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TILTING DUE TO GLACIAL MELTING

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ABSTRACT

To investigate tilting and changes in level in the United States and Canada, results from the records of tide gauges of different stations were analyzed. In the Great Lakes region all results indicate a tilting of the land upward in a northerly direction, by about 10 cm. per 100 km. per century. Along the Pacific Coast a small rising of the land is indicated at the north, whereas in California the changes in height seem to be negative, but small and irregular. Along the Atlantic Coast of Canada the changes are small and within the limits of error nearly everywhere, but south of Portland (Me.) sinking prevails clearly. It is very probable that the tilt in the Great Lakes region is due to forces which tend to restore isostatic equilibrium, disturbed by the melting of ice after the Ice Age.

In some parts of the continents which were covered by ice during the Ice Age recent uplift has been found continuing up to the present time. It is considered by many scientists, but questioned by others, that this uplift is a consequence of forces which tend to restore isostatic equilibrium disturbed by the melting of the ice. The strength of the material close to the surface of the earth is of the order of 10^9 dyn./cm.^{2}. A mountain with a height of the order of 10 km. (relative to the neighborhood) is needed to produce a vertical pressure of the order of this strength. Such an effect of glaciation therefore usually will not occur, and if tilting of the earth's crust connected with flowing movements at deeper layers is observed due to the formation of ice caps or to melting of ice, it may be concluded from this fact that the strength at depth is considerably less than close to the surface. For this and other reasons it is very important to investigate whether any tilting observed is due to glacial melting.

The best results available on tilting of this type are around the Baltic Sea. In the early part of the eighteenth century Celsius found that the shores of this sea were rising by an average amount of 1 cm. per year. Holmström found that Södra Helsö, fronting the open Skagerrak on the west coast of Sweden, rose 30 cm. between 1820 and 1870, and Stockholm 48 cm. between 1774 and 1875. A very detailed investigation based on records of tide gauges has been

TABLE I

	North		Central Part			South		
	West	East	West	East		West	East	
	Ratan	Toppila	Väster-vik	Jung-frusund	Kron-stad	Freder-icks havn	Wismar	Memel
I	+1.2	+1.1	+0.6	+0.2	−0.7	+0.1	−0.1	+0.3
II	1.5	1.5	.7	.6	+0.1	+ .1	+ .1	+ .0
III	0.8	1.0	+ .3	.6	+1.1	− .3	− .2	+ .6
IV	+1.0	+0.6	−0.3	+0.3	+0.8	+0.5	−0.1	−0.4
Average	+1.1	+1.0	+0.4	+0.4	+0.3	+0.1	−0.1	+0.1

carried through by R. Witting.[1] He used records of more than fifty stations and corrected them for effects of meteorological changes. For the Baltic Sea he found from his data, covering fifteen years, a yearly uplift of more than 1 cm. along the northern shores, about $\frac{1}{2}$ cm. in the middle part (60° N. latitude), and no change on the southern coast. The following data are taken from his tables. "I" means average yearly change of the height of the coast in centimeters, 1899–1902; "II," 1902–5; "III," 1905–8; and "IV," 1908–11. The changes were not completely regular, and Witting states that years with irregular movements show more earthquakes in these regions than occur usually.

[1] Rolf Witting, "Hafsytan," *Geoidytan och landhöjningen* (Helsingfors, 1918), Fennia XXXIX, No. 5.

The data found by Witting for points around the North Sea are very much less regular, owing probably to the fact that there the effects of storms on the height of the sea level are very much more considerable than in the Baltic Sea. The changes shown in Table II were given by Witting (periods as before, the values are centimeters per year).

TABLE II

	Aberdeen	Dundee	Vlissingen	Helder	Bremerhaven	Kattegat
I.	+0.2	+0.2	+0.7	+1.9	−0.3	+0.0
II.	− .3	+ .8	−2.2	−2.1	+ .3	+ .1
III.	− .1	− .2	−0.8	−0.1	+ .4	− .0
IV.	+0.4	+0.3	+0.8	+0.1	−0.3	+0.2
Average..	0.0	+0.3	−0.4	0.0	0.0	+0.1

Witting also investigated older (but less accurate) marks of the average height of sea level in the Baltic Sea,[2] and, from observations covering a time interval of more than one hundred years, he found the following changes in height in meters per one hundred years (feet per one hundred years): 6 stations north of 62° latitude: between +0.95 and +1.00 m. (about 3 ft.); 9 stations around 60°: between +0.2 and +0.75 m. ($\frac{1}{2}$–$2\frac{1}{2}$ ft.); Swinemünde (south shore) between 0.00 and +0.05 m. (less than 2 in.).

Geological investigations show that since the end of the Ice Age the maximum rise in Scandinavia took place around the Baltic Sea between 62° and 64° latitude by an amount of over 250 m.[3] Assuming that this rise began ten thousand years ago, we find an average rise of more than $2\frac{1}{2}$ m. per century, which amount is very much larger than that which we are now observing. Witting calculated that an uplift of about 50–60 m. is still to be expected. In spite of the good agreement between calculations and observations, there is some doubt as to the extent to which these movements today are caused by the melting of the ice long ago. Especially R. Schwinner[4]

[2] "Le soulèvement récent de la Fennoscandie," *Geografisca Annaler*, 1922, p. 458.

[3] A. Born, *Isostasie und Schweremessung* (Berlin, 1923); V. Tanner, "Studier över Kvartärsystemet," *Fennoskandias mordliga delar. Bull. de la Comm. Géologique de Finlande* (Helsingfors, 1930), No. 88.

