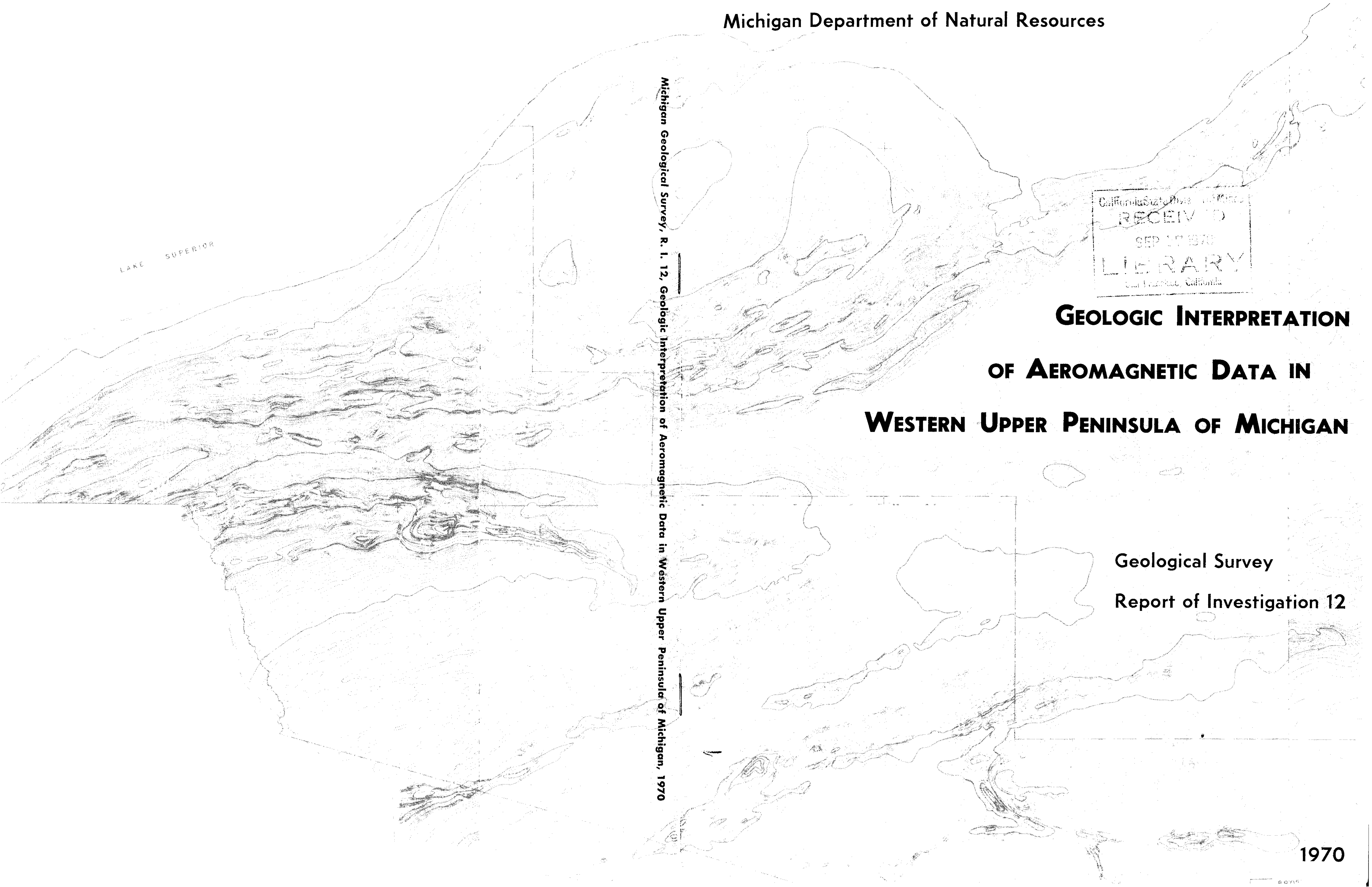
Michigan Department of Natural Resources



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Geological Survey

Report of Investigation 12

1970

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State of Michigan
Department of Natural Resources

Geological Survey

Report of Investigation 12

GEOLOGIC INTERPRETATION OF AEROMAGNETIC DATA IN WESTERN UPPER PENINSULA OF MICHIGAN

by
W. M. Meshref
and
W. J. Hinze

Prepared in cooperation with Michigan State University

1970

STATE OF MICHIGAN
William G. Milliken, *Governor*

DEPARTMENT OF NATURAL RESOURCES
Ralph A. MacMullan, *Director*

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Gerald E. Eddy, *State Geologist and Chief*

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PREFACE

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The Geological Survey Division of the Michigan Department of Natural Resources furnished magnetic maps. The financial support provided the author by the United Arab Republic made this study possible.

This publication is an outgrowth of a Ph.D. thesis completed by the senior author under the supervision of the junior author.

Cairo, United Arab Republic

Wafik M. Meshref
Assistant Professor
Atomic Energy Establishment

East Lansing, Michigan
December 1969

William J. Hinze
Professor
Department of Geology
Michigan State University

ILLUSTRATIONS

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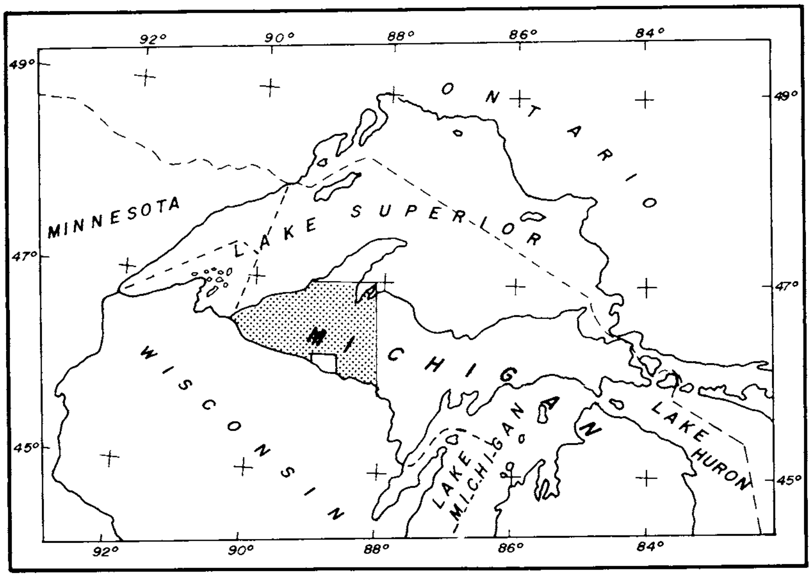

