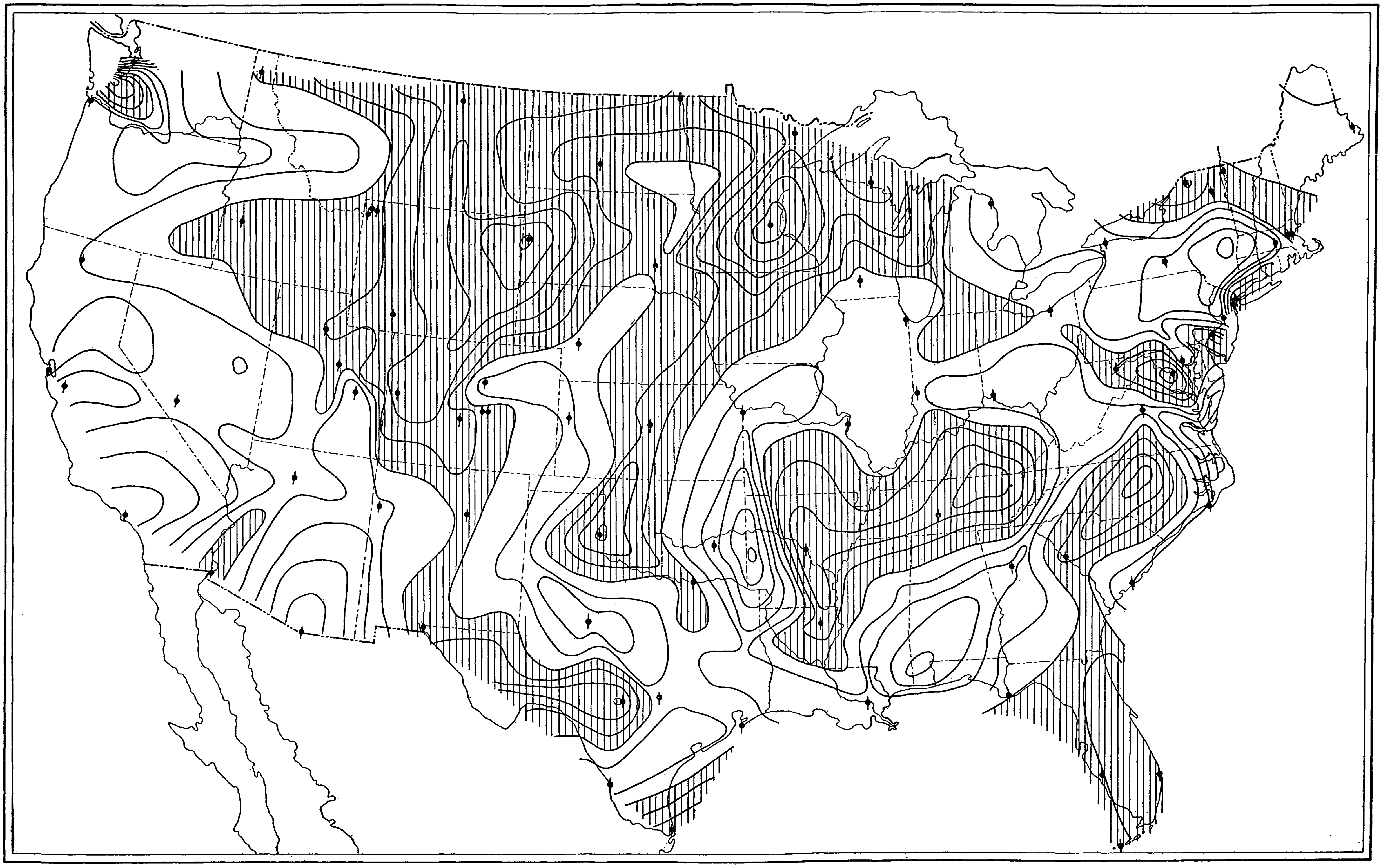
To exhibit the geographic distribution of anomalies the authors cited have drawn lines of equal anomaly on a map of the United States;[1] and these lines are reproduced in Plate IV. The contour interval is 0.01 dyne, and areas of plus anomaly are distinguished from areas of minus anomaly by shading. The positive and negative anomalies are not indiscriminately mingled, as should be expected if the anomalies had the character of accidental errors, but fall into groups. Large districts of plus anomaly appear and other large districts of minus anomaly. This effect is undoubtedly heightened by the fact that the distances between stations are large, but is not created thereby. A comparison of parts of the map controlled by numerous stations with parts controlled by few and a comparison of this map based on 124 stations with an earlier map based on 87 stations leave no question in my mind that there is a veritable areal grouping of the anomalies. With the multiplication of gravity stations the courses of the lines will be modified, and contrasted areas will become more clearly defined, but the type of the future map is shown by the one we now have.