[4] "Die Schwere am Ostrand des Fennoskandischen Schildes," *Gerlands Beiträge zur Geophysik*, Vol. XXXIV (1931), p. 436.

pointed out that observations of gravity seem to contradict the idea that we have today a "postglacial uplift" in Fennoscandia.

When the ice cap formed, at depth there must have been an outflow of subcrustal material corresponding to the sinking of land in the area where the ice masses increased. That this event took place in such a way seems to be reasonable since the measurements of the thickness of ice in Greenland have shown that there is indeed a very flat trough filled with ice. One maximum height of rocks is near the coast, where in most regions heights of more than 1,000 m. occur, another seems to be in the central part. In the interior the values shown in Table III have been found.[5] When, after the Ice

TABLE III

Distance from the west coast	small	15	20	30	50	120	400 km.
Rock surface above sea level	1,000+	640	385	460	370	600–200	1,000± m.
Thickness of ice	—	330	600	750	1,200	1,600–2,000	2,000± m.

Age, the ice cap of Scandinavia had melted away, the land rose and, at some depth, the material flowed back. If this movement is still going on, then we must still have lack of material (compared with the state of isostatic equilibrium) beneath the rising region and too much material at some distance from it; this means too low gravity in the rising region, too high gravity at some distance from it. Schwinner, in his publication cited above, did not find either a well-marked region of too low gravity in the rising region, though the very scanty values there indicate a slightly negative anomaly, or a marked ring of positive anomalies around this region. Rather he found some areas with positive and other areas with negative anomalies. This could be explained by supposing that in some of these outer regions equilibrium has been restored, while in others with higher strength or viscosity there is still a remainder of the material, which flowed away from the region of glaciation when the ice caps

[5] Ernst Sorge, "Die ersten Dickenmessungen des grönländischen Inlandeises," *Zeitschrift für Geophysik*, Vol. VI (1930), p. 22; Kurt Wegener, "Die Ergebnisse der 'Deutschen Grönland Expedition Alfred Wegener,'" *Forschungen und Fortschritte*, Vol. VIII (1932), p. 143. Geophysikalische Forschungen der beiden letzten Jahre in den Polargebieten." *ibid.*, p. 422.

were formed. Besides, we must consider that the maximum anomalies which are to be expected[6] if isostatic equilibrium has not been restored since the Ice Age are probably less than 0.01 cm./sec.^{2} The effects of other causes, especially the geological conditions,[7] and the errors introduced by the methods of reduction are noticeably larger than this value. Therefore, we cannot draw the conclusion that the gravity measurements disprove the theory of isostatic uplift in Scandinavia.

Conditions similar to those in Scandinavia prevailed in North America. Large parts of Canada were covered by ice during the Ice Age, which has melted away since that time. Gravity measurements are still fewer than in Europe. Small negative anomalies seem to prevail, according to A. Born,[8] in the region of former glaciation; small positive anomalies south of it. The maps showing the gravity anomalies calculated by W. Bowie[9] by use of different methods neither support nor disprove such a result, especially if we again consider the small amount of the anomalies to be expected.

Geological evidence shows that here, too, the regions which had been covered by large masses of ice during the Pleistocene Ice Age have risen since that time. The investigations especially concern the regions of the Great Lakes and around Newfoundland.[10]

In the Great Lakes region Gilbert calculated from tide-gauge rec-

[6] U. Pesonen, "Relative Bestimmungen der Schwerkraft in Finnland," *Veröff. des Finn. Geodat. Inst.* (Helsinki, 1930), No. 13, p. 162.

[7] H. Reich, "Die Bedeutung der finnischen Schweremessungen," *Gerlands Beiträge zur Geophysik, Ergänzungshefte,* Vol. II (1931), p. 1.

[8] *Op. cit.*, p. 106.

[9] "Investigations of Gravity and Isostasy," *U.S. Coast and Geodetic Surv.* (Washington, 1917), Spec. Pub. 40; "Isostatic Investigations and Data for Gravity Stations in the United States Established since 1915," *ibid.* (1924), Spec. Pub. 99.

[10] G. K. Gilbert, "Recent Earth Movement in the Great Lakes Region," *U.S. Geol. Surv., Eighteenth Ann. Rept., 1896–97,* Part II, p. 595; J. W. Goldthwait, "Isobases of the Algonquin and Iroquois Beaches," *Bull. Geol. Soc. Amer.*, Vol. XXI (1910), p. 227; F. Leverett and F. B. Taylor, "The Pleistocene of Indiana and Michigan and the History of the Great Lakes," *U.S. Geol. Surv., Monog. 53* (1915); J. W. Spencer, "Post-glacial Earth Movements about Lake Ontario . . . . ," *Bull. Geol. Soc. Amer.*, Vol. XXIV (1913), p. 217; R. A. Daly, "Oscillations of Level . . . . ," *Bull. Geol. Soc. Amer.*, Vol. XXXI (1920), p. 308; "Post-glacial Warping of Newfoundland and Nova Scotia," *Amer. Jour. Sci.* (5th ser.), Vol. I (1921), p. 381; "Pleistocene Changes of Level," *ibid.*, Vol. X (1925), p. 281.

ords the changes shown in Table IV in height difference. From these data he derived an average change in slope of 0.42±0.044 feet (12 cm.) per 100 miles per century. This maximum tilting is supposed to be upward from S.SW. to N.NE. Spencer, on the other hand, considered that these results are erroneous and that there is no tilting now going on in the lake region. He calculated the mean water level

TABLE IV

Sacketts Harbor–Charlotte......	1874–96	−0.061 ft.	(±0.03)
Cleveland–Pt. Colborne.........	1858–95	− .239	(.06)
Milwaukee–Pt. Austin..........	1876–96	− .138	(.03)
Escanaba-Milwaukee...........	1876–96	+0.173	(±0.02)

for quinquennial periods between 1855–59 and 1906–10 at Colborne and at Cleveland and found by this less accurate method no noticeable change during this whole time interval.