Figure 1 -- Location of area.

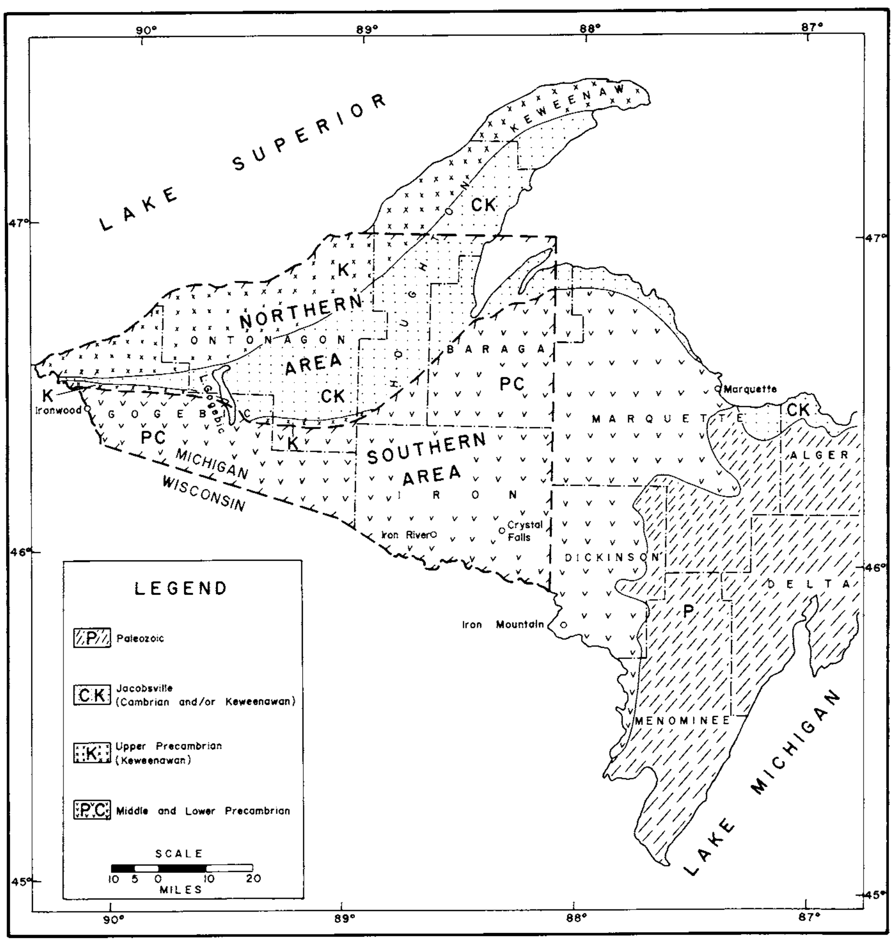

Figure 2 -- Regional geology of western Upper Peninsula; division of study area

GEOLOGIC INTERPRETATION OF AEROMAGNETIC DATA IN WESTERN UPPER PENINSULA OF MICHIGAN

Abstract

The regional structure and lithology of Precambrian formations in parts of Ontonagon, Gogebic, Iron, Baraga, and Houghton counties is interpreted using available geologic data and published aeromagnetic maps.

The position and attitude of the near-surface contact between the North Trap Range (Portage Lake) lavas and the Jacobsville Sandstone is uncertain west of longitude 89° 20' W. A linear magnetic anomaly south of the Keweenaw fault may be the result of cross-faulting or sliding of the southern portion of the lavas subsequently buried by sandstone. The near-surface contact between the lavas and the sandstone may dip south.

The Porcupine Mountains are believed to be a lopolithic intrusion of rhyolite. Withdrawal from a magma chamber to the south formed the Iron River syncline. South of the Keweenaw fault, a linear magnetic source, the Middle Trap Range is interpreted as an up-faulted block of the South Trap Range lavas.

South of the Barb Lake fault granitic rocks occupying the center of the Marenisco anticline are probably Early Precambrian. Magnetic strata south of the Marenisco anticline are interpreted as the Ironwood Iron-formation of the Tyler Slate series.

INTRODUCTION

The U.S. Geological Survey, in cooperation with the Geological Survey Division of the Michigan Department of Natural Resources, is conducting a comprehensive restudy of the mineral-bearing districts of Michigan. As a part of this program, aeromagnetic surveys have been completed over much of the Northern Peninsula of Michigan. Geologic interpretation of portions of these surveys were published by Balsley and others (1949), Wier and others (1953), and Case and Gair (1965). The present investigation is based upon a portion of these aeromagnetic maps.

Location

The area of study covers about 5,000 square miles, including most of the western half of the Upper Peninsula of Michigan. It includes Ontonagon, Gogebic, Iron, and parts of Baraga and Houghton counties (fig. 1) south of 47° 00' N latitude, west of 88° 07' 30" longitude, and is bounded on the west and south by the Michigan-Wisconsin border.

