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DEPARTMENT OF THE ENVIRONMENT

An Engineering Study of Crustal Movement Around the Great Lakes

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DEPARTMENT OF THE ENVIRONMENT
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Abstract

Vertical movement of the earth's crust in the Great Lakes region can be computed from lake level measurements over long periods of time. This report summarises the methodology used and provides results for all of the Great Lakes. An earlier report describes in detail the background, literature survey and the theory and development of a methodology for data on Lake Superior.

The study was conducted by the Central Region, Engineering Division, as part of an ongoing investigation into the hydrology and hydraulics of the Great Lakes.

Acknowledgments

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INTRODUCTION

Crustal movement in the Great Lakes region was first reported by a surveyor in 1853 who observed that the eastern end of Lake Superior was subsiding relative to the lake level. Since that time many people have investigated the phenomenon. It is a general consensus of opinion today that the Great Lakes region is tilting at a very slow rate with the northwestern area rising relative to the southeastern area. Comparisons have been made with the Scandinavian - Baltic area where a similar uplift is believed to be due to a form of isostatic adjustment following the retreat of the last major glaciation.

If a lake subject to crustal movement has two or more water level gauging stations around its shoreline, it is possible to obtain some quantitative measurement of the rate of relative movement around the lake. Taking differences in water surface elevations as recorded at two gauges at some discrete time interval, e.g. mean monthly elevations, will produce a time series with a length equal to the period of record common to each gauge. If the lake were not subject to crustal movement the time series, when plotted, would be seen to scatter evenly about a horizontal line. The scatter is due to many causes, some meteorologic such as barometric pressure gradients, seiches, etc., and some instrument errors and reading errors.

On the other hand, if there is vertical crustal movement between the two gauges then the time series of gauge differences will have a trend present, a positive or negative slope which can be measured. This slope, in length units per unit time, commonly feet or centimetres per 100 years, is a measure of the rate of vertical crustal movement between the two gauges.

Most investigators agree that the trend in elevation which remains when seasonal variations have been removed is evidence of an uplift of the land surface resulting from the removal of the ice after the last glacial period. It has been pointed out, however, (Lilly, 1953) that the same effect would be measured if the centre of gravity of the whole earth or of the local area were to be moved.

Previous studies using lake levels to investigate vertical crustal movement around the Great Lakes had two major weaknesses:

(a) The assumption was made, without any real justification, that time series made up of differences in lake elevations as recorded at different points around the lake's shoreline can be adequately represented by first order linear trends.

(b) Trends in differences in levels can only indicate relative movement between gauges. To convert these rates of movement to absolute rates of movement a stable datum must be used.

The present study analysed statistically a sample set of data to determine if hypothesis (a) above could be justified and then, on the basis of this information, computed relative rates of vertical movement around the Great Lakes, converted the relative movements to absolute movements and, to the extent possible, tied all the lakes to a common datum.

PROCEDURE

An earlier report on crustal movement around the Great Lakes (Kite, 1972) described in detail the development of a method of computing and adjusting crustal movement rates as well as a justification for the use of first order linear trends in practical analysis. In brief, the methodology developed is as follows:

(a) Determination of Relative Rates of Crustal Movement

A pair of gauging stations having a relatively long period of common record was used as a sample data set in developing this section of the procedure. Differences in mean monthly elevations between the two gauges for each month of the year were put through the following steps:

(1) Various techniques including the variate difference method, stepwise regression and polynomial regression were used to identify and remove any significant linear trends present in the data set.

(2) The residual from step (1) was analysed for periodicity in the mean and variance. Any periodicities found to be significant were removed.

(3) The residuals from steps (1) and (2) were checked for distribution against the normal and log-normal distributions and also checked for the presence of first or second order linear Markov models.

Using Marquette and Duluth as sample data sets it was found that the time series made up of differences in mean monthly elevations was made up of the following components:-

(a)	Linear trends	48
(b)	Periodicity in the mean	14
(c)	Periodicity in the standard deviation	4
(d)	Residual	34

where the figures refer to the percent of the variance of the original time series which could be explained by the corresponding time series component.

Making the assumption that other time series of differences in gauge elevations are basically of similar composition to the sample data analysed, it was decided that for the objectives of this report time series made up of differences in gauge elevations can be adequately represented by first order linear trends.

For each lake, two time series with long records were selected and the first order trend in the differences in mean monthly elevation determined. Then the trends in differences in elevation between each other gauge around the lake and each of the "master" gauging stations in turn were determined. This resulted in a computed rate of relative movement between each pair of gauges. However, because of the different lengths of record involved, these rates were not completely in accord with each other.

Lists of the gauges used on each of the Great Lakes and their respective periods of record is given in Tables 1, 6, 11 and 16.

The relative rates of movement were adjusted using a least squares triangulation technique in which each rate of movement between two points was assigned a "weight" or measure of relative reliability. These weights were computed for each rate of movement as R^2N where R is the simple linear correlation coefficient relating differences in mean monthly elevations between two gauges to time and N is the number of months of record common to both stations. In this way the applied weight increases as the proportion of the variance of the time series is explained by the linear trend (as measured by the coefficient of determination, R^2) and increases as the period of common record increases. The larger the explained variance and the longer the period of common record the greater is the reliability that can be attached to the corresponding rate of relative movement and so the higher is the weighting factor used in the adjustment. This method assumes that the accuracy of the method of determining a rate of movement is independent of the distance between gauges.

The computed and computed-adjusted rates of relative movement are listed in Tables 2, 7, 12 and 17.

A second technique was also used to plot relative rates of movement around individual lakes. If a gauging station were available in the centre of the lake and rates of movement to other equi-distant gauging stations located around the circumference of the lake were computed and plotted against the whole circle bearing of each station a form of sine curve should result. Since no gauging stations are available in lake centres, practical results are approximations to sine curves, as shown on Figures 2, 4, 6 and 8 for each of the Great Lakes.

(b) Determination of Absolute Rates of Movement.

The rates of crustal movement determined in section (a) are between pairs of gauges only and must be referred to some absolute datum. Mean sea level is the obvious choice but this is not practical because of inaccuracies involved in the extremely long levelling line from the sea coast to the lakes. This situation may change when, in 1972 or 1973, the second set of precise levels run from Father Point to the upper lakes is available. It is also well known that mean sea level cannot remain constant during the glaciation-deglaciation cycle. The change in level of the sea continues today (Grant, 1970; Harrison and Lyon, 1963; Milliman and Emery, 1968; Schofield, 1964) but the rate of change is not sufficiently well defined that sea level in one particular year could be used as a datum.

The Nipissing shoreline is the remains of one of the last major glacial lakes in the Great Lakes region. Remains of the beach can be found approximating the shoreline of the present Lakes Superior and Michigan-Huron. In northern areas the Nipissing shoreline slopes upwards while in southern areas the shoreline is horizontal. The line joining points of change from horizontal beach to sloping beach is known as the Nipissing zero isobase. According to geological theory, this zero isobase represents the most southerly extension of post-glacial uplift since Nipissing time and, therefore, offers a possible datum for the presently computed rates of relative crustal movement.

Using the latter datum for this study, and assuming that all changes are related to isostatic rebound, it follows that there can be no negative rates of absolute movement and that relative rates of movement should increase to the north. The Nipissing zero isobase is shown on the attached maps of the Great Lakes, Figures 1, 3, 5, 7.

(c) <u>Determination of Movement of the Mean Lake Surfaces.</u>

The rates of movement described so far have been the absolute rates of movement of particular land areas at points around the circumferences of the Great Lakes. This is fine, but for many practical purposes it is necessary to known the probable movement of the land at a particular point relative to the mean lake level. The mean lake level, however, is changing as the surrounding land rises.

One method of determining any changes in lake level over the historical period of record is to determine the first order linear trend in the records of gauges around the lakes. The results of these computations are shown in Tables 3, 8, 13 and 18. The recorded correlation coefficients indicate that these results are not very accurate. This is to be expected since linear trends in the original gauge records are less important components of the time series than are the linear trends in the time series made up of differences between gauge elevations used to compute relative rates of movement.

Consider a simplified case of a lake subject to crustal movement. If the lake outlet is rising relative to some other section of the lake (not necessarily relative to all sections of the lake) then the rise in outlet elevation will reduce the lake outflow until the lake level (and so, storage) rises sufficiently to restore outlet conditions. It follows, then, that the mean lake level must rise at the same rate as the outlet region is rising. This applies for a lake with natural outlet conditions. Two of the Great Lakes, Michigan-Huron and Erie, are naturally controlled but the other two lakes, Superior and Ontario, are subject to regulation to maintain their levels within certain limits.

In the case of lakes regulated to maintain as near as possible, a constant water surface elevation, there will be no change in storage. The result of tipping the lake basin can be determined in this case by considering a cross-section taken at right angles to the iso-lines of crustal movement. An upward movement of the land at one end of the section by x feet in any given period relative to the land at the other end of the section must result in a rise in mean lake level of x/2 feet in the same time period, assuming that the lake moves as a complete unit.

It should be noted that the use of the methods described above assumes no changes in the effective cross-sectional areas of the lake outlet channels and no changes in the elevations of outlet sills through causes other than vertical crustal movement.

(d) Determination of Rate of Movement of the Land Relative to the Lake Surface.

Combining the absolute rates of movement derived in Section (b) with the rates of movement of the mean lake levels derived in Section (c) results in rates of movement of points around the lake relative to the mean lake levels. These results are listed in Tables 5, 10, 15 and 20.

Tables 4, 9, 14 and 19 present the relative rates of crustal movement on all four lakes as computed in this study alongside rates for the same gauging stations computed in previous studies. In most cases, differences are due to differing periods of record being available to the investigators.

RESULTS

(a) Lake Superior

Lake Superior was the first lake for which the crustal movement rates were computed in this study. It also proved to be the most straight-forward lake. The position of the Nipissing hinge-line (see Figure 1) agrees very well with the computations of relative rates of movement (Table 2). On Table 2, it can be seen that the only station not having a significant rate of movement relative to Duluth is Two Harbors and so the line of zero movement or datum is taken to be somewhere between Two Harbors and the next nearest station, Keweenaw Lower Entrance.

It was determined that the mean lake level of Lake Superior is rising relative to Duluth at a rate of around 0.80 foot/100 years. This results, Table 4, in a list of rates of movement of points around the lake relative to mean lake elevation.

The control structure across the outlet of Lake Superior was completed in August 1922 under the orders of approval issued by the I.J.C. in 1914. No formal regulation plan was followed for the first 6 years, all major interests agreed on each operation undertaken. On July 31, 1928, the Lake Superior Board of Control adopted an operating rule curve known as "Tentative Rule Curve D". Due to the Long Lake diversion into Lake Superior a new rule curve "P5" was adopted by the Board in 1941. A further diversion, Ogoki, and the study of crustal movement around Lake Superior by Sherman Moore (Moore, 1948) led to a further curve "1949 Rule" being initiated in May, 1951. At the time that the "1949 Rule" was introduced it was decided that the gauges at Marquette, Duluth, Port Arthur and Michipicoten would be corrected for crustal movement. Marquette, Duluth, Port Arthur and Michipicoten were to be corrected by -0.08, -0.14, -0.06 and -0.10 foot respectively from 1950 on. It appears that preliminary daily elevations for the gauges at Duluth and Marquette are corrected by the Lake Survey Center, U.S. Dept. of Commerce for crustal movement while published mean daily elevations for these two gauges are not corrected. The present (summer, 1971) corrections used are -0.12 foot for Duluth and -0.08 foot for Marquette. The Canadian gauges at Port Arthur (now Thunder Bay) and Michipicoten Harbour are not corrected for crustal movement.