Proof that these movements are still going on has been given by Sherman Moore[11] and John R. Freeman.[12] Moore used the readings of nineteen pairs of gauges during the five months June to October as most free of disturbances.

Differences in the elevation of the water surface for each season between all possible pairs of gauges on each lake were then taken out, plotted on cross-section paper, and a line drawn through the points. . . . . The slope of this line determined the probable rate of change. . . . . Equations were then written of the form

$$ax+by-c=0,$$

in which a and b were the distances in miles north and east respectively between the gauges, c was the observed rate of change in elevation . . . . and x and y were unknown quantities, the north and east components of the rate of movement.

He found the results shown in Table V.

In conclusion Moore stated that the present axis of tilt is approximately W. 20° N. (maximum uplift toward N. 20° E.), still in the same general direction as it has been since the formation of the old beaches, and that the rate is not uniform, but is about twice as

[11] "Tilt of the Earth in the Great Lakes Region," *Military Engineer*, Vol. XIV (May-June, 1922), p. 151.

[12] *Regulation of the Great Lakes* (Chicago Sanitary District, 1926), pp. 149–72.

great in the Superior Basin and three times as great in the Ontario Basin as in the remainder of the region.

Freeman used twenty pairs of gauge comparisons. By a thorough examination he found that "continuous progressive tilting upward toward the north at the rate of about half a foot per 100 miles per century in the southern part of the Lake region, with indications of double this rate over some parts of the Lake system, is proved beyond all doubt." His results are given in Figure 1.

As results of gauge readings have accumulated since the investigation of Freeman, especially concerning Lake Superior, where Moore

TABLE V

Lake	Number of Equations	Maximum Tilt per Century		
		Amount Ft./100 Mi.	Cm./100 km.	Direction To
All four lakes....	19	0.43	8.1	N. 25° E.
Superior........	3	(0.94)	(17.8)	Indefinite
Michigan-Huron	9	0.47	8.9	N. 18 E.
Erie............	3	0.46	8.7	N. 31 E.
Ontario.........	4	1.44	27.3	N. 18 E.

and Freeman could use only three stations in one line, so that the direction of tilt was indefinite, it has seemed worth while to recalculate the changes in level by using all data available. Gauge readings were provided through the courtesy of the United States Lake Survey Office at Detroit, the Canadian Hydrographic Service of the Department of Marine at Ottawa, and the United States Engineer Office at Duluth. For each lake certain pairs of stations were used, especially those covering long periods and running in different directions. It is assumed that the difference in the gauge readings of each two stations are given by $a+bt$, where t is the time, a the difference in the gauge readings at the time $t=0$, which usually was taken in the middle of the interval, and b the average change in this reading per unit of t (year). a and b were calculated by means of the method of least squares for all pairs of stations given in Table VI, except the two pairs concerning Escanaba, which were taken from the calcula-

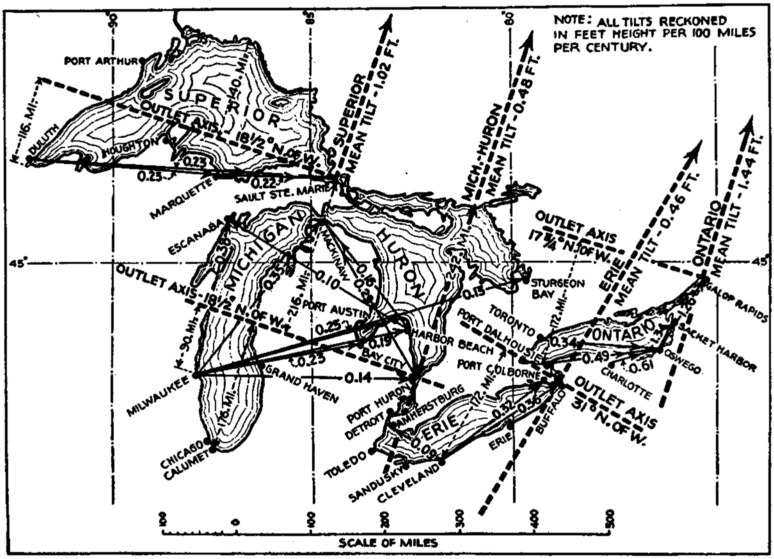

FIG. 1.—Rates and directions of earth tilt for each of the Great Lakes. (Taken from John R. Freeman, *op. cit.*, p. 150.)