For the purpose of discussion the study area (fig. 2) is divided into a northern part and a southern part, based primarily on geologic considerations. The northern part includes rocks of Keweenawan age, as well as younger rocks. The southern part includes mostly pre-Keweenawan rocks (both Lower and Middle Precambrian) and is further subdivided. The western portion covers mainly the area west and south of Lake Gogebic. The eastern portion includes the Iron River-Crystal Falls district and the Amasa oval.

General Geology

The geology of the study area is varied and highly complex. Though studied for nearly a century, the regional geology has not been completely defined primarily because of the covering of Paleozoic sediments, and glacial drift. Because these Precambrian rocks have varied magnetic properties, the magnetic method should provide an excellent tool for delineating the regional geology and structural patterns.

Lower, Middle, and Upper Precambrian rocks underlie most of the area. The Lower Precambrian forms the basement and consists of granite, gneisses, greenstones, and other igneous and metamorphic types. One or more periods of metamorphism and deformation occurred before the end of Early Precambrian time. These basement rocks are separated from the overlying metasedimentary rocks of Middle Precambrian age (Animikie) by a major unconformity. Widespread deformation and regional metamorphism occurred at the close of Middle Precambrian time. Prior to that time intrusive bodies of both Lower and Middle Precambrian age were emplaced.

The Keweenawan (Upper Precambrian) rocks are separated from the underlying Animikie by another major unconformity. Keweenawan rocks include lava flows, conglomerates, sandstones, and shales. During Keweenawan time, diabase dikes, having a dominant eastward trend, intruded the older rocks. In the central part of the area the flat-lying Jacobsville Sandstone and glacial debris of Pleistocene age generally conceal the Precambrian.

Purpose

The general purpose of this study is to delineate regional structure and the lithology of the Precambrian rocks with aeromagnetic data.

The specific objectives are:

1. To interpret the Precambrian geology where information is sparse due to the lack of outcrops or inaccessibility.

2. To trace the location of the Keweenaw fault.

3. To delineate the structure of the Keweenawan rocks of the area.

Techniques

In magnetic interpretation, the main object is to draw inferences about the attitude, depth, configuration, and lithology of the subsurface structure. To accomplish this, information must be obtained about the regional geology and the induced and remanent magnetization of the underlying basement complex. In this investigation, therefore, geologic information was re-compiled on the same scale as the aeromagnetic map. This facilitated the correlation of the known geology with major magnetic anomalies and broad areas having characteristic magnetic patterns. The character of these magnetic anomalies was used to interpret the geology of unmapped areas. Rock samples were collected representing most of the lithologies in the area to determine their magnetic properties.

Qualitative and quantitative magnetic interpretations were accomplished by using the following techniques:

1. Published depth determination techniques were applied to interpret the geology and structure of the basement rocks.

2. A magnetic trend analysis was conducted to help define the major structural trends and the direction as well as the nature of the tectonic forces involved in developing these trends.

3. A second vertical derivative map of the total magnetic intensity was prepared for the central area to aid in depth determinations and to isolate the boundaries of magnetic units.

4. Theoretical magnetic profiles were calculated for assumed geologic bodies and compared with the observed magnetic profiles.

In addition, the magnetic interpretation was checked against the regional gravity map of the study area.

The *aeromagnetic maps* are divided into two groups. The first group that covers the area east of longitude 88° 30' W, west of longitude 88° 07' 30" W, and south of latitude 46° 25' N, was mapped at a scale of 1:31,680. The flight traverses for this area were flown in an east-west direction because in this area most of the geologic units and structures, such as the Amasa oval and the rocks of the Lower Precambrian south of the western Marquette Range, strike approximately north-south.

The second group of maps covers the rest of the study area. These maps were published at a scale of 1:62,500 and the flight traverses were flown in a north-south direction which is perpendicular to the general strike of the trend of the geologic structures in this part of the area.

The contour interval of these maps varies between 50 gammas, which is the basic unit, to 1000 gammas depending on the intensity of the magnetic field.

A constant flight elevation of 500 feet from the ground surface was maintained throughout the study area, although this might deviate in areas of rugged relief. Traverses were spaced at intervals of approximately one-quarter mile. The flight path of the aircraft was recorded by a gyrostabilized continuous strip camera, and the elevation was continuously recorded by a radioaltimeter.

Magnetic measurements were made by a

fluxgate magnetometer. Base lines were flown perpendicular to the flight traverses in two directions to obtain data to correct for diurnal magnetic variations.

In this study the aeromagnetic maps for the area were assembled and compiled to a common arbitrary magnetic base level, and common scale of 1:250,000 (plate 1). Available geologic information was also compiled to this scale, to facilitate correlation of magnetic anomalies with known geology.

Previous Investigations

Balsley, James and Wier (1949) published a geophysical report including some preliminary interpretation of an aeromagnetic survey of parts of Baraga, Iron, and Houghton counties. They concluded that the correlation of the magnetic data with the known geology is good in most parts of the area.

Campbell (1952) investigated the vertical component of the magnetic field and the gravitational field in the Silver Mountain area. He considered the subsurface structure to be quite complex.

Bacon and Wyble (1952) conducted a gravity investigation in the Iron River-Crystal Falls mining district of Michigan. They concluded that there is some possibility that gravity methods may be able to differentiate between large iron ore bodies and the iron-formation in the Iron River-Crystal Falls district. They stated that the regional gravity work outlines quite clearly the major structural features of the Iron River-Crystal Falls synclinal basin. They also pointed out that a large anomaly occurring about fifteen miles west of Iron River may well be associated with a structurally similar basin and consequently may be another potential iron ore district.

Thiel (1956) and Bacon (1957) illustrated the relationship of Bouguer gravity anomalies to geology of the south shore of Lake Superior. Thiel correlated the "mid-continent gravity high" with the gravity anomalies over the Keweenawan of Wisconsin. The regional gravity study by Bacon showed a similar high in the Upper Peninsula of Michigan.

