The UNIVERSITY of WISCONSIN

Geophysical & Polar Research Center

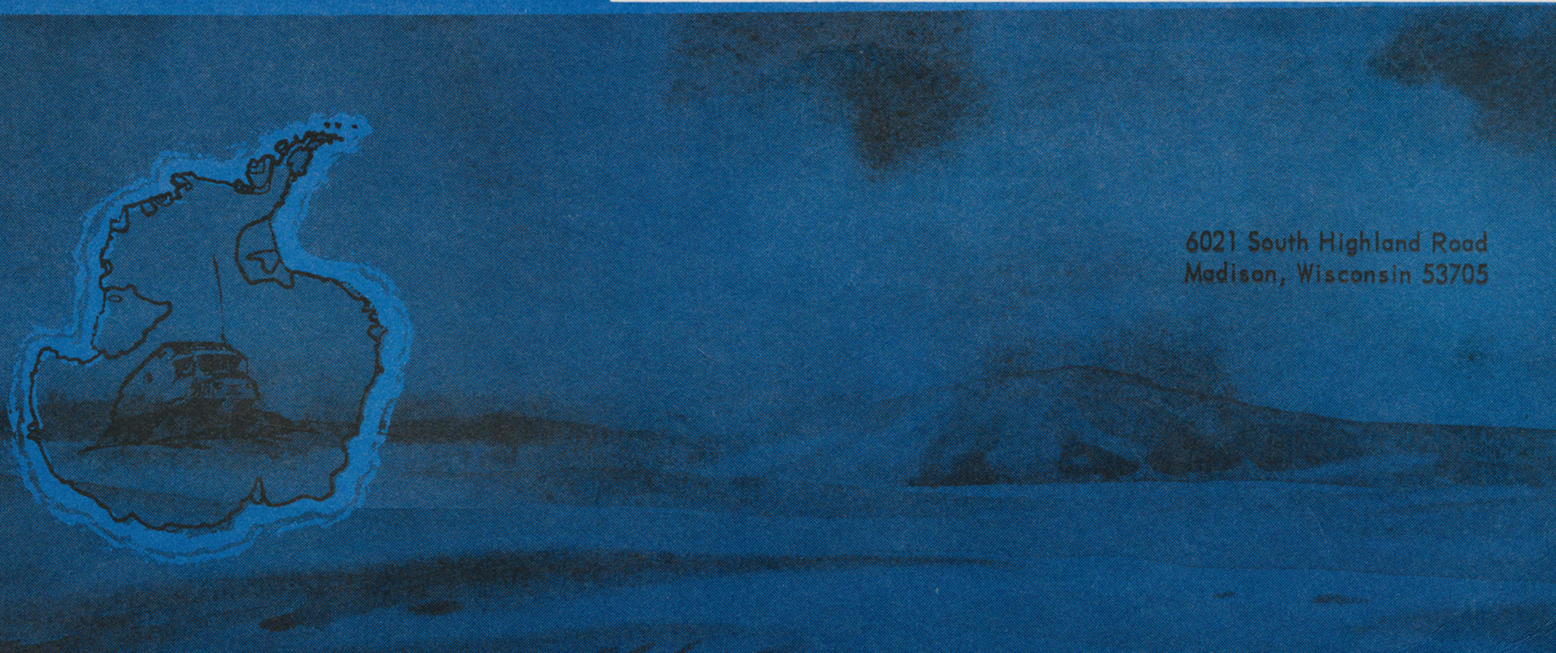
DEPARTMENT OF GEOLOGY

Research Report Series

RESULTS OF REGIONAL AEROMAGNETIC SURVEYS OF EASTERN UPPER MICHIGAN, CENTRAL LOWER MICHIGAN, AND SOUTHEASTERN ILLINOIS

by Robert W. Patenaude

RESEARCH REPORT NO. 64-2-APRIL, 1964



6021 South Highland Road
Madison, Wisconsin 53705

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ABSTRACT

With the exception of the area between Marquette and Sault Ste. Marie, Michigan, formations of Precambrian age consisting in large part of Keweenawan volcanics constitute the margin of Lake Superior. Between Marquette and Sault Ste. Marie the Precambrian formations are concealed by sediments of Paleozoic and possible Late Precambrian age. Results of a 1400 mile regional aeromagnetic survey indicate that Keweenawan volcanics also constitute much of the Precambrian basement concelaed beneath these sediments. The data further suggest that the Keweenaw fault continues in a southeasterly direction with diminishing displacement through the vicinity of Munising, Michigan. The presence of a fault is also indicated south of Sault Ste. Marie, Michigan. Gravimetric and geologic evidence substantiates the interpretation of the magnetic data.

In addition, aeromagnetic data of central Lower Michigan suggest that Keweenawan volcanics may extend south from eastern Upper Michigan to the center of the Michigan Basin.

Depth estimates based on the aeromagnetic data of central Lower Michigan and southeastern Illinois correspond in magnitude to depths estimated on the basis of stratigraphic data.

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INTRODUCTION

This report consists of four parts; part one, two and four deal with regional aeromagnetic surveys of eastern Upper Michigan, central Lower Michigan and southeastern Illinois. The subject of part three is a single aeromagnetic profile over northern Lake Michigan.

The purpose of the regional aeromagnetic surveys presented here was to furnish a means of estimation of depth to crystalline basement in the deeper portions of the Michigan and Illinois basins, and to furnish information concerning the nature of the crystalline basement between Lake Michigan and Lake Superior in eastern Upper Michigan.

Aeromagnetic data were obtained in each regional survey area during the summers of 1961 and 1962. The Beaver Island profile over northern Lake Michigan was flown during the summer of 1962. Gravity traverses in eastern Upper Michigan were conducted during the summer of 1963.

EQUIPMENT AND PROCEDURES

Magnetic observations were made at an elevation of 3000 feet above sea level along township lines using an Elsec 592/D proton precession magnetometer in conjunction with a camera recording system installed in a Cessna model 170B aircraft. The sensing head was towed sixty feet beneath the plane. The magnetometer was actuated by a timing system to record the total magnetic field intensity every eight seconds. An effort was made to maintain a ground speed of 90 mph, resulting in observations at approximately 1000 foot intervals. Flights were conducted during the early morning hours before thermal instability had risen to flight altitude. Ground control was by visual positioning with a limit of error generally less than 500 feet. The survey crew consisted of pilot and instrument operator.

A standard aneroid altimeter of the type commonly installed in light planes was used to indicate flight altitude. The altimeter was set to airport elevation before each flight. No attempt was made to correct for change in station pressure, and therefore in indicated altitude, between the commencement and the completion of a flight. Flights were made during periods of stable weather conditions. Comparison of data indicates that error originating from possible variations in altitude was negligible.

Correction for regional magnetic gradients was computed from the U. S. Coast and Geodetic Survey Total Intensity Chart of the United States for 1955 projected, on the basis of annual secular change, to 1961 and 1962. Dashed lines on the survey index maps indicate the regional magnetic gradients in 100 gamma increments computed for 1961.

Diurnal corrections were computed from records of a continuous recording Gulf Flux Gate magnetometer located at the Geophysical and Polar Research Center at Madison. The diurnal records indicate that no survey flights were made during periods of significant magnetic activity.

As an indication of the degree of data reliability, the average deviation of the two data points closest to the intersection of two flight lines, representing sixty-nine intersections of data lines flown the summer of 1961 in Lower Michigan, is 5.6 gammas and the root mean square deviation is 7.1 gammas. The average deviation of twenty-nine corresponding intersections from the 1961 survey in Upper Michigan is 4.8 gammas and the root mean squares deviation is 6.7 gammas.

A North American gravity meter was used for the gravity traverses in Upper Michigan. Observations were taken at bench marks or at road intersections where elevation was specified on 1/62,500 topographic maps. The elevation at six stations was estimated with the aid of two aneroid altimeters in conjunction with interpolation of twenty foot contours on the topographic maps.

ACKNOWLEDGMENTS

This work was made possible by National Science Foundation Grant G16375 to Professor George P. Woollard. Financial grants from the Wisconsin Alumni Research Foundation and grants of time on the University CDC 1604 computer also contributed to execution of the project, as did personnel and the use of facilities of the Geophysical and Polar Research Center at Madison.

An aeromagnetic survey requires the participation of many people. Three individuals who performed especially critical functions in this survey are: James Scherz, who designed and built the camera-sequencing system used in conjunction with the magnetometer; Peter Wolfe, who programmed the reduction of the magnetic data and the gravity and magnetic model studies for the CDC 1604 computer; and Paul McFee, who furnished valued assistance through his knowledge of electronics and of University and state business procedures.

The gravity traverses in Upper Michigan were made with one of ten North American gravity meters donated to Professor George P. Woollard by Mandrel Industries of Houston, Texas.

The Gulf Flux Gate magnetometer used for diurnal correction was on loan to Professor George P. Woollard by the Gulf Oil Company.

PART I

GEOLOGIC BACKGROUND AND DISCUSSION OF RESULTS, EASTERN UPPER MICHIGAN

Physiography

The area covered by Paleozoic sediments (Fig. 1) has the form of a gently southward dipping cuesta upon which is superimposed the poorly integrated drainage pattern common to recently glaciated areas. Topographic expression is subdued; surface elevation varies from 580 feet to slightly over 1000 feet above sea level. Major elevation differences result from differential erosion of the resistant Au Train formation and locally to recessional moraines, drumlins and sea cliffs. In many places bedrock is covered by up to 400 feet of ground moraine and lake clays (Hamblin, 1958). Much of the area is covered by swamp, with drainage to Lake Michigan, except for a zone adjacent to Lake Superior and the Tehquamenon system of drainage to Whitefish Bay. The western end of the flight lines overlapped for a few miles the system of east-west trending valleys and ridges differentially eroded into the Huronian series, where elevations approach 1500 feet above sea level.

Geology

The survey area represents the northern extremity of the Michigan structural basin. Off-lapping Cambrian, Ordovician and Silurian sediments constitute a southward dipping cuesta that overlies the non-marine Jacobsville sandstone of Upper Keweenawan or Lower-Middle Cambrian age. The Paleozoic section appears to be thickest in the area of Seul Choix Point and Gilchrist as evidenced by geologic sections cut in water wells. A well at Seul Choix Point was completed at 1710 feet in the Dresbach formation of basal Upper Cambrian age (Thwaites, 1934).

There are few well data available for the estimation of the thickness or areal extent of the underlying Jacobsville sandstone which is present in outcrop along the Lake Superior shore of eastern Upper Michigan, and there is no indication on this peninsula of sediments older than Jacobsville sandstone from well data or outcrop. At Grand Marais on Lake Superior a well was bottomed in Jacobsville sandstone after penetrating 1000 feet of the formation (Thwaites, 1934). South of Sault Ste. Marie the Jacobsville sandstone is in excess of 1300 feet thick, but pinches out abruptly a few miles to the north and east in Ontario (Vanlier and Deutsh, 1958). A well, recently drilled 12 miles north-northeast of Newberry, located in the center of the peninsula, penetrated about 1000 feet of Jacobsville sandstone before drilling was completed at a depth of about 1500 feet.

The age of the non-fossiliferous Jacobsville sandstone is disputed. Oetking (1951) correlates it with the Bayfield group of Northern Wisconsin that is considered to be Upper Keweenawan in age (Thwaites, 1912).

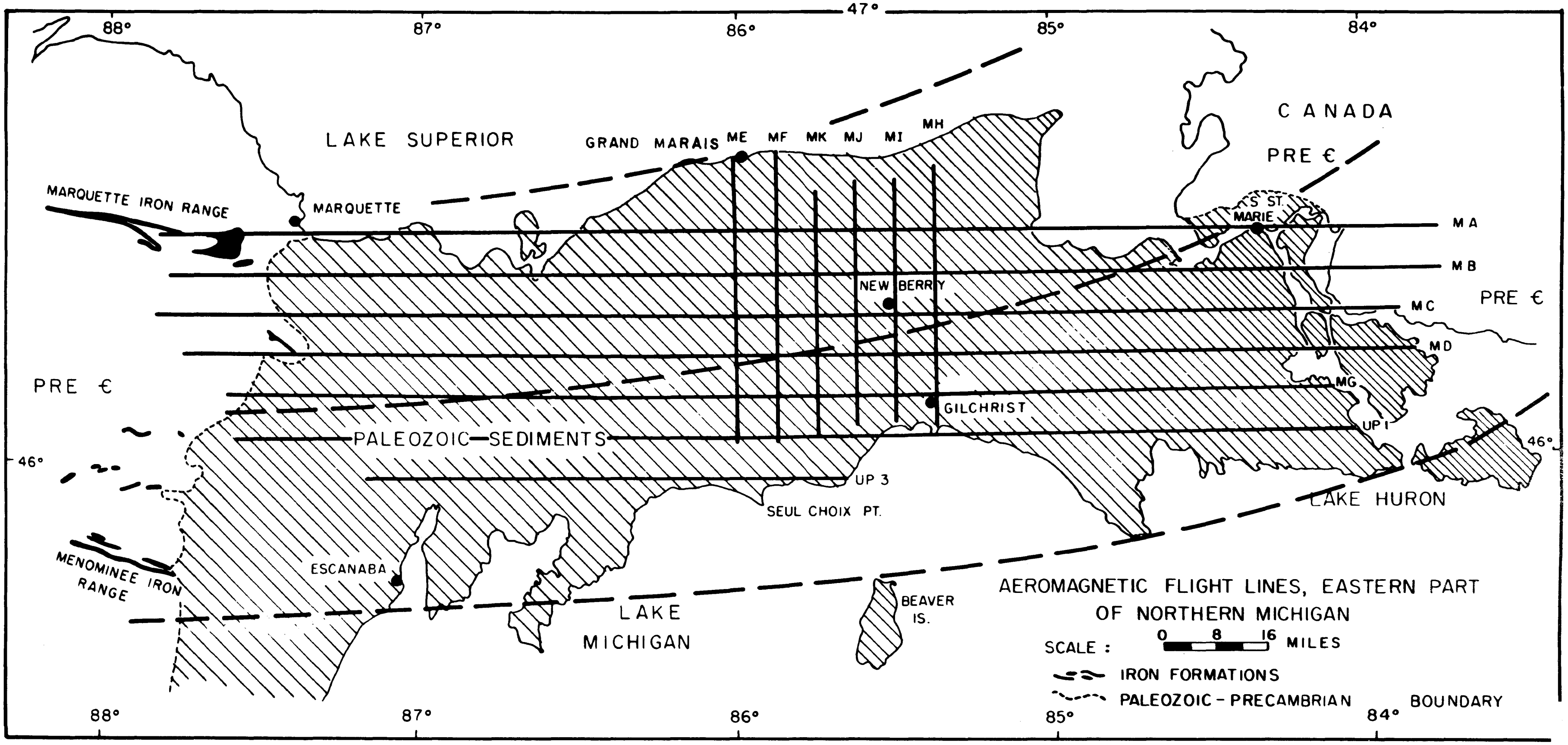

47°
88°
87°
86°
85°
84°
46°
LAKE SUPERIOR
GRAND MARAIS
MARQUETTE
MARQUETTE IRON RANGE
ME
MF
MK
MJ
MI
MH
CANADA
PRE €
S. ST. MARIE
MA
MB
MC
MD
MG
UP 1
UP 3
NEW BERRY
GILCHRIST
PRE €
PALEOZOIC SEDIMENTS
SEUL CHOIX PT.
LAKE HURON
ESCANABA
MENOMINEE IRON RANGE
LAKE MICHIGAN
BEAVER IS.
AEROMAGNETIC FLIGHT LINES, EASTERN PART OF NORTHERN MICHIGAN
SCALE : 0 8 16 MILES
IRON FORMATIONS
PALEOZOIC - PRECAMBRIAN BOUNDARY

Figure 1

Hamblin (1958) considers the Jacobsville sandstone to be Lower or Middle Cambrian in age. The Jacobsville sandstone is included in the symbol for Paleozoic sediment of Figure 1.

Formations older than the Jacobsville sandstone are concealed by Paleozoic sediments for an east-west distance of 150 miles, but crop out to the west in the area of Marquette and to the east beyond Sault Ste. Marie. The general patterns of Precambrian formations east and west of the area concealed by Paleozoic sediments are similar in gross aspect, and constitute an east-west trending series of shelf and synclinal environment sediments infolded into a volcanic, granitic and metasediment complex with widespread injection of diabase dikes and intrusions of granite. Subsequent erosion reduced this surface to one of low relief by late Precambrian time. The western infolded sediments are classified as Huronian in age and contain iron formation of the type characteristic of the Precambrian.

Stratigraphically above the Huronian series and below the Paleozoic sediments is the Keweenawan series, which consists of great thicknesses of volcanic and clastic material and which occurs in many areas about Lake Superior (Fig. 2, modified after White, 1957). Basic and acidic intrusives also occur in the Keweenawan series. North of Whitefish Bay at Mamainse Point there is an apparent thickness of 16,000 feet of amygdaloidal lava flows with interbedded boulder conglomerate. Here the formation strikes generally north-south and has an average dip of 30 degrees towards Lake Superior. Dikes and irregularly shaped bodies of felsite intrude the lavas and sediments (Thompson, 1954). Mamainse Point is indicated in Figure 2 by the symbol for middle Keweenawan rock located on the southeast shore of Lake Superior.

Volcanic rocks of Keweenawan age constitute Michipicoten Island, indicated in Figure 2 by the symbol for middle Keweenawan rock in eastern Lake Superior near the bulge in the shoreline, and most of Isle Royal, indicated by the elongate northeast trending symbol for middle Keweenawan rock near the northwest shore of Lake Superior. Sediments of Lower Keweenawan age are present on the north shore of Lake Superior in the vicinity of Black and Nipigon Bays, where the basal Keweenawan section is best developed. Here the basal Keweenawan consists of a thick section of clastic, dolomitic and calcareous rocks.