The anomaly map is in some way an expression of subterranean structure, for it tells of the distribution of mass. As the subterranean structure is a product of the earth's history, the distribution of anomalies has a historical significance. To determine the nature of this significance is a problem in interpretation.

Bowie[2] has classified the anomalies according to the geologic formations occurring at the stations to which they pertain, thus in effect attempting a correlation between the map of anomalies and the geologic map, but the correspondences are not important. By a series of computations he shows that such local excesses or defects of mass as may be ascribed to the densities and volumes of formations visible at the stations are not at all adequate to explain the anomalies.

Hayward and Bowie have compared the anomalies with areas of large recent unloading of the crust by erosion and with areas of large recent loading by deposition, but have not found such correspondence as to support the hypothesis of cause and effect;[3] and a similar negative result followed an attempt to correlate anomalies with the loadings and unloadings of certain districts by the ice of glacial time.[4] Spencer[5] emphasizes the fact that there are large plus anomalies within the region once covered by the Laurentian ice sheet and regards it as proof

[1] Special Pub. No. 12, illustration No. 2.
[2] Am. Jour. Sci., 4th ser., vol. 33, pp. 237-240, 1912. See also U. S. Coast and Geodetic Survey Special Pub. No. 10, pp. 113-117, 1912.
[3] Special Pub. No. 10, p. 112.
[4] Idem, p. 116.
[5] Am. Jour. Sci., 4th ser., vol. 35, pp. 569-570, 1913.



MAP OF THE UNITED STATES SHOWING LINES OF EQUAL ANOMALY OF GRAVITY.

Areas of plus anomaly are shaded. Contour interval, 0.01 dyne. Gravity stations are indicated by dots.

that the rising of that region after the removal of the ice load was not caused by the removal of load.

In the drawing of inferences from the relations of anomalies to loading and unloading much depends on the mode of interpreting anomalies; and, conversely, the relations of anomalies to loading and unloading may be used as tests of modes of interpretation. In a general way the continental shelves have long been areas of loading and adjacent land districts have been areas of unloading. To whatever extent isostatic compensation for this loading and unloading has been imperfect, to whatever extent the readjustment lags behind the disturbance of equilibrium, there should be an excess of mass under the submerged shelf and a deficiency under the land. Under the hypothesis of interpretation which correlates excess of mass with plus anomalies and defect of mass with minus anomalies we should expect to find, as a general fact of the anomaly map, an anomaly gradient from ocean to land in coastal regions. Such a gradient is, in fact, found between Boston, Mass., and Trenton, N. J., and between Florida and the Rio Grande, the two stretches comprising one-third of our coast; but the gradient is unequivocally oceanward between Delaware and Florida, and elsewhere its direction is parallel to the coast. The Appalachian belt south of the region of glaciation has been practically free from loading during two geologic ages and has been unloaded to the extent of many thousands of feet of rock. Isostatic adjustment may be supposed to have added mass in compensation for the unloading, or for part of it, but may not plausibly be supposed to have overcompensated so as to create an excess of mass. Nevertheless, there are large plus anomalies in that belt, and their existence evidently creates a difficulty in interpreting plus anomalies as due to crustal excess of mass. The district of greatest loading in recent time is the Delta of the Mississippi, and if isostatic adjustment has not fully kept pace with the loading there should be in this district a local excess of mass. The fact that the local anomaly is minus instead of plus calls in question the mode of interpretation which infers crustal defects of mass from minus anomalies.

The hypothesis that certain Pleistocene sinkings and risings of the land were caused by the associated additions and removals of ice load is in general accord with the theory of isostatic adjustment. If it is true that the crust became approximately adjusted to the last loading and that the subsequent deformation, of which we have record in the inclined shores of glacial lakes, was caused by a readjustment during and after the final unloading, then there should be no excess of mass in the readjusted or readjusting area. Because there is a tract of plus anomaly within this area Spencer discredits the hypothesis of deformation through unloading, but the fact may equally be used to discredit the hypothesis underlying his mode of interpreting anomalies.