Negative corrections to the gauges at Marquette and Duluth can only aggravate the problem of flooding in the S.W. corner of Lake Superior since they lower the computed mean lake level. The rule curve used in lake regulation will then specify a discharge lower than if there were no correction which will result in a higher lake level and more likelihood of flooding. The effect on lake regulation will be to increase the percent of time at which lake elevations are high. Even given the correct algebraic sign the U.S. corrections do not effectively correct for rates of crustal movement, only for differences in mean elevation. In explanation, if the equation relating gauge difference,

Table 1

List of Gauging Stations Around Lake Superior and the Periods of Record Used

Station	From*	To*	No. of Months of Record
Port Arthur**	1860	1970	1331
Michipicoten	1915	1970	653
Sault Ste. Marie***	1908	1970	747
Point Iroquois	1930	1970	408
Marquette	1860	1970	1332
Keweenaw L.E.	1890	1961	829
Houghton	1892	1963	295
Duluth	1860	1970	1211
Two Harbors	1941	1970	350

* Inclusive (note that because of gaps in the data the number of months of record does not always correspond to the number of years).

** Thunder Bay.

*** Later dropped because of drawdown effects.

Table 2

Computed and Computed-Adjusted Rates of Relative Crustal Movement around Lake Superior.

GAUGE B	GAUGE A							
	Marquette				Duluth			
	Rates of Movement A-B							
	Correlation Coefficient	Unadjusted Rate, ft/100 years	Adjusted Rate, ft/100 years	No. of Months of Common Record	Correlation Coefficient	Unadjusted Rate, ft/100 years	Adjusted Rate, ft/100 years	No. of Months of Common Record
Port Arthur	0.7396	0.7088	0.7413	1210	0.8940	1.1639	1.1392	1089
Michipicoten	0.8306	0.9902	1.0134	653	0.8827	1.4345	1.4113	653
Sault Ste. Marie	0.5755	0.5525	-	742	0.7727	0.9913	-	742
Point Iroquois	0.5261	0.3314	0.3659	408	0.6871	0.7983	0.7638	408
Marquette					0.6856	0.3597	0.3979	1211
Keweenaw L.E.	0.0897*	0.0393	0.0393	829	0.7233	0.4371	0.4371	829
Houghton	0.1607*	-0.0826	-0.0111	295	0.5856	0.4583	0.3868	295
Duluth	0.6856	-0.3597	-0.3979	1211				
Two Harbors	0.3978	-0.5394	-0.4134	350	0.1441*	0.1106	0.0154	350

* Statistically non-significant regressions

Table 3

Determination of Trend in Surface Elevation, Lake Superior

Station	Period Used (Months)							
	1211	1210	829	742	653	408	350	295
	(upper figure of each pair is the linear trend in feet per 100 years, lower figure of each pair is the corresponding correlation coefficient)							
Marquette	0.70	0.69	0.38	0.82	0.63	-0.55	-2.07	-0.15
	0.34	0.36	0.12	0.23	0.16	0.13	0.31	0.03
Duluth	1.06							
	0.47							
Port Arthur		-0.01						
		0.00						
Keweenaw L.E. *			0.34					
			0.11					
Sault Ste. Marie				0.26				
				0.08				
Michipicoten					-0.35			
					0.09			
Point Iroquois						-0.88		
						0.21		
Two Harbors							-1.53	
							0.23	
Houghton*								-0.06
								0.01

*Note: These periods of record do not extend to 1970.

Table 4

Crustal Movement Around Lake Superior in
Feet per 100 Years Relative to Marquette

Gauge	Author								
	Gutenberg, 1933	Gutenberg, 1941	Moore, 1948	V.C.S., 1957 unadjusted	V.C.S., 1957 adjusted	Kite, 1967	Kite, 1972 unadjusted	Kite, 1972 adjusted	Period of common record, months
Port Arthur	+0.97	+0.65	+0.68	+0.60	+0.65	+0.59	+0.71	+0.74	1210
Michipicoten Harbor	+0.70	+0.49	+0.55	+1.01	+1.04	+1.01	+0.99	+1.01	653
Point Iroquois			+0.53	+0.39	+0.27	+0.33	+0.33	+0.36	408
Whitefish Point				-0.43	-0.42	+0.16			
Grand Marais				+0.20	+0.13	0.00			
Munising			-0.46	+0.46	+0.42	+0.51			
Presque Isle				+0.04	-0.01	-0.14			
Keweenaw L.E.				-0.06	-0.05	-0.08	+0.04	+0.04	829
Houghton			+0.05	-0.08	+0.03	-0.02	-0.08	+0.01	295
Keweenaw U.E.				+0.14	+0.09	+0.27			
Grand Traverse Bay				+0.28	+0.30	-0.30			
Copper Harbor			+0.36	+0.33	+0.31	+0.31			
Ontonagon			-0.08	-0.04	-0.16	-0.20			
Eagle Harbor				+0.06	+0.14	+0.19			
Black River				-0.89	-0.87	-0.41			
Ashland			-0.41	-0.63	-0.62	-0.55			
Cornucopia				-0.40	-0.44	-0.60			
Port Wing			-0.24	-0.26	-0.32	-0.29			
Duluth	-0.59	-0.39	-0.40	-0.34	-0.31	-0.36	-0.36	-0.40	1211
Two Harbors			-0.21	-0.14	-0.28	-0.47	-0.54	-0.41	350

Table 4 (Cont'd)

Crustal Movement Around Lake Superior in
Feet per 100 Years Relative to Marquette

Gauge	Author								
	Gutenberg, 1933	Gutenberg, 1941	Moore, 1948	V.C.S., 1957 unadjusted	V.C.S., 1957 adjusted	Kite, 1967	Kite, 1972 unadjusted	Kite, 1972 adjusted	Period of common record, months
Beaver Bay				+0.06	+0.08	-0.37			
Lutsen				-0.67	-0.61	-0.63			
Grand Marais			+0.25	+0.20	+0.09	-0.08			
Rock Harbor				+0.51	+0.47				
Washington Harbor				+0.33	+0.33				
Sault Ste. Marie	+0.39					+0.61✓	+0.55	(4)	742
Isle Royal			+0.39						

Notes: (1) A + ve rate of movement indicates a rise of the land adjacent to the gauging station with respect to Marquette.

(2) V.C.S. is an abbreviation for Vertical Control Subcommittee, Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data.

(3) Check (✓) marks signify those stations which, in 1967, had over 20 years of record. Other figures for 1967 are given merely to update V.C.S. results, they are not considered reliable.

(4) Figures for Sault Ste. Marie are not considered reliable because of drawdown.

Table 5

Rates of Movement of the Land Around Lake Superior Relative to the Lake Surface, Feet per 100 Years.

Port Arthur	+0.34
Michipicoten	+0.61
Point Iroquois	-0.04
Marquette	-0.40
Keweenaw L.E.	-0.36
Houghton	-0.41
Duluth	-0.80
Two Harbors	-0.80