As indicated by Figure 2, the most extensive exposures of Keweenawan rock are found about the southwestern margin of Lake Superior. The series has been studied extensively on the Keweenawan Peninsula where volcanic flows have been mineralized with copper. In this area the basal Keweenawan consists of a thin conglomerate. This is overlain by an estimated 20,000 to 30,000 feet of basic extrusives and interbedded conglomerates intruded by laccoliths and sills, comprising the Middle Keweenawan Portage Lake group. This, in turn, is overlain by perhaps 15,000 feet of Upper Keweenawan non-marine sediments consisting of sandstones, shales and conglomerates.

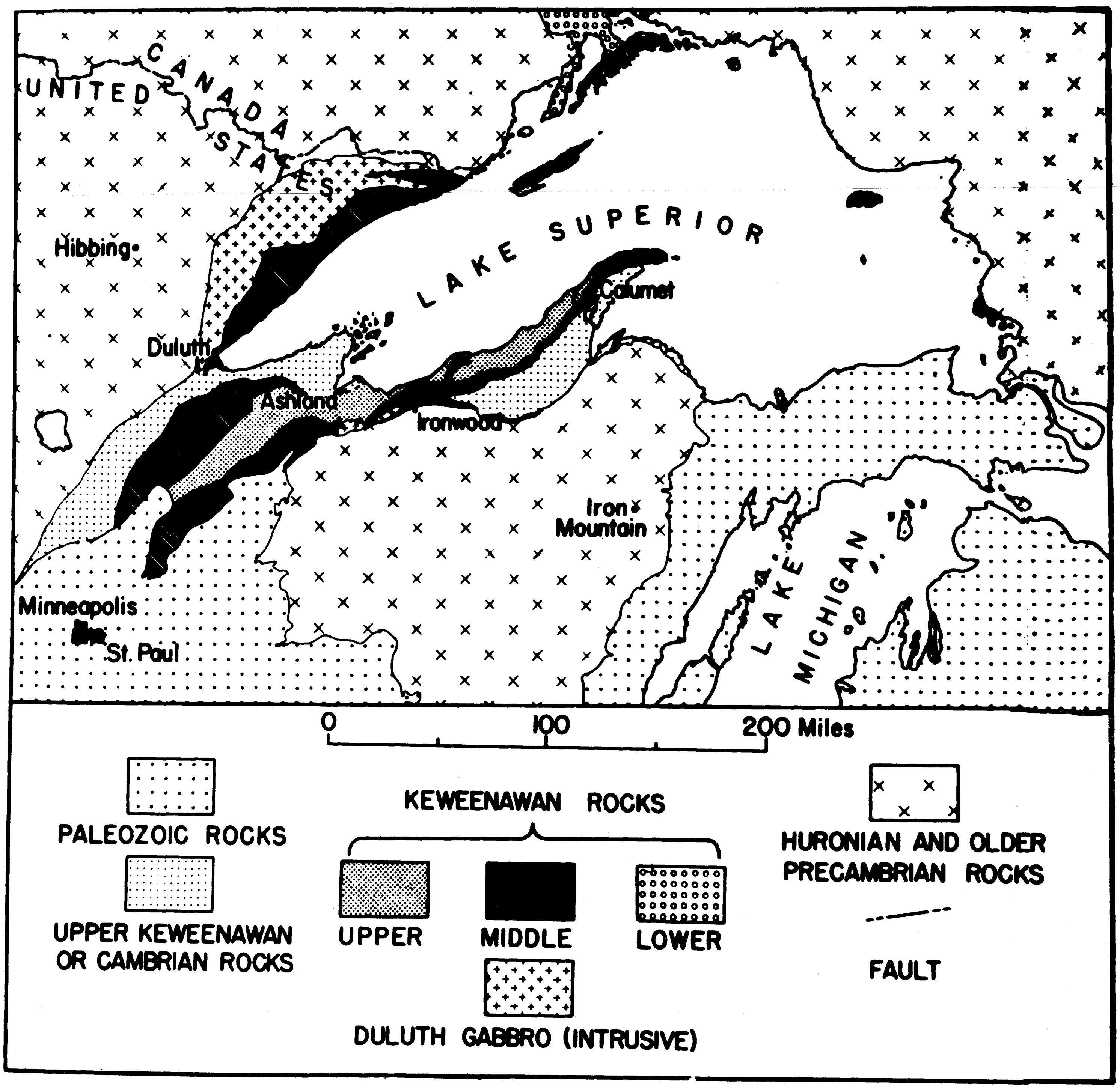

UNITED STATES
CANADA
LAKE SUPERIOR
Hibbing
Duluth
Ashland
Ironwood
Calumet
Iron Mountain
Minneapolis
St. Paul
LAKE MICHIGAN
0
100
200 Miles
PALEOZOIC ROCKS
UPPER KEWEENAWAN OR CAMBRIAN ROCKS
KEWEENAWAN ROCKS
UPPER
MIDDLE
LOWER
DULUTH GABBRO (INTRUSIVE)
HURONIAN AND OLDER PRECAMBRIAN ROCKS
FAULT

Figure 2.

Structure of the Lake Superior Basin

The most commonly accepted explanation for the origin of the Lake Superior structural basin is that it is a foundered batholithic roof (Hotchkiss, 1923). On the basis of estimates of the original dips of the Keweenawan flows, together with flow directions of the extrusives as indicated by bent "pipe" amygdules and sediment structure at the base of the flows, Hotchkiss concluded that flows originated in the area of what is now the Lake Superior basin. Hotchkiss theorized that the present basin was a topographically positive area during Middle Keweenawan time, resulting from the emplacement of a huge batholith beneath the crust. The extrusives resulted from escape of the basaltic material, with contemporaneous and equivalent subsidence of the crust. Contraction of the remainder of the batholith due to cooling and loss of volatiles eventually resulted in complete failure of the batholith roof.

Lake bottom topography (Hough, 1958, Fig. 3) suggests that the Lake Superior Basin may be composed of two separate structural units, as indicated by a general northeast-southwest orientation of structure in the western part of the basin and a north-south structural lineation of the eastern part of the basin. A narrow zone of more shallow depths extending north-east from the Keweenaw peninsula separates the two structural units and divides the lake into two basins. The north-south structural trend of the eastern basin is in diametric contrast to the regional east-west structural grain of the surrounding area.

Geologic Evidence of Crustal Adjustment in the Eastern Peninsula of Upper Michigan

Sedimentary evidence of crustal adjustment in the area of Au Train Point is afforded by the occurrence of clastic dikes, thrust faults, and joints in the Jacobsville sandstone. "Numerous tabular sandstone dikes in the Jacobsville formation have been briefly described by Oetking (1951, p. 61). They seem to be restricted to the Grand Island area where thirty dikes were mapped on the island itself and four on the mainland between Munising and Au Train Bay. Elsewhere along the coast dikes are absent," (Hamblin, 1958, p. 131).

Hamblin concluded that the clastic dikes resulted from tension features in the Jacobsville sandstone being filled with clastic material similar in character to that of the overlying Munising formation. Hamblin (1958, p. 126) also reports the presence of a joint system in the Jacobsville sandstone on the northwest side of Grand Island.

Oetking (1951, p. 77) reports the presence of thrust faults in the same area. "Minor thrust faults in the Jacobsville rocks, such as those on the east side of Laughing Whitefish Point, Au Train Island (in western Au Train Bay), and the southeast corner of Au Train Bay, and the lack of evidence of these faults in the overlying Croixan indicates considerable pre-Croixan faulting," (see Fig. 3 for locations). Also, "The northern one-half of Au Train Island dips 16 degrees south and is separated from the gently dipping southern part of the island by a nearly vertical fault of unknown displacement striking N 70 W. The fault may well be a continuation of the fault line suggested by Thwaites (1935) based upon the sublacustrine topographic map of the bottom of Lake Superior. Further evidence of faulting occurs on the mainland on Laughing Fish Point and in the southeast corner of Au Train Bay," (Oetking, 1951, p. 80).

To the southeast, on the Lake Michigan shore, structure is locally evidenced at Seul Choix Point, which coincides with the crest of a northwest-southeast trending anticline developed in Silurian dolomite (Ehlers and Kesling, 1957). Small scale faulting is reported eight or ten miles northwest of Seul Choix Point on the projection of this structure (Slaughter, personal communication).

Results of a ground water survey at the eastern end of the peninsula suggest the presence of large scale faulting in the vicinity of Sault Ste. Marie. Vanlier and Deutsh (1958) report the presence of anomalous mineralization of ground water, in excess of 1000 ppm dissolved minerals, detected in wells located in a zone extending south and east from Sault Ste. Marie and northeast of Pickford. They suggest that the mineralization may originate with connate water that may have migrated along a fault zone extending north from the Michigan basin.

Previous Interpretations of the Precambrian Structure of Eastern Upper Michigan

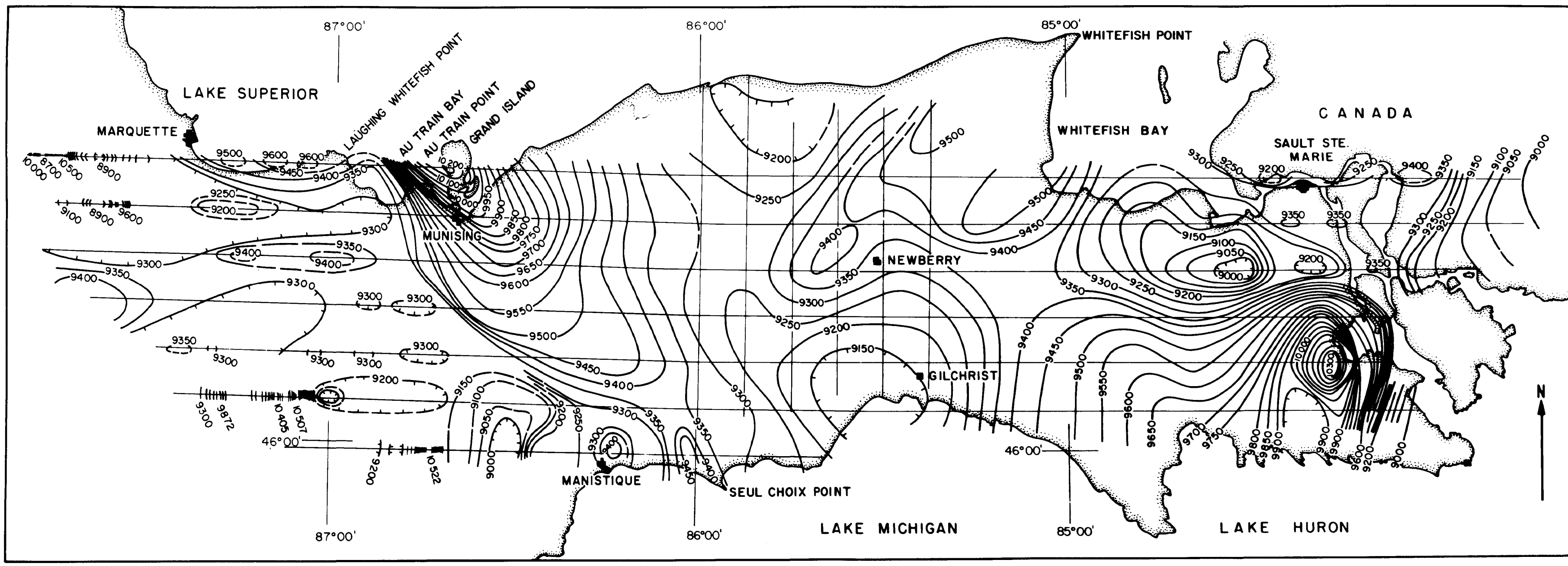
Two diametrically opposed schools of thought exist concerning the nature of the Precambrian basement between Marquette and Sault Ste. Marie. On the basis of field geology and petrology, Irving (1883, p. 197) suggests that the basin-ward dipping volcanics of Michipicoten Island and Batchawana Bay in Eastern Lake Superior continue south into the Whitefish Bay area of eastern Upper Michigan. He also suggests that Mount Houghton on Keweenaw Point and Stannard Rock are of the same felsite horizon in the Keweenaw volcanics and that the Keweenaw Fault continues to curve in a southeast direction to Stannard Rock and beyond. (Batchawana Bay is located south of Mamaise Point. Stannard Rock designates a few square feet of rock exposed above the level of Lake Superior, part of an isolated reef located 45 miles north 10 degrees east from Marquette and 29 miles south 51 degrees east from the eastern extremity of Keweenaw Point.) Thwaites (1935) suggests that the eastern Lake Superior basin is the northward extension of the Michigan structural basin. Cross sections of Lake Superior are presented, drawn on the basis of lake bottom topography. An east-west cross section of the area of eastern upper Michigan shows Keweenawan flows slightly downwarped in the center and thrust faulted outward near either end. An extension of the Keweenawan fault is shown entering the peninsula at Au Train Point, while two north-south faults are shown near the eastern limit of the peninsula in eastern Whitefish Bay.

More recent interpretations of the structure of eastern Upper Michigan have ignored the possible existence of Keweenawan volcanics or a north-south structural saddle connecting Lake Michigan and Lake Superior, and rather have endorsed the existence of an east-west ridge of Huronian rock as comprising the Precambrian basement surface in this area. In particular, Hamblin (1958) concludes from a study of the sandstone of eastern Upper Michigan that a structurally positive area exists between Canada and the Wisconsin Arch and suggests that it be called the Northern Michigan Highland. Hamblin states (1961, p. 14) that this highland "was probably formed near the beginning of Keweenawan time and persisted as a highland up until middle Late Cambrian time. The Northern Michigan Highland (1961, p. 15) remained as a positive area during Jacobsville Bayfield time and supplied sediments to the subsiding basin to the north."

Remanent Magnetization of the Portage Lake Volcanics

DuBois (1957) states that thermal demagnetization curves indicate that thermo-remanent magnetism is the principal cause of magnetization of the Portage Lake volcanics of Middle Keweenawan age. Random orientation of magnetization of boulders of Portage Lake lava in the overlying Copper Harbor member indicates that the direction of magnetization of the volcanics has not changed since Keweenawan time. DuBois further states that after having reconstructed the original dip of the volcanics, the direction of remanent magnetization of 31 specimens was 282° east with an inclination of plus 41°. The radius of a 95% circle of confidence was 4°. Results similar to those of DuBois concerning the relative magnitude of remanent and induced magnetization were obtained by Bath (1960). In his analysis of two aeromagnetic traverses across the Keweenawan volcanics southwest of Lake Superior, Bath concluded that the induced magnetization was not sufficient to explain the large anomaly over the volcanics. A calculated anomaly profile assuming a 0.002 gauss induced magnetization and a 0.01 gauss remanent magnetization approximated the observed profile.

Similar values of declination and inclination were also obtained by the U. S. Geological Survey in studies of basic igneous rocks near Duluth. "The majority of the gabbro, basalt, diabase, and granophyre samples from the Duluth area have a remanent magnetization with an azimuth of about 290° and an inclination downward of about 35°. Twenty-nine samples from seven strongly magnetized diabase outcrops have an average moment of 0.01 cgs with 288 degrees azimuth and 36° inclination. Their average susceptibility is 0.003 cgs.



TOTAL FIELD AIRBORNE MAGNETIC MAP EASTERN NORTHERN MICHIGAN

CORRECTED FOR REGIONAL AND DIURNAL VARIATION
FLOWN AT 3000 FEET MEASURED SEA LEVEL
CONTOUR INTERVAL 50 GAMMAS

SCALE MILES
0 4 8 12 16

Figure 3.

GEOPHYSICAL DATA, EASTERN UPPER MICHIGAN

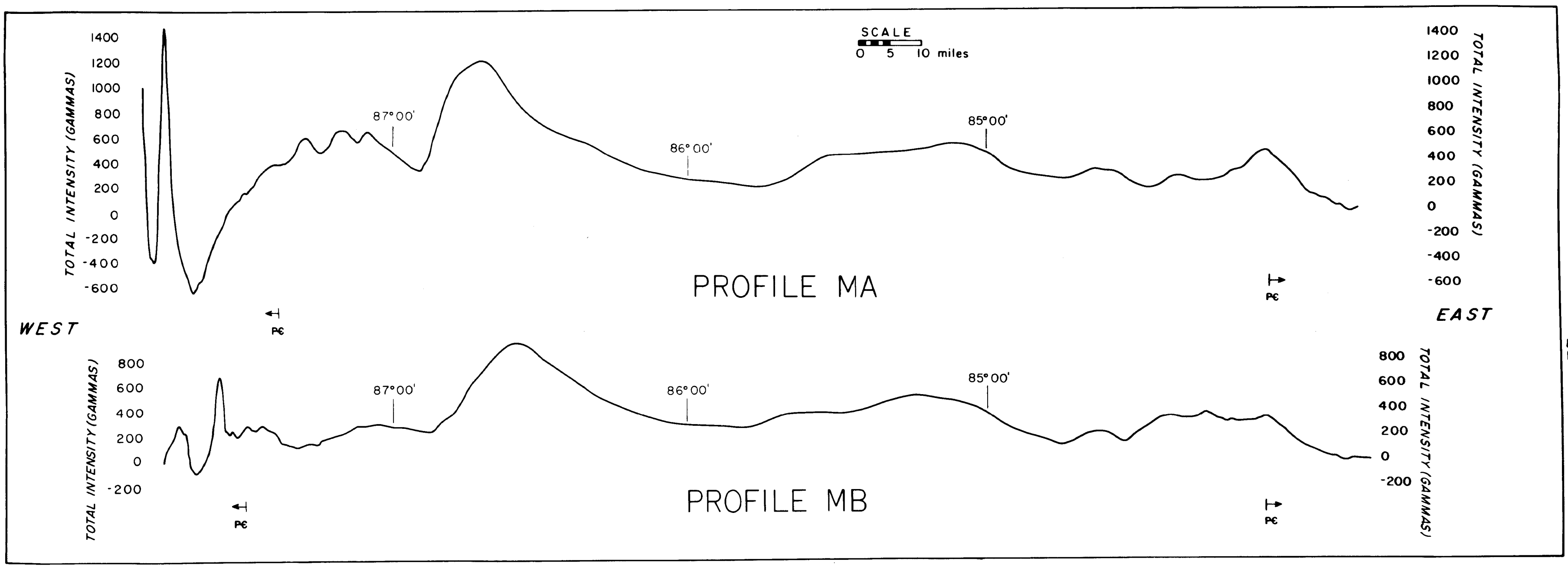
Interpretation of Magnetic Data

Figure 3 is a total intensity aeromagnetic map of eastern Upper Michigan. To the west of the 9350 gamma contour extending southeast from Au Train Bay to midway between Manistique and Seul Choix Point, the magnetic pattern is not well defined and correlation between flight lines is poor. This portion of the east-west profiles (Figs. 4, 5, and 6) exhibits a distinct irregularity in contrast to the smoothness characteristic of the portion of the profiles to the east of this line. This irregularity of pattern and lack of correlation between flight lines is considered indicative of the presence of a heterogeneous pre-Keweenawan basement complex of east-west structural grain, an eastward continuation of the east-west trending Huronian formations exposed west of the Paleozoic cover. The large amplitude anomalies that occur at the western extremity of profile MA correspond to the Marquette iron range. Sharp positive anomalies near the western end of profile UP1 and UP111 correspond to magnetic anomalies that have been correlated with iron formation at a depth of 1000 feet beneath the surface (Frantti, 1956).

