BUSSEY, F.R.

ANALYSIS OF GRAVITY MEASUREMENTS

IN THE

GREAT LAKES REGION

59

F. R. BUSSEY
M.S. Aug 1949

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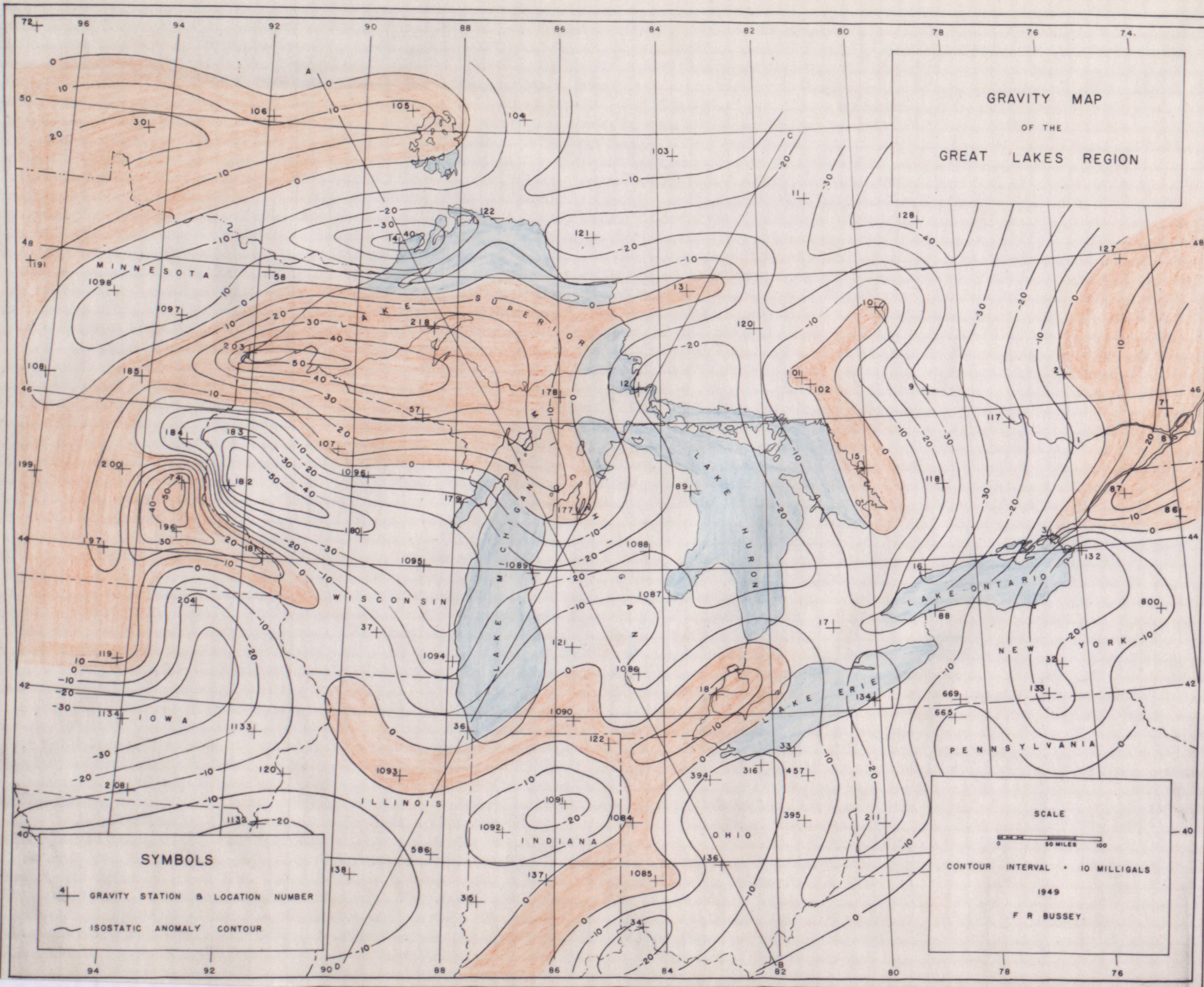
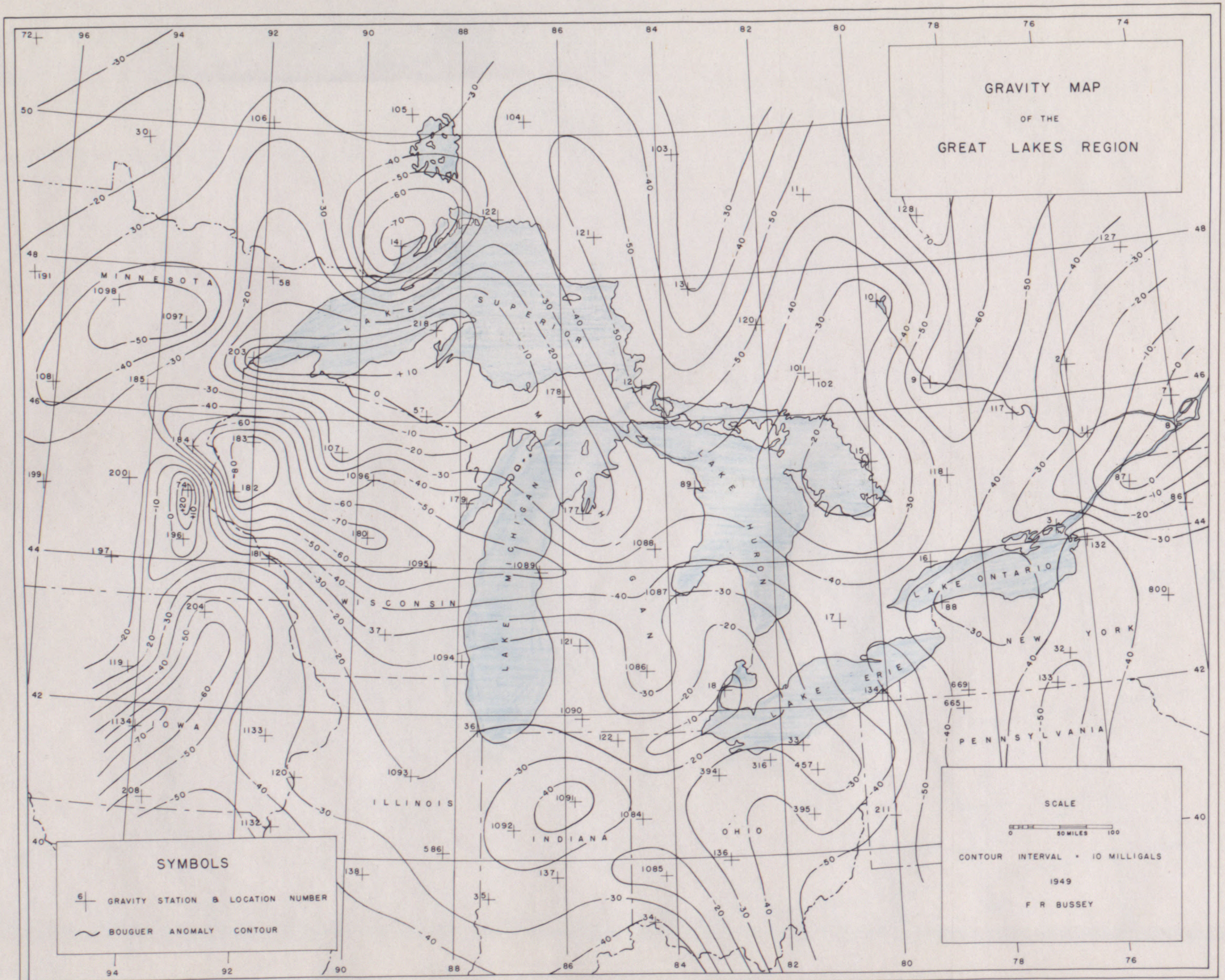

