

REGIONAL GRAVITY INVESTIGATION OF THE EASTERN PORTION OF THE
NORTHERN PENINSULA OF MICHIGAN

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A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

Department of Geology

1971

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ABSTRACT

REGIONAL GRAVITY INVESTIGATION OF THE EASTERN PORTION OF THE NORTHERN PENINSULA OF MICHIGAN

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A regional gravity investigation was conducted to delineate the Precambrian features of the eastern portion of the Northern Peninsula of Michigan in relation to the tectonic framework of the Lake Superior region and the Southern Peninsula of Michigan. During the survey, an area of 12,000 square miles in the Northern Peninsula of Michigan was covered by a total of 1,003 gravity stations. An additional 851 gravity stations previously observed in the Southern Peninsula of Michigan, Beaver Island, northern Lake Huron, northern Lake Michigan and Sault Ste. Marie area of Canada were used to establish the regional gravity pattern.

The Bouguer Gravity Anomaly Map with the aid of a Double Fourier Series Residual Gravity Map indicates that the eastern portion of the Northern Peninsula is associated with two major linear positive gravity anomalies. One of these anomalies trends south from Whitefish Point on the south shore of Lake Superior and is associated with basalts upthrown into a horst within the eastern limb of the Lake Superior syncline. This anomaly is correlated with the Middle Keweenawan

volcanics outcropping on Mamainse Point, Ontario. The other anomaly trends southeast from Grand Island in Lake Superior and can be traced magnetically to the Middle Keweenaw volcanics of the Keweenaw Peninsula. This anomaly represents the edge of the western limb of the Lake Superior syncline. The edge of the eastern limb of the syncline is also defined by a positive gravity anomaly. These positive gravity anomalies which are also associated with positive magnetic anomalies merge in the vicinity of Beaver Island and mark the termination of the Lake Superior syncline. South of Beaver Island, the Keweenaw basalts continue in a narrow belt and are expressed by the "Mid-Michigan gravity high." The Bouguer Anomaly Map indicates two local gravity minimums in the Whitefish Bay area on the south shore of Lake Superior. These are interpreted to result from a thick accumulation of Upper Keweenaw clastic sediments.

The interpretive results obtained from two dimensional model studies suggest that the Lake Superior syncline in the eastern portion of the Northern Peninsula consists of up to 12,000 feet of basaltic flows overlain by Upper Keweenaw clastic rocks. The basalts are faulted into a horst in the Whitefish Bay area. The presence of yet another horst with a graben to the east occurs in the Grand Traverse Bay region.

Theoretical curves from two different geological models can be fitted to the observed anomalies in the northern portion of the Southern Peninsula of Michigan. The basalts either extend throughout the northern tip of the Southern Peninsula where they are highly faulted into a series of horsts and grabens or they are confined to the Grand Traverse Bay area in which case pre-Keweenaw extrusives and intrusives underlie the northern tip of the Southern Peninsula.

ACKNOWLEDGMENTS

The author wishes to express his gratitude to Dr. William J. Hinze for his direction, aid, and suggestions and thorough review of all phases of this study. Special thanks are due to Drs. Hugh F. Bennett, James W. Trow, and Chilton E. Prouty for their helpful suggestions.

I am also indebted to Dr. Donald W. Merritt for his assistance in developing computer programs, Robert C. Reed for criticizing portions of the manuscript, and William Marsh for his assistance while collecting the data. Much appreciation is due to my wife for her help during the preparation and typing of the manuscript.

The financial support which made the gravity survey of the eastern portion of the Northern Peninsula of Michigan possible was furnished by the U. S. Army, Topographical Command and the Cleveland-Cliffs Iron Company.

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CHAPTER I

INTRODUCTION

Nature and Objective

The basement complex of the Midwest has been the subject of considerable recent interest for the purpose of determining the Precambrian geologic history. Exploration for mineral resources has provided valuable information about the shallow formations, but few drill holes have penetrated the basement rocks. Therefore, basement studies in the Midwest depend to a large degree upon geophysical surveys and the extrapolation of information available from a few basement wells.

A number of geophysical studies in areas adjacent to the eastern portion of the Northern Peninsula of Michigan where Precambrian rocks are exposed have indicated that considerable gravity and magnetic relief can be correlated with lithologic and structural features of these rocks. The aeromagnetic studies of eastern Lake Superior (Hinze, et al., 1966) which includes the eastern portion of the Northern Peninsula of Michigan have indicated similar results. However, only limited gravity data are available in this area. Therefore, a regional gravity investigation was conducted to supplement the existing geological and geophysical studies of Precambrian geology under the Paleozoic cover in the eastern portion of the Northern Peninsula of Michigan.

The general objective of this study is to delineate the Precambrian features of the eastern portion of the Northern Peninsula of Michigan

in relation to the tectonic framework of the Lake Superior region and Southern Peninsula of Michigan, while the specific objective is to quantitatively investigate the extension of the Lake Superior basin into the area of study. Although available magnetic data have been considered in the quantitative structural interpretations, the main source of information is the gravity data.

Organization and Scope

An area of 12,000 square miles in the Northern Peninsula of Michigan was covered during the survey (Figure 1). A total of 1,003 gravity stations were established using a LaCoste and Romberg, Model G, Geodetic Gravimeter. The station spacing varied from one mile in areas where detailed coverage was considered necessary for geological interpretation to a regional coverage of four miles. Observations were taken at road intersections where elevations are specified on U.S. Geological Survey maps or at "bench marks." Elevations at 93 stations were determined with the aid of aneroid altimeters. An additional 851 gravity stations previously observed in the Southern Peninsula of Michigan, Beaver Island, northern Lake Huron, northern Lake Michigan and Sault St. Marie area of Canada were used to establish the regional gravity pattern.

Specific information regarding the collection, reduction, presentation and methods of interpretation of the gravity data will be discussed in sections treating each of the subjects individually.

Physiography of the Area

The study area constitutes the eastern lowland topographic province of the Lake Superior region (Hamblin, 1958) which occupies the entire Northern Peninsula of Michigan east of $87^{\circ} 45'W$. Although the greater part of this area is covered by glacial drift, it has the form of a

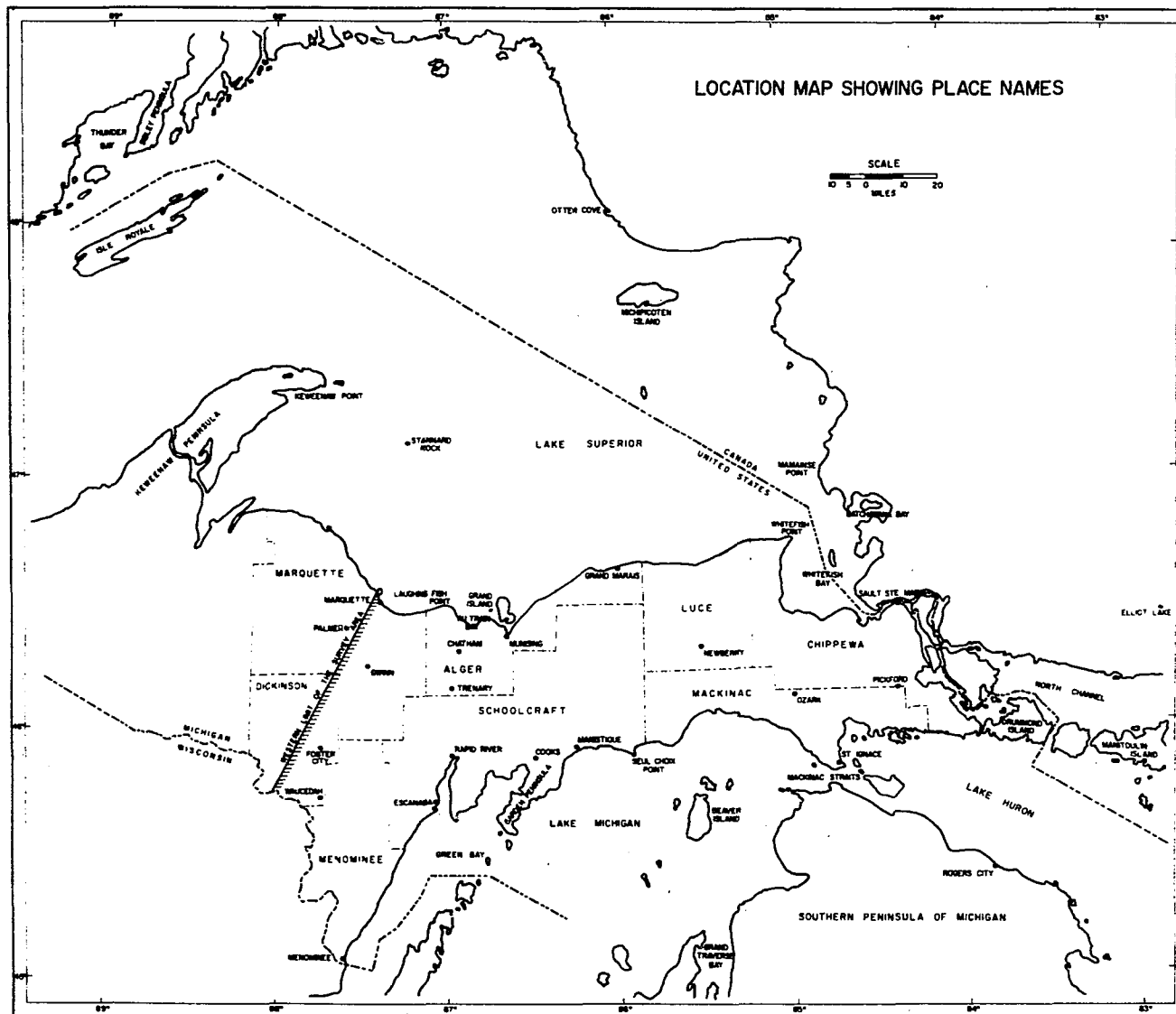


Figure 1.--Location map showing place names.

gently southward dipping cuesta. Au Train, Laughing Whitefish and Rock Rivers are the only breaks through this cuesta which has formed on the resistant Au Train formation, of Upper Cambrian or possibly Ordovician age. A number of waterfalls have been formed by north-flowing streams in Alger County as they cross the cuesta. From Munising eastward to Beaver Lake the face of the cuesta follows the Lake Superior shoreline and forms the famous Pictured Rocks.

The surface elevation within the lowland topographic province nowhere rises more than 900 feet above sea level or 300 feet above Lake Superior. Major elevation differences are due to differential erosion of the resistant Au Train formation.

In many places bedrock is covered by lake clays and recessional and ground moraines as much as 400 feet thick. The drainage in general is poor and swamps cover large areas in Schoolcraft and Luce Counties.

Several drumlins east of Waucedah and Foster City and also south of Chatham, 30 miles southwest of Munising in Alger County, form striking topographic features.

A more comprehensive description of the physiography of Northern Peninsula of Michigan is presented by Van Hise and Leith (1911).

Geology of the Area

General

The study area represents the northern extremity of the Michigan structural basin which also includes the Southern Peninsula of Michigan, eastern Wisconsin, northeastern Illinois, northern Indiana, northwestern Ohio and southwestern Ontario. Cambrian, Ordovician and Silurian sediments conceal the Precambrian basement rocks for an east-west distance of 150 miles from Marquette to Sault Ste. Marie, Figure 2. Within this

Figure 2.--Outcrop lithology and basement structures of Michigan and the surrounding area.

area few basement drill tests are available for a direct investigation of the crystalline basement. However, the general nature of Precambrian formations east and west of the study area are similar in gross aspect. Therefore, geologic information from the adjacent Precambrian exposures is presented to establish the regional Precambrian geology of the area.

There is no widely accepted reference framework of eras and periods to correlate Precambrian lithologic units and geologic events. Therefore, in discussing Precambrian geology from different areas the terminology used by the U.S. Geological Survey will be followed (James, 1958), the Precambrian being subdivided into lower (Archean), middle (Animikie) and upper (Keweenawan) divisions and the Keweenawan in turn subdivided into three groups, lower, middle and upper.

Lower Precambrian Rocks-Archean Series

The oldest rocks found in Michigan occur in the western extremity of the study area. Kitchi and Mona schist in the Marquette area and Norway Lake granite near Norway in Dickinson County are thought to be of Lower Precambrian age. These rocks mainly consist of gneisses, granites, greenstones and other metavolcanic rocks. One or more periods of metamorphism and deformation occurred before the end of early Precambrian time and the period was finally brought to an end by the Algoman orogeny (2.4 b.y.) causing a major unconformity between the Archean rocks and the overlying Middle Precambrian rocks.

Middle Precambrian Rocks-Animikie Series

The Middle Precambrian rocks of Michigan are correlated with the Animikie Group of northeastern Minnesota and the Thunder Bay area, Ontario (James, 1958). These rocks consist of a thick sequence of metasediments and metavolcanics and scattered bodies of metagabbro and

of granitic rocks. This sequence was referred to as the Huronian series until James established its correlation with Animikie series.

Middle Precambrian time was a period of extensive sedimentation with minor volcanic activity. Iron formations deposited during this period are an important source of iron ore. They locally produce magnetic anomalies in excess of 20,000 gammas.

The Penokean orogeny which caused widespread deformation and regional metamorphism brought to a close Middle Precambrian time (1.6 b.y.). During this orogeny, emplacement of small dikes and sills of basic rocks, such as diabase and gabbro, was followed by intrusions of granite and pegmatite dikes. Crustal compression then folded, faulted and metamorphosed the Animikean rocks resulting in east-west trending folds and metamorphic belts.

Upper Precambrian Rocks-Keweenaw Series

Upper Precambrian rocks are widely and extensively exposed in the Lake Superior region and from drill hole and geophysical data they are believed to subcrop beneath the Paleozoic sediments over extensive areas of the Midwest. These rocks are best known on the Keweenaw Peninsula due to intensive prospecting for copper mineralization. Therefore, this area serves as the type stratigraphic section for most of the Keweenaw sequence. The Keweenaw rocks around Lake Superior can be correlated either directly or indirectly with the Northern Peninsula sequence as shown in Table 1 (Green, 1971).

Middle Keweenaw igneous rocks have been dated isotopically at 1.2-0.9 b.y. (Goldich, et al., 1961). Since the dated interval represents only a part of Keweenaw time, it can be assumed that Keweenaw time extends from at least 1.4 to between 0.9 and 0.6 b.y. (Halls, 1966).

TABLE 1... Tentative correlations for the Keweenaw of Northern Peninsula of Michigan (after Green, 1971)

	MINNESOTA	St. Royale	Nipigon-Thunder Bay	Northern Wisconsin	Upper Michigan	Eastern L. Super. Ontario	MAG. POLARITY
UPPER	Hinckley Sst.			Bayfield Gp.	Jacobsville Sst.	Jacobsville Sst.	NORMAL
	Fond du Lac Sst.			? Oronto Gp.	? Nonesuch Sh. Copper Harbor Conglom.	sandstone	
MIDDLE	Logan intrusions Duluth Gabbro Complex Beaver Bay Complex	sandstone and cong. lavas		Portage Lake lava series Mellen Gabbro (Keweenaw Fault) sandstone? felsite? sandstone? felsite?	Portage Lake lava series sandstone? felsite? sandstone? felsite?	Michipicoten l. lavas	
	Grand Portage lavas			Mellen-Hurley lavas	"Seeth Range" lava series	Mamouise Pt. lavas Gargantua Pt. lavas	
LOWER	Logan intrusions Duluth Gabbro Complex Gunflint prong Hespering lavas Packwunge Sst.	North Shore Volcanic Group	Osler Series Sibley Series	quartz sandstone	quartz sandstone	Alona Bay lavas	REVERSED
ANIMIKIE	Thomson Fm. Rove Fm. Virginia Fm.		Rove Fm.	Tyler Sl.	Tyler Slate		NORMAL

Lower Keweenawan Rocks-The sediments which are younger than the Aniskie series and underlie the earliest Keweenawan lavas are assigned a Lower Keweenawan age. They are well developed on the Sibley Peninsula, east of Thunder Bay on the north shore of Lake Superior, and consist predominantly of sandstones, marls and shales. These sediments thin rapidly to the southwest and are represented by a thin conglomerate near Duluth. Further south, the Barron quartzite of Wisconsin and the Sioux formation of southern Minnesota are correlated and thought to be of Lower Keweenawan age (Goldich, et al., 1961).

Middle Keweenawan Rocks-On the Keweenaw Peninsula, the Middle Keweenawan rocks are known as the Portage Lake lava series. They range in composition from basalt to andesite and are interbedded with thin layers of conglomerate and sandstone. Over 300 flows occur in the upper part of this sequence, with an average individual thickness of 43 feet (White, 1966a) although much thicker flows have been recognized. This leads to an estimated total thickness of between 15,000 to 25,000 feet. This enormous thickness gradually decreases away from the axis of the Lake Superior syncline indicating a progressive subsidence of the syncline contemporaneous with the accumulation of lavas. Another characteristic of the Middle Keweenawan is that movement of lava flows appears to have been outward from the center of the lake according to evidence supplied by bent "pipe" amygdules in the lava (Hotchkiss, 1923; Butler and Burbank, 1929) whereas interflow sediments show current flow in the opposing direction according to current bedding and imbricate structure studies (Hamblin and Horner, 1961). White (1957, 1960) explained this by periodic reversals in slope within the basin. First, flows spread out from the central parts of the basin toward the margins over a flat surface. Then

due to this load, the surface of the crust subsided forming a physiographic basin which accommodated the deposition of conglomerates and sandstones by currents flowing toward the center of the basin.

Intrusives within the Middle Keweenaw are widespread in the Lake Superior region, the largest being the Duluth gabbro with a total thickness of about 20,000 feet (Taylor, 1964). Numerous diabase dikes have been observed intruding the Keweenaw volcanics. Although some unmetamorphosed diabase dikes have been found cutting the Middle Keweenaw sequence of Michigan they are most frequently found in pre-Keweenaw rocks (Halls, 1966). Some of these dike swarms exhibit strong reverse magnetization.