In all these cases involving loading or unloading the hypothesis that the anomalies represent imperfect compensation and imperfect adjustment yields results which are unsatisfactory because they are opposed to plausible expectation, and the expectation is plausible because it is founded on the theory—we need no longer call it the hypothesis—of isostatic adjustment. In all these cases the distribution of anomalies may be reconciled with rational expectation by assuming local irregularities in the vertical distribution of densities, and the irregularities thus assumed need be only of the order of magnitude of those irregularities in horizontal distribution of densities which have been assumed in the reduction of the geodetic observations.

In my opinion these considerations connected with phenomena of loading and unloading serve to show that the anomalies may not properly be interpreted as due exclusively to crustal excesses and defects of mass existing because of imperfection of isostatic adjustment. Some additional mode of interpretation must be admitted, and at least one other mode, that connected with irregularities in the vertical density gradient, appears to be both qualitatively and quantitatively competent.

If the two modes of interpretation are accepted as coordinate, it becomes possible to extend the conclusion of Hayford and Bowie as to the perfection of isostatic adjustment. The one mode of interpretation, if used exclusively, yields an average imperfection of adjustment measured (positively or negatively) by the weight of a layer of rock 630 feet thick; the other, if used exclusively, implies no imperfection of adjustment. Any combination of the two yields the conception of an adjustment more nearly perfect than would be implied by the measure of 630 feet of rock.

If vertical irregularity of density were to be accepted as the exclusive cause of gravity anomaly, the map of gravity anomaly would become (approximately) a map of vertical density anomaly, each area of minus gravity anomaly being replaced by an area in which departures from the normal density gradient of the crust are negative near the surface and positive below and each area of plus anomaly by one in which density departures are positive near the surface and negative below. Such a change would remove the problem of interpretation to a new position, by raising the question of the origin of the anomalies in density. Giving attention to this new question, I have been led to the suggestion that a competent cause for the peculiarities of density distribution would be apt to find expression also in the greater facts of the structure of the continent. Among those greater facts, so far as we are able to read them in the visible structure and physiography, are (1) the Appalachian-Ozark belt of corrugation and (2) the strong contrast, farther west, between a cordilleran region of strong orogenic disturbance and a plains region of relative freedom from disturbance; and I have studied the relation of these features to the features of the anomaly map. The correspondences are so slight that they may be regarded as accidental, and the general relation is that of independence and discordance. The result is of limited significance because the visible structure elements may constitute but a small fraction of the structure of the crust, but so far as it goes it fails to support the hypothesis that the anomalies of gravity are due exclusively to anomalies in the vertical distribution of density within the crust.

THE LOCUS OF ADJUSTMENT.

Hayford has given an analysis of the general mechanics of isostatic readjustment when the isostatic equilibrium has been disturbed by erosion and deposition.[1] The analysis reveals stresses tending to cause an undertow within the crust, and adjustment is ascribed by Hayford to the undertow. My own conception of the process of adjustment accords with these features of his analysis, but adds the idea of relative mobility as an important condition in determining the place of underflow and the perfection of the adjustment.

Now that the argument from tides has been efficiently supported by that from the speed of earthquake waves, we may accept with confidence the doctrine of the high rigidity of the earth's nucleus. The theory of high rigidity accords also with the fact of high density, provided the nucleal materials are similar to the crustal, for with sufficient compression the viscosity of even the most mobile fluids become high rigidity. Immobility at all depths below that of compensation is either explicitly or implicitly assumed by Hayford and Bowie.

On the other hand, there is much geologic evidence of mobility somewhere below the surface. Part of this evidence is volcanic. The continuous or secular relations of pressure, temperature, and density in the subterranean region from which liquid rock rises at intervals may be assumed to be such that moderate change of condition either induces liquefaction or else so lowers the density of rock already liquid as to render it eruptible; and such a balancing of conditions implies some sort of mobility. Other evidence is diastrophic. In some regions, such as the Appalachian, overthrusts and folds testify to great reduction in the horizontal extent of rocks near the surface, the reduction having been accomplished in a small fraction of geologic time. If the subjacent portion of the nucleus had been correspondingly forced into narrower space there would have resulted an enormous mountain range, but the actual uprising was of moderate amount. Plausible explanations of the phenomena necessarily include horizontal movements of the upper rocks without corresponding movements of the nucleus and thereby imply mobility in an intervening layer. In certain block-mountain districts of the West the master faults are antithetic in type to the overthrust and demon-

[1] Science, new ser., vol. 33, p. 202, 1911.

strate pronounced extension of the upper part of the crust. The nucleal tract beneath could not share in this extension without creating an enormous depression, which does not exist; and the interpretation of the phenomena involves horizontal shear in material more mobile than the visible upper rocks.

