

SCIENCE

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THE AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE

THE RELATIONS OF ISOSTASY TO GEODESY, GEOPHYSICS AND GEOLOGY¹

WITHIN the past ten years geodetic observations have furnished positive proof that a close approximation to the condition called isostasy exists in the earth and comparatively near its surface.

Let the depth within which isostasy is found be called the depth of compensation. Think of a prismatic column which has for its base a unit area of the horizontal surface which lies at the depth of compensation, which has for its edges vertical lines, and has for its upper limit the actual irregular surface of the earth (or the sea surface if the upper end of the column is in the ocean). The condition called isostasy is defined by saying that the masses in all such columns are equal.

Fig. 1 (p. 202) represents two such columns. Column *A* is under the land and column *B* is adjacent to it under the ocean. If the condition called isostasy exists in two such columns having equal bases they have equal masses. Note that if this is true the average density in column *A* must be less than the average density in column *B*, for the volume of column *A* is greater than that of column *B*. This may be partially expressed by the statement that each excess of mass represented by material lying above sea level is compensated for by a

¹ Address of retiring vice-president of Section D (Mechanical Science and Engineering) of the American Association for the Advancement of Science, at Minneapolis, December 29, 1910, by John F. Hayford, director, College of Engineering, Northwestern University, Evanston, Ill.

defect of density and, therefore, of mass in the material in the same vertical line below sea level and above the depth of compensation.

Note that isostasy is defined in terms of masses and densities without regard to the manner in which this arrangement of masses and densities has been produced.

Isostasy is a condition of approximate equilibrium, not perfect equilibrium. The total weight of column *A* being the same as that of column *B*, the pressure at the depth of compensation due to weight is the same under the two columns, and at this level there is equilibrium. Above any selected higher level in the two columns such as that marked depth *X* in the figure, the mass is greater in column *A* than in column *B*.² Therefore, at depth *X* the pressure due to weight is greater in *A* than in *B*, equilibrium does not exist, and the material in *A* at this level tends to move downward and to the right into *B*.

The geodetic observations which have furnished a positive proof that a close approximation to the condition called isostasy exists in the earth are, first, 765 series of astronomic observations scattered over the United States from the Atlantic to the Pacific and from Canada to Mexico, and all connected by continuous triangulation,³

² The density in column *A*, in which a defect of density exists to compensate for the excess of mass at the surface, being less than in column *B*, in which the reverse condition exists, the mass in column *A* below depth *X* is necessarily less than in column *B* below that level. Hence the total masses in the two columns being equal, the mass in column *A* above depth *X* must be greater than in column *B*, as stated.

³ The evidence from these observations is given in full in "The Figure of the Earth and Isostasy from Measurements in the United States" and "Supplementary Investigation in 1909 of the Figure of the Earth and Isostasy," both by John F. Hayford and both published by the Coast and Geodetic Survey.

and, second, determinations of the intensity of gravity at 89 stations scattered over the whole of the United States.⁴

The geodetic observations show that the most probable depth of compensation is 76 miles and that it is practically certain that it is not less than 62 nor more than 87 miles.⁵

Let the isostatic compensation be considered complete if in every column, such as those shown in Fig. 1, the mass above the depth of compensation is the same as in every other column. If the mass is greater or less than this in any one column, let us characterize the isostatic compensation as incomplete and measure the degree of incompleteness in terms of the excess or defect of mass.

The geodetic observations show that the isostatic compensation under the United States is nearly complete. It is not merely a compensation of the continent as a whole, it is a compensation of the separate, large, topographic features of the continent.

⁴ These have furnished evidence which corroborates that from the astronomical observations and triangulation. This evidence has not been published except in brief and incomplete form (report of the sixteenth general conference of the International Geodetic Association, Vol. 1, pp. 365-389, "The Effect of Topography and Isostatic Compensation upon the Intensity of Gravity," by John F. Hayford), but it will probably be published in full within a year in a paper which is being prepared by Mr. William Bowie, inspector of geodesy, Coast and Geodetic Survey, and the speaker. It is expected that this will be published by the Coast and Geodetic Survey under the same title as the report presented at the International Geodetic Association to which reference has just been made.

⁵ This is the depth of the compensation if uniformly distributed with respect to depth, which seems to be the most probable assumption. If the compensation is distributed in some other manner with respect to depth, the limiting depth of compensation is different, see pp. 77-78 of the "Supplementary Investigation in 1909 of the Figure of the Earth and Isostasy."