GRAVITY MAP
OF THE
GREAT LAKES REGION
SCALE
0 50 MILES 100
CONTOUR INTERVAL = 10 MILLIGALS
1949
F R BUSSEY
SYMBOLS
GRAVITY STATION & LOCATION NUMBER
ISOSTATIC ANOMALY CONTOUR
MINNESOTA
WISCONSIN
IOWA
ILLINOIS
INDIANA
OHIO
MICHIGAN
PENNSYLVANIA
NEW YORK
LAKE SUPERIOR
LAKE MICHIGAN
LAKE HURON
LAKE ERIE
LAKE ONTARIO



GRAVITY MAP
OF THE
GREAT LAKES REGION
SCALE
0 50 MILES 100
CONTOUR INTERVAL = 10 MILLIGALS
1949
F R BUSSEY
SYMBOLS
GRAVITY STATION & LOCATION NUMBER
BOUGUER ANOMALY CONTOUR
MINNESOTA
WISCONSIN
ILLINOIS
INDIANA
OHIO
IOWA
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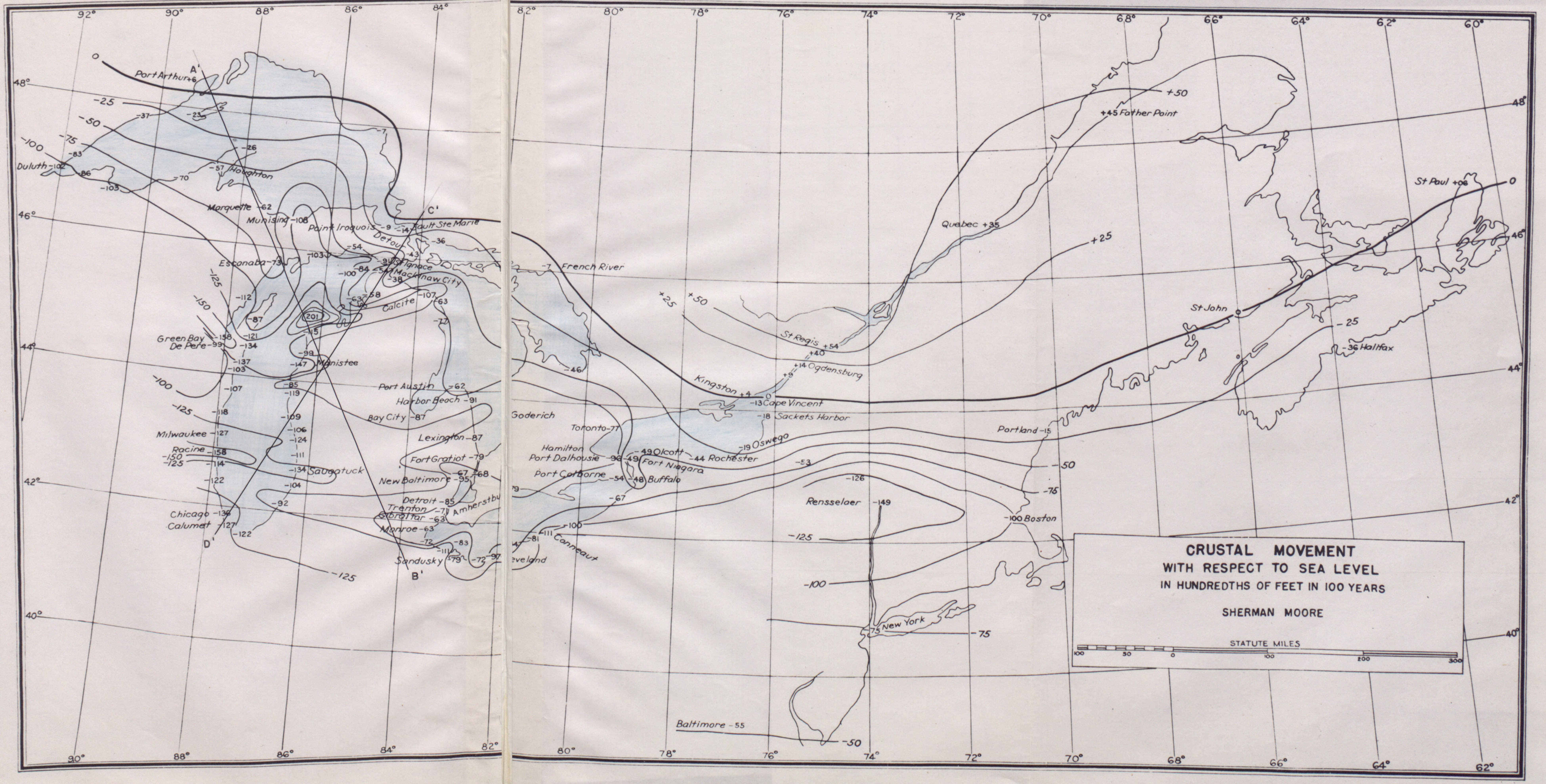
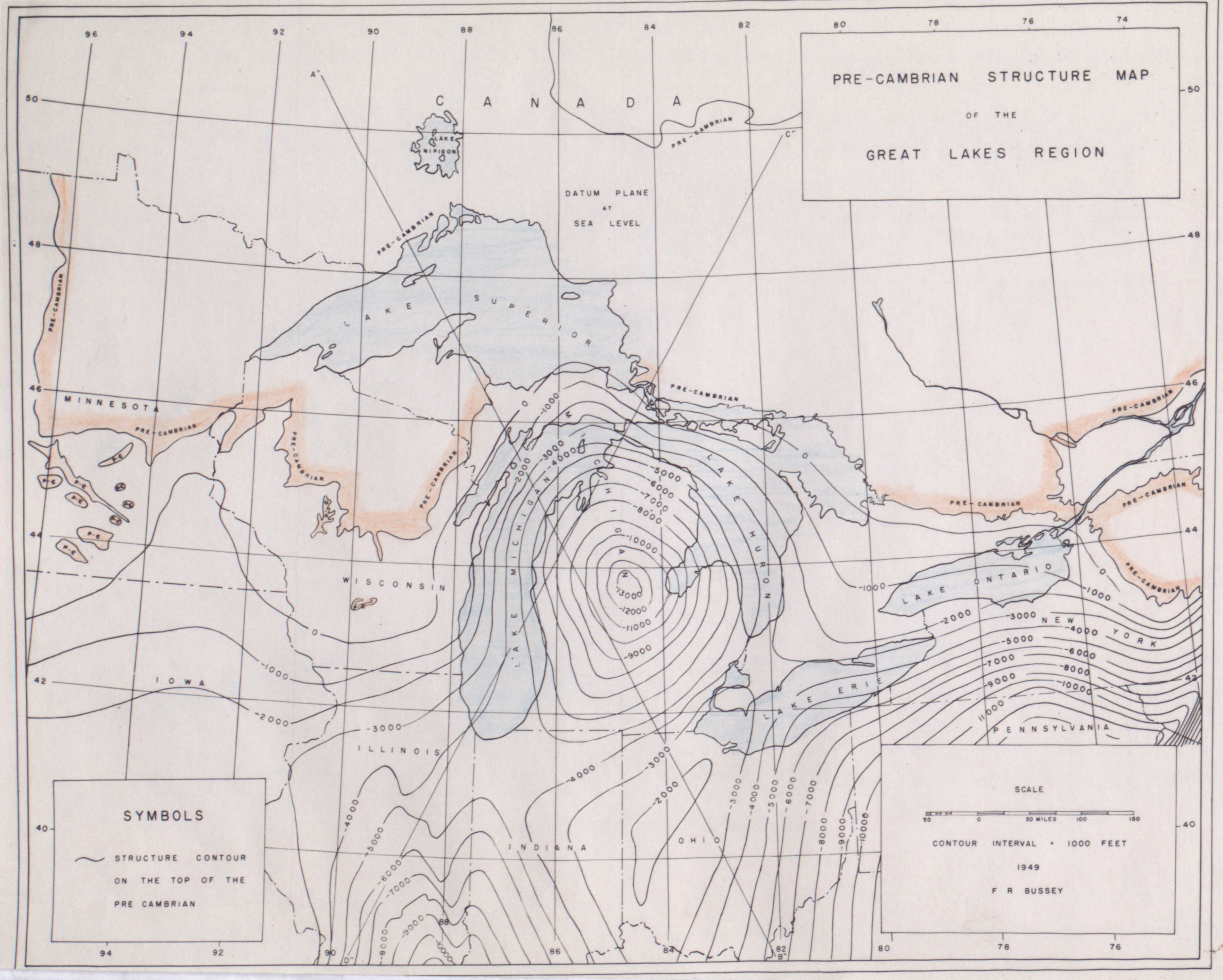
LAKE ONTARIO


CRUSTAL MOVEMENT
WITH RESPECT TO SEA LEVEL
IN HUNDREDTHS OF FEET IN 100 YEARS
SHERMAN MOORE
STATUTE MILES
100 50 0 100 200 300
Port Arthur +6
Duluth -102
Houghton
Marquette -62
Munising -108
Point Iroquois -9
Sault Ste Marie
Detour
St Ignace
Mackinaw City
Escanaba -73
Calcite
Green Bay
De Pere -99
Manistee
Port Austin -62
Harbor Beach -91
Bay City -87
Lexington -87
Fort Gratiot -79
New Baltimore -95
Milwaukee -127
Racine -158
Saugatuck
Chicago -136
Calumet -127
Detroit -85
Trenton
Gibraltar -63
Monroe -63
Amherstburg
Sandusky
Cleveland
Conneaut
French River
Goderich
Toronto -77
Hamilton
Port Dalhousie
Port Colborne -54
Olcott
Fort Niagara
Buffalo
Rochester
Oswego
Sackets Harbor
Cape Vincent
Kingston +4
Ogdensburg
St Regis +54
Quebec +35
+45 Father Point
St Paul +06
St John
-36 Halifax
Portland -15
-100 Boston
Rensselaer -149
New York
Baltimore -55
A'
B'
C'
D'