To the east of the Au Train Bay--Seul Choix Point line the smooth nature of the magnetic profiles and the good correlation between profiles is interpreted as an indication of the presence of Keweenawan basic flows that are without appreciable vertical offset due to faulting or significant disection as a result of erosion (See Fig. 7 for north-south profiles). Structurally undisturbed volcanic flows of large lateral extent afford a unit of essentially uniform magnetic characteristics.

The aeromagnetic profiles across the large asymmetric positive anomaly that decreases in amplitude southeast from Au Train Point suggest the possibility that this anomaly originates with a fault which diminishes in displacement to the southeast. This magnetic anomaly coincides with the possible continuation of the Keweenawan fault as suggested by Thwaites (1935), and corresponds in location to the zone of structural adjustment as reported by Oetking (1951). This magnetic anomaly again increases in amplitude adjacent to Lake Michigan, coincident with the structure reported on Seul Choix Point (Ehlers and Kesling, 1957).

The eastern limit of the volcanics is not as clearly discernible as the western limit. The eastern extremities of profiles MA and MB traverse exposed pre-Keweenawan basement complex where they cross into Ontario without any significant change in the characteristics of the profiles (see Fig. 4). This suggests the possibility that the pre-Keweenawan complex east of the volcanics may consist of larger and less sharply defined lithologic units than exist west of the volcanics. The magnetic pattern over structurally distrubed volcanics appears not to differ significantly from the magnetic pattern over the pre-Keweenawan complex in the area south and east of Sault Ste. Marie. In the vicinity of Sault Ste. Marie the area underlain by volcanics may roughly correspond to the area where Jacobsville sandstone is present.



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-200
-400
-600
TOTAL INTENSITY (GAMMAS)
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86°00'
85°00'
PROFILE MA
P€
WEST
EAST
800
600
400
200
0
-200
PROFILE MB

Figure 4.

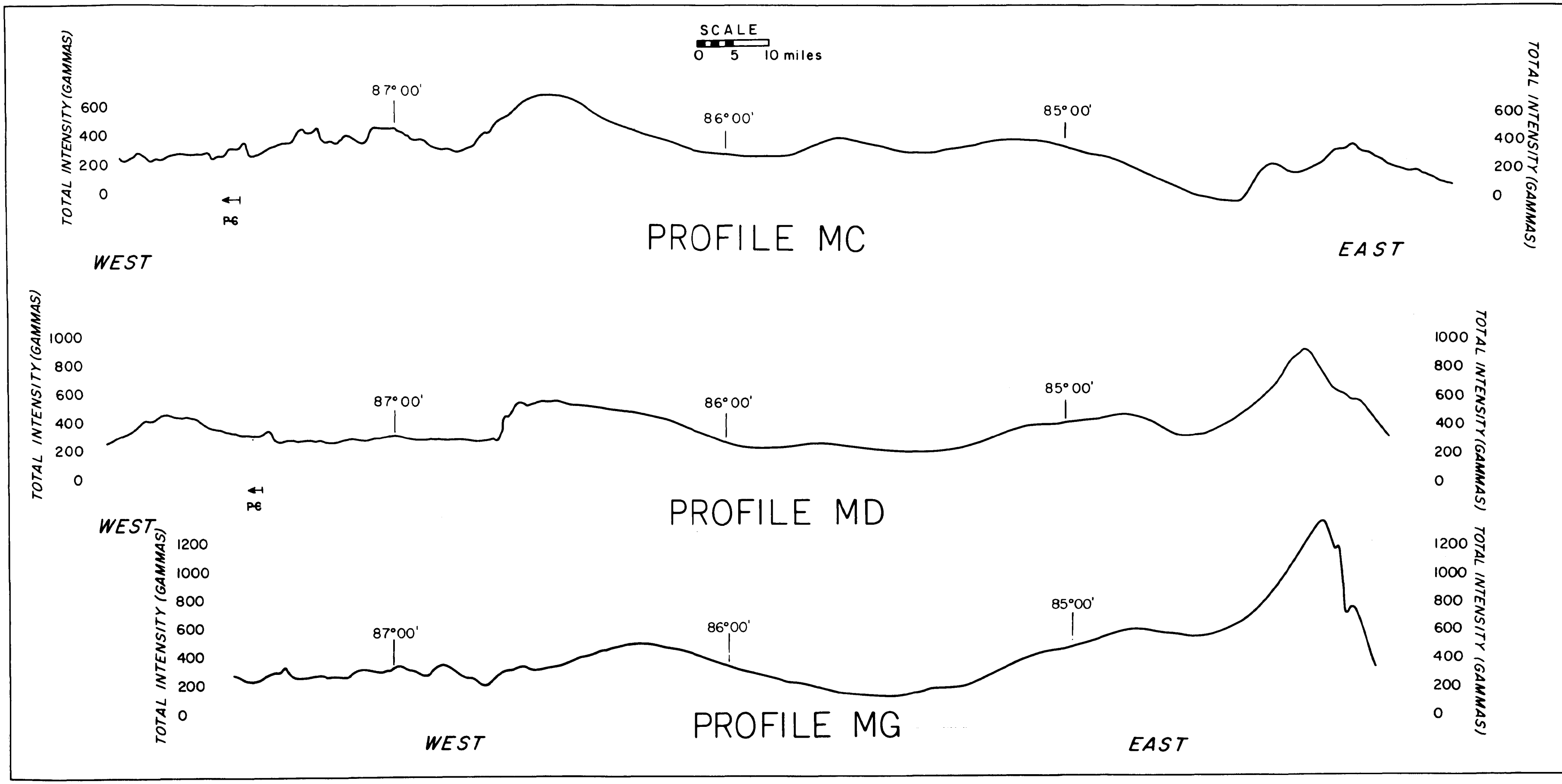
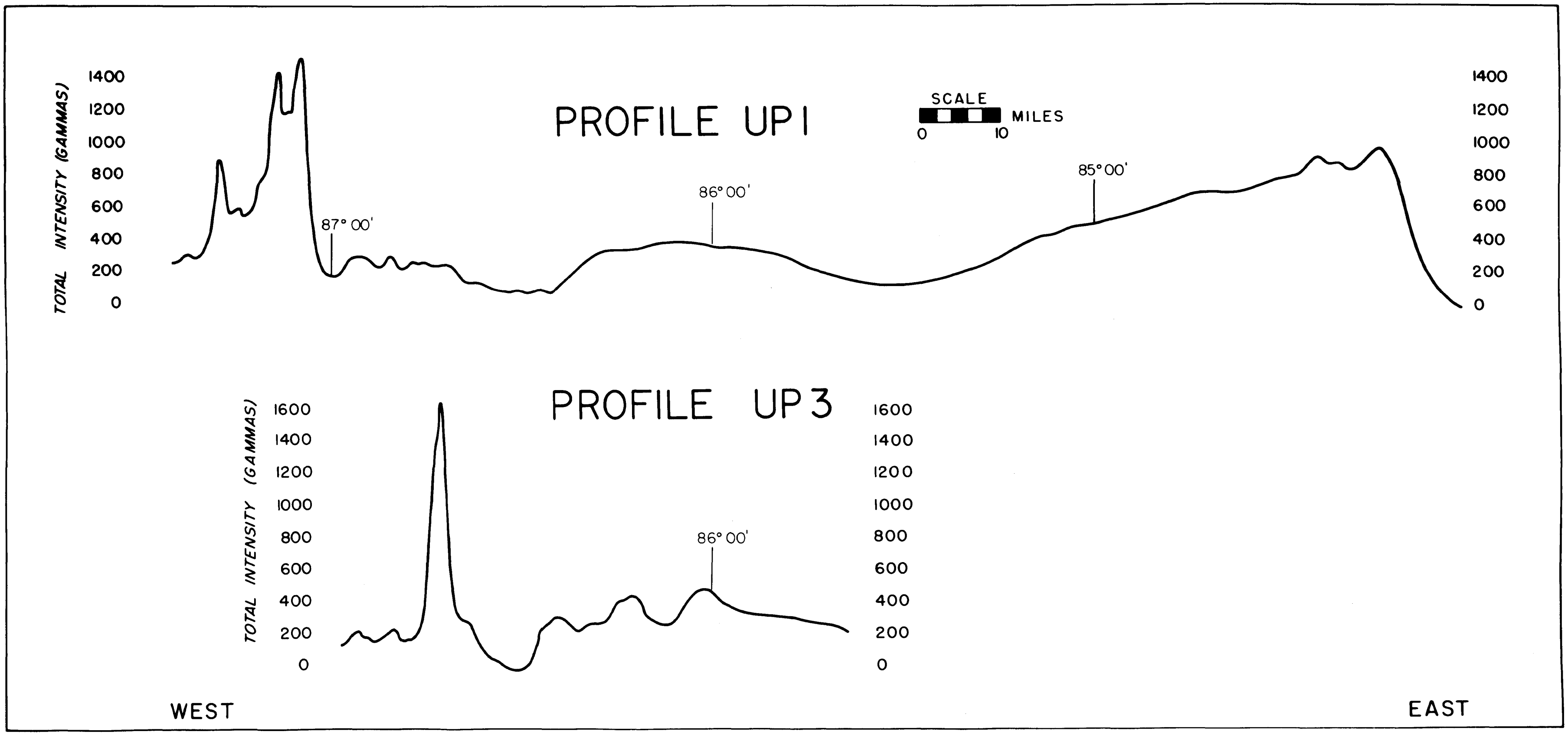

SCALE
0 5 10 miles
TOTAL INTENSITY (GAMMAS)
600
400
200
0
87° 00'
86° 00'
85° 00'
P6
PROFILE MC
WEST
EAST
1000
800
PROFILE MD
1200
PROFILE MG

Figure 5.


PROFILE UP1
SCALE
MILES
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10
TOTAL INTENSITY (GAMMAS)
1400
1200
1000
800
600
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200
0
87° 00'
86° 00'
85° 00'
PROFILE UP3
TOTAL INTENSITY (GAMMAS)
1600
1400
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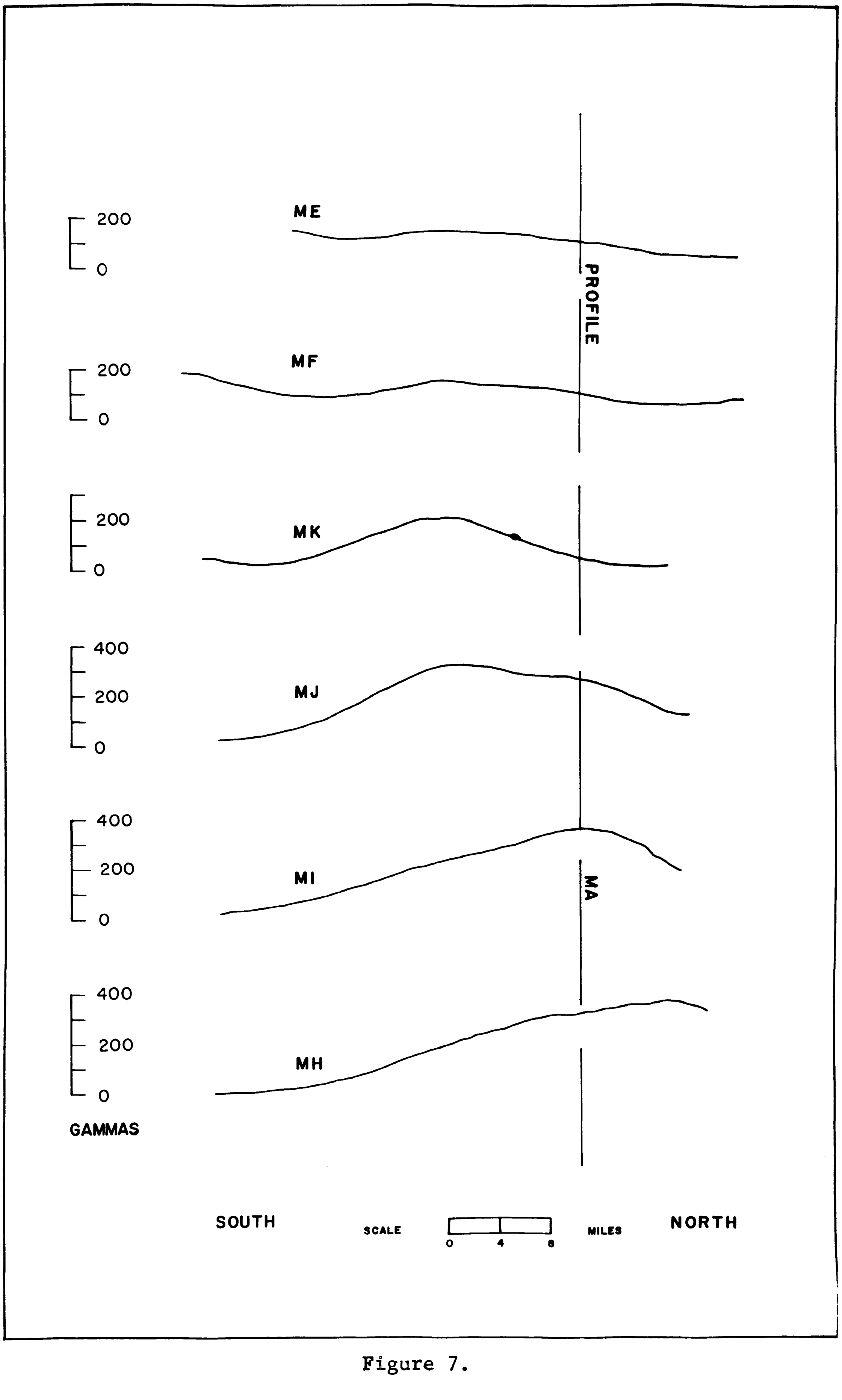
0
86° 00'
WEST
EAST

Figure 6.



ME
MF
MK
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MI
MH
PROFILE
MA
200
0
400
GAMMAS
SOUTH
NORTH
SCALE
0
4
8
MILES

Figure 7.

The abrupt positive anomaly between Sault Ste. Marie and Lake Huron is considered to reflect the presence of a steep north-south striking fault, upthrown to the west, that appears to extend south into Lake Huron. The development of an east-west negative anomaly to the north of this positive anomaly suggests that the greatest offset of the north-south fault may terminate with development of an east-west trending fault system, extending west between flight lines MC and MD to south of Whitefish Bay. The oval positive anomalies extending southwest from Whitefish Point may also reflect structure in the volcanics.

Gravimetric Evidence

Figure 8 is a Bouguer gravity map of eastern Upper Michigan (after Bacon, 1956). The pattern of the Bouguer map is similar in gross features to the pattern of the magnetic map. The location of the linear zone of relatively high gravity values trending southeast from the vicinity of Munising approximates the position of the magnetic anomaly that extends from Munising to Seul Choix Point. The relatively positive gravity values probably result from the large density contrast between volcanics and subsequent clastics, and also from the smaller density contrast between the volcanics and underlying Precambrian formations. No gravimetric data is indicated to the east in the area of the Pickford magnetic anomaly.

A gravity low near Whitefish Point occurs in an area where incomplete aeromagnetic data indicate a zone of relatively high magnetic values. Thickening of clastics in this area may efface the gravitational effect of increased thickness or structure in the underlying volcanis. Assuming the gravity low near Whitefish Point is the result of thickening of post-Portage Lake clastics, a rough calculation using 0.5 gm/cc as the average density differential between clastics and volcanics (computed from data by Thiel, 1956) gives a 5000 foot increase in the thickness of clastics between the -10 mgal contour near Munising and the -40 mgal contour to the east on Whitefish Point. Instances of lack of correlation between the gravity and magnetic data in this area reflect the condition that the magnetic pattern is influenced principally by the presence of volcanic flows, whereas the gravimetric data is most sensitive to the relative thickness of subsequent low density clastics.

The absence of large amplitude gravity and magnetic anomalies in central eastern Upper Michigan suggests that volcanics that may be present are in the form of relatively undisturbed surface flows. This occurrence is in contrast to the structural complexity of Keweenawan volcanics associated with the mid-continent gravity high, where the amplitude of this feature has been interpreted as indicating a thick horst, or root system, of volcanics (Thiel, 1956, Craddock, et al., 1963).