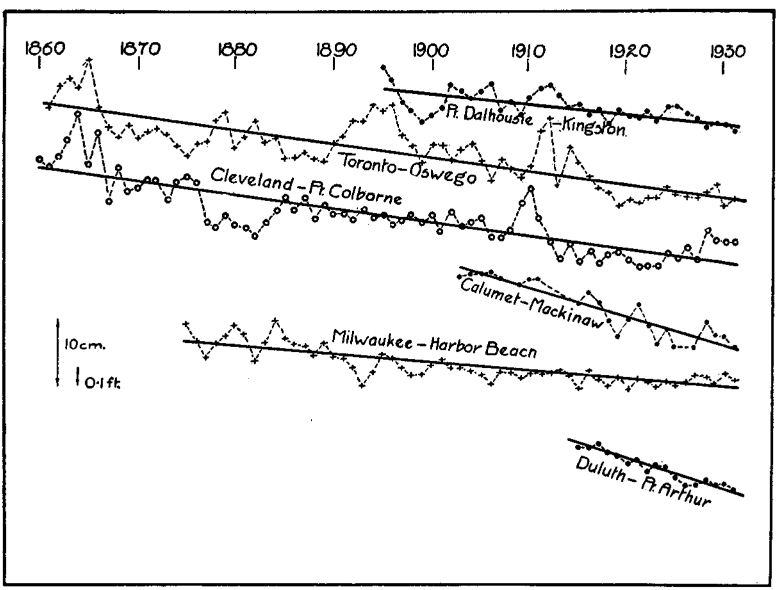

FIG. 2.—Changes in differences in gauge readings in the Great Lakes (cf. Table III and Fig. 3).

tions of Freeman, and the pair Sault Ste Marie–Marquette, taken from the results of Moore.

The changes given in Table VI were plotted on a map (Fig. 3). It is not very difficult to draw lines of equal changes in level, as has

TABLE VI*

CHANGES IN DIFFERENCES OF GAUGE READINGS

Lake	Stations	Change per Century		Period Used for Calculation
		Ft.	Cm.	
Superior	Duluth–Pt. Arthur	1.49±0.12	45± 4	1915–1931
Superior	Duluth-Marquette	0.59±0.06	18± 2	1889–1931
Superior	Marquette–Pt. Arthur	0.97±0.11	30± 3	1915–1931
Superior	Marquette-Michipicoten	0.70±0.23	21± 7	1918–1931
Superior	Michipicoten–Pt. Arthur	0.25±0.25	8± 8	1918–1931
Superior	Marquette–Sault Ste Marie	0.39± ?	12± ?	1872–1919
Michigan-Huron	Milwaukee-Escanaba	0.75± ?	23± ?	?
Michigan-Huron	Milwaukee-Mackinaw	0.60±0.07	18± 2	1900–1931
Michigan-Huron	Calumet-Milwaukee	0.98±0.21	30± 4	1903–1931
Michigan-Huron	Calumet-Mackinaw	1.46±0.14	44± 4	1903–1931
Michigan-Huron	Calumet–Harbor Beach	1.02±0.14	31± 4	1903–1931
Michigan-Huron	Milwaukee–Harbor Beach	0.41±0.03	12± 1	1875–1931
Michigan-Huron	Harbor Beach–Escanaba	0.27± ?	9± ?	?
Michigan-Huron	Mackinaw-Collingwood	0.05±0.19	2± 6	1916–1931
Michigan-Huron	Harbor Beach–Collingwood	0.55±0.13	17± 4	1916–1931
Michigan-Huron	Calumet-Collingwood	1.30±0.38	40±12	1916–1931
Michigan-Huron	Harbor Beach–Goderich	0.13±0.19	4± 6	1920–1931
Michigan-Huron	Goderich-Collingwood	0.47±0.11	17± 4	1920–1931
Michigan-Huron	Harbor Beach–Mackinaw	0.27±0.05	8± 2	1900–1931
Erie	Cleveland-Amherstburg	0.07±0.15	2± 5	1899–1918
Erie	Cleveland–Pt. Colborne	0.67±0.05	20± 2	1860–1931
Erie	Cleveland-Buffalo	0.62±0.06	19± 2	1887–1931
Ontario	Toronto–Pt. Dalhousie	0.16±0.08	5± 2	1861–1931
Ontario	Toronto-Oswego	0.64±0.06	19± 2	1861–1931
Ontario	Toronto–Cape Vincent	1.35±0.19	41± 6	1900–1931
Ontario	Pt. Dalhousie–Kingston	0.43±0.09	13± 3	1895–1931
Ontario	Kingston–Cape Vincent	0.65±0.07	20± 2	1900–1931
Ontario	Oswego–Cape Vincent	0.48±0.09	15± 3	1900–1931

* ± indicates the mean error. Decrease of water level (uplift of land) in the direction toward the station at the second place. Some special data are shown in Fig. 2.

been done in Figure 3. The position of the zero line is arbitrary; it is drawn through Calumet, where the least upheaval (or the largest subsidence) occurs of all points used in Figure 3. The average tilt per century is about ½ foot per 100 miles, or about 10 cm. per 100 km. The same values are found in Scandinavia.

The fact that different results do not check completely is due to the use of data covering different periods. In some cases they may be influenced by instability of bench marks, but the fact that stations close together and stations situated on lines nearly parallel to the axis of uplift show no great changes in the difference of level shows that the errors caused in this way usually are very small. The large tilt between Calumet and Milwaukee has looked suspicious to all investigators, but it has been determined on several occasions that the gauge at Calumet Harbor has been stable. Another unusual feature is the considerable uplift at Cape Vincent. The self-registering