PRE-CAMBRIAN STRUCTURE MAP
OF THE
GREAT LAKES REGION
DATUM PLANE AT SEA LEVEL
CANADA
LAKE NIPIGON
LAKE SUPERIOR
LAKE MICHIGAN
LAKE HURON
LAKE ONTARIO
LAKE ERIE
MINNESOTA
WISCONSIN
IOWA
ILLINOIS
INDIANA
OHIO
NEW YORK
PENNSYLVANIA
PRE-CAMBRIAN
SYMBOLS
STRUCTURE CONTOUR ON THE TOP OF THE PRE CAMBRIAN
SCALE
50 0 50 MILES 100 150
CONTOUR INTERVAL = 1000 FEET
1949
F R BUSSEY

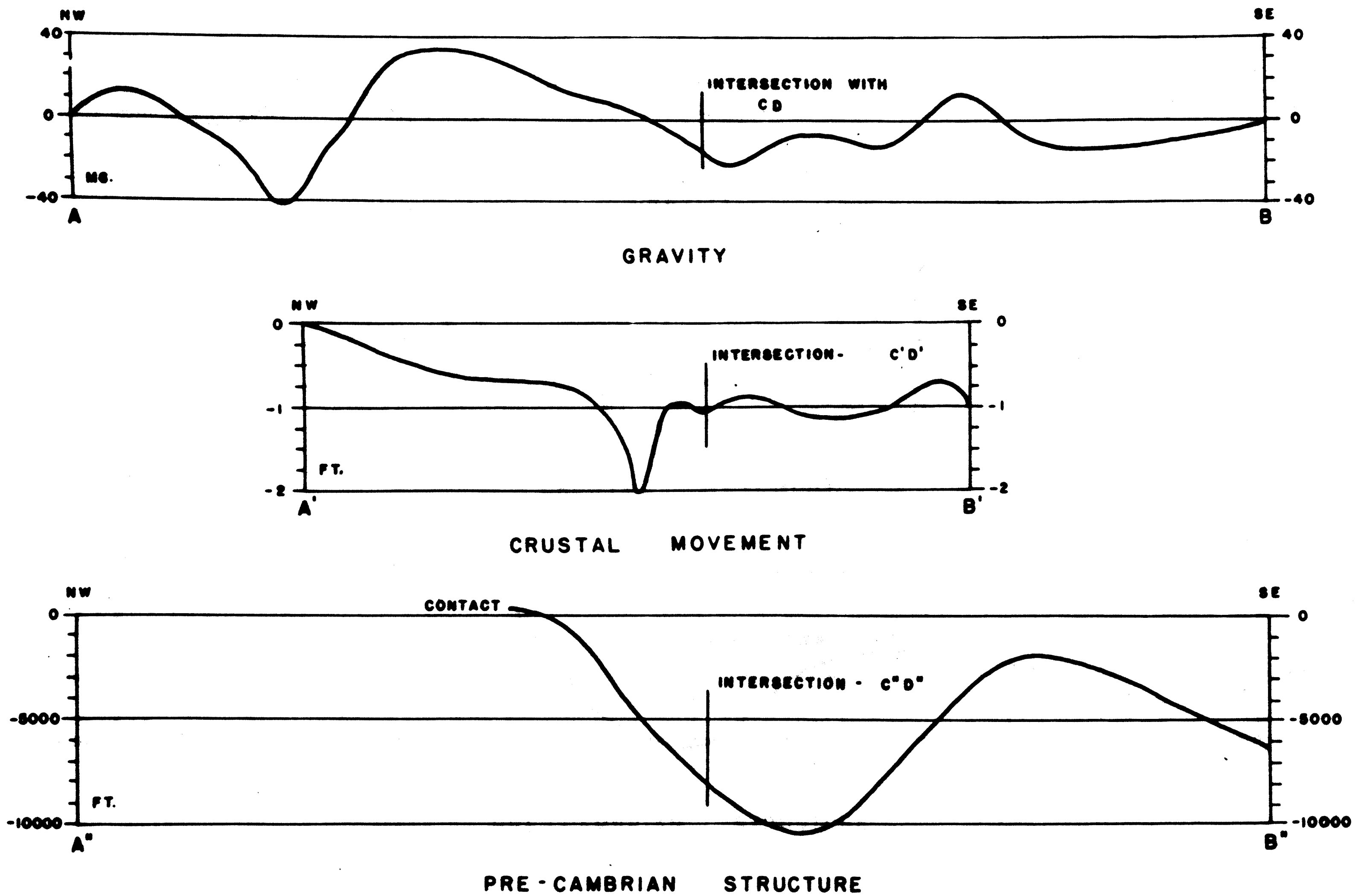

NW
SE
40
0
-40
MG.
A
B
INTERSECTION WITH
CD
GRAVITY
NW
SE
0
-1
-2
FT.
A'
B'
INTERSECTION- C'D'
CRUSTAL MOVEMENT
NW
SE
0
-5000
-10000
FT.
A"
B"
CONTACT
INTERSECTION - C"D"
PRE-CAMBRIAN STRUCTURE