Bacon (1960) advanced the hypothesis that a major fault parallel to the Keweenaw fault exists in approximately the central portion of the Jacobsville Sandstone. Bacon (1966) on the basis of geophysical data explored more fully some of the structure in the area to the east and south of the Keweenaw fault. He suggested that a Middle Range of basalt lies beneath the Jacobsville Sandstone, and that it may be either the northern limb of a shallow symmetrical syncline plunging to the west, with the South Range as the southern limb, or that the Middle Range lavas are a horst. He also indicated the possibility of another fault parallel to the Keweenaw fault in the graben area between the Middle Range and Northern Trap Range.

Wold and Ostenso (1966) flew 7,500 miles of magnetic traverses over the western Lake Superior region. This survey consisted of 37 north-south oriented profiles, spaced at six-mile intervals. In general, Wold and Ostenso correlated their findings only with Keweenawan lavas and clastics.

Case and Gair (1965) in their aeromagnetic study of parts of Marquette, Dickinson, Baraga, Alger, and Schoolcraft counties, Michigan, covered a small strip of the extreme eastern portion of the investigation area. They correlated the major magnetic anomalies and broad areas that have characteristic magnetic patterns with the geology as determined from published reports.

Miller (1966) conducted a gravity investigation of the Porcupine Mountains and adjacent area. He concluded that, in general, the gravity map correlates very well with the geology as mapped by White and Wright (1962). He further indicated from gravity profiles observed over the Keweenaw fault that there is a decrease in the throw of the fault from northeast to southwest, varying from 6,000 feet north of Ewen, to 3,000 feet west of Lake Gogebic. He also indicated that the dip of the fault where it is in contact with the Jacobsville Sandstone appears to be to the south, instead of to the north as previously postulated.

Several reports have been published by the U.S. Geological Survey on limited portions of the area, involving aeromagnetic studies and their geologic interpretation; these include:

1. Gair and Wier (1956) investigated the geology of the Kiernan Quadrangle, Iron County, Michigan.

2. Bayley (1959) mapped the geology of Lake Mary Quadrangle, Iron County, Michigan.

3. Wier (1967) studied the geology of Kelso Junction Quadrangle, Iron County, Michigan, based partly on the aeromagnetic map of the area.

4. Prinz (1967) studied the Pre-Quaternary geology of part of the eastern Penokee-Gogebic Range, Michigan, utilizing results from ground magnetic surveying.

# # #

REGIONAL GEOLOGY

The geology of the Precambrian terrane of the Upper Peninsula of Michigan has been described in many publications of the U. S. Geological Survey, and the Michigan Geological Survey (Irvin and Van Hise, 1892; Van Hise and Bayley, 1897; Clements and Smyth, 1899; Van Hise and Leith, 1911; Allen and Barrett, 1915; Barrett, Pardee, and Osgood, 1929; Leith, Lund and Leith, 1935; Martin 1936).

Unlike the Phanerozoic, the Precambrian is not divided into a widely accepted framework of eras and periods to which lithologic units and geologic events can be related. James (1958) introduced new formal names and summarized the stratigraphic nomenclature used by the U.S. Geological Survey for the Precambrian of northern Michigan. His nomenclature is used in this report.

Northern Area

In figure 2 (page vi) the area labelled "Northern Area" consists of mostly Keweenawan rocks and Jacobsville Sandstone.

Table 1 -- Generalized geologic column for Northern area

Phanerozoic	Cenozoic	Quaternary		Glacial Deposits
				Unconformity
Phanerozoic	Paleozoic	Cambrian		Jacobsville Sandstone
		?	?	Unconformity — ?
Precambrian	Upper Precambrian	Keweenawan	Upper	Freda Sandstone Nonesuch Shale Copper Harbor Group Outer Conglomerate Lake Shore Trap Great Conglomerate
Precambrian	Upper Precambrian	Keweenawan	Middle	Portage Lake Lava Series Eagle River Group Ashbed Group Central Mine Group Bohemian Group
Precambrian	Upper Precambrian	Keweenawan	Lower	South Trap Lavas Quartzite Member
				Unconformity

Stratigraphy

Table 2 shows the generalized geologic column for this area.

Lower Keweenawan

Hubbard (1967) pointed out that the Keweenawan volcanic rocks in the western Upper Peninsula of Michigan should be divided into two sequences. A younger sequence, about 15,000 feet thick, is equivalent to the Portage Lake Lava Series of Keweenaw Point. An older sequence exposed in the South Range, is about 8,000 feet thick. He suggested these two sequences are separated by more than 7,000 feet of sedimentary rocks.

Hubbard's studies indicate the upper flows of the South Range contain groundmass feldspars uniformly more sodic and generally finer-grained than the Portage Lake flows. South Range lavas are underlain by a quartzite member about 500 feet thick.

Kenneth Book (Hubbard, p. 21) of the U.S. Geological Survey has found that the paleomagnetic field directions of the Portage Lake lava series near Ironwood are similar to those of the lavas of Keweenaw Point and that the paleomagnetic field directions of the South Range traps are distinctly different. The paleomagnetic properties of the rocks within each sequence are internally consistent.

Differences in petrology and magnetic properties between the two sequences indicate a difference in age. The South Range lavas are believed to be Early Keweenawan.

Middle Keweenawan

The *Portage Lake Lava Series* consists of a thick sequence of basalt and andesite flows, with a few interbedded rhyolitic conglomerates and local rhyolites (White, 1953) divided into the following four groups (Irving, 1883).

Bohemian Range Group is a sequence of amygdaloidal basalt flows with subordinate conglomeratic beds and rhyolites. It attains a thickness of 10,000 feet.

