— 1199 —

MODIFICATION OF THE GREAT LAKES BY EARTH MOVEMENT.

BY

G. K. GILBERT.

FROM THE SMITHSONIAN REPORT FOR 1898, PAGES 349-361.

WASHINGTON:
GOVERNMENT PRINTING OFFICE.
1900.

MODIF

— 1199 —

MODIFICATION OF THE GREAT LAKES BY EARTH MOVEMENT.

BY

G. K. GILBERT.

FROM THE SMITHSONIAN REPORT FOR 1898, PAGES 349-361.

WASHINGTON:
GOVERNMENT PRINTING OFFICE.
1900.

MODIFIC

The histor
of the Pleist
vasion of the
came from th
rentian basin
Susquehanna
period when
lands south
whose outlet
stream from
Wabash Riv
flowed from
Illinois Rive
Basin across

The posit
consisting o
by their wa
hundreds o
found that t
south and s
must origin
is due to un
the south-so
and their g
to 3 or 4 fe

The epoc
with the di
of the mod
one at a ti

[1] Reprinted
1897. A mor
the Great La
United State

MODIFICATION OF THE GREAT LAKES BY EARTH MOVEMENT.[1]

By G. K. GILBERT,

United States Geological Survey.

The history of the Great Lakes practically begins with the melting of the Pleistocene ice sheet. They may have existed before the invasion of the ice, but if so their drainage system is unknown. The ice came from the north and northeast, and spreading over the whole Laurentian basin invaded the drainage districts of the Mississippi, Ohio, Susquehanna, and Hudson. During its wandering there was a long period when the waters were ponded between the ice front and the uplands south of the Laurentian basin, forming a series of glacial lakes whose outlets were southward through various low passes. A great stream from the Erie Basin crossed the divide at Fort Wayne to the Wabash River. A river of the magnitude of the Niagara afterwards flowed from the Michigan Basin across the divide at Chicago to the Illinois River; and still later the chief outlet was from the Ontario Basin across the divide at Rome to the Mohawk Valley.

The positions of the glacial lakes are also marked by shore lines, consisting of terraces, cliffs, and ridges, the strands and spits formed by their waves. Several of these shore lines have been traced for hundreds of miles, and wherever they are thoroughly studied it is found that they no longer lie level, but have gentle slopes toward the south and southwest. Formed at the edges of water surfaces, they must originally have been level, and their present lack of horizontality is due to unequal uplift of the land. The region has been tilted toward the south-southwest. The different shore lines are not strictly parallel, and their gradients vary from place to place, ranging from a few inches to 3 or 4 feet to the mile.

The epoch of glacial lakes, or lakes partly bounded by ice, ended with the disappearance of the ice field, and there remained only lakes of the modern type, wholly surrounded by land. These were formed one at a time, and the first to appear was in the Erie Basin. It was

[1] Reprinted from the National Geographic Magazine, Vol. VIII, No. 9, September, 1897. A more extended paper of similar scope entitled "Recent earth movement in the Great Lakes region," was printed in the Eighteenth Annual Report of the United States Geological Survey, Part II, pp. 595–617.

much smaller than the modern lake, because the basin was then comparatively low at the northeast. Its outline is approximately shown by the inner dotted line of the accompanying map. Instead of reaching from the site of Buffalo to the site of Toledo, it extended only to a

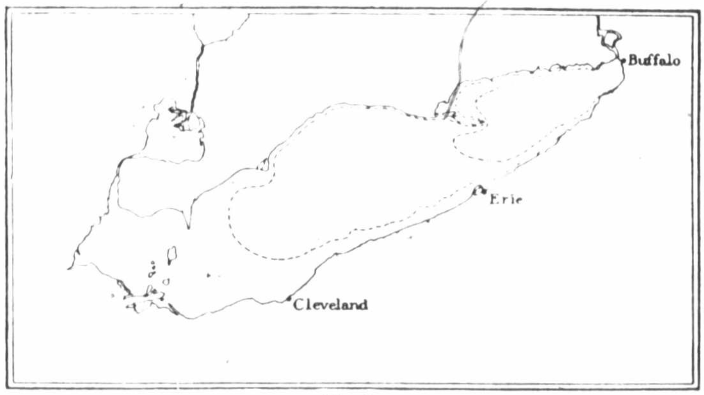

Fig. 1.