There is an excess of mass in some columns and a defect in others, but the evidence indicates that the average excess in the areas of undercompensation is properly represented by a stratum only 250 feet thick having the same density as the surface portion of the earth (2.67). Similarly, the average defect of mass in the areas of overcompensation corresponds to a stratum only 250 feet thick.

Contrast these small excesses and defects of 250 feet with the actual elevations in the United States, 2,500 feet on an average for the whole country. If there were no isostatic compensation these actual elevations would represent excesses of mass. The compensation may properly be characterized as departing from completeness only one tenth on an average.

These are the facts, established by abundant geodetic evidence. These facts may not be removed or altered by showing that difficulties are encountered when one attempts to make them fit existing theories geological or otherwise. The theories must be tested by the facts and modified if necessary.

A close approach to the condition called isostasy certainly exists. It is uncertain how this condition has been produced; upon that point the geodetic observations furnish no direct evidence.

The recognition of isostasy in a definite and reasonable manner in the computations of the figure and size of the earth from astronomical observations and triangulation has nearly doubled the accuracy of the computed results. This recognition, combined with other improvements in methods of computation, has enabled the Coast and Geodetic Survey to compute the equatorial radius and the flattening of the earth from observations in the United States alone with greater accuracy than it was formerly possible to compute it from

all the observations of the world combined—by such computations, for example, as those made by Bessel and Clark.

The evidence is clear that the present isostatic compensation is not an initial condition which has persisted since early geologic times. There is abundant geological evidence⁶ that within the interval covered by the geologic record many thousands of feet of thickness of material have been eroded from some parts of the United States and adjacent regions and deposited in other parts, that changes of elevation of the surface amounting to thousands of feet have been produced in this and other ways, and that these changes have continued to take place in recent time. Hence it is evident that if there had been complete isostatic compensation in early geologic time, and no readjustment toward the isostatic condition had taken place since, the departure from complete compensation would now be measured by strata thousands of feet thick upon an average. In fact, the present departures from complete compensation are measured by strata only a few hundred feet thick—250 feet on an average. It is certain that a readjustment toward isostasy has been in progress during the period covered by geologic record.

Let us consider the tendency of gravitation to produce readjustment toward isostasy. Recur to the case indicated in Fig. 1. Columns *A* and *B* have been assumed to contain equal masses. There is complete isostatic compensation. The pressures at the bases of the two columns

⁶ The paper entitled "Paleogeography of North America," by Charles Schuchert, pp. 427-606 of volume 20 of the *Bulletin of the Geological Society of America* may be cited as an example of such evidence marshaled in systematic form. Consult the fifty maps at the close of this publication for a graphic indication of the changes which have probably taken place on this continent.

are equal, and at any less depth, X , the pressure is greater in A than in B . Now assume that in the normal course of events a large amount of material is being eroded from the high surface of column A and deposited on the low surface of column B . After this erosion has been in

of the two columns were at the same level. During the process of erosion and deposition the excess of pressure in A at any level above the neutral level will continually decrease. Similarly, at any level below the neutral level the excess of pressure in B will continually increase as the

