

DYNAMICS OF THE LITHOSPHERE.*

O. C. JONES and GEORGE D. HUBBARD

Department of Geology, Oberlin College, Oberlin, Ohio

INTRODUCTION—

1. Definitions.
2. Thesis.

ASTRONOMICAL AND PHYSICAL DATA—

1. Precession.
2. Nutation.
3. Variation of Latitude.
4. Shape of Earth.
5. Plumb Line.
6. Pendulum.
7. Cavendish Method.
8. Chemical Balance.
9. Tides.
10. Support of Load.
11. Relative Density of Solid and Molten Rocks.
12. Behavior of Rocks under Pressure.

GEOLOGIC AND SEISMOGRAPHIC DATA—

1. Geological Climates.
2. "Original Crust."
3. Geographic Distribution of Igneous Intrusion.
4. Seismographic Records.

DATA OF ISOSTASY.

DATA OF DIASTROPHISM.

CENTROSPHERE.

CRUST—

1. Depth.
2. Density.
3. Adjustability.
4. Vulcanism.
5. Mountain-making.
6. Faulting.
7. Causes of Lack of Adjustment.
8. Earthquakes.
9. Continental Creep.
10. Some Immediate Causes of Adjustments.
11. Deltas.
12. Continental Masses and Ocean Basins.

CONCLUSIONS.

* Presented before the Geology Section of the Ohio Academy of Science April 15, 1922.

INTRODUCTION.

It is a characteristic of the human mind that the things least easily understood are the things most desirable to know; and this insatiate curiosity frequently devises means to unlock the hidden and to overcome the impossible. It has been in large measure this psychological impetus that has prompted studies dealing with the unattainable central structure of our globe, and with the slow, invisible adjustments and responses, to which terrestrial matter is subject.

By lithosphere is meant the solid or rock part of the earth, not water and air, but probably all the rest from center to circumference. In order to gain an accurate impression of the adjustments taking place in the earth's outer part and of its physical condition, it is necessary to consider the whole problem of the interior of the earth. All evidence relating to the physical condition of the interior of the earth or to the adjustments of the earth's substance will, therefore, be first drawn together without statement of its reference to the problem; then conclusions will be drawn from the facts. In this way the influence of theories which may or may not be true will be avoided to some extent.

Our thesis is that essentially all the problems of the dynamics of the lithosphere resolve themselves into the problem of adjustment of strains and stresses in the structures and materials of the earth, adjustment to the equilibrium form of the earth, through the force of gravity, involving diastrophism, vulcanism, and gradation.

THE ASTRONOMICAL AND PHYSICAL DATA.

Astronomy has furnished the geologist three lines of argument pertaining to the physical condition of the earth's substance: These are precession and nutation, variation of latitude, the shape of the earth.

Precession.—Because the axis of the earth describes a cone in its motions, tracing a circle about the pole of the ecliptic, the equator, which preserves about the same inclination to the ecliptic, moves so that its intersections with the ecliptic pass in a retrograde direction opposite to the earth. This motion is termed the precession of the equinoxes.¹ Precession

¹Encyclopaedia Britannica.

is caused by the fact that the attractions of the sun and moon are not a single force acting through the earth's center of gravity. Since the variation is due to the attraction of forces which are estimatable, methods of calculation are possible by which the mass of the earth may be revealed.

*Nutation*² is a vibratory motion of the earth's axis, producing a wavy circle of precession, due to the unequal attraction of the moon on the equatorial ring of the earth. This, too, affords another method or means of calculating the earth's mass.

*Variation of latitude*³⁻⁵ is caused by a shifting of the axis of rotation within the sphere so that its polar extremities wander in a circle of about fifteen (15) meters in diameter. By computation it should have a period of 305 days; but Chandler, from a great mass of data, discovered an actual period of 427 days.⁴ Such a retardation can be due only to a shifting of the equatorial bulge, by the lagging adjustment of which retardation of the period is effected. Now since adjustment in the rocks is slow and incomplete, a tide must be set up in response to the strains developed by the shifting of the axis, because water is very adaptable to external force. Dr. Bakheyzer and Mr. Christie have independently investigated this problem of tides and both conclude that there is a tidal variation with about a 430-day period.