The conception thus engendered, of a relatively mobile layer separating a less mobile layer above from a nearly immobile nucleus, appears to me in full accord with the evidence which geodesy affords of isostatic adjustment. The geodetic "depth of compensation" agrees with such suggestions as to the position of the horizon of maximum mobility as might be afforded by the volcanic and diastrophic phenomena. The existence of a horizon of mobility accords with the inference of approximate perfection of isostatic adjustment.

It is not necessary to suppose that the degree of mobility at the horizon of mobility is that of a liquid at the surface. When such mobility is attained by any but the densest rocks eruption takes place. It is not necessary to think of the degree of mobility as uniform, either from place to place or from time to time. Its place variation would naturally be coordinate with that of rock types, and its time variation coordinate with epochs of elevation and subsidence. Neither should the depth of the horizon of maximum mobility be thought of as uniform.

INTERPRETATION BY NUCLEAL HETEROGENEITY.

The inner earth is the inalienable playground of the imagination. Once it contained the forges of blacksmith gods; or it was the birthplace of our race, or the home or prison of disembodied spirits. Later Symmes hollowed from it a vast habitable empire, concave like the world of Koresh. Science now claims exclusive title but holds it chiefly for speculative purposes; and the freedom of speculation practically recognizes but two limitations: The inner earth is dense, and it is rigid. As to all other properties opinion is untrammeled.

It is my own view that the inner part of the nucleus is not merely hot, but very hot. If the law of compression by pressure and the law of expansion by heat, as we know them at the surface, apply equally to the nucleus, then the mean temperature of the earth must be enormous in order to afford a mean density so low as 5.6. An enormous temperature implies an enormous store of heat. This is the source of the energy involved in the hypogene activities of the earth, and it is fed to the crustal region by conduction. If the earth were composed of homogeneous shells diversity of crustal activity would depend on outside conditions only and would be connected with latitude. In fact, however, the diversity of crustal activity is largely independent of latitude. It is in part related to visible diversity of crustal material, but in larger part it appears unrelated to things visible. Deformation sometimes shows or seems to show dependence on erosion and deposition, but any such scheme of causation yields a running-down process and fails to account for the perpetual initiative of geologic activity through the ages. The deformations which have not only developed but perpetually remodeled the continents have a source below the surface. Their method probably involves reactions between temperature, pressure, and the physico-chemic constitution of rocks, but these reactions, like the superficial reactions, yield running-down processes and do not afford a fundamental explanation of crustal activity. The factor to which I appeal is primordial heterogeneity of earth material, a heterogeneity which gives diversity to the flow of heat energy and to the physical and chemic changes of crustal regions. It does not seem sufficient that the crust be heterogeneous; there should be heterogeneity also below the horizon of mobility.

Under this speculative view of the earth's constitution the anomalies of gravity may be in part occasioned by tracts below the level of compensation which are characterized by exceptional density. It appears to me quite possible that underflow in a mobile layer might effect a practically perfect adjustment for differences in density above the layer, so as to bring crustal densities and crustal relief into harmony, and yet leave uncompensated the differences in density of the nucleus.

To obtain some idea as to the quantitative ability of nucleal heterogeneity to modify gravity, let us assume that abnormalities of density are as great in the nucleus as in the crust. Let us assume that just below the horizon of compensation is a nucleal tract in which the abnormality of density is ± 0.025, and that the form and dimensions of the tract are those of a right cylinder with height and radius each equal to 122 kilometers. The computed attraction of the nucleal abnormality of mass, exerted at a gravity station situated directly above the center of the cylindric tract, is ± 0.023 dyne; and this is of the same order of magnitude as the mean anomaly of gravity, 0.020 dyne. The influence of such an abnormality of mass would have its maximum at the station and would diminish with increasing distance from the station, the general result being a hill or a hollow on the contour map of anomalies of gravity.