Patches of Middle Keweenaw lavas also occur along the eastern shore of Lake Superior. This indicates the continuity of these rocks in an easterly direction from Keweenaw Peninsula. North of Whitefish Bay at Mamainse Point, there is an apparent thickness of 16,000 feet of amygdaloidal lava flows with interbedded boulder conglomerates. This sequence is correlated with the Portage Lake lavas of Michigan. At Mamainse Point, the formation strikes generally north-south and is inclined lakeward at angles not exceeding 30° . Dikes and felsite intrusions have also been found in this area (Thomson, 1953).

Extensive exposures of Middle Keweenaw rocks are also found on Michipicoten Island in eastern Lake Superior. The maximum thickness of lavas on the island reach 11,000 feet. This Middle Keweenaw sequence is unique because acidic lavas make up at least one-half of the section (Halls, 1966).

Upper Keweenaw Rocks-The Upper Keweenaw sequence consists predominantly of fine grained sandstones and shales, overlying a thick

conglomerate. The basal unit, the Copper Harbor conglomerate, lies conformably over the Middle Keweenaw lavas. It is mainly composed of rhyolite cobbles. Within the Copper Harbor conglomerate are lenses of fine to coarse grained, red arkosic sandstone. The thickness of Copper Harbor varies considerably. However, on the Keweenaw Peninsula it retains a uniform thickness between 4,000 and 5,000 feet.

A sharp lithologic change from conglomerate to siltstone marks the boundary between Copper Harbor conglomerate and the Nonesuch shale. Although there is no structural discordance, this contact is thought to be a disconformity because of the significant difference between the paleomagnetic pole positions of the two formations (Du Bois, 1962). The Nonesuch shale retains a constant thickness of about 600 feet along the Keweenaw Peninsula.

The Nonesuch is overlain by 5,000 feet of Freda formation. This formation consists of interbedded arkosic sandstone and red micaceous silty shale. The Freda reaches a thickness of 12,000 feet in Wisconsin and is known as the Oronto group. It contains a large average percentage of heavy minerals (7.4 percent). This characteristic coupled with an abundance of feldspar indicates that the sediments were subjected to incomplete weathering and short distances of transportation. Therefore, nearby Keweenaw volcanics and pre-Keweenaw rocks are the likely source rocks of Freda formation.

Overlying the Freda is a sequence of red quartzose sandstone and micaceous shale more than 2,000 feet thick known as Jacobsville sandstone in Michigan. Seismic reflection data (Bacon, 1964) indicate that the thickness of this formation can be as great as 12,000 feet. The relationship of the Jacobsville with the Freda is still conjectural, however, the

Jacobsville appears to be younger as pebbles of red siltstone and mudstone possibly derived from the Freda are found in it along the coast from L'Anse to Marquette (Hamblin, 1958). The Jacobsville may therefore be considered as having a late Upper Keweenawan or Lower Cambrian age. Further evidence to support this conclusion is the low dip angular unconformity between the Jacobsville and the Munising formation of Late Cambrian age on the east side of Grand Island (Hamblin, 1958). However, it is impossible to estimate the time gap represented by this unconformity and therefore neither Upper Keweenawan nor Cambrian age can be assigned to Jacobsville with any certainty. The more recent studies of this long existing Jacobsville problem seem to favor its equivalence with Bayfield group in Wisconsin which is of Upper Keweenawan age.

The Jacobsville sandstone may be traced eastward from the Keweenaw Peninsula to the Sault Ste. Marie area as narrow discontinuous shoreline outcrops (Hamblin, 1958). At all these occurrences the dip is very gentle and generally does not exceed 1° or 2° in a lakeward direction. In addition to quartzose Jacobsville sandstones, feldspathic sandstones which resemble the Freda formation lithologically are found in the Batchawana Bay and Sault Ste. Marie areas. However, there is doubt about the time-equivalence of these feldspathic rocks to the Freda formation (Hamblin, 1958).

Major Precambrian Structural Features

The dominant structural feature in the Lake Superior region is the Lake Superior basin known as the Lake Superior syncline. In the western half of the lake, the syncline trends northeasterly and is strongly asymmetrical toward the south. The Keweenawan rocks within the syncline show dips ranging from only a few degrees to vertical. The highest dips

occur in the vicinity of major thrust faults which strike parallel to the axis of the syncline. The structure contours clearly show closure of the syncline south of Duluth although Keweenaw rocks continue southward in a narrow trough to Kansas according to gravity, aeromagnetic and borehole data (Thiel, 1956; Lyons, 1959; Craddock, et al., 1963; Zietz, 1965). At the western end of the basin the structural pattern is rather complex. A north-south trending ridge extends from the vicinity of Mellen, Wisconsin to the Minnesota shoreline (White, 1966a). Wold and Ostenso (1966) detected the presence of another ridge which extends from Isle Royale southwestward to the ridge interpreted by White. Halls (1966) suggested that much of the western half of the Lake Superior syncline developed on the site of a former geosyncline, evolved during the Animikean and terminated by Penokean orogeny which had little effect on the north shore of Lake Superior. The Animikean geosyncline cannot be traced eastward because there are no known Animikean rocks around eastern Lake Superior. However, the Middle Precambrian rocks occurring along the north shore of Lake Huron may be equivalent of Animikean (Young, 1966) indicating that they may form the northern margin of an easterly extension of the Animikean geosyncline. In contrast to this former geosyncline, the axis of the Lake Superior syncline parallels the Keweenaw Peninsula in western Lake Superior and then gradually turns and becomes southerly in the eastern part of the lake according to aeromagnetic data (Hinze, et al., 1966). The gravity evidence of the present study indicates closure of the syncline east of Beaver Island and continuation of Keweenaw rocks southward in a narrow belt into the Southern Peninsula of Michigan.

One of the major structural features of the Lake Superior region is the Keweenaw fault. It extends through the center of the Keweenaw

Peninsula bringing the Middle Keweenaw flows to the north into contact with the Upper Keweenaw sediments. The age, extension and the amount of displacement of the Keweenaw fault has been a matter of conjecture for many years. The amount of displacement necessary to bring the Middle Keweenaw basalts in contact with the Jacobsville is in the order of 15,000 feet (Butler and Burbank, 1929). Halls (1966) believes that the fault is at least 10,000 feet downthrown to the south in the Keweenaw Peninsula, confirming the earlier studies. However, a much smaller displacement is suggested by Hamblin (1958) who argues that the Keweenaw series were tilted and eroded before the deposition of Jacobsville sandstone. Therefore, the minimum amount of displacement on the fault is not the thickness of the Upper Keweenaw rocks but only the thickness of the Jacobsville which is in the order of magnitude of 2,000 feet. Hamblin (1958) also believes that the age of the Keweenaw fault is post-Jacobsville and probably post-Devonian since Devonian and Jacobsville rocks at the Limestone Mountain area are affected by the same folding process which is related to the compressional forces that caused the faulting. However, generally the Keweenaw fault is believed to be related to the origin of the Lake Superior syncline. Therefore, the post-Devonian faulting at the Limestone Mountain area is likely a rejuvenation of movements along the old lines of weakness.

The genetic relationship of the Keweenaw fault to other faults in the area and its possible eastward extension is also a controversial matter. The Lake Owen fault of northern Wisconsin which occurs to the southwest of the Keweenaw fault is thought to be an extension of it. To the east, O'Hara (1967) interprets from aeromagnetic data a southeasterly trending fault extending from Keweenaw Point through Au Train Bay

to the Manistique area on the Lake Michigan shore and suggests that this fault may be an eastward extension of the Keweenaw thrust fault. Thwaites (1935) on the basis of bottom topography studies of eastern Lake Superior suggested the existence of such a fault. Further geological evidence for extending the Keweenaw fault in this manner came from Oetking's (1951) studies which show minor thrust faults in the Jacobsville sandstone on the east side of Laughing Fish Point, Au Train Island and in the southeastern corner of Au Train Bay. In addition, Patenaude (1964) suggested the existence of a nearly vertical fault on Au Train Island. Although the geological evidence for extending the Keweenaw fault further southeast from Au Train Bay is weak, small scale faulting near Seul Choix Point on Lake Michigan shore has been observed to substantiate this interpretation (Patenaude, 1964).

Newcombe (1933) traced the Keweenaw fault to Stannard Rock and suggested that the fault possibly extended eastward. He further stated a genetic relationship between the Keweenaw fault and the Murray fault in Ontario. However, the apparent direction of movement on these two faults is opposite and such a relationship does not appear to be feasible on the basis of geophysical evidence.

Patenaude (1964) as a result of his geophysical studies in the eastern extremity of the eastern portion of the Northern Peninsula proposes the existence of a north-south trending fault of major proportions. This fault extends southward into Lake Huron and is upthrown to the west. Patenaude further suggests that this fault may be related to the Keweenaw fault system.

The discontinuous configuration of the magnetic anomalies near the north shore of Northern Peninsula has led O'Hara (1967) to suggest the

existence of nearly east-west trending faults in this area. Patenaude's (1964) studies also revealed such an east-west striking fault south of Whitefish Bay.

Local east-west trending pre-Keweenawan structures predominate in the western extremity of the study area. Two such structures are the Marquette syncline and Gwinn trough which are considered to be areas of complex folding and faulting, probably the result of a period of a major orogeny. Frantti (1956) on the basis of geophysical data interpreted a similar syncline in the vicinity of Trenary which has a major magnetic anomaly associated with it. The association of iron-formations with folded Animikean rocks in this part of the study area is a rule rather than an exception. A metasedimentary belt extends from Waucedah to Escanaba (Allen, 1914) and is clearly seen in magnetic maps.

Another school of thought concerning the nature of the Precambrian basement between Marquette and Sault Ste. Marie has also been considered in the geological literature. Hamblin (1958) ignoring the possibility of a basement of Keweenawan volcanics, endorsed the existence of an east-west trending ridge of Middle Precambrian rocks based on sediment dispersal patterns in the Jacobsville sediments. This structurally positive area which is called the Northern Michigan Highland is believed to have existed in the eastern portion of the Northern Peninsula of Michigan during Jacobsville time. Hamblin (1961) states that this highland was probably formed near the beginning of Keweenawan time, either as a result of uplift by faulting or arching of the Northern Peninsula or by differential sinking of the region beneath the eastern Lake Superior, and persisted as a highland until Middle Cambrian time. As a further evidence, Hamblin (1958) interprets the broad east-west gravity high of

Bacon's (1957) reconnaissance survey in the Northern Peninsula to be caused by a buried Precambrian ridge extending from the Wisconsin Arch to Canada.

Origin of the Lake Superior Syncline

Several theories have been developed to explain the origin of the Lake Superior syncline. An early, commonly accepted theory was put forth by Hotchkiss (1923). On the basis of estimates of the original dips of the Keweenawan flows, together with flow directions as indicated by bent "pipe" amygdules and sedimentary structures at the base of the extrusions, Hotchkiss concluded that the source of the flood basalts was along the axis of the Lake Superior syncline. He further envisions a batholithic intrusion during pre-Keweenawan time located beneath the present trough which had a surface expression as a topographically positive area. During the Middle Keweenawan time, escaping basaltic material produced great thicknesses of extrusives on the surface which led to an equivalent subsidence of the crust. The escape of basaltic material together with contraction of the remainder of the batholith due to cooling and loss of volatiles resulted in complete collapse of the batholithic roof.

Hotchkiss' theory on the origin of the Lake Superior syncline agrees with Van Hise's (1911) conclusion that the Lake Superior syncline probably originated during Middle Keweenawan time. Van Hise further stated that the folding of the basin was practically complete by the end of the Keweenawan time and large scale strike faulting affected the area in post-Cambrian and possibly in post-Cretaceous time. However, Irving's work (1883) shows an earlier Animikean sedimentary basin with essentially the same structural features. Halls (1966) confirms the early studies of Irving and concludes that the western half of the Lake Superior syncline developed on the site of an east-west trending Animikean geosyncline.

For many years it has been hypothesized that the Lake Superior and the Michigan basins are interrelated. Robinson (1923) in an unpublished manuscript suggested an early connection between the Lake Superior syncline and the Michigan basin. He explains the later separation of the two basins in the following way: a synclinal area extended from St. Paul, Minnesota through the present Lake Superior region into the Southern Peninsula of Michigan which was filled with Cambrian sandstone; a period of early Paleozoic erosion removed a large part of the sandstone in the Southern Peninsula but did not similarly affect the Lake Superior area; this was followed by deposition of thick sediments in the basin; a second period of erosion in possibly Tertiary time affected the Lake Superior basin and removed the Paleozoic sediments from the area; the result of this erosion was the formation of a ridge not far north of the present south shore of Lake Superior which separated the two basins. Newcombe (1933) accepting the idea of Robinson, proposed a new hypothesis to explain the separation of the Lake Superior syncline from the Michigan basin. He concluded that the major Keweenaw movements resulted in the separation rather than a complex erosional history.

A possible connection between the eastern Lake Superior basin and the Michigan structural basin also was suggested by Thwaites (1935). His east-west cross section in the eastern portion of the Northern Peninsula shows Keweenaw flows slightly downwarped in the center and thrust faulted near either end. Thwaites' other cross sections also show the Keweenaw fault entering at Au Train Point and two other north-south faults near the eastern extremity of the Peninsula.

Most geologists and geophysicists presently working on various segments of the Lake Superior syncline attribute its origin and development

to one of two hypotheses. The first suggests that the basin was formed primarily by downwarp of the crust either by loading when mafic lavas were extruded in great volume, or by crustal compression (White, 1966b). The second and recently more favored hypothesis is that, crustal rifting has taken place during the accumulation of the flood basalts and sediments presently filling the trough. This second hypothesis explains very well the thick crust beneath the lake by attributing its cause to isostatic adjustment to the high density basic material which appears to have intruded the crustal rocks (Smith, et al., 1966).

Hinze, et al. (1971), associating the origin of the Lake Superior syncline to continental rifting, have compared the Lake Superior region with the East African rift system. They find strong similarities between the two areas and attribute the observed dissimilarities to different stages of development of the rifting process.

The above theories exemplify the variation of ideas proposed to explain the origin of the Lake Superior syncline. The structural extent, framework and time of origin of this feature have been the subject of many geological and geophysical studies.

Paleozoic Rocks

In the eastern portion of the Northern Peninsula of Michigan sedimentary formations of Paleozoic age overlap the Precambrian basement complex and dip gently south into the Michigan Basin. Beds younger than late Silurian are not present in the Northern Peninsula.

Cambrian Rocks-The Munising formation which is given a Late Cambrian age on the basis of its fossil content represents the Cambrian rocks in the area. The contact between the Munising formation and the older rocks is well exposed in numerous outcrops in Alger and Dickinson Counties.

In Alger County the Munising rests upon the Jacobsville formation with a low dip angular unconformity (Hamblin, 1958). In Dickinson County the Jacobsville is absent and the Munising lies upon the highly deformed Animikean rocks with a major unconformity.

The Pictured Rocks cliffs constitute the principal exposure of the Munising formation which consists of, in ascending order, a basal conglomerate, the Chapel Rock member and the Miner's Castle member. The basal conglomerate is an orthoquartzite and attains a maximum thickness of 15 feet. It wedges out southward and, therefore, is restricted to the northern part of the Northern Peninsula. The Chapel Rock member overlies the basal conglomerate and consists of well sorted medium grained sandstone characterized by large-scale cross-bedding. Along the Pictured Rocks the Chapel Rock is 40 to 60 feet thick and thins gradually to the east. The contact between the Chapel Rock and Miner's Castle members is sharp as indicated by significant changes in sorting, sedimentary structures and heavy mineral assemblages. Therefore, the source areas of these two members were probably different and a disconformity separates them (Hamblin, 1958). The Miner's Castle member consists of poorly sorted sandstone and is 140 feet thick at the type locality in the Pictured Rocks.

Ordovician Rocks-The Munising formation throughout the Northern Peninsula is overlain by a sequence of sandy dolomites and dolomitic sands. The age of these beds is a matter of conjecture. Van Hise and Bayley (1900) proposed the term Hermansville for the limestones which overlie the Lake Superior Sandstones in Wisconsin and the Munising formation (Upper Lake Superior Sandstone) in the Menominee district of the Northern Peninsula of Michigan. These limestones were described as

being sandy and dolomitic and assigned a Lower Ordovician age (now Prairie Du Chien group). The Au Train formation described by Hamblin (1958) at Au Train Falls near Munising overlies the Munising formation and has the stratigraphic position and general character of the Trempealeau formation of Upper Cambrian age in the Southern Peninsula. However, Oetking (1951) described fossils which are believed to be of Middle Ordovician age from the Au Train formation near Miner's Castle, Munising. Therefore, the age of the Au Train is in doubt and its relationship to the Hermansville is questioned, as there is no contact relations observed in the small, isolated outcrops of the Northern Peninsula. A disconformity must exist between the Munising formation and well established Black River limestones of the Middle Ordovician age as the Lower Middle Ordovician (Chazy) has never been recognized in the Northern Peninsula. The time represented by this disconformity depends on the true age of the Hermansville and the Au Train which at present remains problematical.

Overlying the Au Train formation in the Northern Peninsula is either the Black River or Trenton, depending on the age of the Au Train. Major outcrops of Trenton occur in the vicinity of Escanaba, Menominee and the northern part of Drummond Island. The Trenton group consists of dolomitic limestone and limestones alternating with cherty layers. The deposition of these rocks is followed by the deposition of the Late Ordovician rocks which consist of shales and fossiliferous limestones over extensive areas of the upper Midwest indicating uniform depositional conditions.

Silurian Rocks-During Silurian time seas covered the area and laid down a variety of sediments, the most common being carbonates formed in

clear seas. Reef formation was common around the margin of the Michigan basin. Silurian time in Michigan was also a period of considerable downwarping.

Early Silurian rocks consist largely of shales and carbonates whereas the Middle Silurian rocks are predominantly dolomite and occur in an arcuate belt from St. Martin, Poverty, Big and Little Summer Islands at Green Bay to east of Drummond Island. The uppermost formation of Middle Silurian age, the Engadine dolomite is a scarp former, forming the Garden Peninsula southwest of Manistique and the Drummond and the Manitoulin Islands.

