SCIENCE

FRIDAY, MAY 15, 1914

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ISOSTASY AND THE SIZE AND SHAPE OF THE EARTH[1]

IT is the speaker's desire, in this paper, to touch briefly on some phases of geodesy which should be of general interest to the physicist.

Geodesy is one of the oldest sciences; probably second in this respect to astronomy alone. What is the extent of the earth in the horizontal plane, to what depth does it extend, and what is on the other side are questions which must have been asked by men of the earliest times. The history of geodesy will have to be passed over, for lack of time, although it would be interesting to follow the accumulation of data as to the shape and size of the earth.

Before one can study efficiently the great geophysical facts and comprehend them, he must know the shape and size of the earth with considerable accuracy. For some time before the end of the seventeenth century, it was taken for granted that the earth was a true sphere.

The announcement by Newton in 1687 of his theory that the earth was an oblate spheroid added much interest to the subject of its exact shape.

A meridional arc of about 8½ degrees, extending north and south of Paris, was measured by J. and D. Cassini between the years 1683 and 1716. The results of the first computations of this arc indicated that the length of the degree was less at the northern than at the southern end. This gave to the earth the shape of a prolate spheroid. A great controversy arose over

[1] Read on December 30, 1913, before Section B of the American Association for the Advancement of Science, at Atlanta, Ga.

the question as to whether the earth has the form of an oblate or prolate spheroid, and to settle it the French Academy sent expeditions to Peru in 1735 and to Lapland the following year to measure arcs near the equator and within the arctic circle. The result of these measurements confirmed the theory of the oblate spheroid. A revision of the computations of the Paris arc also showed that the northern degrees were the longer, thus confirming the results obtained from the work done in Peru and Lapland.

The first near approach to the size of the earth resulted from triangulation done in the last decades of the eighteenth century to connect the observatories of Paris and Greenwich and to determine the length of the earth's meridian quadrant. For the latter purpose an arc of the meridian of nearly ten degrees was measured in France. One ten-millionth of the resulting length was adopted as the standard of length (the meter). Any other length could have been selected as the standard, for the meter bears no such exact relation to a quadrant as later and more accurate data show.

Geodesists were very active during the nineteenth century and will be for some time to come, in making geodetic measurements to determine the mean figure of the earth with greater and greater degrees of accuracy. There comes a time, for any one given area, when it is useless to add more geodetic data for the purpose of obtaining a more exact mean figure, for there are constant or systematic errors present in the data, the effect of which is probably much greater than that of the accidental errors.

But there is much to be gained by extending geodetic surveys to new areas and especially to new continents. (By geodetic survey is meant, here, triangulation and connected astronomic stations.) All of the values of the earth's figure now available are the results of geodetic measurements in the northern hemisphere and, with the exception of India, the measurements have been confined to Europe and the United States. We may hope to get, before long, values for the figure of the earth from geodetic operations in South America and Africa, most of whose areas are below the equator, and Australia, all of which is in the southern hemisphere. It is believed that the mean figures resulting from accurate and extensive geodetic data in those continents will agree closely with the figures gotten from continents in the northern hemisphere. The geodetic surveys of the several nations on each continent should be connected and the reductions made on one spheroid and referred to a single initial position for each continent. Should this be done we shall be able eventually to compute a mean figure of the earth which will be of such great precision that it will satisfy the most exacting demands of science. The same spheroid and datum have already been adopted by Mexico, Canada and the United States.[2]

Coincident with the extension of geodetic surveys there will be carried on the computation of the geoid or the actual surface of the earth. This surface is probably so complex in shape that the work necessary to define it will have to be continued long after the satisfactory spheroid has been determined.

The geoid may be defined as that surface which coincides with the surface of the sea at rest. We can imagine an extension into the continents of an intricate network of sea-level canals. Then the surface of the oceans and the water in the canals would define the surface of the geoid. At some

[2] See news note in *Bulletin of the American Geographical Society,* August, 1913, page 614, on "The Adoption of the North American Datum."

points, probably not exactly at the sea shore, the mean figure of the earth—the spheroid—would intersect the actual sea surface, the geoid. Under the coastal plains the geoid would be slightly above the spheroid; while under great mountain ranges the geoid would be far above the spheroid, possibly as much as one hundred meters. Over the oceans the geoid would be under the spheroid surface by amounts varying directly with the depths of the water.