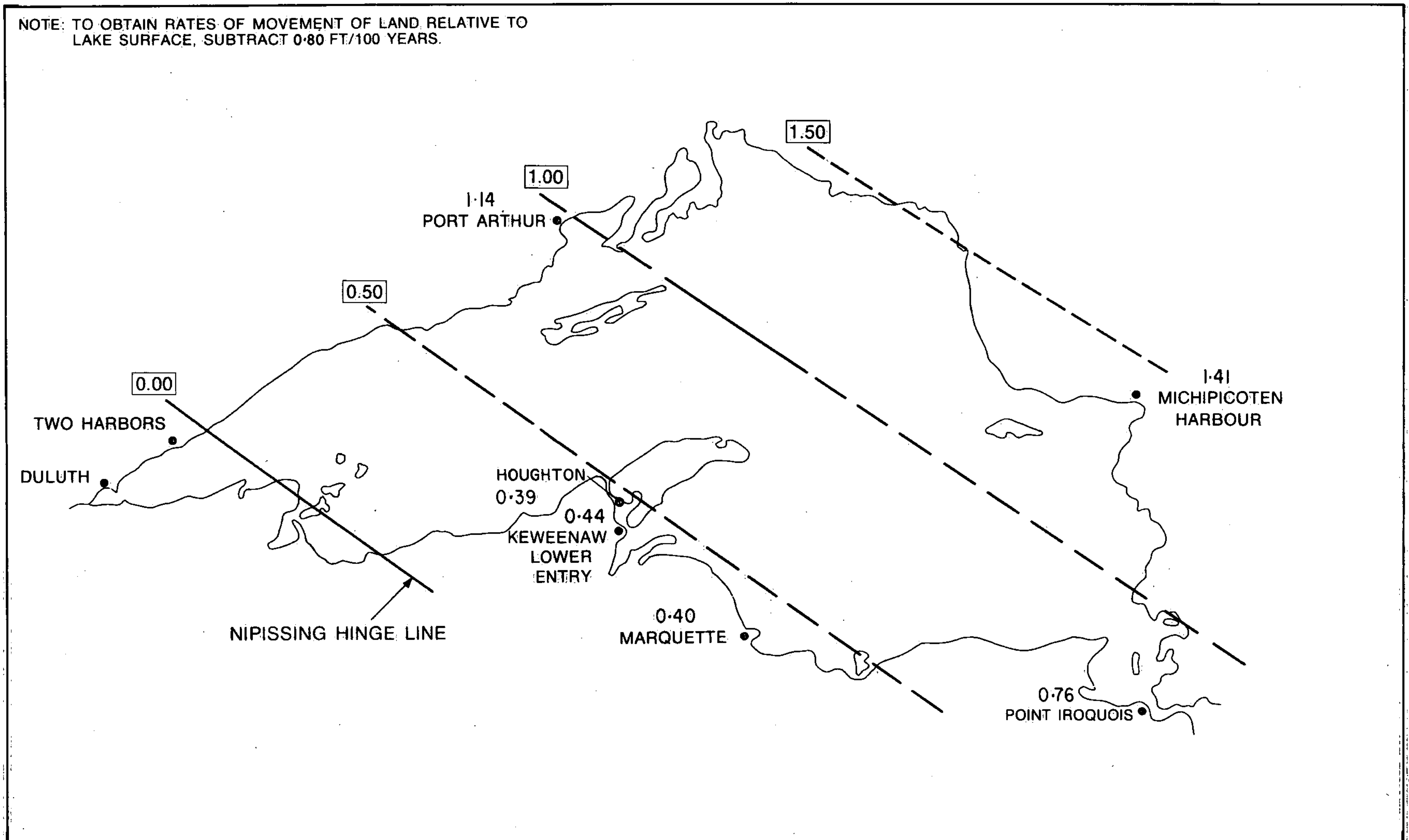


FIGURE 1

CRUSTAL MOVEMENT ON LAKE SUPERIOR
LINES OF EQUAL RATE OF ABSOLUTE MOVEMENT, FT/100 YEARS

CIRCULAR DISTRIBUTION OF CRUSTAL MOVEMENT
AROUND LAKE SUPERIOR

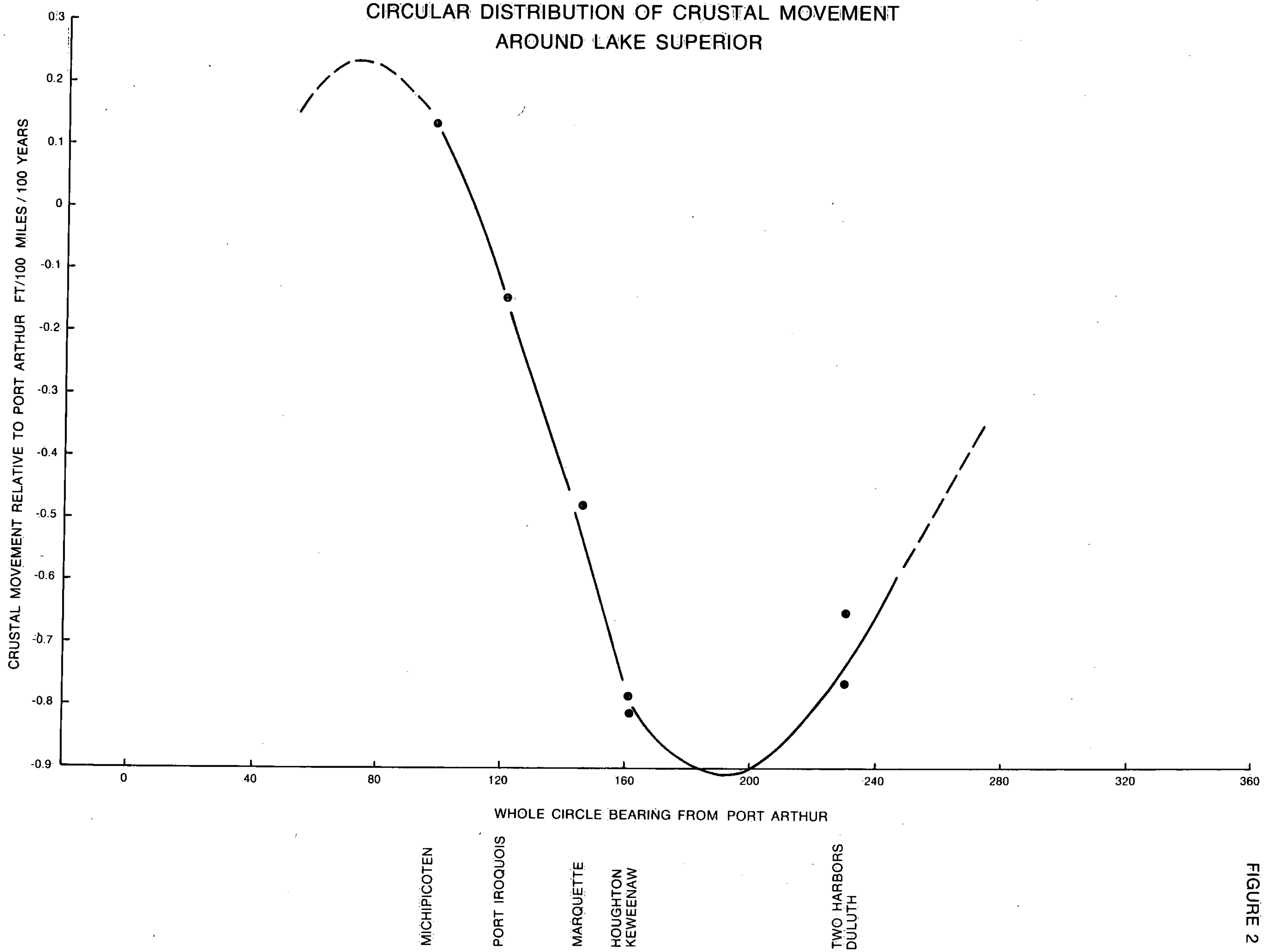


FIGURE 2

y, to time, t, is expressed by a general polynomial of the form:

$$y = a + bt + ct^2 + \ldots$$

consisting of at least a constant, a velocity term and an acceleration term, then the corrections applied to the U.S. gauges adjust the constant term only. Every few years this constant would need adjusting to account for the higher order terms.

Presently the rule curve followed is the "1955 Modified Rule of 1949" which provides improved benefits to power and navigation. Currently studies are continuing on the development of a more sophisticated plan to regulate Lake Superior in conjunction with other lakes in the Great Lakes chain.

(b) Lake Michigan-Huron

Two base stations were chosen, Milwaukee on Lake Michigan and Harbor Beach on Lake Huron, on the basis of their relatively long periods of record (135 and 111 years) and their apparent stability. Calumet Harbor would appear to be a desirable station for a base being located at the southern end of Lake Michigan and having a long period of record, but the Calumet gauge has a record of instability or inaccuracy (see Gutenberg, 1941).

Table 7 shows the results of determining first order linear trends in the time series made up of differences in mean monthly elevations between two gauging stations. The same two base stations were used, Milwaukee and Harbor Beach, and the rate of movement of each other location was determined with respect to each of the base stations. In the cases where a relatively long period of record is common to both gauges (say >500 months) the correlation coefficient for the first order trend is generally high, 0.7 - 0.8.

It appears from Table 7, that there are no real correlations between Milwaukee and any gauging stations located south of Ludington. For this reason, the line of zero rate of crustal movement has been assumed to pass through Milwaukee and to the south of Ludington. The line of zero movement on Figure 3 does not correspond to the geological Nipissing zero isobase. (see Maclean, 1961 plate 1; Hough, 1958, p. 256; Leverett and Taylor, 1915, plate 9). Other lines of equal rates of crustal movement have been placed on Figure 3 at 0.25 foot/100 years intervals.

Table 8 shows the results of using the Milwaukee gauge as a base for determining any first order linear trend in the lake level. The upper figure for each station is the rate of movement of the lake level in feet per 100 years, negative being a downward movement. The second figure of each pair, the lower one, is the correlation coefficient corresponding to the trend detailed above. If there is a first order linear trend in the level of Lake Michigan-Huron then Table 8 indicates that it is probably in the order of -2.50 foot/100 years - i.e., a lowering of lake level. This figure should be compared with the results of Rowe (1969) who determined that the recession of the lake level since 1860 is 3.40 feet at the Harbor Beach gauge, 3.10 feet at the southern tip of Lake Huron and the southern half of Lake Michigan and 3.59 feet along the most northerly shore of Lake Huron. Rowe used 5-year mean elevations to obtain these figures. The total rate of movement of mean lake level on Lakes Michigan-Huron is made up of several components as follows:

(a) Smooth upward movement due to crustal movement estimated in this report as +0.2 foot per 100 years.

(b) Intermittent downward trends due to dredging and gravel removal on the St. Clair River as follows:
   (1) 1890-1900, dredging; estimated lowering of Lake Huron, 0.4-0.5 foot.
   (2) 1904-1924, sand and gravel removal; estimated lowering of Lake Huron, 0.4-0.5 foot.
   (3) 1933-1938, dredging of 25' navigation channel; estimated lowering of Lake Huron, 0.2-0.3 foot.
   (4) 1960-61, dredging of 27' navigation channel; estimated lowering of Lake Huron, 0.10 foot.

In addition dredging in the Detroit River has been estimated to have caused an additional lowering of Lake Huron of

(1) 1870-1957, 0.3 foot
(2) 1960-1961, 0.12 foot

The figures given above are from a report of the Canadian Interdepartmental Committee on Compensating Sills in the St. Clair River, dated March 1962. The total lowering of Lake Huron in the period 1890-1970, using these figures for dredging in the St. Clair and Detroit Rivers is between 1.5 and 1.8 feet. Brunk (1968) estimated that the effect of the dredging in the St. Clair and Detroit Rivers has been to lower the level of Lake Michigan-Huron by about 2 feet since the 1880's. Other sources have indicated that the lowering has been roughly 1 foot since 1900. Since 1930 over 50 million cubic yards of material have been dredged from the St. Clair and Detroit Rivers, not including routine maintenance dredging. Some of this material, taken from navigation channels, has been subsequently dumped back into the rivers in such positions as to partially compensate for the original channel changes.

(c) A reduction in the winter ice retardation due to pollution and dredging. This has been estimated as being up to 0.5 foot since 1900.

(d) Diversions into the Great Lakes at Long Lake and Ogoki would produce a net rise in the water level of around 0.37 foot on Lake Michigan-Huron. This is counterbalanced to some extent by an increasing consumptive use

Table 6

List of Gauging Stations Around Lake Michigan-Huron and the Periods of Record Used

Station	From*	To*	No. of Months of Record
Milwaukee	1836	1970	1389
Sturgeon Bay Canal	1905	1970	669
Escanaba	1874	1964	450
Thessalon	1926	1970	525
Collingwood	1906	1970	714
Goderich	1860	1970	1288
Point Edward**	1927	1970	519
Harbor Beach	1860	1970	1324
Mackinaw City	1900	1970	846
Ludington	1895	1970	304
Grand Haven	1894	1965	644
Calumet Harbor	1903	1970	811
Chicago	1854	1962	965

*Inclusive (note that because of gaps in the data the number of months of record does not always correspond to the number of years).

**Later dropped because of drawdown effects.

Table 7

Computed and Computed-Adjusted Rates of Relative Movement Around Lake Michigan-Huron

GAUGE B	GAUGE A							
	Milwaukee				Harbor Beach			
	Correlation Coefficient	Rate of Movement A-B Unadjusted	Rate of Movement A-B Adjusted	No. of Months of Common Record	Correlation Coefficient	Rate of Movement A-B Unadjusted	Rate of Movement A-B Adjusted	No. of Months of Common Record
Milwaukee					0.7155	-0.4748	-0.4877	1318
Sturgeon Bay Canal	0.6300	0.4722	0.4662	663	0.0369	-0.0276	-0.0216	669
Escanaba	0.5568	0.4674	0.4499	450	0.0940	-0.0554	-0.0379	446
Thessalon	0.8083	1.2538	1.1912	519	0.8283	0.6409	0.7035	525
Collingwood	0.8087	1.1019	1.0833	708	0.8652	0.5795	0.5956	714
Goderich	0.5298	0.2928	0.3004	1282	0.4963	-0.1797	-0.1873	1280
Point Edward	0.5744	1.1287	-	513	0.3591	0.5111	-	519
Harbor Beach	0.7155	0.4748	0.4877	1318				
Mackinaw City	0.7268	0.7881	0.7798	840	0.4507	0.2838	0.2921	846
Ludington	0.5741	0.3154	0.2849	303	0.4762	-0.2332	-0.2027	306
Grand Haven	0.0981	0.0817	0.1176	644	0.3859	-0.3341	-0.3700	644
Calumet Harbor	0.2264	0.1536	0.1418	805	0.4429	-0.3577	-0.3459	811
Chicago	0.0628	-0.0498	-0.0390	909	0.5337	-0.5158	-0.4876	885

Table 8

Determination of Trend in Surface Elevation, Lake Michigan-Huron

Station	Period Used (Months)											
	1318	1282	909	840	805	708	663	644	519	513	450	303
	The upper figure of each pair is the linear trend in feet per 100 years, the lower figure of each pair is the corresponding correlation coefficient.											
Milwaukee	-2.35 0.57	-2.36 0.57	-3.65 0.71	-0.89 0.16	-0.83 0.14	-0.41 0.06	-0.91 0.15	-1.90 0.31	1.99 0.21	1.68 0.17	-3.22 0.62	-1.47 0.22
Harbor Beach	-2.82 0.64											
Goderich		-2.65 0.62										
Chicago*			-3.60 0.71									
Mackinaw City				-1.68 0.29								
Calumet Harbor					-0.98 0.16							
Collingwood						-1.50 0.22						
Sturgeon Bay Canal							-1.38 0.22					
Grand Haven*								-1.98 0.33				
Thessalon									0.74 0.08			
Point Edward										0.56 0.06		
Escanaba*											-3.69 0.67	
Ludington												-1.79 0.27

*Note, these periods of record do not extend to 1970.