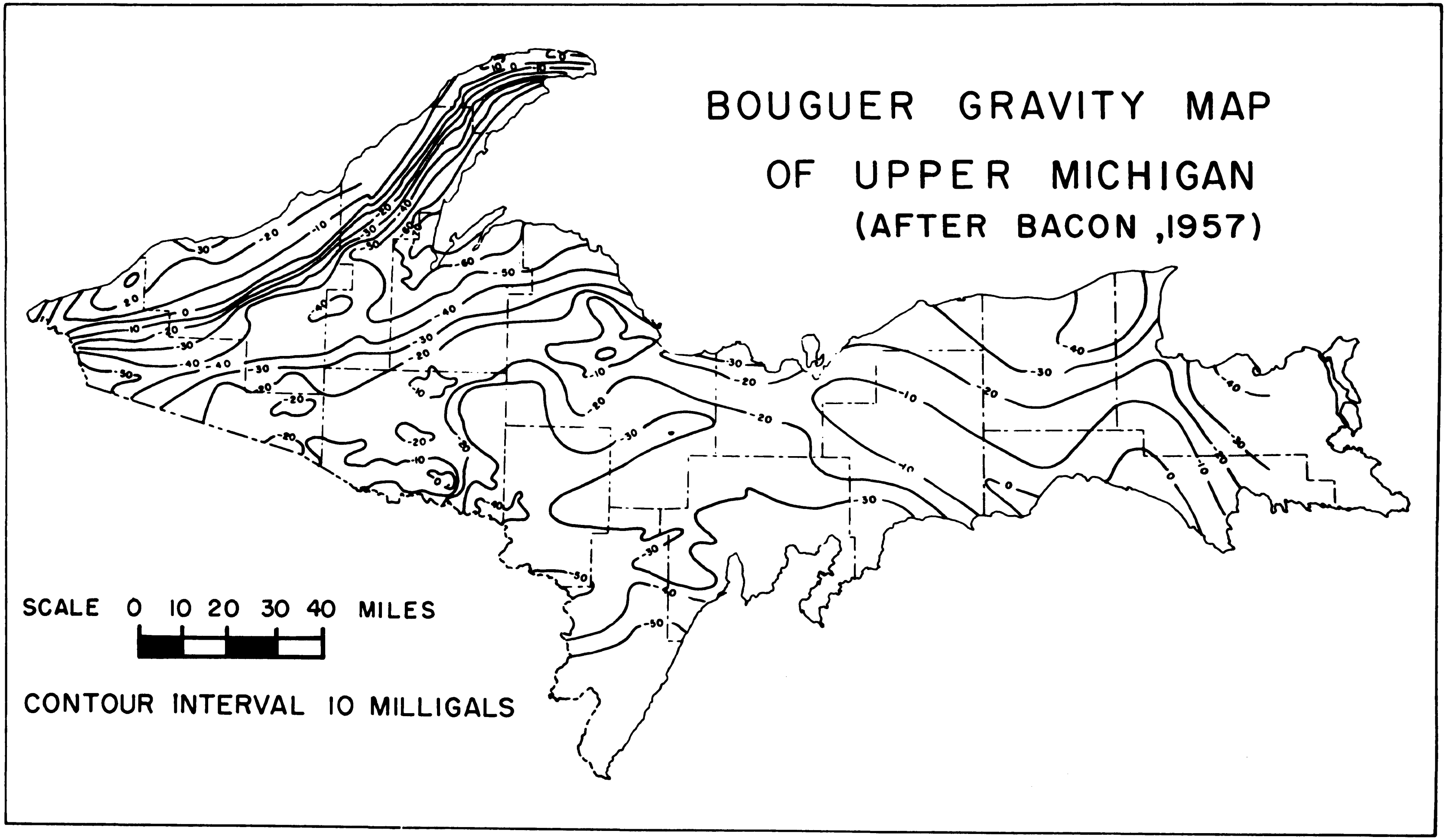

BOUGUER GRAVITY MAP
OF UPPER MICHIGAN
(AFTER BACON, 1957)
SCALE 0 10 20 30 40 MILES
CONTOUR INTERVAL 10 MILLIGALS

Figure 3.

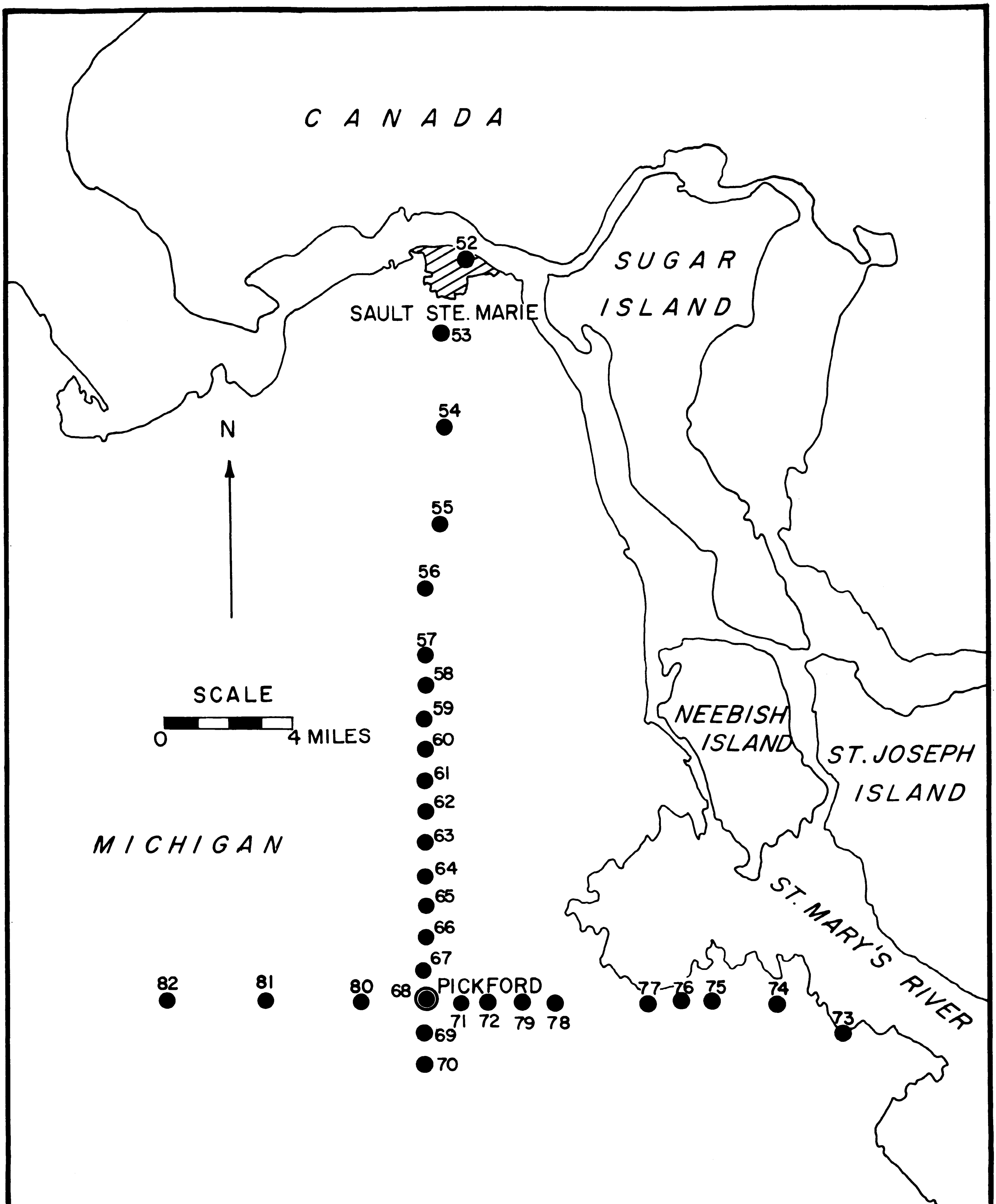
Model Studies

In order to further test the possibility of faulting as suggested by the magnetic data, gravity traverses were made by the author across zones of steep magnetic gradients. Figure 9 shows the location of gravity stations across the Pickford magnetic anomaly. Figure 10 consists of simple Bouguer values from Pickford north to Sault Ste. Marie. The low gravity values in the Sault Ste. Marie area may reflect the presence of a thick section of post-Portage Lake clastics.

The circled values in Figure 11 represent simple Bouguer values observed in an east-west direction across the Pickford magnetic anomaly. The steep east flank of the observed anomaly indicates a steep contact between two units of different density. This steep contact is considered to represent a high angle fault, while the less steeply dipping western flank of the anomaly is believed to be representative of westward dipping volcanics and resultant thickening of clastics to the west of the fault. In order to illustrate the plausibility of this interpretation, the gravity effect of the model of Figure 11 was computed by the method of Talwani and Ewing (1960). This model is intended to simulate volcanic flows of density 2.90 gm/cm in vertical contact with sandstone of density 2.30 gm/cm. The density of 2.90 is reported by Thiel (1956) as the average density of the Keweenawan volcanics; he reports a density of 2.30 for the Bayfield group group of sandstones which are considered by Oetking (1958) to be equivalent to the Jacobsville sandstone. An arbitrary depth of 1550 feet was used for the uppermost surface of the model; there is no geologic control for this estimate, with the exception that a well is reported to have been completed at a depth of 1500 feet in sandstone at Pickford (Vanlier and Deutsh, 1958). The similarity between the observed and computed gravity profiles (Fig. 11) indicates that a steep contact between volcanic flows and sandstone is one possible interpretation of the gravity anomaly.

In addition, three magnetic profiles were computed by the method of Heirtzler, et al. (1962) for the model used to approximate the observed gravity profile. Figure 12 shows a portion of the observed aeromagnetic profile MG together with three computed magnetic profiles. Profile 1 was computed using a direction of remanent magnetization determined by DuBois to be characteristic of the Keweenawan volcanics, and a magnitude of remanent and induced magnetization used by Bath to simulate observed profiles across Keweenawan volcanics southwest of Lake Superior. Profile 2 was computed using a susceptibility of 0.002 cgs given by Nettleton (1940, p. 202) as the probable average susceptibility of the most common igneous rocks. This value makes no provision for remanent magnetization. The third profile was computed using the magnitude of induced and remanent magnetization determined for the Keweenawan volcanics, but with a direction parallel to the present earth's field, as if the effect were totally of induction.

The profile computed from values of magnitude and direction of magnetization characteristic of the Keweenawan volcanics most nearly corresponds to the observed profile in magnitude. An obvious discrepancy exists



GRAVITY STATIONS PICKFORD ANOMALY

Figure 9.

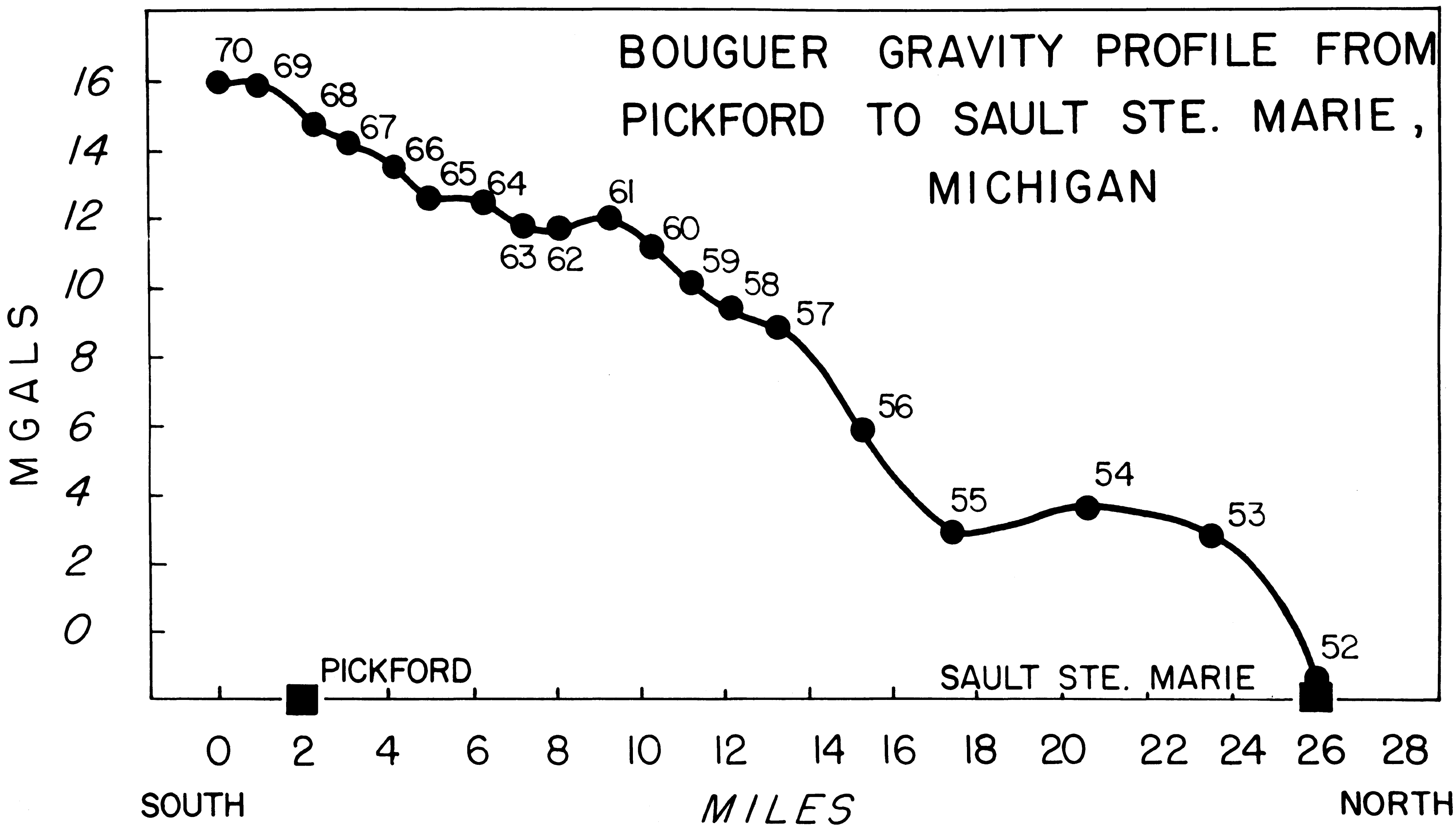

BOUGUER GRAVITY PROFILE FROM PICKFORD TO SAULT STE. MARIE, MICHIGAN
MGALS
16
14
12
10
8
6
4
2
0
70
69
68
67
66
65
64
63
62
61
60
59
58
57
56
55
54
53
52
PICKFORD
SAULT STE. MARIE
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
SOUTH
MILES
NORTH

Figure 10.

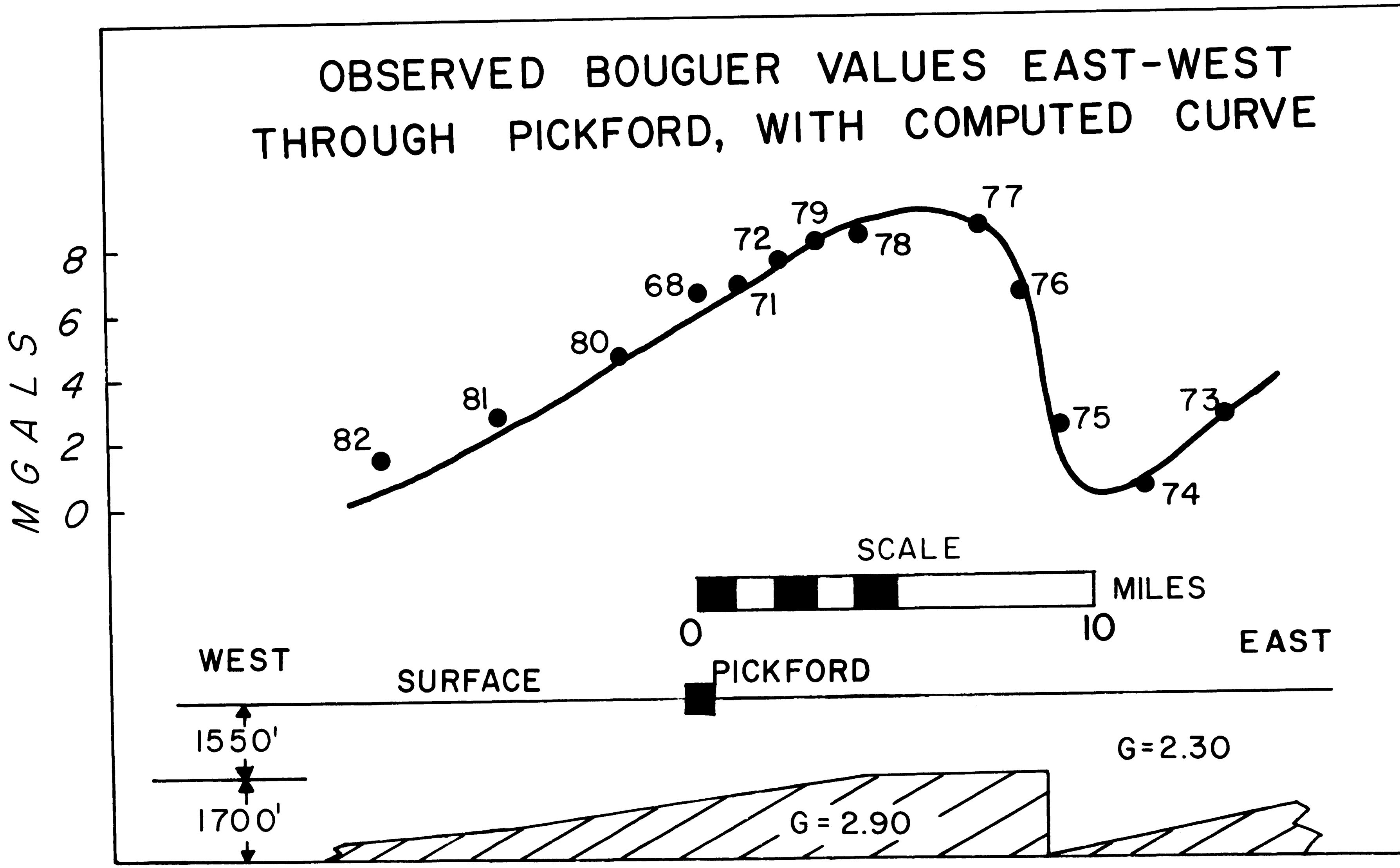

OBSERVED BOUGUER VALUES EAST-WEST
THROUGH PICKFORD, WITH COMPUTED CURVE
MGALS
0
2
4
6
8
82
81
80
68
71
72
79
78
77
76
75
73
74
SCALE
MILES
0
10
WEST
EAST
SURFACE
PICKFORD
1550'
1700'
G=2.30
G = 2.90

Figure 11.