FIGURE 1

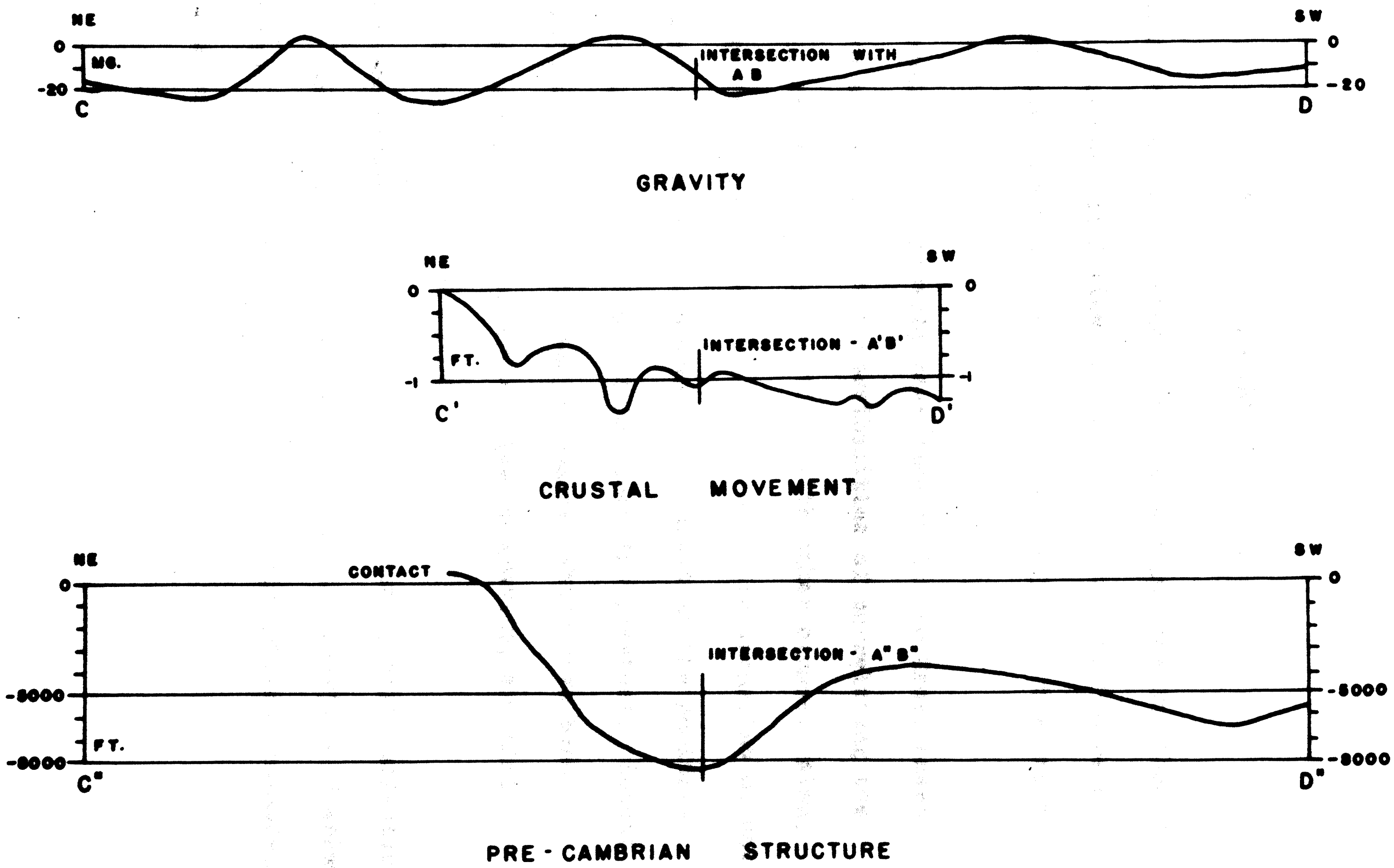

NE
SW
0
-20
MG.
C
D
INTERSECTION WITH
A B
GRAVITY
NE
SW
0
-1
FT.
C'
D'
INTERSECTION - A'B'
CRUSTAL MOVEMENT
NE
SW
CONTACT
0
-5000
-8000
FT.
C"
D"
INTERSECTION - A"B"
PRE - CAMBRIAN STRUCTURE

FIGURE 2

ABSTRACT

Gravity results in Fennoscandia have supported the theory of isostatic adjustment following the ice age, and it has been assumed that the same would be true for the region of the Great Lakes.

In analyzing the gravity measurements in the Great Lakes region there appear to be many possibilities of correlating the anomalies in at least certain sections with other causes. Also, certain regional characteristics of the isostatic anomalies do not fit the theory of isostatic recovery. Foremost is the positive increase to the north where uplift has been the greatest. Recent investigations of present crustal movements, which have been included because of the possible bearing on gravity, are also difficult to explain by the theory.

The anomalies have been compared with such gravity affecting factors as the elevation of the pre-Cambrian, the location of known heavy igneous and ore bodies, and subsurface disturbances revealed by earthquakes.

INTRODUCTION

Four maps and two sets of cross sections are presented here in an attempt to analyze the results of gravity measurements taken at stations throughout the Great Lakes region.

The most common explanation for the anomalies has been that of an isostatic readjustment following the end of the recent ice age. Gravity measurements and measurements of crustal uplift have well supported this principle in Fennoscandia.[1] The uplift has been greatest at the point where the glacier was thickest and where there was the most depression. The gravity anomalies are negative and increase negatively in towards the same center of maximum uplift. The negative anomaly can be interpreted as indicating a deficiency of subsurface rock. Such a condition would be due to a subsurface flow of plastic rock out from the depression caused by the weight of the glacier. Following the removal of the weight, the crust began to rise and the plastic rock started to return to the area. But this occurs with considerable lag so that until complete equilibrium has been established there will be a subsurface rock deficiency and, consequently, negative anomalies.

Early work in the Great Lakes Region found the then existing gravity measurements to be predominantly negative and increasing in

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[1] See reference #2

negative value from south to north where the ice was undoubtedly thickest. Old lake beaches for the same period were found to be higher to the north than the south showing that since their formation they had been tilted up in this direction. Thus the crustal movement was also greatest to the north.

More recent developments in both uplift and gravity measurements have thrown doubt on the application of the theory for this region. This directs attention to other factors on which gravity can be dependent. Such factors include the elevation of pre-Cambrian crystalline rock, and the existence of large intrusive bodies of heavy rock.

Meaning of Isostatic Anomalies

A gravity anomaly is the difference between a measured value and a calculated value.