ANCIENT AND MODERN OUTLINES OF LAKE ERIE.

The broken lines show the positions of the shores at two epochs of the lake's history.

point opposite the present city of Erie, and it was but one-sixth as large as the modern lake. Since that time the land has gradually risen at the north, canting the basin toward the south, and the lake has gradually encroached upon the lowlands of its valley. At a date to

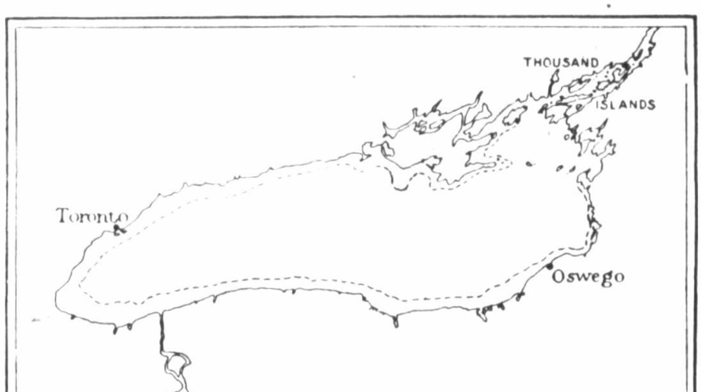

Fig. 2.

ANCIENT AND MODERN OUTLINES OF LAKE ONTARIO.

The broken line shows the original extent of the lake.

be presently mentioned as the Nipissing, the western end of the lake was opposite the site of Cleveland, as indicated by another dotted line.

The next great lake to be released from the domination of the ice was probably Ontario, though the order of precedence is here not equally clear. Before the Ontario Valley held a land-bound lake it was occupied by a gulf of the ocean. Owing to the different attitude of the land, the water surface of this gulf was not parallel to the present lake surface but inclined at an angle. In the extreme northeast, in the vicinity of the Thousand Islands, the marine shores are nearly 200 feet above the present water level, but they descend southward and westward, passing beneath the lake level near Oswego, and toward the western end of the lake must be submerged several hundred feet. This condition was of short duration, and the rising land soon divided the waters, establishing Lake Ontario as an independent water body. The same peculiarity of land attitude which made

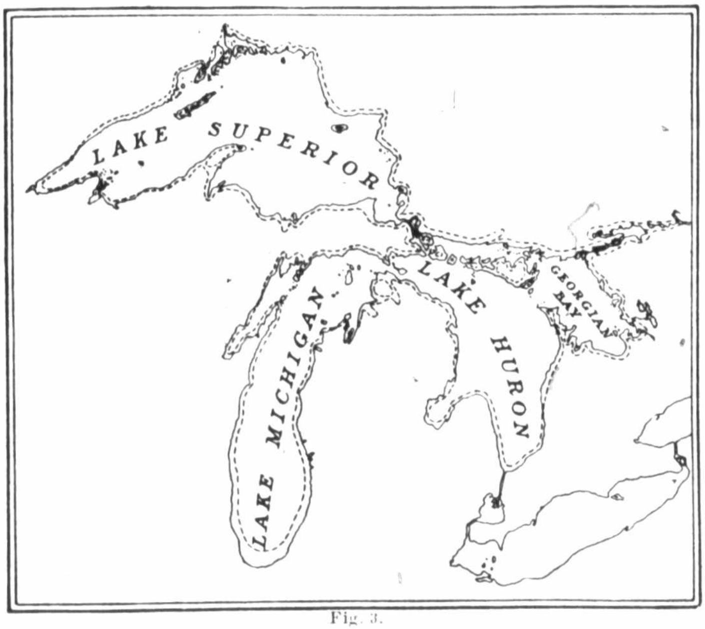

Fig. 3.

THE NIPISSING GREAT LAKE (AFTER TAYLOR).

