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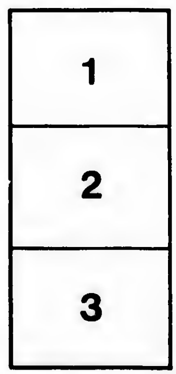

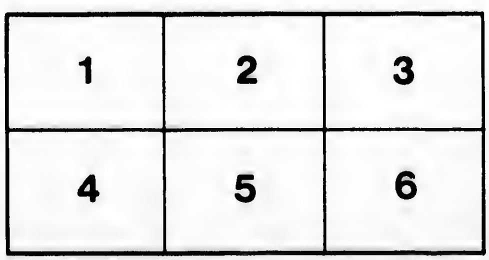

DEPARTMENT OF THE INTERIOR—U. S. GEOLOGICAL SURVEY
CHARLES D. WALCOTT, DIRECTOR

RECENT EARTH MOVEMENT

IN THE

GREAT LAKES REGION

BY

GROVE KARL GILBERT

EXTRACT FROM THE EIGHTEENTH ANNUAL REPORT OF THE SURVEY, 1896-97
PART II—PAPERS CHIEFLY OF A THEORETIC NATURE

WASHINGTON
GOVERNMENT PRINTING OFFICE
1898

RECENT EARTH MOVEMENT IN THE GREAT LAKES REGION.

BY

GROVE KARL GILBERT.

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RECENT EARTH MOVEMENT IN THE GREAT LAKES REGION.

By G. K. Gilbert.

INTRODUCTION.

The geologic history of the earth shows that in all parts of its surface there have been great oscillations of level. Modern history also records upward and downward movements of the land at various points. The modern movements are of small amount, but it is believed that they are of the same kind as the ancient, and that the great changes of the geologic past were effected slowly. Nearly all discoveries of modern change have been made at the seashore, but there is no reason to suppose that the land is now more stable in the interior of the continents than along their coastal borders. Observations are restricted to the coast because the sea level affords the best available datum plane for comparison. The present paper discusses the stability of the region of the Laurentian lakes, and uses the surfaces of the lakes as datum levels or planes of reference.

OBSERVATIONS BY MR. STUNTZ.

In 1869 there was presented to the American Association for the Advancement of Science a paper by G. R. Stuntz, a land surveyor of Wisconsin, describing certain observations on Lake Superior made by him in 1852 and 1853. He states that in those years a certain mill race at the falls of St. Marys River was entirely dry. As St. Marys River is the outlet of Lake Superior, its volume and the supply of water for the mill race depend on the height of water in the lake, and he therefore inferred that at that end of the lake the water was low. He also states that a small stream at Pindle's mill, entering Lake Superior not far from the outlet, runs with swift current to the lake, and has no widening, marshes, or other indication that its valley overflows by the lake setting back into it. He then describes the strongly contrasted condition of streams entering the lake near its western end:[1]

> As you go westward, the Ontonagon River exhibits a slight filling up. The valley near the mouth shows that at the time it was excavated the surface of the lake was lower than at present. The same is also apparent at the mouth of Bad River, still

[1] On some recent geological changes in northeastern Wisconsin: Proc. Am. Ass. Adv. Sci., Vol. XVIII, 1870, pp. 206-207.

farther west. At the mouth of Bois Brulé the same thing is exhibited, only to a greater extent. From this to the west end of the lake not only does the lake set k into the valleys of the streams, but the waters are making rapid encroach- s on the banks. So rapidly is the filling back, that the deposits of the streams keep pace with the filling up. The consequence is, that there is a large nd pond in the mouth of the valley of Bois Brulé and Aminecan River. But re is this filling up more apparent than in the bay above the mouth of the uis River. In several parts submerged stumps, several feet below the present level, are found. The numerous inlets surrounding the main bay, when we consider the nature of the soil and the formation (a tough, red clay), in all of which the water is deep, could not have been excavated in the natural course of events with the water at its present level. The testimony of the Indians also goes to strengthen the same conclusions. At the time of running the State line above mentioned, the Indians, ever jealous of their rights, called me to a council to

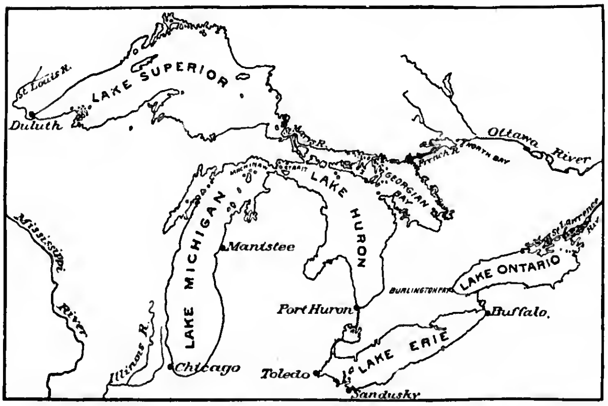


FIG. 93.—Map of Laurentian lakes.

inquire why I ran the line through Indian land. In the explanation, I gave, using the language of the law, as a starting point, the lowest rapid in the St. Louis River. The chief immediately replied that formerly there was a rapid nearly opposite the Indian village. Start, said he, from that place, and you will be near the treaty line. After he had been further questioned, I learned that it was only a few years since the river was quite rapid at the Indian village. At the time the said line was run the first rapid was about 1 mile by the stream above the village. From these facts I conclude that a change is taking place gradually in the level of this great valley.

From these data Stuntz infers "the gradual rise of water at this [west] end of the lake and the falling of the same at the east," and it is evident from the context that he refers this change of the water to a westward canting of the basin, the western part becoming lower as compared with the eastern.

So far as I am aware, this paper broaches for the first time the idea of differential elevation in the Great Lakes region, and it contains the only observations that have ever been cited as showing recent changes of that character. In later years the subject has been approached from the geologic side, and Dr. J. W. Spencer has expressed his opinion that a warping or tilting of the whole region is now in progress.

EARTH MOVEMENTS DURING THE CLOSING EPOCHS OF THE PLEISTOCENE PERIOD.

The Great Lakes came into existence in the latest of the geologic periods, the Pleistocene. Their number and position underwent numerous and important changes during the latter part of the period, and their area and drainage systems have been greatly modified even within the time to which human history belongs. In late Pleistocene time, while the great Laurentide ice field, which just before had covered the entire lake basin, was slowly growing less through the melting away of its edges, there were a series of lakes along its southern margin. These were held in at the north by ice and on other sides by uplands, and they found outlet southward over the lowest passes of the divide between the Laurentian basin and the basins of the Mississippi, Susquehanna, and Hudson. With changes in the position of the ice barrier, individual lakes were from time to time divided or drained and separate lakes united, so that the lacustrine geography had a complex history. After the ice had wholly disappeared from the region, the drainage did not at once assume its present system, for Lake Huron, instead of overflowing to Lake Erie, discharged its surplus water over the pass at North Bay, Canada, and thence down the Mattawa and Ottawa rivers to the St. Lawrence.

In the decipherment of this history much use is made of the shore lines of the vanished lakes. These consist of sand and gravel terraces that were once deltas, of cliffs and strands carved from hillsides by the waves, and of spits and beach ridges thrown up by the same agency. A number of these lines have been traced for great distances, and wherever thus traced it is found that they are no longer level, but are gently inclined. When formed they were of course horizontal, for they were made by waves generated on a water surface, and the fact that they are not now level shows that the land on which they are marked has undergone changes of relative height. The general direction of inclination of the shore lines is toward the south southwest, showing that the basin of the lakes has been canted in that direction. The amount of change has not been everywhere the same, and it is probable that the direction of the canting varies somewhat from place to place. Where several shore lines are traced on the same slope the first made are usually more steeply inclined than the last made, and hence it is inferred that the general change of relative altitude was in progress through the whole epoch of the glacial lakes. The plane of the Iroquois shore line in the basin of Lake Ontario descends toward the south-southwest at an average rate of 3½ feet a mile, the slope being steeper at the north than at the south.[1] The Oswego shore line, in the same basin, slopes in the same direction at the rate of more than 3 feet a mile. The Warren shore line, traced from Lima, New York, about the sides of the Ontario, Erie, and Huron basins to Pompeii, Michigan, is nearly level in the Maumee basin, but rises northeastward with a rate gradually increasing to 2 feet a mile. Its northward rise in Michigan is 1½ feet a mile.[2] The present southward inclination of the water plane of Lake Algonquin, which occupied the Superior, Michigan, and Huron basins, ranges from a few inches to 3 feet a mile.[3] Great Lake Nipissing, which occupied the same basins after the disappearance of the ice and had its outlet at North Bay, conformed more nearly to the present slopes, the general inclination of its water plane being about 7 inches to the mile.[4]

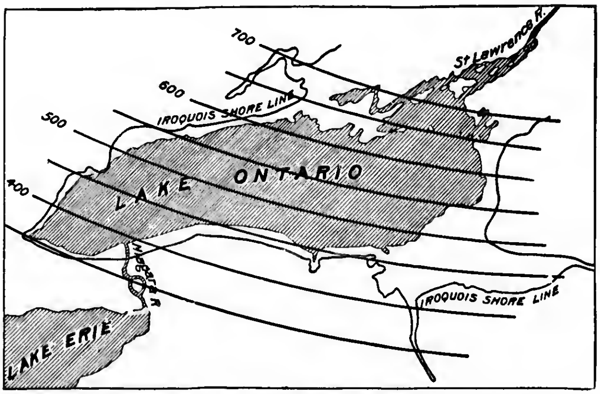


Fig. 94.—Map of the Iroquois shore line. Modern water bodies are shaded. A line shows the boundary of the ancient lake. The parallel curves are isobases.

On the accompanying maps of Lake Iroquois and Great Lake Nipissing (figs. 94 and 95) the character of the tilting is shown by means of isobases, or lines drawn at right angles to the direction of tilting. All points on one of these lines have been uplifted the same amount since the time of the corresponding lake. If we think of the plane of the water surface of one of the old lakes as having been deformed by uplift or warping, then the isobases are contours, or lines of equal present height, on the deformed plane.

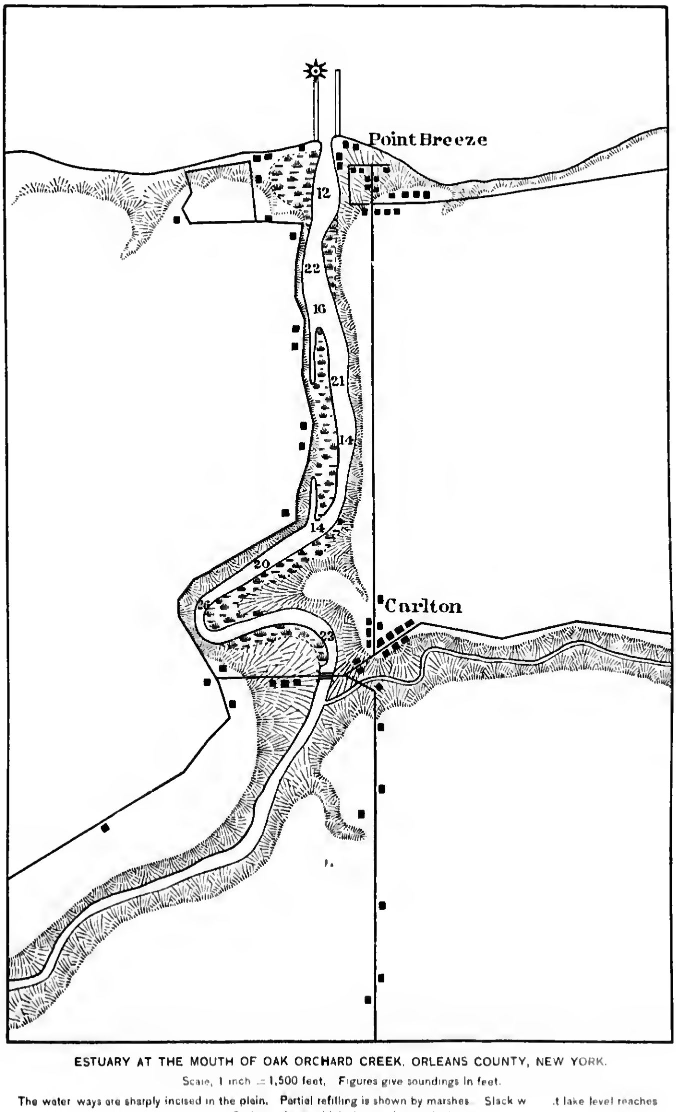
Other evidence of the tilting of the land is found in the character of

[1] J. W. Spencer, Trans. Roy. Soc. Canada, Section IV, 1889, pp. 121-134; G. K. Gilbert, Sixth Ann. Rept. Commissioners of the State Reservation at Niagara, Albany, 1890.

[2] F. B. Taylor, Bull. Geol. Soc. America, Vol. VIII, 1897, p. 55.

[3] F. B. Taylor, A Short History of the Great Lakes, Terre Haute, 1897.

[4] Ibid.



ESTUARY AT THE MOUTH OF OAK ORCHARD CREEK, ORLEANS COUNTY, NEW YORK.

Scale, 1 inch = 1,500 feet. Figures give soundings in feet.