Anomaly = measured - calculated

The calculated value is assumed to be the normal value for the area and the anomaly shows any irregularity. A positive isostatic anomaly results when the measured value is the greater and indicates that the underlying rock is heavier than had been supposed when making the isostatic reductions. If this condition is being corrected by isostatic readjustment then the area must be sinking. Likewise, a negative isostatic anomaly results when the measured value is the smaller and this indicates that the underlying rock is lighter than was assumed in making the isostatic reductions. If this condition is being corrected by isostatic readjustment then the area must be rising.

Except when the crust is streng enough to support an abnormal load or force without bending, it is assumed that there is a constant tendency towards isostatic adjustment.

PREPARATION AND EXPLANATION OF MAPS

Gravity Maps

The isostatic Gravity Map includes the area about the Great Lakes. Isostatic anomalies were recorded from over a hundred gravity stations throughout the area in both Canada and the United States. This information was obtained from the "Catalogue of the Isostatically Reduced Gravity Stations" by Dr. W. Heiskanen and "Principle Facts for Gravity Stations in the United States," part 6. The Hayford isostatic anomalies, computed for a depth of compensation of 113.7 km. were used.

The stations were plotted on a base map. Then contour lines were drawn with an interval of 10 milligals. The resulting map makes it possible to locate quickly positive and negative areas and observe any trends that might exist.

In preparing the finished map only the location number was included for each station. This makes it possible to look up any anomaly in the reference mentioned.

The Bouguer anomaly map was prepared in the same manner, the only difference being the use of Bouguer anomalies at the gravity stations and the consequent change in the contour lines.

It was intended to try to correlate the Bouguer map with elevation changes. However, there is little change in elevation throughout this area and the correlation was not good enough for use. Since the map was prepared it has been included for possible use in other connections.

Pre-Cambrian Structure Map

Preparing the Pre-Cambrian Structure Map was a matter of collecting individual state and area information and connecting it together with the help of small pieces of information such as depths from well drillings.

There were three main sources for the needed information. Foremost was a pre-Cambrian structure map of Michigan and adjacent areas by Cohee.[1] Secondly, a pre-Cambrian structure map of New York State has been prepared by Broughton.[2] Thirdly, a pre-Cambrian structure map of a large portion of Illinois has been given by Workman and Bell.[3]

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[1]See reference #5
[2]See reference #6
[3]See reference #7

Other information was obtained from the Tectonic Map of the United States, and from several sources containing small pieces of information on the pre-Cambrian.

The purpose of the map is to show the areas where the pre-Cambrian formations are near the surface and where they are deeply buried. The contours have a 1000 foot interval and since there are none above sea level have a negative value. Outcrop areas are marked "pre-Cambrian" or "P-C" where space was lacking.

Moore's Crustal Movement Map

The Crustal Movement Map by Sherman Moore[1] represents movement in hundredths of feet in 100 years. The information was determined from the readings of water gauges over a long period of years. The water gauges are situated at the points given on the map. The readings are based on the assumption that the lakes are level and it appears that such is the case during at least the summer months. After plotting the points, Moore contoured the movement with an interval of .25 feet.

A measurement in hundredth of a foot in 100 years may seem negligible at first but it is sufficient to observe that Chicago at the present rate would sink 680 feet in 50,000 years and be below sea level.

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[1]See reference #1

The movement is given with respect to sea level, and some doubt exists as to the stability of sea level. In fact, measurements along the Northeast coast of the United States have shown a rise.

At New York City sea level has risen 1.66 feet since 1893. At Baltimore it has risen .47 feet since 1903. And at Boston sea level has risen .32 feet since 1930.[1]

Assuming a constant rate over one hundred years, sea level at New York would have risen 3.32 feet, Baltimore 1.0 feet and Boston 1.60 feet. An average of the three would be approximately 2 feet. This would nullify the subsidence on Moore's Map for anything less than a 2 foot subsidence would actually be a rise.

However, measurements of sea level are at best difficult to make. This point can be in dispute but there is no doubt that a differential movement has occured and that the northern shore of Lake Superior is "up" in respect to the southern shore of Lake Michigan and Lake Erie.

EXPLANATION OF CROSS-SECTIONS

Two sets of cross-sections have been drawn. One set contains those that were taken along the AB group of lines (figure 1). The other set was made along the CD group (figure 2). On any map the intersection of the AB line with the CD line is in western Michigan

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[1]See Reference #4

since the lines follow the same geographic directions on each map. (Cross-sections were not prepared for Bouguer Map).

The AB line sections were then mounted one above the other so that the points of intersection with CD fall in a vertical line. And as the cross-sections are the same scale they are easily compared in a vertical direction.

The Gravity Map cross-sections show the rise and fall of the isostatic anomalies along AB and CD. Those for Moore's map show the crustal movements along A'B' and C'D'. And the cross-sections from the Pre-Cambrian Structure Map show the changes in pre-Cambrian elevation along A"B" and C"D".

CORRELATION

Gravity and Crustal Movement Maps

Upon comparing the Gravity Map with Moore's Crustal Movement Map one fact is quickly noticed. The contours showing crustal movement have a definite east-west trend while the gravity contours have no recognizable trend.

If the crust is sinking and if it is the result of isostatic recovery (this would be completely opposite to the expected adjustment with the release of glacial weight), then gravity anomalies should be positive to show a correlation.

The western end of Lake Superior shows considerable subsidence and a high positive anomaly which fits into the situation mentioned above. But, there is no consistency to be found. Up the St. Lawrence River, for example, the crust has risen yet the anomalies are still positive. And along the southern shores the crust is subsiding at a greater rate yet here the isostatic anomalies are predominantly negative.

The cross-sections in figure 1 show the same result. The gravity cross-section shows a general change from positive in the northwest to negative in the southeast over the same portion that the crustal movement section changes from zero movement to a decided downward movement. Although the section C'D' in figure 2 shows the same increase in subsidence from northeast to southwest, the gravity section oscilates between positive and negative without apparent regard to the crustal movement.