The single greatest episode of sinking and the accumulation of thick evaporites, carbonates and shales, mark Upper Silurian time in the Michigan basin.

Devonian rocks do not occur in the Northern Peninsula. However, the so called Mackinac Breccia found in the vicinity of St. Ignace contains Devonian fragments indicating that the Devonian rocks were once present in the area.

Previous Geophysical Studies

Seismic

A seismic survey to study the deep crustal structure of the Northern Peninsula of Michigan and Wisconsin was undertaken by Slichter as early as 1940 and was reported in 1951 (Slichter, 1951). The results of this investigation included one shot point at Palmer in the Marquette area and another at Manistique, but none in the eastern portion of the Northern Peninsula showed that:

1. There is a superficial layer with a compressional wave velocity of 4.16 km/sec and a thickness of about 3 km.

2. The superficial layer is underlain by a homogeneous layer of velocity 6.16 km/sec and a thickness varying from 33 to 38 km.
3. The depth to Moho in the Palmer area is 40 km. Slichter used a velocity of 8.17 km/sec for mantle material in calculating the depth to the Mohorovicic discontinuity.

In connection with the International Upper Mantle Project, during the summers of 1963 and 1964 refraction data were obtained along a line crossing Lake Superior from Duluth, Minnesota to Otter Cove on the eastern shore of Lake Superior in Ontario. The results of various interpretations of these data show that the Moho discontinuity deepens from about 35 km in the western part of Lake Superior to 60 km in the region northwest of Keweenaw Point and there is no significant change in depth further east (Meyer, 1964; Smith et al., 1966; Berry and West, 1966; Meyer and Ocola, 1967; O'Brien, 1968). There is an upper refractor at a depth of 7 km and the compressional wave velocity under the upper refractor is unusually high (6.8 km/sec) while that of the upper mantle is normal (8.1 km/sec).

Magnetic

Patenaude (1964) reported seven east-west and six north-south aeromagnetic traverses in the eastern portion of the Northern Peninsula of Michigan. His work indicates that Keweenaw volcanics extend to the eastern limit of the Peninsula.

Hinze, et al., (1966) conducted a regional aeromagnetic survey of the eastern Lake Superior and eastern half of the Northern Peninsula of Michigan. The results of the survey support the geological interpretation that the Lake Superior structural basin consists of thick basic volcanics overlain by clastic sediments and extends southward into the Northern Peninsula of Michigan.

Case and Gair (1965) in their aeromagnetic study of parts of Marquette, Dickinson, Baraga, Alger and Schoolcraft Counties, Michigan correlated the major magnetic anomalies and broad areas that have characteristic magnetic patterns with the geology as determined from published reports. This study was extended by U.S. Geological Survey (1970) to cover the neighboring areas. The resultant aeromagnetic maps reflect the east-west trending pre-Keweenawan structures.

Kellogg (1971) has studied the basement geology of the Southern Peninsula of Michigan using the results of geophysical anomalies from the periphery of the Michigan basin. He correlates a large positive gravity anomaly and the discontinuous magnetic anomaly, the "Mid-Michigan anomaly," with Middle Keweenawan basic volcanic rocks differentially uplifted against the gneisses, granites and metasediments of the older basement provinces. Hinze and Merritt (1969) concluded that this large positive feature extends northwards into the Lake Superior region.

O'Hara and Hinze (1971) have reported on an aeromagnetic investigation of Lake Michigan, Green Bay, Traverse Bay and the eastern portion of the Northern Peninsula of Michigan immediately north of Lake Michigan. In this study, they trace the east-west striking magnetic anomalies in northern Michigan into generally north-south striking anomalies which they correlate with Keweenawan basalts in the Lake Superior basin.

Gravity

A reconnaissance gravity survey of the Northern Peninsula of Michigan was conducted by Bacon (1957). The major feature of Bacon's Bouguer Anomaly Map is a broad southeast trending anomaly which was interpreted as caused by a ridge between the Lake Superior and Michigan basins. Bacon suggested that this gravity anomaly may merge with the "Mid-Michigan

gravity anomaly" and was similar to the "Mid-Continent gravity high" which extends from the western end of the Lake Superior basin south through Minnesota, Iowa, Nebraska and Kansas.

Patenaude (1964) analyzed four gravity profiles, two of them in Pickford-Sault Ste. Marie area and the other two in Au Train-Munising area. The results of his model studies show a fault of major proportions in the vicinity of Au Train Point which is genetically related to the Keweenaw fault. Patenaude also suggests a high angle fault about 8 miles east of Pickford which also may be related to the Keweenawan tectonics.

A Bouguer Anomaly Map covering the midwestern states and southern Ontario was compiled by Rudman, et al., (1965). This map shows that the "Mid-Continent gravity high" is genetically related to the linear "Mid-Michigan gravity anomaly."

Gravity surveys were conducted in Lake Superior during the summers of 1963 and 1964. The Bouguer Anomaly Map compiled by Weber and Goodacre (1966) is characterized by steep gradients which can be best explained by shallow gologic structures no more than 10 km in depth from the surface.

Berkson (1969) conducted a gravity survey in the vicinity of Michipicoten Island, Lake Superior. His studies show a positive belt of gravity values trending southeast flanked by a negative anomaly to the northeast. The linear positive gravity anomaly is interpreted to result from high density Keweenawan lavas of the north limb of the Lake Superior syncline while the negative anomaly is attributed to a low density area of the pre-Keweenawan basement under the lake.

The geological and geophysical studies up to the present indicate that Keweenawan rocks extend southward from the Lake Superior basin and the structures associated with the "Mid-Continent" and "Mid-Michigan"

anomalies are similar. These conclusions have led to speculation that the Lake Superior syncline had its origin in a rift of the continental crust. Hinze, et al., (1971) have compared the North American Mid-Continent basement with the East African Rift System and have proposed a mechanism for the development of continental rifts. Their proposed process explains the geological and geophysical observations of the East African Rift System to its present stage of development and of the late Precambrian paleo-rift system of north-central United States.

CHAPTER II

FIELD METHODS AND DATA REDUCTION

Survey and Instrumentation

The gravity observations of the survey were taken with a La Coste and Romberg, Model G, No. 103 Geodetic Gravimeter. It has a range of 7000 milligals and has a reading accuracy of ± 0.01 milligal. The gravimeter was provided by the U.S. Army, Topographical Command.

Seventeen base stations were established during the course of the survey to expedite the field work. These stations were distributed throughout the survey area near accessible roads and away from busy highways.

The magnitude of the instrument drift was found by reoccupation of base stations at four hour intervals. Each base station was triple looped as shown in Figure 3, in four closed systems. The closure errors of the systems are as follows:

<u>System</u>	<u>Station</u>	<u>Closure Error (mgal)</u>
1	SB	0.01
2	OB	0.005
3	MB	0.015
4	KB	0.0

The base station at Ozark was also triple looped with North and South Mackinac Bridge base stations. The station at the south end of Mackinac Bridge was tied to the base station WU 17 in front of the Physics-Astronomy Building at Michigan State University, East Lansing (Behrendt

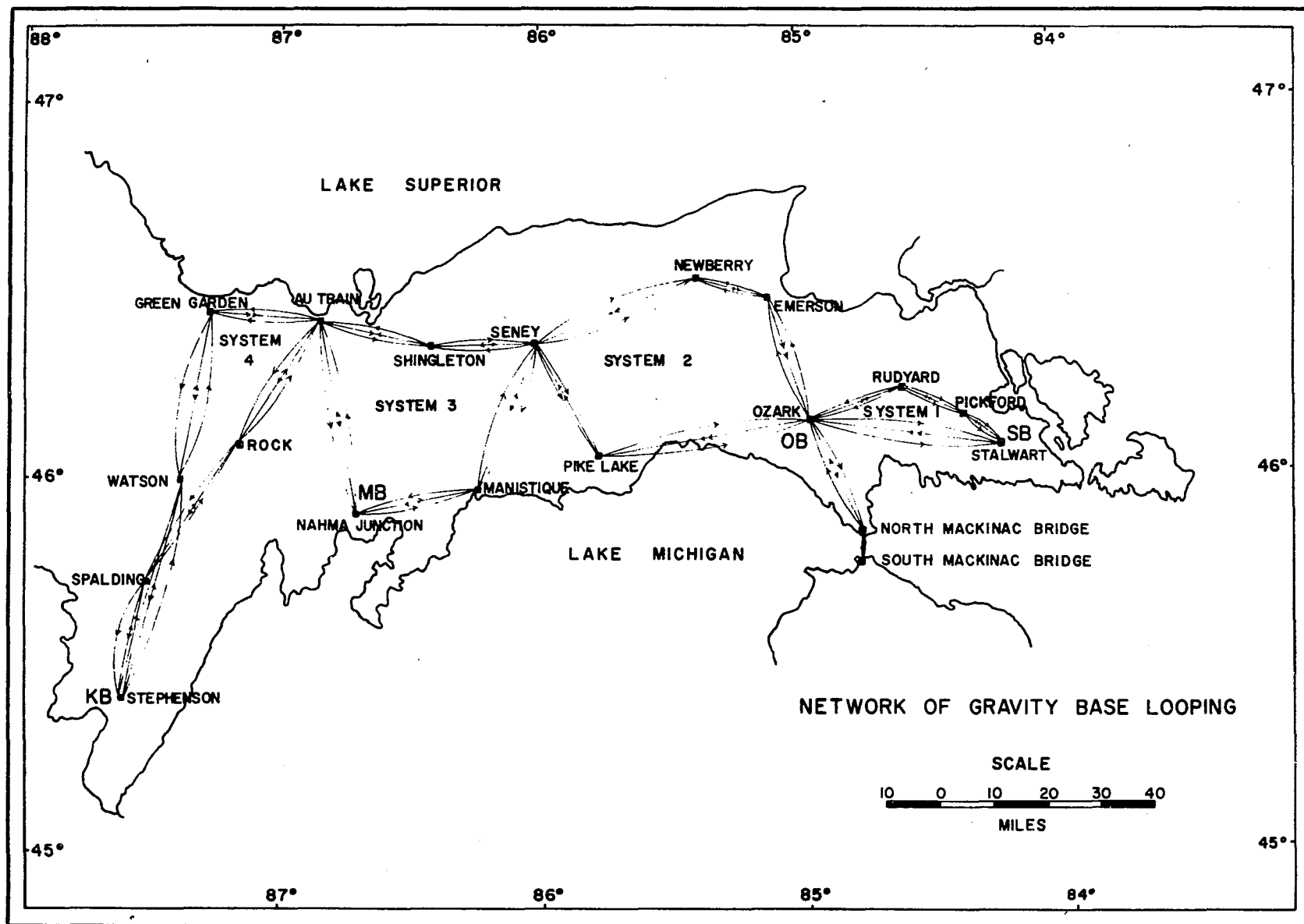


Figure 3.--Network of Gravity Base Looping in the eastern portion of the Northern Peninsula of Michigan.

and Woollard, 1961). Gravimeter drift for this tie was eliminated by the method described by Woollard and Bonini (1955), which required establishing the slope of the drift curve by hourly interval observations at stations at the south end of the Mackinac Bridge, Harrison Rest Area, Mount Pleasant and the Physics-Astronomy Building, Michigan State University. The Harrison Rest Area and Mount Pleasant stations are located at roughly equal intervals between the ends of the loop. This tie was conducted four times with a maximum discrepancy of 0.02 milligal when earth tides were eliminated.

The station in front of the Physics-Astronomy Building at Michigan State University was then tied by triple looping to airport base station WA 117 at the Lansing Airport (Behrendt and Woollard, 1961).

A total of 26 stations were reoccupied and after applying the drift correction, the maximum discrepancy for reoccupied stations was 0.04 milligals with an average of 0.015 milligals.

During the course of the survey, the gravimeter sensitivity and level adjustments were checked once a week. The displacement sensitivity was 0.7 and the level setting remained correct throughout the survey.

Accuracy of Horizontal Coordinates and Elevations

Gravity stations with spacings varying from 1 to 5 miles were plotted from U.S. Geological Survey maps of 7.5 and 15 minute quadrangles and Michigan State Highway Department maps of scale 1:62,500. Highway Department maps were used only where U.S. Geological Survey maps were unavailable.

Horizontal coordinates (latitude and longitude for each station) were calculated from these maps using a different latitude constant for 2.5 minute intervals for 7.5 minute series, 5 minute intervals for 15 minute series and 10 minute intervals for State Highway maps. Stations

plotted from U.S. Geological Survey maps have an error of ± 1 second and stations plotted from Highway Department maps have an error of ± 3 seconds in their horizontal coordinates. The accuracy of locating the stations on the maps is of the order of 250 feet. This causes an error of 3 to 4 seconds. The total error in the horizontal coordinates is estimated to be ± 4 seconds for stations plotted from U.S. Geological Survey maps and ± 6 seconds for those plotted on State Highway maps.

From a total of 1003 gravity stations, 210 are located at U.S. Geological Survey or U.S. Coast and Geodetic Survey elevation "bench marks." A total of 700 stations are at road intersections whose elevations are given on U.S. Geological Survey maps. Elevations at road intersections obtained from U.S. Geological Survey maps with a contour interval of 20 feet have an accuracy of roughly ± 2 feet. A small number, approximately 10, of these stations were established at road intersections and the elevations were interpolated from the 20 feet contour interval. The error of these elevations does not exceed ± 10 feet.

The elevations of 93 stations were established by using four Wallace & Tiernan Surveying Altimeters, Type FA-112. A single base method with two observers was employed. Exceptionally clear days were chosen and all reasonable precautions were taken for the altimeter survey. The accuracy of these elevations is therefore, estimated to be ± 5 feet and in no case exceed ± 8 feet. A test survey using the survey altimeters under the conditions described above showed a maximum error of ± 5 feet.

Reduction of Data

The observed readings were first corrected for the gravimeter drift relative to the bases which were tied by triple looping. The calibration table for the La Coste and Romberg, No. 103 Geodetic

Gravimeter was then used to convert the drift corrected readings from scale division to milligals and the values were adjusted to the national gravimetric datum.

The theoretical gravity for each station was determined by the 1930 International Gravity Formula and the vertical gradient of gravity of 0.09406 milligals per foot was used to calculate the Free-air correction. The Bouguer or mass correction which accounts for the mass of material between the point of observation and sea level is 0.01276ρ milligals per foot where ρ is the density of the material above sea level which was assumed to be 2.67 g/cc.

The above corrections were applied to the observed gravity to obtain the Free-air and simple Bouguer anomalies in the equations:

Free-air anomaly = observed gravity - sea level gravity + Free-air correction
and

Simple Bouguer anomaly = observed gravity - sea level gravity + Free-air correction - Bouguer correction.

No terrain corrections were needed since the relief in the study area was low and the stations were carefully placed away from any local topographic features.

A CDC 3600 Computer was utilized in the calculation of anomalies. Contouring of maps was done both by hand and by machine.

The principal facts of gravity stations in the eastern portion of the Northern Peninsula of Michigan are available from the U.S. Army, Topographical Command in Washington, D.C.

Lake Michigan and Lake Huron Gravity Data

Bouguer gravity anomaly values for stations located in the northern Lake Michigan and Lake Huron were obtained from N. W. O'Hara of the University of Michigan, Great Lakes research Institute. These values were provided to Dr. O'Hara by the U.S. Topographical Command.

CHAPTER III

INTERPRETATION OF GRAVITY DATA

Sources of Anomalies

Geological and geophysical studies indicate that the Precambrian rocks of the upper Midwest are structurally complex and are composed of a broad spectrum of lithologies. Gravity and magnetic maps are particularly useful in deciphering this complex pattern where the Precambrian surface is buried beneath Paleozoic sediments because of the paucity of direct geological information from deep drill holes. Specific gravity and magnetic susceptibility contrasts leading to gravity and magnetic anomalies are commonly associated with basement lithologic variations. Furthermore, Hinze and Merritt (1969) have shown that gravity and magnetic anomalies originating from intra-basement lithologic and structural variations are an order of magnitude greater than anomalies originating from basement topography, sedimentary structure and bedrock topography. Although there is an obvious relationship between major magnetic and gravity anomalies and basement lithology, assigning specific lithologies and configurations to sources of many anomalies is uncertain without supporting geological information. In general, specific gravity and magnetic susceptibility contrasts are uncertain and little is known about the configuration of the causative bodies except that they reside within the basement rocks. Even if the physical properties are known the configuration of the anomalous mass cannot be determined with certainty because of the fundamental ambiguity of potential

field data. Conversely, if the source can be delineated by geologic knowledge and the characteristics of the anomaly, the calculated physical property does not lead to an unique determination of lithology of the source because the specific gravities and magnetic susceptibilities of rocks generally overlap (Grant and West, 1965). The problem is further complicated because remanent magnetic polarization may contribute significantly to the magnetic polarization of the rock. As a result, rocks which should cause magnetic highs on the basis of their susceptibility may cause magnetic lows or the opposite may occur.

In spite of the difficulties of assigning lithologies to intra-basement features in the eastern portion of the Northern Peninsula of Michigan, certain generalizations are possible particularly when both gravity and magnetic information are available. These generalizations are the result of geological and geophysical studies conducted over the vast exposures of igneous and metamorphic rocks of the Canadian Shield. Thiel (1956), Craddock, Thiel and Gross (1963), and Sims and Zietz (1967) have found that large positive gravity and magnetic anomalies are associated with great thicknesses of Middle Keweenaw basic extrusives and intrusives in the western part of the Lake Superior syncline. This large positive anomaly which extends as far south as Kansas was designated the "Mid-Continent gravity high" by Thiel. Thiel showed that the lavas in the center of the syncline have been thrust upward as a horst, in places, juxtaposed against low specific gravity clastic sediments of Upper Keweenaw age. These sediments give rise to strongly negative gravity and magnetic anomalies. However, a portion of the minimums flanking the central high is attributed to regional downwarping of the crust-mantle boundary caused by the great weight of the overlying volcanics (White, 1966b; Cohen and

Meyer, 1966). Keweenaw basalt flows are also responsible for the gravity and magnetic highs in the western portion of the Northern Peninsula of Michigan (Bacon, 1966; Meshref and Hinze, 1970).