Its boundaries are shown by the broken line.

the original Erie a small lake served to limit the extent of Ontario, but the restriction was less in amount because of the steeper slopes of the Ontario basin. Here again the southward tilting of the land had the effect of lifting the point of outlet and enlarging the expanse of the lake.

There is some reason to think that the upper lakes—Huron, Michigan, and Superior—were at first open to the sea, so as to constitute a gulf, but the evidence is not so full as could be desired. When the normal lacustrine condition was established they were at first a single lake instead of three, and the outlet, instead of being southward from Lake Huron, was northeastward from Georgian Bay, the outlet river following the valleys of the Mattawa and Ottawa to the St. Lawrence. The triple lake is known to us chiefly through the labors of F. B. Taylor, who has made extensive studies of its shore line. This line, called the Nipissing shore line, is not wholly submerged, like the old shores of Lakes Erie and Ontario, but lies chiefly above the present water surfaces. It has been recognized at many points about Lake Superior and the northern parts of Lakes Huron and Michigan, and measurements of its height shows that its plane has a remarkably uniform dip, at 7 inches per mile, in a south-southwest direction, or, more exactly, S. 27° W. As will be seen by the accompanying map, reproduced from Taylor, it crosses the modern shore line of Lake Superior near its western end, thereby passing beneath the water surface, and it similarly passes below the surface of Lake Michigan near Green Bay and below the surface of Lake Huron just north of Saginaw Bay. The southward tilting of the land, involving the uplift of the point of outlet, increased the capacity of the basin and the volume of the lake, gradually carrying the coast line southward in Lake Huron and Lake Michigan, until finally it reached the low pass at Port Huron and the water overflowed via the St. Clair and Detroit channels to Lake Erie. The outlet by way of the Ottawa was then abandoned, and a continuance of the uplift caused the water to slowly recede from its northern shores. This change after a time separated Lake Superior from the other lakes, bringing the St. Marys River into existence, and eventually the present condition was reached.

These various changes are so intimately related to the history of the Niagara River that the Niagara time estimates, based on the erosion of the gorge by the cataract, can be applied to them. Lake Erie has existed approximately as long as the Niagara River, and its age should probably be reckoned in tens of thousands or hundreds of thousands of years. Lake Ontario is much younger. All that can be said of the beginning of Great Lake Nipissing is that it came long after the beginning of Lake Erie, but the date of its ending, through the transfer of outlet from the Mattawa to the St. Clair, is more definitely known. That event is estimated by Taylor to have occurred between five thousand and ten thousand years ago.[1]

The lake history thus briefly sketched is characterized by a progressive change in the attitude of the land, the northern and northeastern portions of the region becoming higher, so as to turn the waters more and more toward the southwest. The latest change, from Great Lake Nipissing to Great Lakes Superior, Michigan, and Huron, involving an uplift at the north of more than 100 feet, has taken place within so short a period that we are naturally led to inquire whether it has yet ceased. Is it not probable that the land is still rising at the north and the lakes are still encroaching on their southern shores? J. W. Spencer, who has been an active explorer of the shore lines of

[1] Studies in Indiana Geography, X. A short history of the Great Lakes. Terre Haute, 1897.

the glacial lakes and has given much study to related problems, is of opinion that the movements are not complete, and predicts that they will result in the restoration of the Chicago outlet of Lake Michigan and the drying of Niagara.[1]

The importance of testing this question by actual measurements was impressed upon me several years ago, and I endeavored to secure the institution of an elaborate set of observations to that end. Failing in this, I undertook a less expensive investigation, which began with the examination of existing records of lake height as recorded by gage readings, and was continued by the establishment of a number of gage stations in 1896. To understand fully the nature of this investigation it is necessary to consider the difficulties that arise from the multifarious motions to which the lake water is subject.

If the volume of a lake were invariable, and if its water were in perfect equilibrium under gravity, its surface would be constant and level, and any variation due to changes in the height of the land could be directly determined by observations on the position of the water surface with reference to the land; but these conditions are never realized in the case of the Great Lakes, where the volume continually changes and the water is always in motion. The investigator therefore has to arrange his measurements so as to eliminate the effect of such changes.