*The shape of the earth*⁶⁻⁷ has been a subject of long and extensive study into which we do not need to enter. Suffice it to say that the shape has been determined to be very nearly an ellipsoid of revolution, showing that the earth's substance is sufficiently plastic to be nearly perfectly adjustable to rotational forces. The superficial exceptions will be discussed later.

Schweyder⁸ has recently determined the nutation period as 432.8 days.

The physical data throwing light on the condition and responsiveness of the earth's substance are varied and extensive.

²Encyclopoedia Britannica.

³Ibid.

⁴Darwin: Tides, Chap. xv.

⁵Chamberlain, Reed, Hayford Schlesinger, Smithsonian Rpt., 1916.

⁶Encyclopoedia Britannica.

⁷Poynting & Thompson: Text Book on Physics.

⁸Schweyder W. Naturwissenschaften, 1917, Potsdam, Germany, pt. 38.

Quoted from Jour. Geol. 1921, v. 29, p. 396.

*The plumb line*⁹⁻¹⁰ has been used near mountains to estimate the mass of the earth. The deflection from the vertical, due to the attraction of the mountain, is measured. The mass of the mountain is then calculated, and from these data the mass of the earth is calculated. By this method Maskelyne, in 1775, secured a mean density of 5. and James, in 1854, obtained 5.32.

*The pendulum*⁹⁻¹⁰ was first used by Bouguer. The number of swings of the pendulum at the surface are compared with the number on a mountain, and the comparative attraction worked out. Carlini, 1821, obtained a mean density of the earth of 4.84; Airy, 1854, obtained 6.57; Pechman, 1865, 6.13; Mendenhall, 1880, 5.77; Sterneck, 1883, 4.77, and in 1885, 6.77; Preston, 1892, 5.13.

The Cavendish method.—In this experiment two small balls are placed at opposite ends of a wire and their movement measured when attracted by a large ball of known mass. A comparison is then made between the attraction of the earth and the attraction of the ball. Cavendish, in 1798, found 5.45 to be the mean density of the earth; Bailey, 1843, secured 5.67; Reide, 1852, 5.58; Corne and Baille, 1878, 5.5; Wilsing, 1889, 5.56; Preston, Bays and Braun, in 1895 and 1896, all secured 5.53; in 1902, Burgess obtained 5.55.

The chemical balance has been successfully used by determining the attraction of a known mass placed above or below the scale, and comparing with mass of earth. By this method Poynting, 1891, secured a specific gravity of the earth of 5.49; and Richarz and Krigar Menzel in 1898 obtained 5.51.

Tides.—The evidence from tides is very simple yet very conclusive. If the earth is liquid with a crust or lacking in rigidity, then the entire crust will yield for a tide; but if it is rigid—as rigid as steel—there will be some rock tide, but the tidal force will be largely consumed in raising tides in the more responsive hydrosphere. Calculations on the height of tides by Darwin¹¹ and others shows that the tides are exactly what are to be expected on an earth of the rigidity of steel. Prof. Millikan has, however, measured tides in the rocks.

⁹New International Encyclopaedia.

¹⁰Osmond Fisher: Physics of Earth's Crust.

¹¹Darwin: Tides.

Support of load.—Physicists have pointed out that a liquid interior would not support continental masses rising 3,600 to 5,400¹² meters above the ocean floor. But probably this argument is of little value when isostatic measurements have shown them to be of lower specific gravity.

*Relative density of solidified and molten rocks*¹³ is such that a crust could not permanently form on a molten sphere in which convection currents are possible, since solidified rocks are denser than molten rocks.

Behavior of rocks under pressure.—It is a well-known law of physics that the melting point increases or rises with pressure¹⁴. Barus found the rise of the melting point of diabase to increase directly as the pressure. This would give a melting point of 76,000° C. at the center of the earth. Under such pressures as exist at the center of the earth, many physicists claim, it would be impossible to obtain molten rocks, because such an adjustment would be necessary as gave the least space, and it is certain that crystalline rocks occupy less space than molten rocks do. An increment of temperature increase amounting to about 1° C. for every 18 meters of descent has been found. Assuming the radius to be 6,268 km., this would give a temperature of 347,600° C. at the center, which is more than four times the melting point of diabase under the pressures assumed at the center. But it is unlikely that such a rate of increase can be supposed. Deeper borings seem to indicate a lessening rate, and a point may be attained, perhaps comparatively near the surface, where temperature ceases to rise. It is not our problem to account for the heat. It may be due to the mechanical work done, to radio-activity, to chemical action, or compression, or all together.