Locally, in the Lake Superior area, both Keweenaw mafic intrusives and extrusives may produce negative magnetic anomalies due to remanent magnetization (Case and Gair, 1965; Corbett, et al., 1967; Meshref and Hinze, 1970). Granite intrusives generally cause negative gravity anomalies (Weaver, 1967; Gibb and McConnell, 1969) and either negative or positive magnetic anomalies depending on the nature of the country rock (MacLaren and Charbonneau, 1968).

Dutton and Bradley's (1970) compilation of the Precambrian geology, and geophysical anomalies in Wisconsin indicate that belts containing metasedimentary rocks, mainly quartzites, are regional gravity and magnetic lows and massive granites are related to magnetic highs. Some of these belts can be traced eastward into Lake Michigan where magnetic lows are associated with metasediments and low grade felsic rocks (O'Hara and Hinze, 1971). O'Hara and Hinze have also traced some magnetic highs from Wisconsin into Lake Michigan and they relate these magnetic highs to basic volcanic rocks and also to intermediate to basic intrusions which have penetrated a primarily granitic terrane.

In summary, the following generalizations will be applied in assigning sources to relative gravity and magnetic anomalies in the eastern portion of the Northern Peninsula of Michigan and the surrounding area:

1. Positive Bouguer gravity anomalies are caused by accumulations of mafic extrusives and intrusives of Keweenaw age;
2. Negative Bouguer gravity anomalies are commonly associated with metasediments and granitic rocks;

3. Magnetic highs are often accompanied by Keweenawan basic extrusives and intrusives, iron formations, and with some pre-Keweenawan granitic rocks;
4. Magnetic lows are frequently associated with metasediments and low grade gneisses;
5. Areas showing both marked positive gravity and magnetic anomalies are associated with accumulations of Keweenawan basic rocks which lie close to the surface;
6. Areas showing both negative gravity and magnetic anomalies are interpreted as indicating either the absence of Keweenawan basic rocks and/or the presence of thick accumulations of Keweenawan sediments or the presence of relatively non-magnetic and low density masses of pre-Keweenawan rocks which lie near the surface;
7. Areas showing positive gravity anomalies and negative or no magnetic anomaly are associated with deep intrusions into the pre-Keweenawan complex or large remanent magnetization effects of the Keweenawan volcanics which oppose the induced magnetization;
8. Areas showing negative gravity but positive magnetic anomalies are interpreted as indicating the presence of relatively thin near surface sequence of Keweenawan basic extrusives associated with a thick sequence of Keweenawan sediments or pre-Keweenawan rocks.

In conclusion, it is possible to assign a lithologic type to a gravity or magnetic anomaly only in the most general sense because of the overlapping physical property parameters among rock types and the ambiguity

of potential field methods. In addition, the regional relationship must be used cautiously because the source of anomalies, particularly the gravity anomalies, may be deep seated and, therefore, not truly reflect the basement surface lithology.

General Characteristics of Gravity Anomalies

Discussion of Bouguer Anomaly Map

Interpretation of gravity maps generally begins with a qualitative approach which consists of noting trends and inspecting gradients, amplitude and shape of anomalies. The most important anomaly on the Bouguer Gravity Anomaly Map (Figure 4) is a positive anomaly which extends from the Southern Peninsula of Michigan to the vicinity of Beaver Island where it bifurcates, with one branch trending northwest and the other north. This anomaly is known as the "Mid-Michigan gravity high" in the Southern Peninsula and extends nearly the whole length of the Peninsula (Hinze, 1963). The width of the anomaly is very narrow in the vicinity of Beaver Island, but rather broad elsewhere. Its magnitude is of the order of 30 mgals in the Southern Peninsula and Northern Lake Michigan but decreases to 20 mgals in both northerly and northwesterly directions.

The northwestern branch of the anomaly is strongly asymmetric, with steeper gradients on the southwestern side. Patenaude (1964) and O'Hara (1967) have interpreted the steep gradients to indicate a northwest-southeast trending fault contact between Keweenaw volcanics and the older Precambrian rocks on the southwest. This anomaly extends to the vicinity of Munising and on the basis of magnetic evidence, which will be discussed in the following section and is presented in Figure 8, represents the continuation of the Middle Keweenaw basic volcanics from the Keweenaw Peninsula (Hinze, et al., 1966). The northern branch

of the anomaly extends across the eastern end of Lake Superior and ties in with Keweenaw basalts outcropping on Mamainse Point. The anomaly also extends to the east with considerable amplitude, finally decaying in amplitude near the Saint Marys River. The eastern branch gravity anomaly is associated with a very strong magnetic anomaly and is believed to indicate the extension of the Keweenaw basalts in an easterly direction to Saint Marys River.

These gravity anomalies correlate in general with positive magnetic anomalies (Figure 5). Hinze, et al., (1966) and O'Hara and Hinze (1971) have interpreted the magnetic anomalies to represent the limbs of the Lake Superior basin extending into the Northern Peninsula of Michigan. They further suggest that the basin terminates in the vicinity of Beaver Island where the magnetic positives join to form a single magnetic high which becomes strongly negative in the Grand Traverse Bay area and connects to the south with the "Mid-Michigan gravity and magnetic anomaly." The intense magnetic minimum in the Grand Traverse Bay region is interpreted to be the magnetic expression of reversely polarized magnetic basalts as observed elsewhere in the Lake Superior basin (Books, 1968).

The negative gravity anomaly to the west of the northern branch of the major positive gravity anomaly in the vicinity of Whitefish Point exhibits a magnitude of the order of 15 mgals. The steep gradients on the eastern side of the anomaly may be due to a fault downthrown to the west. The magnetic values over this gravity low are relatively high suggesting the presence of structurally disturbed volcanics in the area under an increased thickness of the Keweenaw sediments.

The negative gravity anomaly in the Whitefish Bay area to the east of the northern branch of the positive gravity anomaly is similar to the

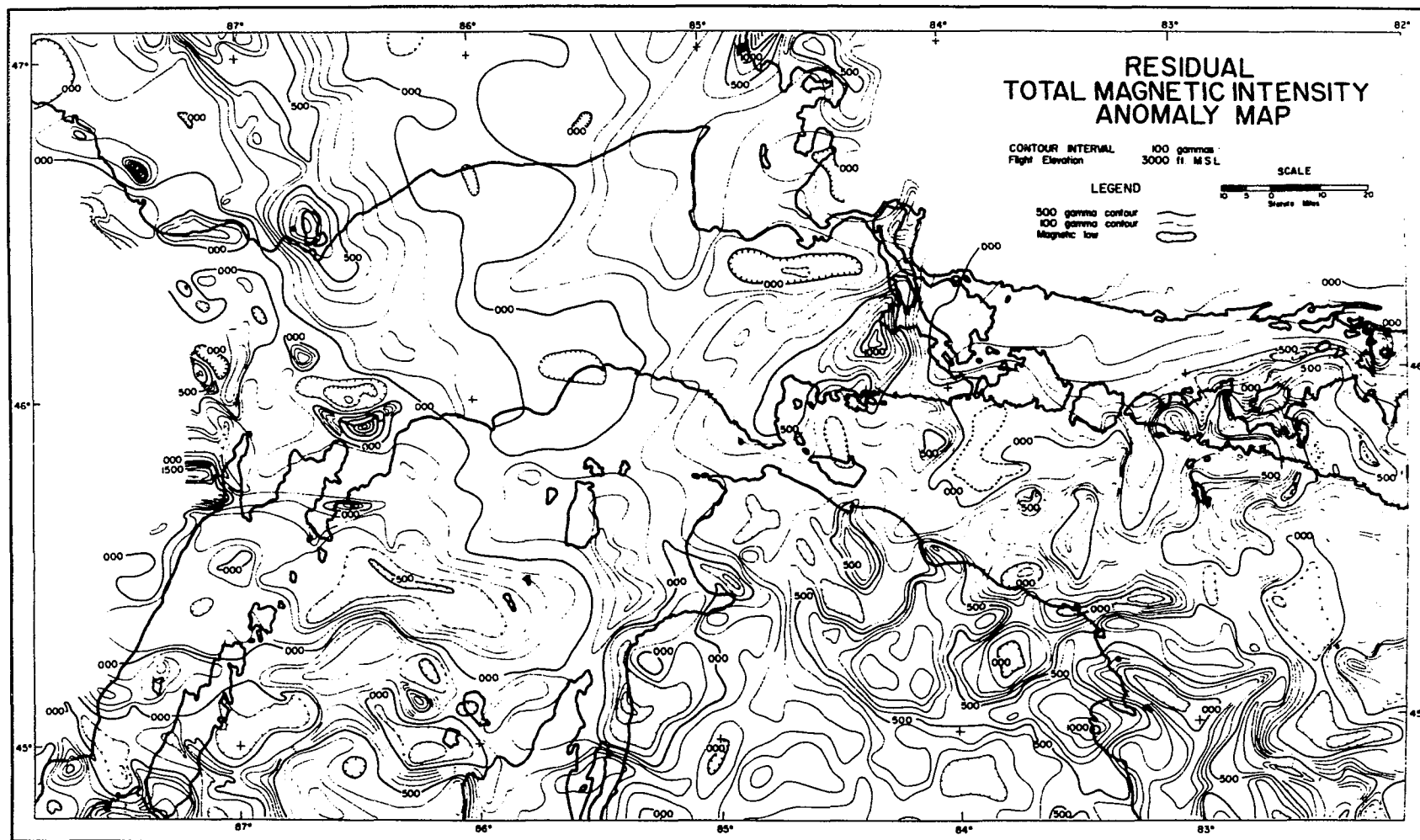


Figure 5.--Total Magnetic Intensity Anomaly Map of the eastern portion of the Northern Peninsula of Michigan.

previously described gravity low and probably has a similar source, that is a fault downthrown to the east and thickening of the Keweenawan sediments.

The positive gravity anomaly south of the Mackinac Straits is characterized by relatively steep gradients on both the eastern and the western sides and has a magnitude of 20 mgals. It is considerably elongated in a north-south direction. The magnetic values over this positive anomaly are relatively high, but there is no correlative magnetic high. In their magnetic study of Lake Huron, Secor, et al., (1967) have interpreted this area to be associated with a pre-Keweenawan mafic igneous complex extending south to Rogers City, Michigan. However, it is also possible that the positive gravity and magnetic anomalies are caused by an upfaulted block of Keweenawan volcanics.

The area east of $84^{\circ} 30'$ W on the Bouguer Gravity Anomaly Map (Figure 4) is characterized by broad negative anomalies, with the exception of a positive gravity anomaly centered in the vicinity of Elliot Lake in Ontario, whose magnitude is of the order of 20 mgals. It is associated with an east-west trending positive gravity anomaly which extends to Sudbury, Ontario as shown on the Bouguer Gravity Anomaly Map of Canada. This positive belt of gravity anomalies is identified with Precambrian metasedimentary and metavolcanic rocks within a structurally complex belt of folds and faults. The Total Magnetic Intensity Anomaly Map of the region east of $84^{\circ} 30'$ W is rather complex and exhibits in general, east-southeast trending anomalies with steep gradients and amplitudes ranging up to 1000 gammas or more. Hinze and Merritt (1969) have associated this complex pattern of magnetic anomalies in the eastern part of the northern tip of Southern Peninsula with metavolcanics, metasediments

and gneisses of pre-Keweenawan age. Further north, in the vicinity of North Channel, the major east-west trending negative magnetic anomaly is interpreted to indicate a predominantly granitic province (Secor, et al., 1967).

The western part of the Bouguer Gravity Anomaly Map is dominated by a very broad negative gravity anomaly which extends southward into Lake Michigan. There are a number of smaller anomalies within this negative anomaly which are associated with synclinal structures containing Animikean sediments and iron formations. In the vicinity of Escanaba, the continuation of Menominee iron range is clearly shown on both gravity and magnetic maps. Another gravity and magnetic high in the vicinity of Trenary, Michigan is associated with an east-west trending syncline filled with Animikean sediments (Frantti, 1956). Still another local positive gravity and magnetic anomaly occurs over Paleozoic sediments near Cooks, Michigan which may be associated with an east-west striking Precambrian iron formation (Hinze, et al., 1966). The amplitude of the broad negative gravity anomaly which encloses all the local anomalies, decreases in a southerly direction. In Green Bay and the western part of northern Lake Michigan where there is no gravimetric coverage, an intense regional magnetic minimum striking east-west from the western shore of Green Bay to the south of Beaver Island characterizes the southwestern portion of the study area (O'Hara and Hinze, 1971). This magnetic minimum is on strike with felsic rocks of the Mountain-Amberg area of Wisconsin which is also characterized by magnetic and gravity minimums.

In summary, the Bouguer Gravity Anomaly Map of the eastern portion of the Northern Peninsula of Michigan and the surrounding area is dominated

by a major positive gravity anomaly of considerable amplitude which is attributed to Keweenaw basalts and the local gravity minimums in the Whitefish Bay area, which are associated with thickening of the Keweenaw clastic sediments. This major anomaly transects roughly east-west trending gravity anomalies whose sources are generally believed to be pre-Keweenaw rocks. Although, the peaks of magnetic and gravity anomalies do not always correspond, their signs are, in general, the same. The main exceptions are the negative magnetic anomaly in the Grand Traverse Bay region and the relatively positive magnetic anomaly in the vicinity of Whitefish Point.

Discussion of the Double Fourier Series Residual Gravity Map

A Double Fourier Series Residual Gravity Map of the eastern portion of the Northern Peninsula of Michigan and surrounding area was prepared in an attempt to isolate anomalies which are less obvious in the Bouguer Gravity Map.

The double Fourier series has recently come into use in geology and geophysics as an alternative approach to the least-squares polynomial method for isolating anomalies. A method of double Fourier series for surface fitting of irregularly spaced data has been described by James (1966). This method was used to calculate the Double Fourier Series Residual Gravity Map as shown in Figure 6. The residual values were obtained by removing from the Bouguer Gravity Map fundamental wavelengths of 475 miles in the east-west direction and 575 miles in the north-south direction. Thus, all wavelengths in excess of 95 miles in the east-west direction and 113 miles in the north-south direction have been removed in the Double Fourier Series Residual Map. The selection of the fundamental wavelengths was based on the observation of the half-wavelengths

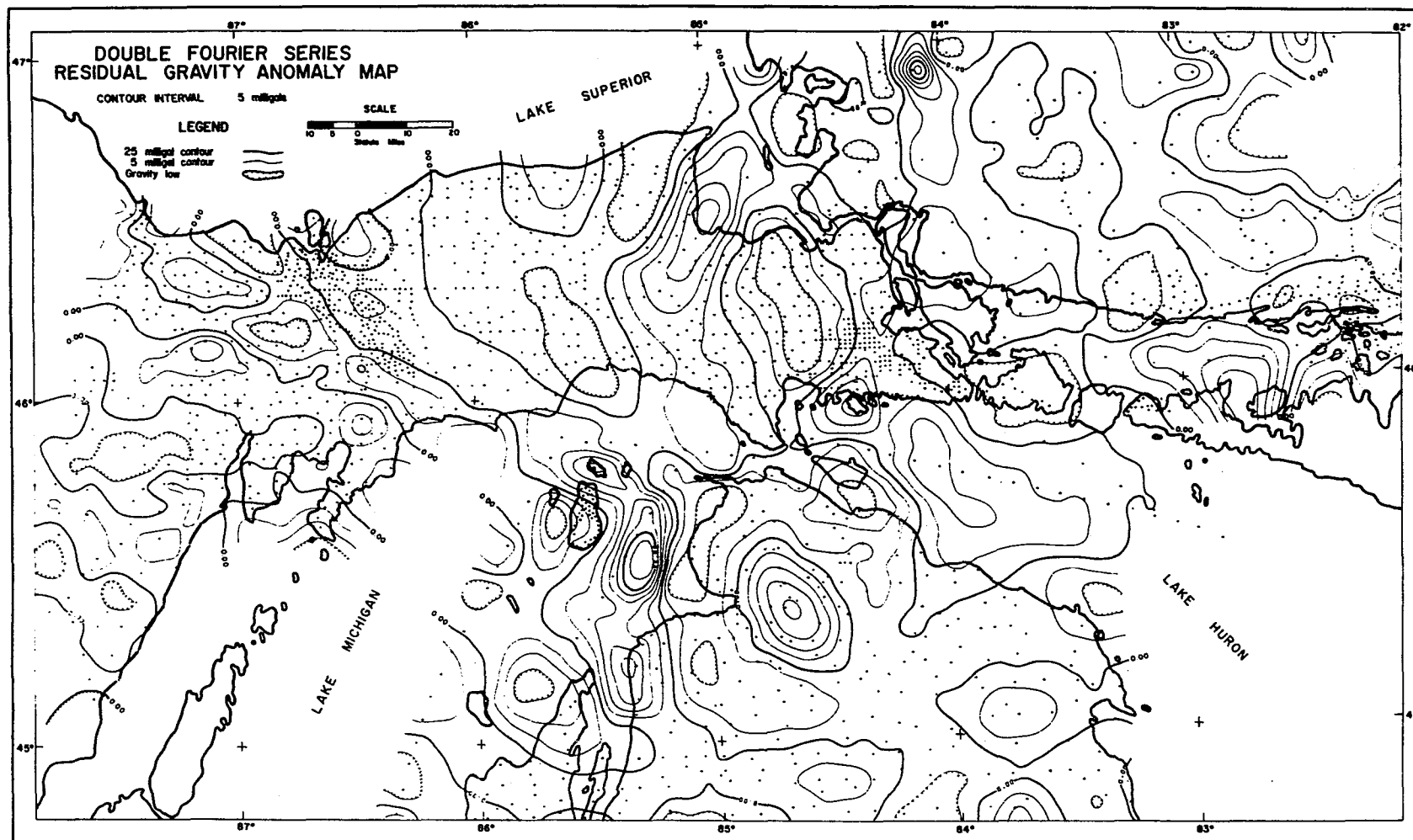


Figure 6.--Double Fourier Series Residual Gravity Anomaly Map of the Northern Peninsula of Michigan.

of the major gravity anomalies of the Bouguer Anomaly Map. Anomalies trending significantly different than either east-west or north-south may be considerably distorted as a result of the directions of the fundamental wavelengths (Whitten, 1969). In addition, the removal of the long wavelength components from predominantly short wavelength anomalies also causes distortion of these anomalies.