Central Mine Group is a similar sequence characterized by thick lava flows with associated minor interbedded rhyolitic conglomerates and thin ash beds.

Ashbed Group is a series of interbedded lava flows and subordinate coarse, sedimentary rocks. In the Porcupine Mountains, the lower part is a thick sequence of rhyolite (Thaden, 1950).

Eagle River Group is a 2,000-foot sequence of basic lava flows, interbedded with minor amounts of rhyolitic conglomerates.

Upper Keweenawan

The Copper Harbor Group is the thickest and most persistent conglomerate of the Keweenawan sequence. It can be traced from Keweenaw Point to Black River near the Michigan-Wisconsin border and further west. In the Porcupine Mountains it is 5,000 feet thick and consists of three distinct units, formerly designated the *Great Conglomerate*, the *Lake Shore Traps* and the *Outer Conglomerate*.

The sedimentary units are poorly stratified conglomerates, containing minor interbedded medium-to coarse-grained arkosic sandstones. These units interfinger and pinch out in relatively short distances. The ratio of sandstone to conglomerate is unknown due to the absence of continuous exposures. The *Lake Shore Traps* are a 300- to 400-foot thick series of basic lava flows forming the escarpment overlooking Lake of the Clouds in the Porcupine Mountains.

A sharp lithologic break separates the Copper Harbor Conglomerate from the overlying Nonesuch Shale and Freda Sandstone. These units are a series of silty shales, siltstones and sandstones, several thousands of feet thick.

The Nonesuch Shale is predominately a flaggy, grey to reddish-grey siltstone, 800 feet thick, with interbedded grey to greenish-grey, silty shales. The presence of ripple marks and mud cracks indicates a shallow marine or continental environment, possible deltaic. Nonresistant heavy mineral suites and angular detritus suggest deposition near source. The contact between the Nonesuch Shale and the Freda Sandstone is gradational.

The Freda Sandstone is a well-sorted, fine- to medium-grained, red to greenish-grey arkose. It contains minor amounts of red to green micaceous shales and siltstones. Although accurate measurements are not available, scattered exposures near the Porcupine Mountains indicate a thickness of 14,000 feet (Hamblin, 1958).

Jacobsville Sandstone

The Jacobsville Sandstone comprises the rock unit southeast of the Keweenaw fault. It is medium- to fine-grained, red to white, arkosic sandstone about 4,000 feet thick (Hamblin, 1961). Its relationship with the underlying Freda Sandstone is conjectural. Hamblin places it in the Cambrian.

Structure

Lake Superior occupies a great synclinal structure, the Lake Superior basin, in the southern part of the Canadian Shield. The western half of the basin is margined with rocks of Keweenawan age. Except for a subordinate fold in the Porcupine Mountains, the beds dip toward the center of the basin. They are steeper on the south limb than on the north. A general flattening of dip occurs from the base to the top of the Keweenawan section, with thickening of the units downdip.

Folds

The south limb of the Lake Superior basin is quite irregular with broad transverse anticlines and synclines plunging down-dip toward the center of the basin. The Porcupine Mountains structure is an arcuate dome, parallel to Lake Superior and connected to the Northern Trap Range by a saddle. Thaden (1950) confirmed the presence of rhyolite in the center of the Porcupine Mountains reported by Butler and Burbank (1929).

The Iron River syncline lies between the Porcupine Mountains and the Keweenawan Trap Range. It is asymmetric, strikes northeast, and is truncated on the northeast by the White Pine fault. The beds on the north limb south of the Porcupine Mountains are near vertical and locally overturned. The Presque Isle syncline plunges northwest on the west flank of the Porcupine Mountains.

Several other folds exist, many the result of drag along faults. They vary in size from a few feet to several miles.

Faults

In the study area the Keweenaw fault is a high angle reverse fault, striking northeast and dipping northwest. It has been mapped along the southern edge of the Keweenawan Trap Range from the end of the Keweenaw Peninsula to the northern edge of Lake Gogebic. A broad trough-like area exists between the Keweenaw fault on the north and the South Trap Range and Precambrian highlands to the southeast.

The rocks are offset in many places by other faults. The White Pine fault, the major transverse fault, strikes northwest and dips steeply northeast. It is a right hand transverse fault with a lateral displacement of about one mile and vertical displacement of several hundred feet (White, 1954).

Southern Area

In figure 2 (page vi) the area labelled

"Southern Area" consists primarily of Middle and Lower Precambrian rocks. The Lower Precambrian rocks are widely exposed west of Lake Gogebic.

Stratigraphy

Table 3 shows the stratigraphic sequence and nomenclature used by previous investigators in the several districts.

Lower Precambrian

These rocks are the oldest in the area. They form the basement and consist of syenites, granites, gneisses, greenstones and other igneous and metamorphic rocks. Granites and granite gneisses predominate. One or more periods of metamorphism and deformation occurred before the end of Lower Precambrian time.

Middle Precambrian (Animikie)

The *Chocolay Group* and its correlatives as defined here are equivalent to Lower Huronian of earlier reports. It comprises two major units, a thick basal quartzite (Sturgeon, Mesnard, and Sunday quartzites of the different localities) and an equally thick dolomite (Randville, Kona and Bad River dolomites). Both units contain some slaty members. The quartzite formation is made up of a basal conglomerate overlain by the rather coarse-grained quartzite. The quartzite member is separated from the underlying Lower Precambrian by a major unconformity. The quartzite grades upward into the dolomite member. The aggregate thickness of the two units is typically about 4,000 feet, but in many places these strata are thin or absent because of nondeposition or post-dolomite erosion.