Another line of experiment giving some possible light on the condition of the interior of the earth is furnished by those investigations dealing with the crushing and flowage of rock. Van Hise¹⁵ states that more than 1,700 kilograms of pressure per square centimeter are necessary to crush granite.

Fisher¹⁶ has estimated 3,000,000 atmospheres of pressure at the earth's center.

¹²Chamberlin & Salisbury, Text II, 7.

¹³Fisher: Physics of Earth's Crust.

¹⁴Chamberlin and Salisbury: Textbook in Geology II, 7.

¹⁵Van Hise: Principles of Pre-Cambrian Geol., U. S. G. S., 16th Annual Report.

¹⁶Fisher: Physics of Earth's Crust.

Hayford¹⁷ and Bowie give the crushing strength of granite as about 1,425 kilograms per square centimeter, which place the zone of no cavities at about 8 kilometers. Van Hise, working on this problem, using the crushing point of rock as 1,700 kilograms per square centimeter, obtained a depth of 10,000–12,000 meters.

GEOLOGIC AND SEISMOGRAPHIC DATA.

Geologic Climates.—It was the problem of variability of geologic climate that caused the final overthrow of the Laplacian hypothesis. There have been in geologic history seven periods of climatic change.¹⁸ Four of these have been glacial periods: the first two, early and late proterozoic, are well down the geologic column, and indicate a cold climate early in geologic history not at all reconcilable with a cooling globe, which is implied by a molten interior. The other periods of climatic change are the Silurian, Permian, Triassic, Cretaceous, Eocene, and Pleistocene, of which the Permian and Pleistocene are glacial.

"Original Crust".—The great granite embossments of Scandinavia, Canada, and other countries, formerly believed to be the exposed surface of the original crust, have been shown to be but intrusions in older sedimentary rocks, or in some cases greatly altered sediments.¹⁹ The fact that there are now no known exposures of the original crust, certainly none that could have served as an original source of the sedimentary rocks—such a lack of original feeding grounds, certainly militated against the idea of an original crust at all.

It is obvious, too, that if our earth has been built up from planetesimals which have been gathered in upon a nucleus there will be no uniform gradation of material in any direction, nor any zoning into concentric layers so that any one layer will be essentially homogeneous as to density, melting point and composition. Presumably this heterogeneity is not as great as it was ages ago when the infall of planetesimals was more frequent and when the larger part of the accretionary accumulation was not so far remote.

¹⁷Hayford and Bowie: Spec. Rept., U. S. C. & G. S.

¹⁸Pirsson and Schuchert: Text Book of Geol.

¹⁹Chamberlin, T. C., 1916, Smithsonian Rpt.

This theory leaves no place for a "crust" conception as in the La Placian theory. But it does make place for enough variation in the composition and fusibility of earth materials even at the same depth that given a certain temperature in a zone only parts will become fluid. Fluid parts might tend to rise toward the surface. Parts remaining solid must then collapse leaving a solid zone. This would tend to produce a zonal arrangement of the earth materials. That such a gigantic banding is not perfected is shown by the persistence of volcanic intrusion and probably by diastrophism.

Geographic Distribution of Igneous Intrusion.—A third line of evidence is that afforded by the extent and distribution of igneous intrusion.¹⁷ Were a molten globe surrounded by a thin crust, strains and stresses within the sphere would be in large measure relieved by igneous extrusion. The extent of igneous extrusion does not seem in any way commensurate with the stresses that are found. The localization of its geographic extension to certain well-defined areas would hardly be expected of lavas extruded from a molten interior; and it is therefore unlikely that igneous phenomena have more than a local and perhaps rather shallow source.