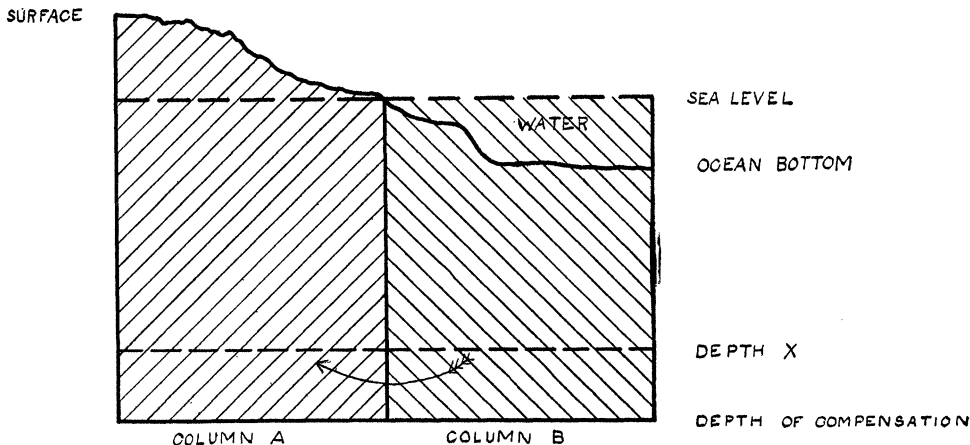


Fig. 1

progress for some time the isostatic compensation will no longer be perfect. The pressure at the base of B will be greater than at the base of A . The pressure very near the top of B will still be less than at the same level in A so long as the top of A remains higher than the top of B . There will be some intermediate level at which the pressure in the two columns is the same. Call this level of temporary equality of pressure in the two columns the neutral level. As the process of erosion and deposition progresses the neutral level will gradually progress upward from its original position at the base of the columns. Eventually if no interchange of mass took place between the columns except at the surface, and no vertical displacement occurred in either column, the neutral level would reach the surface when the process of erosion and deposition became complete and the upper surfaces

erosion progresses and the neutral level will rise. Thus there will be established a continually increasing tendency for the material below the neutral level in B to be squeezed over into A . If the stresses tending to produce this undertow from the lower part of B to A become greater than the material can stand, the flow will take place as indicated by the arrow in the figure. If the material flows without change of volume, as if it were incompressible, the upper part of A and its surface will be raised, the upper part of B and its surface will be lowered, the neutral level will sink and an approximation to the original conditions with complete isostatic compensation will be reestablished.

This is the general case of isostatic readjustment by the action of gravitation alone. Gravitation tends to produce a deep undertow from the regions where deposition is taking place to the regions

where erosion is in progress, in the direction opposite to that of the surface transfer of material.

Let us suppose that the isostatic compensation at a given stage in the earth's history is practically complete for a continent, that the process of erosion from the greater part of the continent and deposition around its margins is in progress, and that the process of readjustment by a deep undertow is in progress. These processes will cause changes of pressure and temperature within the earth at certain places. It is important to study the probable effect of these changes upon the condition and especially upon the density of the material involved.

At this point, in order to keep our subject in proper perspective, it is desirable to recall that the average defect in density under a continent corresponding to complete isostatic compensation is one per cent. or less, the average excess of density under an ocean only about two per cent. and the maximum defect or excess under the highest parts of the continents or under the deepest parts of the ocean are but little greater than three per cent. These are very small differences in density. Differences larger than these are frequently observed between samples supposed to be alike.

If a layer of material 1,000 feet thick is eroded from one part of the earth's surface and deposited on another part the pressures must become appreciably reduced for a considerable distance below the eroded region and increased below the region of deposition. The heterogeneous material composing the earth is continually undergoing chemical changes. The expression chemical change is here used in its widest sense, the sense in which it includes the processes of solution, crystallization and changes of state between the

solid, liquid and gaseous forms; includes the solution of gas in liquids, the solution of rock ingredients in water and their redeposition as new materials different from the original materials, and changes from an amorphous to a crystalline state, and vice versa. All these and more are concerned in the complicated processes of metamorphism. In the heterogeneous mixture at any point in the earth a great many changes are impending. A relief of pressure at any given point tends to favor such changes as are accompanied by increase of volume and reduction of density, and an increase of pressure tends to have the reverse effect. Many of these suggested chemical changes are accompanied by a change of much more than three per cent. in density. Changes of this nature in a small part of the material in any cubic mile may alter the average density as much as three per cent.

A large reduction of pressure may reasonably be expected, by favoring certain chemical changes within the earth and opposing others, to bring about gradually with the lapse of ages a decrease of two or three per cent. in the density of the material relieved of pressure.

Under a region where erosion is in progress or has recently been in progress one should expect, therefore, that the chemical changes guided by reduced pressure will gradually produce increase in volume and a raising the surface; and conversely, under a region of deposition the chemical changes guided by increased pressure will gradually produce increase of density, reduction of volume and a lowering of the surface. The surface changes will then favor more erosion and more deposition in the same regions as before. During this process the stresses due to gravitation, tending to produce an undertow and thereby an isostatic re-

adjustment, gradually increase until an undertow takes place and the isostatic condition is restored or nearly restored. In this last state the surface of the continent will still be elevated, its margins will still be low and the processes of erosion, deposition and isostatic readjustment by an undertow will still tend to continue.

Note that the processes just indicated explain the existence of defective density (light material) in the continent and to great depths below the surface, not by the supposition that the light material was there originally, but by the supposition that the processes of chemical change are such as to increase the volume and decrease the density of the material after it is in position as a part of a continent.