The water ways are sharply incised in the plain. Partial refilling is shown by marshes. Slack w[illegible]t lake level reaches to Carlton, above which the creeks are shallow.

stream channels as they approach lake shores. The streams reaching Lake Superior from the southwest have already been described in the quotation from Stuntz, and similar characters are found in the basins of Lake Erie and Lake Ontario. Considerable tracts of land along the southern shores and about the western ends of these lakes are smooth plains, their surfaces having been leveled by deposits of fine sediment from the Pleistocene lakes just mentioned. The creeks and rivers traversing the plains have readily cut the soft deposits, carving out narrow valleys. In the upper parts of these valleys the streams are shallow and descend with lively current, but on approaching

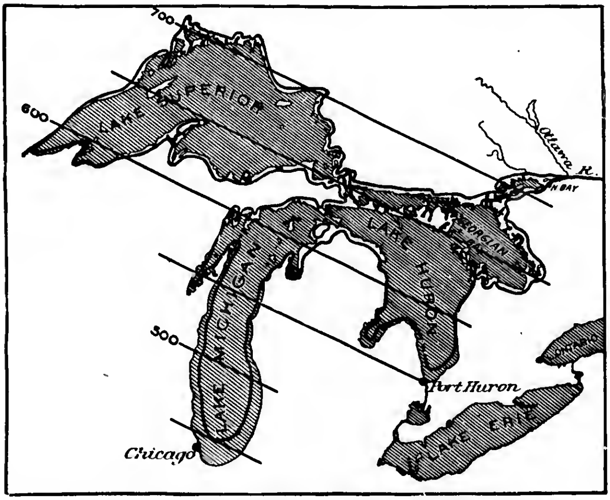


FIG. 95.—Map of the shore line of Great Lake Nipissing. Modern water bodies are shaded. A line shows the boundary of the ancient lake. The parallel lines are isobases.

the lake they become deep and sluggish, the change usually occurring several miles from the lake shore. Stated in another way, each stream, instead of debouching into the lake, enters the head of a long, narrow bay or estuary. The origin of such estuaries is well understood. They are found on all sinking coasts, and their meaning in this region is that the land has gone down or the lake level has risen, so that the waters of the lake occupy portions of the channels carved by the streams in the lowland plain. This description applies to the greater number of streams entering Lake Ontario between the Genesee and Don rivers and to those entering Lake Erie between Cuyahoga River and Maumee Bay. Individual mention may be made of Oak Orchard, Eighteenmile, and Twelvemile creeks in New York, of Twelvemile and Twentymile creeks and the Credit and Humber rivers in Ontario, and of Rocky River, Black River, Vermilion River, Old Womans Creek, Pike Creek, Turtle Creek, and Ottawa River in Ohio. Even the largest rivers of the district, including the Genesee, Niagara, Cuyahoga, and Maumee, have features indicative of the same history.[1]

By reference to the map (fig. 93, p. 602) it will be seen that the outlets of these lakes are at their northernmost points, and this fact is related to the conditions of the stream channels. The water level of a lake is maintained by the balance between inflow and outflow. It is just high enough to enable the outflowing stream to carry off the excess from inflow, and the height of water on all shores is thus determined by the height of the outlet. So if these basins are canted northward the outlets are thus lowered with reference to other parts, and the waters recede on the southern shores. If they are canted southward, the outlets are raised and the waters are made to advance on the southern shores. Reasoning from effect to cause, the fact that the lake water invades the new-made stream channels on the southern shores is evidence of the southward canting.

It should not be assumed that the "drowning" of stream channels is restricted to the tracts mentioned above. Those tracts are specified because they fall within the range of the writer's personal observation and are known to exhibit the phenomena in a striking way. It is believed that similar features may be found wherever the local conditions are favorable throughout the whole coast lines of Lake Ontario and Lake Erie, about the head of Lake Michigan from Manistee, Michigan, to Kewaunee, Wisconsin, and about the whole of the American shore of Lake Superior.

REASONS FOR REGARDING A PROGRESSIVE MODERN CHANGE AS PROBABLE.

Independent of the phenomena described by Stuntz, there are various considerations tending to direct attention to the question of the stability or instability of the Laurentian area at the present time. The first to be mentioned is purely geologic. The epoch during which the overflow from the upper lakes followed the valleys of the Mattawa and Ottawa is definitely associated with a certain stage of the Niagara River. The cataract of Niagara is at the present time increasing the length of the Niagara gorge at a somewhat rapid rate. The formation from which the water leaps is a firm limestone 60 feet thick, and beneath this are shales which are comparatively soft and weak. The cataract, by eroding the shale, undermines the limestone, which falls away in blocks, and these blocks are in turn utilized by the water as an instrument with which to grind the shale. Whirled about by the

[1] F. B. Taylor mentions a few other localities on the same lakes: Am. Geologist, Vol. XV, 1895, pp. 174-176.

water, the blocks not only wear away the face of the shale cliff. but drill down deeply, so that beneath the cataract there is a pool nearly or quite 200 feet deep. Working in this way, the cataract has extended the gorge several hundred feet since the first accurate measurements were made, the average annual rate being between 4 and 5 feet.

With the present arrangement of the drainage system the Niagara carries the surplus water from the basins of lakes Huron, Erie, Michigan, and Superior; but when the upper lakes sent their overflow to the St. Lawrence by way of the Ottawa, the Niagara carried only the discharge from the Erie basin. Its volume was then only one-eighth of the present volume and its power was correspondingly less. It could not move the great blocks of limestone which fell from the cliff, and, instead of scooping out a deep pool, as now, it excavated a comparatively shallow channel. whose bottom was cumbered with limestone débris. Owing to this difference in method of erosion it is possible to discriminate the parts of the gorge excavated when the river was small and when it was large, and thus to determine the place of the cataract when the outlet of Lake Huron was shifted from North Bay and the Ottawa River to Port Huron and the St. Clair and Detroit rivers. That place is at the head of the Whirlpool Rapids, 11,600 feet from the present cataract. Assuming that the cataract worked at its present rate through this distance, we may compute the time consumed. At 4½ feet a year, it would be about two thousand six hundred years. F. B. Taylor, making allowance for various qualifying factors, estimates the time to have been not less than five thousand years.[1]

When Lake Huron changed its outlet, the plane of its water surface extended from the pass at North Bay to the pass at Port Huron, but the North Bay pass now stands 140 feet higher than the Port Huron. This difference of altitude, amounting to 6 inches a mile, has, therefore, been wrought within the period of about five thousand years. In view of the gradual nature of such movements, this is not a long period to assign to the measured change, and it is natural to inquire whether the movement is not still in progress.

Dr. J. W. Spencer, who has devoted much time to the study of the Niagara gorge and the glacial lakes, is confident that change of level has not yet ceased and that it will eventually turn the water of the upper lakes southward to the Illinois and Mississippi rivers, leaving the Niagara channel dry. Addressing the American Association for the Advancement of Science in 1894, he said:[2]

> The end of the falls seems destined, if we read the future by the past, to be effected, not by the erosion expending itself on the rocks, but by terrestrial deformation turning the drainage of all the upper lakes into the Mississippi, by way of Chicago, just as the Huron waters were lately turned from the Ottawa into the Niagara drainage; and at the recent rate it would seem that about 5,000 or 6,000 years at most will be needed. The change of drainage should arrive before the cataract shall have receded to Buffalo.

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[1] A short history of the Great Lakes.
[2] Proc. Am. Ass. Adv. Sci., Vol. XLIII, 1894, p. 246.

Another consideration of the same tendency is found in the condition of the estuaries described in the last section. Most of the streams flowing into these rise in districts of unconsolidated drift and carry forward in flood time a considerable load of detritus. This is deposited in the estuaries, the coarser part making deltas at their heads, and the finer settling as mud in the deeper water. The process tends to convert the estuaries, first, to marshes, and then to dry land, but in most instances little progress in that direction has been made. There are a few creeks rising in sandy districts which have succeeded in filling their estuaries, changing them to marshes; but as a rule the delta at the head of the estuary invades it but a short distance, and the marshes which border it here and there at points sheltered from the flood currents are impassable except by boats, and have the appearance of submerged flood plains. These characters, from their close resemblance to the features observable along the subsiding parts of the Atlantic coast, give the impression that a slow flooding of the stream valleys is still in progress.

A third consideration is connected with the record of recent changes on the coasts of the continent. It has long been known that the Atlantic coast south of Connecticut is subsiding, and Prof. G. H. Cook was able to determine the rate in New Jersey as about 2 feet a century.[1] Dr. Robert Bell has recently collated a variety of facts tending to show that the land has risen in the region about Hudson and James bays,[2] and he estimates the rate at from 5 to 7 feet a century. If these two movements are parts of a general movement affecting the northeastern part of the continent, then the Great Lakes region, approximately intermediate in position between the rising and sinking areas, should be found to exhibit a southward tilting.

These various facts, all tending in one direction, are sufficient warrant for the working hypothesis that the tilting of the lake region demonstrated by the slopes of the old shore lines is still in progress; and the writer, who has for many years been interested in the problems of the Great Lakes, has made repeated efforts to secure an investigation by which the hypothesis might be tested.

The mode of investigation first suggested was the establishment of elaborate observation stations at three points—Port Huron, Chicago, and Mackinac. By a suitable series of observations at these points, the relative heights of benches might be established with high precision, the water surface being used as a leveling instrument. Then, after an interval of one or two decades the observations might be repeated and any changes in the heights of benches due to differential uplift detected. The matter was submitted in 1890 to the Superintendent of the United States Lake Survey and to the Superintendent of the United States Coast and Geodetic Survey, but, though it was received favorably by the latter officer, the work was not undertaken.

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[1] Am. Jour. Sci., 2d series, Vol. XXIV, 1857.
[2] Am. Jour. Sci., 4th series, Vol. 1, 1896.

Other plans were then considered, and it was finally decided to make a study of existing records of lake level, and, if necessary, supplement them by additional observations. The results of this investigation are set forth in the following pages.

GENERAL PLAN OF INVESTIGATION.

Variations in the height of the ocean level at any place depend chiefly on tides, winds, and atmospheric pressure. By means of long series of observations the effect of these disturbing factors can be eliminated

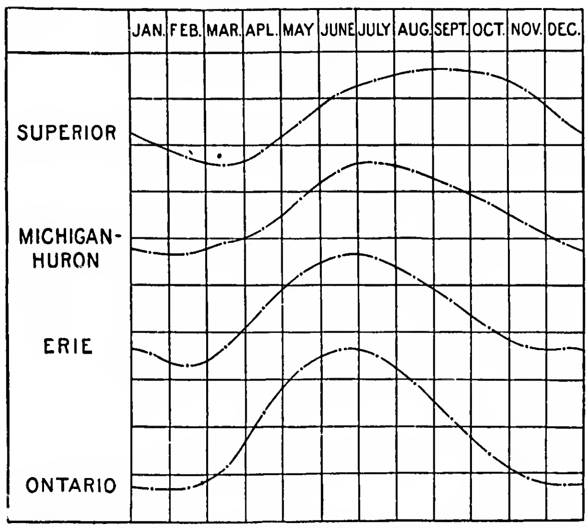


FIG. 96.—Annual oscillations of the surfaces of the Laurentian lakes. Compiled from monthly means published by the Chief of Engineers, U. S. A. Each vertical space represents six inches. The observations for Lake Superior cover the period 1862-1895; for Michigan-Huron, 1860-1895; for Erie, 1855-1895; for Ontario, 1860-1895.

and a mean level obtained which is practically uniform from year to year and decade to decade. The height of the water surface must depend also on the quantity of water in the ocean, but the actual variations of volume are so small as compared to the extent of the ocean surface that the resulting variations of level may be neglected and the mean level used as a standard for the discussion of differential movements of the earth's crust. With the Great Lakes the case is materially different. There are variations due to wind, atmospheric pressure, and tides, but when these have been eliminated by long series of observations the resulting mean level is far from constant, varying from season to season and year to year with the volume of water. In each lake there is an annual change of more than a foot, depending on the seasonal inequality between gain by precipitation and loss by evaporation (fig. 96), and there is a still greater change resulting from the cumulative effect of series of dry and series of moist years. The records show that the water surface in each lake has been several feet higher in some years than in others. (See fig. 97.)

For this reason the water surface of a lake does not afford a datum plane by reference to which the elevation or subsidence of coasts can be directly determined. Fortunately, however, there is an indirect

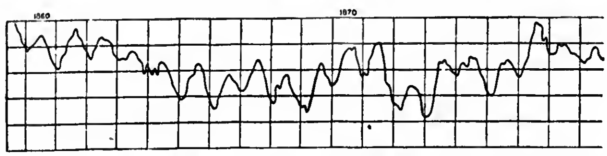


FIG. 97.—Oscillations of the surface of Lake Michigan due to changes in the volume of the lake. Wisconsin, from August, 1859, to June, 1897. Each horizontal

method by which practically the same result may be attained. If the mean level of a lake surface be determined for two parts of the coast at the same time, these two planes may be regarded as parts of the same level surface, and, through reference to this common datum, fixed objects on the land at the two localities can be compared with each other so as to determine their relative altitudes. If, then, after an interval of time, the measurements are repeated, a change in the relative height of the fixed objects may be discovered and measured. The investigation described in the following pages made use of this method.

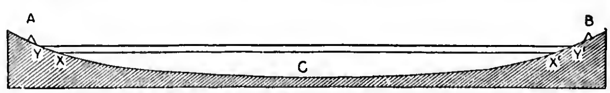
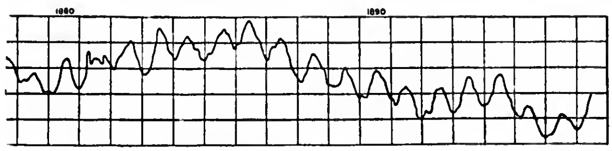


FIG. 98.—Diagram illustrating method of measuring earth movements.