Looking at the situation from the viewpoint that the north area is "up" with respect to the south without regard to the direction of movement does not aid the correlation. For a correlation would call for more negative anomalies to the north regardless of the actual values. The 44th parallel divides the area on the gravity map in two nearly equal parts. The average isostatic anomaly south of the 44th parallel is -9.6 milligals while the average isostatic anomaly north of the 44th parallel is -3.6 milligals. So the average anomaly to the north is far more positive than that to the south.

Gravity and Pre-Cambrian Structure Maps

Since the gravity map shows little or no correlation with the crustal movement, it is of interest to see if there is any rock density change that might check more closely with gravity results.

Pre-Cambrian elevation often has a marked effect on gravity results since crystalline rocks are usually denser than the ordinary sedimentary section. Therefore a more positive anomaly would be expected, if there is a correlation, where the pre-Cambrian came near or to the surface and a more negative anomaly where it is overlain by a large thickness of sedimentary rock.

Checking the map it is first seen that the pre-Cambrian outcrops throughout most of the northern section. A large portion of this area is in the Canadian Shield.

The Michigan Basin is clearly outlined with a depth of 13,000 feet in the center of the state. In western Ohio, close to the Indiana border, the structure comes within 2,000 feet of the surface and dips down sharply to the east into the Appalachian geosyncline and to the southwest into the Illinois basin. In the New York area and the area west of Lake Michigan the dip is to the south.

The first obvious and disconcerting point is the fact that the isostatic anomaly contours run indiscriminately back and forth across the pre-Cambrian contact. And both negative and positive anomalies are represented where the crystalline rock outcrops.

The cross-sections of figure 1 and figure 2 show that northwest and northeast respectively from the pre-Cambrian contact with the surface the anomaly curve on the gravity cross-section oscillates between negative and positive values and shows no correlation.

But along AB to the southeast of the contact there is a reasonable agreement between the change in gravity and the change in pre-Cambrian elevation. At the contact there is a high positive anomaly, and this lowers to a negative value as the structure drops in the Michigan Basin. And the anomaly curves returns to a positive value where the structure rises to within 2,000 feet of the surface.

So there may indeed be some correlation here between the structure and the anomalies. Along CD there is also some similarity. Southwest of the intersections with AB and A"B" the two cross-sections, CD and C"D", follow the same general ups and downs.

The comparison is made with full realization that cross-sections can be misleading. It is evident that the two maps show no general trends in common and it is quite possible that similarities are only coincidental.

GRAVITY EFFECTS DUE TO CHANGES IN ROCK DENSITY

Lithologic Differences

One other cause that can affect gravity results is lithologic differences in the sediments. Any grouping of heavier types of rock formations or heavy minerals will cause a change in gravity.

Undoubtedly lithology plays an important role with the readings at certain stations and thus has an effect on the directions of the anomaly contours. But to actually observe these causes and results on a regional map with a contour interval of 10 milligals and the stations up to 100 miles and more apart would be difficult. In fact, many lithologic effects would not even appear on the map.

Large Igneous and Ore Bodies

It can be expected that large igneous masses will produce regional gravity effects.

The Duluth lopolith,[1] for example, outcrops along both the north and south shores of the western part of Lake Superior. It is composed essentially of a basic gabbro which is more dense than the granite of the area into which it was intruded. The gabbro has a thickness of 6,000 feet. Such a structure could be expected to produce a large positive anomaly, and referring to the map it is seen that this is a positive area with a high of 50 milligals at the Duluth station (203).

Another such igneous body is the Sudbury lopolith[2] located in the vicinity of station 102 just above the eastern end of Lake Huron. The structure is composed mainly of a heavy basic igneous rock, norite, that was intruded into a lighter granite. Although

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[1]See reference #3
[2]See reference #3

the lopolith is not nearly as large as the Duluth lopolith, its size is sufficient to affect a regional map. And here the gravity map shows a positive area as would be expected from heavier material.

The greater part of the Lake Superior area is positive and this section is well known for containing tremendous quantities of rich iron bearing rocks. These two factors produce a very likely correlation.

CORRELATION WITH EARTHQUAKES

On the isostatic gravity map there is a "high running from southern Indiana up through western Ohio to the eastern end of Lake Erie. Although negative contours cover most of Lake Erie and Lake Ontario the average anomaly would be only around -10 milligals. From Lake Ontario on out the St. Lawrence River there is another positive "high." The particular course outlined runs along the same path marked by a zone of earthquakes.[1]

This earthquake zone reveals an area of subsurface disturbance which runs from the lower Mississippi River to the St. Lawrence. The area is remarkably parallel to the Appalachian belt on the east and has been considered as a possible development of a new orogenic belt.

The gravity "high" may well mean the intrusion of heavier igneous rock at depths and lend support to the theory of a new orogeny in the making.

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[1]Reference #8

SUMMARY

Gravity results in the Great Lakes Region show no definite trends and are difficult to relate to one dominant effect.

The most common attempt has been to connect the anomalies with the theory of an isostatic rise following the recent glacial depression. In this respect it may be said that the average isostatic anomaly for Quebec and Ontario (for area included on gravity map) is -8 milligals and for the United States a -6 milligals.

But the fact that the average isostatic anomaly north of the 44th parallel is 6 milligals more positive than the average south of the 44th parallel presents a serious obstacle to the application of the theory. Whether or not one considers the old uplift as indicated by beach levels or the present movement shown on Moore's Map (regardless of possible subsidence), the northern area is "up" and should show a more negative anomaly which it decidedly does not.

The anomalies of some of the areas apparently have definite individual causes. This is probably the case at Duluth and Sudbury where the lopoliths must be responsible for at least a part of the positive anomaly.

The positive areas in western Ohio and out the St. Lawrence River may have a connection with the disturbances that have caused earthquakes along this general line.