The *Menominee Group* and its correlatives as described here are equivalent to Middle Huronian of preceding reports. The type locality of this group consists of two formations, a basal clastic formation (Felch Formation and Ajibik and Palm quartzites) overlain by iron-formation. These commonly are conformable, or nearly so, with the underlying Chocolay Group. The base of the Menominee Group is marked by a thin conglomerate, one to three feet thick. Where it is in contact with the Lower Precambrian, as in parts of the Gogebic area, the pebbles are granite gneiss and green-schist. Where the underlying formation is the dolomite member of the Chocolay Group, the conglomerate includes fragments of chert and dolomite. This basal clastic formation ranges from 10 to 800 feet in thickness. Lithology varies from vitreous quartzite to graywacke and slate (or schist).

The basal unit grades upward into iron-formation consisting primarily of alternating thin layers of chert and iron minerals with a predominance of siderite, hematite, iron silicates, or magnetite. The Negaunee Iron-formation of the Marquette Range attains a maximum thickness of 2,000 feet, whereas the Ironwood Iron-formation of the Penokee-Gogebic Range

Table 2 -- Generalized geologic column for Southern Area

	Iron River-Crystal Falls area (James, 1958)		Marquette district (Van Hise & Leith, 1911)	Lake Gogebic area (C. E. Fritts, 1967)
Upper Precambrian	diabase dikes and sills			
Middle Precambrian (*Animikie*)	granitic intrusive rocks		intrusive contact	
	metadiabase and metagabbro		intrusive contact	
	Paint River Group	Fortune Lakes Slate Stambaugh Formation Hiawatha Graywacke Riverton Iron-formation	absent	absent
	Baraga Group	Badwater Greenstone Michigamme Slate Fence River and Amasa formations Hemlock Formation Goodrich Quartzite Dunn Creek Slate	Michigamme Slate Upper Slate Member Bijiki Iron-formation Member Lower Slate Member Clarksburg volcanics Greenwood Iron-formation Member Goodrich Quartzite	gray slate near Paulding metavolcanic, metasedimentary rocks graywacke near Banner Lake (iron-formation) metatuff and tuffaceous graywacke Tyler Slate (intercalated iron-formation)
	Menominee Group	Vulcan Iron-formation Felch Formation	Negaunee Iron-formation Siamo Slate Ajibik Quartzite	Ironwood Iron-formation Palms Formation
	Chocolay Group	Randville Dolomite Sturgeon Quartzite	Wewe Slate Kona Dolomite Mesnard Quartzite	Bad River Dolomite Sunday Quartzite
Lower Precambrian	syenites, granites, gneisses and greenstones			

rarely exceeds 800 feet. The Vulcan Iron-formation is about 400 feet thick.

The *Baraga Group* and its correlatives comprise most of the strata referred to as Upper Huronian of previous reports. It is chiefly graywacke, slate, and basic volcanic rocks, but conglomerate, quartzite, and iron-formation are common, particularly in the lower part. The principal stratigraphic unit is the Michigamme Slate and its correlatives in the Penokee-Gogebic Range area. The exposed parts of the Michigamme Slate and its correlatives consist of graywacke and slate in about equal proportions. The graywackes are dark gray, massive, and fine- to medium-grained. The slates are light to dark gray and are interbedded in graywacke. Bedding in the slates is commonly indistinct or subordinated to slaty cleavage. Most graywacke beds show no cleavage.

The Michigamme Slate and its correlatives and up to 25,000 - 30,000 feet of basic volcanic rock, now mainly greenstones (Hemlock Formation and correlatives), form several thick units. Much of this formation shows agglomeratic or pillow structures indicating probable submarine origin.

Fritts (1967) published a geologic map of the Lake Gogebic area (Marenisco-Watersmeet). This sequence of rocks includes at its base a metatuff and tuffaceous metagraywacke member consisting of minor quartzite, conglomerate, and magnetic iron-formation in the lower part. It also possibly includes pillow lavas, east of Cup Lake, dipping 60° to the southeast, overlain by the graywacke series, developed near Banner Lake, the upper part of which includes magnetic iron-formation, especially south of the Barb Lake fault. The foregoing sequence is overlain by a metavolcanic and metasedimentary formation which crops out north of the Barb Lake fault. This formation could be separated into two units north of the fault, the metatuff and magnetic iron-formation and the pillow lava and fragmental volcanic rocks. The uppermost member of the entire Baraga Group is a graywacke-slate near Paulding.

The *Paint River Group* which includes productive iron-formation, was formerly considered part of the Michigamme Slate (Leith, Lund, and Leith, 1935). The Iron River-Crystal Falls district is a deep tightly-folded major synclinal structure incompletely bounded by Badwater Greenstone. Immediately east of Crystal Falls, greenstone is absent and the strata rest directly on the Michigamme Slate and appear related to it. The stratigraphic position of the Badwater Greenstone now forms the basis for defining the Paint River Group.

In the Iron River-Crystal Falls area this group includes a basal sequence of siltstone and slates named the Dunn Creek Slate, ranging in thickness between 400 and 800 feet. Much of the Dunn Creek is graywacke and slate indistinguishable from the Michigamme.

Overlying the Dunn Creek is the Riverton Iron-formation consisting dominantly of interbedded chert and siderite. In places the upper part of the formation is absent because of erosion prior to the deposition of the overlying Hiawatha Graywacke which contains considerable interbedded slate. The Hiawatha is overlain by the Stambaugh Formation containing an iron-rich horizon, ranging from chloritic mudstone and slate to a laminated cherty siderite-magnetite. The Stambaugh is overlain by the Fortune Lakes slates consisting primarily of slate and minor graywacke.

The aggregate thickness of the group is at least 4,000 feet.

Middle Precambrian Igneous Rocks

Middle Precambrian igneous rocks in the area fall into two principal groups, metadiabase and metagabbro of Animikie or post-Animikie age, and younger granite and allied rocks.