Table 9

Crustal Movement Around Lake Michigan-Huron
in Feet per 100 Years Relative to Milwaukee

Gauge Site	Author									
	Gilbert, 1897	Freeman, 1926	Gutenberg, 1933 or 1941	Moore, 1947	VCS, 1957 unadjusted	VCS, 1957 adjusted	Kite, 1967	Kite, 1972 unadjusted	Kite, 1972 adjusted	Period of common record, months
Thessalon				0.91	1.34	1.22	1.22	1.25	1.19	519
Collingwood			0.92	0.81	1.00	1.02	1.04	1.10	1.08	708
Goderich			0.33	0.32	0.46	0.47	0.40	0.29	0.30	1282
Lakeport					2.59[t]	2.33[t]	-0.38			
Lexington				0.40[t]	0.44[t]	0.40[t]	0.48			
Port Sanilac					1.38[t]	1.39[t]	1.24			
Harbor Beach		0.57	0.36	0.36	0.42	0.47	0.48	0.47	0.49	1318
Port Austin	1.01	0.71		0.65[t]	0.70[t]	0.63[t]	0.76			
Bay City		0.53		0.40[t]	-0.58[t]	-0.36[t]	0.42			
Alpena				0.50[t]	0.67[t]	0.76[t]	0.73			
Presque Isle				0.64[t]	0.76[t]	0.81[t]	0.82			
Cheboygan				0.89[t]	0.82[t]	0.75[t]	0.81			
Mackinac Island					1.06[t]	0.95[t]				
Mackinaw City		0.93	0.66	0.73	0.78	0.82	0.76	0.79	0.78	840
Petoskey				0.69	0.76	0.78	0.87			
Charlevoix				0.64	0.63	0.72	0.68			
Traverse City					0.02	0.24	0.34			

Table 9 (Cont'd)

Crustal Movement Around Lake Michigan-Huron
in Feet per 100 Years Relative to Milwaukee

Gauge Site	Author									
	Gilbert, 1897	Freeman, 1926	Gutenberg, 1933 or 1941	Moore, 1947	VCS, 1957 unadjusted	VCS, 1957 adjusted	Kite, 1967	Kite, 1972 unadjusted	Kite, 1972 adjusted	Period of common record, months
Leland					0.30	0.46	0.62			
Frankfort				0.12	0.20	0.22	0.30			
Portage Lake				0.28	0.40	0.40	0.42			
Manistee				-0.20	-0.10	-0.14	-0.02			
Ludington				0.42	0.34	0.35	0.35	0.32	0.28	303
Pentwater				0.08	0.00	0.13	0.08			
White Lake				0.18	0.27	0.31	0.24			
Muskegon				0.21	0.14	0.20	0.20			
Grand Haven				0.03	0.15	0.19	0.19	0.08	0.12	644
Holland				0.16	0.08	0.18	0.08			
Saugatuck				-0.07	-0.06	-0.01	-0.03			
South Haven				0.23	0.19	0.22	0.22			
St. Joseph				0.35	0.37	0.42	0.35			
Michigan City				0.25	0.54	0.48	0.38			
Indiana Harbor					0.17	0.13	0.15			
Chicago				-0.09	-0.10	-0.06	-0.09	-0.05	-0.04	909
Calumet Harbor			0.09	0.00	0.07	0.10	0.04	0.15	0.14	805

Table 9 (Cont'd)

Crustal Movement Around Lake Michigan-Huron
in Feet per 100 Years Relative to Milwaukee

Gauge site	Author									
	Gilbert, 1897	Freeman, 1926	Gutenberg 1933 or 1941	Moore, 1947	VCS, 1957 unadjusted	VCS, 1957 adjusted	Kite, 1967	Kite, 1972 unadjusted	Kite, 1972 adjusted	Period of common record, months
Waukegan				0.05	-0.13	-0.14	-0.02			
Kenosha				0.13	0.29	0.28	0.28			
Racine				-0.31	-0.21	-0.17	-0.19			
Port Washington				0.09	0.11	0.10	0.13			
Sheboygan				0.20	0.19	0.25	0.32			
Manitowac				0.24	0.09	0.16	0.10			
Two Rivers				-0.10	0.04	0.09	0.10			
Kewaunee				-0.07	0.09	0.02	0.21			
Algoma				0.06	0.14	0.10	0.28			
Sturgeon Bay Canal		0.61		0.40	0.49	0.50	0.49	0.47	0.47	663
Detroit Harbor					0.23	0.30	0.64			
Jackson Harbor					0.03	0.06	0.60			
Green Bay				-0.31	0.21	0.18	0.21			
Suamico					-0.12	-0.08	0.60			

Table 9 (concluded)

Crustal Movement Around Lake Michigan-Huron
in Feet per 100 Years Relative to Milwaukee

Gauge Site	Gilbert, 1897	Freeman, 1926	Gutenberg 1933 or 1941	Moore, 1947	VCS, 1957 unadjusted	VCS, 1957 adjusted	Kite, 1967	Kite, 1972 unadjusted	Kite, 1972 adjusted	Period of common record, months
Oconto					0.19	0.14	0.23			
Menominee				0.15	0.30	0.32	0.33			
Escanaba	0.86	0.82	0.75	0.54	0.59	0.59	0.57	0.47	0.45	450
Manistique				0.24	0.50	0.47	0.66			
Naubinway				0.73	0.70	0.80	0.84			
St. Ignace				0.36	0.75[t]	0.76[t]	0.82			
Detour				0.84	0.93[t]	0.98[t]				
St. James				0.27	0.87	0.82				
Port Huron		0.42								
Point Edward								1.13		513

NOTES:

(a) t signifies derived by triangulation from the author's results

(b) + ve rate indicates a rise of the land with respect to Milwaukee

(c) VCS is an abbreviation for Vertical Control Subcommittee, Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data.

Table 10

Rates of Movement of the Land Around Lake Michigan-Huron Relative to the Lake Surface, Feet per 100 Years

Milwaukee	-0.20
Sturgeon Bay Canal	0.27
Escanaba	0.25
Thessalon	0.99
Collingwood	0.88
Goderich	0.10
Point Edward	-
Harbor Beach	0.29
Mackinaw City	0.58
Ludington	0.08
Grand Haven	-0.20
Calumet Harbor	-0.20
Chicago	-0.20

NOTE: Dashed line (-) signifies that the rate of movement is not certain.

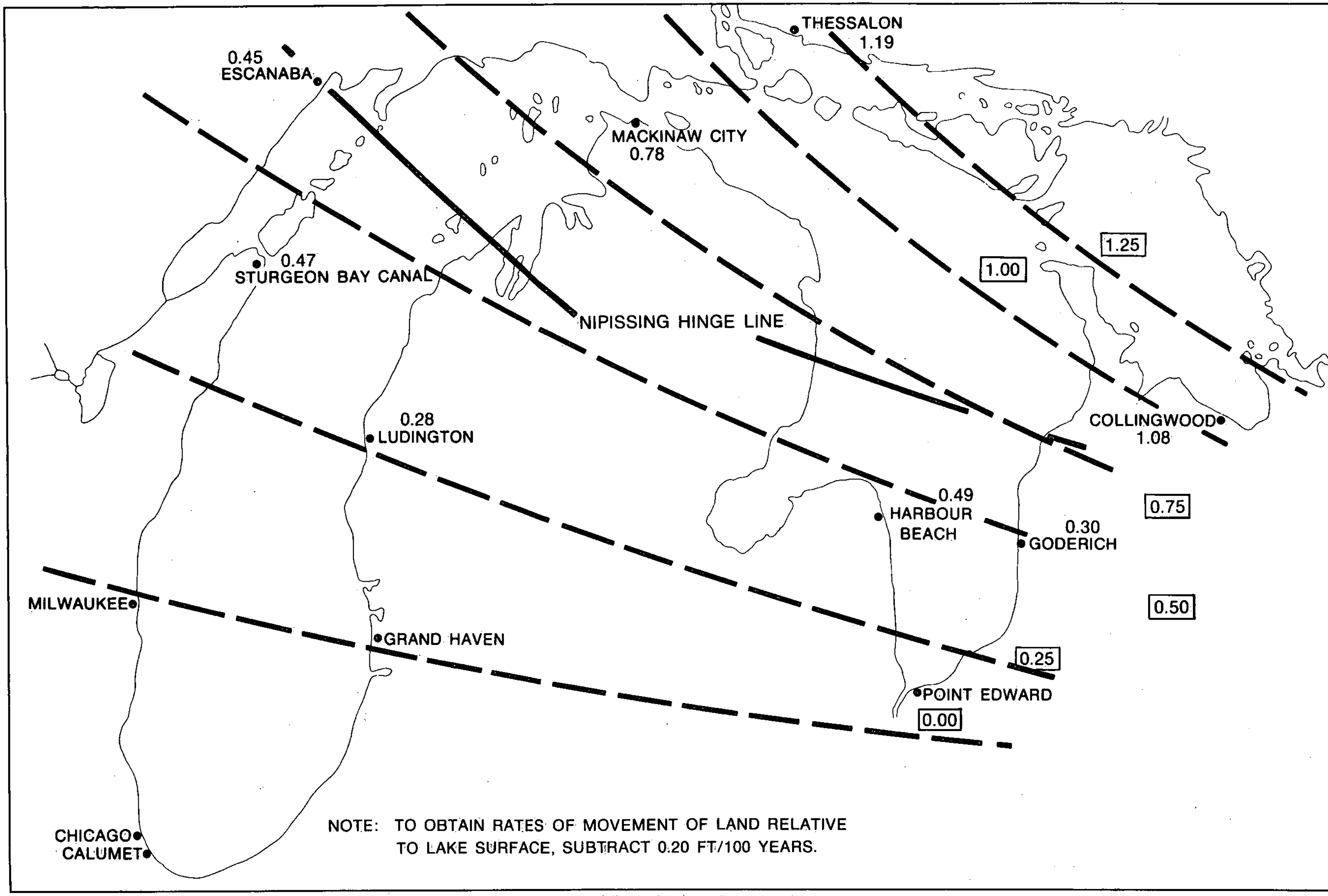
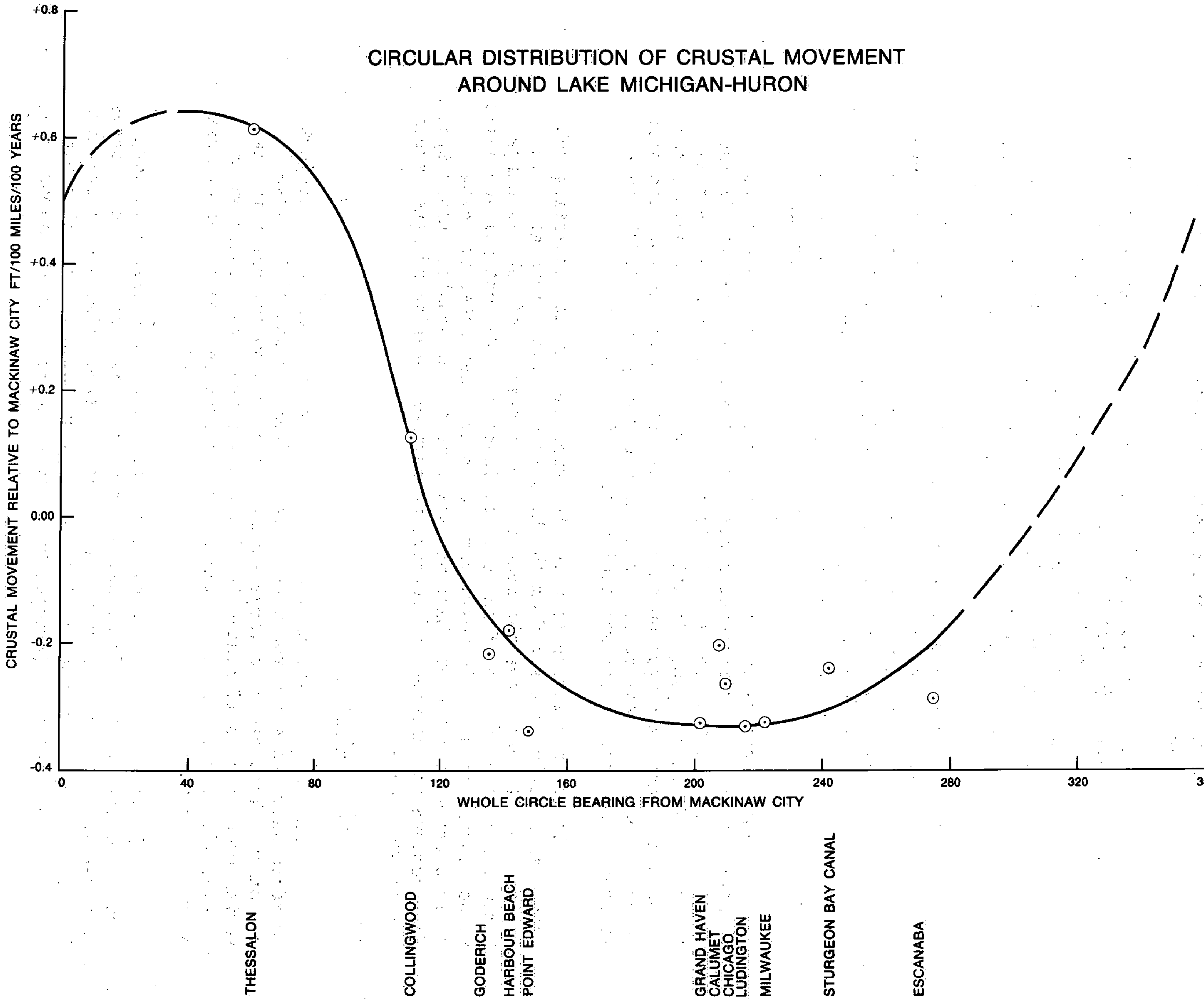


FIGURE 3

CRUSTAL MOVEMENT ON LAKE MICHIGAN - HURON
LINES OF EQUAL RATE OF ABSOLUTE MOVEMENT, FEET/ 100 YEARS.