Seismographic Records.—The invention of the seismograph, by which earth tremors are automatically recorded with the exact time of their occurrence, has contributed much to the solution of our problem. From every seismic focus there proceed three sets of waves: those that travel along the surface and those that pass through the earth, of which there are two kinds—compressional and distortional.²⁰ Those which pass through the interior increase in velocity with depth below the surface, and increase more rapidly than the density, showing that the earth is rigid, and that its rigidity increases toward the center. Waves have never been recorded along a diameter, but as far as they have passed into the earth's interior, geologists may be sure that the earth is solid, for transverse waves cannot exist in a liquid and they are always recorded with the longitudinal (compressional) waves.

These records have made it possible to get at the depth of the seismic focus. In the case of the Neapolitan earthquake $10\frac{1}{2}$ kilometers was the calculated depth.²¹ The mean depth

²⁰Interior of Earth: Oldham, Q. J., G. S. Lon., v. 62, 1906.

²¹Davidson: Earthquakes.

of the focus in the Ischian disturbance was about 500 meters., and of the Andalusian of 1884, $12\frac{1}{2}$ kilometers; the Charleston showed a depth of seven and one-third kilometers, and the Rivera 18 kilometers. The San Francisco earthquake showed a depth of disturbance of about 24 kilometers.

Many attempts have been made to measure the velocity of the waves at the surface, but with such varying results as to indicate inaccuracy of method or data, or perhaps to some degree to indicate varying density.

THE DATA OF ISOSTASY.²²

Isostasy is the theory that any given column of rock taken from the center of the earth to the surface will have the same mass as any other column of the same cross-sectional dimensions. But as density of rocks varies the height of the column will vary. The inequality of density, however, is found only in the part of the column near the surface, and the difference in the length of the column is due to difference of density in the upper 122 kilometers (77 miles) of the column. The adjustment of material toward this balance under the force of gravity is called "isostatic adjustment." Defective density resulting in a taller column and excessive density causing oceanic basins, that is, a shorter column, constitute "isostatic compensation."

The density of any given column is calculated from the vertical component of the forces operative on a swinging pendulum or the forces deflecting a plumb-bob. Corrections must be made for the effect of topography. The pendulum method has been found most satisfactory and is generally used.

The scheme followed by the U. S. Coast and Geodetic Survey is as follows: eighty-nine stations were selected in the United States, and sixteen over the rest of the world. At these stations pendulum apparatus is set up, and the vertical component of gravity worked out. In order to correct for topography the entire earth is divided into 317 compartments, and the effect of each compartment computed. These corrections are applied to obtain the actual value of gravity due to density below the station. Next the value of gravity at the station is computed, a mean surface density of 2.67 being

²²Special Rpt. No. 10, U. S. C. & G. S., pp. 6, 7, 108.

assumed. The computed density subtracted from the observed density gives an anomaly which is approximately 1 part error and 4 parts departure in density from the normal. When observed density is less than the computed density the anomaly is negative. The anomalies thus secured bear no relation to topography.

The following conclusions have been pointed out:

1. The anomalies bear no definite relation to loading and unloading.
2. The United States is in isostatic adjustment with a mean departure of 171 m. of rock with 2.67 density.
3. A relation to geologic formation exists by which the older formations have a positive anomaly.
4. Intrusive and effusive rocks give an anomaly very near to complete and perfect isostatic compensation.

DATA OF DIASTROPHISM.²³

It is hardly necessary to review here the evidence of actual crustal movement. One might, however, mention a few of the most important, such as mountain making, folding, faulting, tilting of lakes, elevated or depressed shorelines with their familiar accompanying physiographic features, actual measurement of movements, and submergence of oceanic islands. There was much change of level in and after the Pleistocene in the Great Lakes region, in Scotland, and in Scandinavia.²⁴

The most noticeable fact of diastrophism is that it is most intense in regions of thick sedimentation, that is, where geosynclines have been filled. The Appalachian geosyncline presents 12,000 meters of sediment; others have nearly as great thickness; 10,000 meters are found in the Laramide structure; 3,000 meters of Eocene rocks were deposited in the Rocky Mountain geosyncline. The Alps present 15,000 meters of sediment.

Experiments reveal an expansive coefficient of 1 cm. to 19.2 meters for every rise of 100° C. in average rock. In the case of the Appalachians, 800° at the bottom of the geosyncline would have given 1650 meters expansion. In Pennsylvania

²³The most satisfactory discussion of the facts and theories of this problem is found in Dana's Manual of Geology, fourth edition.