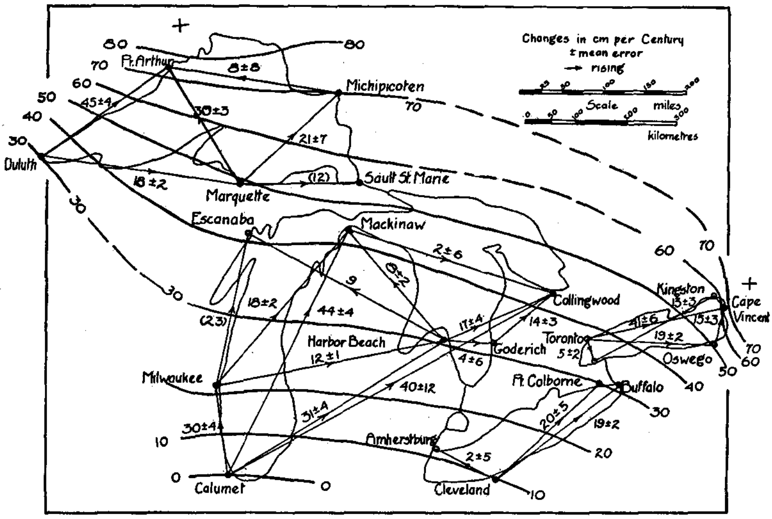

FIG. 3.—Actual changes in level in the Great Lakes region in centimeters per century. (Arrows point in direction of uplift; lines of equal uplift from 10 to 10 cm.)

gauge was removed in 1915 from Tibetts Point to Cape Vincent, but this fact is not indicated by the results. The three pairs of sets of observations concerning this station run very smoothly and the final errors are below average. The calculated uplift of Cape Vincent compared with Kingston, for example, is 0.20 feet between 1900 and 1931, the calculated errors for three years are −0.12, +0.11, and +0.06 feet, while in all other years their absolute amount is less than 0.06 feet. The statement by Freeman that this method of finding changes in level is more accurate than geodetic leveling is true without any doubt.

Another possibility of finding changes in level is through examination of the readings of tide gauges at the coasts, though these are very much more affected by the tides and meteorological conditions than the readings of gauges on the shores of lakes.

In the case of Newfoundland, geological evidence shows an uplift in recent time. On the other hand, W. B. Dawson found[13] from tide-gauge records in 1917 that at that time there was no measurable change in height of the land at Halifax, Charlottetown, and St. Paul Island (Cabot Strait), and R. A. Daly[14] drew the conclusion that the New England Coast seems to have been sensibly stable for at least one hundred years. More recent data on the Tide Levels and datum planes for Eastern Canada and the Pacific Canadian Coast were provided by courtesy of the Canadian Hydrographic Service (Tidal Division) of the Department of Marine, Ottawa. Mr. F. Anderson, hydrographer of this Department, stated that the only instance in which there has been a direct evidence from tidal observations of an upheaval occurred in the lower St. Lawrence region during an earthquake.

Similar values for the United States were provided by courtesy of the United States Coast and Geodetic Survey. The data concerning Canada are based on mean yearly values, calculated by the Hydrographic Service of Canada (Marine Dept.) from the harmonic analysis of the hourly ordinates of the records of tide gauges, whereas the data concerning the United States have been calculated by the United States Coast and Geodetic Survey by averaging the hourly heights for that year; they have not been subjected to harmonic analysis.

In Table VII the changes between the first complete period of five years, or if incomplete at least three years, and the last period of five years are given as derived from these data just mentioned. To get more dependable results from all data at each station, the change in sea level has been calculated by the method of least squares and under the assumption that the mean sea level undergoes changes proportional to the time (Fig. 4). These results are given

[13] *Tide Levels and Datum Planes in Eastern Canada* (Ottawa: Department of the Naval Service, 1917).

[14] "Post-glacial Warping . . . . ," *op. cit.*, p. 390.

in Table VIII. If the mean error, indicated by $\pm$ in the table, is equal to the calculated change, the probability that the direction of the change is true is about 92 per cent, supposing that there is no systematic error; if the calculated change is twice the mean error, the corresponding probability is $98\frac{1}{2}$ per cent, and in case of a result equal to three times the mean error, it is 99.9 per cent. Therefore, calculated changes less than the mean error, at one station only, do