There is only one way to determine accurately the size of the earth, and that is by measurement on the continents of the lengths of arcs connecting points where the astronomic latitude and longitude have been determined. The measurements of such arcs may be direct, or they may be by means of triangulation. The earliest measurements were by the former method, but with the introduction of accurately graduated circles and the application of wires in the eye-pieces of telescopes, the indirect method came into general use.

At frequent intervals, in triangulation, the sides of some of the triangles in the scheme are accurately measured, in order to control the lengths. At the present time, this is done almost exclusively with nickel-steel (invar) tapes or wires. The probable accidental error of a measured length is seldom greater than about one part in one million. The constant error in such a measurement may be as great as one part in three hundred thousand. This accuracy is, however, far greater than that of the lengths of the triangle sides, as computed through the chain of triangles. The uncertainty of any one line between bases is about one part in one hundred thousand, on an average. A long arc, say one across a continent, can be measured with greater accuracy than that, for even the systematic and constant errors of the various sections of the arc would probably act as accidental errors, and the greater portion of their effect would be eliminated.

The observations for latitude, longitude and azimuth, or direction, are made on the stars; and in the most refined work a correction is made for the variation of the pole.

One might think that the determination of the figure and size of the earth is a very simple process, consisting merely of obtaining by astronomic observations the accurate angular distances between each two of several points on a meridian, and then measuring accurately the linear distances between them. Three such points being sufficient to obtain the equation of the curve formed by the intersection of the meridional plane and the spheroid, the shape and size of the earth would be known. This would be true if the spheroid and the geoid coincided throughout, but, as stated above, they do not do so. The plumb line to which all astronomic observations are referred is, at each point, normal to the geoid, which is a very irregular surface and, therefore, very many astronomic stations must be established and used. The greater part of each of the differences between the astronomic positions, as actually observed, and the theoretical positions, based on an adopted smooth mean surface, must be treated as an accidental error. These differences reach a maximum value of about twenty-five seconds of arc (within the area of the United States) which is nearly one half mile. In the island of Porto Rico, the relative deflection between two astronomic stations, one at Ponce and the other at San Juan, was 56 seconds of arc, about one mile.

The shape, but not the size, of the earth may be determined from the observed value of gravity at stations widely distributed in latitude. But here again a few stations are not sufficient, for the value of gravity does not follow any known definite law, owing to the disturbing influences of masses above sea level and the deficiency of mass in the oceans.

Helmert derived a formula in 1901 from the observed values of gravity at about 400 selected stations. This formula gives theoretical values which will agree well, on an average, with the observed values, but for any one station the difference may be large, even after one of the values has been corrected for the elevation of the station above sea level.

Helmert's formula, in the Potsdam system, is

$$\gamma_0 = 978.030\ (1 + 0.005302 \sin^2\phi - 0.000007 \sin^2 2\phi)$$

in which γ_0, expressed in dynes, is the theoretical value at sea level in latitude ϕ.

It is evident that the difference between the theoretical and the observed values of gravity, and the deflections of the plumb line (which, as stated above, are the differences between the observed and the theoretical astronomic positions) are due to the disturbing influence of the topography and the effect of deviations from the normal densities in the earth's crust. The term "topography" is applied to the visible land masses and the deficiency of mass in the oceans. But when the attractions of the topography are applied as corrections, the differences may still be large, but of the opposite sign.

About sixty years ago Archdeacon Pratt of England arrived at the conclusion, from a study of the deflections in India, that there must be a deficiency of mass under the Himalayan Mountains and that the deficiency extended to a limited depth. The advancement of this theory marked an epoch in geodesy. From time to time, writers in different countries have elaborated on the mere statement of Pratt. But it was Hayford who gave this theory a quantitative expression when, as a member of the United States Coast and Geodetic Survey, he corrected the astronomic latitudes, longitudes and azimuths in the United States for the effect of topography and its negative equivalent, called "isostatic compensation," when making two determinations of the figure of the earth.[3]

A preliminary report on the application of the theory of isostasy to the study of the deflections in the United States was made by Messrs. Tittmann and Hayford to the Fifteenth General Conference of the International Geodetic Association, held at Budapest, Austria-Hungary, in 1906.[4]

Isostasy was also considered by Hayford and the writer in reducing the gravity stations in the United States.[5]