In studies of the earth it is frequently assumed tacitly that the material is sensibly incompressible under changes of pressure produced by the shifting of loads, by erosion and deposition. It would be as sensible as this supposition, not more absurd, to compare the material beneath an eroded surface to the contents of a vichy siphon. Upon a slight reduction in pressure, of a few pounds per square inch, the contents of a vichy siphon double their volume in a few seconds. After the reduction of pressure caused by the erosion of a layer a mile thick from the surface of the earth in a given region the material below to a depth of 76 miles probably changes its volume by one per cent. in the course of the next few ages.

Now consider the effects of the changes of temperature which would be produced by the erosion, deposition and undertow which have been indicated.

Near the surface the temperature is known to increase about 1° C. for each 100 feet increase in depth below the surface. At great depths the rate of increase is probably much smaller. Assume that it

is 1° C. for each 200 feet on an average down to the depth of compensation, 76 miles. Then if a stratum 1,000 feet thick is eroded from a region the temperature will be lowered under that region in the course of ages by 5° C. upon an average to the depth of 76 miles. Assuming that the coefficient of vertical expansion is 1 part in 60,000 per degree Centigrade, the material to the depth 76 miles will contract 1 part in 12,000 in thickness or 30 feet. On these assumptions then for every 1,000 feet eroded there is a tendency to produce by cooling and contraction 30 feet of sinking of the surface, that is, one foot of sinking by thermal contraction for each 33 feet of erosion. It is unimportant whether this ratio 1:33 is a close approximation. It is important to note that whereas the reduction of pressure caused by erosion tends to make the material expand, the lowering of temperature caused by erosion tends to make the material contract, an opposite effect.

Probably expansion by chemical change begins to occur promptly after a certain amount of erosion has occurred, since a change of pressure would probably be felt comparatively promptly even at considerable depths. On the other hand, the cooling is necessarily slow and may require ages to penetrate 76 miles. Hence following erosion in a given region the expansion due to chemical change will tend to begin first. Later, and developing much more slowly, the contraction due to the lowering of the temperature will occur. The latter may in time become as rapid or more rapid than the former, the volume may cease to increase or may even decrease, the surface may stop rising or it may even sink, and the region of erosion be changed into one of deposition.

Similarly, under a region of deposition two effects of opposite sign tend to occur.

The effect of increased pressure tends to produce chemical changes accompanied by decrease of volume and so to produce a sinking of the surface. The blanket of deposited material tends to raise the temperature in each part of the material covered, to increase the volume of this material, and thereby to raise the surface. The temperature effect may serve in time

comparatively neutral region between the two in which neither erosion nor deposition is much in excess of the other, see Fig. 2. Hence the undertow by increasing the temperature and causing a change of density may be directly effective in changing the elevation of the neutral region between two regions of deposition and erosion.

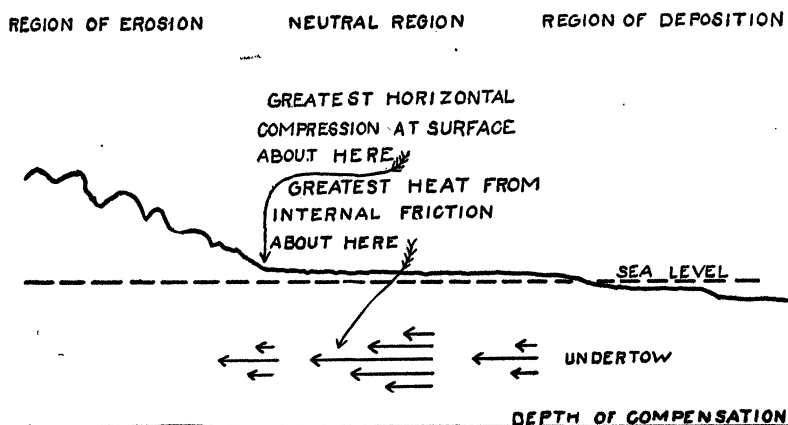


FIG. 2

to arrest the subsidence caused by increased pressure or even to raise the surface and change the region of deposition into one of erosion.

The changes of temperature just described are due directly to erosion and deposition. If as an effect of erosion and deposition an undertow is started tending to reestablish the isostatic condition, this undertow, a flow of material presumably solid, necessarily develops considerable heat by internal friction. The increase of temperature so produced tends to cause an increase of volume. It may favor new chemical changes, including changes from the solid to the liquid state, which may be accompanied by a change of volume. The undertow tends to be strongest not under the region of rapid erosion nor under the region of rapid deposition, but under the

Horizontal compressive stresses in the material near the surface above the undertow are necessarily caused by the undertow. For the undertow necessarily tends to carry the surface along with it and so pushes this surface material against that in the region of erosion, see Fig. 2. These stresses tend to produce a crumpling, crushing and bending of the surface strata accompanied by increase of elevation of the surface. The increase of elevation of the surface so produced will tend to be greatest in the neutral region or near the edge of the region of erosion, not under the region of rapid erosion nor under the region of rapid deposition.