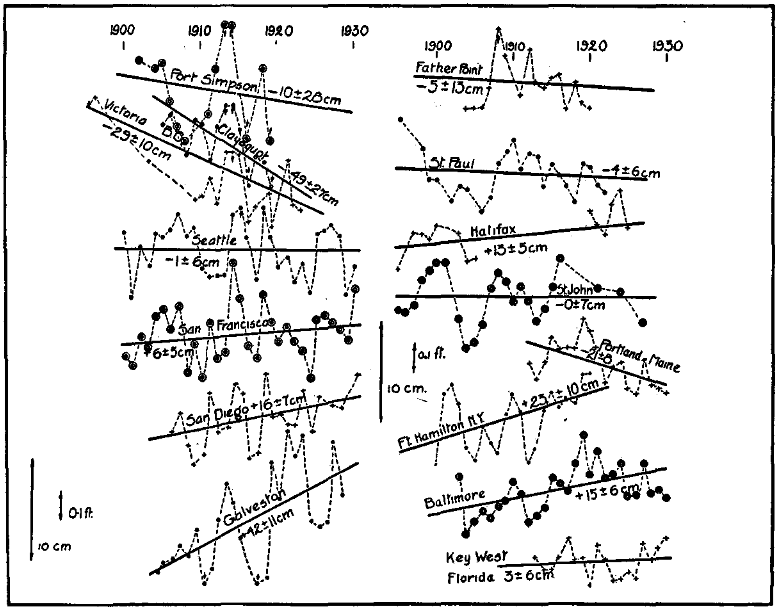

FIG. 4.—Changes in sea level

not indicate any decisive result; if the amplitude of the changes is of the order of twice the mean error, the direction is very probable, especially if similar values occur in the neighborhood, and results larger than three times the mean error indicate that a change of that order in the calculated direction is nearly beyond doubt, supposing that there are no systematic errors, as, for example, effects of very long-period tides or long-period meteorologic changes. The amplitudes of long-period tides are usually very much less than the errors calculated in Table VIII, and according to data collected by Freeman very probably this holds too in the case of effects of changes in pressure over the Atlantic Ocean. Considering all these facts, we see that there has been no noticeable change in sea level along the eastern coast of Canada. Along the southeastern coast of the United States there is a clear though not very rapid rise in sea level, corresponding to a sinking of the coast. The maximum calculated in Table VIII occurs at Galveston; its amount is about ½ cm. per year,

TABLE VII

CHANGES IN SEA LEVEL IN FEET

(1 ft.=30.5 cm.; 1 cm.=*ca.* 0.033 ft.)

	Atlantic Coast	
Father Pt.	1904/1909–1916/20	−0.05
St. Paul	1898/1900–1919/22	− .03
Halifax	1897/1900–1920/25	+ .06
St. John	1895/1901–1913/16	−0.02
Portland, Me.	1912/16 –1926/30	−0.07
Ft. Hamilton, N.Y.	1900/05 –1916/20	+ .11
Baltimore, Md.	1903/07 –1926/30	+ .08
Key West, Fla.	1913/17 –1926/30	+ .02
Galveston, Tex.	1904/08 –1924/28	+0.19
	Pacific Coast	
Pt. Simpson	1904/08 –1916/18, 19	−0.09
Clayoquot	1908/10 –1915/19	− .17
Vancouver	1905/09 –1921/23	+ .03
Victoria, B.C.	1909/13 –1919/22	−0.04
Seattle, Wash.	1900/04 –1926/30	+0.03
San Francisco	1900/04 –1926/30	.08
San Diego, Calif.	1906/10 –1927, 28, 30	+0.15

or about ⅕ inch per year. More data are needed to get more accurate results, and it would be very useful for all investigations of this kind, which are important in many respects, if more tide gauges could be installed along all coasts.

Results relative to the northern part of the Pacific Coast show a decrease in sea level. The individual figures are not decisive, as the errors are rather large. This is caused partly by the small number of data (e.g., thirteen yearly averages from Port Simpson and fourteen from Clayoquot) and partly by the fact that there is a region of very large change in air pressure caused by the low-pressure areas which frequently pass over this region. Therefore, on account of meteorological effects, the yearly averages of sea level differ very much more than they do anywhere else in the region considered in Table VIII.

TABLE VIII

CHANGES IN SEA LEVEL CALCULATED BY MEANS OF THE METHOD OF LEAST SQUARES

Location of Tide Gauge	Period of Observ.	Change Ft./100 Yrs.	Cm./100 Yrs.
Atlantic Coast (from North to South)			
Father Pt. (St. Lawrence estuary)	1904–1920†	−0.2±0.4	− 5±13
St. Paul (Cabot Strait)	1895–1922†	−0.1±0.2	− 4± 6
Halifax	1895–1925†	+0.4±0.2	+13± 5
St. John (Bay of Fundy, lower part)	1895–1927†	−0.0±0.2	− 1± 7
Portland, Me.	1912–1930	−0.7±0.3	−21± 8
Ft. Hamilton, N.Y.	1900–1920	+0.8±0.3	+23±10
Baltimore, Md.	1903–1930	+0.5±0.2	+15± 6
Key West, Fla.	1913–1930	+0.1±0.3	+ 3± 6
Galveston, Tex.	1904–1928	+1.8±0.4	+54±13
Pacific Coast (from North to South)			
Pt. Simpson (northern B.C.)	1902–1919†	−0.3±0.9	−10±28
Clayoquot,* B.C.	1905–1919†	−1.6±0.9	−49±27
Vancouver, B.C.	1903–1923†	−0.1±0.4	− 2±13
Victoria, B.C.	1895–1922†	−0.9±0.3	−29±10
Seattle, Wash.	1900–1930	−0.0±0.2	− 1± 6
San Francisco, Calif.	1900–1930	+0.2±0.2	+ 6± 5
San Diego, Calif.	1906–1930†	+0.5±0.2	+16± 7

* West coast of Vancouver Island.
† Incomplete.

For example, very large differences occurred during the period 1913–16 at the stations on the North Pacific Coast. The calculated "errors" are (in 1/100 ft.) as indicated in Table IX. These "errors" change gradually from station to station, and there can be no doubt that they are influenced by meteorological effects. This has already been found by W. B. Dawson.[15]

Owing to this fact, a part of the "errors" will be eliminated if the

[15] *Tide Levels and Datum Planes on the Pacific Coast of Canada* (Ottawa: Department of Marine and Fisheries, 1923).

differences between the levels at the different stations are used in a similar way as has been done in the case of the data concerning the Great Lakes. But unfortunately the data cover different periods, so that this method can be used in a few cases only, and even in these the number of values is considerably less than in the case when each

TABLE IX

Year	Pt. Simps.	Clay.	Vanc.	Vict.	Seat.	San Franc.	San Diego
1912	+ 8	+ 4	− 2	−10	− 9	− 7	− 2
1913	+27	+20	+ 5	+ 7	− 9	− 6	− 5
1914	+28	+29	+15	+21	+11	+24	+13
1915	?	+ 8	+10	+ 9	+18	+12	+ 9
1916	−23	−24	−20	−17	+ 4	− 5	−12
1917	?	+ 2	+ 1	− 7	−16	− 9	−11
1918	+11	+ 2	+12	+20	+14	+12	+14

TABLE X

Stations	Change in Difference in Sea Level*	
	Ft.	Cm/100 Yrs.
Clayoquot-Vancouver	−1.4±0.6	−42±17
Vancouver-Seattle	+0.1±0.7	+ 4±21
Seattle–San Francisco	−0.2±0.3	− 7± 8
San Francisco–San Diego	−0.3±0.2	− 9± 6

* + means that the water at the first is rising, or that the land there is sinking compared with the second.

station is considered separately. The results shown in Table X have been found in this way. The results confirm those of Table VIII.