The fundamental principle of the method is illustrated by the diagram, fig. 98, in which A C B is the cross profile of a lake basin. At a certain time the mean plane of the water surface occupies the position XX'. By means of the engineer's level it is ascertained that a bench mark A has a certain height above the water plane at X, and that a bench mark B has a certain height above X'. The difference between these two measurements is the difference in altitude between A and B. After an interval of years the measurements are repeated. The water plane then stands at some different level, say YY'. The height of A above Y is measured, and the height of B above Y'; the difference between the two measurements gives the relative height of A and B. If earth movements have occurred during the interval between the two sets of measurements, the second determination of the comparative height of A and B will differ from the first determination, and the amount of difference will measure the differential earth movement.

AVAILABLE DATA.

Gage readings.—In order to eliminate the temporary effects of disturbing factors, it is necessary to have a series of observations of the height of the water surface at each of the localities compared. The gages by



Compiled under the direction of the Chief of Engineers, U. S. A., from gage readings at Milwaukee. space represents a calendar year; each vertical space, one foot.

means of which such observations are made are of various kinds. One of the simplest is a graduated plank, fixed vertically by attaching it to a dock or other structure, so that one end is above water and the other below. Sometimes the plank is omitted and the graduation marked upon the side of a dock or pier. The height of the water surface is ascertained by direct comparison with the lines of the graduation. Another form of gage which has been extensively used in the lakes consists of a graduated rod, not fixed, but held in the hand; with this the distance from the water surface to a fixed point is measured. Usually the fixed point chosen is above the water surface, but at one station, Port Colborne, it is the submerged sill of a canal lock. Another form of gage includes a float to which a graduated vertical rod is fixed, and the graduations of the rod are compared with a fixed point on the land; or a chain attached to the float may pass over a pulley and carry a counterpoise, in which case an index, fastened to some part of the chain or counterpoise, moves up and down past a stationary graduated scale. There are also automatic gages making periodic or continuous records.

Previous to the year 1859 records of lake level are meager, and not of such nature as to be suited to the purposes of this investigation. A general account of them is given by Col. Charles Whittlesey, in Volume XII of the Smithsonian Contributions to Knowledge, and a fuller account in the Report of the United States Deep Waterways Commission for 1896. In 1859 the investigation of lake levels was undertaken by the United States Lake Survey. Several stations were established on each lake, and at these regular observations were made, usually three times a day. From time to time stations were discontinued and others were established, and after the close of the field work of the Lake Survey the observations were, in many cases, continued by officers of the Engineer Corps in charge of harbor improvements. With reference to the present investigation, I have examined United States Lake Survey and other United States engineer records for the following stations:

On Lake Superior: Superior City, Duluth, Ontonagon, Marquette, and Sault Ste. Marie.

On Lake Michigan-Huron: Chicago, Milwaukee, Grand Haven, Lockport, Sand Beach, Port Austin, Pointe Aux Barques, Tawas, Escanaba, Thunder Bay.

On Lake Erie: Monroe, Rockwood, Cleveland, Ashtabula, Erie, Buffalo.

On Lake Ontario: Port Dalhousie, Niagara, Charlotte, Oswego, Sacketts Harbor.

These records are for the most part published in the form of monthly means, but the individual observations are preserved in the Engineer Office at Washington, and these have been made accessible to me through the courtesy of Gen. William P. Craighill, Chief of Engineers. By the Canadian Department of Railways and Canals, I have been enabled to make use of a long series of observations at Port Colborne, on Lake Erie, the head of the Welland Canal; observations at Toronto, on Lake Ontario, have been furnished me by the city engineer, and observations at Collingwood, on Lake Huron, by Mr. Frank Moberly.

Benches.—As gages at the water side are subject to various accidents, it is rarely possible to maintain their zeros for long periods at a constant level, and unless they are connected by leveling with bench marks of a permanent character their records have little value for purposes of comparison. Previous to 1871 such connection with benches was not made by the United States Lake Survey, or, if made, the records are lost. There were, however, certain stations, notably Chicago, Milwaukee, Cleveland, Port Colborne, Buffalo, Charlotte, and Oswego, at which this matter had received attention. The structures at Chicago on which the early bench marks were made are thought to have afterwards settled.[1] At Milwaukee the early bench marks no longer exist, and although there is reason to believe that other benches were substituted with care, my researches have not discovered a satisfactory record. The same remark applies to Buffalo; and the record of the original bench at Charlotte has been lost. At Port Colborne and Oswego the zeros of gages are permanent structures, which have probably suffered no change; and at Cleveland, although the oldest benches no longer exist, it is believed that the record of transfer is complete and satisfactory.

In 1870 Gen. C. B. Comstock was placed in charge of the United States Lake Survey, and the scientific methods introduced by him

[1] Report on Chicago City Datum and City Bench Marks, by W. H. Hedges, Chicago, 1895.

included the establishment of a complete system of benches in connection with the gages. From 1872 until the completion of the field work of the Lake Survey there was an annual inspection of the gages, and the relations of their zeros to the bench marks were redetermined as often as seemed necessary. From 1871 to 1878 the supervision of gages and the reduction of records were in charge of Mr. O. B. Wheeler, and from 1879 to 1882, of Mr. A. R. Flint. The results of the present investigation are largely indebted to the care and thoroughness with which these engineers performed their work.

SELECTION OF STATIONS AND YEARS.

Under the general method outlined above the first step was the selection of suitable pairs of stations on the shores of the various lakes. As

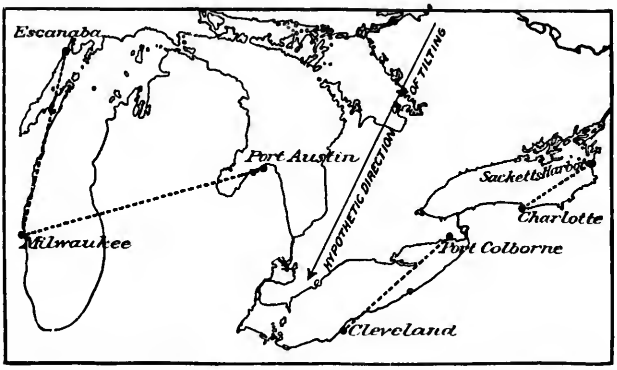


FIG. 99.—Arrangement of selected stations.

the geologic data indicated a tilting of the land toward the south-southwest, or, more precisely, in the direction S. 27° W., it was desirable to have each pair of stations separated by a long distance in that direction. As the hypothetic change was exceedingly slow, it was desirable to compare observations separated by the longest practicable time intervals. It was essential that the gage readings before and after the time intervals be accurately connected with the same benches. Consideration was also given to the fact that the results might be vitiated if use were made of observations taken during the prevalence of storms, when the water is sometimes driven by the wind so as to stand abnormally high on certain shores; and in order that the use of such observations might be avoided it was important to select years during which the force of the wind was daily recorded. With these considerations in view the available data were examined, and the following selection was made of stations (see fig. 99) and years:

For Lake Ontario, Charlotte and Sacketts Harbor, 1874 and 1896.

For Lake Erie, Cleveland and Port Colborne, 1858 and 1895.

For Lake Michigan-Huron, Milwaukee and Port Austin, 1876 and 1896, and Milwaukee and Escanaba, 1876 and 1896.

No comparison was undertaken for stations on Lake Superior.

SPECIAL OBSERVATIONS IN 1896.

Certain of the selected stations are not now maintained by the United States engineers, and in order to complete the data it was necessary to make special observations. This was done in the summer of 1896, during the months of July, August, September, and October. The necessary attention was also given to bench marks, and provision was made for observations of a special character at the regular engineer stations.

At Sacketts Harbor use was made of a gage which had been established for temporary purposes by Maj. W. S. Stanton, U. S. E. It was connected, by leveling, with an old bench mark, and an observer was employed. At Charlotte the relation of the gage zero to a bench mark was determined by leveling, and special series of observations were made by the observer employed by the United States engineers. At Port Austin a new gage was established and a special observer employed. At Milwaukee and Escanaba the relative heights of gages and bench marks were determined under direction of Capt. George A. Zinn, U. S. E., and special observations were made by the observers regularly employed by the United States engineers.

The "special" observations at these stations consisted of series of readings intended to eliminate the effect of the oscillations called "seiches." The equilibrium of a lake surface is disturbed not only by winds, which blow the water toward the lee shore, but by inequalities of atmospheric pressure occurring during thunderstorms and during the passage of cyclones; and the impulses thus received are not quickly dissipated, but cause a long-continued swaying of the water. In large lakes these oscillations are so enduring as to cover the interval from one disturbing impulse to another, and keep the water perpetually in motion. Near the ends of the lakes and in bays with gradually converging sides the range of oscillation may be as great as 1 foot, and it ordinarily amounts at all lake stations to from 1 inch to 4 inches. For this reason a single observation may not approximate closely to the mean level of the water, and the actual mean level can be determined only by a series of observations at short intervals. In arranging the work of 1896 the observers were instructed to record the water level every five minutes for an hour each morning and evening of all days when the wind was light; and at Sacketts Harbor, where the seiche has an exceptionally long period, the length of the series was afterwards increased.

DISCUSSION OF DATA FROM PAIRS OF STATIONS.

SACKETTS HARBOR AND CHARLOTTE.

In 1874 the zeros of gages at these stations were points marked on docks, and readings were made by means of graduated vertical rods attached to floats. They give the distance of the water surface below the gage zeros. At the time of each observation record was also made of the direction and force of the wind. The work was under the direction of the United States Lake Survey. Mr. A. Wilder was the observer at Charlotte, and Mr. Henry Metcalf at Sacketts Harbor.

The gage at Charlotte was put in place in November, 1871, and the measurements showed its zero to be 32.7 feet below a bench mark. In January, 1873, its zero was found to be 32.959 feet below the same bench mark. On May 11, 1874, it was again compared with the bench mark, and the difference was found to have increased to 33.003 feet. It is probable that this change of .044 foot was occasioned by the settling of the dock to which the gage was attached. A manuscript report dated February 3, 1875, says: "The bank is here partly of timbers and partly of earth. The earth has been washed out and has fallen away from the timber in some places." The gage at Sacketts Harbor was also found unstable. The report of an inspection in May, 1874, states that the zero of gage "has been lowered 0.555 foot;" and a report dated February, 3, 1875, says: "This gage is fastened to the timbers of an old and unused dock. The whole structure is quite dilapidated and unstable." The instability of gages determined the selection of time for the comparison of stations. Both gages having been compared with benches in May, 1874, that at Charlotte on the 11th and that at Sacketts Harbor probably on the 14th, the computations were based on a period including these dates. Within this period selection was made of those times of observation when the wind force at both stations was less than 3 on a scale of 10. Thus treated, the observations of 54 days gave 51 comparisons.

Computation of the height of the gage zero at Sacketts Harbor, New York, above the gage zero at Charlotte, New York, in the spring of 1874.

Day.	Hour.	Gage reading.		Difference.
		Sacketts Harbor.	Charlotte.	
1874.		*Feet.*	*Feet.*	*Feet.*
Apr. 17	9 p. m.	5.43	3.15	2.28
19	9 p. m.	5.33	3.01	2.32
22	9 p. m.	5.23	2.98	2.25
23	7 a. m.	5.16	2.80	2.36
	2 p. m.	5.18	2.78	2.40
24	7 a. m.	5.20	2.80	2.40
25	7 a. m.	5.18	2.80	2.38
	2 p. m.	5.11	2.81	2.30
27	7 a. m.	5.08	2.78	2.30
	9 p. m.	4.88	2.78	2.10
28	2 p. m.	5.13	2.87	2.26
	9 p. m.	5.06	2.88	2.18
May 3	7 a. m.	5.06	2.95	2.11
4	7 a. m.	5.43	2.95	2.48
	2 p. m.	5.09	2.94	2.15
	9 p. m.	5.16	2.94	2.22
5	9 p. m.	5.18	2.91	2.27
6	9 p. m.	5.12	2.85	2.27
7	7 a. m.	5.06	2.87	2.19
8	9 p. m.	5.17	2.85	2.32
11	9 p. m.	5.17	2.82	2.35
14	9 p. m.	5.12	2.83	2.29
15	7 a. m.	5.17	2.84	2.33
	2 p. m.	5.25	2.82	2.43
18	2 p. m.	5.13	2.82	2.31
	9 p. m.	5.18	2.83	2.35
20	7 a. m.	5.05	2.83	2.22
	2 p. m.	5.10	2.82	2.20
21	7 a. m.	5.02	2.81	2.21
22	9 p. m.	5.02	2.82	2.20
24	7 a. m.	5.12	2.95	2.17
	2 p. m.	5.08	2.92	2.16
	9 p. m.	5.08	2.91	2.17
26	9 p. m.	5.08	2.86	2.22
27	7 a. m.	5.00	2.86	2.14
	9 p. m.	5.10	2.84	2.26
28	7 a. m.	4.98	2.83	2.15
	9 p. m.	5.02	2.83	2.19

Computation of the height of the gage zero at Sacketts Harbor, New York, above the gage zero at Charlotte, New York, in the spring of 1871—Continued.