Consider first the influence of wind. The friction of the wind on the water produces waves. These are temporary and practically cease in periods of calm; the perpetual ground swell of the ocean is not known on the lakes. The friction of the wind on the water also drives the water forward, producing currents. The water thus driven against the lee shores returns in undercurrents, but the internal friction of the water resists and delays the return, and there is consequently a heaping of water against lee shores and a corresponding lowering of its level on other shores. During great storms these differences amount to several feet, reaching a maximum in Lake Erie; in October, 1886, a westerly gale is reported to have raised the water 8 feet at Buffalo and depressed it 8 feet at Toledo.[2] For light winds the changes of level are much smaller, but they are nevertheless appreciable, and they have even been detected in the case of the gentle "land and sea" breezes which in calm weather are created by the diurnal cycle of temperature change on land.

The water is also sensitive to atmospheric pressure. If the air pressed equally on all parts of the lake surface, the equilibrium of the water would not be disturbed; but its pressure is never uniform. As shown by the isobars on the daily weather map, there are notable differences of pressure from point to point, and within the length of one of the Great Lakes these often amount to several tenths of a barometric inch.

[1] Proc. Am. Ass. Adv. Sci., Vol. LIII, 1894, p. 246.

[2] Science, Vol. VIII, pp. 34, 391. The effect of a storm in October, 1893, is ably discussed by William T. Blount, in Ann. Rept. Chief of Engineers, U. S. A., for 1894, part 6, pp. 3431-3435.

A column of mercury 0.1 inch high weighs as much as a column of water 1.3 inches high; and whenever the atmospheric pressure at one point on a lake exceeds the pressure at another point by the tenth of a barometric inch, the water level at the first point is, in consequence, 1.3 inches lower than the water level at the second point. When a cumulus cloud forms over the water, there is a reaction on the water, disturbing its equilibrium, and the passage of a thunderstorm often produces oscillations attracting the attention of even the casual observer. Such sudden and temporary variations of pressure give rise to waves analogous to those caused by a falling pebble, except that they are broad and low, and these waves not only travel to all parts of a lake, but are continued by reflection, so that a local storm at one point is felt in the water surface at all points and for a considerable period. The passage of the great atmospheric waves associated with ordinary cyclonic storms and the impulses given by winds are also able to set the whole body of the lake in motion, so that it sways from side to side or end to end like the swaying water in a tub or basin, and these swaying motions are of indefinite continuance. In the deeper lakes, and probably in all the lakes, they are so enduring as to bridge over the intervals from impulse to impulse. Such oscillations, which appear at any point on the coast as alternate risings and fallings of the water, with periods ranging from a few minutes to several hours, are called seiches. Their amplitude is usually a few inches, but at the ends of lakes is sometimes a foot or more.

The lakes, like the ocean, are swayed by the attractions of the sun and moon. Their tides are much smaller than those of the ocean, and are even small as compared to the seiches, but they are still measurable. At Milwaukee the lunar tide rises and falls more than an inch and the solar tide a half inch. At Chicago and Duluth each tide amounts to an inch and a half, and their combination at new and full moon to 3 inches.

Water is continually added to each lake by rivers and creeks, but the rate is not uniform. Usually a few freshets, occurring within two or three weeks, contribute more water than comes during all the remainder of the year. Water is also added in an irregular way by rain and snow falling directly on the lake. It is subtracted by evaporation, the rate of which varies greatly, and by overflow, which varies within moderate limits. The volume of water contained in the lake, being subject to these variable gains and losses, is itself inconstant, and the general height of the water surface therefore oscillates. In average years the range of variation for Lake Superior is 12 inches; for Lakes Michigan and Huron, 12 inches; for Lake Erie, 14 inches, and for Lake Ontario, 17 inches. Low water occurs normally in January or February for all the lakes except Superior, where it occurs in March. High water is reached sooner in the lower lakes, June being the usual month for Ontario, June or July for Erie, July for Michigan and Huron, and August or September for Superior. Figure 4 shows the character of the annual oscillations, as given by averages of long series of years.