The "high" in western Ohio may correlate with the pre-Cambrian elevation. The same may be said for Northern Michigan and the negative area through the Basin. This can be followed best along AB and A"B" in figure 1.

The complete lack of a regional trend on the isostatic gravity map is perhaps the best indication that several different factors are responsible for the resulting anomalies.

References

1. Moore, Sherman: "Crustal Movement in Great Lakes Area." Geological Soceity of America, Bulletin, vol. 59, August, 1948.

2. Daly, R. A.: "Strength and Structure of the Earth." New York 1940, page 309-335.

3. Daly, R. A.: "Igneous Rocks and their Origin." New York, 1914, page 325 and 348.

4. Transaction American, Geophysical Union, April 1949, Vol. 30, #2.

5. Cohee, George V.: "Cambrian and Ordovician Rocks in Michigan Basin and Adjoining Areas." American Association of Petroleum Geologists. Vol. 32, page 1440.

6. Heck, E. T.: "New York Subsurface Geology." American Association of Petroleum Geologists, Vol. 32, page 1450.

7. Workman, L. E. and Bell, A. H.: "Deep Drilling and Deeper Oil Possibilities in Illinois." American Association of Petroleum Geologists, vol. 32, page 2061.

8. O'Halloran, D. J.: "Correlation of Earthquakes with Tectonics." Thesis, University of Michigan, May, 1949.

APPENDIX

Gravity Stations

Canada		Isostatic Anomaly Depth of Comp.--113.7 ft. (milligals)	Bouguer Anomaly (milligals)
Quebec			
8	Ste. Anne de Bellevue	21	7
7	St. Jerome	24	6
127	Parent	2	-34
2	Maniwaki	0	-28
128	Taschereau	-46	-76
Ontario			
1	Ottawa	-9	-26
3	Kingston	2	-32
117	Pembroke	-26	-46
118	Haliburton	-20	-45
9	Mattawa	-32	-61
16	Whitby	-32	-46
10	New Liskeard	2	-26
15	Rose Point	10	-12
17	Woodstock	-17	-47
102	Sudbury	1	-27
11	Cochrane	-28	-54
101	Chelmsford	6	-27
119	Kincardine	-22	-40

Ontario	Isostatic Anomaly Depth of Comp.--113.7 km. (milligals)	Bouguer Anomaly (milligals)
120 Biskolasing	-18	-50
18 Windsor	-13	- 8
13 Chapleau	9	-30
103 Hearst	- 6	-31
12 Sault Ste. Marie	-21	-51
121 White River	-29	-59
104 Nakina	-16	-47
122 Scheiber	-13	-34
105 Armstrong	15	-23
14 Port Arthur	-46	-73
106 Sioux Lookout	7	-32
30 Kenora	26	-15
Manitoba		
72 Riverton	- 8	-39
United States		
New York		
32 Ithica	-19	-43
86 Lake Placid	5	-27
87 Potsdam	21	3
88 Wilson	-12	-24
132 Watertown	-27	-42
133 Southport	-25	-55

New York (cont)		Isostatic Anomaly Depth of Comp.--113.7 km. (milligals)	Bouguer Anomaly (milligals)
319	Buffalo	-18	-36
669	So. of Orlean	- 2	-38
800		-11	-38
Pennsylvania			
134	Erie	-28	-50
211	Pittsburth	-25	-51
333	Unientown	- 8	-42
334	Summit Mills	4	-36
665	Cyclone P. O.	5	-32
Ohio			
33	Cleveland	- 4	-26
34	Cincinnati	-22	-41
136	Columbus	-12	-37
316	Oberlin	-11	-33
394	Tiffin	-14	-34
395	Dover	- 4	-30
457	Kent State College	- 3	-27
1084	Celina	2	-23
1085	Wright	8	-18
Indiana			
35	Terre Haute	- 9	-26
122	Angola	9	-11

	Indiana (cont)	Isostatic Anomaly Depth of Comp.—113.7 km. (milligals)	Bouguer Anomaly (milligals)
137	Indianapolis	0	-22
1091	Wabash	-22	-45
1092	West Lafayette	-11	-32
	Michigan		
57	Iron River	31	+ 1
89	Alpena	-22	-38
121	Grand Rapids	- 2	-19
177	Traverse City	2	-17
178	Seney	3	-16
218	North Tamarack	31	11
1086	Mason	-14	-37
1087	Bay City	-11	-30
1088	West Branch	-20	-44
1089	Ludington	-22	-41
1090	Three Rivers	6	-16
	Illinois		
36	Chicago	- 2	-20
120	Keithsburg	- 8	-29
138	Springfield	-13	-32
586	Univ. of Illinois	- 9	-26
1093	Streator	1	-20
1132	Hamilton	-23	-44

Iowa		Isostatic Anomaly Depth of Comp.--113.7 km. (milligals)	Bouguer Anomaly (milligals)
119	Fort Dodge	13	-19
204	Osage	-26	-59
208	Leon	-10	-41
1133	Iowa City	-12	-37
1134	Dallas Center	-37	-70
Wisconsin			
37	Madison	- 6	-30
107	Prentice	19	-15
179	Oconto	-24	-46
180	Grand Rapids	-40	-72
182	Baldwin	-50	-82
183	Cumberland	-49	-82
1094	Franksville	-22	-13
1095	Oshkosh	-34	-59
1096	Merrill	-13	-50
Minnesota			
58	Ely	- 5	-18
74	Minneapolis	57	+29
108	Fergus Falls	- 7	-44
181	Winona	18	-15
184	Cambridge	-26	-60
185	Brainerd	12	-26

Minnesota (cont)		Isostatic Anomaly Depth of Comp.--113.7 km (milligals)	Bouguer Anomaly (milligals)
191	Crookston	11	-24
196	Faribault	36	+ 3
197	St. James	7	-29
199	Dawson	18	-22
200	Cokata	6	-27
203	Duluth	50	16
1097	Grand Rapids	-13	-54
1098	Bemidji	-18	-59
1099	Baudette	11	-27