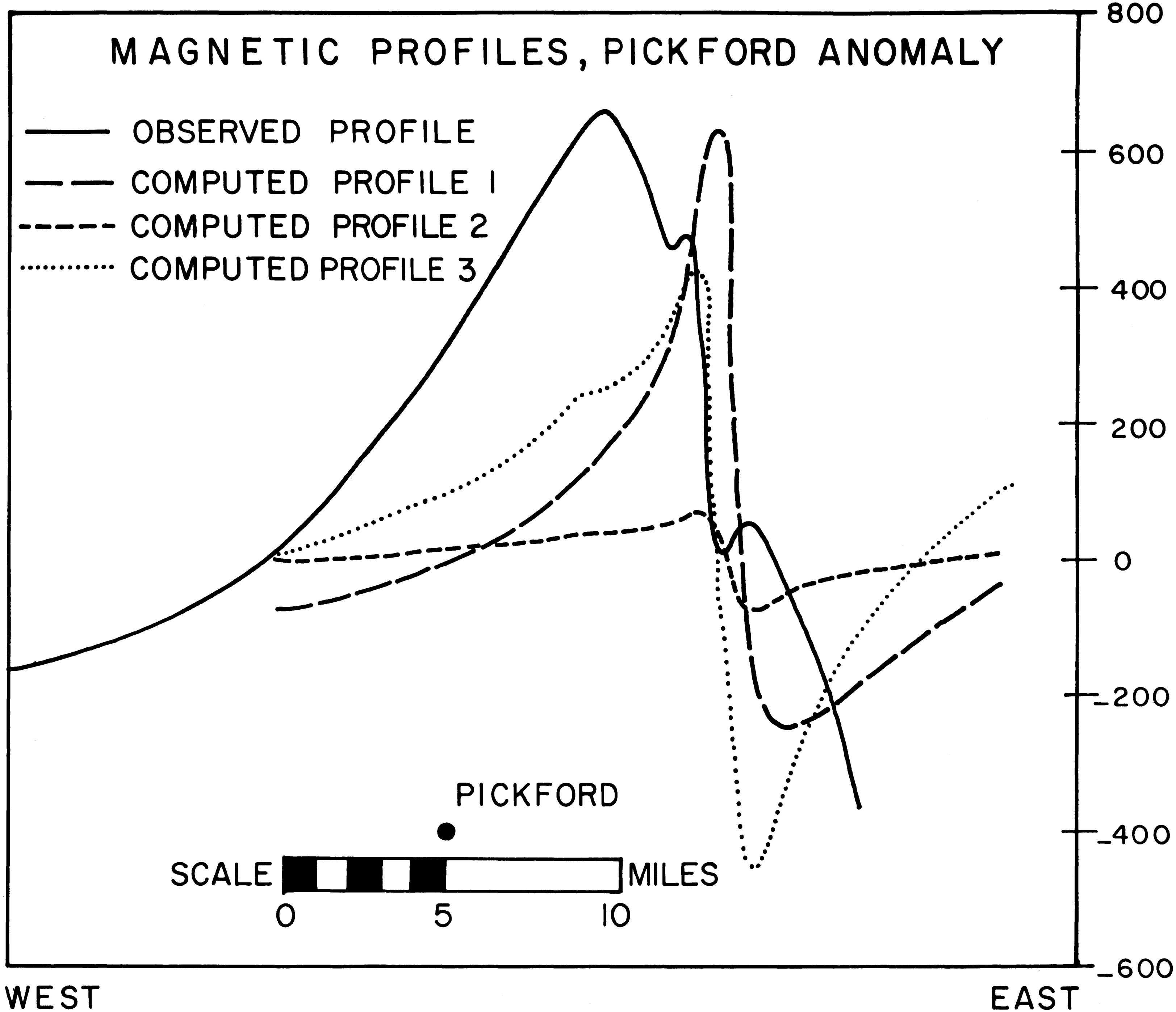

MAGNETIC PROFILES, PICKFORD ANOMALY
OBSERVED PROFILE
COMPUTED PROFILE 1
COMPUTED PROFILE 2
COMPUTED PROFILE 3
PICKFORD
SCALE
MILES
0
5
10
800
600
400
200
0
-200
-400
-600
GAMMAS
WEST
EAST

Figure 12.

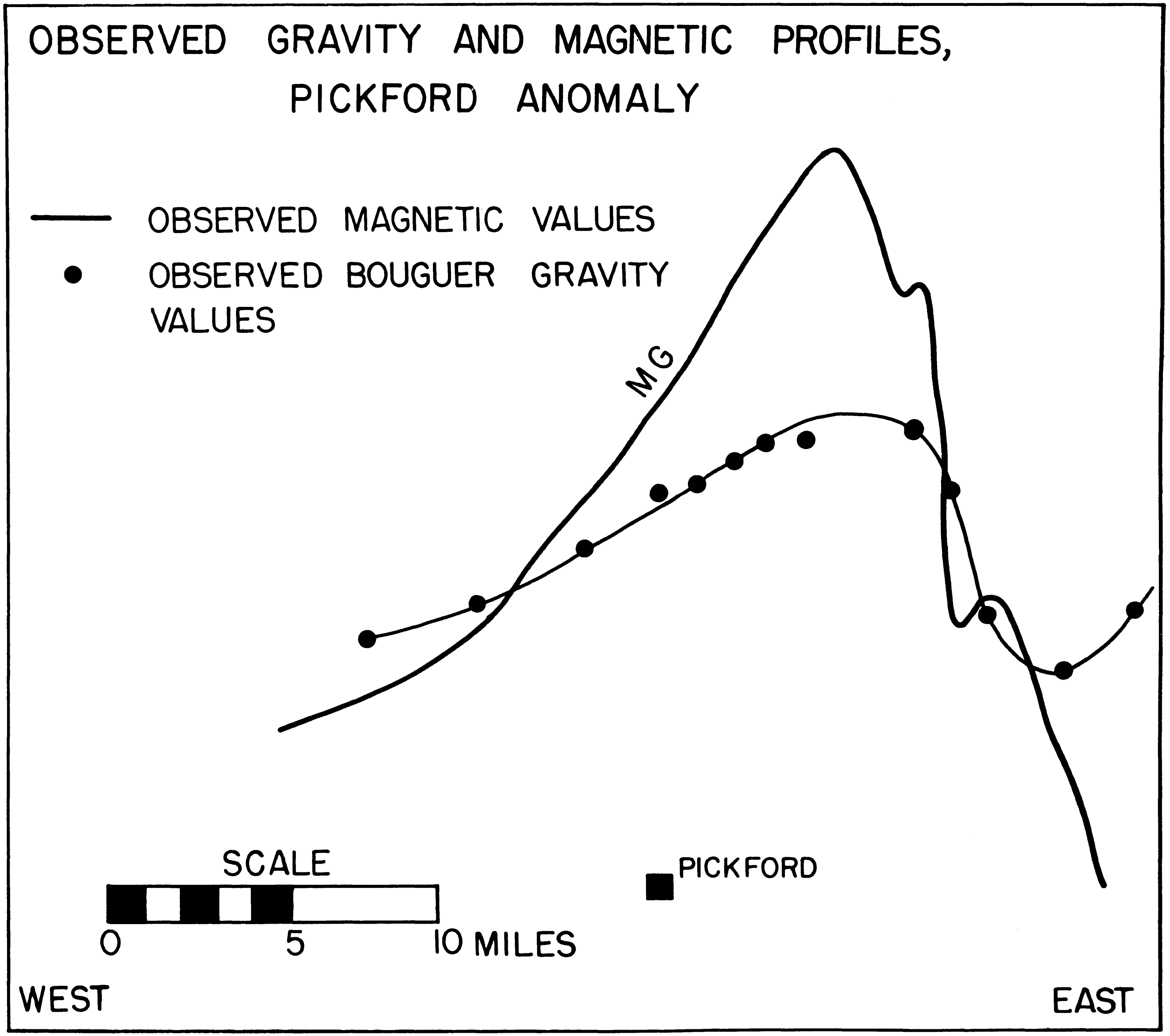

OBSERVED GRAVITY AND MAGNETIC PROFILES,
PICKFORD ANOMALY
OBSERVED MAGNETIC VALUES
OBSERVED BOUGUER GRAVITY VALUES
MG
SCALE
0
5
10 MILES
PICKFORD
WEST
EAST

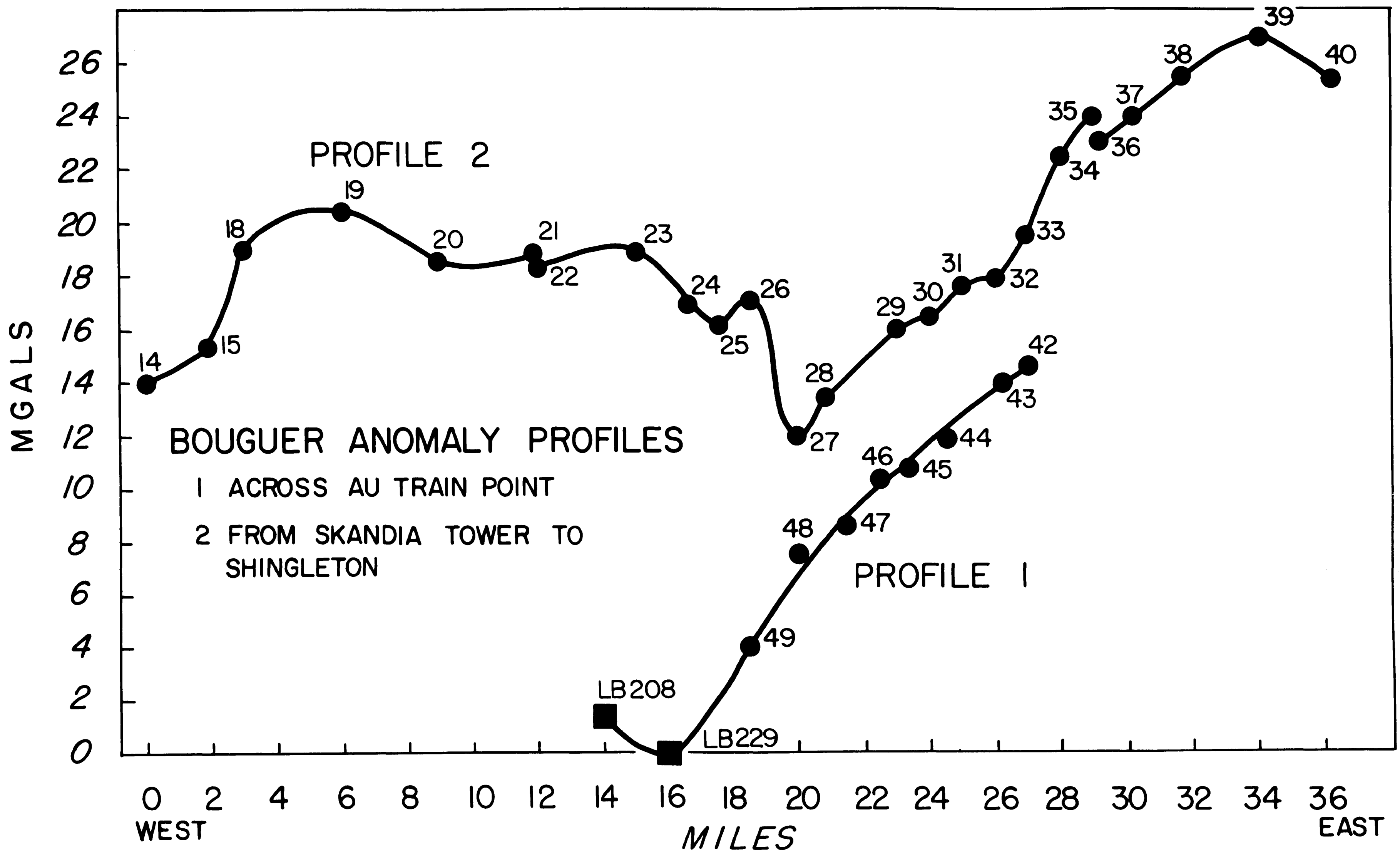
Figure 13.

in the relative width and position of the observed and computed profiles. Exact correspondence of observed magnetic data with magnetic data computed from the gravity model is unlikely, as the observed gravity values are assumed to result solely from the volcanic-clastic interface, and no assumption is made concerning the nature of the lower surface of the volcanics. The magnetic values could also be influenced by additional parameters, such as variations in magnetic characteristics within the flows or variation in attitude of the flows. To some extent, the position of the observed magnetic anomaly also does not exactly coincide with the position of the observed gravity anomaly (see Fig. 13). The computed magnetic profiles do suggest that a lithologic unit of anomalous positive magnetization, such as the magnetization characteristic of the Keweenawan volcanics, is required to produce the observed magnetic anomaly.

Figure 14 shows the plotted simple Bouguer gravity values obtained from two traverses across the Au Train magnetic anomaly. The location of the observations are shown in Figure 15. The two western-most observations of the northern or Au Train profile are from data taken under the direction of Professor Lyle D. Bacon of the Michigan College of Mining and Technology at Houghton. The southern or Shingleton profile is somewhat more irregular than the Au Train profile. This is partially due to the fact that the deployment of stations is not as linear as in the Au Train profile. The offset in the profile between stations 21 and 22 and between 35 and 36 is probably the result of north-south offsets of the stations in an area where the greatest gravity gradient is northeast. The smaller slopes of the Au Train and Shingleton profiles compared to the east-west Pickford profile indicate a less steep contact between units of different densities at Au Train than at Pickford. Figure 16 illustrates a model and the resulting computed gravity curve, together with the observed values of the Au Train traverse.

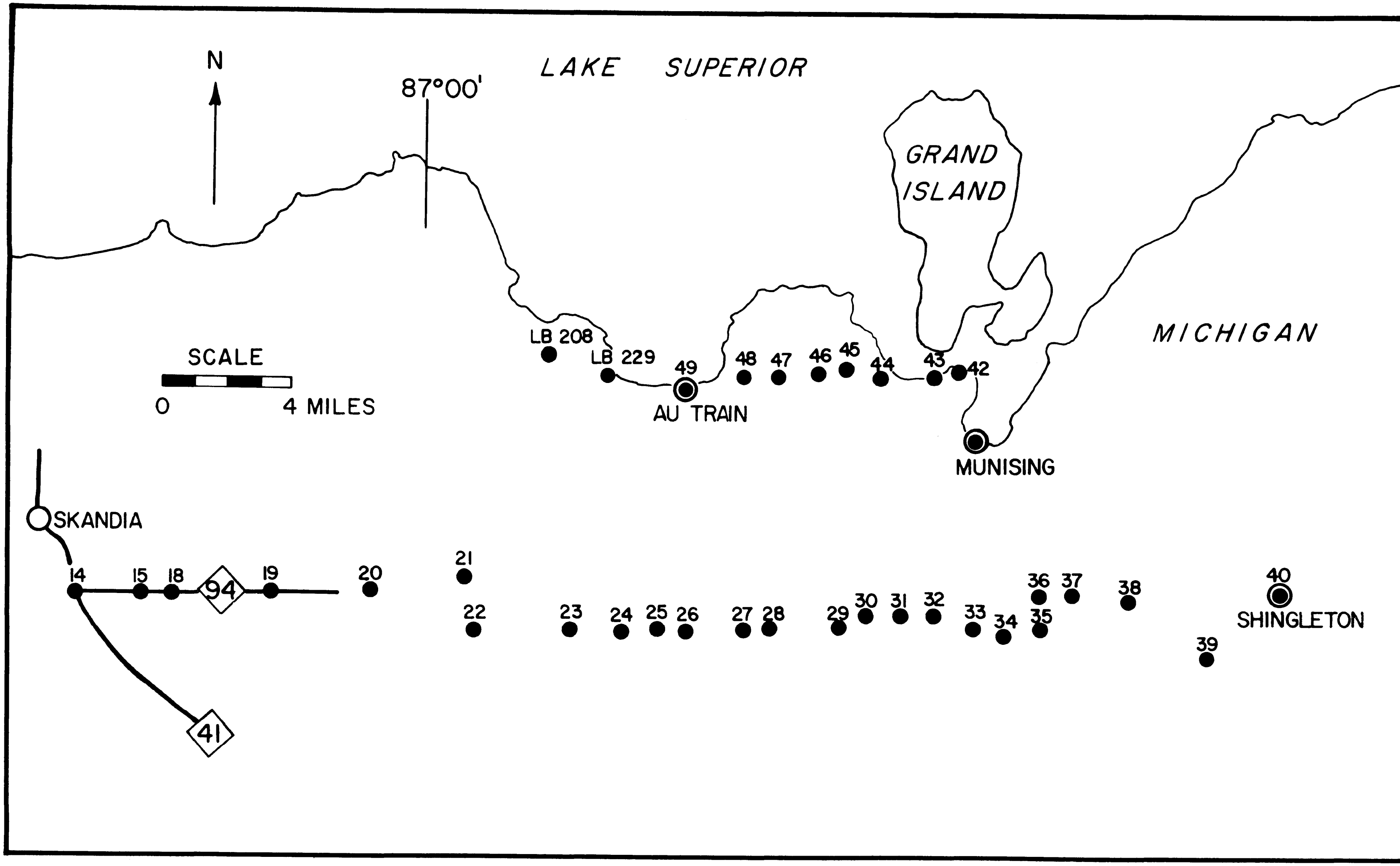
The relatively gently sloping contact suggested by the gravity data is not evidence for, or against, the presence of a fault. However, the author believes that this gently sloping contact may represent an eroded fault scarp. He further suggests that the structural features reported by Oetking (1951) and Hamblin (1958) in the vicinity of Au Train Point are ancillary to a major fault as indicated by the magnetic data, and evidence minor adjustment subsequent to the principal movement. This conclusion is similar to that of Irving and Chamberlin (1885, p. 106) concerning the relationship of the Keweenawan volcanics and the Eastern (Jacobsville) sandstone of Keweenaw Point. "Our chief conclusions are as follows: That the Keweenawan Series is much older than the Eastern Sandstone; that it was upturned, faulted along the escarpment, and much eroded before the deposition of the Eastern Sandstone; that the latter was laid down uncomformably against and upon the former, and that subsequently minor faulting along the old line ensued, disturbing the contact of the sandstone."