²⁴W. B. Wright: Quaternary Ice Age, 1914, pp. 406-426.

the actual shortening lies between 70 and 140 km., thoroughly beyond the power of increased temperature to create.

Intense normal faulting follows intense folding almost without exception.

Extensive faulting is usually apparently confined to regions of thick sedimentation. It is difficult, however, to detect faults in igneous rocks, also in some metamorphics. This may help to explain the apparent distribution of faults.

THE CENTROSPHERE.

The term "centrosphere" may be used to include that portion of the earth throughout which rocks are adjustable to stress through flowage, and in which cavities and fractures do not exist. It would thus be within the so-called "crust" or zone of fracture. The seismographic evidence shows two very important things in regard to this interior; first that it is solid, because it everywhere transmits transverse waves, which cannot pass through a liquid—this evidence is conclusive; secondly, that it is increasingly dense toward the center, attaining a specific gravity of 6 at .4 radius distance from the center—evidence calculated from the rate of wave transmission through the interior. At this rate of progression a density of 8.22 would be attained at the center, assuming the surface density to be 2.67. It is unlikely that this progression holds beyond this depth, because the mean density of 5.6 requires a central density of 11. Down to a depth of .6 radius the increased density is thought to be only that due to increased pressure; below this depth the earthquake researches of Oldham²⁷ may throw some light on the problem. He found that at a distance of approximately of 130 degrees from the point of origin, distortional waves were suddenly broken off to be continued beyond this distance approximately 11 minutes later. Just what inferences should be drawn from this, it is not possible to say, except that it is altogether likely that there exists a central core of about .4 radius extent from the center, required by other facts to have a density very high, probably between 8 and 11, and if dense to have a refraction of at least 2.

Some conclusions may be drawn as to rock flowage through the centrosphere. Granite has a crushing strength of 1,425

kgm. per cm.²⁵ while the pressure at the center of the earth is estimated at approximately 3,380,000 kgm. per sq. cm.²⁶ There can be no question but that rocks under these conditions will readily adjust to stress or strain. Yet Oldham²⁷ calculates that waves emerging at a point 90 degrees distant from their origin have passed through material having 12 times the resistance of granite and 15 times its rigidity. He adds: "Probably this is only what can be traced to increased pressure."

THE CRUST.

The term "crust" is used to describe that portion of the earth which lies above the level of compensation, and consequently includes all fractures, cavities, and most of the adjustment of the earth's solid substance. Crust and centrosphere constitute the lithosphere.

Depth.—Isostatic investigations have placed the compensation surface—by which is meant the surface at which compensation is complete—at 122 kilometers, which seems by results obtained to be near the truth; from other evidence the allowance seems ample. Van Hise, assuming the crushing strength of rocks to be 1,700 kilograms per square centimeter, surface density to be 2.7, and cavities to be supported by hydrostatic pressure, found that no cavities or crevasses would be possible at a depth of 10,000–12,000 meters. Fracture, however, might occur at this depth. Seismographic evidence would bear out this conclusion. Most seismic foci lie above 17 kilometers of depth. In the case of the Neapolitan earthquake, the deepest estimate fell near 39 kilometers, although the mean depth fell at 10½ kilometers. It is unlikely that this estimate is correct, because of the imperfect methods of calculation and the unknown density of the rocks through which the waves passed. Assuming it to be correct, it is still a very shallow phenomenon and well within the limits of 122 kilometers. Oldham²⁸ believes the more or less heterogeneous material may not be more than a score of miles thick.

²⁵Special Rpt. No. 10, U. S. C. & G. Survey, p. 111.

²⁶Fisher, O.: Physics of the Earth's Crust.

²⁷Oldham: Some Conclusions as to the Interior of the Earth. Q. J. Geol. Soc. Lond. (1906), V. 62, p. 456-75; Vol. 63, pp. 344-350.

²⁸Oldham, R. D., loc. cit.

Density.—Surface density by estimation of its known components cannot be far from 2.67. A gradual increase with pressure due to recalescence, and compression and inclusion of gases, due also to the closing of cavities, might be expected. This gradual increase is supported by seismic investigations.

This topic and many others have been elucidated by the recent papers of the Chamberlins in Jour. of Geol. Vol. 29–30.