Day.	Hour.	Gage reading.		Difference.
		Sacketts Harbor.	Charlotte.	
1871.		*Feet*	*Feet.*	*Feet.*
May 30	7 a.m.	5.00	2.81	2.19
	9 p.m.	5.03	2.82	2.21
June 1	9 p.m.	4.97	2.82	2.15
2	7 a.m.	5.00	2.83	2.17
	9 p.m.	5.02	2.85	2.17
4	9 p.m.	5.10	2.82	2.28
5	9 p.m.	5.00	2.78	2.22
6	7 a.m.	5.00	2.78	2.22
	9 p.m.	5.09	2.79	2.30
7	7 a.m.	5.10	2.79	2.31
	2 p.m.	5.00	2.81	2.19
8	9 p.m.	4.97	2.81	2.16
9	7 a.m.	4.97	2.82	2.15
Mean				2.247 ± .008

In 1896 the gage at Charlotte was a graduated plank spiked to a pile just north of the western abutment of the Rome, Watertown and Ogdensburg Railroad bridge. The readings give the distance of the water surface above the zero of the gage. At Sacketts Harbor the arrangement was similar, the gage being spiked to an unused dock. The observer at Charlotte was Mr. J. W. Preston, harbor master; at Sacketts Harbor, Mr. Wilbur S. McKee. Observations were made morning, noon, and night, the morning and evening observations being extended into series whenever the water was so little agitated by waves that the position of its surface could be determined with precision. As the times selected for these periods of observation were also comparatively free from atmospheric disturbances, and therefore favorable to a general equilibrium of lake surface, the computations were restricted to such times. In the four months of observations there were but five occasions when series were made at both stations.

Computation of the height of the gage zero at Sacketts Harbor, New York, above the gage zero at Charlotte, New York, in the summer of 1896.

Date.	Hour of commencing observation.		Number of five-minute readings.		Mean of readings.		Difference.
	Sacketts Harbor.	Charlotte.	Sacketts Harbor.	Charlotte.	Sacketts Harbor.	Charlotte.	Charlotte minus Sacketts Harbor.
1896.					*Feet.*	*Feet.*	
Aug. 8	7.15 a.m.	7 a.m.	13	13	0.984	0.962	−0.022
8	6.30 p.m.	6 p.m.	13	12	0.912	0.934	0.022
Sept. 9	5.30 a.m.	7 a.m.	13	13	0.351	0.428	0.077
11	5.00 p.m.	6 p.m.	13	13	0.270	0.368	0.098
Oct. 27	8.15 a.m.	7 a.m.	15	11	−0.118	−0.018	0.100
Mean							+0.055 ±0.014

The bench at Charlotte is a mark on the upper surface of the water table of the old light-house. The walls of the building show no cracks, and there is every reason to believe the bench stable. On May 11, 1874, the zero of gage was found by Mr. E. S. Wheeler, assistant engineer United States Lake Survey, to be 33.003 feet below this bench mark. On June 30, 1896, I leveled from the zero of the present gage to the bench mark, obtaining 38.950 as the mean of two measurements. On July 11, 1897, Mr. Warner W. Gilbert obtained 38.954 feet as a mean of two measurements.

The only bench mark existing at Sacketts Harbor in 1874 and 1896 is a point on the upper outer edge of the water table at the northeast corner of the stone building known as the Masonic Temple. In May, 1874, this was determined by Mr. Wheeler to be 12.225 feet above the zero of gage. On June 28, 1896, by duplicate measurements, I found it to be 20.425 feet above the zero of the present gage. The building bearing this mark rests on a foundation of bed rock, but nevertheless has yielded to such extent that its walls are cracked. I was informed that the cracking and repairing of the walls took place some years previous to 1874, and regard it as probable that there has been no change since that date in the height of the bench mark.

These several data are combined in the following table:

Computation of the height of the bench mark at Charlotte, New York, above the bench mark at Sacketts Harbor, New York, in 1874 and 1896.

	1874.	1896.
	Feet.	*Feet.*
Charlotte bench mark above Charlotte gage zero	+33.003	+38.950
Charlotte gage zero above Sacketts Harbor gage zero	− 2.247	− 0.055
Sacketts Harbor gage zero above Sacketts Harbor bench mark	−12.225	−20.425
Sum of above = Charlotte bench mark above Sacketts Harbor bench mark	+18.531	+18.470
Difference	−0.061	

The results of the computations indicate that the height of the Charlotte bench mark above the Sacketts Harbor bench mark has diminished in twenty-two years to the extent of 0.061 foot. This quantity is the algebraic sum of six other quantities, two measurements through water leveling and four measurements by the engineer's level. The probable errors of the water levelings are ±0.008 and ±0.014 foot; the probable errors of my own instrumental levelings were each ±0.01 foot. Assigning the same precision to the earlier levelings, we obtain for the resulting quantity (0.061 foot) a probable error of about ±.03 foot.

This probable error attempts to express only such deviations from accuracy as are exhibited by the discordance of observations; it does not include errors of the class called constant. The result may be vitiated by the instability of either bench or by river freshets in 1874, and there are qualifications related to tides and cyclonic gradient.

The data at Sacketts Harbor are not subject to errors from stream floods. The gages at Charlotte were on the bank of the Genesee River near its mouth. The channel is deep, and at ordinary river stages the current is so gentle that river level and lake level are the same, but in time of river flood the river level is somewhat higher. In 1896 no flood periods were included, but the records for 1874 are not full enough to insure freedom from flood influences. If the Charlotte data include errors due to that cause, their correction would increase the computed change of relative height.

The tides of the Great Lakes are so small as to be masked by the seiches, but they are nevertheless of sufficient magnitude to affect an investigation of this sort. Lieut. Col. J. D. Graham determined a lunar tide of Lake Michigan at Chicago amounting to 1¾ inches and a spring tide amounting to 3½ inches.[1] Gen. C. B. Comstock determined a lunar

[1] Ann. Rept. Chief of Engineers, U. S. A., for 1860, p. 296.

tide of Lake Michigan at Milwaukee of 1 inch and a solar tide of one-half inch; and a tide of 1½ inches was found at the west end of Lake Superior.[1] The tides of Lake Ontario have not been investigated, and therefore a correction for them can not be applied. It would be quite possible to eliminate their effect by making the periods of observation include complete tidal cycles; but the local conditions gave greater importance to other criteria for the selection of times. An inspection of dates with reference to tidal cycles shows that the observations are so distributed that the influence of tide can not be great.

A complete comparative discussion of lake levels should also take account of differences of atmospheric pressure. It is evident that in a condition of equilibrium the level water surface must be deformed by local inequalities of atmospheric pressure, and the effect of pressure differences of course coexists with inequalities due to other causes. In planning these computations the intention was to apply corrections for barometric gradient, but this intention was afterwards relinquished because of the difficulty of properly discussing the available barometric data. Such examination as was given to the subject led to the opinion that during the stormless periods selected for the comparison of gage readings the error arising from the neglect of the pressure correction is small.

PORT COLBORNE AND CLEVELAND.

The character of the gage used at Cleveland in 1858 is not described in the records I have seen. Neither is the name of the observer given, but various circumstances indicate that the readings were made either by Col. Charles Whittlesey or under his immediate direction. The readings give the distance of the water surface below the high-water level of 1838, and that level was adopted by the United States Lake Survey as the plane of reference for all observations on Lake Erie. At Port Colborne the upper sill of Lock No. 27 of the Welland Canal was the zero of measurement, and the measurement was made by the lock master, Mr. John McGillivray, by thrusting a graduated pole into the water until the end rested on the lock sill. As the reference point at Cleveland was above the water surface and that at Port Colborne below, their difference in height is obtained by adding the two readings. Most of the observations at Cleveland were made at 8 a. m. and the observations at Port Colborne at noon. At Port Colborne the direction of the wind was recorded; at Cleveland, the direction and force. I do not know the scale of force employed, but the record numbers range from 0 to 5. All observations at both stations were rejected when the wind force at Cleveland was recorded as greater than 1.

The gage zero used at Cleveland in 1895 was the upper edge of a cleat nailed to a plank forming one wall of a well in a wharf. From

[1] Ann. Rept. Chief of Engineers, U. S. A., for 1872, pp. 1033, 1035, 1040; 1875, pp. 1173, 1192, 1194.

this the observer measured to the water surface in the well with a graduated rod. The gage zero was set at the level of high water in 1838, which is mentioned in the records as "the plane of reference." Three observations were made daily, at 7 a. m., 1 p. m., and 7 p. m., the work being under the direction of the United States Engineers. At Port Colborne observation was made by means of a float connected through a chain with a counterpoise, and was therefore indirect; but the readings were checked by occasional observations with a pole, after the method of 1858. An index on the counterpoise was so adjusted as to indicate on a scale the depth of water on the lock sill. I inspected the gage in 1896, finding it in close adjustment, except that an error in either direction of a fraction of an inch might arise from friction. The observer in 1895 was Mr. John Henshaw. In the following table the readings at Port Colborne, which were recorded in feet and inches, have been converted to feet and hundredths. The record of wind at the two stations was the same as in 1858, and there were also available the wind and pressure observations of the United States Weather Bureau. From an inspection of these data three periods were selected for comparison: June 28 to July 3, July 18 to 28, and August 3 to 18. These periods are so related to the tidal cycle as nearly to eliminate tidal error.

Computation of the height of the "plane of reference" at Cleveland, Ohio, above the sill of Lock No. 27 of the Welland Canal at Port Colborne, Ontario, in 1858 and 1895.

Date.	Reading at Cleveland.	Reading at Port Colborne.	Sum.	Date.	Readings at Cleveland. 7 a. m.	1 p. m.	7 p. m.	Mean.	Reading at Port Colborne.	Sum.
1858.	*Ft. in.*	*Ft. in.*	*Ft. in.*	1895.	*Feet.*	*Feet.*	*Feet.*	*Feet.*	*Feet.*	*Feet.*
Aug. 20	0 9.0	14 7	15 4.0	June 28	....	3.30	3.50	3.40	10.92	14.32
24	0 8.0	14 6	15 2.0	29	3.55	3.50	3.53	3.53	10.75	14.28
25	0 8.5	14 6	15 2.5	30	3.55	3.50	3.53	3.53	11.08	14.61
28	0 5.0	14 0	14 5.0	July 1	3.30	3.40	3.50	3.40	10.75	14.15
31	0 8.0	14 3	14 11.0	2	3.47	3.45	3.55	3.49	10.83	14.32
Sept. 1	0 7.2	14 4	14 11.2	3	3.57	3.60	....	3.58	10.92	14.50
3	0 8.0	14 0	14 8.0	18	3.57	3.80	3.83	3.73	11.00	14.73
6	0 9.5	13 11	14 8.2	19	3.85	3.50	3.70	3.68	10.75	14.43
9	0 9.4	14 1	14 10.4	20	3.80	3.68	3.53	3.67	11.25	14.92
12	0 8.7	14 0	14 8.7	21	3.33	3.87	3.63	3.61	11.00	14.61
14	0 10.7	13 8	14 6.7	22	3.90	3.50	3.60	3.67	10.75	14.42
15	0 6.0	13 11	14 5.0	23	3.60	3.70	3.70	3.67	10.83	14.50
16	0 2.3	13 9	13 11.3	24	3.68	3.60	3.70	3.66	10.83	14.49
18	0 6.7	14 3	14 9.7	25	3.72	3.73	3.82	3.76	10.67	14.43
20	0 9.3	14 0	14 9.3	26	3.70	3.73	3.63	3.69	11.00	14.69
23	1 0.8	13 11	14 11.8	27	3.75	3.70	3.32	3.59	10.92	14.51
24	1 1.5	13 5	14 6.5	28	3.50	3.43	3.80	3.58	10.75	14.33
25	1 0.9	14 0	15 0.9	Aug. 3	....	3.70	3.80	3.80	11.00	14.80
27	1 1.8	14 2	15 3.8	4	3.80	3.73	3.73	3.75	10.75	14.50
30	1 2.5	14 5	15 7.5	5	3.73	3.68	3.68	3.70	10.58	14.28
Oct. 4	1 1.6	14 0	15 1.6	6	3.90	3.73	3.70	3.78	11.33	15.11
10	1 3.0	13 10	15 1.0	7	3.93	3.95	3.60	3.83	11.75	15.58

Computation of the height of the "plane of reference" at Cleveland, Ohio, above the sill of Lock No. 27 of the Welland Canal at Port Colborne, Ontario, in 1858 and 1895—Continued.

Date.	Reading at Cleveland.	Reading at Port Colborne.	Sum.	Date.	Readings at Cleveland. 7 a. m.	Readings at Cleveland. 1 p. m.	Readings at Cleveland. 7 p. m.	Readings at Cleveland. Mean.	Reading at Port Colborne.	Sum.
1858.	*Ft. in.*	*Ft. in.*	*Ft. in.*	1895.	*Feet.*	*Feet.*	*Feet.*	*Feet.*	*Feet.*	*Feet.*
Oct. 11	1 4.0	13 6	14 10 0	Aug. 8	3.75	3.60	3.80	3.72	10.67	14.39
14	1 2.2	14 3	15 5.2	9	3.72	3.70	3.59	3.67	10.83	14.50
15	0 11.0	14 3	15 2 0	10	3.60	3.75	3.70	3.78	10.75	14.53
16	0 10.5	14 5	15 3.5	11	3.80	3.50	3.64	3.65	10.67	14.32
18	1 5.0	14 2	15 7.0	12	3.54	3.78	3.68	3.67	11.00	14.67
19	1 4.9	13 5	14 9.9	13	3.60	3.67	3 60	3.62	10.83	14.45
20	1 2.0	13 3	14 5.0	14	3.68	3.65	3.70	3.68	11.00	14.68
21	1 4.7	13 2	14 6.7	15	3.61	3.72	3.65	3.66	11.06	14.60
22	1 4.8	13 7	14 11.8	16	3.52	3.59	3.67	3.59	10.83	14.42
25	1 1.8	12 5	13 6.8	17	3.76	3.68	3.70	3.69	10.75	14.44
26	1 4.4	12 7	13 11.4	18	3.80	3.83	3.70	3.78	11.17	14.95
27	1 4.9	12 7	13 11.6							
28	1 4.3	12 11	14 3.3							
30	1 6.1	13 3	14 9.1							
Mean (in feet)			14.800 ±.057							14.561 (±.022)

Height of Cleveland plane of reference above Port Colborne lock-sill—

1858	14.800	±.057
1895	14.561	±.022
Difference	—0.239	±.06

The zero of gage at Port Colborne, being submerged masonry, is of unquestioned stability. The canal was constructed in 1833, and if any settling followed construction it was doubtless complete before 1858; but the appearance of the masonry above the water gives no suggestion of yielding.