In order that a clear idea of isostasy[6] may be obtained, I shall quote Hayford:

> If the earth were composed of homogeneous material, its figure of equilibrium, under the influence of gravitation and its own rotation, would be an ellipsoid of revolution.
>
> The earth is composed of heterogeneous material which varies considerably in density. If this heterogeneous material were so arranged that its density at any point depended simply on the depth of that point below the surface, or, more accurately, if all the material lying at each equipotential surface (rotation considered) were of one density, a state of equilibrium would exist and there

[3] "The Figure of the Earth and Isostasy from Measurements in the United States," by John F. Hayford, U. S. Coast and Geodetic Survey, 1909; "Supplementary Investigation in 1909 of the Figure of the Earth and Isostasy," by John F. Hayford, U. S. Coast and Geodetic Survey, 1910.

[4] "Geodetic Operations in the United States, 1903–06."

[5] "The Effect of Topography and Isostatic Compensation Upon the Intensity of Gravity," Spec. Pub. No. 10, U. S. Coast and Geodetic Survey, 1912, by John F. Hayford and William Bowie; same, second paper, by Wm. Bowie, 1912.

[6] The term *isostasy* was first proposed by E. C. Dutton. See *Transactions of the Philosophical Society of Washington, D. C.*, Vol. XI., pp. 51–64.

would be no tendency toward a rearrangement of masses.

If the heterogeneous material composing the earth were not arranged in this manner at the outset, the stresses produced by gravity would tend to bring about such an arrangement; but as the material is not a perfect fluid, as it possesses considerable viscosity, at least near the surface, the rearrangement will be imperfect. In the partial rearrangement some stresses will still remain, different portions of the same horizontal stratum may have somewhat different densities, and the actual surface of the earth will be a slight departure from the ellipsoid of revolution in the sense that above each region of deficient density there will be a bulge or bump on the ellipsoid, and above each region of excessive density there will be a hollow, relatively speaking. The bumps on this supposed earth will be the mountains, the plateaus, the continents; and the hollows will be the oceans. The excess of material represented by that portion of the continent which is above sea-level will be compensated for by a defect of density in the underlying material. The continents will be floated, so to speak, because they are composed of relatively light material; and, similarly, the floor of the ocean will, on this supposed earth, be depressed because it is composed of unusually dense material. This particular condition of approximate equilibrium has been given the name *isostasy.*

The adjustment of the material toward this condition, which is produced in nature by the stresses due to gravity, may be called the *isostatic adjustment.*

The compensation of the excess of matter at the surface (continents) by the defect of density below, and of surface defect of matter (oceans) by excess of density below, may be called the *isostatic compensation.*

Let the depth within which the isostatic compensation is complete be called the *depth of compensation.* At and below this depth the condition as to stress of any element of mass is isostatic; that is, any element of mass is subject to equal pressures from all directions as if it were a portion of a perfect fluid. Above this depth, on the other hand, each element of mass is subject in general to different pressures in different directions—to stresses which tend to distort and to move it.

In terms of masses, densities and volumes, the conditions above the depth of compensation may be expressed as follows: The mass in any prismatic column which has for its base a unit area of the horizontal surface which lies at the depth of compensation, for its edges vertical lines (lines of gravity) and for its upper limit the actual irregular surface of the earth (or the sea surface if the area in question is beneath the ocean) is the same as the mass in any other similar prismatic column having any other unit area of the same surface for its base. To make the illustration concrete, if the depth of compensation is 114 kilometers below sea level, any column extending down below sea level and having one square kilometer for its base has the same mass as any other such column. One such column, located under a mountainous region, may be three kilometers longer than another located under the sea coast. On the other hand, the solid portions of such a column under one of the deep parts of the ocean may be 5 kilometers shorter than the column at the coast. Yet, if isostatic compensation is complete at the depth of 114 kilometers, all three of these columns have the same mass. The water above the suboceanic column is understood to be included in this mass. The masses being equal and the lengths of the columns different, it follows that the mean density of the column beneath the mountainous region is three parts in 114 less than the mean density of the column under the sea coast. So, also, the mean density of the solid portion of the suboceanic column must be greater than the mean density of the seacoast column, the excess being somewhat less than five parts in 114 on account of the sea water being virtually a part of the column.