Three magnetic profiles (Fig. 17) were also computed for the model used to approximate the observed Au Train gravity values. The computed Au Train magnetic profiles correspond, in regard to values of magnetization used for their computation, to the computed Pickford profiles of



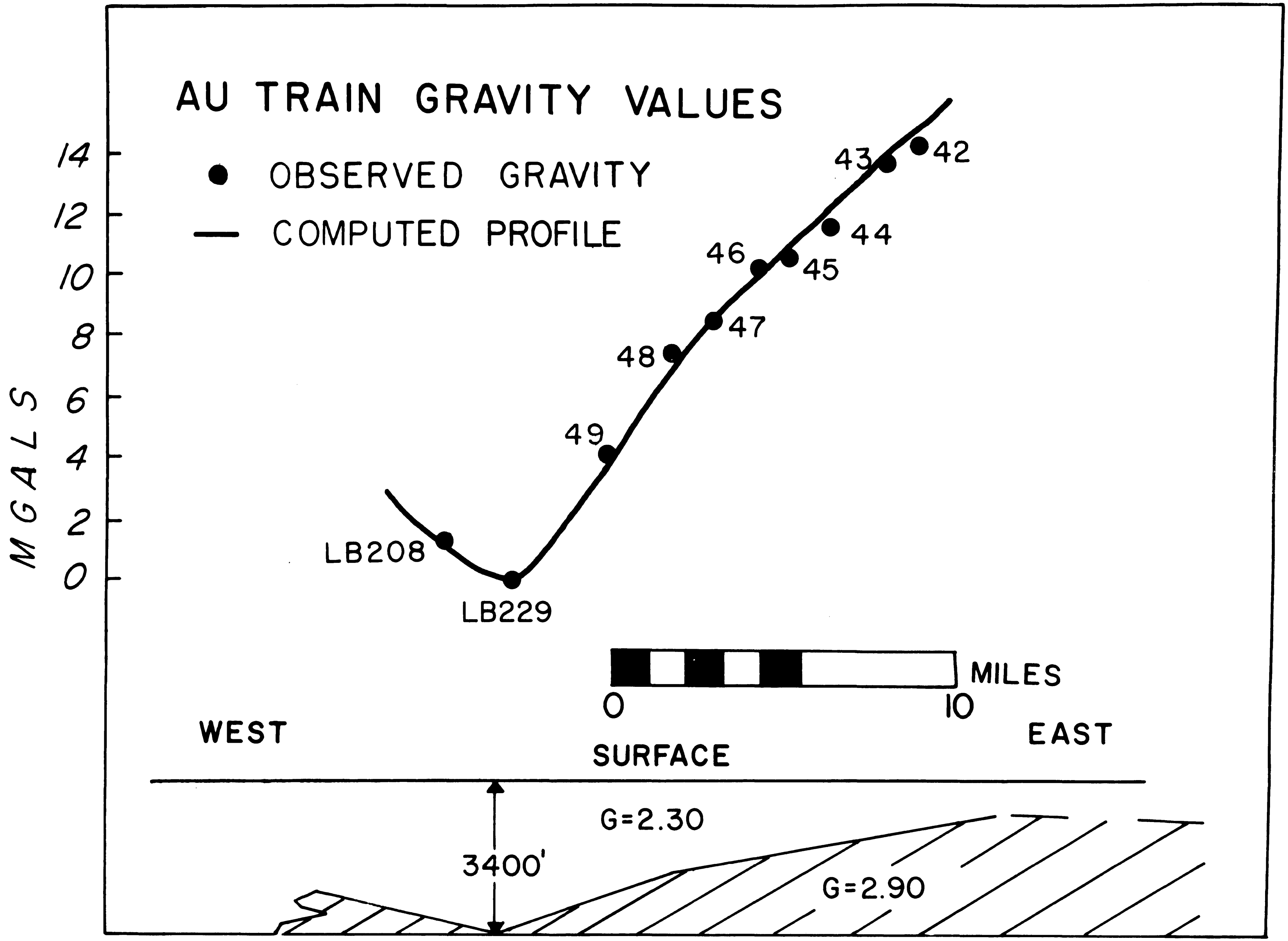
PROFILE 2
PROFILE 1
BOUGUER ANOMALY PROFILES
1 ACROSS AU TRAIN POINT
2 FROM SKANDIA TOWER TO SHINGLETON
MGALS
MILES
WEST
EAST
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36
0 2 4 6 8 10 12 14 16 18 20 22 24 26
14 15 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40
42 43 44 45 46 47 48 49
LB208
LB229

Figure 14.



GRAVITY STATIONS AU TRAIN ANOMALY

Figure 15.



AU TRAIN GRAVITY VALUES
OBSERVED GRAVITY
COMPUTED PROFILE
MGALS
14
12
10
8
6
4
2
0
42
43
44
45
46
47
48
49
LB208
LB229
MILES
0
10
WEST
EAST
SURFACE
G=2.30
3400'
G=2.90

Figure 16.

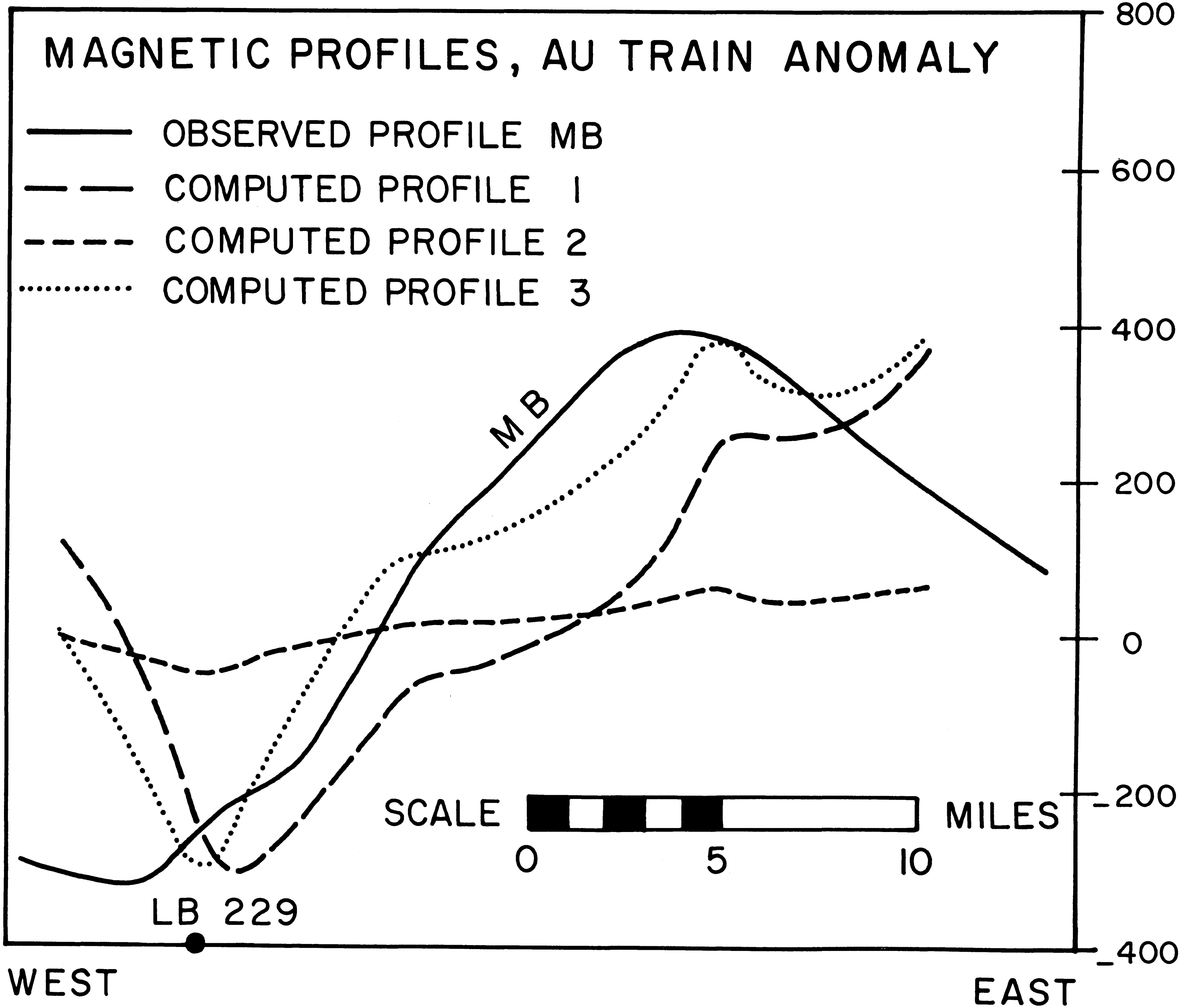

MAGNETIC PROFILES, AU TRAIN ANOMALY
OBSERVED PROFILE MB
COMPUTED PROFILE 1
COMPUTED PROFILE 2
COMPUTED PROFILE 3
MB
SCALE
MILES
0
5
10
LB 229
WEST
EAST
800
600
400
200
0
-200
-400
GAMMAS

Figure 17.

identical number. As in the case of the Pickford profiles, the Au Train profiles computed using a magnitude of magnetization characteristic of the Keweenawan volcanics approximate the observed magnetic profile in magnitude, but do not correspond closely in shape. In this case the result is not inconsistent with information concerning the nature of the Keweenaw fault, which is characterized by steep dips in the Keweenawan volcanics adjacent to the fault. If the original attitude of a body possessing remanent magnetization were changed, the magnetic anomaly over the body would be altered in shape and magnitude. Calculation of the resultant anomaly would require that the new relative direction of remanent magnetization be considered. This calculation is difficult if the body is significantly curved or warped. In addition, exact correspondence between one of the computed magnetic profiles and the observed profile is unlikely, as the Au Train gravity profile from which the model was derived is located one to two miles north of aeromagnetic profile MB.

CONCLUSIONS

The magnetic and gravity data presented here support the interpretation of Irving (1883) and in particular the interpretation of Thwaites (1935) concerning the composition, configuration and structure of the crystalline basement of eastern Upper Michigan.

Specifically the conclusions are:

(1) Keweenawan volcanic flows exist east of a line from Au Train Bay to Seul Choix Point, extending to the eastern limit of the peninsula.

(2) A fault of major proportions exists in the vicinity of Au Train Point that either constitutes a southern extension of the Keweenawan fault or is genetically related to the Keweenaw fault.

(3) A high angle fault occurs in the southeastern part of the peninsula, about eight miles east of Pickford, which may also be related to the Keweenaw fault system.

PART II

GEOLOGIC SETTING AND DISCUSSION OF RESULTS, LOWER MICHIGAN

Physiography of the Central Portion of the Lower Peninsula of Michigan

A broad, featureless, lobate-shaped till plain with an elevation of 600 to 800 feet above sea level extends southwest from Saginaw Bay. This plain, which extends westward to the vicinity of Mt. Pleasant (Fig. 18), is the result of the deposition of ground moraine and lake clays in late Pleistocene time. Beyond the till plain to the west and south, the survey area is characterized by poorly integrated drainage and more variable topography, with elevations of 800 to more than 1300 feet above sea level, resulting from arcs of recessional moraine and intervening outwash plain concave to Saginaw Bay. The physiography of the western margin of this survey reflects the influence of a Lake Michigan glacial lobe by an incipient arcuation of moraine towards the west.

Regional Geology of the Michigan Basin

The Michigan structural and sedimentary basin consists of a roughly circular depression approximately 400 miles in diameter, with the base of the Paleozoic sediments estimated by stratigraphic methods to be 14,000 feet beneath the surface in the central part of Michigan's Lower Peninsula, west of Saginaw Bay (Cohee and Landes, 1955; Pirtle, 1932). No wells have penetrated formations of Precambrian age in this central area. The preponderance of Paleozoic sediments in the Michigan Basin are of Cambrian, Ordivician and Silurian age. The remainder is mostly Devonian, but also includes Mississippian and Pennsylvanian and possibly some formations of Permian age. Overlying glacial drift, reported locally to be in excess of one thousand feet thick, is believed to cover the Lower Peninsula of Michigan more deeply than any other section of the United States (Ver Wiebe, 1957; Eardly, 1951).

The Michigan Basin is bordered on the west by the Wisconsin arch in central Wisconsin, to the south by the Kankakee arch in northern Indiana and northeastern Illinois and by the Findlay arch in northwestern Ohio, while to the east it terminates with the Algonkian axis of Ontario. To the north, it appears to terminate with the arc of lower Paleozoic formations that constitute the pre-glacial surface of the eastern end of the Northern Peninsula of Michigan, although the possibility of a connection through this area with the eastern Lake Superior basin has been suggested (Pirtle, 1932; Thwaites, 1935). Northwest-southeast trending folds occur in the southeastern, central and northeastern parts of the central basin area. Newcombe (1932) has suggested that these folds are related to deep seated faults in the basement complex.

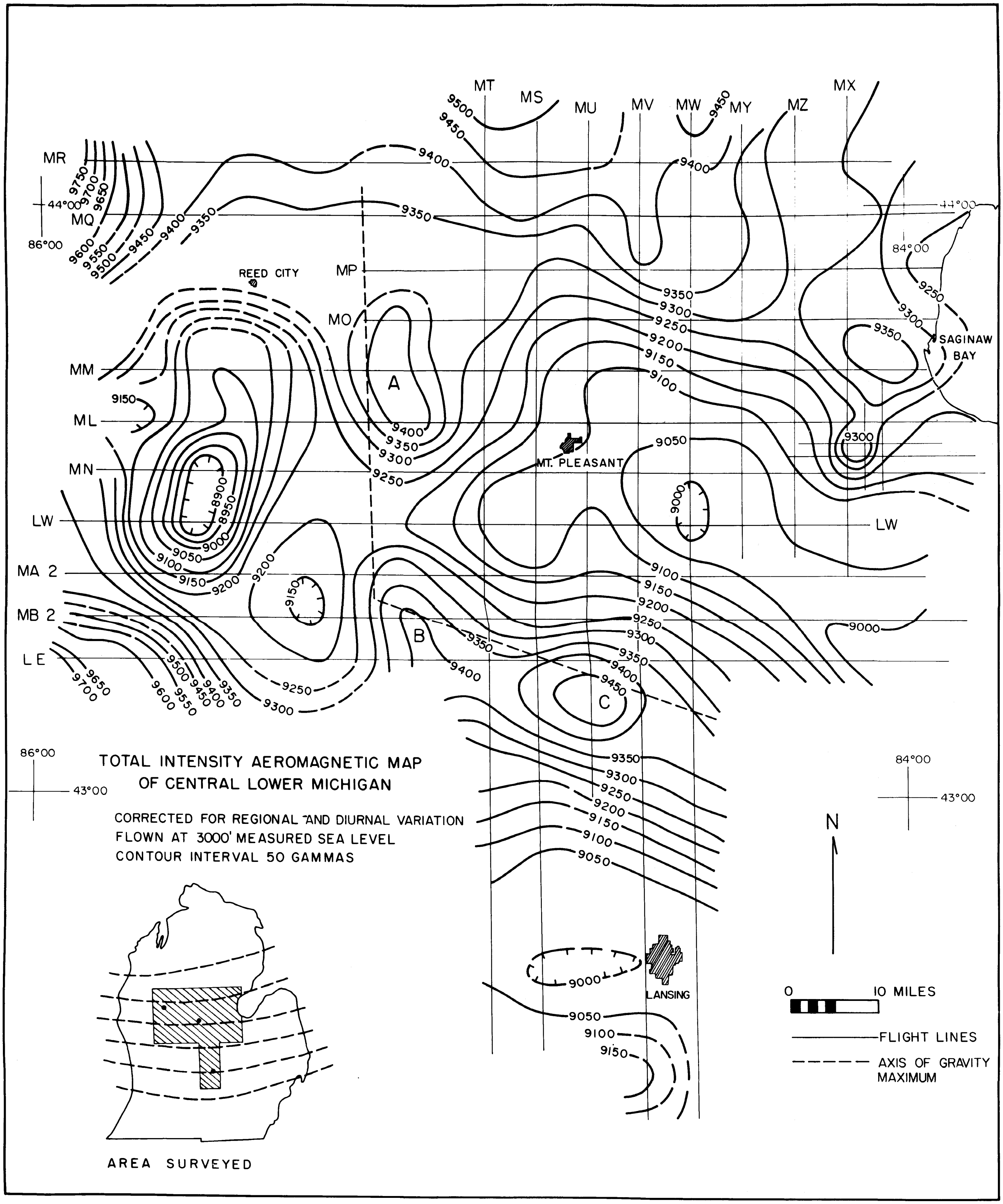

TOTAL INTENSITY AEROMAGNETIC MAP
OF CENTRAL LOWER MICHIGAN
CORRECTED FOR REGIONAL AND DIURNAL VARIATION
FLOWN AT 3000' MEASURED SEA LEVEL
CONTOUR INTERVAL 50 GAMMAS
AREA SURVEYED
0
10 MILES
FLIGHT LINES
AXIS OF GRAVITY MAXIMUM
N
REED CITY
MT. PLEASANT
LANSING
SAGINAW BAY
A
B
C
86°00
84°00
44°00
43°00
MR
MQ
MP
MO
MM
ML
MN
LW
MA 2
MB 2
LE
MT
MS
MU
MV
MW
MY
MZ
MX

Figure 13.