CIRCULAR DISTRIBUTION OF CRUSTAL MOVEMENT
AROUND LAKE MICHIGAN-HURON
CRUSTAL MOVEMENT RELATIVE TO MACKINAW CITY FT/100 MILES/100 YEARS
+0.8
+0.6
+0.4
+0.2
0.00
-0.2
-0.4
0
40
80
120
160
200
240
280
320
360
WHOLE CIRCLE BEARING FROM MACKINAW CITY
THESSALON
COLLINGWOOD
GODERICH
HARBOUR BEACH
POINT EDWARD
GRAND HAVEN
CALUMET
CHICAGO
LUDINGTON
MILWAUKEE
STURGEON BAY CANAL
ESCANABA

FIGURE 4

of water which would lower the level of Michigan-Huron by around 0.1 foot.

(e) Because of local inflow to Lake Michigan and no alternate outlet (except for the effect of the Chicago diversion, as mentioned below) there is a discharge from Lake Michigan to Lake Huron through the Straits of Mackinac averaging around 50,000 cfs, with a corresponding small constant difference in elevation between gauges on Lake Michigan and those on Lake Huron.

(f) The diversion of water out of Lake Michigan at Chicago also has an effect on the levels of Lake Michigan-Huron and the downstream lakes. It has been estimated that the present maximum allowable diversion of 3,200 cfs lowers the levels of Lake Michigan-Huron by 0.23 foot. In 1928, however, the diversion was as high as 10,000 cfs and so the effect on the levels is not constant.

The functions (b) to (f) produce short or long term trends in levels of Lake Michigan-Huron but these trends are removed in the process of subtracting one set of elevations from another since these functions affect all gauge locations equally. Table 10 summarises the results for Lake Michigan-Huron and it is interesting to note the good agreement between these results and those given by Lewis (1970) using sediment sequences around Manitoulin Island in Lake Huron.

It is interesting to note also that the divide separating the Great Lakes Drainage Basin from the Mississippi River Drainage Basin is less than 8 feet above the mean surface elevation of Lake Michigan-Huron, so that at a rate of increase of level of 0.20 foot per 100 years it would take about 4,000 years for the upper Great Lakes to change their outflow from the St. Lawrence River to the Mississippi River System. This computation assumes, of course, no further lowering of lake levels due to other causes.

(c) Lake Erie

Lake Erie is the shallowest of the Great Lakes and is subject to rapid short-term fluctuations in level from one end of the lake to the other. This causes a large stochastic or random component in time series made up of differences in elevations between two gauges which, coupled with a shortage of reliable gauging stations, makes the evaluation of crustal movement around Lake Erie very uncertain.

There are only three gauging stations on Lake Erie with long periods of record; Port Colborne, Buffalo and Cleveland. Table 12 shows that generally the correlation coefficients between time and differences in mean monthly elevation are low (the highest value is less than 0.6). For 3 stations out of 9 (Erieau, Port Dover and Erie) it was impossible

Table 11

List of Gauging Stations Around Lake Erie
and the Periods of Record Used

Station	From*	To*	No. of Months of Record
Erieau	1957	1970	158
Port Stanley	1908	1970	561
Port Dover	1958	1970	146
Port Colborne	1860	1970	1332
Buffalo	1860	1970	1071
Erie	1958	1970	149
Cleveland	1860	1970	1329
Toledo	1877	1970	722
Monroe	1860	1965	286

*Inclusive (note that because of gaps in the data the number of months of record does not always correspond to the number of years).

Table 12

Computed and Computed-Adjusted Rates of Relative Movement Around Lake Erie.

GAUGE B	GAUGE A							
	Cleveland				Port Colborne			
	Rates of Movement A-B							
	Correlation Coefficient	Unadjusted Rate ft/100 years	Adjusted Rate, ft/100 years	No. of Months of Common Record	Correlation Coefficient	Unadjusted Rate, ft/100 years	Adjusted Rate, ft/100 years	No. of Months of Common Record
Erieau	0.2199	-0.4013	-	155	0.0946	-0.4165	-	158
Port Stanley	0.4960	0.3197	0.2530	558	0.3196	-0.2701	-0.2034	561
Port Dover	0.3918	1.7739	-	143	0.5098	1.6560	-	146
Port Colborne	0.5988	0.4557	0.4564	1329				
Buffalo	0.4294	0.3250	0.3233	1071	0.3196	-0.1345	-0.1332	1071
Erie	0.1903	0.6089	-	149	0.3399	0.6340	-	149
Cleveland					0.5988	-0.4557	-0.4564	1329
Toledo	0.1490	0.1601	0.2476	722	0.0691	-0.1212	-0.2087	722
Monroe	0.5366	0.2200	0.1993	289	0.3514	-0.2778	-0.2571	289

Table 13

Determination of Trend in Surface Elevation, Lake Erie

Station	Period Used (Months)							
	1329	1071	722	549	289	155	149	143
	The upper figure of each pair is the linear trend in feet per 100 years, the lower figure of each pair is the corresponding correlation coefficient.							
Cleveland	-0.75 0.25	-0.43 0.12	0.63 0.12	1.43 0.20	-0.60 0.21	8.64 0.36	10.16 0.41	10.35 0.40
Port Colborne	-1.21 0.39							
Buffalo		-0.76 0.22						
Toledo			0.47 0.08					
Port Stanley				1.12 0.16				
Monroe*					-0.82 0.27			
Erieau						9.04 0.39		
Erie							9.55 0.40	
Port Dover								8.57 0.35

*Note: This period of record does not extend to 1970.

Table 14

Crustal Movement Around Lake Erie
in Feet per 100 Years Relative to Port Colborne

Gauge Site	Author									
	Gilbert, 1897	Freeman, 1926	Gutenberg, 1933, 1941	Moore, U.S. Lake Survey, 1947	VCS, 1957 unadjusted	VCS, 1957, adjusted	Kite, 1967	Kite, 1972 unadjusted	Kite, 1972 adjusted	Period of common record, months
Port Dover							+0.39	1.66	-	146
Port Stanley			-0.55	-0.25	-0.07	-0.18	-0.37	-0.27	-0.20	561
Buffalo		-0.04 t	-0.07 t	-0.06 t	-0.04	0.00	-0.14	-0.13	-0.13	1071
Lackawanna					+0.72	+0.80	+0.64			
Dunkirk				-0.13	-0.12	-0.13	-0.04			
Erie				-0.46	-0.63	-0.57	-0.64	-0.63	-	149
Conneaut				-0.57	-0.47	-0.47	-0.18			
Ashtabula				-0.27	-0.41	-0.35	-0.27			
Fairport				-0.10 t	-0.58	-0.47	-0.47			
Cleveland	-0.71	-0.49	-0.67	-0.33	-0.43	-0.37	-0.36	-0.46	-0.46	1329
Rocky River					-0.61	-0.67	+0.37			
Lorain				-0.43	-0.59	-0.48	-0.35			
Vermilion				-0.18	-0.44	-0.35	-0.30			
Huron					-0.39	-0.29	-0.05			
Sandusky				-0.25	-0.12	-0.02	-0.31			
Port Clinton				-0.57	-0.45	-0.48	-0.19			
Toledo				-0.18	+0.01	-0.12	-0.27	-0.12	-0.21	722
Monroe				-0.09	-0.21	-0.18	+0.06	-0.28	-0.26	289
Erieau							-0.34	-0.42	-	158

NOTES: (a) t signifies derived by triangulation from the author's results.
(b) + ve rate indicates a rise of the land with respect to Port Colborne.
(c) VCS is an abbreviation for Vertical Control Subcommittee, Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data.

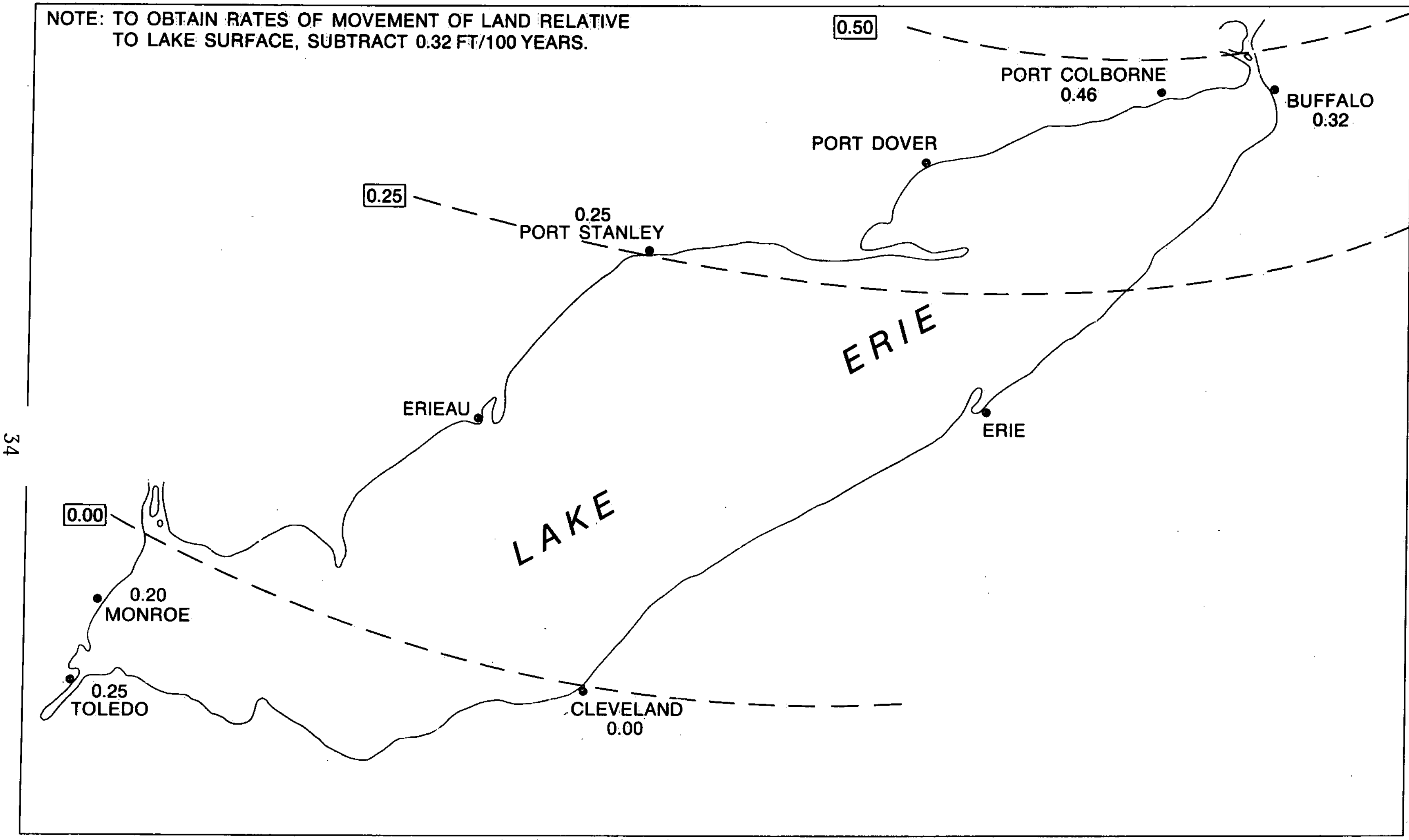


FIGURE 5

CRUSTAL MOVEMENT ON LAKE ERIE
LINES OF EQUAL RATE OF ABSOLUTE MOVEMENT, FEET/100 YEARS

Table 15

Rates of Movement of the Land Around Lake Erie
Relative to the Lake Surface, Feet per 100 Years

Erieau	---
Port Stanley	-0.07
Port Dover	---
Port Colborne	+0.14
Buffalo	0.00
Erie	---
Cleveland	-0.32
Toledo	---
Monroe	---

Note:

Dashed line (---) signifies that the rate of movement is not certain.