The rise of land along the northern part of this coast seems to be a very few millimeters per year (about $\frac{1}{10}$ in.). At the two Californian stations the figures indicate a very small sinking of the land during the last twenty-five years, not very much exceeding the mean error of the results.

It is very important that investigations of other kinds and covering earlier periods have been made in a few cases. There are, especially, two investigations by John R. Freeman,[16] the first concerning the vicinity of New York and the second concerning Boston. Using all the data on height of mean sea level around New York from 1843 to 1902, Freeman, Burr, and Hering found that during the sixty years from 1843 to 1902 the apparent subsidence was 0.45 foot, or at the rate of 9 inches (23 cm.) in one hundred years. It is a coincidence that we find exactly the same figure in Table VIII from the records 1900–1920, but this makes it nearly certain that there was a noticeable subsidence of land during the last one hundred years. According to the second very detailed study by Freeman, the land around Boston is sinking at the rate of 1 foot (30 cm.) in one hundred years. In 1930 the datum plane to which all elevations are referred by the engineering department ("Boston base") probably coincided almost exactly with mean low water at the Charleston navy yard; in 1878 the Boston base was found to be 0.64 foot below mean water, and in 1902 0.79 foot below. Making a similar comparison on the basis of mean sea level, Freeman finds a change of 0.71 foot in seventy-two years. Besides, he quotes similar results from many other observations (e.g., water level near rocks, soundings) around Boston, found by W. O. Crosby and John H. Sears. The point nearest to Boston, from which we have data in Table VIII, is Portland (Me.), about 160 km, to the north, and there we find a probable uplift of the land.

Along the Pacific Coast there is geological evidence for recent gradual changes, as has been found, for example, by Buwalda[17] and Wood.[18] But in this region traversed by many fault zones apparently the amount and even the direction of the movements change very much more with distance and time than they do in the Atlantic region. Gradual (and abrupt) block movements seem to prevail.

[16] W. H. Burr, R. Hering, and J. F. Freeman, *Report of the Commission on Additional Water Supply for the City of New York* (New York, 1904), p. 650; John R. Freeman, "Subsidence of Land and Harbour Bottom," Appendix 20 to the *Report of the Committee on Charles River Dam* (Boston: State of Massachusetts, 1903), pp. 529–72.

[17] John P. Buwalda, "Nature of the Late Movements on the Haywards Rift," *Central Calif. Bull. Seism. Soc. Amer.*, Vol. XIX (1929), p. 187.

[18] H. O. Wood, "On a Possible Causal Mechanism for Heave-Fault Slipping in the California Coast Range Region," *Bull. Seism. Soc. Amer.*, Vol. V (1915), pp. 214–29.

Geodetic measurements have been carried out and repeated in a few cases, but the time elapsed since these investigations have been started is not long enough to give decisive results. A comparison of triangulation made before 1900 and repeated between 1922 and 1925 has been calculated by Bowie.[19] This shows that during this time interval noticeable horizontal movements occurred only in the region adjacent to the San Andreas fault and very probably not exceeding 7 feet (2 m.); how far these movements originated during the earthquake of San Francisco in 1906 is not known.

From an investigation on the levels in Los Angeles Harbor region G. F. Nicholson[20] found an uplift of land in the northern part of the harbor of about 0.2 foot (6 cm.) between 1919 and 1927, under the supposition that a bench mark on Deadman's Island in the southern part did not change. It is not impossible that the limit between the area of small and that of noticeable change is determined by a fault, as Nicholson believes.

If we try to sum up the results, we see that along the Pacific Coast of North America, especially in California, gradual changes seem to be very much more irregular than along the Atlantic Coast. In Western Canada perhaps a small rise of land may be going on. The eastern part of North America seems to show a rise of land in the north caused probably by uprising following the melting of ice after the Ice Age, which is very clearly marked in the Great Lakes region; also by geological evidence, rather than by recent measurements, along the Atlantic Coast, where recent movements seem to be less than ± 5 cm. during the last twenty-five years. Along the southeastern coast of the United States there seem to be subsidences of land by different amounts—for example, about $\frac{3}{4}$ foot ($\frac{1}{4}$ m.) in one hundred years near New York and perhaps twice as much near Galveston (Tex.) but nowhere has any indication been found there of vertical movements larger than $\frac{1}{2}$ cm. per year.

It is of interest that the changes in level found for the west coast

[19] "Comparison of Old and New Triangulation in California," *op. cit.* (Washington, 1928), Spec. Pub. 151.