The earlier work at Cleveland was connected with several bench marks, all of which have been destroyed, but before the disappearance of the last one the datum was transferred by leveling to other points. The chain on which the record depends is as follows:

1. "Top of coping of the northeast wall of the Ohio Canal lock where it joins the river." The high water of 1838 was directly compared with this bench, and Whittlesey states that it is 6.30 feet above that high-water plane.[1] As the observations in 1858 were made near the lock, and as Whittlesey, who reports them, was a civil engineer whose writings show that he appreciated the importance of precise bench marks, it is probable that the observations were properly connected with the bench. Explicit statement, however, is lacking; the record merely refers the lake level to the high water of 1838. The bench was destroyed in 1877 or 1878.

[1] Canadian Naturalist, Vol. VII, 1875, p. 412.

2. "Cross on water table, northeast corner of Johnson House block, southwest corner of Front and East River streets." On June 15, 1875 (as shown by manuscript records in the office of the Chief of Engineers, U. S. A.), Assistant Engineer T. W. Wright, United States Lake Survey, leveled from this bench mark to the canal lock coping (1), finding the difference (1 above 2) to be 3.67 feet. This bench mark is still in existence. The walls of the building are cracked in such manner as to indicate some settling of the northeast corner, and the broad flagstone on which the bench is marked stands (in 1897) 0.04 foot lower than the next stone of the water table toward the west. As the lower stone supports part of the building and the higher stone carries no load, the latter may be assumed to show the original level of the former. It is impossible to say whether this settling affects the record of water levels. The building was erected in 1842, and is therefore 55 years old; it was 33 years old in 1875 when the datum of levels was transferred to it. The datum remained with it eighteen years, until 1893. If settling has progressed at a uniform rate, the datum was affected 0.013 foot, but it is equally possible that the settling belonged to the early history of the building and that a condition of practical stability was reached prior to 1875.

3. "Bottom of west angle iron, on bottom of north longitudinal plate girder, middle of first full-depth bent, close to stone pier, new L. S. & M. S. R. R. drawbridge, now [1893] being finished." As the bridge is symmetric and reversible, this description applies to two different points, but measurement shows that they have the same height. It was copied from manuscript records in the United States Engineers office at Cleveland, courteously placed at my service by Col. Jared A. Smith. The records show that in June, 1893, the bridge bench (3) was connected by leveling with the Johnson House bench (2) and also with the gage zero, and that the gage zero was checked by the bridge in 1896 and found correct. The gage readings in 1895 (used in our computations) are thus referred to the bridge bench. The height of the bridge bench is given as 4.34 feet above the "plane of reference," and by implication as 1.71 feet above the Johnson House bench (2). The drawbridge rests on a stone pier many years older than the present bridge, and there can be little question of its stability.

In these records of bench marks and levelings in Cleveland there is certainly much to be desired, but the presumption is nevertheless in favor of good work.

It appears from the computation that the ground at Port Colborne has risen, as compared to the ground at Cleveland, 0.239 foot, or about 2⅞ inches in thirty-seven years. The probable error of this measurement, as indicated by the discordance of gage data, is three-fourths of an inch.

As a check upon this result, a third computation was made from gage readings in the summer of 1872, a year in which the gage zero at Cleveland was connected with the canal-lock bench mark by instrumental leveling. That computation gives for the height of the plane of reference at Cleveland above the lock sill at Port Colborne 14.714 feet. If we assume a gradual change from 1858 to 1895, and interpolate between 14.800 feet, the determination for 1858, and 14.561, the determination for 1895, we obtain for the summer of 1872 the value 14.710 feet, which differs from the result of that year's observations by only 0.004 foot. The observations on Lake Erie thus accord well with the theory of a progressive southward tilting of the land.

The Port Colborne gage is not so related to streams as to subject its readings to error from floods. The Cleveland gage, like the Charlotte, is on a river estuary, and the readings are subject to influence by floods. The records include no systematic account of the condition of the river, and it is therefore possible that some of the observations were made when the river level was above the lake level.

PORT AUSTIN AND MILWAUKEE.

At each of these stations automatic gages were maintained for several years, and their tracings give the height of water level with an amount of detail permitting the complete elimination of seiches and tides; but there was, unfortunately, some uncertainty as to the position of the zeros, and the danger of thus introducing constant errors led me to avoid the automatic records and choose times when other gages were employed. The earlier period selected for the comparison was the summer of 1876, and the gages then used were floats carrying graduated vertical rods. The force and direction of the wind were recorded at Port Austin by the gage observer, and at Milwaukee by the United States Weather Bureau. From an inspection of these records, together with the Weather Bureau records of barometric gradient, selection was made of the periods July 11 to 19 and August 16 to 24, excepting only certain hours when the force of the local wind was recorded as greater than 3 in a scale of 10. This gave 46 separate comparisons, from which the difference in height of the gage zeros was computed. The chosen periods are well disposed with reference to tides. The readings at Milwaukee were made at 7 a. m., 1 p. m., and 6 p. m., by Mr. John McCabe; at Port Austin the hours were 7 a. m., 2 p. m., and 9 p. m., and the observer was Mr. J. W. Kimball. In the computations the midday observations, though one hour apart, and the evening observations, though three hours apart, were treated as simultaneous.

Computation of height of gage zero at Port Austin, Michigan, above gage zero at Milwaukee, Wisconsin, in the summer of 1876.

Date.	Readings at Milwaukee.			Readings at Port Austin.			Differences.		
	7 a.m.	1 p.m.	6 p.m.	7 a.m.	2 p.m.	9 p.m.			
1876	*Feet.*	*Feet.*	*Feet.*	*Feet.*	*Feet.*	*Feet.*	*Feet.*	*Feet.*	*Feet.*
July 11	2.17	2.23	2.12	7.22	7.31	7.47	5.05	5.08	5.35
12	2.12	2.03	2.16	7.54	7.25	7.22	5.42	5.22	5.06
13	2.20	2.05	2.35	7.35	7.37	7,35	5.15	5.32	5.00
14	1.95	2.12	2.10	7.50	7.41	7.30	5.55	5.29	5.20
15	2.16	2.15	2.06	7.33	7.35	7.30	5.17	5.20	5.21
16	2.13	2.12	2.11	7.34	7.25	7.40	5.21	5.13	5.29
17	2.15	2.20	2.21	7.37	7.37	7.30	5.22	5.17	5.09
18	2.20	2.07	2.20	7.21	7.25	7.28	5.01	5.18	5.08
19	2.18	....	....	7.34	....	....	5.16	....	....
Aug. 16	2.29	....	2.20	7.50	....	7.35	5.21	....	5.15
17	2.19	....	2.21	7.33	....	7.50	5.14	....	5.29
18	2.23	2.02	2.27	7.50	7.35	7.40	5.27	5.33	5.13
19	....	2.22	....	....	7.45	....	....	5.23	....
20	....	2.18	2.23	....	7.62	7.37	....	5.44	5.14
21	2.25	2.20	2.21	7.41	7.34	7.37	5.16	5.14	5.13
22	2.32	2.18	2.33	7.38	7.51	7.40	5.06	5.33	5.07
23	2.26	1.91	2.10	7.38	7.60	7.59	5.12	5.69	5.49
24	2.25	....	2.42	7.49	....	7.49	5.24	....	5.07
Mean									5.240 ±.013

In 1896 the gage at Milwaukee consisted of a graduated rod held in the observer's hand in measuring down to the water from a fixed point or zero. At Port Austin a board, carrying a graduated scale, was spiked to the side of a timber crib, and the position of the water surface on the scale was noted by the observer. At each of these stations a series of 12 observations, at five-minute intervals, was made every morning and evening when the surface of the water was nearly smooth. The mean of a series was afterwards treated as one observation, and the computation was based on the simultaneous pairs of observations—53 in number. The selection of times was thus determined by conditions favorable for the elimination of seiches, but it appears by inspection that tidal influences also are very nearly eliminated. The observers were: At Milwaukee, Mr. John McCabe; at Port Austin, Mr. John P. Smith.

As the zero at Milwaukee was above the water, and the zero at Port Austin below, the sum of the readings gives the height of one zero above the other.

Computation of height of gage zero at Milwaukee, Wisconsin, above gage zero at Port Austin, Michigan, in the summer of 1896.

Date.		Time.	Readings (means of series). Milwaukee.	Port Austin.	Sum.
1896.			*Feet.*	*Feet.*	*Feet.*
July	20	A. M.	5.528	1.271	6.799
	24	A. M.	5.483	1.333	6.816
	28	A. M.	5.703	1.385	7.088
	29	A. M.	5.470	1.351	6.824
		P. M.	5.560	1.375	6.935
Aug.	1	A. M.	5.436	1.297	6.733
	2	P. M.	5.620	1.425	7.045
	7	P. M.	5.447	1.420	6.867
	9	A. M.	5.519	1.448	6.967
	11	A. M.	5.575	1.433	7.008
	14	A. M.	5.338	1.455	6.793
	20	A. M.	5.587	1.340	6.927
	20	P. M.	5.571	1.406	6.977
	21	A. M.	5.558	1.330	6.888
		P. M.	5.588	1.391	6.979
	22	A. M.	5.505	1.259	6.764
		P. M.	5.540	1.229	6.769
	21	P. M.	5.595	1.375	6.970
	25	A. M.	5.721	1.221	6.942
	25	P. M.	5.792	1.268	7.060
	28	P. M.	5.721	1.279	7.000
	30	P. M.	5.797	1.239	7.036
Sept.	1	P. M.	5.725	1.259	6.984
	2	P. M.	5.748	1.203	6.951
	4	P. M.	5.720	1.248	6.968
	5	P. M.	5.515	1.134	6.649
	7	P. M.	5.739	1.275	7.014
	8	A. M.	5.649	1.203	6.852
		P. M.	5.595	1.139	6.734
	9	P. M.	5.585	1.077	6.662
	14	A. M.	5.584	1.208	6.792
	15	A. M.	5.560	1.181	6.741
	20	P. M.	5.892	1.281	7.173
	23	A. M.	5.791	1.307	7.098
	25	A. M.	5.932	0.803	6.735
	28	P. M.	5.755	1.167	6.922
	29	A. M.	5.615	1.013	6.628

Computation of height of gage zero at Milwaukee, Wisconsin, above gage zero at Port Austin, Michigan, in the summer of 1896—Continued.

Date.	Time.	Readings (means of series).		Sum.
		Milwaukee.	Port Austin.	
1896.		*Feet.*	*Feet.*	*Feet.*
Oct. 2	A. M.	5.566	1.250	6.816
3	A. M.	5.594	1.465	7.059
	P. M.	5.574	1.186	6.760
4	P. M.	5.632	1.101	6.733
5	P. M.	5.705	1.085	6.790
10	P. M.	5.506	0.889	6.395
15	A. M.	5.784	0.769	6.553
17	A. M.	5.642	1.444	7.086
18	A. M.	5.720	1.398	7.118
19	A. M.	5.846	1.215	7.061
22	A. M.	6.182	1.212	7.394
25	A. M.	6.139	0.800	6.939
26	P. M.	5.960	0.858	6.818
27	A. M.	5.918	0.750	6.668
	P. M.	5.809	0.722	6.531
29	A. M.	5.864	0.724	6.588
Mean				6.875 ±.019

Milwaukee is well provided with engineer bench marks, and it is probable that thorough research would establish the connection of the gage zeros at each epoch with several of the bench marks; but after inspection of the data readily accessible, I thought it best to make use of only one bench, that called the "check point." This consists of the top of a copper bolt leaded into the north side of the center pier of the swing bridge over the river between Chestnut and Division streets. The gage observer is required at stated intervals to check the stability of the zero of his gage by means of this check point. Using two rods, with the aid of an assistant he makes a series of simultaneous measurements from the check point and from the gage zero down to the water level, and from these measurements the relation of the gage zero to the check point is determined. Their relation has also been determined by means of the engineer's level at various times, and was so determined on August 8, 1876, by Assistant Engineer L. L. Wheeler, who found the check point 0.843 foot above the gage zero. In 1896 the check observations by the observer were very thorough, series of twenty simultaneous readings being made every fortnight, and from five of these series the relation of the two points is computed as follows:

Computation of height of Milwaukee check point above Milwaukee zero of gage in the summer of 1896.

	Feet.
July 12 (mean of twenty comparisons by simultaneous readings)	1.203
July 26	1.212
August 14	1.200
August 28	1.203
September 16	1.206
Mean	1.205 ±.002

In response to a letter of inquiry as to the stability of the Milwaukee check point, Capt. George A. Zinn, United States engineer in charge of harbor improvements, writes as follows:

The Chestnut Street Bridge, on the center pier of which the check point is established, was built in 1872.

Mr. G. H. Benzenberg, city engineer, states that the pier rests on a pile foundation; that to his knowledge the drawbridge has never been releveled since put in place, and that if any appreciable settlement had taken place in the center pier it would have interfered with the operating of the swing bridge. He stated positively that no settlement had occurred.