CIRCULAR DISTRIBUTION OF CRUSTAL MOVEMENT AROUND LAKE ERIE

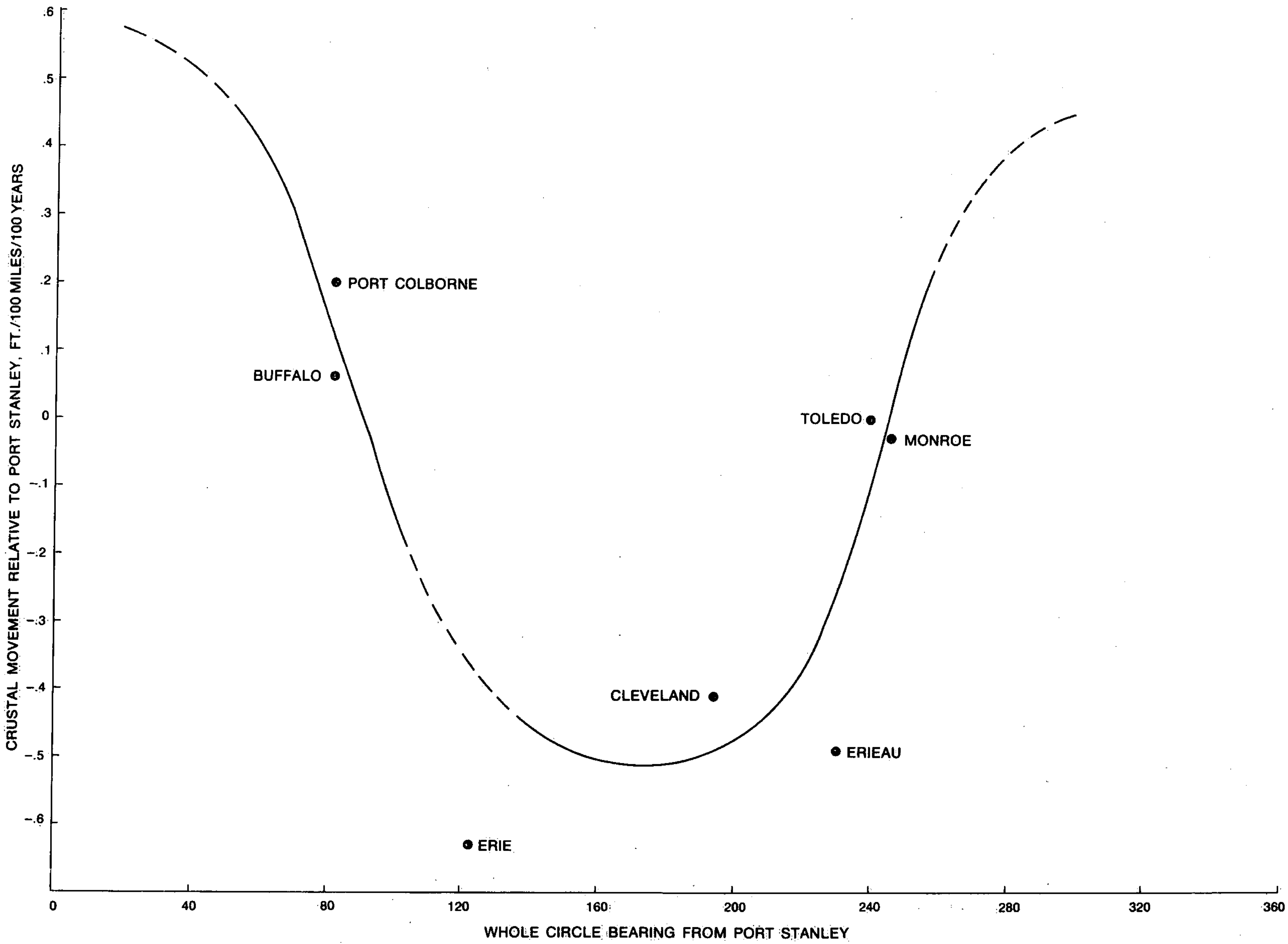


FIGURE 6

to arrive at a reasonable adjusted rate of crustal movement and for 2 other gauging stations (Toledo and Monroe) the adjusted rates are extremely doubtful, due to a very low correlation coefficient in the first case and a short period of record in the second. At this stage in the analysis it is evident that only results from the four stations Port Colborne, Buffalo, Cleveland and Port Stanley can be considered further.

Observation of graphs of differences in mean monthly elevations versus time shows that, for a few pairs of gauging stations on Lake Erie, certain portions of the plots seem to show no trend in gauge differences. These periods of zero or very low trend appear to be separated by "jumps" or abrupt changes in the record, so that the graph shows a series of step-like changes rather than a smooth trend. These steps in the record could be due to movement at a fault line(s) located between the pair of gauges used (Kite (1967)) or the jumps could be due to gauge relocation or other gauge disturbances not corrected for in the original gauge records.

The significance of the observed "flat" data sequences can be checked by examining statistically the differences between the mean levels for each flat sequence. This is necessary because of the large random component present in these time series, particularly on Lake Erie. Assuming a statistical significance is verified, then an explanation of the "jumps" in level can be sought in geological records and in gauge histories and records of harbour construction. In a recent publication, Korkigian (1972) has shown that for Cleveland minus Buffalo the "jumps" in the time series of gauge differences correspond with the dates of gauge relocations at the two sites. Korkigian, however, used only one elevation per year at each station (made up of the mean of the four monthly means, June through September). Using 12 monthly means per year, as in this study, the distinction between "flats" and "jumps" could not be proved statistically except in one case, Port Colborne. Graphs of Port Colborne minus Buffalo, minus Cleveland and minus Port Stanley show a strong possibility that the period 1926 to 1950 is not compatible with the remaining period of record, 1860 - 1925 and 1951 - 1970. A statistically significant difference in mean was shown and the period 1926 to 1950 was eliminated from the Port Colborne data.

As an example Port Colborne minus Buffalo shows the following first order linear trends: -

(1)	1860 - 1970	-0.1345 ft/100 years
(2)	1860 - 1925	-0.0537 ft/100 years
(3)	1926 - 1950	+0.0090 ft/100 years
(4)	1951 - 1970	+0.0089 ft/100 years,

between (2) and (3) is a jump of +0.02 foot and between (3) and (4) is a jump of -0.10 foot. It is apparent that the rate of movement shown over the period 1860 - 1970 is, in reality, due to the effect of the jumps in record and is not a true trend. A check of the gauge histories (Coordinating Committee (1969)) reveals no corresponding reasons for the jumps in record.

It has been shown then that the presence of crustal movement around Lake Erie is open to question but, at the present time, the evidence is not sufficient to provide a definite answer to the problem. For this reason, the rates of movement derived from first order linear trends in gauge differences will be retained in this study, although with serious reservations.

Referring the computed relative rates of movement to a datum is not simple on Lake Erie since there is no Nipissing zero isobase. The only solution appears to be to accept the southernmost gauge, Cleveland, as a datum although this is not very satisfactory.

One of the gauging stations with a long period of record is Buffalo, located near the outlet of Lake Erie. Since Lake Erie is, at present, unregulated, the mean lake level must rise at the same rate as the outlet rises. The Buffalo gauge is apparently rising, relative to Cleveland, at a rate of around 0.32 foot/100 years. Table 15 lists the rates of movement of each gauge site relative to the mean lake level.

Lake Erie mean lake level has been affected over the last hundred years by several factors. It has been computed that the Long Lake and Ogoki diversions have raised the lake level by 0.23 foot, the Chicago diversion has lowered the lake level by 0.14 foot, and the Welland Canal and New York State Barge Canal decrease the level by 0.33 foot. Some small effect on the mean lake level may be expected from the operation since 1964 of the ice boom in the Niagara River. Table 13 shows an overall trend in lake level of perhaps -1.00 foot/100 years although, again, this is subject to a large uncertainty as shown by the small correlation coefficients.

Figures 5 and 6 show lines of equal rates of absolute movement and the circular distribution of crustal movement around Lake Erie.

(d) Lake Ontario

Lake Ontario is the second of the Great Lakes presently regulated. Four gauging stations, Port Dalhousie, Toronto, Kingston and Oswego have over 1,000 months of record with Rochester very close at 953 months. The range of correlation coefficients in Table 17 is large, varying from 0.0527 to 0.8057 generally being proportional to the length of common record between the gauging stations concerned; the only exceptions to this being between Toronto and Port Weller and Oswego and Port Weller. Toronto and Oswego were chosen as base stations having long periods of record and being at opposite ends of the lake. In addition, the gauge at Oswego has special significance since it is used in the regulation of Lake Ontario levels.

Table 16

List of Gauging Stations Around Lake Ontario and the Periods of Record Used

Station	From*	To*	No. of months of record
Port Weller	1929	1970	205
Port Dalhousie	1849	1956	1289
Toronto	1861	1970	1294
Cobourg	1956	1970	174
Kingston	1860	1970	1329
Cape Vincent	1898	1970	650
Oswego	1840	1970	1433
Rochester	1846	1970	953
Fort Niagara	1860	1963	385

* Inclusive (note that because of gaps in the data the number of months of record does not always correspond to the number of years).

Table 17

Computed and Computed-Adjusted Rates of Relative Movement Around Lake Ontario

Gauge B	Gauge A							
	Oswego				Toronto			
	Rates of Movement A-B							
	Correlation Coefficient	Unadjusted Rate, ft/100 years	Adjusted Rate, ft/100 years	No. of Months of Common Record	Correlation Coefficient	Unadjusted Rate, ft/100 years	Adjusted Rate, ft/100 years	No. of Months of Common Record
Port Weller	0.1547	-0.0760	-0.2182	202	0.7056	0.2289	0.3711	205
Port Dalhousie	0.2279	-0.4943	-0.4833	1193	0.0527	0.1170	0.1060	1124
Toronto	0.7826	-0.5917	-0.5893	1291				
Cobourg	0.1122	-0.1663	-0.2371	171	0.2279	0.2814	0.3522	174
Kingston	0.2537	0.0737	0.0741	1326	0.8057	0.6659	0.6634	1294
Cape Vincent	0.4433	0.1418	0.0008	650	0.7342	0.4491	0.5901	650
Oswego					0.7826	0.5917	0.5893	1291
Rochester	0.4694	-0.1997	-0.2186	828	0.7112	0.3497	0.3686	767
Fort Niagara	0.7020	-0.3597	-0.3521	385	0.5698	0.2449	0.2373	373

Table 18

Determination of Trend in Surface Elevation, Lake Ontario

Station	Period Used (Months)							
	1326	1291	1193	828	650	385	202	171
	The upper figure of each pair is the linear trend in feet per 100 years, the lower figure of each pair is the corresponding correlation coefficient.							
Oswego	-0.65 0.18	-0.62 0.17	-0.63 0.15	-0.73 0.25	0.86 0.11	-0.64 0.24	-1.61 0.19	3.72 0.17
Kingston	-0.72 0.20							
Toronto		-0.02 0.01						
Port Dalhousie*			-0.13 0.03					
Rochester				-0.53 0.18				
Cape Vincent					0.71 0.09			
Fort Niagara*						-0.28 0.11		
Port Weller							-1.54 0.18	
Cobourg								3.89 0.17

* Note, these periods of record do not extend to 1970.