[20] "Variation in Levels, 1919 to 1927, in Los Angeles Harbor," *Bull. Seis. Soc. Amer.*, Vol. XIX (1929), p. 200.

of Europe are very similar to those found for the east coast of North America. Figure 5[21] shows in Northern Europe the uplift of Scandinavia which we considered above. The data concerning France are

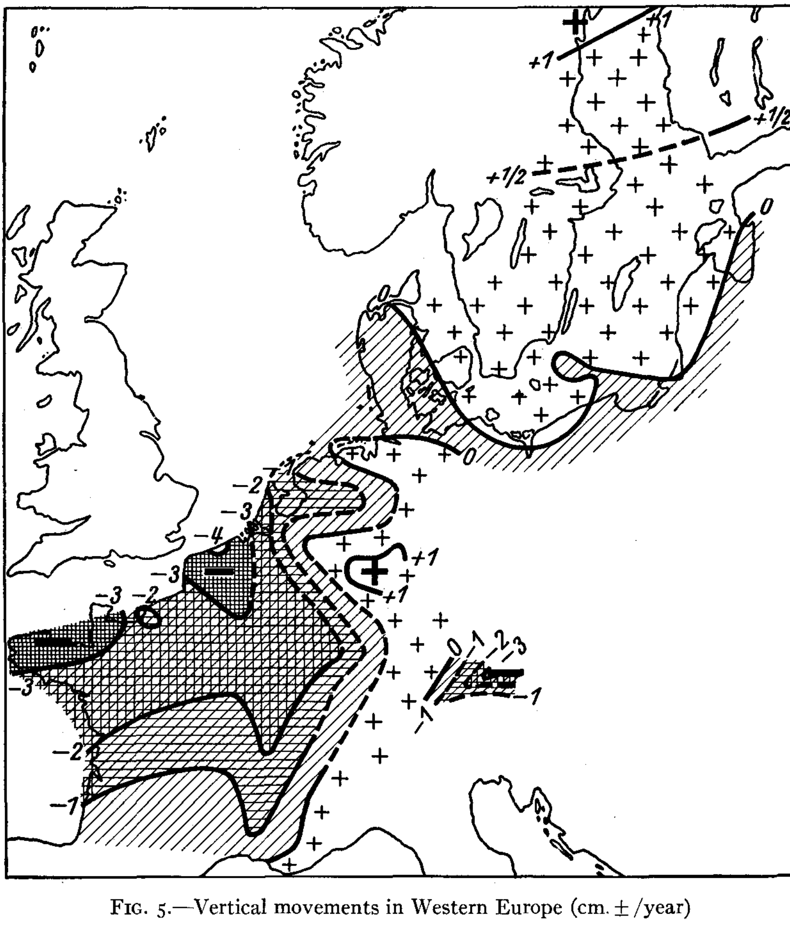

FIG. 5.—Vertical movements in Western Europe (cm. ± /year)

based on a comparison of levelings between 1857–64 and 1884–93, calculated by M. Schmidt.[22] There is some doubt as to what extent

[21] From Gutenberg, "Geotektonische Hypothesen," *Handbuch der Geophysik* (Berlin: Verlag Gebr. Borntraeger, 1930), Vol. III, p. 462.

[22] "Neuzeitliche Erdkrustenbewegungen in Frankreich," *Sitzungsberichte der Bayrischen Akademie der Wissenschaften* (München: Math.-phys. Klasse, 1922), p. 1. The connection of these changes with the geology has been discussed by Em. Kayser in the same volume (p. 51).

these results are reliable. The maximum subsidence of land would correspond to nearly 15 feet per one hundred years. On the other hand, the changes are so large that their direction at least seems to be true, and, in addition, they do not disagree with the data which have been found for other parts of Central Europe,[23] and which have been used in drawing Figure 5. In Bavaria, Schmidt (*loc. cit.*) found, besides, horizontal movements from triangulation amounting to about 4 m. (13 ft.) in one hundred years at maximum.

It is, of course, very difficult to explain these changes. The uplift of Scandinavia and of parts of Northern North America is caused probably by forces still tending to restore isostatic equilibrium, which has been disturbed by the melting of ice after the Ice Age. Gravity measurements do not contradict this hypothesis, as we have seen. The results of geological investigations which seem to show that the uplift since the Ice Age is about proportional to the probable thickness of the ice at that time support this idea considerably. The general sinking of the coasts of the northern Atlantic Ocean may be due to the process which formed the Atlantic Ocean and perhaps is still going on, but no emphasis is put upon this explanation.[24] On the other hand, it does not seem to be very probable that the sinking of the coasts in France and the Southeastern United States is due to the fact that material is still flowing at depth from beneath these regions under the rising regions in the north, as the maximum uplift seems to be too far to the south in both cases, and the volume of the outflowing mass would be very much larger than the corresponding volume of the masses in the rising regions.

[23] J. L. Wilser, *Heutige Bewegungen der Erdkruste, erkennbar an Ingenieurbauten im Oberrhein-Gebiet*, (Stuttgart, 1929); M. Schmidt, "Untersuchungen von Höhen- und Lagenänderungen im bayrischen Alpenvorland" (*op. cit.* München: Akademie, 1918), p. 373; H. Schütte, "Krustenbewegungen an der deutschen Nordseeküste," *Aus der Heimat*, Vol. XL (1927), p. 325; J. Weissner, *Der Nachweis jüngster tektonischer Bodenbewegungen im Rheinland* (Haarfelddruck, 1929); Gutenberg, *op. cit.*, p. 458.

[24] B. Gutenberg, "Hypotheses on the Development of the Earth," *Jour. Wash. Acad. Sci.*, Vol. XX (1930), p. 21.