The principal bench mark used in 1876 at Port Austin, called the Wisner bench mark, was a copper bolt leaded into bed rock; but in 1896 I was unable to find it, and, as at Milwaukee, I had recourse to a bench mark originally established and used as a check point. It is the top of an iron bolt driven into a vertical face of bed rock on the west side of a promontory opposite the residence of Mr. J. W. Kimball. In July, 1875, and October, 1876, Assistant Engineer T. W. Wright found the check point 7.424 feet below the Wisner bench mark; in June, 1896, I found the gage zero 5.125 feet below the check point, this quantity being the mean of two measurements.

Manuscript records in the archives of the Lake Survey state that the Port Austin gage zero was originally placed on a level with the Wisner bench mark, but that in July, 1875, it was 0.003 foot too low, and that on October 18, 1876, it was 0.040 foot too low, having settled during the interval. As the observations used fall within this interval, it was necessary to make some assumption in regard to this settling, and the assumption made was that it had been at uniform rate through the whole period. The correction interpolated for the time of observation was 0.034 foot. Combining this correction with data from leveling in 1875 and 1876, I obtained as the height of the gage zero above the check point in July and August, 1876, 7.460 feet. The various data thus described are combined in the following table.

Computation of height of Milwaukee check point above Port Austin check point in the summers of 1876 and 1896.

	1876.	1896.
	Feet.	*Feet.*
Milwaukee check point above Milwaukee gage zero	0.843	1.205
Milwaukee gage zero above Port Austin gage zero	—5.210	6.875
Port Austin gage zero above Port Austin check point	7.460	—5.125
Sum of above = Milwaukee check point above Port Austin check point	3.093	2.955
Difference	—0.138	

This result indicates that the ground at Milwaukee, as compared to the ground at Port Austin, has subsided 0.138 foot in the twenty years from 1876 to 1896. It is the algebraic sum of six measurements, of which three are levelings by water surface and three by the engineer's level. The probable errors of the water-level measurements are ±0.019, ±0.013, and ±0.002. The probable errors of the Port Austin levelings in 1896, as indicated by the discordance of two independent results, is ±0.008. If the probable error of each of the other measurements was ±0.010, the probable error of the result is less than ±.03 foot. There is also an uncertainty arising from the possibility that the stone pier to which the Milwaukee check mark is attached has settled, another uncertainty due to the possibility of river floods, and a third involved in the assumption that the settling of the Port Austin gage zero in 1876 was at a uniform rate. If all the settling of the Port Austin zero took place before the period of observation, the assumption makes the result too large by 0.006 foot; if all the settling took place after the observations, the assumption makes the result too small by 0.031 foot. The Port Austin record is free from stream-flood influences, but the Milwaukee gage station is on a narrow estuary, like the stations at Charlotte and Cleveland.

ESCANABA AND MILWAUKEE.

In comparing Escanaba with Milwaukee the same general periods of observation were employed as in comparing Port Austin with Milwaukee, but the individual days, though selected in the same manner, were in part different. Fifty-one separate comparisons were made in 1876, and 52 in 1896. The selection of times was controlled by conditions favorable for the elimination of seiches, but the combination of days chosen was found to approximately eliminate tidal effects also.

The observations at Escanaba in 1876 were conducted in the same manner as at Milwaukee and Port Austin, the hours being 7 a. m., 2 p. m., and 9 p. m., and the observer Mr. George Preston. In 1896 the system was the same as at Milwaukee, the observer being Mr. Clinton

B. Oliver. The following tables give the computations for the two years:

Computation of height of gage zero at Milwaukee, Wisconsin, above gage zero at Escanaba, Michigan, in the summer of 1876.

Date.	Readings at Escanaba.			Readings at Milwaukee.			Differences.		
	7 a. m.	2 p. m.	9 p. m.	7 a. m.	1 p. m.	6 p. m.			
1876.	*Feet.*	*Feet.*	*Feet.*	*Feet.*	*Feet.*	*Feet.*	*Feet.*	*Feet.*	*Feet.*
July 11	1.86	1.90	1.78	2.17	2.23	2.12	0.31	0.33	0.31
12	1.90	1.75	1.78	2.12	2.03	2.16	.22	.28	.38
13	2.00	2.07	1.95	2.20	2.05	2.35	.20	—.02	.40
14	2.10	2.15	2.05	1.95	2.12	2.10	—.15	—.03	.05
15	1.96	1.95	2.00	2.16	2.15	2.06	.20	.20	.06
16	1.90	1.95	1.85	2.13	2.12	2.11	.23	.17	.26
17	1.89	1.80	1.85	2.15	2.20	2.21	.26	.40	.36
18	2.05	1.85	1.95	2.20	2.07	2.20	.15	.22	.25
19	1.75	....	....	2.18	....	....	.43	....	....
Aug. 16	2.07	1.94	1.90	2.29	2.30	2.20	.22	.36	.30
17	2.00	1.95	1.95	2.19	2.13	2.21	.19	.18	.26
18	1.70	1.93	2.00	2.23	2.02	2.27	.53	.09	.27
19	1.78	2.00	....	2.13	2.22	....	.35	.22	......
20	1.95	1.90	1.85	2.23	2.18	2.23	.28	.28	.38
21	1.85	2.05	2.10	2.25	2.20	2.24	.40	.15	.14
22	1.83	2.05	1.90	2.32	2.18	2.33	.49	.13	.43
23	1.91	1.83	1.75	2.26	1.91	2.10	.35	.08	.35
24	1.95	1.85	1.90	2.25	2.10	2.42	.30	.25	.52
Mean									0.255 ±.012

Computation of height of gage zero at Escanaba, Michigan, above gage zero at Milwaukee, Wisconsin, in the summer of 1896.

Date.		Time.	Readings (means of series).		Difference.
			Milwaukee.	Escanaba.	
1896.			*Feet.*	*Feet.*	*Feet.*
July	2	P. M.	5.465	5.917	0.452
	7	A. M.	5.434	5.907	.473
	8	A. M.	5.505	5.920	.415
	9	A. M.	5.348	5.837	.489
		P. M.	5.356	5.765	.409
	10	A. M.	5.442	5.771	.329
		P. M.	5.567	5.694	.127
	11	P. M.	5.576	5.771	.195
	13	A. M.	5.411	5.869	.458
		P. M.	5.493	5.776	.283
	14	A. M.	5.574	5.750	.176
	17	A. M.	5.431	5.865	.434
	19	A. M.	5.524	6.007	.483
		P. M.	5.496	5.887	.391
	20	A. M.	5.528	5.803	.275
	21	A. M.	5.573	5.973	.400
	23	A. M.	5.645	5.908	.263
	25	A. M.	5.601	5.856	.255
	28	A. M.	5.703	5.857	.154
	31	A. M.	5.446	5.938	.492
Aug.	1	P. M.	5.360	5.859	.499
	4	A. M.	5.654	5.912	.258
	8	P. M.	5.347	5.954	.607
	9	A. M.	5.519	5.658	.139
	10	P. M.	5.328	5.546	.218
	13	A. M.	5.273	5.616	.343
		P. M.	5.378	5.752	.374
	14	A. M.	5.338	5.670	.332
	15	A. M.	5.360	5.730	.370
		P. M.	5.402	5.710	.308
	19	A. M.	5.414	5.878	.464
	21	A. M.	5.558	5.935	.377
		P. M.	5.588	5.872	.281
	22	A. M.	5.505	5.698	.183
Sept.	4	A. M.	5.734	6.028	.294
	13	P. M.	5.452	5.848	.396
	14	A. M.	5.584	5.762	.178
	16	A. M.	5.500	5.937	.437

Computation of height of gage zero at Escanaba, Michigan, above gage zero at Milwaukee, Wisconsin, in the summer of 1896—Continued.

Date.	Time.	Readings (means of series). Milwaukee.	Escanaba.	Difference.
1896.		*Feet.*	*Feet.*	*Feet.*
Sept. 18	A. M.	5.701	6.047	.346
26	A. M.	5.911	6.187	.273
28	P. M.	5.755	6.224	.469
29	P. M.	5.510	6.133	.623
Oct. 7	A. M.	5.514	6.164	.650
14	A. M.	5.731	6.270	.539
14	P. M.	5.813	6.157	.344
17	P. M.	5.622	6.160	.538
19	A. M.	5.846	6.287	.441
20	A. M.	5.857	6.346	.489
22	A. M.	6.182	6.539	.357
	P. M.	6.148	6.540	.392
26	A. M.	6.080	6.471	.391
	P. M.	5.980	6.514	.564
Mean				0.374 ±.012

The bench employed at Milwaukee has already been described. At Escanaba there were three bench marks in good standing, as follows: No. 1, the top of the water sill on the southeast corner of the Adler building, northwest corner of Ludington street and Druseman avenue; No. 2, the top of the water sill of the Escanaba light-house at the north side of front door, against the brick wall; No. 3 is described in 1876 as the "center of a copper bolt set horizontally in the foundation of the light-house, west side, north corner, 3 feet north from steps." In a description by Capt. George A. Zinn, dated June 30, 1896, the top of the bolt is specified. I am informed by Mr. Clinton B. Oliver, the gage observer, that the diameter of the bolt is three-eighths inch. The relative heights of two or more of these bench marks have been determined in at least six different years, the measurements being made independently with the engineer's level. It is advantageous to compare these measurements, not only to learn what confidence is to be reposed in the individual benches, but for the sake of whatever light may be cast on the general precision of such data.

Comparison of Escanaba bench marks with one another.

Year.	Above zero of gage.			Difference between bench marks.			Deviation from mean.		
	No. 1.	No. 2.	No. 3.	1—2.	1—3.	2—3.	1—2.	1—3.	2—3.
	Feet.	*Feet.*	*Feet.*	*Feet.*	*Feet.*	*Feet.*	*Feet.*	*Feet.*	*Feet.*
1874..	4.135	—2.100	....	*a*6.235	....	....	....	....	....
1875..	7.859	2.382	....	5.477	....	....	+0.003	....	....
1876..	7.874	2.409	1.392	5.465	6.482	1.017	— .009	+0.002	+0.005
1880..	7.878	2.402	1.035	5.476	*a*6.843	*a*1.367	+ .002	....	....
1887..	7.753	2.285	1.280	5.468	6.473	1.005	— .006	— .011	— .007
1896..	7.780	2.297	1.283	5.483	6.497	1.014	+ .009	+ 013	+ .002
Mean.	....	....	....	5.474	6.484	1.012	....	....	....

a Not used in computing means.

In this table the reading of the height of bench mark No. 3 in 1876 is corrected for the distance between center and top of bolt. In the first division of the table the benches are referred to zero of gage, but as the gage was not constant in position these numbers differ widely from year to year. In the second division the relations of the gages one to another are given, being deduced by subtraction from the numbers of the first division, and these figures are more accordant. It appears, however, that the difference between benches 1 and 2 in 1874 departs widely from differences found in other years, and it is therefore probable that a blunder of measurement or record was made in that year. It appears further, by inspection, that the difference between benches 1 and 3 and the difference between benches 2 and 3 in 1880 are not in accord with the differences found in other years, and it is evident that some blunder was made in the measurement or record of the height of bench 3 for that year. These figures were accordingly thrown out and not used in the computation of the means. The numbers of the third division were obtained by subtracting the means from the several numbers of the second division, and they show the deviations from mean after rejecting the records showing gross errors. Inspection of the table of deviations shows that their signs are irregularly distributed, and discovers no evidence of progressive change from year to year. It is therefore probable that all three of the benches are stable, and that the deviations of the measurements from uniformity represent ordinary errors of observation. They may accordingly be used as a rough measure of the precision, barring blunders, of the instrumental leveling on which the results of this investigation largely depend. Their mean is 0.006 foot, and the computed probable error of a single measurement is ±0.008 foot. In comb ng various data for the comparison of Escanaba with Milwaukee, bench mark No. 1 of Escanaba was first used.

Computation of the height of Escanaba bench mark No. 1 above Milwaukee check point in the summers of 1876 and 1896.

	1876.	1896.
	Feet.	*Feet.*
Escanaba bench No. 1 above Escanaba gage zero	7.874	7.780
Escanaba gage zero above Milwaukee gage zero	—0.255	.374
Milwaukee gage zero above Milwaukee check point	—0.843	—1.205
Sum of above = Escanaba bench No. 1 above Milwaukee check point	6.776	6.949
Difference	+ .173	

The result indicates that the ground at Escanaba, as compared with the ground at Milwaukee, has risen 0.173 foot in twenty years. This quantity is the algebraic sum of six measurements, of which three were made through water leveling and three by instrumental leveling. The probable errors of the water levelings are ±0.012, ±0.012, and ±0.002 foot; the estimated probable error of the instrumental levelings at Milwaukee is ±0.010 foot, and of the two levelings at Escanaba each ±0.008 foot. This gives as the probable error of the result ±0.022 foot.

A similar computation, using bench mark No. 2 instead of bench mark No. 1, gives 0.155 foot instead of 0.173, and a compution based on bench mark No. 3 gives 0.156. The mean of the three results is 0.161 foot, with a probable error of ±0.022 foot. The only important uncertainties to which this result is subject, besides those indicated by the discordance of measurements, arise from the possibility of the settling of the bridge pier to which the Milwaukee check point is attached and the possibility of river floods.

DISCREPANCY NOTED BY CAPTAIN MARSHALL.