In a wet year more water enters the lake than leaves it, and there is a net rise of the surface; in a dry year there is a net fall. A series of wet years produce exceptionally high water and a series of dry years exceptionally low, so that the entire range of water height is considerably greater than the annual range. The recorded range for Lakes Superior, Michigan, and Huron is between 5 and 6 feet; for Erie and Ontario, between 4 and 5 feet.

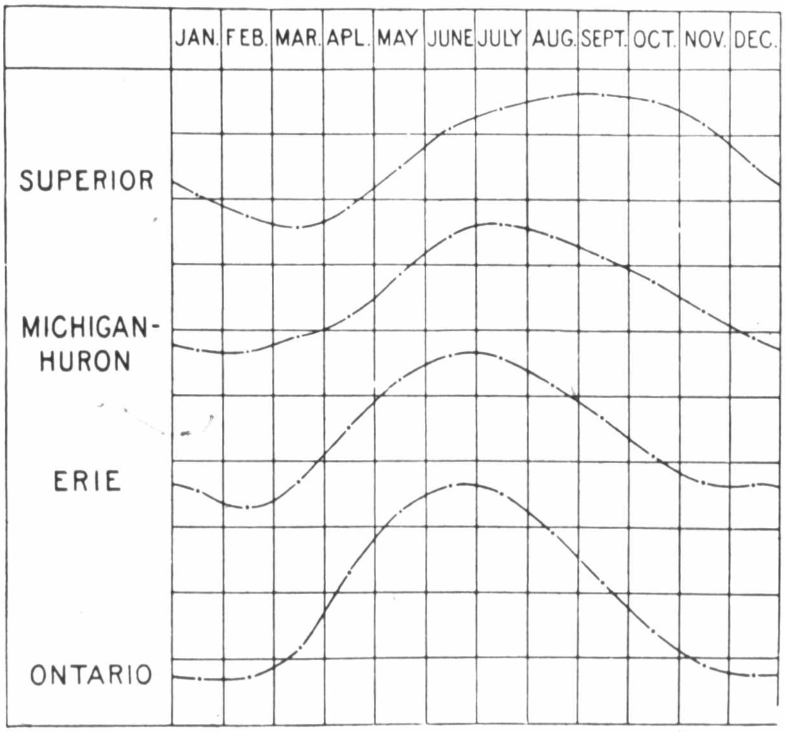

Fig. 4.

ANNUAL OSCILLATIONS OF THE SURFACES OF THE LAURENTIAN LAKES.

Compiled from monthly means published by the Chief of Engineers, U. S. A. Each vertical space represents 6 inches. The observations for Lake Superior cover the period 1862–1895; for Michigan-Huron, 1860–1895; for Erie, 1855–1895; for Ontario, 1860–1895.

The accompanying diagram (fig. 5) of the oscillations of Lake Michigan illustrates the annual cycle and also the progressive changes from year to year. Being compiled from monthly means of gauge readings, it does not show tides and seiches nor the oscillations of short period.

These various oscillations of the water, though differing widely in amplitude, rate, and cause, yet coexist, and they make the actual movement of the water surface highly complex. The complexity of movement seriously interferes with the use of the water plane as a datum level for the measurement of earth movements, and a system of observations for that purpose needs to be planned with much care.

The main principles of such a system are, however, simple, and may readily be stated. The most important is that the direct measurement of the heights of individual points should not be attempted, but comparison should always be made between two points, their relative height being measured by means of the water surface used as a leveling instrument.

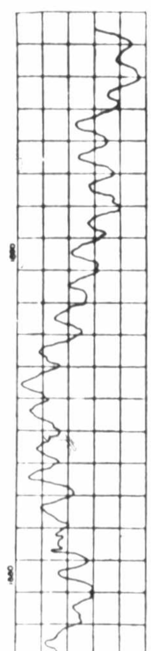

Fig. 5.

OSCILLATIONS OF THE SURFACE OF LAKE MICHIGAN, DUE TO CHANGES IN THE VOLUME OF THE LAKE.

Compiled under the direction of the Chief of Engineers, U. S. A., from gage readings at Milwaukee, Wis., from August, 1859, to June, 1897. Each horizontal space represents a calendar year; each vertical space 1 foot.