Adjustability.—The most important result of our studies is the establishment of the fact that adjustment throughout the crust to external forces or to internal stresses is almost perfect. We have seen that the variation of latitude occurs because the equatorial bulge persists in shifting with the shift of axis. But back of this we have evidence of adjustment in the shape of the earth itself, which is very nearly the true form of an ellipsoid of revolution. That it varies at all from this form is evidence, equally good, perhaps better, of its plasticity. Its apparent inequalities are the result of its adjustment of heterogeneous density to the equilibrium of the ellipsoid of revolution. (See note.) We believe that the whole problem of volcanism, mountain-making, continent and ocean-basin formations, and all diastrophism are but phases of the problem of maintaining adjustment to this form of the earth. That this adjustment is nearly perfect, having an average departure of only 171 meters of rock of 2.67 specific gravity in the United States, has been proven beyond the stage of hypothesis. Even the maximum anomaly or lack of adjustment found in the United States corresponded to a stratum only 1,000 meters thick or a deficiency of pressure of 278 kilograms per square cm. or less than one-fifth the crushing strength of granite. This is an extreme and unusual anomaly. That this adjustment has been demonstrated in a broad way in regard to ocean basins and continental masses is beyond doubt.

The fact that there is essentially no relation to loading and unloading in the gravity anomalies would indicate rather rigid adjustment. The quick submergence of volcanic islands having a positive anomaly is also good evidence. There is no doubt that the area of deficient density through Nevada, part of Colorado, Arizona, and Southern California is in a stage of uplift.

NOTE—By equilibrium is meant an equilibrium of density, essentially what is implied in the term "isostasy."

*Volcanism.*²⁹—The evidence of geographic distribution, extent of extrusion, and differentiation of magmas indicates that volcanism is a local phenomenon. Seismic evidence clinches the argument.³⁰ Distortional waves will not pass through a liquid, yet they pass with perfect freedom through any part of the crust at which observations have been made. There cannot, therefore, be any considerable lava lakes beneath the earth's surface. Isostatic investigations throw an illuminating line of evidence on the problem. Igneous intrusions and extrusions of all rocks are almost perfectly compensated.³¹ It would seem then that volcanism is simply one method of quick adjustment to the equilibrium figure. It would be found in places of defective density where decreased pressure produces liquefaction in the form of a vesicle which rises to the surface, and in one way or another is ejected by force. Most of the vesicles stop before they reach the surface. Denser material is thereby added to, or replaces, lighter material bringing about isostatic compensation. The method would appear to be thoroughly delicate to reach isostatic adjustment so perfectly. One would expect the process once set off to continue this inertia beyond the point of perfect compensation. This is known to occur frequently in the case of volcanic islands that are thrown up with a positive anomaly, but which soon sink into a state of equilibrium.

Mountain Making.—This is another process resulting from the tendency of the crustal substance to maintain a state of equilibrium in reference to the figure of the earth through the force of gravity. The process is this: Marine sediments are laid down in a geosyncline, or along the edge of a continent. To maintain adjustment subsidence takes place until great depths of sediments are found. Isostatic adjustment is practically perfect throughout the process. The sediments thus laid down have, of course, a lesser density than the sediments or rocks on either side. There is, therefore, an imperfect horizontal adjustment to the bottom of the geosyncline. Now, as the sediments are forced downward temperature rises. Probably 800 degrees is attained at the bottom of the geosyncline, and since it contains rocks with more or less water inclusion, the steam developed, or at least the heated water when pressure is too great

²⁹Iddings: Problem of Volcanism.

³⁰Smithsonian Rpt. (1916), The Earth's Figure, etc.

³¹Special Rpt. No. 10, U. S. C. & G. Survey.

for steam, weakens the rocks, and the expansion caused by increased temperature, amounting to 1 cm. to every 19.2 meters for every 100 degrees C. rise of temperature, causes a slight disturbance which is carried on by the pressure from the sides; erosion and deepening of the geosyncline tend to maintain isostatic adjustment throughout the process. Now inertia may carry the process beyond isostatic adjustment; certainly the rock thus thrown up cools to some extent. Both things may occur; at least there is always a period of normal faulting³² succeeding a period of folding which might be caused by these factors. The mountain making process may be aided by lateral pressure developed by crustal expansion due to rising temperature of the crust. This, however, is mere supposition, and perhaps unsupported by geologic evidence.