This relation of the masses in various columns, and consequently of the densities, follows from the requirement of the definition of the expression "depth of compensation," that, at that depth, each element of mass is subject to equal pressure from all directions. In order that this may be true the vertical pressures, due to gravity, on the various units of area at that depth must be the same.

If this condition of equal pressure, that is of equal superimposed masses, is fully satisfied at a given depth the compensation is said to be complete at that depth. If there is a variation from equality of superimposed masses the differences may be taken as a measure of the degree of incompleteness of the compensation.

The investigations of the deflections and of gravity referred to seem to prove rather conclusively that in the United States a condition of isostasy exists. How perfect it may be, and what is the area of the crosssection and the depth of the unit columns which are supposed to have equal masses, have not yet been accurately determined.

The depth of compensation is probably somewhere between one hundred and ten and one hundred and thirty kilometers.

It is reasonably certain that the compensation is not always complete nor always uniformly distributed to the depth of compensation. (The above statements are, of course, intended to apply only to the area of the United States. Later on a brief statement will be made in regard to the rather limited results obtained in the other countries.) But the average conditions in the United States indicate a close approximation to those postulated.

The application of isostasy reduced considerably the apparent anomalies, or deflections, in the United States and Hayford was able to compute a figure of the earth which is generally considered one of the best, and probably the very best, now existing. His dimensions[7] are:

Equatorial radius, 6,378,388 $\pm$ 18 meters.
Polar semi-diameter, 6,356,909 meters.
Reciprocal of flattening, 297.0 $\pm$ 0.5.

The application of isostasy to the reduction of the gravity observations has reduced the average anomaly in the United States to 0.018 dyne, and at only one station is the anomaly greater than 0.060 dyne. It is, therefore, now possible to compute a value for gravity at any point in this country with an uncertainty of 0.018 dyne. By either of the previous two generally used methods of reduction, in which isostasy was not employed, the average anomaly in the United States was much greater.[8] The largest free air anomaly was 0.216 dyne and there were five other anomalies with values greater than 0.100 dyne. There were five Bouguer anomalies greater than 0.200 dyne and twenty-eight other anomalies greater than 0.100 dyne. It was found from the anomalies developed by the investigations of deflections and of gravity that there was no apparent relation between the topography and the size and sign of the anomalies nor between the anomalies and the areas of erosion or deposition. Some relations to the geological formation were developed.[9]

A severe test of the new method of reduction of gravity observations, with isostasy considered, was the determination of the flattening of the earth, from the stations in the United States alone. The resulting value is 1/298.4. This value agrees almost exactly with Helmert's value of 1/298.3 which resulted from a consideration of gravity stations widely scattered over the earth and with a great range in latitude. The anomalies by each of the older methods of reduction, in which isostasy is ignored, gave values which differed greatly from the generally accepted best values.

A brief statement of the method of making the gravity observations and of the accuracy attained will suffice. All of the stations in the United States used in the recent investigations had gravity determined by means of the quarter-meter invariable pendulum[10] which makes an oscillation in approximately one half second. It is a modification of the pendulums devised by

[7] See p. 54, "Supplemental Investigation in 1909 of the Figure of the Earth and Isostasy."

[8] The average free air anomaly was 0.028 dyne and the average value of the Bouguer anomaly was 0.063 dyne.

[9] See pp. 18–21 of "Effect of Topography and Isostatic Compensation upon the Intensity of Gravity" (second paper).

[10] This pendulum and its case are described in App. 1, Report of the Superintendent of the Coast and Geodetic Survey for 1894, by G. R. Putnam. The method of obtaining the flexure of the case and the support is described in App. 6 of the Report for 1910, by W. H. Burger.

von Sterneck of Austria and first used by him about the year 1887.

The method employed is to determine the period of oscillation at a base station and then at the new station and from the relation between the two periods the difference in gravity between the two stations is determined. This is called the differential or relative method of determining gravity. The difference in gravity may be obtained with an accuracy represented by a possible error of about ± 0.0018 dyne, on an average.

The base station for the United States is at the office of the Coast and Geodetic Survey in Washington, D. C. The value for it was determined by the relative method, from the station at Potsdam, Germany, at which the absolute gravity had been determined from a long series of observations made with reversible pendulums.

It is difficult to determine the absolute gravity with a great precision, as is shown by the determination of the difference in gravity at Vienna and Potsdam, by the relative method. Each of these stations had its absolute value determined by many years of observations and each value was considered to be correct by an amount represented by a probable error of only a few thousandths of a dyne. The relative determination showed an error between them of 0.016 dyne.