The predominant anomalies of the Double Fourier Series Residual Map (Figure 6) correlate with the previously discussed major positive gravity and magnetic anomalies on Figures 4 and 5. A major anomaly extends north from the Southern Peninsula of Michigan and bifurcates northeast of Beaver Island, with one branch trending north through Whitefish Bay and the other trending northwest through Grand Island. The north trending anomaly with large amplitude and steep gradients is much more obvious on Figure 6 than the corresponding anomaly shown on the Bouguer Gravity Anomaly Map of Figure 4. However, the northwest trending branch is rather subdued in amplitude. The eastern extension of the major gravity anomaly has been isolated as a positive gravity anomaly northeast of the Mackinac Straits, which in general correlates with the positive magnetic anomaly in the Pickford area. However, its position is slightly to the south of the magnetic anomaly.

The well defined gravity lows on either side of the north branch of the major gravity anomaly in the vicinity of Whitefish Bay on the Bouguer Gravity Anomaly Map are shown to have more regional extent in Figure 6 as a result of the isolation of the positive anomalies. Also a positive anomaly has been isolated between Grand Island and Whitefish Bay.

The positive gravity anomaly south of the Mackinac Straits is shown to be isolated in the Double Fourier Series Residual Gravity Map, but still has a northwest-southeast trend.

The east-west trend of the pre-Keweenawan structures in the western part of the area is shown well in Figure 6. Most important, however, is the separation of the positive gravity anomaly south of Marquette from the northwest branch of the major gravity anomaly. This anomaly has a distinct east-west trend and, therefore, is associated with the pre-Keweenawan rocks.

Figure 7 shows the Bouguer, double Fourier residual and the regional gravity curves along profile E-E'-E" at the eastern portion of the Northern Peninsula. The regional gravity values were obtained by subtracting the contoured double Fourier series residual values from the Bouguer gravity values. The purpose of Figure 7 is to illustrate the characteristics of the regional values which have been removed from the map of Figure 6. The regional profile shows long wavelength and relatively large amplitude anomalies which result partly from the longer wavelength components of the volcanics and partly from deep crustal specific gravity variations, perhaps associated with intrusions related to Keweenawan igneous activity.

In conclusion, the Double Fourier Series Residual Gravity Map has added information to the anomalous trends of the Bouguer Gravity Anomaly Map.

Comparison of Profiles With the Aid of Upward Continuation

In this study, five gravity and magnetic profiles were constructed from the Bouguer Gravity Anomaly Map (Figure 4) and the Total Intensity Magnetic Anomaly Map (Figure 5) of the eastern portion of the Northern Peninsula of Michigan and the surrounding area, the Total Magnetic Intensity Anomaly Map of the Eastern Lake Superior (Hinze, et al., 1966) and the

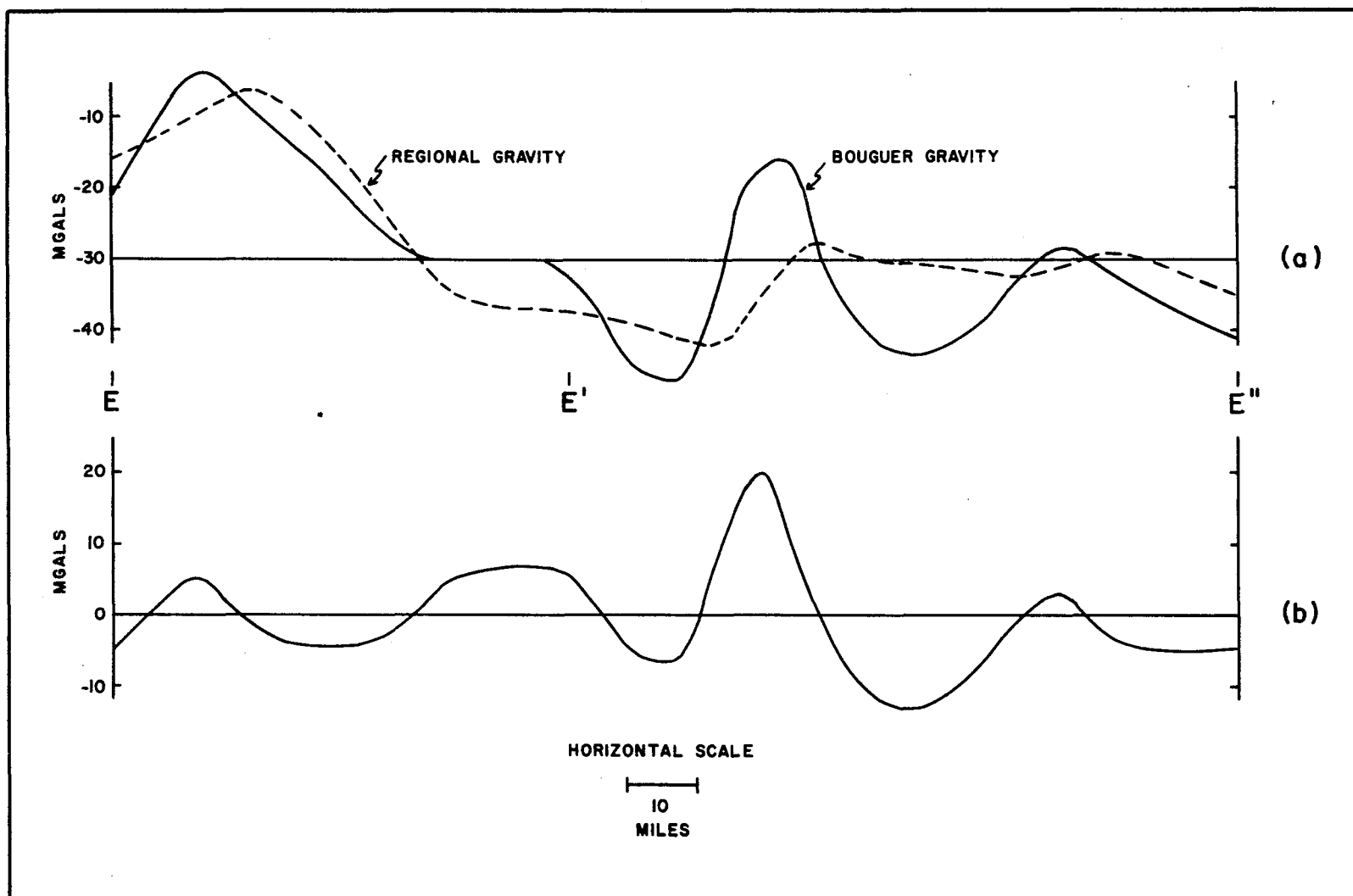


Figure 7.--Profile of a) the Bouguer and regional gravity curves, and
 b) residual values for double Fourier series fit.
 (Location of this profile is shown in Figure 8)

Bouguer Gravity Anomaly Map of the Lake Superior Region (Weber and Goodacre, 1966). The selected profiles are presented in Figure 8. The profiles are approximately perpendicular to the major anomalies and have been plotted from a common datum. In addition, all profiles have been analytically upward continued using a 17 point upward continuation formula developed by Hinze (1960), to make the level of gravity observations for all profiles approximately an equal distance from the basement. Upward continuation has made little change in these because of the broad wavelengths of the anomalies.

The magnetic anomalies on the southwestern side of the profiles show good continuity, therefore, the correlation of gravity anomalies on the same side of the profiles will be discussed first. On Profile A-A', the magnetic anomaly with a magnitude of about 1000 gammas originates from the Middle Keweenaw basic volcanics outcropping on the Keweenaw Peninsula. The Keweenaw fault which has a near vertical dip in this area extends along the southern margin of the volcanics. The volcanics are overlain to the north by clastic sediments and the Keweenaw fault brings them into contact with the Upper Keweenaw clastics to the south. This positive magnetic anomaly and the flanking lows associated with it are directly related to a gravity anomaly which becomes obscure to the north because of lack of gravity data. However, the positive gravity anomaly which is flanked by a minimum to the south is interpreted to indicate the presence of thick volcanics in the area.

The magnetic and gravity anomalies are continuous from profile A-A' to profile B-B'. However, on profile B-B', the peaks of the magnetic and gravity anomalies do not correspond. This could be attributed to the scarcity of gravity data in the area. However, it is also possible that the volcanics are near the surface under the magnetic high but are at a

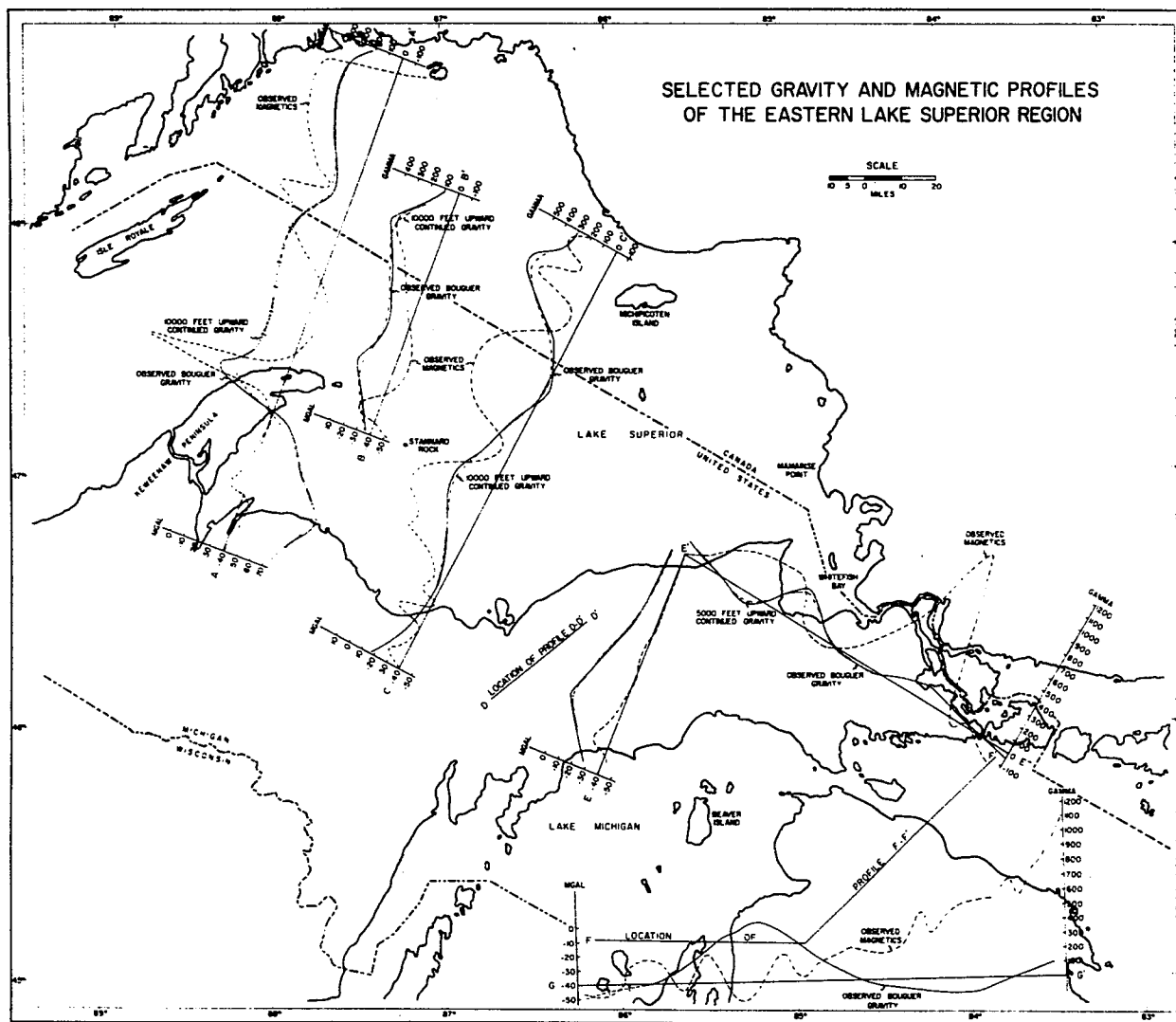


Figure 8.--Selected gravity and magnetic profiles of the eastern Lake Superior Region.

considerable depth and thicker under the gravity high. In addition to having offset peaks, the magnetic and gravity anomalies differ in amplitude and gradients from those on profile A-A'. This can be explained by either differing thickness or dip of volcanics in the two areas.

Profile C-C' exhibits much the same pattern as the previous two profiles. The magnetic anomaly on profile C-C' corresponding to the Middle Keweenaw volcanics is broader and slightly lower in amplitude than the same magnetic anomaly on profile A-A'. Hinze, et al., (1966) have interpreted a fault at the southwestern side of this anomaly and suggested that it is the continuation of the Keweenaw fault.

The interpretation of magnetic and gravity highs on profile A-A', B-B' and C-C' indicates continuation of the Middle Keweenaw volcanics from Keweenaw Point in a southeasterly direction. This is substantiated by volcanic rocks found on Stannard Rock, which occurs in Lake Superior roughly midway between Keweenaw Point and Grand Island.

Further southeast from profile C-C', profile E-E' is characterized by a broad gravity high which correlates well with the corresponding positive gravity anomaly on profile C-C'. It has approximately the same width, amplitude and the gradients, thus indicating the extension of the Middle Keweenaw volcanics into the eastern portion of the Northern Peninsula of Michigan. However, the amplitude of the associated magnetic anomaly is considerably less indicating that the volcanics in this area are relatively undisturbed having low dips and under a considerable thickness of sedimentary cover.

A strongly asymmetric positive magnetic anomaly with steeper gradients on the northern side, marks the central part of profile A-A'. This anomaly is interpreted as the extension of the Middle Keweenaw basic

volcanics on Isle Royale with Isle Royale thrust fault marking the northern edge of the anomaly (Hinze, et al., 1966). Further north along profile A-A' another positive magnetic anomaly is also believed to be associated with basic volcanics dipping toward the axis of the Lake Superior syncline. This positive magnetic anomaly is directly related to a broad positive gravity anomaly.

The central part of profile C-C' is associated with a gravity minimum and a magnetic high. Both these anomalies are broad and of considerable amplitude. The broad positive magnetic anomaly is believed to result from faulted and relatively thin near surface volcanics. The positive gravity and magnetic anomalies on the northeastern end of profile C-C' are correlated with basic Keweenaw volcanic rocks of Michipicoten Island. The complex nature of the magnetic anomalies in this area is believed to reflect the existence of two roughly northwest-southeast trending faults (Hinze, et al., 1966).

The positive gravity anomaly situated in Whitefish Bay, on profile E'-E" is very similar in its characteristics to the gravity anomaly west of Michipicoten Island. This anomaly may represent the continuation of the Keweenaw volcanics of Mamainse Point which Green (1971) has placed in both the Lower and Middle Keweenaw or it may be the extension of the Middle Keweenaw volcanics of Michipicoten Island. If future gravity studies in eastern Lake Superior confirm the latter suggestion, then perhaps the Michipicoten thrust fault extends along the eastern edge of the positive gravity anomaly. The gravity minimums on either side of the positive anomaly suggest a thickening of the Keweenaw sediments over the volcanics in the area. The broad positive magnetic anomaly which is associated with the gravity minimum to the northwest of

the gravity high is interpreted to result from faulted and steeply dipping volcanics. The southeastern end of profile E'-E" exhibits a positive magnetic anomaly whose amplitude reaches 1000 gammas. The gravity anomaly which is associated with this magnetic high is very broad and has a relatively small amplitude. These magnetic and gravity anomalies are interpreted to indicate a thinning of the Keweenaw volcanics to the east with near surface extrusives or intrusives causing the high amplitude of the magnetic anomaly.

The positive gravity anomalies on profiles E-E' and E'-E" join together to form a single gravity high on profile G-G'. The peak of this anomaly is inversely related to a negative magnetic anomaly which has been interpreted to be the magnetic expression of reversely polarized magnetic basalts (O'Hara and Hinze, 1971). Profile G-G' was further compared with an upward continued typical Bouguer gravity anomaly profile of the "Mid-Continent gravity high." This comparison showed that the gravity anomalies differ in amplitude and gradients but the width of the anomalies are similar. A possible explanation for this is that the volcanics are thicker and the structure is very complex in areas associated with the "Mid-Continent gravity high."

In summary, the comparison of gravity and magnetic profiles strongly indicate that the Middle Keweenaw volcanics of the Keweenaw Peninsula curve southward through Stannard Rock and extend into the eastern portion of the Northern Peninsula of Michigan, and join the Middle Keweenaw volcanics extending south from Mamainse Point, Ontario, in the vicinity of Beaver Island to become associated with the "Mid-Michigan gravity and magnetic anomaly" of the Southern Peninsula of Michigan.

Model Studies

The purpose of the gravity model studies in this section is to quantify the qualitative interpretation of the previous sections. The configuration and horizontal and vertical extent of principally the Keweenawan rocks, both the clastic sediments and igneous rocks, are studied by the method of model studies and matching observed and calculated gravity curves. Magnetic effects from gravitationally constructed models were also calculated and compared with the observed magnetic curves. Four profiles of observed Bouguer gravity and total intensity magnetic anomalies were selected for quantitative investigation. The location of these profiles is shown in Figure 8.

Gravity and magnetic effects of basement structures were computed using standard two dimensional theory developed by Talwani, et al., (1959). The assumption of two dimensionality is justified because most anomalies are horizontally linear having greater lengths than widths. However, the results of model studies are not unique because of uncertainties in the physical properties of the rock units. In the models, high density basalts and low density sedimentary rocks overlie the pre-Keweenawan rocks. In addition, the observed gravity and magnetic curves can be matched in more than one way by varying the thicknesses of the rock units. Therefore, in constructing the models, geologically reasonable structures based on studies elsewhere in the Lake Superior region were considered and no attempt was made to precisely match calculated and observed anomaly profiles.