Table 19

Crustal Movement Around Lake Ontario
in Feet per 100 Years Relative to Toronto

Gauge Site	Freeman, 1926	Gutenberg, 1933	Moore, U.S. Lake Survey, 1947	Price, Canadian Hydrographic Service, 1954	VCS, 1957 Unadjusted	VCS, 1957 Adjusted	Kite, 1967	Kite, 1972 Unadjusted	Kite, 1972 Adjusted	Period of Common Record, Months
Port Weller							+0.09	+0.23	+0.37	205
Cobourg					+0.17	+0.20	+0.03	+0.28	+0.35	174
Kingston		+0.59[t]	+0.81	+0.66	+0.71	+0.69	+0.66	+0.67	+0.66	1294
Port Dalhousie	-0.45	+0.16	-0.19	-0.10	+0.16	+0.12	+0.05	+0.12	+0.11	1124
Tibbetts Point					+1.00	+0.76				
Sacketts Harbor			+0.59		+0.56	+0.45	+0.53			
Port Ontario					+0.50	+0.36	-0.05			
Little Sodus Bay					+0.01	+0.10				
Sodus Bay					-0.24	-0.15	-0.16			
Rochester			+0.33		+0.36	+0.24	+0.13	+0.35	+0.37	767
Oak Orchard					+0.43	+0.29				
Olcott			+0.28		+0.41	+0.23	+0.27			
Wilson					+0.32	+0.18	+0.52			
Fort Niagara			+0.28		+0.24	+0.10	+0.40	+0.24	+0.24	373
Oswego	+0.23	+0.64	+0.58	+0.45	+0.62	+0.56	+0.41	+0.59	+0.59	1291
Cape Vincent		+1.35	+0.64	+0.66	+0.45	+0.58	+0.36	+0.45	+0.59	650
Hamilton							-0.26			

Notes:

(a) t signifies derived by triangulation from the author's results

(b) + ve rate indicates a rise of the land with respect to Toronto

(c) VCS is an abreviation for vertical control Subcommittee, Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data.

Table 20

Rates of Movement of the Land Around Lake Ontario Relative to the Lake Surface, Feet per 100 Years

Port Weller	---
Port Dalhousie	---
Toronto	-0.75
Cobourg	-0.40
Kingston	-0.09
Cape Vincent	-0.16
Oswego	-0.16
Rochester	-0.38
Fort Niagara	---

Note:

(a) Dashed line (---) shows those relationships which are uncertain.

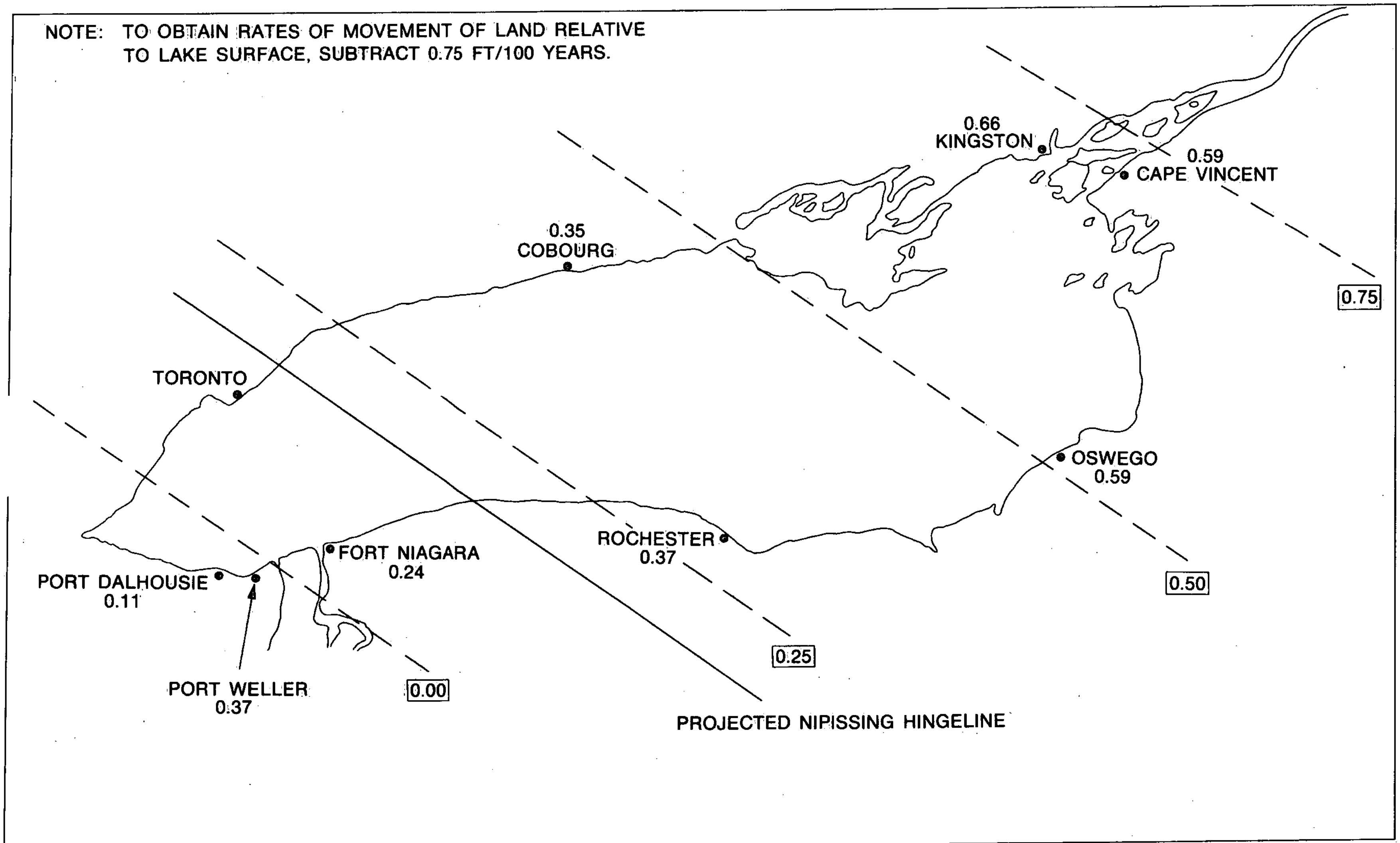


FIGURE 7

CRUSTAL MOVEMENT ON LAKE ONTARIO
LINES OF EQUAL RATE OF ABSOLUTE MOVEMENT, FEET/100 YEARS

CIRCULAR DISTRIBUTION OF CRUSTAL MOVEMENT
AROUND LAKE ONTARIO

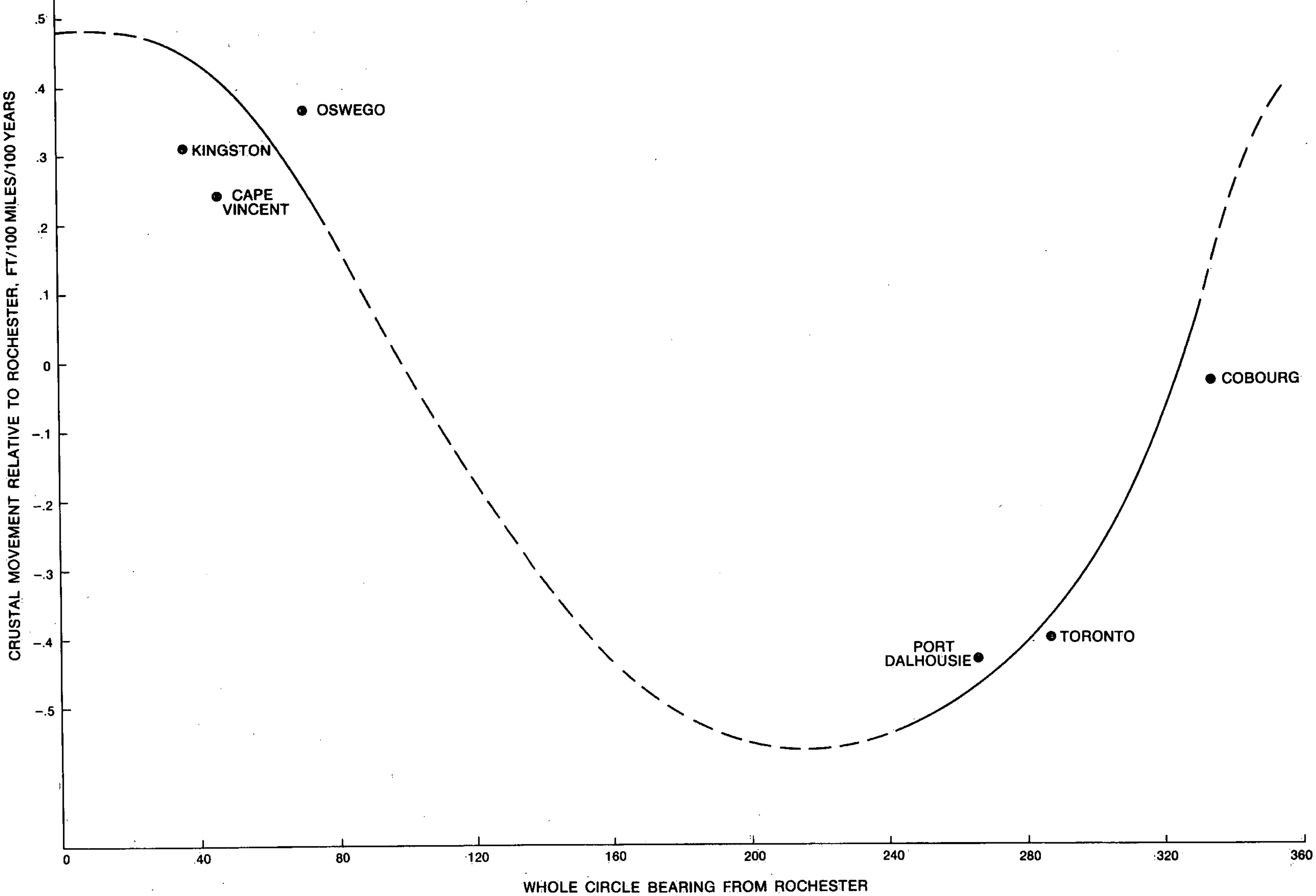


FIGURE 8

Table 17 indicates a rise of the eastern end of Lake Ontario relative to the western end of around 0.75 foot per 100 years. No additional information is provided by the trends in surface elevations. If the outlet of the lake is rising at 0.75 foot per 100 years then the mean lake level must also be rising at this rate. Regulation of Lake Ontario has been in effect only since 1958 so that this is not yet an important factor in long-term lake levels.

The Nipissing hinge-line has been projected (Maclean, 1961) to pass north of Toronto. Since this is only a projection, a small deviation may be acceptable which would agree better with the results of this study. Figure 7 shows lines of equal rates of crustal movement. The line of zero movement is parallel to the geologist's projected Nipissing hinge line but shifted slightly towards the western end of the lake. This provides the datum for computing absolute rates of movement.

The effect of crustal movement on the regulation of Lake Ontario is interesting. The regulation limits for Lake Ontario adopted by the Canadian and U.S. Governments were defined in terms of the fixed land to water level relationship at the Oswego gauge. However, the land in the area of the regulation structures (International Rapids Section of the St. Lawrence) is rising relative to the land at Oswego by around 0.16 foot per 100 years while the land at the western end of the lake is sinking relative to Oswego at a rate of over 0.5 foot per 100 years.

Assuming a simple outflow relationship for Lake Ontario this means that water levels at Oswego are rising relative to the land at a rate only one-third the rate at which water levels at the western end of the lake are rising. The present arrangement is therefore a compromise; if the lake were regulated using elevations at the outlet, flooding would eventually occur at the western end of the lake. If, on the other hand, regulation of Lake Ontario were effected using elevations measured at the western end of the lake, this would reduce the flooding risk but would necessitate increased channel excavation to compensate for the naturally decreasing cross-section of the St. Lawrence River.