Of course, the same constant error which may be present in the base station of a system will also be present at each station of that system determined by the relative method. Potsdam is now generally used as the base station for the world, although the values are also occasionally referred to the Vienna station. The values in the two systems will differ by 0.016 dyne.

A comparatively small error in the value of gravity at the base station of the system does not appreciably affect the flattening of the earth, derived from the gravity data of the system.

The investigations made in the Coast and Geodetic Survey show that, on an average, the gravity anomalies and the unaccounted for residuals of the deflections of the vertical are small for the United States. They also show that the area of the United States as a whole is practically in a state of perfect isostatic equilibrium. But there are many places where the gravity anomalies and the deflections indicate departures from the state of equilibrium. It is very important that additional data may be gotten which will permit of a determination of the degree of deviation from the perfect state and of the horizontal extent of the affected regions.

In one of the illustrations[11] of the second report on the gravity investigations, which shows by contours the Hayford anomalies, the evidence would lead one to believe that the causes of the largest anomalies are confined to small areas. For instance, there is an anomaly at Washington of $+0.037$ dyne, while at Baltimore, only 40 miles distant, the anomaly is -0.011 dyne. At Seattle, the anomaly is -0.093 dyne, while at Olympia it is $+0.033$ dyne, and the distance between the two places is only about 50 miles. There are other cases of decided differences in the anomalies in short distances, and no doubt more will develop when additional gravity stations have been established.

The data shown in the illustration referred to lead to the conclusion that there is no extensive area in the United States which is very much under or over compensated. This is equivalent to saying that

[11] No. 2 of the "Effect of Topography and Isostatic Compensation upon the Intensity of Gravity" (second paper).

there is no large area which departs much from the perfect isostatic state.

It has been held by some[12] that the crust of the earth within the area of the United States is at all places in a state of perfect isostasy and that the gravity anomalies are caused by the investigators' erroneous distribution of the compensating deficiency of mass. This, no doubt, is true to a certain extent, but no rational distribution will account for the larger anomalies except upon the theory that there are local actual departures from the perfect isostatic state.

Earlier in this paper it was stated that there were developed some relations between the size and sign of the gravity anomalies and the geological formation. The stations established on the oldest rocks show an average anomaly of + 0.024 dyne, that is they indicate too much mass in the earth's crust, while the most recent formations and the effusive and intrusive rocks give average negative anomalies which vary from —0.005 to —0.015 dyne. These show deficiencies of mass. It is not clear whether these anomalies are due to local deviations from the adopted mean surface density of the earth (2.67) or to actual departures from a state of complete isostasy.

The following table shows a summary of the gravity anomalies arranged in the several geological groups.

A stratum of material 100 feet in thickness, and of indefinite extent will cause an attraction of 0.0030 dyne. Therefore, the average anomaly 0.019 dyne would correspond to a stratum 630 feet in thickness. The average elevation of the United States is about 2,500 feet. Therefore, the isostatic compensation may be considered

12 "Interpretation of Anomalies of Gravity," by Grove Karl Gilbert, Part C of Professional Paper 85, Contributions to General Geology, 1913, U. S. Geological Survey.

Geologic Formation	Number of Stations			Mean Anomaly	
	All	With plus Anomalies	With Minus Anomalies	With Regard to Sign	Without Regard to Sign
Archeozoic and Paleozoic	9	9	0	+0.024	0.024
Paleozoic	32	13	19	— .004	.019
Mesozoic	20	9	11	+ .001	.015
Cenozoic	33	15	17	— .007	.021
Effusive	8	2	6	— .005	.016
Intrusive	5	1	4	— .016	.018
Unclassified	16	10	6	+ .008	.020
All stations	123	59	63	— .001	.019

to be about 75 per cent. complete on an average for stations in this country. But the average gravity anomaly with regard to sign is 0.000 dyne, or nearly so, therefore it is safe to conclude that the area of the United States as a whole is in a state of perfect isostasy.

A more exact knowledge of the precise location with respect to depth of the compensating deficiency or excess of mass would be of very great interest and value. This is particularly true in the case of the areas where there are stations with large gravity anomalies. A preliminary study by the Survey will be made of this question in the near future. For this purpose the value of gravity and the deflections of the vertical in the vicinity of the anomalous areas will be used jointly. The preliminary studies may show whether much is to be expected from future investigations after much more gravity and deflection data are available.