Furthermore, only the upper basement structures were considered in the models. Cohen and Meyer (1966) in their study of the "Mid-Continent gravity high" in northeastern Minnesota and northwestern Wisconsin

combined the effect of a basalt trough with the effect from a downwarped Moho. Their analysis is based on loading of the crust and its subsequent deformation by a two dimensional body. The crust behaves like an elastic beam, while conserving isostatic balance. Kellogg (1971) has studied a similar model across the "Mid-Michigan gravity high" in the eastern part of the Southern Peninsula of Michigan. He reports that the gravity gradient attributed to the downwarped Moho is only 0.2 mgal per mile. Therefore, the downwarped Moho can account for only a small portion of the negative anomaly associated with the "Mid-Michigan high," the remainder coming from specific gravity contrasts within the upper crust.

Specific gravities and magnetic properties used in the models are based on published measurements. Table 2 presents a brief summary of the specific gravities of rocks of the Lake Superior area from previous studies. Magnetic susceptibilities of pre-Keweenawan rocks and other magnetic rocks, with the exception of Keweenawan basalts, were modified to match the observed magnetic profiles. Remanent as well as induced magnetic polarization was used in the calculation of the magnetic effect of the Keweenawan basalts. Approximate values given by Du Bois (1962) for the remanent magnetic polarization component of basic Keweenawan volcanics were vectorially combined with the induced magnetization component, to calculate the total magnetic polarization vector. The induced susceptibility value in Table 3 which summarizes the results, was also taken from Du Bois (1962). Calculation of the combined vector was made assuming no rotation of the remanent magnetization component of the Keweenawan lavas due to deformation. It is realized that this assumption has introduced error in the calculated anomalies because the basalts have been deformed. Furthermore, negative magnetic polarization of basalts as observed at Mamainse Point can cause error in the calculated profiles.

TABLE 2

Specific gravities of Precambrian rocks in the Lake Superior Region

<u>Source</u>	<u>Jacobsville Formation- Bayfield Group</u>	<u>Oronto Group</u>	<u>Middle Keweenawan Volcanics</u>	<u>Pre-Keweenawan Rocks</u>
Theil, 1956	2.30 ± 0.06	2.36 ± 0.12	2.90 ± 0.10	
White, 1966	2.30 2.37	2.44 2.62	2.90 2.92	2.67
Bacon, 1966	2.25	2.66 (Freda)	2.88	2.70
Weber and Goodacre, 1966	average of both groups 2.50		2.97	2.70
Steinhart and Smith, 1966	2.30-2.36	2.43-2.54		2.70-2.80
Steinhart et al., 1968	2.30	2.66		

TABLE 3... Parameters of induced, remanent and combined polarization components of the Keweenaw basalts.

Component	Magnetic Polarization	Inclination	Declination
Induced	0.00091 emu/cc	+71°	0°
Remanent	0.00354 emu/cc	+45°	285°
Combined	0.00425 emu/cc	+53°	292°

Interpreting gravity anomalies by the method of matching profiles is ambiguous. Therefore, the thicknesses used in the models must be geologically reasonable. The guide for this is published thickness estimates of geological units which are summarized in Table 4.

Profile E-E'

Profile E-E' is oriented southwest-northeast in the central part of the eastern portion of the Northern Peninsula. The positive gravity anomaly on this profile is attributed to the Middle Keweenaw basalts extending from the Keweenaw Point. The specific gravity of these basalts was taken to be 2.95. The basalts gradually thin out in a southwesterly direction. A reverse fault with limited vertical displacement was included in the model on the basis of previous geophysical interpretation. However, the gravity curve could be equally well matched without the fault (Figure 9a). The thicknesses used in this model are well within the limitations given in Table 4.

The magnetic profile, which was calculated from the gravitationally constructed model, agrees in general with the observed magnetic profile. There is no well data available in the vicinity of this profile to check

TABLE 4

Thicknesses (km) of the Keweenaw rock units in the Lake Superior Region

<u>Source</u>	<u>Jacobsville Formation- Bayfield Group</u>	<u>Oronto Group</u>	<u>Middle Keweenaw Volcanics</u>	<u>Location</u>
Tyler et al., 1940	1.3	4.2		Southwestern Lake Superior
Bacon, 1966	3.0			Keweenaw Fault
White, 1966b			6.1-9.1	Lake Superior Basin
Halls, 1966			7.6 4.6	North Shore Volcanics Mamainse Point
Berkson, 1969 (after Ocola, 1968)	1.0-1.5	1.0-1.5	4.0-5.0	Eastern Lake Superior
Berkson, 1969 (After Anzoleaga, 1968)	1.0	1.5-3.8	5.8	Western Lake Superior

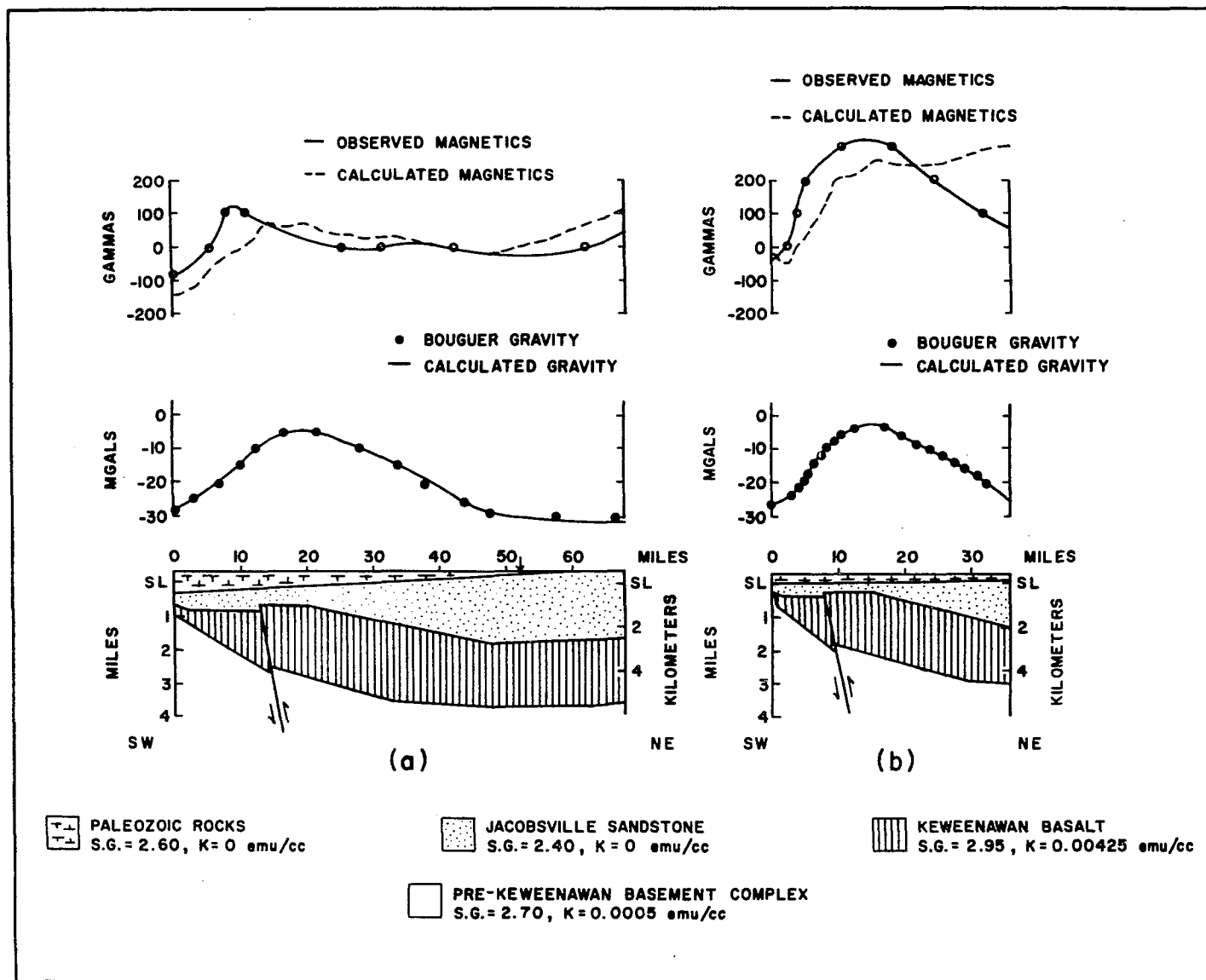


Figure 9.--Geological model and observed and computed gravity and total magnetic intensity anomaly profiles along a) E-E' and b) D-D'.

the feasibility of the model. The deepest well drilled in the vicinity is sixteen miles to the east at mile 52 of the profile. It penetrated 1000 feet of Jacobsville sandstone before drilling was halted.

Profile D-D'

Another model along profile D-D', approximately 30 miles west of profile E-E', was studied (Figure 9b) to further define the source of the anomaly investigated in the previous model. The resulting model from both magnetic and gravity calculations is similar. The fault is again, not a major feature and therefore subject to question.

An alternative geological model to Profile E-E'

An alternative model to profile E-E' based on the geology in the vicinity of Batchawana Bay, Ontario (Halls, 1966) was studied and is illustrated in Figure 10. In this alternative model the Freda sandstone lies between the Middle Keweenawan basalts and the Jacobsville sandstone. Therefore, to accommodate the Freda, basalts are thinner and deeper northeast of the fault as compared with the previous interpretation along profile E-E'. This model is not unique although the thickness of the Freda sandstone is based on thicknesses measured elsewhere. The Freda could be thinner which would lead to thicker basalts or if it is thicker, the basalts are thinner than shown in Figure 10.

The important difficulties with the geological model of Figure 10 are, first, the thickness of the basalts which is less than the observed geological measurements and second, the identification of the Freda sandstones in the vicinity of Batchawana Bay is open to question (Trow, 1971). The magnetic profiles computed from models of Figures 9a and 10 are not sufficiently different to aid in the selection of optimum model.

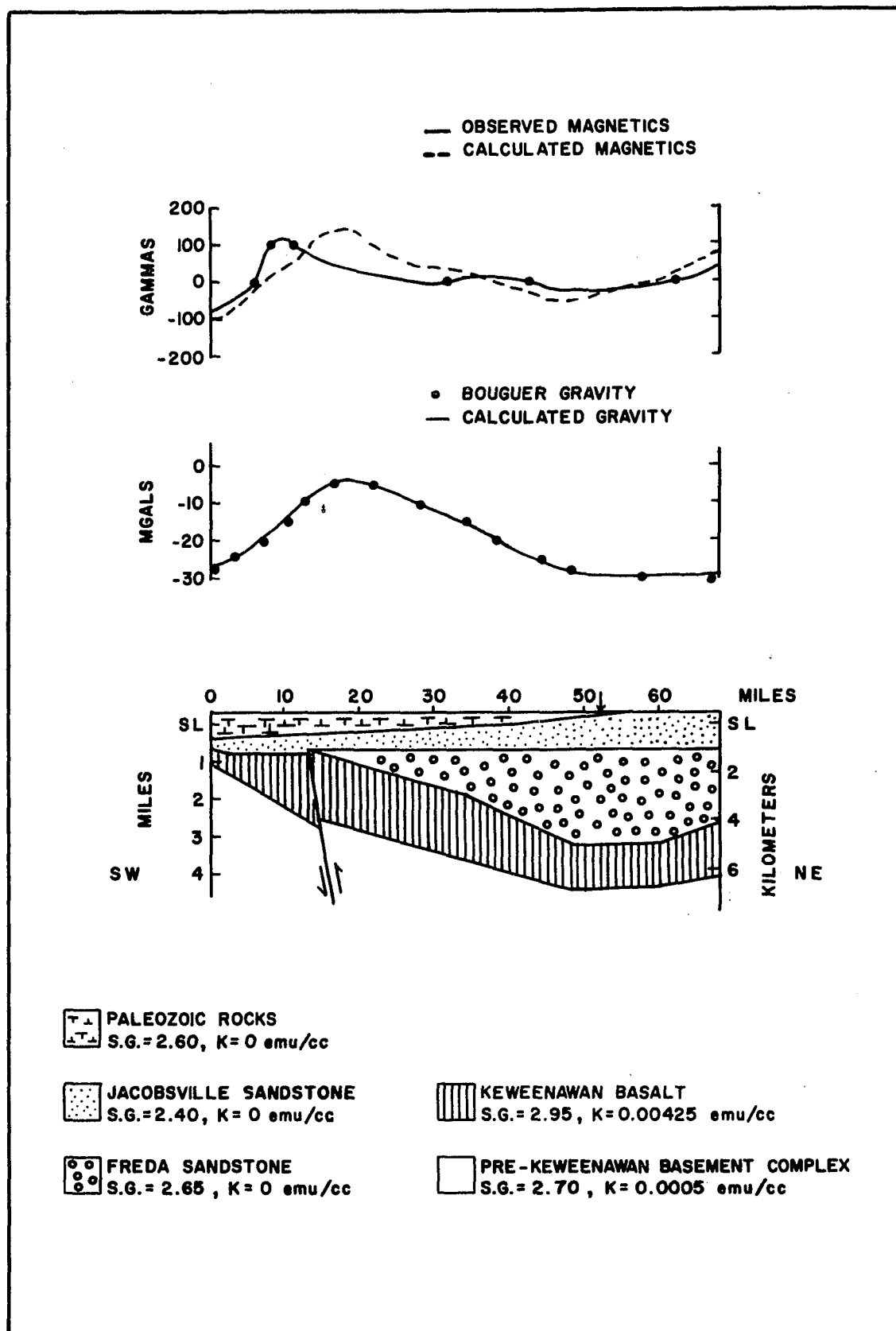


Figure 10.--Alternative geological model to profile E-E'.

Profile E'-E''

Figure 11 illustrates the geologic model of profile E'-E'' which extends northwest-southeast through the shores of Whitefish Bay and terminates south of Drummond Island. An upfaulted block of the Middle Keeweenawan basalts which extend to Mamainse Point, Ontario is shown to cause the positive gravity anomaly. The basalts in general, have low dips except in the vicinity of faults. Low specific gravity sediments of Jacobsville age overlie the basalts. Both the sediments and the basalts thin out to the east.

The observed and theoretical gravity curves match well. However, the calculated magnetic profiles show appreciable deviations. The observed magnetic curve corresponds to upfaulted and downfaulted blocks and agrees with the gravity curve. The lack of correlation of the theoretical and observed magnetic profiles may result from deviation of the magnetic vector from that assumed and deformation of the basalts.

There is a very high amplitude magnetic anomaly near the southeastern end of the profile in Figure 11. This anomaly was approximated by a high magnetic polarization source, essentially twice that of normal basalts. In order to match the observed anomaly, the susceptibility of this body was taken to be 0.01 emu/cc. This is a high susceptibility value, but can be considered to include the remanent magnetization effects. The source of the high amplitude magnetic anomaly is shown in Figure 11 as an intrusive, perhaps associated with extrusive rocks with strong remanent magnetization effects. Patenaude (1964) interpreted this magnetic maximum to indicate a high angle fault in the basic volcanic rocks. However, the gravity anomaly corresponding to the magnetic high has gentle slopes and therefore, does not substantiate the presence of a fault.

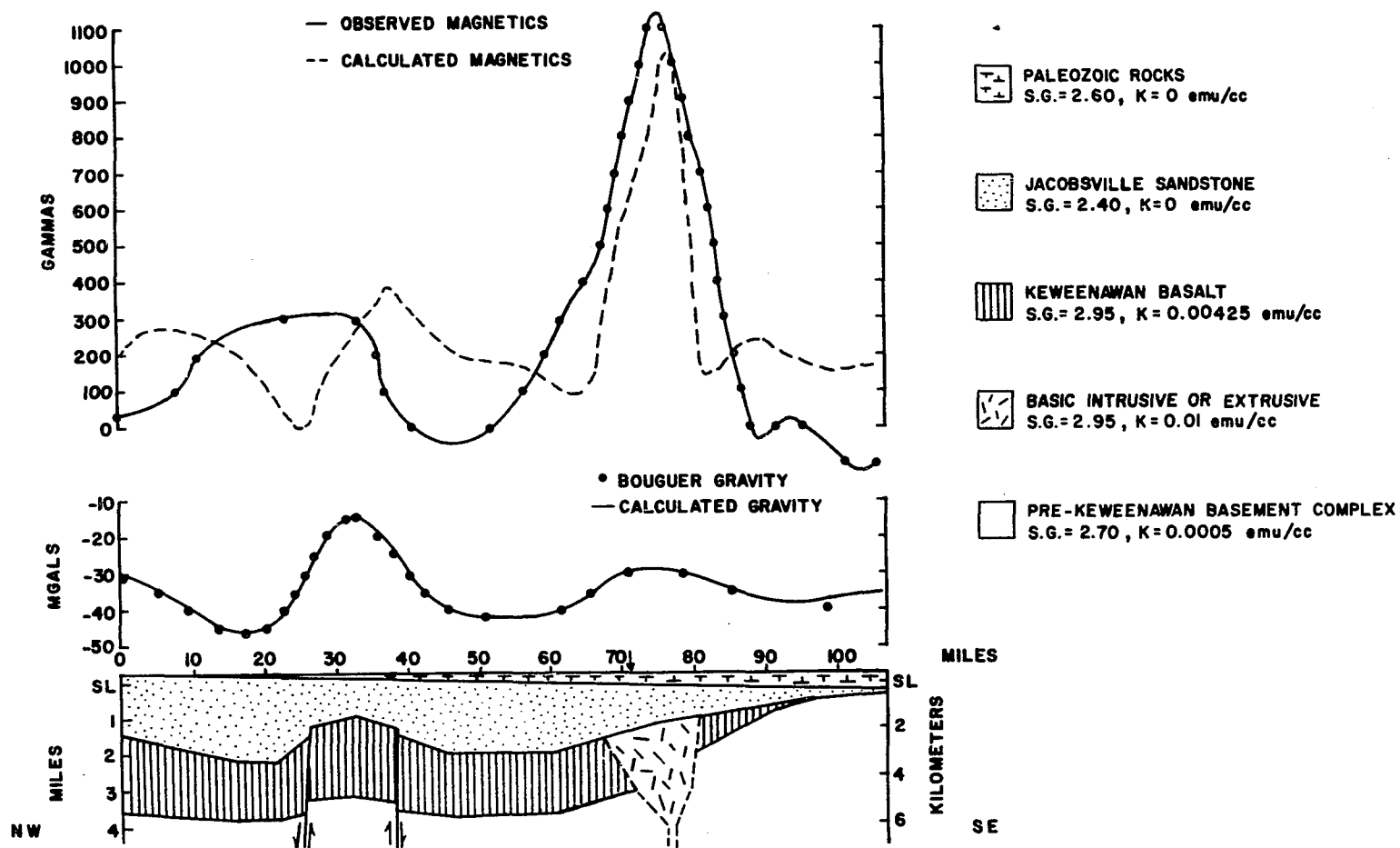


Figure 11.--Geological model and observed and computed gravity and total magnetic intensity anomaly profile along E'-E''.