In the diagram, figure 6, A C B is the profile of a lake basin, A and B are fixed objects on opposite shores, and we will suppose the water surface to have the position X X′. Assuming the water in equilibrium, all parts of this surface have the same height. If the height of A above the water at X be accurately measured by the surveyor's level, and the height of B above the water at X′ be similarly measured, then the difference between these two measurements gives the difference in height between A and B. After an interval of some years or decades the work is repeated. The water surface then has some different position, Y Y′, and the heights measured are of A above Y and of B above Y′. The difference between the two heights gives, again, the relative height of A and B; and if earth movement has tilted the basin toward A or B, the change in their relative height may be shown by the difference in the two results of measurement.

As the water is in fact not still, but in continual motion, the mere running of lines of level from A and B to the water does not suffice, and it is necessary to determine from observations on the oscillating water surface what would be its position if still. Such observations are made by means of gages. These are of various forms, but each consists essentially of a fixed point, or zero, close by the water, and a graduated scale, by means of which the vertical distance of the water surface from the zero is measured.

Changes in the volume of the lake influence all parts of its surface equally and at the same time. To eliminate their effects from the measurements it is only necessary that the gage observations at the two stations be simultaneous. The effects of wind waves can be prevented by breakwaters. Disturbances due to currents propelled by strong winds can be avoided by choosing times when there is little wind. The effects of light winds can be approximately eliminated by taking the average of many observations, and so can the effects of seiches and tides. The effects of differences of atmospheric pressure can be computed from barometric measurements of air pressure, and the proper corrections applied. It is also possible, by the discussion of long series of observations at each station, to determine the local tidal effects and afterwards apply corrections; and the land and sea breeze effect may be treated in the same way.

In the investigation I was able to make, consideration was given to these various sources of error, but it was not practicable to take all desirable measures for avoidance or correction, because the reading of gages was only partly under my control. Gage stations have been established on the Great Lakes at various times and at various places, and the records of readings have been preserved. In some cases the zeros of gages were connected by leveling with bench marks of a permanent character, and in a few instances the gages themselves are stable and enduring structures. The most important body of information of this character is contained in the archives of the United States Lake Survey, which were placed at my service by the Chief of Engi-

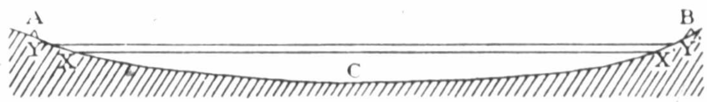

Fig. 6.

DIAGRAM ILLUSTRATING THE METHOD OF USING A LAKE SURFACE FOR THE DISCOVERY AND MEASUREMENT OF EARTH MOVEMENTS.

neers, United States Army. By searching the records I was able to select certain pairs of stations at which the relative heights of permanent points on the shore (equivalent to A and B of the diagram) had been practically determined twenty or more years ago. At some of these stations gages are still read; at others I established gages and ran the leveling lines necessary to connect them with the old benches. At all of them observations were maintained from July to October, 1896, and these observations, in combination with the levelings, afforded measurements that could be compared with those made earlier, so as to discover changes due to earth movement.

It will not be necessary to give here the details of observation and computation, as they are fully set forth in a paper soon to be printed by the Geological Survey,[1] but the general scope of the work may be briefly outlined. As the tilting shown by the geologic data was toward the south-southwest, stations were, so far as possible, selected to test the question of motion in that direction. The most easterly pair were Sacketts Harbor and Charlotte, New York, connected by the water surface of Lake Ontario. (See map, fig. 7.) From observations by the United States Lake Survey in 1874, it appeared that a bench mark on

[1] U. S. Geol. Surv., 18th Ann. Rept., Part II, pp. 595–647, 1898.