In the later work of the United States Lake Survey all determinations of lake level were referred to the high-water level of 1838, which is called the "plane of refereuce." That plane was directly observed by Dr. I. A. Lapham, the geologist, and with the aid of a bench mark on his house at Milwaukee was permanently recorded. For other stations on Lake Michigan-Huron its position was determined by assuming that the level of 1838 had everywhere the same height above the mean lake level as determined by long series of observations. For the determination of this plane at Escanaba use was made of observations for the period from January 1, 1860, to December 31, 1875. In 1887 Capt. W. L. Marshall, U. S. E., under whose direction the gage readings at Milwaukee and Escanaba were then made, detected a discrepancy, which he reported to the Chief of Engineers in a letter dated October 1.[1]

[1] Ann. Rept. Chief of Engineers, U. S. A., for 1887, part 3, p. 2417.

In former reports the zero of Escanaba gage has been assumed as 0.76 foot above the plane of reference, but a comparison of corrected readings at Milwaukee and Escanaba shows that the determinations of the plane of reference at Milwaukee and Escanaba vary 0.187 foot, the Escanaba plane being too high or the Milwaukee determination too low.

In the light of present knowledge it seems probable that the discrepancy thus noted by Captain Marshall as an error was occasioned either wholly or in chief part by the progressive tilting of the land. This conclusion is difficult of verification, because little record survives of such checks as may have been made upon the heights of gage zeros during the period 1860–1875; but the indicated change agrees in direction, and approximately in rate, with the change deduced from the present investigation. From the middle of the period 1860-1875 to the summer of 1887 was an interval of twenty years, equal to the interval 1876–1896 here used, and the discrepancy of 0.187 foot discovered by Captain Marshall differs from the change of 0.161 foot here deduced by a quantity little greater than the probable error ascribed to the latter determination.

SUMMARY OF RESULTS.

In the following table are assembled the numerical results as to changes in relative height of the four pairs of stations. Besides the measured changes, the table includes the periods intervening between dates of measurement and distances between the stations of each pair. The lines connecting pairs of stations have a southwesterly direction (fig. 99, p. 613), and it is the northeastern station of each pair that appears to have risen as compared to the other.

The results thus show a general agreement with the working hypothesis, that the latest change recorded by geologic data is still in progress. To make the comparison quantitative there should be substituted for the direct distances between stations the corresponding distances in the assumed direction of tilting, S. 27° W., and the measured results for various distances and various time intervals should be reduced to a common basis. In the third column of the table are the reduced distances, and in the sixth the reduced rates of change. Assuming the change to have a uniform rate and to be the same for all parts of the region, the measurements at the different pairs of stations give for a distance of 100 miles and a period of a century the quantities of the sixth column. The seventh column contains the probable errors of quantities in the sixth, and is based on the probable errors of the measured changes in pairs of stations.

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 measurement.	Change in relative height.	Change per 100 miles per century.	Probable error of quantities in last column.
	Miles.	*Miles.*	*Years.*	*Feet.*	*Feet.*	*Feet.*
Sacketts Harbor and Charlotte	88	76	22	0.061	0.37	0.18
Port Colborne and Cleveland	158	141	37	0.239	0.46	0.11
Port Austin and Milwaukee	259	176	20	0.137	0.39	0.09
Escanaba and Milwaukee	192	186	20	0.161	0.43	0.06
Mean					0.41	
Weighted mean					0.42	±0.044

IS THE LAND TILTING?

With the numerical results of the investigation before us we may now recur to the main subject and ask whether the evidence warrants the conclusion that a general, gradual tilting of the basin is in progress. In the discussion of the data used in comparing the several pairs of stations it has been found that, taken at their face value, they indicate a tilting in the hypothetic direction, but it has also been found impossible to resolve all doubts as to the stability of the gages and benches and the accuracy of the measurements. By reason of these doubts the result from no single pair of stations is conclusive, but when assembled they exhibit a harmony which argues strongly for their validity. As tabulated, there are four results, but these are not all independent, since observations and measurements at Milwaukee are used twice. There are, however, three results wholly independent and a fourth partly independent. To these may be added a fifth partly independent, namely, the determination of change between Port Colborne and Cleveland for the shorter period, 1872–1895. Not only do all these results indicate a change of the same sort, but they agree fairly well as to quantity. The computed change for 100 miles in a century ranges only from 0.37 to 0.46 foot, and the greatest deviation of an individual result from the mean of four is 12 per cent. This measure of harmony appeals strongly to the judgment, and is also susceptible of approximate numerical expression. If the four determinations tabulated in the sixth column are, in fact, measures of the same quantity—that is, if the tilting has been uniform throughout, as we have assumed—then the probable error of the determined value of that quantity (0.42 foot) is less than ±0.05 foot.

The most important factors tending to throw doubt on the conclusion are the possibilities of accidental change in the various benches to which the measurements are referred. The bench at Port Austin, being a mark on bed rock, is trustworthy, and the agreement between the three benches used at Escanaba is good evidence of their stability; but the bench at Milwaukee, with which both are compared, is a pier of a bridge in daily use and may, perhaps, be slowly settling. If it is settling, the comparisons with benches at Escanaba and Port Austin may merely reveal that fact and not measure the subsidence of the land. The fact that the swing bridge on the pier has not required re-leveling is certainly favorable to the stability of the pier, especially when it is considered that a change of fully 1½ inches is to be accounted for; and there is further confirmation in the discovery of a discrepancy between Milwaukee and Escanaba by Captain Marshall, whose data are probably independent of the check mark. Of the benches on Lake Erie, the one at Port Colborne is satisfactory, but those at Cleveland may have settled at critical times, and if so their change would influence the result in the direction found. Of the benches on Lake Ontario, the one at Charlotte is eminently stable; the only practical question affects the bench at Sacketts Harbor, which is on a building that has not been wholly stable since its construction, although presumably so since the making of the bench. If the building at Sacketts Harbor settled between 1874 and 1896, the effect of the lowered bench was to produce, not such a change as appears from the measurements, but one with the opposite sign.

It seems to me that the harmony of the measurements and their agreement with prediction from geologic data make so strong a case for the hypothesis of tilting that it should be accepted as a fact, despite the doubts concerning the stability of the gages.

RATE OF MOVEMENT.

The deduced mean rate of change—0.42 foot to the 100 miles in a century—depends on assumptions which are convenient rather than probable. These are: (1) that the whole region moves together as a unit, being tilted without internal warping, and (2) that the direction of its present tilting is identical with the direction of the total change since the epoch of the Nipissing outlet of the upper lakes. What we know of the general character of earth movements gives no warrant for such assumptions of uniformity, but no better assumptions as to this region are now available. Under the law of probabilities, the close agreement of four measurements, three of which are wholly independent, gives a good status to their mean, but there are other considerations tending to weaken this status. The probable errors of the individual measurements are rather high, ranging from 14 to 50 per cent, and this suggests the possibility that the closeness of their correspondence may be accidental. It should be remembered also that at two or three stations there was reason to believe that the gage zeros were settling during the period in which the observations were made, and the results involve the doubtful assumption that the rate of settling was uniform. There is room for doubt as to the precision of the instrumental leveling; in only a few instances is the fact of duplicate measurements recorded, and single measurements are notoriously insecure. Error was doubtless admitted by ignoring the effects of barometric gradient. River floods may have introduced errors. In the absence of flood records the records of rainfall at Rochester (near Charlotte), Cleveland, and Milwaukee were compared with the gage readings, the results showing only that if flood errors are involved they must be small. There may also be personal equations of observers, especially as the gages at pairs of stations were not in every case of the same type. For all these reasons I am disposed to ascribe only a low order of precision to the deduced rate of change, and regard it as indicating the order of magnitude rather than the actual magnitude of the differential movement.

The rate of change indicated by Stuntz's observations is more rapid. As already quoted, he states that at a time when Lake Superior was exceptionally low at its outlet, it was nevertheless so high at its western extremity as to obliterate from the St. Louis River a rapid which had been visible only a few years before. This statement involves no definite measures, but it implies that the change within the memory of individuals involves feet rather than the inches deduced from the studies in the other lakes. Similar inferences may be drawn from his statement as to submerged stumps. The recorded range of water level in Lake Superior is about 5 feet, and trees would grow little if any below high-water mark. If, then, with low stage at the east end, stumps are submerged at the west, a change of 5 feet or more would seem to have occurred during the period covered by the growth of a tree and the survival of its stump. The differences between the inferences drawn from this evidence and the result based on gage readings on the other lakes is so wide as to suggest the possibility of error in the Lake Superior observations. It is certainly important that they be verified. Unfortunately I have not been able to visit the region, and the gage records accessible to me are not so connected with bench marks as to give a satisfactory basis for computation. The United States Lake Survey made observations of lake level at Superior City from 1859 to 1871, and then transferred the station to Duluth, where it was continued for two or three years. No bench mark at Duluth is described, and the only recorded bench mark at Superior City is upon a wooden structure, Johnson & Alexander's sawmill. If this bench survives, a good test could be made by renewing the gage station at Superior City. At the other end of the lake, at Sault Ste. Marie, there are authentic benches dating from 1855.

If we assume that the rate of 0.42 foot per 100 miles per century is uniform and secular, and project it backward to the time when the drainage of Lake Huron was shifted from North Bay to Port Huron, we obtain for the period since that change about 10,000 years. From studies at Niagara, Taylor has estimated the same period as between 5,000 and 10,000 years;[1] and the comparison indicates that the rate of modern change is of such magnitude as to accord well with the idea that it merely continues the geologic change.

It is to be hoped that eventually a better measure of the rate of tilting and a surer indication of its direction may be obtained, but even with present knowledge there is interest and profit in considering the economic and geographic consequences of the tilting.

GEOGRAPHIC CHANGES RESULTING FROM THE MOVEMENT.

Assuming that the general result of this investigation is substantially correct—that the whole lake region is being lifted on one side or depressed on the other, so that its plane is bodily canted toward the south-southwest, and that the rate of change is such that the two ends of a line 100 miles long and lying in a south-southwest direction are relatively displaced four-tenths of a foot in 100 years—certain general consequences may be stated. The waters of each lake are gradually rising on the southern and western shores or falling on the northern and eastern shores, or both. This change is not directly obvious, because masked by temporary changes due to inequalities of rainfall and evaporation and various other causes, but it affects the mean height of the lake surface. In Lake Ontario the water is advancing on all shores, the rate at any place being proportional to its distance from the isobase through the outlet (AA, fig. 100, p. 640). At Hamilton and Port Dalhousie it amounts to 6 inches in a century. The water also advances on all shores of Lake Erie, most rapidly at Toledo and Sandusky, where the change is 8 or 9 inches a century. All about Lake Huron the water is falling, most rapidly at the north and northeast, where the distance from the Port Huron isobase (CC, fig. 100) is greatest; at Mackinac the rate is 6 inches, and at the mouth of French River 10 inches, a century. On Lake Superior the isobase of the outlet (DD, fig. 100) cuts the shore at the international boundary; the water is advancing on the American shore and sinking on the Canadian. At Duluth the advance is 6 inches, and at Heron Bay the recession is 5 inches, a century. The shores of Lake Michigan are divided by the Port Huron isobase. North of Oconto and Manistee the water is falling; south of those places it is rising, the rate at Milwaukee being 5 or 6 inches a century, and at Chicago 9 or 10 inches. Eventually, unless a dam is erected to prevent, Lake Michigan will again overflow to the Illinois River, its discharge occupying the channel

[1] Bull. Geol. Soc. America, Vol. IX, 1898, p. 83.

carved by the outlet of a Pleistocene glacial lake. The summit in that channel is now 8 feet above the mean level of the lake, and the time before it will be overtopped (under the stated assumption as to rate of tilting) may be computed. Evidently the first water to overflow will be that of some high stage of the lake, and the discharge may at first be intermittent. Such high-water discharge will occur in 500 or 600 years. For the mean lake stage such discharge will begin in about 1,000 years, and after 1,500 years there will be no interruption. In about 2,000 years the Illinois River and the Niagara will carry equal portions of the surplus water of the Great Lakes. In 2,500 years the discharge of the Niagara will be intermittent, failing at low stages of the lake, and in 3,500 years there will be no Niagara. The basin of

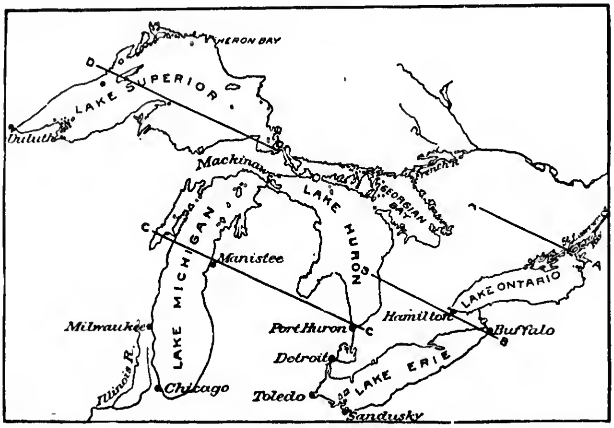


FIG. 100.—Relations of the shores of the Great Lakes to the isobases drawn through their outlets.

Lake Erie will then be tributary to Lake Huron, the current being reversed in the Detroit and St. Clair channels.

The most numerous economic bearings of this geographic change pertain to engineering works, especially for the preservation of harbors and regulation of water levels. But the modifications thus produced are so slow as compared to the growing demands of commerce for depth of water that they may have small importance. It is a matter of greater moment that cities and towns built on lowlands about Lakes Ontario, Erie, Michigan, and Superior will sooner or later feel the encroachment of the advancing water, and it is peculiarly unfortunate that Chicago, the largest city on the lakes, stands on a sinking plain that is now but little above the high-water level of Lake Michigan.

PLANS FOR PRECISE MEASUREMENT.