The mode of interpreting gravity anomalies which appeals to nuclear heterogeneity is applicable not only to those anomalies which encounter difficulty in dealing with districts of loading and unloading, but also to those grouped anomalies whose areas and contours exhibit independence of all visible geologic structure. It seems, in fact, to be competent to account for all anomalies except such as exhibit very steep gradient. On the other hand, if the development of the subject shall show that there are anomalies which can be explained in no other way, the existence of such anomalies may constitute evidence of nucleal heterogeneity.

Hayford and Bowie, by ignoring the possibility of nucleal density anomalies, implicitly assume isostatic adjustment in the nucleus, such an adjustment as would exist in a nucleus composed of concentric homogeneous shells. The alternative interpretation of gravity anomalies just outlined is founded on the supposed inexactness of that assumption.

REVIEW AND CONCLUSION.

The mean density of the earth is about twice the average density of earth material at the surface. In a general way density increases from the surface downward. If the density gradient were everywhere the same the earth might be described as composed of concentric layers, each homogeneous as to density. The actual departures from such an equable arrangement may be called anomalies of density. Anomalies of density systematically related to topographic relief have been assumed by Hayford and Bowie in computing theoretic gravity at each gravity station, the difference between the theoretic gravity and observed gravity being the local anomaly of gravity. An anomaly of gravity (except as affected by errors of observation, etc.) is caused by anomalies of density other than those systematically introduced into the computations. Hayford and Bowie's system of density anomalies is one which assumes isostatic equilibrium at a depth of 122 kilometers. The distribution of the additional anomalies of density necessary to account for the anomalies of gravity is unknown. So many different distributions seem possible that the actual distribution may not be determinable. One suggested distribution (Hayford and Bowie) includes only horizontal variation and restricts variation to the crustal region. It involves moderate imperfection of isostatic equilibrium at the depth of 122 kilometers, and it encounters difficulties when applied to the anomalies of regions which have recently gained or lost mass through loading or unloading. A second suggested distribution, or element of distribution, involves vertical variation within the crustal region. Taken by itself it seems equally competent with the first, and it does not involve the same imperfection of isostatic equilibrium. A third suggestion, coordinate with the others in that it is quantitatively adequate, is that the additional anomalies of density are not confined to the crustal region but occur also at depths greater than 122 kilometers and below the region of isostatic adjustment. A fourth suggestion, that the distribution of the additional anomalies of density is connected with variation in the depth of the horizon of adjustment, may supplement either of the others but is not by itself sufficient to account for the anomalies of gravity.

Volcanic phenomena and phenomena of crustal shortening and crustal extension indicate a horizon of relative mobility above the rigid nucleus. To whatever extent a subcrustal layer is mobile the means are furnished for approximately perfect isostatic adjustment at that level. It is inferred that the actual adjustment is more nearly perfect than would be indicated by the geodetic data if those data were interpreted according to the first of the above-mentioned suggestions. The geologic evidence in favor of a mobile layer combines with the evidence from approximate isostasy despite surface transfers of load to show that the anomalies of gravity are not due chiefly to uncompensated excesses and deficiencies of mass in the crust; and I incline to the view that the hypothesis which so interprets them is one of the least probable of the four suggested.

The second and third suggested interpretations—that by vertical arrangements of anomalies of density within the crust, and that by anomalies of density below the horizon of isostatic adjustment—are not competitive, and each may prove to have its field of application. The second has a sound basis, for vertical variation of density in the crust is demonstrated as far down as the sources of volcanic eruption. The third has perhaps no more than a presumption in its favor. The failure of anomalies of gravity to group themselves in harmony with large features of crustal structure makes it easy to think that their grouping may be related to nucleal structure. When the multiplication of gravity stations shall have relieved some of the broad areas of the anomaly map from their present vagueness, the groupings may be found more significant than they seem at present. Crustal diversity may be to an important extent a product and record of the geologic chapter of earth history. Nucleal diversity, if it exists, belongs to pregeologic chapters.

Starting with geodetic and topographic data and assuming certain uniformities, Hayford and Bowie have demonstrated isostasy and developed a gravity anomaly map. The map contains a body of observational data coordinate with the geodetic and topographic. By a future mathematical discussion which treats the three bodies of data together and which recognizes alternative interpretations of the anomalies of gravity it may be possible to practically demonstrate the meaning of the anomaly map. At present the map seems to express chiefly an effect of heterogeneity in the nucleus and an effect of irregularity in the vertical distribution of densities within the crust.

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