(e) Combined Great Lakes

For each of the Great Lakes rates of crustal movement have been computed relative to some absolute datum. It should be possible to combine the information on Figures 1, 3, 5 and 7 and produce a figure showing crustal movement over the whole Great Lakes Basin. Figure 9 is an attempt at this. The lines of 1.0 and 0.5 foot per 100 years movement were placed first and these show reasonable consistency on all lakes except Erie. Finally the common datum line was placed on the figure; this approximates the previously determined zero lines on Lakes Superior and Michigan-Huron but is not in agreement with the data determined individually for Lakes Erie and Ontario.

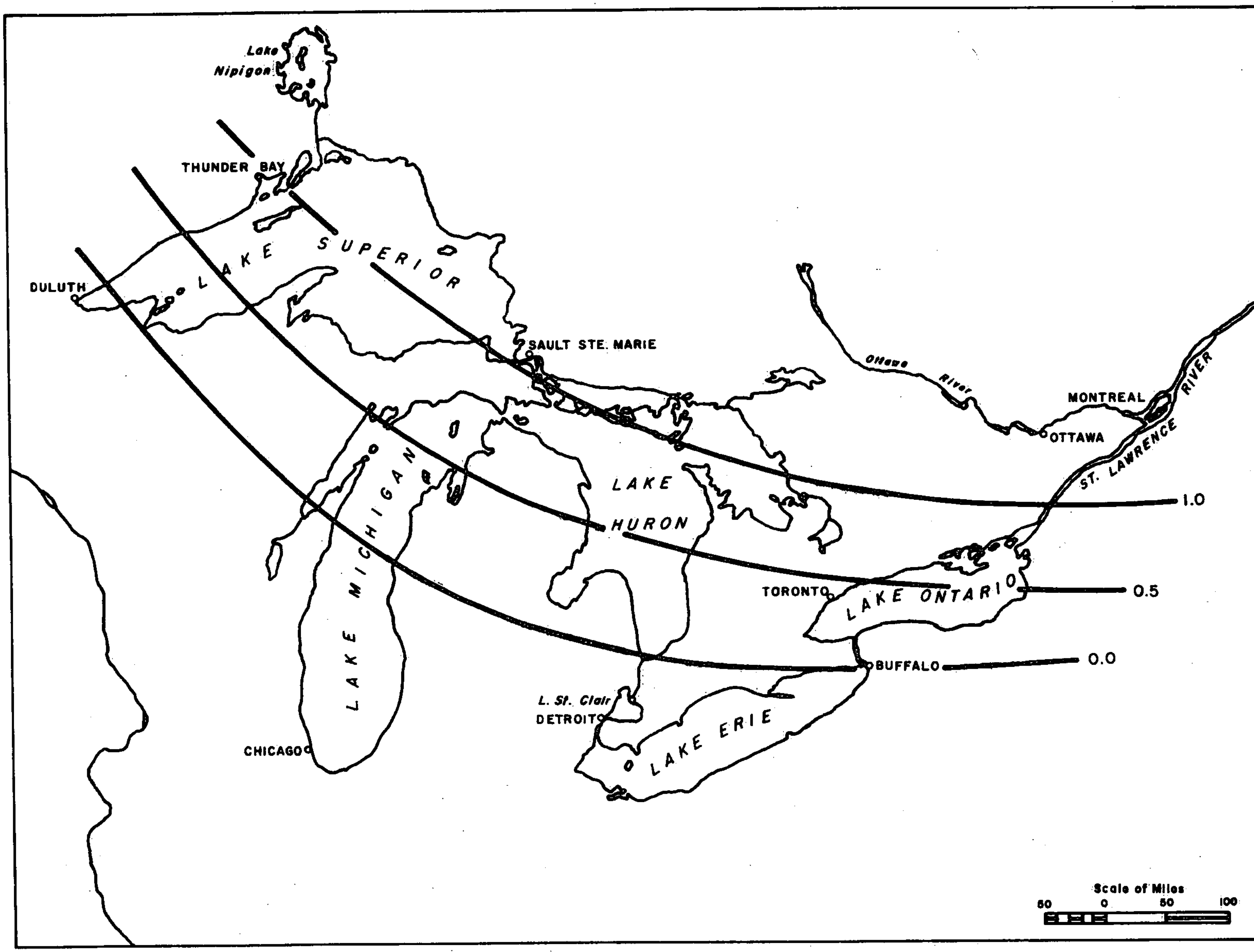


FIGURE 9

CRUSTAL MOVEMENT WITHIN THE GREAT LAKES BASIN

RATES OF MOVEMENT IN FEET PER 100 YEARS

The iso-lines on Figure 9 would appear to confirm the opinions held by many investigators that Lakes Superior and Ontario are affected more by crustal movement than the other two lakes. The shape of the lines also agrees generally with iso-bases derived by other investigators using other methods. As an example, Innes and Argun-Weston (1966) in a paper relating crustal uplift to the gravity field indicate the position of isobases at 100-foot intervals in the Arctic, Hudson's Bay and Great Lakes region. Their isobases were derived from the observed elevations of raised beaches. Other investigations resulting in isolines include Andrews (1970), using post-glacial recovery and rebound curves and Walcott, (1970) studying the isostatic response to crustal loading. It may be noted that on Figure 9 no crustal movement is indicated around Lake Erie. This results from the large uncertainty in computed rates of movement around this lake together with the fact that the trend in isolines based on the other three lakes is to pass to the north of Lake Erie.

SUMMARY

Several previous investigations beginning in the late nineteenth century have computed relative rates of vertical movement between points around the Great Lakes using long term records of lake elevations. It is thought that this movement is due to the isostatic adjustment of the earth's crust to the reduction in pressure which occurred as the Laurentide ice sheet began to retreat some 16-20,000 years ago. Ice recession from the Great Lakes basin took place over the period from about 14,500 to 9,500 years ago (Prest, 1970). Most of the previous investigations which used lake elevations as a means of computing rates of movement suffered from two drawbacks:

(a) It was assumed, but not shown, that time series composed of differences in elevations between pairs of lake level gauging stations could be represented by first order linear trends.

(b) Computed rates of vertical movement were only relative i.e. they implied movement of one point relative to another on the shore of the same lake and were not referred to any stable datum, nor could they be used to study the movement of land at one point on a lake's shoreline relative to the surface elevation of the lake itself.

A previous report (Kite, 1972) has described in detail the analysis of a sample set of data and the subsequent breakdown of the time series. It was found that the test data (Marquette minus Duluth) was made up of the following components:

Linear trends	48%
Periodicities in the mean and variance	18%
Residual	34%

where the percent figures refer to the proportions of the variance of the original time series explained by each of the components. The linear trends were made up overwhelmingly of a first order trend while the periodicities, as might be expected, were mainly the annual cycle. The residual was found to be nearly normally distributed with no significant autoregressive components present.

The method then computed relative rates of movement between gauges, referred these relative movements to a suitable datum and computed movements of land relative to lake level. In some cases it was possible to use the Nipissing zero isobase as a datum which has a theoretical justification; in other cases it was only possible to use the southernmost gauge having significant movement as a datum.

On Lake Superior general agreement was found between the geological positioning of the Nipissing zero isobase and the computed line of zero rate of crustal movement. In addition, the rates of vertical crustal movement computed for Lake Superior in this study agree very well with rates of movement computed from Nipissing shoreline elevations obtained by Farrand (1960). This adds confidence to the results in this report for Lake Superior.

Lake Michigan-Huron is not as straight-forward to analyse as Lake Superior. As explained in the relevant section this is due to two factors:

(a) the lowering of lake levels by dredging, diversion, ice retardation etc.

(b) the incompatibility between the Nipissing zero isobase location and the location of the line of zero crustal movement as computed in this study. Both lines are shown on Figure 3.

It has been discussed in the results section of this paper but it should be emphasized again that taking differences in elevations eliminates the trends introduced by dredging. The rates of movement computed from these time series are therefore independent of the lowering of lake level and can be regarded as accurate.

Crustal movement on Lake Erie is very difficult to evaluate. The lake is relatively shallow and is subject to frequent seiche action. This introduces high amplitude pseudo-periodic and stochastic components into the time series which reduces the variance explained by first order linear trends. This is shown in Table 12 by the low correlation coefficients and high proportion of non-significant regressions. This low significance plus the geologic opinion that there is no current movement does not add confidence to the results. However, as shown on Figure 5, it is possible that a small rate of crustal movement does exist across the lake.

The results from the analysis of Lake Ontario are generally acceptable. Toronto and Oswego were used as base stations. The computed line of zero crustal movement is not far different from the geologists' projected Nipissing zero isobase.

The results for all of the individual lakes have been combined, on a common datum where possible, to provide an overall picture of vertical crustal movement within the Great Lakes basin.

CONCLUSIONS

1. General Conclusions

(a) Facilities such as major shore protection works, marinas, wharves, and navigation structures with useful lives of around 50 years will obviously be affected during their lifetimes by crustal movement. As examples, Freeman (1926) states that "probably Duluth and Superior Harbors have become one foot deeper than 50 years ago", "... the depths of the harbors on the north side of Georgian Bay probably now present an average depth of water 0.60 foot less than that possessed by each of these harbors 50 years ago".

(b) Time series created by taking differences in mean monthly lake elevations at two gauges are generally made up of the following three components.

(1) A dominant first order linear trend with less significant higher order linear trends.

(2) Periodicity in the mean and standard deviation, chiefly the annual and six-monthly cycles.

(3) A near-normal, non-autoregressive, residual.

(c) First order linear trends can be used as adequate representations of time series made up of differences in lake elevations.

(d) Rates of relative movement computed by previous investigators are generally correct for those pairs of gauges having periods of common record of around 20 years or more. Gauges with records of less than this can give inaccurate results.

(e) It has been shown possible to compute absolute rates of crustal movement in the Great Lakes area using a stable datum.

(f) The use of any datum to convert relative movements to absolute movements is only an approximation since, of course, there can be no sharp "movement - no movement" boundary, only a gradual change. In addition any datum referred to is only stable as regards the Great Lakes area. It may be that on a continental scale the vertical position of the Great Lakes area is changing, and on a world-wide scale the vertical position of the North American continent could be changing, but these could not be determined by lake level measurements around the Great Lakes.

(g) The use of the first order linear trends as representative of time series made up of differences in lake elevations is justified for the time series analysed. If, however, 1000 years of data were available instead of 100 it is probable that the dominant trend would be non-linear, maybe exponential, since nature is not usually as obliging as we would wish and a linear crustal movement is suspiciously simple.

(h) The plots of circular distribution of relative crustal movement indicate that generally the lake basins are moving as complete units at homogeneous rates.

2. Conclusions for specific regions

(a) Relative rates of crustal movement are well defined on Lake Superior and can be referred to the Nipissing hinge line datum. The northeast shoreline of the lake is rising at a rate of around 1.0 - 1.5 feet per 100 years while the southwest shoreline is virtually stable. This results in a falling lake level relative to the land at the northeast end of the lake and a rising lake level relative to the land at the southwest end of the lake. The lake outlet at Sault Ste. Marie is rising at virtually the same rate of movement as the mean lake level.

(b) All of Lake Huron and approximately the northern two thirds of Lake Michigan are subject to vertical crustal movement. The most northerly shoreline of Lake Huron is rising at a rate of about 1.25-1.50 feet per 100 years referred to a datum just north of Milwaukee.

(c) It is concluded that there may be crustal movement around Lake Erie although the evidence for this is far from satisfactory.

(d) The outlet of Lake Ontario is rising relative to the rest of the lake. Lake Ontario, however, is regulated, and if the regulation plan compensated for the effects of crustal movement some of the detrimental effects of the rise in lake level could be avoided.

RECOMMENDATIONS

On the basis of the methodology developed and the results presented in this study the following recommendations are made:

(a) In two or three years time, a means of confirming the rates of absolute crustal movement given by this study will be available. A second set of levels from Father Point to the Great Lakes will have been run by that time and, within the limits set by the accuracy of levelling and the small time period between sets of levels (15 years) it will be possible to compute absolute changes in elevation of key points around the lake.

(b) The study be repeated in fifteen years when more data will be available. Particular attention should be paid to crustal movement around Lake Erie.

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