While it is believed that the general fact of earth movement has been established by the present investigation, the measurement of its rate and the determination of its direction fall far short of the precision which is desirable. For the purposes of science the order of magnitude of the change is more important than its precise measurement, but there are involved great economic interests, and these demand more definite information. The account of the present investigation is therefore supplemented by an outline plan of the more elaborate investigation which appears necessary to give measurements of the precision that is desirable.

Existing data are neither full enough nor exact enough to give satisfactory measures of the small quantities sought. Doubtless a more elaborate discussion would yield better results than I have obtained, but the improvement could not be great. Observations by the Lake Survey were conducted for purposes not demanding a high order of precision, and high refinement was not attempted. The supplementary work done in 1896 attempted only to be good enough for use in combination with the work of 1874 and 1876, and can not serve as the first term of a new comparison. The problem requires a new set of high-grade observations at each station of a carefully planned system, to be followed, after an interval of at least a decade, by a second set of observations at the same stations.

Foreseeing no opportunity to undertake such a work myself, I have formulated in the following paragraphs a plan embodying the results of my experience—a plan intended to afford useful suggestions to some investigator by whom the work may be actually undertaken.

Selection of stations.—To measure the rate of change in any given direction, observations at two stations suffice; but to determine also the direction of change, it is necessary to use three stations grouped in the form of a triangle. The longer the sides of the triangle the better the measurement of rate, and the larger its smallest angle the better the determination of direction. A brief inspection shows that the shores of Lake Michigan and Lake Huron give the best opportunity for the planning of a well-conditioned triangle. Though the narrowness of their connecting strait has led to the giving of separate names, they are really a single lake, and the stretch of their water surface is in every direction greater than that of Lake Superior.

For the purpose in view the point of first importance is the outlet of the lake at Port Huron. This is peculiar in that the plane of mean water level has here a constant relation to the adjacent land, a relation altogether independent of the progressive deformation of the basin. This station should not be on the St. Clair River, but on the shore of the lake near by.

The second point of vantage is Chicago. As economic interests are more seriously affected by the geographic change at that point than elsewhere, it is desirable to determine directly, by comparison with Port Huron, the rate at which the lake is encroaching on the land.

A third point of prime importance is the Strait of Mackinac. Although the equilibrium levels of the surfaces of the two lakes are the same, there are considerable periods when their equilibrium is disturbed, and during such periods a current flows in one direction or the other through the strait. Only when this current is nil is the whole water body in perfect equilibrium, and it is essential to p cise leveling through the water surface either that times of equilibrium be chosen or

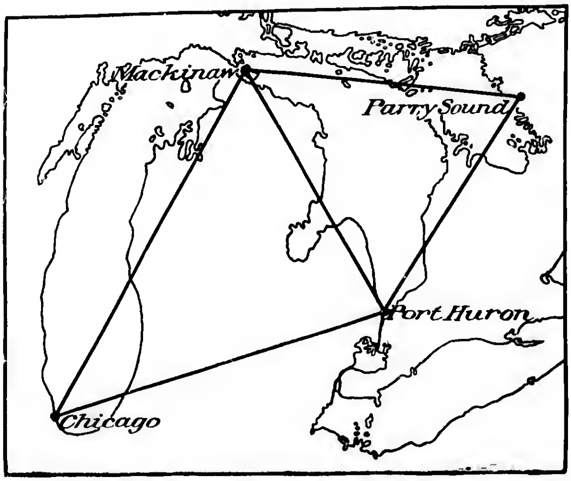


FIG. 101.—Proposed systems of stations for the precise measurement of earth movements.

that due allowance be made for the gradients associated with flow. Observations must therefore be made on the current in the strait, and it is best to connect them with the work of a complete station.

As appears by the annexed diagram (fig. 101), the triangle formed by these three stations is well conditioned as to size and form; the lengths of its sides are approximately 225, 275, and 310 miles, and its smallest angle is about 45 degrees.

While the proper use of these three stations will give answer to the questions of greatest economic and scientific importance, there will be material scientific advantage in adding a fourth station to the system. It should be placed somewhere on the north shore of Georgian Bay, and, giving consideration to accessibility as well as geographic position, it is probable that Parry Sound should be selected. By adding this station another well-conditioned triangle would be completed, and there would result an additional determination of the rate and direction of tilting. If rate and direction vary from place to place the fact will probably be brought out. There would be additional advantage in the fact that Parry Sound and Chicago are separated by the greatest practicable distance in the direction of maximum change, so that a comparatively short period of time might afford a valuable measurement. The approximate results of the present investigation indicate that the change in the relative height of Parry Sound and Chicago in ten years would be about 2 inches.

Conditions controlling equipment.—In order to plan intelligently the system of observations, full consideration should be given to the conditions affecting the problem, and provision should be made for all possible sources of error. Prominent among these are the various factors which modify the water level at points on the lake shore. Such factors have been considered in the preceding discussion of gage data, but they are assembled here in a more systematic way.

The lake continually receives water from streams and from rain, and continually parts with water by discharge at its outlet and by evaporation. In the long run gain and loss are equal, but for short periods they are usually unequal; so that from day to day, from season to season, and from year to year the volume of the lake and the consequent mean level of its surface are continually changing.

In bays and estuaries there are local temporary variations occasioned by the floods of tributary streams.

There are solar and lunar tides, small as compared to those of the ocean, but not so small that they may be neglected.

The wind pushes the lake water before it, piling it up on lee shores and lowering the level on weather shores. During great storms these changes have a magnitude of several feet, and the effect of light wind is distinctly appreciable. Even the land and sea breezes, set up near the shore by contrasts of surface temperature, have been found to produce measurable effects on the water level.

There is also an influence from atmospheric pressure. When the air is in equilibrium, if that ever occurs, the pressure is the same on all parts of the lake surface, and the equilibrium of the lake is not disturbed; but when the air pressure varies from point to point this variation of pressure is a factor in the equilibrium of the water surface, the surface being comparatively depressed where the air pressure is greater and elevated where it is less.

When a storm wind ceases, the water not merely flows back to its normal position but is carried by momentum beyond, and an oscillation is thus set up which continues for an indefinite period. A similar oscillation is started whenever the equilibrium is disturbed by differences of atmospheric pressure; and these swaying motions, called seiches, analogous to the swaying of water in a tub or hand basin, persist for long periods. In fact, they bridge over the intervals from impulse to impulse, so that the water of the Great Lakes never comes to rest.

Every disturbance which causes the water to rise on one shore of the lake and fall on the other interferes with the equilibrium between the two lakes at the Mackinac Strait. If a strong wind blows the water eastward, raising the level on the east shores of the lakes and lowering it on the west shores, there is high water at the west end of the strait and low water at the east, producing a current toward the east; and when the wind ceases the water that has poured from Lake Michigan to Lake Huron must return, producing a current in the opposite direction. Theoretically, analogous effects should be produced by tides and barometric gradients, and there can be little question of their detection if the phenomena at the strait are studied.

These various influences work independently but simultaneously, and their effects are blended in the actual oscillations of the water surface at any point. In using the water surface for the purpose of precise leveling, it is necessary to take account of all such factors and make provision for the avoidance or correction of the errors they tend to produce.

Equipment.—In view of the complexity of the phenomena to be analyzed, it is desirable that most of the instruments employed be of the automatic kind, giving continuous record. While such instruments accomplish much more than could be done by an observer alone, they do not dispense with his services. They are complex as compared to the apparatus for personal observation, and can be successfully employed only by a man of scientific training. The first essential, therefore, at each of the stations is an expert observer.

The gage employed for the determination of water height should be of some automatic type, giving a continuous record. This is necessary in order that the study of the record may furnish data for the complete elimination of errors from tides, seiches, and land and sea breezes. The gage should be protected, not only from the direct shock of waves, but from all secondary agitation of the water due to wave shock. It should be so installed as to be secure from settling. The height of its zero should be readily verifiable.

Near each station there should be at least three benches, constructed with special reference to permanence and stability. They should be independent of one another and independent of other structures.

Pressure of the air should be continuously recorded by a barograph, carefully standardized. A wind vane and anemometer should give automatic records.

At Mackinac there should also be means for securing a record of the direction and velocity of water currents.

Treatment of observations.—Stress having already been laid on the importance of putting the work in expert hands, it would be unwise to attempt the formulation of a code of instructions for either the making or the reduction of observations; but there may be advantage in a few suggestions based on experience acquired in the present investigation.

While it is doubtless possible to deduce from a study of currents in Mackinac Strait a theory of the relation of those currents to the equilibrium conditions of the two lakes, it will probably be found best to use the current observations chiefly for the discrimination of favorable and unfavorable times, and to compare the lake-level observations only for times when the current at Mackinac is gentle. It will also be better to avoid the use of observations during the prevalence of strong winds or high barometric gradients than to attempt the application of corrections for those factors.

The times not barred by high winds, high gradients, and currents will ordinarily not be found to have such duration and distribution that tidal effects can be eliminated by including complete tidal cycles. It will therefore be necessary to discuss the solar and lunar tides for each station and prepare tables of correction to be applied to all observations employed. The same treatment will be necessary for the effects of land and sea breezes. Barometric gradient of amount too great to be ignored nearly always exists, and this, as determined by observations at the stations themselves, should be the subject of computation and correction.

Seiches should be fully discussed for each station, and the observations finally used should be grouped in periods of sufficient length to eliminate the seiche effect.

SUPPLEMENT.—INVESTIGATION BY MR. MOSELEY.

The main body of manuscript for this paper was prepared in June and July, 1897. An abstract was communicated in August to the American Association for the Advancement of Science, meeting in Detroit, and a fuller abstract was printed in the September number of the National Geographic Magazine.[1] As a result of this publication I became acquainted with a cognate investigation by E. L. Moseley, of Sandusky, Ohio. His data and results were communicated to the Ohio Academy of Sciences in December, 1897, and printed soon afterwards in a Sandusky newspaper. They received more permanent as well as fuller presentation in an article contributed to the Lakeside Magazine,[2] and this article reaches me while the proof sheets of the present paper are in hand. As will be readily understood from the following abstract, the data he has gathered constitute an important contribution to the subject.

[1] Modification of the Great Lakes by earth movement: Nat. Geog. Mag., September, 1897, Vol. VIII, pp. 233-247.

[2] Lake Erie enlarging; the islands separated from the mainland in recent times; by E. L. Moseley: The Lakeside Magazine, Lakeside, Ohio, April, 1898, Vol. I, pp. 14-17.

North of Sandusky Bay, near the west end of Lake Erie, is a cluster of islands, of which the five largest are each several miles in extent.[1] About them the water is shallow, and if the lake were lowered 30 to 35 feet they would all be connected with the mainland. On these islands grow many species of wild plants, and the origin of this flora is related to the geologic history of the islands. There was a time during the ice retreat when the whole basin was covered by a glacial lake. If the water was gradually lowered from the plane of the glacial lake to the present plane of Lake Erie, the islands were at first barren and were eventually occupied only by such plants as were in some way conveyed across the intervening straits, from 2½ to 3 miles wide. As Moseley points out, there are many modes of such adventitious introduction, but they could not be expected to give to the islands a flora so varied as that of the adjacent mainland.

If, on the other hand, as inferred from the slopes of the old shore lines and other data, the attitude of the land was different when the glacial lake was drained away, the original Lake Erie occupied only the eastern part of the Erie basin, and the western part, including the district of the islands, was dry land. Subsequently, from the tilting of the land, the lake waters advanced westward so as to flood the straits and convert the lowland hills into the present islands. In connection with such a geologic history the islands would have acquired their flora at the same time with the mainland, and should now present the same variety of species, so far as local conditions permit. Moseley has carefully compared the insular flora with that of the mainland, and finds that the only mainland species which do not occur on the islands are such as do not find there a congenial soil. The botanic evidence thus supports the geologic, and verifies the conclusion that the land has been tilted toward the southwest since the birth of Lake Erie.

The islands are composed largely of limestone and are surrounded by limestone cliffs. In South Bass or Put-in Bay Island there are caves opening at the water's edge and partly occupied by lake water. Exploring these, Moseley finds stalactites extending from the roof down into the water, and stalagmites lying 3 or 4 feet below the present surface of the lake. Comparing the present water level with the lowest levels known in recent times, it appears that these stalagmites have not been above water during the present century, and as stalagmites are formed only in the air, it is clear that the lake has encroached on the land since they were made.

These data show only that a change has occurred, and ascribe no date, but other phenomena observed in the neighborhood of Sandusky indicate clearly that change is now in progress. A tract of land on which hay was made in 1828 is now permanently under water. A tract of land one-half mile square, surveyed in 1809, has since become marsh, with water and mud 12 to 18 inches deep. Various parts of Sandusky

[1] For the relation of these islands to the lake and the isobase of its outlet, see fig. 100, p. 640.

Bay where rushes grew within the memory of men still living are now covered with open water. "By the high water that prevailed in 1858 to 1860 large trees were killed in many places where the waves could not reach them." "Hundreds of walnut stumps are still standing on the border of the marshes east of Sandusky where even now, although the water is lower than usual, it is too wet for walnut trees to grow. One that stood recently on ground only 6 inches above the present lake level measured 5 feet 4 inches in diameter. We may infer from this that during the life of this tree, probably over 300 years, the water was not so high as in the present century." Many stumps and prostrate trunks with roots and branches attached are found from 1 to 4 feet below the present lake level, and in one locality it is inferred that the lake during the life of the trees must have been as much as 8 feet lower than "during much of the time for the last forty years."

These various facts, and others of the same tenor enumerated by Moseley, are in complete accord with the qualitative results derived from the discussion of gage readings, but, like the data gathered by Stuntz, they suggest a more rapid rate of change than do those results.