An attempt will be made shortly to correct the deflections for the effect of the excesses and deficiencies of mass as shown by the gravity anomalies. It is possible that some of the unaccounted for portion of the deflections may be eliminated. The ideal condition would be to have only such residuals of the deflections as are caused by an error in the adopted figure of the earth, for then a new figure might be computed which would have far greater accuracy than any now existing.

The theory of isostasy has been applied in several other countries in the reduction of deflections and of gravity, but not to any great extent. In Switzerland the new method makes the observed and computed gravity agree more closely than do other methods which do not consider isostasy. In India the theory of isostasy has been applied and the preliminary results indicate that that country is not so completely compensated as is the United States.[13] The complete reductions have not been made. Their results will be of world-wide interest and importance.

The reduction, by the new method, of all the gravity stations of the world should be made in order that additional data may be available for studying the distribution of the materials in the earth's crust in different parts of the world, and because the results would make it possible to compute a better shape of the earth. There is no necessity for delaying this reduction. Mr. Tittmann, the superintendent of the Coast and Geodetic Survey, in his report to the conference, at Hamburg, in 1912, of the International Geodetic Association, stated:

> It is hoped that the International Geodetic Association in the near future may reduce all the available gravity stations of the world by this method, for it is reasonably certain that a value for the flattening of very great precision could be deduced from the results.

While each of the great nations and many of the smaller ones are making gravimetric surveys, yet there are many sections of the globe which have very few or no gravity stations. Some great institutions may, in the not distant future, see the importance of a world-wide gravimetric survey and start out parties to make one.

The geodesist is in great need to-day of an apparatus for measuring gravity accurately on a vessel at sea. We have no accurate values over the vast ocean areas. Dr. Hecker's gravity determinations at sea, with the boiling point thermometer apparatus, are subject to uncertainties as large as the largest new method anomalies of gravity in the United States, that is, between 0.050 dyne and 0.100 dyne. Gravity at sea should have actual errors not greater than about 0.010 dyne.

Some of the geological questions may or may not be answered by a consideration of isostasy,[14] but with isostasy an established fact, at least for large areas, the problems should not be as difficult as when various theories were held as to the degree of rigidity of the earth's crust.

One of the problems is as to the manner in which the earth's surface assumed an irregular shape. This is probably the most difficult one to answer. Of the theories proposed by a number of great men of science, none seems to be entirely satisfying. The theory of the unequal contraction of the outer layers of the earth during the change from the liquid to the solid state sounds reasonable until we consider that the thickness of the crust which could be affected is only about 70 miles, according to the theory of isostasy. There are extensive areas on land which average several miles in height. Also the great deeps in the oceans for considerable areas have average depths as great as four miles.

[13] In a letter from Col. Burrard, published in *Nature*, May 8, 1913, he makes the statement: "Both the pendulum and plumb-line observers find the attraction of the Himalayas to be largely compensated, whilst the Windhyan Mountains are not compensated at all." It should be noted that the Himalayan range is about 4 miles in height, and the Windhyan range only 0.6 mile in height.

[14] See "The Relations of Isostasy to Geodesy, Geophysics and Geology," by J. F. Hayford, SCIENCE, N. S., Vol. XXXIII., No. 841, pages 199–208, February 10, 1911.

It is impossible that the same materials could have densities differing by six parts in seventy, or nine per cent., due simply to unequal contraction from loss of heat. It is conceivable that the chemical elements of the earth's crust were the same everywhere before solidification, but they must have formed different chemical compounds in order to have had such different densities as must obtain in order to have the earth's crust in a state of equilibrium. The materials in the crust below the depth of 70 miles are assumed in the investigations to be in hydrostatic equilibrium and consequently they should have the same density in any layer at a given depth.

A theory, held by some, would make the depth of compensation a function of the elevation of the surface. The mountains would, according to this theory, have long roots of low density extending far down into the plastic materials, which are supposed to be below the seventy-mile depth. The investigations of the Coast and Geodetic Survey do not seem to substantiate this theory. If it were true we should have all of the crust under the continent of the same density down to a certain, unknown depth at which the plastic substrata began. The compensation would take place below that depth and it would consist in protuberances extending down into the plastic matter. The interior of the earth must be solid, but yielding to long-continued stress differences. Just how the depression of the sea bottoms is to be accounted for under this theory, the writer does not recall having heard. The crust there would probably have to be very thin.