There has been indicated a complicated set of changes of pressure, temperature and density and of movements of material beneath the surface, a set of changes which

have been started by erosion and deposition and continued by the action of gravitation tending to bring about a readjustment to isostatic conditions.

Attention is invited to the thought that during the actions indicated the pressure, temperature and relative movements in any small portion of the material are a function not simply of the facts at that place but also largely of the facts at many other places, some at considerable distances.

For example, in the neutral region between a region of erosion and one of deposition there may be movements beneath the surface (the undertow), changes of temperature in the flowing material, a crumpling of the surface material, changes of volume and changes of elevation of the surface, all of which are dependent primarily upon the facts in adjacent regions of erosion and deposition.

Let us limit our thoughts still to the cycle of changes which have been sketched roughly. Keep it in mind that the actions at any given point in the material depend on the facts at many other points. Keep it in mind also that a region of erosion in one age may, and often does, become a region of deposition in another, and that, therefore, the actions taking place at any instant in a given portion of the material are necessarily dependent upon the past as well as the present conditions. Is it not evident that even if the cycles of action which have been indicated were the only actions taking place in the outer portions of the earth, the resulting series of movements observable at the surface would be very complicated? Is it at all certain that under the influence of such actions the geological record at the earth's surface at the end of 50 to 100 million years would be appreciably less complicated than the geologic record which is actually before

us? I think that it would be fully as complicated as the actual record.

Let me illustrate, by a single example, the kind of reasoning which the considerations just stated should lead one to avoid.

It has been stated to me that mountains are sometimes eroded to a peneplain, and that thereafter the peneplain sometimes sinks. It has been suggested to me that such a case can not be reconciled with the theory of isostasy. It is said that as the material is eroded from the surface the underlying material must increase in volume to keep the isostatic compensation complete, hence that according to the theory of isostasy a peneplain may rise but never sink.

This reasoning contains several errors. In the first place, in Fig. 1, after a portion of the surface of column *A* has been carried away by erosion and the pressure at the bottom of the column thereby reduced to less than that under column *B*, the mere vertical expansion of column *A* will not reestablish equality of pressure. The equality may be reestablished only by restoring mass to column *A* by forcing material into it from some other column. This gravitation tends to do. Secondly, when gravitation, by producing an undertow, forces material into column *A* the new material may enter by processes which increase the density of column *A*. Column *A* may thus become heavier without any raising of its upper end. An eroded surface does not necessarily rise. Thirdly, a time may come when by virtue of the lowering of the temperature by erosion the material in column *A* may increase in density by thermal contraction and the surface may thus be lowered without any masses passing to other columns. If so, the isostatic condition remains unchanged, the relative pressures at the bases of *A* and *B* remaining unchanged. Such a process

may cause a region which has been eroded from mountains to a peneplain to sink thereafter. Fourthly, such reasoning as that cited ignores the history of the region before the mountains were there. That early history is essential to a full understanding of late movements. Fifthly, such reasoning entirely ignores the relations of the region considered to adjacent regions. As the evidence shows that the material concerned in isostatic readjustment is 76 miles deep, it is but sensible to estimate that the influences concerned in any one movement of isostatic readjustment extend over horizontal distances of at least 76 miles, probably over distances as great as 200 miles. Therefore, valid reasoning in regard to the peneplain in question should include a consideration of the conditions surrounding it to a distance of 200 miles, whereas in fact in the reasoning cited the surrounding conditions were entirely ignored.

How is it possible to form an estimate of the relative effectiveness of gravitation tending to produce isostatic readjustment, on the one hand, and of all other forces acting on the outer portion of the earth, on the other hand? Gravitation is the only force which continuously tends to produce isostatic readjustment. The rigidity of the material tends continuously to oppose the readjustment toward isostasy. Other forces than gravitation are equally likely to help or to oppose gravitation. Therefore, the fact that the isostatic compensation is everywhere nearly complete is a proof, first, that the material composing the outer portions of the earth has but small effective rigidity, and, second, that the forces in operation other than gravitation are relatively ineffective. If either of these propositions were untrue the present close approach to complete isostatic compensation would not exist.