The metadiabase and metagabbro were metamorphosed during the post-Animikie, pre-Keweenawan interval (James, 1955). Post-Animikie granite has been known for more than a hundred years, but its extent is uncertain. Absolute dating suggests that the age of the Post-Animikie, pre-Keweenawan epoch of diastrophism, metamorphism, and granite intrusion is more than 1,400 million years, as compared with 1,100 million years for the Keweenawan (Duluth Gabbro). James (1955) used the term Killarney for the post-Animikie, pre-Keweenawan granite rocks in Michigan, but its validity is uncertain.

Structure

The major structure in the southeastern portion of the southern area is a large tightly-folded triangular-shaped syncline, the Iron River-Crystal Falls basin, with apices at Iron River and Crystal Falls, Michigan and Florence, Wisconsin. Secondary folds on the east limb maintain a northwest trend and generally plunge in that direction. Transverse faulting has occurred subparallel to the secondary folding. The beds have been tightly folded producing a very irregular outcrop pattern. To the northeast the major structure is the Amasa oval, a domal uplift, the long axis of which plunges north-northwest and south-southeast. The major structures in the far eastern portion, beyond the report area, are three Precambrian metasedimentary synclinoriums: the Marquette syncline, the Felch trough and the Gwinn basin. The first two generally trend east-west, while the third trends northwest-southeast. These

Table 3 -- Magnetic susceptibility measurements

Rock type	Total Samples	Range of volume (K) x 10^{-6} c.g.s.	Average volume (K) x 10^{-6} c.g.s.
Keweenawan			
sediments	18	11-48	32
acidic flows	5	143-1000	438
basic flows	4	1220-1773	1561
basic intrusives	6	1881-9730	5683
acidic intrusives	2	31-56	43
pre-Keweenawan			
Animikie rocks			
metasediments	44	21-112	58
limonitic & hematitic iron ore	12	64-752	141
metamorphosed iron-formation	1	4230	4230
Stambaugh Formation	1	10260	10260
metabasic intrusives	2	72-79	76
acid intrusives	9	8-1000	121
"Archean" rocks			
acid intrusives and gneiss	9	11-86	40
greenstones	8	10-57	37

Table 4 -- Summary of magnetic properties
(after Hinze, O'Hara, Secor, and Trow, 1966)

Rock type	Susceptibility (K) x 10^{-6} c.g.s.	Konigsberger Ratio, $Q = I_{RM}/KH$ H = 0.6 Oersted
Paleozoic sediments	negligible	negligible
Keweenawan rocks:		
sediments	negligible	negligible
basic flows	10,000-1,000	3.0-1.0
basic intrusives	9,000-2,000	2.0-1.0
acid intrusives and flows	3,000	-------
pre-Keweenawan rocks:		
acid intrusives & gneisses	3,000-100	generally low
metabasic intrusives and flows	4,000-200	2.0-0.5
iron-formations	900,000-500	10.0-0.0
metasediments	200-0	negligible

areas exhibit extremely complex folding and faulting, probably the result of major orogeny.

The major structural feature in the western portion of the area is the Penokee-Gogebic Range, a steeply northward-dipping monocline. The most noticeable features are the great thrust fault at Wakefield and to the east the Barb Lake fault which strikes east-west. With the exception of the general northward-tilting, the folding and faulting of the Animikie rocks took place prior to Keweenawan time and after the deposition and induration of the Middle Animikie Series. The structure around Lake Gogebic is very complicated. In this area the Animikie rocks are believed to be compressed into a syncline with the axial plane striking northeast-southwest and dipping to the northwest.

# # #

MAGNETIC PROPERTIES OF ROCKS

Magnetic susceptibility measurements were made with an MS-3 magnetic susceptibility bridge on 120 rock specimens representative of most lithologies of the area. The results are presented in table 3. In view of the limited number of samples compared to the wide variety of lithologies and their wide range of magnetic values, care must be exercised in drawing conclusions. The following general conclusions, however, can be drawn from this work.

1. Sediments (excluding iron-formation), greenstone and acid intrusives have the lowest magnetic susceptibility values in the area. Sediments and greenstones have a susceptibility of less than 100 x 10^{-6} c.g.s. units.

2. Limonitic and hematitic iron-formations and acidic lava flows have rather moderate values of magnetic susceptibility.

3. Basic flows and intrusives and metamorphosed iron-formations have relatively high magnetic susceptibility.

4. Metabasic intrusives show remarkably low magnetic susceptibility values.

The magnetic properties of Keweenawan rocks of the Lake Superior region have been studied in more detail than the pre-Keweenawan rocks (Cox and Doell, 1960 and Irving, 1964).

By reconstructing the original dip of the Keweenawan volcanics, Dubois (1962) and Jahren (1965) found an average inclination of +45° and a declination of approximately 285° for the remanent magnetic field of the Keweenawan lavas. These values were used for quantitative interpretation of magnetic profiles in this study.

Graham (1953) reported on the paleomagnetism of certain dikes in Baraga County, Michigan. These and similar dikes occur in the eastern part of the study area in an east-trending swarm. The dikes were found to have consistent magnetization with declination of 90° and steep upward dip of -87°.

Hinze, O'Hara, Secor, and Trow (1966) summarized Lake Superior magnetic properties reported by Mooney and Bleifuss (1953), Bath and Schwartz (1960), Cox and Doell (1960), Jahren (1960,1963), Bath (1962), Irving (1964) and Case and Gair (1965) and others. Their compilation is given in table 4. The measured values shown in table 3 agree well with the ranges of magnetic susceptibilities shown in table 4.

The following generalizations appear valid for the rocks in the area:

1. High amplitude anomalies are expected to be associated with iron-formations and basic intrusives and extrusives. However, Keweenawan lava flows are not expected to produce as high a magnetic response as magnetic iron-formations.