the old light-house in Charlotte was then 18.531 feet above a certain point on the Masonic Temple in Sacketts Harbor. In 1896 the measurement was repeated, and the difference found to be 18.470 feet, the point at Sacketts Harbor having gone up, as compared to the point at Charlotte, 0.061 foot, or about three-fourths of an inch. Similarly it was found that between 1858 and 1895 a point in Port Colborne, at the head of the Welland Canal, as compared to a point in Cleveland, Ohio, rose 0.239 foot, or nearly 3 inches. Between 1876 and 1896 a point at Port Austin, Michigan, on the shore of Lake Huron, as compared to a point in Milwaukee, on the shore of Lake Michigan, rose 0.137 foot, or 1½

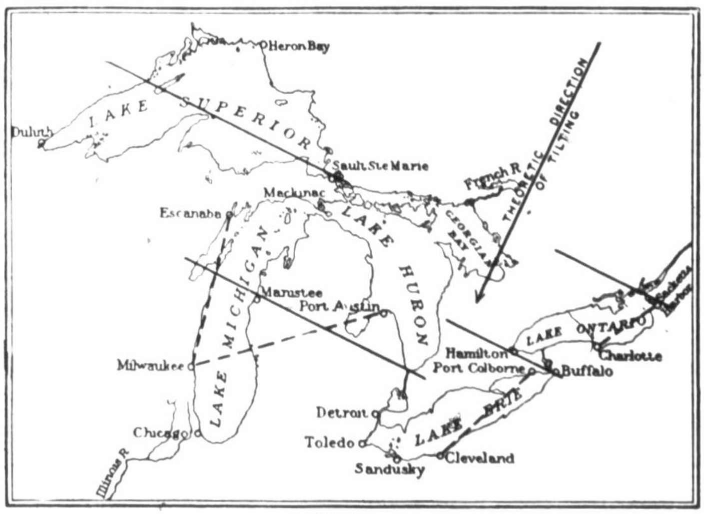

Fig. 7.

MAP OF THE GREAT LAKES, SHOWING PAIRS OF GAGING STATIONS AND ISOBASES OF OUTLETS.

The isobases are marked by full lines. Broken lines show the pairs of stations.

inches; and in the same period a point in Escanaba, at the north end of Lake Michigan, as compared to the same point in Milwaukee, rose 0.161 foot, or about 2 inches.

There is no one of these determinations that is free from doubt; buildings and other structures on which the benches were marked may have settled, mistakes may have been made in the earlier leveling, when there was no thought of subjecting the results to so delicate a test, and there are various other possible sources of error to which no checks can be applied; but the fact that all the measurements indicate tilting in the direction predicted by theory inspires confidence in their verdict. This confidence is materially strengthened when the numerical results are reduced to a common unit and compared.

Summary of distances, time intervals, and measurements of differential earth movements.

Pairs of stations.	Direct distance.	Distance in direction S. 27° W.	Interval between dates of measurements.	Change in relative height.	Change per 100 miles per century.	Probable errors of quantities in last column.
	Miles.	*Miles.*	*Years.*	*Feet.*	*Feet.*	*Feet.*
Sacketts Harbor and Charlotte	86	76	22	0.061	0.37	0.18
Port Colborne and Cleveland	158	141	37	.239	.46	.11
Port Austin and Milwaukee	259	176	20	.137	.39	.09
Escanaba and Milwaukee	192	186	20	.161	.43	.06
Mean					0.41	
Weighted mean					.42 ± 0.05	

The stations of the several pairs are at different distances apart, the directions of the lines connecting them make various angles with the theoretic direction of tilting, and the time intervals separating the measurements are different. To reduce the results to common terms, I have computed from each the rate of tilting it implies in the theoretic direction, S. 27° W. In the sixth column of the preceding table the rate is expressed as the change in relative height of the ends of a line 100 miles long during a century.

Compared in this way, the results are remarkably harmonious, the computed rates of tilting ranging only from 0.37 foot to 0.46 foot per 100 miles per century; and in view of this harmony it is not easy to avoid the conviction that the buildings are firm and stable, that the engineers ran their level lines with accuracy, that all the various possible accidents were escaped, and that we have here a veritable record of the slow tilting of the broad lake-bearing plain.