Discussion of Results

Figure 18 is a total intensity aeromagnetic map of central Lower Michigan. This portion of the survey consists of 1600 miles of aeromagnetic data, from which a regional magnetic gradient of 3.2 gammas per mile to the north has been removed. The purpose of this survey was to furnish an estimation of depth to crystalline basement. Flight lines were flown in a grid pattern over the deeper part of the basin in order to afford two dimensional control for the determination of shape and amplitude of anomalies.

Unfortunately, the magnetic pattern is characterized by generally small magnetic gradients and lack of well defined anomalies. An exception to this generalization is the small circular anomaly about ten miles southwest of Saginaw Bay. This anomaly was reflown at the close spacing indicated in Figure 18 in order to achieve a more accurate estimate of its configuration. After removal of a local magnetic gradient, treatment of this anomaly by a method developed for use on circular total intensity anomalies (Henderson and Zietz, 1948) resulted in a depth estimation to magnetic source of about 14,700 feet below surface, or about 14,000 feet below sea level. This anomaly is located about ten miles west-southwest of the Bateson #1 well of the Gulf Refining Company located in section 2, T4IN, R4E and drilled to 10,447 feet in Cambro-Ordovician sediments (Cohee and Landes, 1955). The anomaly is also located about thirty miles southeast of the area which Cohee estimates to be the center of the Michigan basin, where Paleozoic sediment are estimated to extend to 14,000 feet below the surface.

The magnetic maxima labeled A, B and C, together with the saddlelike depression in the contour between maxima A and B, appear to be components of a linear zone of relatively positive magnetic values that is flanked by zones of low magnetic values. The linear zone of positive magnetic values is nearly coincident with a similarly linear zone of relatively positive gravity values (Fig. 19 after Woollard and Rose, 1963, p. 362) in the region where the axis of the gravity anomaly changes in direction from north-south to east-southeast in the west central part of the state. Where this positive gravity feature assumes a more southeasterly direction, it coincides with the trace of the Howell anticline, the major structural feature known in the southern peninsula of Michigan. The northern extension of this positive gravity feature approaches Lake Michigan slightly to the east of Grand Traverse Bay, across Lake Michigan from Seul Choix Point. This linear gravity feature has a marked resemblance to the mid-continent gravity high that extends from northwestern Wisconsin to north central Kansas (Bacon, 1956). The characteristic association of high density and large apparent polarization, together with the northern direction of the linear gravity high toward the postulated volcanics between Marquette and Sault Ste. Marie, suggests that this feature may reflect an extension of Keweenawan volcanics into Lower Michigan. The linear positive gravity and magnetic features suggest the presence of a horst-root system in Lower Michigan similar to structure postulated to explain the origin of the mid-continent gravity high (Thiel, 1956; Craddock, 1963).

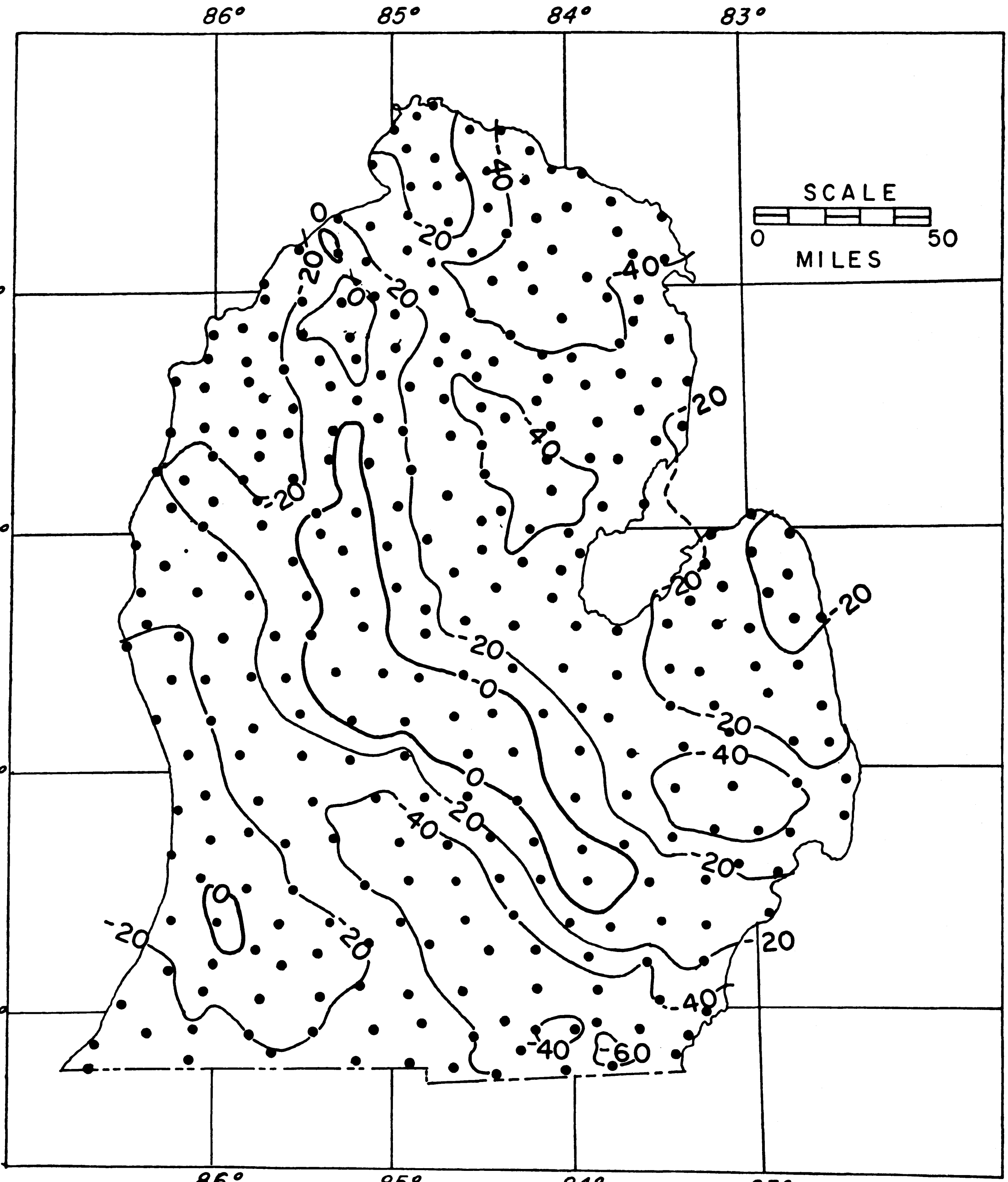


Figure 19.

By analogy with the mid-continent gravity high, the gently developed zones of low magnetic values flanking the magnetic maximum to the north and south may reflect loci of accumulation of Upper Keweenawan clastic sediments comparable to the Oronto-Bayfield group of Northern Wisconsin. If this is in fact the situation, the greatest depth to crystalline basement would probably be near the center of the zone of low values southeast of Mt. Pleasant, and would not necessarily coincide with the greatest thickness of Paleozoic sediments which Cohee estimates to be about thirty miles to the north.

A strongly developed negative magnetic anomaly exists west of the saddle between anomalies A and B. A negative magnetic anomaly in high latitude is the result of a body having a permanent magnetization, such as thermo-remanent or depositional magnetization, that is greater in magnitude than the induced magnetization and that has an orientation such that the resultant of the permanent and induced magnetization is subtractive from the total magnetic field of the earth. This phenomena is often associated with rock masses of high density such as iron formation (Bath and Schwartz, 1960) and basic igneous intrusives containing intergrowths of iron and titanium oxides (Moyd, 1957). Negative magnetic anomalies originating with iron-titanium intergrowths in metamorphic rocks have also been studied (Balsley and Buddingham, 1956). Evidence of reversely magnetized basement material has been reported near the southern margin of Lower Michigan by Hinze (1963). This negative magnetic anomaly corresponds in location to the west flank of the linear positive gravity feature, though there is no evidence in the regional gravity map of a locally coincident gravity anomaly. The negative magnetic anomaly may originate with a lithologic unit of small horizontal dimensions such that any gravitational expression remaining at the surface of observation may have been overlooked as a result of the regional nature of the gravity survey.

The proximity of this negative anomaly to the gravity and magnetic maxima to the east suggests the additional possibility that the negative anomaly may originate with structurally disturbed volcanic flows peripheral to the locus of greatest volcanic accumulation. If Keweenawan volcanic flows having a strong thermo-remanent magnetization with an undisturbed inclination of 41° to the west-northwest were tilted sufficiently, an increasingly negative anomaly would develop with increase of inclination of the negative pole above the horizontal.

Part III

THE BEAVER ISLAND AEROMAGNETIC PROFILE

Discussion of Results

In the hope of obtaining information to assist in the interpretation of the two Michigan aeromagnetic surveys reported here, a single aeromagnetic profile (Fig. 20) was obtained from Seul Choix point in Upper Michigan southeast to Beaver Island, and then east across the northern tip of Lower Michigan to Lake Huron (Fig. 21). Results were inconclusive. The Beaver Island aeromagnetic profile is much more smooth than the western portion of the Upper Michigan profiles obtained over Huronian formations near Marquette, but is less smooth than that portion of the profiles obtained over inferred structurally undisturbed volcanic flows. The profile is similar in character to the eastern end of the Northern profiles where it is difficult to distinguish between inferred structurally disturbed basic flows south of Sault Ste. Marie and the Huronian formations exposed further east in Canada. The positive anomaly at the east end of the Beaver Island profile coincides with the position of the projected trace of the Pickford magnetic anomaly which is thirty miles to the north, suggesting the possibility that the Pickford fault may continue south into Lower Michigan.

Recent drilling indicates the presence of a Precambrian basement of granitic composition beneath Beaver Island, which is located between the postulated volcanic flows of Upper Michigan and the gravity-magnetic high of Lower Michigan. The log of one of two wells drilled into the Precambrian formations indicates that sixty four feet of weathered granite was penetrated beneath twenty one feet of Precambrian sand, with the base of the Paleozoic section indicated at about 4600 feet below lake level. The log of the second well indicates the base of the Paleozoic section to be about 4500 feet below lake level. Eight hundred and seventeen feet of Precambrian sandstone is reported beneath the Paleozoic section in this well, with no penetration of crystalline rock reported. These wells are about five miles apart. The drill logs describe the Precambrian sandstone as multicolored, arkosic, frequently conglomeritic, and as containing occasional rhyolite grains. This description is similar to the description of the Oronto-Bayfield group of Upper Keweenawan age (Thwaites, 1912) which is characteristically found associated with Keweenawan volcanics. The identification of weathered granite may have resulted from mis-identification of arkosic Upper Keweenawan sediment in the cuttings. The mis-identification of Upper Keweenawan sands as granite in well cuttings from wells in proximity to the mid-continent gravity high is discussed by Craddock et al.(1963).

The presence of a crystalline basement of granitic composition at Beaver Island would not negate the possibility of Keweenawan volcanics extending from Lake Superior through the Michigan basin, as many occurrences of acidic rock are known associated with Keweenawan basic extrusives and

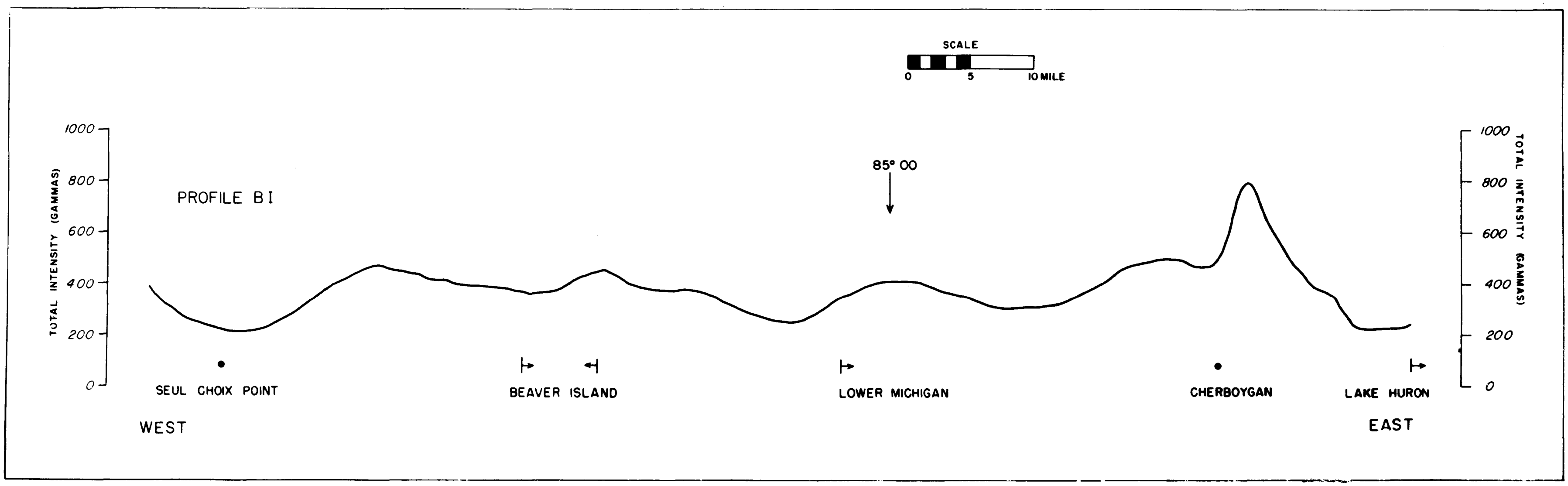

SCALE
0
5
10 MILE
1000
800
600
400
200
0
TOTAL INTENSITY (GAMMAS)
PROFILE B I
85° 00
SEUL CHOIX POINT
BEAVER ISLAND
LOWER MICHIGAN
CHERBOYGAN
LAKE HURON
WEST
EAST

Figure 20.

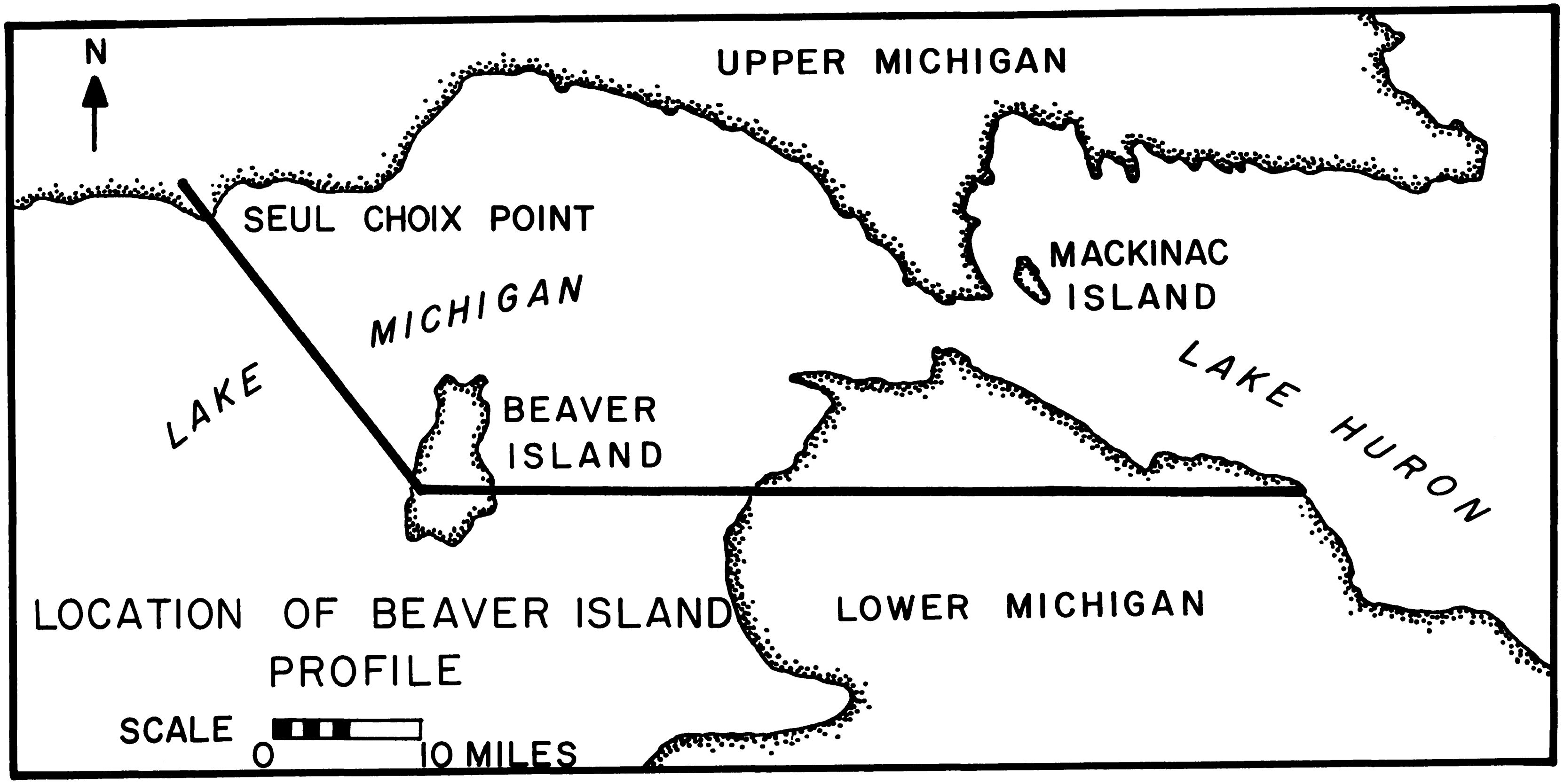

N
UPPER MICHIGAN
SEUL CHOIX POINT
LAKE MICHIGAN
MACKINAC ISLAND
BEAVER ISLAND
LAKE HURON
LOWER MICHIGAN
LOCATION OF BEAVER ISLAND PROFILE
SCALE
0
10 MILES

Figure 21.