Before closing let me remind you that the geodetic evidence shows that the outer portion of the earth is not a solid crust a few miles thick floating on a liquid substratum of slightly greater density.⁷

The existence of isostasy is now thoroughly established by evidence which is available in print. The time has come to speculate upon the manner in which the isostatic readjustments are produced, to look for the relations between the known condition, isostasy, and other known facts. This address is a map showing the results of a reconnaissance in this field. The reconnaissance has involved much more thought than I have been able to put into words here. Some of the statements have been made in rather a dogmatic form. That is simply because I have tried to draw a clear reconnaissance map with few strokes, not that I have forgotten that the field work has been merely reconnaissance. I feel confident, however, that in due course of time when careful surveys shall have been substituted for this reconnaissance, the main features of this reconnaissance map will be found to be correct.

In closing let me give you the reconnaissance map on a small scale with details omitted.

Readjustment toward isostatic conditions has been in progress throughout geologic time.

The differences in density involved in complete isostatic compensation are very small, usually less than one per cent., seldom more than three per cent.

With reference to such small changes of density the earth is not incompressible under the influence of stresses which are applied continuously for geologic ages.

Erosion and deposition cause changes of pressure, which in turn bring about

⁷ "The Figure of the Earth and Isostasy," pp. 163-164.

changes of chemical state in the heterogeneous material within the earth such that increase of pressure in time produces increase of density, and relief of pressure produces decrease of density.

The direct effects of erosion and deposition on temperatures in the underlying material are such as to cause changes of density opposite to those caused directly by the change of pressure and probably occurring later than those caused by changes of pressure.

Gravitation tends continuously to bring about a readjustment to isostatic conditions by producing a deep undertow from a region of deposition to a region of erosion.

This undertow by virtue of heat produced by internal friction and by virtue of surface compressive stresses in the horizontal direction tends to raise the surface of the neutral region between a region of deposition and one of erosion.

The phenomena of isostatic readjustments by gravitation are complicated. Actions involved at any one spot are a function of the facts at many other places and of the facts of earlier ages.

The material in the earth to a depth of 76 miles is weak under the action of forces applied for geologic ages. The effects of gravitation predominate over those of other forces to this depth.

JOHN F. HAYFORD

*THE MERSHON EXPEDITION TO THE
CHARITY ISLANDS, LAKE HURON*

For several years the University of Michigan Museum and the Michigan Geological and Biological Survey have been cooperating in a biological survey of the state. The survey has had a small annual appropriation for this work, and has deposited the collections in the museum, but the expeditions sent out from the latter have nearly all been made possible by gifts from persons interested in the progress of the work or in the institution.

In the summer of 1910, Hon. W. B. Mershon, Saginaw, Mich., placed in the hands of the chief field naturalist of the survey, who is also the head curator of the museum, a sum sufficient to send a small party to the Charity Islands in Saginaw Bay, for the purpose of investigating the fauna and flora.

The Charities comprise a group of three small islands situated near the mouth of Saginaw Bay. The largest of these, Charity Island proper, contains about 650 acres, Little Charity Island, the next largest, about 3 acres, and Gull Island is a small projecting reef, about a quarter of an acre in extent, that is not usually shown on the maps. The group is somewhat nearer the west coast than the east. As plotted on the Lake Huron Coast Chart No. 2, of the United States Lake Survey, the distances of the larger island (where most of the work was done) from the mainland are as follows: to Point Lookout, slightly north of west, six and seven eighths miles; from Caseville, due southeast, nine and five eighths miles; from the end of Sand Point, a little east of south, seven and three fourths miles; from Oak Point, south of east, nine miles.

The islands are of interest biologically in two ways. In the first place, as they have not been connected with the mainland since glacial times, the biota must have reached them over a stretch of water at least as broad as that which now separates them from the mainland. In the second place, they are apparently upon a migration route of many species of birds.

The men engaged to do the work and the groups to which they devoted most of their time were as follows: W. W. Newcomb (butterflies and moths), N. A. Wood (vertebrates), A. W. Andrews (beetles), Frederick Gaige (ants), C. K. Dodge (plants). The museum and survey are greatly indebted to these men, for they did the field work without other remuneration than their expenses, and are now preparing their results for publication. Acknowledgment should also be made of the assistance of the light-house board, Washington, D. C., and Commander C. B. Morgan, inspector of the eleventh light-house district,