The only geological control on this model is a well which was drilled to a depth of 1500 feet in sandstone, 12 miles to the northwest of Pickford, Michigan. The extrapolated location of this drill hole into the plane of the cross-section is at mile 71 of the profile.

An alternative geological model to Profile E'-E''

An alternative geological model to profile E'-E'' is illustrated in Figure 12. It includes the Freda sandstone between the basalts and the Jacobsville sandstone. As in the geological model presented in Figure 10, the presence of Freda sandstone in this model is questionable.

Profile F-F'

Figure 13 illustrates the model study of profile F-F' in the Southern Peninsula of Michigan. In constructing this model, the positive gravity anomaly south of the Mackinac Straits is related to Middle Keweenawan basalts which have been interpreted as the source of the "Mid-Michigan gravity high" to the south. The basalts are highly faulted with vertical displacements from 500 to approximately 4500 feet. The upfaulted blocks of basalt cause the gravity highs and the downfaulted areas filled with light sediments are the source of gravity lows.

A palinspastic cross-section of the basalts is shown in Figure 13 to illustrate their pre-faulting position. The interpreted geological cross-section across the East African Rift zone in the region of Lake Manyara (Girdler, et al., 1969) closely resembles the structure interpreted across Profile F-F'.

The observed and calculated gravity curves of Figure 13 match well. However, the magnetic anomaly curves show considerable deviation from each other. The intense Grand Traverse Bay magnetic minimum corresponds to the gravity high near the western end of the profile. This negative magnetic anomaly was approximated by assuming a trough of reversely

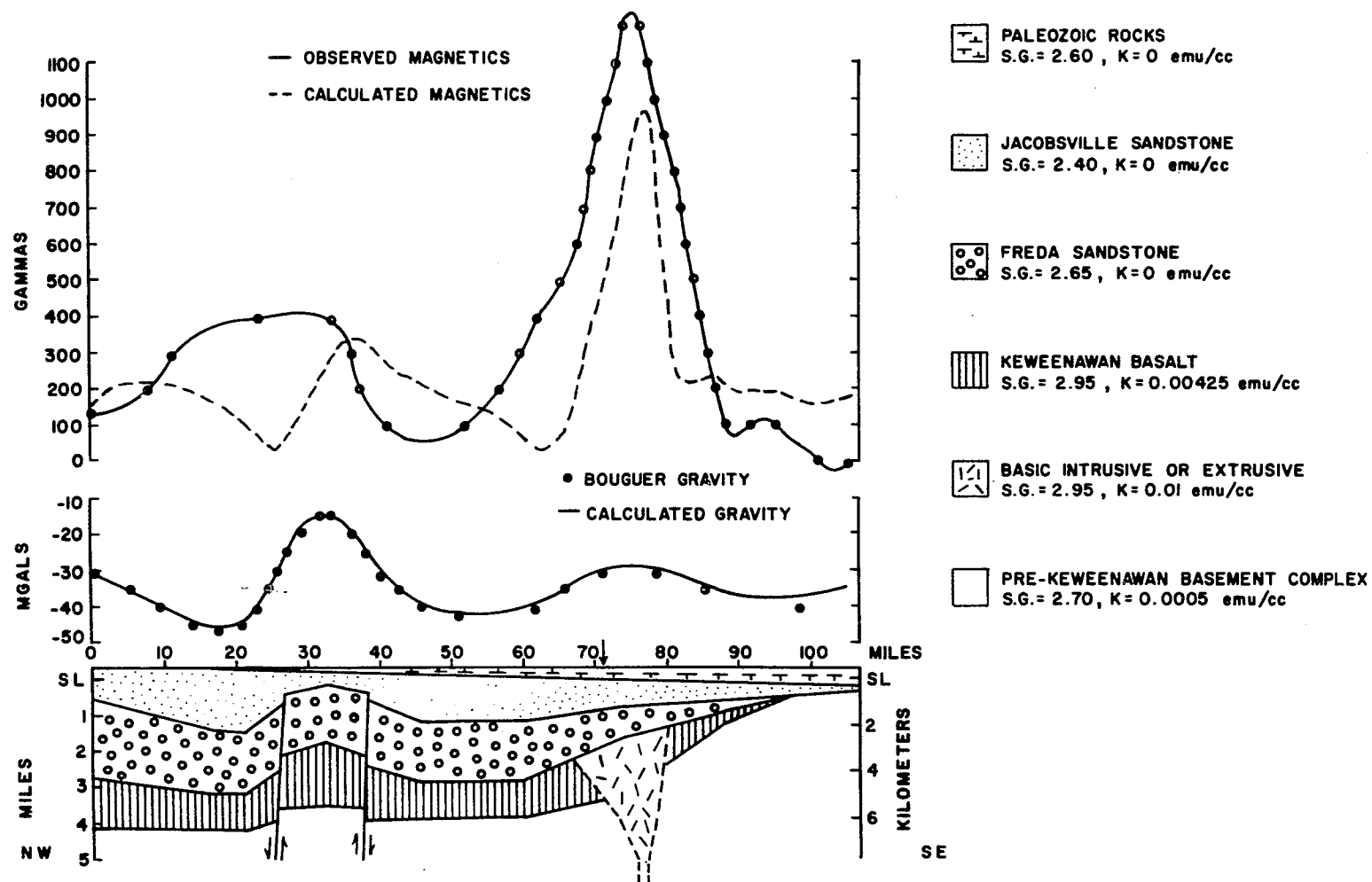


Figure 12.--Alternative geological model to profile E'-E''.

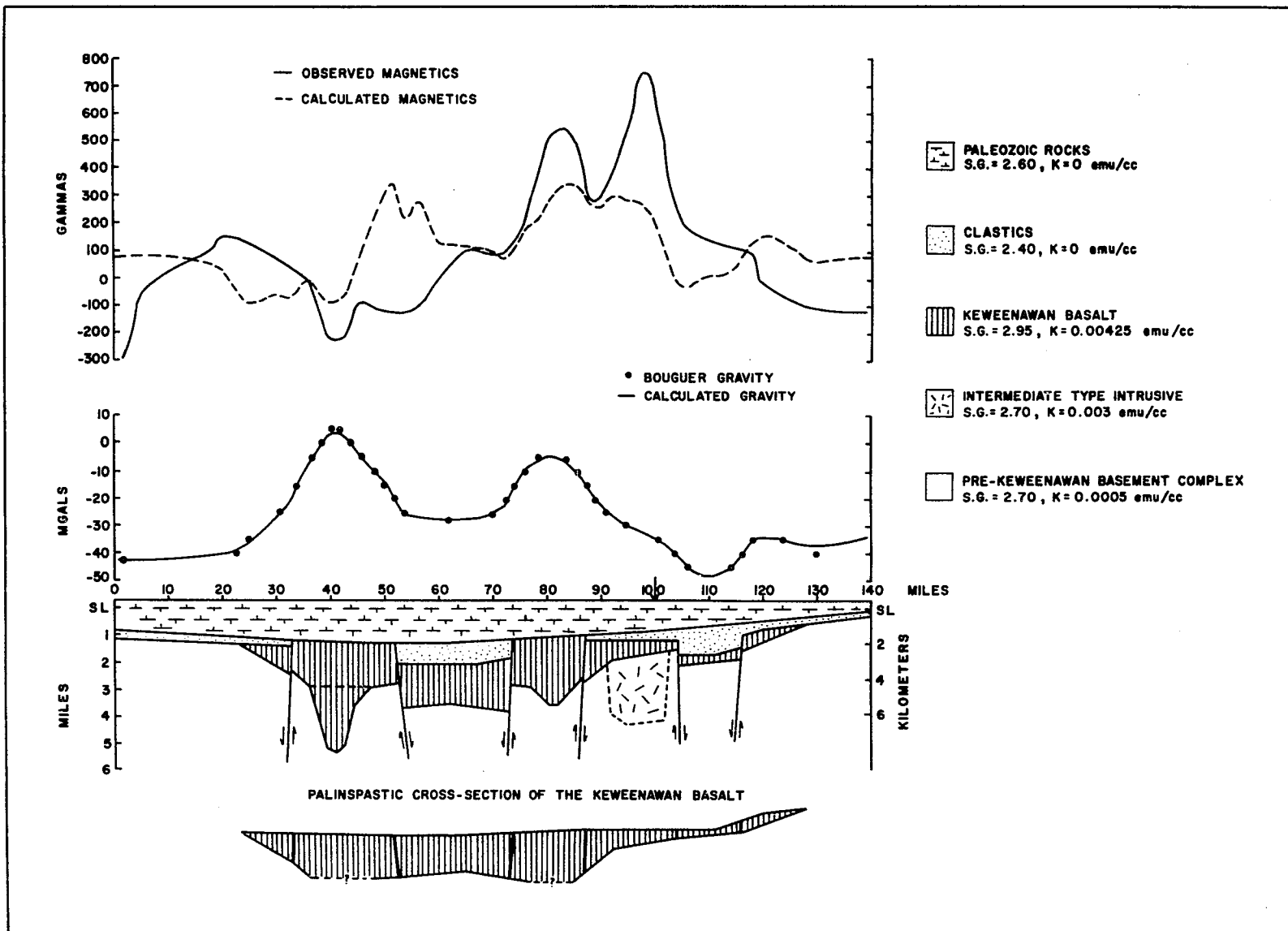


Figure 13.--Geological model and observed and computed gravity and total magnetic intensity anomaly profiles along F-F'.

magnetized older flows. The assumption of older, reversely polarized magnetic flows is justified by the common occurrence of reversely polarized extrusives in the Lower Keweenawan series as shown in Table 1.

Assuming the total magnetization vector of Table 3 that is derived from Du Bois' magnetic studies of the Keweenawan basalts, it is impossible to obtain the observed magnetic anomaly from basalts in the northeastern portion of the profile. Therefore, it is suggested that more highly magnetic rocks underlie the basalts in the vicinity of the observed magnetic high as shown in Figure 13. Although including a body of high magnetization in the model improved the match between the observed and calculated magnetic curves, the observed amplitude is still too high. Therefore, the possibility of faulting cannot be ruled out as a partial explanation for this anomaly.

A basement drill hole twelve miles south of the profile in Presque Isle County, Michigan which was projected into the plane of the cross-section at mile 100 of the profile where Keweenawan clastics are shown as thinning, encountered no abnormally thick sediments beneath the Paleozoic rocks. It bottomed in greenstones at approximately 4900 feet below sea level. Bass (1971), on examination of the greenstone cuttings from this well, has suggested that the greenstones are altered Keweenawan basalts. The greenstones encountered in this well are supportive of this model if indeed they are of Keweenawan age. It is significant to note that the greenstones underlie approximately 200 feet of quartzite which may suggest that the greenstones are of pre-Keweenawan age. In this case, the interpreted geological model may be incorrect or it suggests that the Keweenawan rocks do not extend southeast to the basement drill hole.

An alternative geological model to Profile F-F'

Assuming that basalts are more restricted in their areal extent, the geological model shown in Figure 14 was constructed. In this model, the Middle Keweenaw basalts are shown to wedge out at the center of the profile. The positive gravity anomaly south of the Mackinac Straits is associated with basic extrusives or intrusives of pre-Keweenaw age. A downfaulted block filled with light sediments causes the gravity low near the northeastern end of the profile. This gravity low could also be explained by a granitic intrusive having a lower specific gravity than the surrounding rocks.

Summary of the results

The geological cross-sections considered in this section were constructed by using all the available geological control. However, the results are not unique for two principal reasons. First, the physical properties of the rock units are not known with certainty and, second, observed and calculated curves can be equally well matched in more than one way by varying the thicknesses of the low specific gravity sediments and the high specific gravity basalts with respect to each other.

The calculated gravity profiles over all the models match well with the observed profiles, but the magnetic curves over the gravitationally calculated models show significant deviations from the observed curves on profiles E'-E" and F-F'. This is explained by the unknown total magnetization vector and effects of deformation of the Keweenaw basalts.

More geological data as well as crustal seismic refraction studies are needed to assist in the further evaluation of the models proposed in this study.

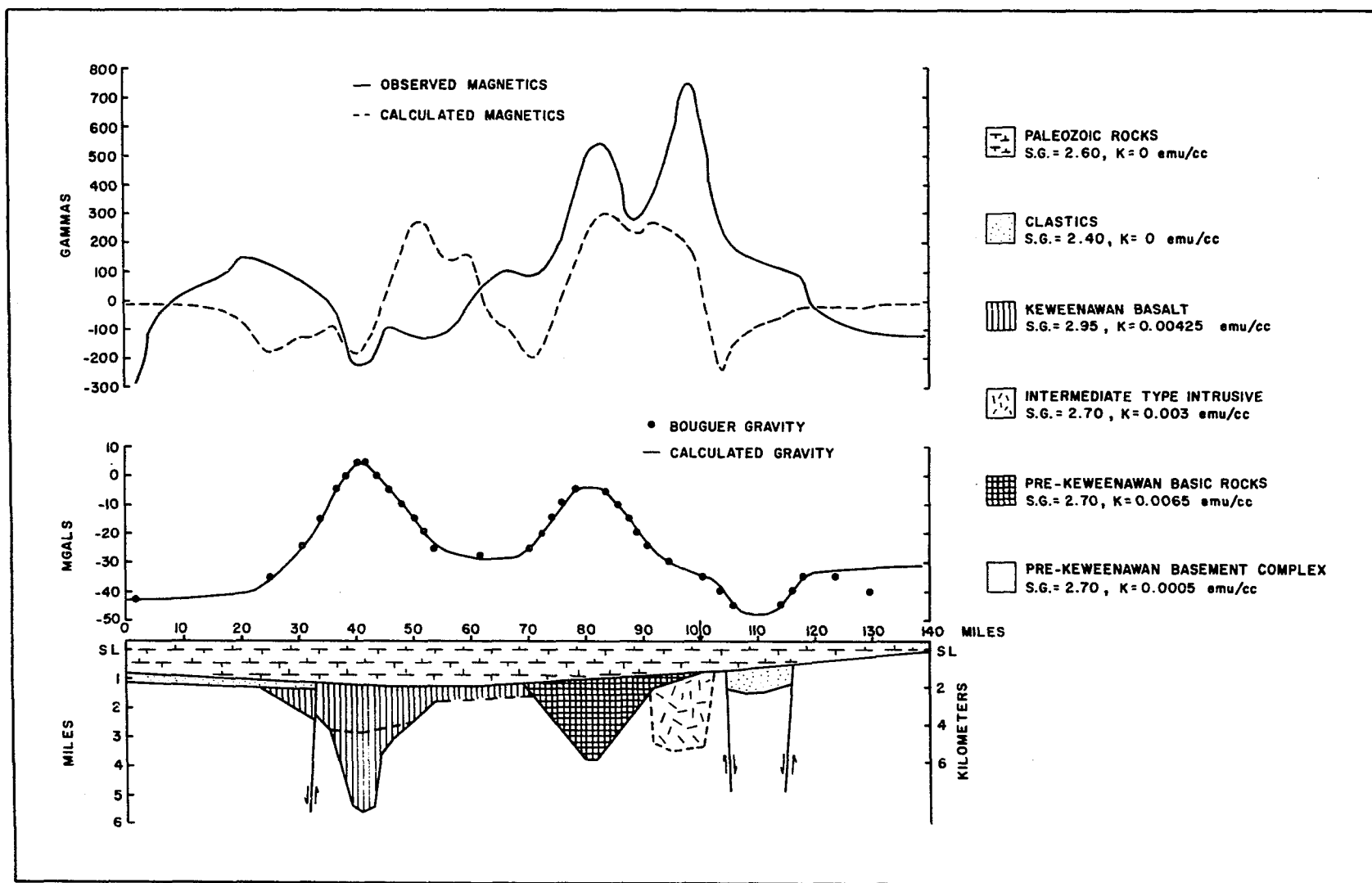


Figure 14.--Alternative geological model to profile F-F'.

Geological Implications

A map (Figure 15) showing the Precambrian structures in the eastern portion of the Northern Peninsula of Michigan was prepared to illustrate the structures of the Keweenawan extrusives as determined in this study and their relationship to known pre-Keweenawan structures. This map has been constructed from the results of the gravity model studies as well as qualitative interpretation of the Bouguer Gravity Anomaly Map (Figure 4), the Total Intensity Magnetic Anomaly Map (Figure 5), the Double Fourier Series Residual Gravity Map (Figure 6) and the Basement Rock Map of the United States (Bayley and Muehlberger, 1968).

The structure contours and the faults in Figure 15, are suggestive only and, therefore, are shown as dashed lines because of the many assumptions made in the model studies. The structure contours on top of the Middle Keweenawan basalts were plotted from the geologic cross-sections of Figures 9, 11 and 13 which do not include the Freda formation above the volcanics. The trend and extension of the faults were qualitatively derived from gravity, magnetic and the double Fourier series maps. The east-west trending pre-Keweenawan structures on the eastern and the western part of the map are based on the Basement Rock Map of the United States.