A short article by Dr. P. G. Nutting,[15] suggested to the writer a possible cause of part of the elevation of the continents and the depression of the ocean beds. Let us assume that the surface of the earth, formerly at a high temperature, had cooled to a point below that of boiling water and that the surface was not level. Then the aqueous vapor would condense and fall in great quantities as rain and remain on the earth and flow to the lowest areas. This added mass would tend to produce an isostatic adjustment which would cause an undertow of material from the lower areas to the more elevated ones, with a resulting further depression of the low areas and elevation of the higher ones. How much effect this could have had is difficult or impossible to estimate. Of course, if there had been no irregularities in the earth's surface before the precipitation, the water would have covered the earth to a uniform depth.

The correct answer to another question would be of great value to several branches of science. The earth's crust, at least that part of it within the United States, may now be considered in a state of perfect isostatic equilibrium. But what was its condition in past geologic ages? It seems reasonable to suppose that the earth's crust was in the past in a state of isostatic equilibrium at least as perfect as at present, if it is assumed that the earth's crust is gradually getting cooler. With a high temperature the materials of the crust would have been more plastic than at present and should have yielded more readily to stress differences.

If we have now and always have had a condition of equilibrium in the earth's crust, can the recorded movements be explained on the isostatic theory?

The deflections and the pendulum observations show that the areas from which great masses of materials have been eroded are in equilibrium; also that areas within

[15] "Isostasy, Oceanic Precipitation and the Formation of Mountain Systems," SCIENCE, October 6, 1911.

which there have been great depositions are in isostatic equilibrium. We, therefore, must conclude that the mountains have been maintained for long ages at approximately the same elevation by an undertow of material toward them, while the areas of deposition maintain their depth in spite of the added material by a sinking due to the undertow from the crust under such areas. Consequently, the continent may be considered as not being leveled off as a result of erosion, but as kept at approximately the same general elevation.

While an isostatic adjustment by means of a transposition of material may account for the normal condition under the areas of erosion and deposition, it does not account for the great elevation, into mountains and plateaus, of rock which was once under the ocean. Evidently there must have been a change in the density, under such areas, and an expansion of the materials in the earth's crust to the extent indicated by the height of the topography above the sea. This change was not due to a mere expansion from change of temperature, as a bar would expand. The expansion of the crust must have been due to chemical or physical changes which made the elements present form compounds with densities differing from what they had been previously. What could cause such rearrangement as to change the density by several parts in one hundred is a problem for the geophysicist and geologist.

The fact that material which was once under the sea now forms a mountain range seems to disprove the "root of the mountain" theory of compensation. It is difficult or impossible to see how the crust with its surface at or below sea level (supposedly in isostatic equilibrium) could, in addition to expanding to form the mountains, also decrease its density in that portion far below the average depth of compensation (122 kilometers). As a matter of fact, the deflections and the gravity observations indicate that the compensation is not deep down in the crust, but in general within the depth stated above.

The movements noted in the exposed earth's materials have been slow and were in most cases due to stress differences which were below the rupturing point of the rock. There has been much slow yielding, without fracture, to long-continued stress differences. The isostatic adjustment of the earth's materials in the upper crust after or during erosion might cause many of the movements that have been recorded in the strata.

In conclusion, the immediate work which the geodesists should perform is to reduce all the existing gravity stations of the world by the same method which should be based on a rational theory of isostasy. As opportunity permits, a gravimetric survey should be extended to new regions and especially to oceanic islands. And as soon as an apparatus is designed which may be used successfully on a vessel, an extensive gravimetric survey of the oceans should follow.

WILLIAM BOWIE
U. S. COAST AND GEODETIC SURVEY

SAFEGUARDING THE HEALTH OF COLLEGE STUDENTS[1]

ATTENTION has frequently been called to the fact that many educational institutions fail to make adequate provision for safeguarding the health of their students. These criticisms find expression most often in connection with the report of the injury or death of a student who has been allowed to participate in athletics without proper medical supervision; or when some serious sanitary fault causes, or contributes to, an epidemic among the stu-

[1] Based upon paper presented at Fourth International Congress on School of Hygiene, Buffalo, 1913.