Faulting is another process through which equilibrium is maintained. It differs from mountain making largely in that rock flowage and bending are predominant there; whereas faulting is the result of adjustment with fracture of the rocks rather than flow. It is not usually associated with the deeper synclines, although it is confined probably to regions of rather deep sedimentations.

Causes of lack of adjustment may be external, such as the tidal influence of the sun or moon, the shifting of the rotational axis, pressure of the atmosphere, increased load due to formation of glaciers, or the accompanying emptying of the seas, great evaporation or excessive precipitation; but probably the great cause of lack of adjustment is the shift of load due to erosion.

Earthquakes, so far as is known, present no opposition to our thesis that all the dynamics of the crust are the result of processes of adjustment of heterogeneous density to the form of the earth through the forces of gravity. The fact that calculations of depth of focus invariably indicate not a point but a plane lying more or less vertical to the surface, and that many earthquakes actually accompany slipping along a fault plane, would indicate that the phenomena of tectonic earthquakes are invariably of this character. The fact that many earthquakes show merely lateral stresses without elevation or depression in no way militates against our general thesis. Lateral stresses

³²T. M. Reade: Evolution of Earth Structure, p. 137-8.

would be set up in surrounding rocks by elevation or depression at a distance without local diastrophism. The amount of accumulated stress resulting in sudden adjustment by fracture and displacement will depend upon (1) the intensity of the lateral stresses, and (2) the plasticity of the rocks by which strain and stress can be adjusted without fracture.

Continental Creep has not entered into our studies. It is not, however, too much to suppose, since we know the rocks to be highly plastic, that the difference of pressure on the land side and water side of the continental slope will result in creep toward the ocean; the same sort of phenomena that give rise to mountains. Yet if this is true, the whole process maintains isostatic adjustment throughout, for anomalies of gravity nowhere indicate a general excess of gravity along the continental platform, which lack of adjustment would require.

Some Immediate Causes of Adjustments.—While much of the evidence presented in this section on "The Crust" indicates rather rapid adjustment to anomalies, it is true that there would be no anomalies if the adjustment did not lag more or less behind the causes which produce maladjustments. This is only another way of saying that stresses and strains are cumulative, that they may be held by the structures for some time, but that ultimately the earth structure has failed to hold them, as shown by Leith.³³ If the strains are held a longer time and become great, their release causes large and widespread adjustments. If the stresses are frequently released, only smaller and often local adjustments are necessary. When the balance of stress and structural strength is almost struck, but little is necessary to start adjustments. Tides, distant earthquakes, or even changes in atmospheric pressure are believed to be competent to start potential movements.

Deltas furnish a good line of evidence of almost continuous adjustment, for if adjustment did not take place rather rapidly, deltas and other areas of loading would indicate a positive anomaly. A positive anomaly is found at the mouth of the Hudson and through the Chesapeake Bay region. But we know that these areas are in a stage of subsidence, so that adjustment, if not complete, is taking place. On the other hand the delta of the Mississippi shows negative anomaly, due perhaps to the

³³C. K. Leith, *Structural Failure of the Lithosphere*, Science, 1921, pp. 195 ff.

tending of physical movements to carry beyond adjustment through inertia.

Continental masses and ocean basins have been demonstrated through isostatic measurements to be in isostatic compensation. This means that the continents and basins must be due to differential density, and that in this large configuration the shape of the crust is still in accordance with our thesis. Earthquake studies have thrown light on this problem also.³⁴

CONCLUSION.

We have seen that the phenomena of mountain-making, volcanism, faulting, and earthquakes, together with density differentiations, are due to the processes of adjustment, through gravity of varying mass, to the equilibrium figure of the earth, and that continental creep and sedimentary loading, especially in deltas, though not due to this cause, yet are kept in isostatic adjustment. Our conclusion is therefore as follows: the dynamics of the lithosphere are essentially the processes of adjustment of strains and stresses in the varied structures and materials of the earth, adjustments to the equilibrium form of the earth, through the force of gravity, involving diastrophism, volcanism, and gradation.

³⁴Oldham, R. D., Q. J. G. S. London, Vol. 63, 1907, pp. 344-350.