The computed mean rate of tilting, 0.42 foot per 100 miles per century, is not entitled to the same confidence as the fact of tilting. Its probable error, the mathematical measure of precision derived from the discordance of the observational data, is rather large, being one-ninth of the whole quantity measured. Perhaps it would be safe to say that the general rate of tilting, which may or may not be uniform for the whole region, falls between 0.30 and 0.55 foot.

While the credit of formulating the working hypothesis or geologic prediction which has thus been verified by measurement belongs to Spencer, it is proper to note that the fundamental idea of modern differential earth movement in the Great Lakes region was announced much earlier by G. R. Stuntz, a Wisconsin surveyor. In a paper communicated to the American Association for the Advancement of Science in 1869, he cites observations tending to show that in 1852–53 the water of Lake Superior stood abnormally high at the west end, while it was unusually low at the east, and he infers that the land is not stable.

The geographic effects of the tilting are of scientific and economic importance. Evidently the height of lake water at a lake's outlet is regulated by the discharge and is not affected by slow changes in the attitude of the basin, but at other points of the shore the water advances or retreats as the basin is tipped. Consider, for example, Lake Superior. On the map (fig. 7) a line has been drawn through the outlet at the head of St. Marys River in a direction at right angles to the direction of tilting. All points on this line, called the isobase of the outlet, are raised or lowered equally by the tilting and are unchanged with reference to one another. All points southwest of it are lowered, the amount varying with their distances from the line, and all points to the northeast are raised. The water, always holding its surface level and always regulated in volume by the discharge at the outlet, retreats from the rising northeast coasts and encroaches on the sinking southwest coasts. Assuming the rate of tilting to be 0.42 foot per 100 miles per century, the mean lake level is rising at Duluth 6 inches per century and falling at Heron Bay 5 inches. Where the isobase intersects the northwestern shore, which happens to be at the international boundary, there is no change.

Lake Ontario lies altogether southwest of the isobase of its outlet, and the water is encroaching on all its shores. The same tilting that enlarged it from the area marked by the dotted line of figure 2 is still increasing its extent. The estimated vertical rise at Hamilton is 6 inches per century. The whole coast of Lake Erie also is being submerged, the estimated rate at Toledo and Sandusky being 8 or 9 inches per century.

The isobase of the double lake Huron-Michigan passes southwest of Lake Huron and crosses Lake Michigan. All coasts of Lake Huron are therefore rising as compared to the outlet, and the consequent apparent lowering of the mean water surface is estimated at 6 inches per century for Mackinac and at 10 inches for the mouth of the French River, on Georgian Bay. In Lake Michigan the line of no change passes near Manistee, Mich. At Escanaba the estimated fall of the water is 4 inches per century; at Milwaukee the estimated rise is 5 or 6 inches, and at Chicago between 9 and 10 inches.

These slow changes of mean water level are concealed from ordinary observation by the more rapid and impressive changes due to variations of volume, but they are worthy of consideration in the planning of engineering works of a permanent character, and there is at least one place where their influence is of moment to a large community. The city of Chicago is built on a smooth plain, little above the high-water level of Lake Michigan. Every decade the mean level of the water is an inch higher, and the margin of safety is so narrow that inches are valuable. Already the older part of the city has lifted itself several feet to secure better drainage, and the time will surely come when other measures of protection are imperatively demanded.

Looking to the more distant future, we may estimate the date at which the geographic revolution prophesied by Spencer will occur. Near Chicago, as already mentioned, is an old channel made by the outlet of a glacial lake. The bed of the channel at the summit of the pass is about 8 feet above the mean level of Lake Michigan and 5 feet above the highest level. In five or six hundred years (assuming the estimated rate of tilting) high stages of the lake will reach the pass, and the artificial discharge by canal will be supplemented by an intermittent natural discharge. In one thousand years the discharge will occur at ordinary lake stages, and after fifteen hundred years it will be continuous. In about two thousand years the discharge from Lake Michigan-Huron-Erie, which will then have substantially the same level, will be equally divided between the western outlet at Chicago and the eastern at Buffalo. In twenty-five hundred years the Niagara River will have become an intermittent stream, and in three thousand years all its water will have been diverted to the Chicago outlet—the Illinois River, the Mississippi River, and the Gulf of Mexico.