Figure 15 shows that east of a line from Au Train Bay to Manistique in the eastern portion of the Northern Peninsula, the Paleozoic sediments are underlain by Keweenawan rocks. The western edge of the Keweenawan basalts was interpreted primarily from the Total Intensity Magnetic Map because of the poor resolution of the gravity over areas where basalts thin out. The eastern limit of the volcanics was established using both the Bouguer Gravity Map and the results of the model studies because this

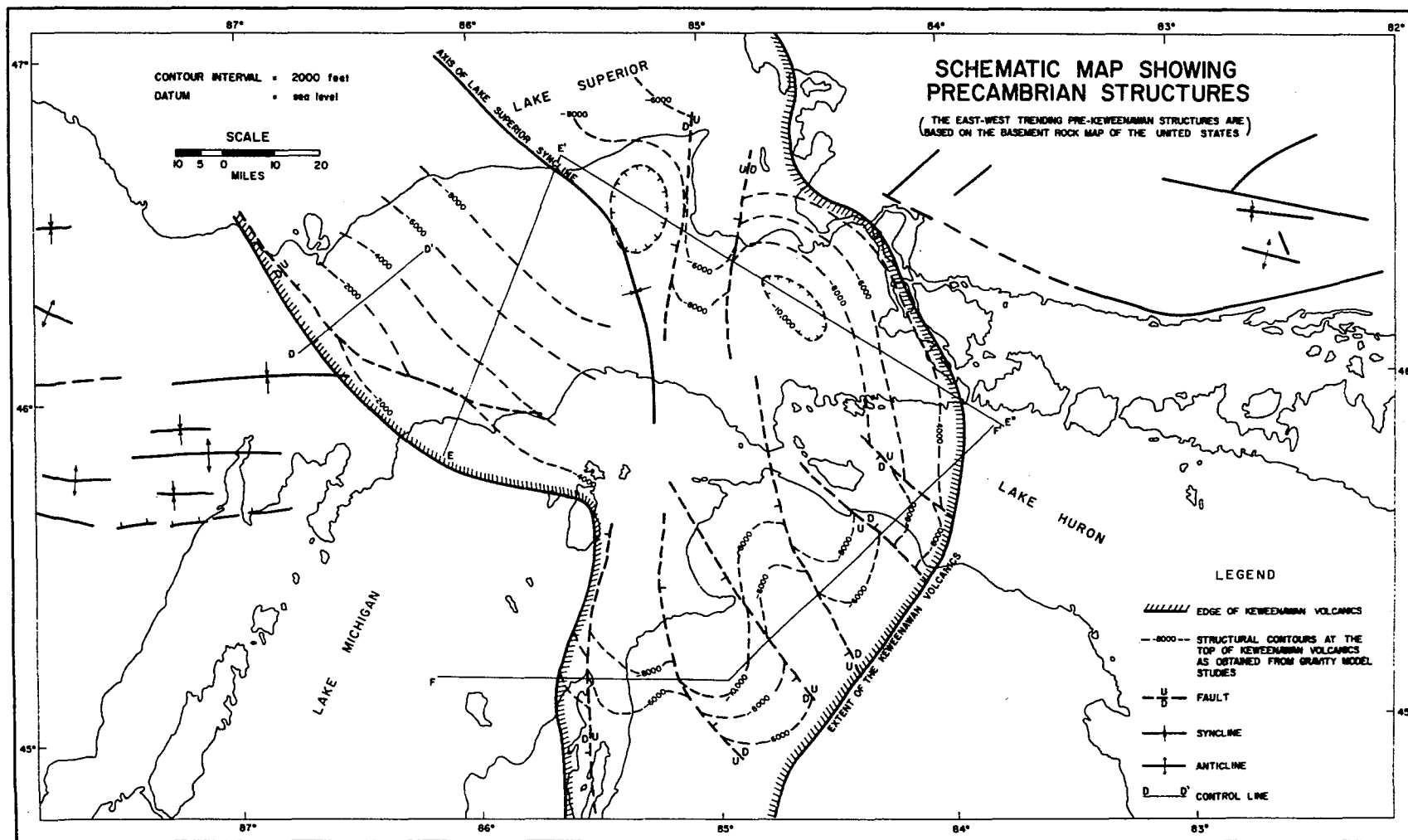


Figure 15.--Schematic map showing interpreted Precambrian structures in the eastern portion of the Northern Peninsula and the northern tip of the Southern Peninsula of Michigan.

part of the study area is magnetically complex. Along the eastern shore of Lake Superior in Canada, known geology (Halls, 1966) was used to establish the edge of the Keweenaw volcanics. To the south, the Keweenaw volcanics become areally restricted and are gravitationally expressed as the "Mid-Michigan gravity high" in the Grand Traverse Bay area of the Southern Peninsula of Michigan.

The structure contours on top of the Middle Keweenaw basalts were interpolated and extrapolated primarily from the model studies. The depths shown in Figure 15 are the minimal depths to the top of the volcanics because Freda sandstone was not considered in the geological cross-sections that incorporate only the Jacobsville sandstone. The structure contours indicate that the limbs of the Lake Superior syncline, which have been traced into the eastern portion of the Northern Peninsula on the basis of gravity and magnetic anomalies as discussed in the previous sections, merge in the vicinity of Beaver Island. South of the latitude of Beaver Island, the subcrop width of the volcanics gradually narrows and is faulted into a series of horsts and grabens which then merge with the source of the "Mid-Michigan gravity high."

Due to the paucity of gravity data in northern Lake Michigan, no structure contours could be established between Beaver Island and the Lake Michigan shore of the Northern Peninsula. However, on the basis of available control, the structure contours outline two local basins in the vicinity of Whitefish Bay, which are associated with relatively large negative gravity anomalies.

The presence of the fault running roughly parallel to the western edge of the Keweenaw volcanics is questionable. However, it may be present with only limited vertical displacement at depth and only minor

topographic expression as a fault scarp at the basement surface. In fact, Patenaude (1964) interpreted the gently sloping contact suggested by the gravity data to indicate an eroded fault scarp.

The northern tip of the Southern Peninsula is interpreted to be highly faulted and is characterized by a series of horsts. A horst flanked by a graben to the east occurs in the Grand Traverse Bay area. The vertical displacement on the boundary faults of this graben is of the order of 4500 feet. Another horst which trends north-south occurs in the Whitefish Bay area. Vertical displacement of the bounding faults of this structure is of the order of 1500 feet. The relationship of the Whitefish Bay horst to the interpreted faults in the northern tip of the Southern Peninsula is unknown, but this horst is on strike with the interpreted horst associated with the "Mid-Michigan gravity high" east of Beaver Island.

The eastern end of the Lake Superior syncline which is schematically illustrated by the structure contours in Figure 15, closely resembles the western end of the syncline. In the western end of the Lake Superior syncline, positive gravity anomalies correlate with the Keweenaw extrusives and intrusives, and the large negative anomalies on the Bayfield Peninsula and Keweenaw Bay reflect thick accumulation of sediments (Thiel, 1956; Weber and Goodacre, 1966). Furthermore, the St. Croix horst of Wisconsin which is bounded by the Douglas-Isle Royale and Keweenaw faults continues into the Lake Superior syncline (Halls and West, 1971).

The Keweenaw structural province of Figure 15 constitutes a key segment of a major geologic feature which extends from southern Kansas along the "Mid-Continent gravity high," through the Lake Superior trough, and southeastward into the Southern Peninsula of Michigan. The occurrence

of an inverse relationship between the Bouguer gravity anomalies and basement elevations along the "Mid-Continent" and "Mid-Michigan" gravity highs has led Lyons (1959) and Hinze (1963) to speculate that the geologic features responsible for the geophysical anomalies originate from elastic deformation in response to the added mass of basic rocks, emplaced in the basement complex in late Precambrian time. McGinnis (1970) expanding on these ideas, has suggested that the Lake Superior basin resulted from elastic deformation due to basic intrusives and extrusives emplaced along a Keweenaw rift zone. Hinze, et al. (1971) have proposed an alternative theory for the origin of the Lake Superior basin. They suggest that the crust undergoes compression at the final stage of the continental rifting process resulting in the slow development of a broad basin over a paleo-rift zone.

In the case of the Lake Superior basin, widespread basalts were extruded within and probably exterior to the rift zone at the earlier stages of rifting. Evidence for the presence of high density intrusions associated with these stages is provided by high compressional wave velocities under the Lake Superior syncline (Smith, et al., 1966). This excess mass of mafic intrusions and extrusions resulted in elastic deformation of the crust and development of local basins. This stage corresponds to the deposition of the Oronto group in the Lake Superior syncline. During this stage, the Freda sandstone may have been deposited in the eastern end of the syncline in shallow water and exposed repeatedly to subaerial conditions as indicated by sediment dispersal studies (Hamblin, 1961). The direction of the currents which deposited the Freda was northwest in the Keweenaw Peninsula but north, south and west in the area of Mamainse Point. Keweenaw basalts, Animikean iron formations

and granite were the dominant rock types in the source area. The deposition of Freda sandstone was followed by compression of the rocks within the rift. Perhaps some of the observed thrust faulting developed at this time. The development of the Lake Superior basin was largely completed with the deposition of the Jacobsville sandstone. Hinze, et al., (1971) have associated the development of the Jacobsville with subsidence of a former "floater" which cooled rather rapidly due to voluminous igneous activity, leaving behind an abnormally denser residuum. The "floater" is defined as a portion of mantle whose specific gravity is less than the surrounding mantle material because of its relatively high temperature.

Contemporaneous subsidence of the surface with that of the "floater" led to the deposition of the Jacobsville sandstone which thins out to the south because the outer edge of the basin subsided less than the central part. The high quartz content, good sorting and simple heavy mineral suite indicate that Jacobsville sandstones were subjected to considerably more transportation than the Freda sandstones. The direction of sediment transport during Jacobsville time was to the northwest near the eastern margins of Lake Superior but due north in an area extending from Grand Marais to Marquette on the south shore of Lake Superior. Since the development of the Lake Superior basin at this time was nearly complete, the subsidence of the basin did not keep pace with sedimentation and, therefore, Jacobsville sedimentation spread southward.

Following the Jacobsville sedimentation, early Paleozoic seas entered the eastern portion of the Northern Peninsula and led to the deposition of the Chapel Rock sandstone of St. Croixan age. A barrier to the Cambrian seas from the south formed in the northern portion of the Southern Peninsula and the eastern portion of the Northern Peninsula following

the termination of Jacobsville sedimentation (Hamblin, 1961). Following this period, the transgressive Cambrian seas covered the whole eastern portion of the Northern Peninsula and the area became the northern most portion of the Michigan basin.

CHAPTER IV

CONCLUSIONS

The gravitational study of the eastern portion of the Northern Peninsula of Michigan, integrated with the available magnetic data and geological information has confirmed some previous geological concepts and brought to light new ideas on the tectonics of the eastern end of the Lake Superior syncline. However, the geophysical interpretation of the gravity and magnetic data is subject to error because of inherent ambiguity and assumptions made in quantitative analysis. Therefore, the conclusions presented here serve as a first order approximation.

The Bouguer Gravity Anomaly Map of the eastern portion of the Northern Peninsula of Michigan is dominated by a major positive gravity anomaly. The source of this anomaly is attributed to Keweenaw basalts. The local gravity minimums in the Whitefish Bay area result from a thick accumulation of Upper Keweenaw clastic sediments. The major gravity anomaly transects roughly east-west trending gravity anomalies whose sources are pre-Keweenaw rocks which are exposed around the periphery of the Lake Superior syncline.

The Bouguer and Double Fourier Series Residual Gravity Anomaly Maps indicate that the major positive anomaly in the eastern portion of the Northern Peninsula is comprised of essentially two major linear positive gravity anomalies and a more subdued positive anomaly along the eastern margin of the Northern Peninsula. One of the major linear anomalies

trends south from Whitefish Point on the south shore of Lake Superior and the other trends southeast from Grand Island in Lake Superior. Positive magnetic anomalies are also found to be associated with these gravity anomalies.

Comparison of major anomalies both magnetically and gravimetrically with anomalies of the Lake Superior region suggests that the northwest-southeast trending anomaly can be correlated to the Middle Keweenaw volcanics of the Keweenaw Peninsula. This anomaly represents the edge of the western limb of the Lake Superior syncline. The north-south trending anomaly which is associated with upfaulted basalts within the eastern limb of the Lake Superior syncline can be correlated with the Middle Keweenaw volcanics outcropping on Mamainse Point, Ontario. The eastern positive gravity anomaly defines the edge of the eastern limb of the syncline. These anomalies merge in the vicinity of Beaver Island and mark the termination of the Lake Superior syncline. South of Beaver Island, the Keweenaw basalts merge with the source of the "Mid-Michigan gravity high."

The interpretive results obtained from two dimensional model studies suggest that the Lake Superior syncline in the eastern portion of the Northern Peninsula consists of up to 12,000 feet of basaltic flows overlain by Upper Keweenaw clastic rocks. The basalts thin both to the east and west and, in general, have low dips except in the vicinity of faults. Low specific gravity clastics of Jacobsville age, which thin to the south overlies the basalts. The Freda sandstone which occupies a stratigraphic position between the basalts and the Jacobsville sandstones was also included in some models.

The presence of a fault extending from Au Train Bay to the vicinity of Manistique as suggested by previous geophysical studies is not supported by the results of this investigation, but this does not preclude the existence of the fault. An approximately north-south trending horst is interpreted to occupy the Whitefish Bay area. The vertical displacement of the bounding faults of this structure is of the order of 1500 feet. The basalts are also highly faulted in the northern tip of the Southern Peninsula. A horst which is flanked by a graben to the east occurs in the Grand Traverse Bay area. The vertical displacement on the boundary faults of the graben is of the order of 4500 feet.

An alternative interpretation of the geology of the northern portion of the Southern Peninsula of Michigan suggests that basalts may be confined to the Grand Traverse Bay area. In this case pre-Keweenawan extrusives and intrusives underlie the area of the northern tip of the Southern Peninsula.

The structure of the eastern end of the Lake Superior syncline resembles that of the western end. It constitutes a key segment of a major geologic feature which extends from southern Kansas along the "Mid-Continent gravity high," through the Lake Superior trough, and southeastward into the Southern Peninsula of Michigan. The origin of this major geologic feature is thought to be in a rift of the continental crust.

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APPENDIX

FREE AIR GRAVITY ANOMALY MAP OF THE EASTERN PORTION
OF THE NORTHERN PENINSULA OF MICHIGAN

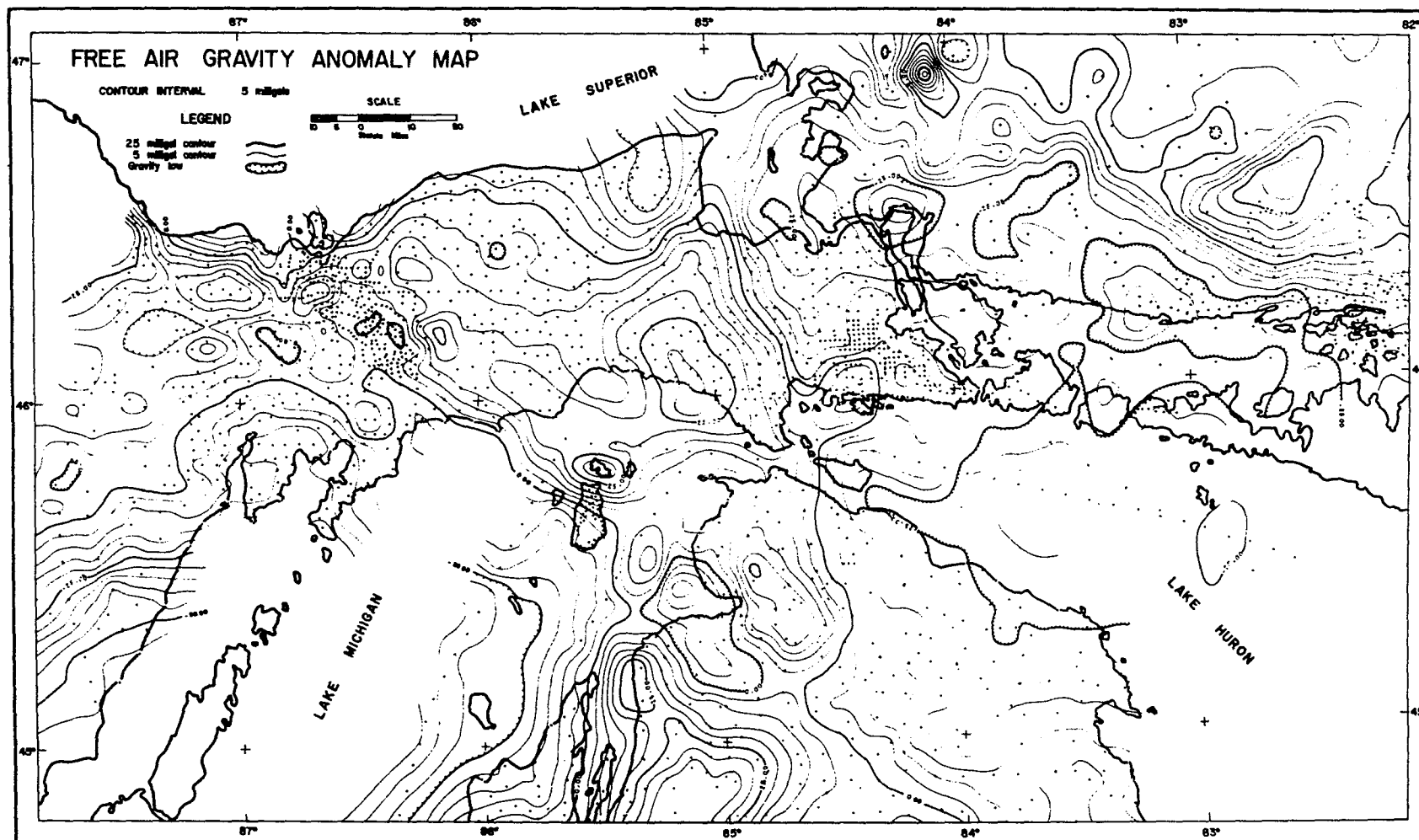


Figure 16.--Free-air Gravity Anomaly Map of the eastern portion of the Northern Peninsula of Michigan.