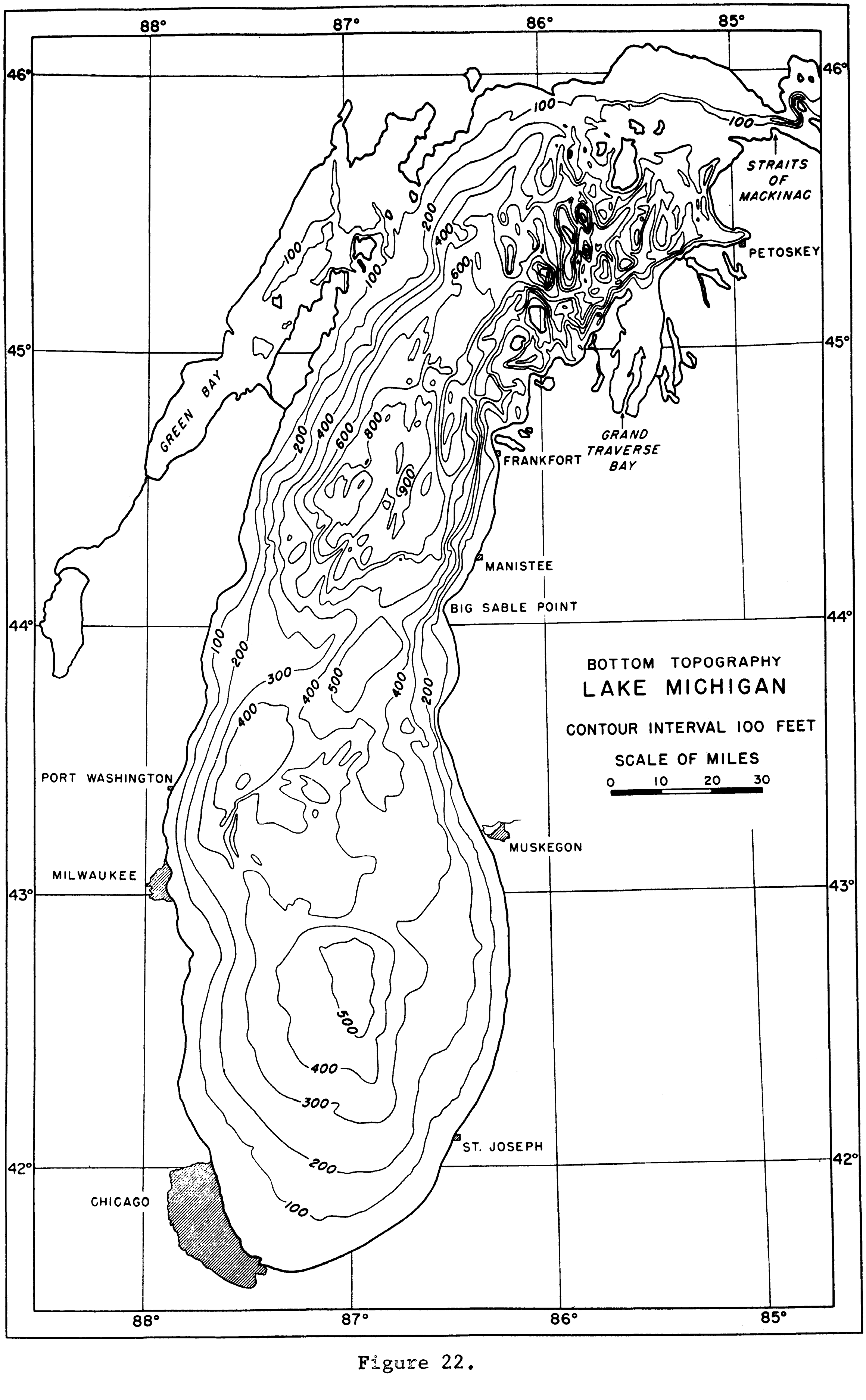

BOTTOM TOPOGRAPHY
LAKE MICHIGAN
CONTOUR INTERVAL 100 FEET
SCALE OF MILES
0 10 20 30
GREEN BAY
STRAITS OF MACKINAC
PETOSKEY
GRAND TRAVERSE BAY
FRANKFORT
MANISTEE
BIG SABLE POINT
PORT WASHINGTON
MILWAUKEE
MUSKEGON
ST. JOSEPH
CHICAGO
88°
87°
86°
85°
46°
45°
44°
43°
42°
100
200
300
400
500
600
800
900

Figure 22.

intrusives; the granophyre associated with the Duluth gabbro, the Mellon granite of northern Wisconsin, and the acidic rocks of Mt. Houghton and Mt. Bohemia on the Keweenawan Peninsula are examples.

South of Seul Choix Point the bottom topography of Lake Michigan is locally anomalous by virtue of the presence of pronounced north-south trending structures, some of which project above the Lake surface as islands (Fig. 22, after Hough, 1958). Lake Michigan and Lake Huron coincide with the margin of the Salina formation of Silurian age, which is characterized by the presence of extensive salt members. It has been suggested by Hindshaw (as reported by Smith, 1914) that these lake depressions resulted in part from the solution of salt in the periphery of the Salina formation, in areas where the salt was sufficiently close to the surface to be dissolved by circulating ground water. In many areas of Ohio and Michigan, solution of the Salina salt has resulted in brecciation and collapse of the overlying formations.

Seul Choix point marks the trace of the magnetic anomaly correlated with the southern extension of the Keweenawan fault in Part I of this report, and it is also the locus of structure in the Niagara dolomite, the formation which underlies the Salina formation. This suggests the possibility, however remote, that recurrent movement along zones of weakness established in Keweenawan time may have localized solution of Salina salt in the northern part of the Michigan basin, resulting in the subsequent collapse of the overlying formations with development of a north-south lineation in the bottom topography of northern Lake Michigan. The north-south orientation of Grand Traverse Bay and adjacent lakes may also reflect a similar structural control.

PART IV

GEOLOGIC SETTING AND DISCUSSION OF RESULTS, SOUTHEASTERN ILLINOIS

Physiography of Southeastern Illinois

The area included in the aeromagnetic survey of southeastern Illinois consists of two distinct physiographic provinces. To the north of Harrisburg (Fig. 23) the land surface is relatively level and slopes gently southward. The elevation of the northern part of the survey area averages about six hundred feet above sea level, while in the vicinity of Harrisburg the elevation averages close to four hundred feet above sea level. This surface is developed on glacial outwash and moraine correlated with the Illinoisan stage of the Pleistocene epoch. To the south of Harrisburg the topography becomes more irregular, with development of a prominent east-west trending ridge and smaller hills and valleys. Elevation varies from less than five hundred to slightly greater than one thousand feet above sea level. This irregular topography is believed to be the result of block faulting of post-Pennsylvanian, pre-Cretaceous age.

Geology of the Illinois Basin

The Illinois basin is an elongate northwest-southeast trending structure, measuring about five hundred miles in length and three hundred fifty miles in width, and located in central and southeastern Illinois and adjacent parts of Kentucky and Indiana. It is considered to have originally been part of a larger structure which also included the Michigan basin. The Michigan and Illinois basin are considered to have begun to separate im Ordovician time by development of the Kankakee arch in northeastern Illinois and northern Indiana. The northeast margin of the Illinois basin was further restricted about Pennsylvanian time by development of the La Salle anticlinal belt which extends over two hundred miles from north central to southeastern Illinois. The Illinois basin is bordered on the north by the Wisconsin arch and on the west by the Ozark dome of Missouri and the Mississippi River arch of northwestern Illinois and Iowa. The western part of the basin shallows rapidly over the north-south trending Du Quoin monocline of south central Illinois. To the east of the basin is the Cincinnati arch of Kentucky and Tennessee, while to the south the relationship of the Illinois basin to the east-west trending Moorman syncline of western Kentucky is obscured by the Rough Creek-Shawneetown fault zone that extends along the Kentucky-Illinois border. The southern termination of the basin is further obscurred by a Cretaceous overlap, associated with the Mississippi embayment which covers the southern tip of the state.

The Paleozoic section of the Illinois basin is represented by sediments of Upper Cambrian through Pennsylvanian age. The basin is estimated to be 12,000 to 14,000 feet deep at the center (Swann and Bell, 1958)

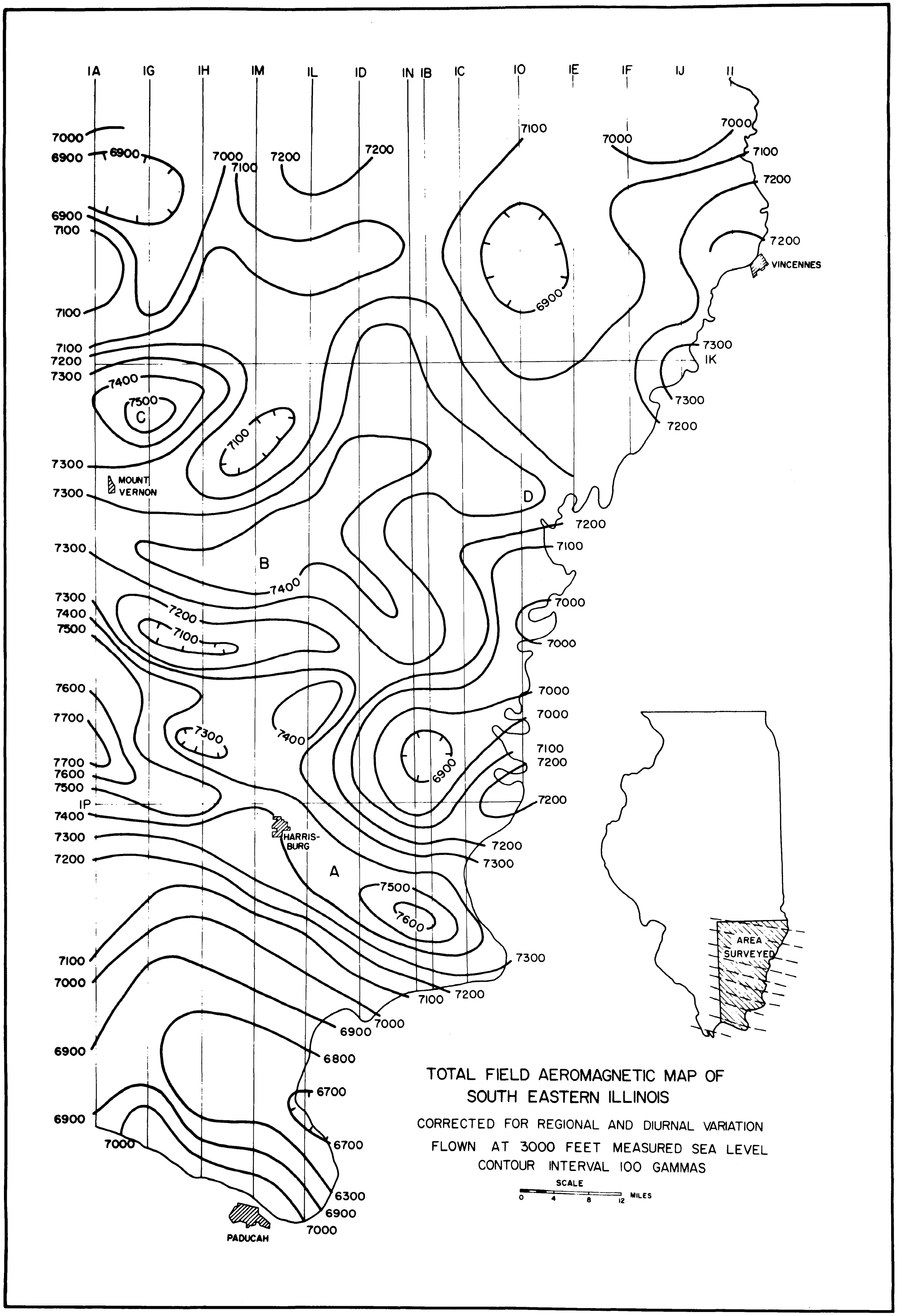

TOTAL FIELD AEROMAGNETIC MAP OF SOUTH EASTERN ILLINOIS
CORRECTED FOR REGIONAL AND DIURNAL VARIATION
FLOWN AT 3000 FEET MEASURED SEA LEVEL
CONTOUR INTERVAL 100 GAMMAS
SCALE
0 4 8 12 MILES
VINCENNES
MOUNT VERNON
HARRISBURG
PADUCAH
AREA SURVEYED
IA IG IH IM IL ID IN IB IC IO IE IF IJ II
IK
IP
A
B
C
D

Figure 23.

which is thought to be in Wayne, White and Hamilton counties (Eardly, 1951). This location generally corresponds to the central part of the survey, extending north from Harrisburg to slightly south of a line west from Vincennes.

Examples of widespread intrusion of basic igneous rock are present in the southeastern part of the Illinois basin. Northwest striking basic dikes and faults have been encountered while mining and drilling for coal in the vicinity of Harrisburg, Illinois (Clegg and Bradbury, 1956). A few sills have also been reported. The dikes are generally only a few feet in width, but one occurrence three hundred feet wide is known. The dikes and sills have been highly altered and are extensively weathered where they are recognized at the surface.

Basic igneous rock has also been encountered in scattered locations northeast and east of Harrisburg while drilling for oil. At one locality basic igneous rock was reported in about a dozen wells drilled on a structure known as the Omaha dome, about ten miles northeast of Harrisburg. Another dome shaped structure known as Hicks dome occurs about fifteen miles southeast of Harrisburg, near several occurrences of basic dikes encountered in fluorite prospects. Two wells drilled to several thousand feet on this structure failed to encounter igneous rock. Hicks dome is located near the northern terminus of the Illinois fluorspar district, which is part of an oval-shaped area extending from southeastern Illinois, south eastward into western Kentucky. Northwest trending basic dikes occur at several locations in the Illinois fluorspar district, together with structures interpreted as diatremes. Basic intrusives are locally common at the east side of the small peninsula that coincides with the southern extremity of profile ID, and are known also to occur to the southeast in Kentucky (Warren, 1956).

The emplacement of the basic igneous rock and the fluroite mineralization appear to represent two separate time intervals. The fluorite mineralization, which usually occurs as fissure fillings, is associated with faults striking northeastward, at right angles to the strike of the basic dikes. These faults are part of the Rough Creek-Shawneetown fault system.

No basic dikes are known for an interval of about twelve miles between Harrisburg, on the southern margin of the coal basin, and Hicks dome, on the northern margin of the fluroite district. This is attributed to the very weathered nature of the dikes in outcrop and the absence of mining in this area (Clegg and Bradbury, 1956).

Koening (1956) has suggested that the basic intrusives and fluorspar mineralization are genetically related, that the dikes were emplaced in tension fractures developed as a result of doming over a magma reservoir, and that the fluorite was subsequently deposited in fissures developed as a result of collapse of the dome by widespread block faulting.

Discussion of Results

Figure 23 is a total intensity aeromagnetic map of southeastern Illinois, from which a regional magnetic gradient of 1-1/2 gammas per mile to the east and 6-2/3 gammas per mile to the north has been removed. As a result of the elongate nature of the area surveyed, the flight lines are north-south, with the exception of two east-west lines. This results in less control over anomaly configuration than afforded by the grid system used in the central parts of the Michigan surveys; for this reason the magnetic map is contoured at one hundred gamma intervals, rather than the fifty gamma interval used to contour the Michigan data. North-south flight lines are at six mile intervals, with the exception of line IN and IB at an interval of two miles and lines IB and IC at a four mile interval. The Illinois aeromagnetic map shows a range of values and a variability of pattern that suggest the presence of a crystalline basement of heterogeneous lithology at depth.

A linear positive anomaly (labeled A) extends northwest-southeast through the vicinity of Harrisburg. The location of this anomaly approximates the median position of the known occurrences of basic igneous rock in this area, and in addition parallels the average strike of the basic dikes and associated faults. This magnetic maximum may be a reflection of the source of the basic intrusives and fluorite mineralization. No anomalous magnetic readings were noted over known dike locations, possibly as a result of their small lateral extent and their highly altered condition. In addition, flight line ID passed directly over Hicks dome without observation of anomalous readings. Unfortunately, no flight lines passed over the Omaha dome. The Rough Creek-Shawneetown fault system was also without apparent magnetic expression.

There appears to be good agreement between this regional aeromagnetic map and the adjacent detailed aeromagnetic map of Indiana published by the U. S. Geological Survey (Henderson and Zietz, 1958). There is less correspondence between the southeastern Illinois magnetic map and the southeast portion of a regional Bouguer gravity map of Illinois (Woollard and Rose, 1963, p. 355). The gravity map does indicate a relatively positive zone in the vicinity of Harrisburg. The lack of stronger correlation between the gravity data and the Harrisburg magnetic maxima suggest that the lithologic unit with which the magnetic anomaly originates may not project a significant distance into the overlying sediments.

Four depth estimates to magnetic source are given in Table 1, which coincide with anomalies labeled A through D. Depth estimates were made by the method of Vacquier (1951) utilizing observed profiles across anomalies B through D, and a profile constructed at a small angle to the observed profile of anomaly A. The use of observed profiles greatly restricts the number of depth of estimates that can be made on an anomaly, but in a regional survey of this nature the resultant depth estimates can be accepted with a greater degree of confidence than depths calculated from assumed slopes. By coincidence, the south slope of the four anomalies was used for calculation. This slope corresponds to the E index of the Vacquier models. No depth estimates were made for the local maxima southeast of Harrisburg, as the peculiar pyramid shape of the anomaly suggests that the lithologic unit with which the anomaly originates cannot be approximated by a flat surfaced prism. As this survey is in an area where the total field inclination is close to seventy degrees, depth estimates were made on the same Vacquier models for inclinations of sixty and seventy five degrees. The result of the seventy five degree model was weighed twice and the three values were averaged for a final depth estimate.

TABLE 1

ILLINOIS DEPTH ESTIMATES

Anomaly	Profile	Vacquier Model	Depth Below Sea Level	Depth Below Surface
A	construction along IL	2 x 6	12,400 feet	13,200 feet
B	IM	2 x 6	11,500 feet	12,000 feet
C	IG	4 x 6	11,200 feet	11,600 feet
D	IO	2 x 6	12,000 feet	12,400 feet

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