2. All sediments of all ages should give the lowest magnetic intensity level in the area.

3. Acidic intrusives and greenstones are expected to show low amplitude magnetic irregularities.

# # #

INTERPRETATION OF MAGNETIC DATA

"Most interpretation of magnetic data is of a qualitative nature. This is due to several factors, (1) The magnetic methods lack depth control, (2) Most quantitative interpretation is indirect, (3) Magnetic properties of geologic formation, particularly of igneous and metamorphic rocks, are subject to great horizontal and vertical variations and are dependent on the thermal and mechanical history, the effects of which are difficult to evaluate, and (4) Magnetism is the only physical rock property which is of a bipolar nature, and variability of polarizations adds another unknown. Quantitative interpretation is further handicapped because the proportion of induced and remanent magnetism is rarely known." (Heiland, 1940)

The above statement still holds true in general for an area with complex Precambrian geology such as the Upper Peninsula of Michigan.

Assuming overlying sediments show no magnetic effect, the broad range of magnetic anomalies can be interpreted as reflecting changes in the composition of the igneous and metamorphic basement rocks. Geological features such as faults, extrusives, and intrusives can frequently be identified by observing the shape and extent of the anomalies over a contact between rock units, particularly when the regional geology is known. Abrupt shifts of the magnetic contour pattern are often indicative of a fault or an unconformity.

The ultimate purpose of magnetic interpretation is to determine the geometry, lithology, and location of magnetic bodies causing the anomalies. Unfortunately an infinite number of subsurface distributions of magnetization can explain a set of magnetic field observations on the earth's surface. This holds true even if the field is known with perfect precision at every point on the surface. Magnetic anomalies alone, therefore, are not sufficient to determine the bodies or structures causing the anomalies. In this study the principal approach has been the indirect method of interpretation using theoretical anomalies, calculated from bodies of plausible shape and magnetic characteristics, plus the extrapolation and interpolation of known geology. In addition, magnetic depth determinations and magnetic trend analysis were used.

The geologic interpretation of the aeromagnetic maps is presented in form of bedrock geology map (plate 2) and geological profiles (plate 3).

Aeromagnetic Maps

The aeromagnetic map depicts the wide range of magnetic intensity characteristic to the Lake Superior region. Positive anomalies range from a few tens of gammas to about 8,000 gammas. Negative anomalies seldom reach a value of 1000 gammas. These anomalies are superimposed on the normal magnetic variation which averages about four gammas per mile over the study area, as computed from the U.S. Coast and Geodetic total intensity map (1955). The normal magnetic variation increases from south to north. The following discussion involves the qualitative interpretation of the aeromagnetic map.

Northern Area

Several lineations are immediately apparent (plate 1). They are associated with the Keweenawan lavas of the Northern, Middle, and Southern Trap Ranges. Extending across the northwestern portion of the area, skirting the south shore of Lake Superior, is a major multipeak magnetic anomaly composed of alternating positive and negative peaks reaching a maximum amplitude of 750 to 2000 gammas. It coincides with, and is caused by, the outcropping Keweenawan lavas of the Northern Trap Range. The width and amplitude of the anomaly are relatively uniform within the area, suggesting the source is a single geologic formation. The elongate shape of the anomaly suggests the trace of a dipping sheet-like mass. The steep magnetic gradient of this anomaly and its narrowness is indicative of the outcrop of the source rock. This anomaly reaches its maximum breadth in the Porcupine Mountains area. The broadening could be explained by a local increase in the volume of the extrusives, or a change in their dip due to doming.

Another major elongate anomaly is shown in the central portion of the area. It extends from west of Keweenaw Bay southwest toward Lake Gogebic and to the west. The amplitude, ranging from 500 to 900 gammas and the discontinuous nature of this anomaly, reflect variations in depth of its source. This anomaly is interpreted as buried Keweenawan lavas of the Middle Trap Range. The Middle Range only outcrops at Silver Mountain which is located in sections 1 and 12 of T49N, R36W and section 6 of T49N, R35W, Houghton County. The Middle Trap Range reaches its steepest magnetic gradient and highest amplitude at Silver Mountain. According to Roberts (1940), this outcrop is composed of at least fourteen uralitized basalt flows. The flows strike N 20° E and dip 15° to the northwest. They are fine-grained amygdaloidal extrusive rocks, and according to Lane (1909), are typical Keweenawan basalts.

The structure of this range is interpreted as a horst. Some magnetic patterns cut through the Middle Trap Range anomaly and are believed to be associated with transverse faults transecting the Range. The difference in elevation of the Middle Range is attributed to these faults. The abrupt termination of the Middle Range anomaly at the northern end is interpreted as an east-west cross fault. The Bouguer gravity map of the area (Bacon, 1957) and the magnetic second vertical derivative map substantiate this conclusion. A negative magnetic anomaly to the south and east of the Middle Trap Range correlates with the Jacobsville Sandstone which terminates at the outcropping of the unconformity between the Jacobsville Sandstone and pre-Keweenawan rocks. Along the western portion of T50 and 51N, R34W, a north-south striking fault is believed to have dropped the lavas a considerable depth to the east. The contact between the Jacobsville Sandstone and the pre-Keweenawan east of this fault can be traced out by the increased wave-length of the magnetic anomalies associated with the mapped Jacobsville Sandstone.

West of Lake Gogebic, at long 89° 50' W, the anomaly associated with the Middle Trap Range, joins with a subparallel anomaly south of it. The southern anomaly is believed due to the South Trap Range which outcrops at the southern edge of the Jacobsville Sandstone. The outcrops of the South Trap Range east of the junction point are associated with no definite magnetic character in contrast to the situation west of the junction. This can be explained by a difference in magnetic polarization of the lavas in these two localities due to a remanent component and/or due to differences in the dip of the lavas. To the east of the junction point some lava outcrops were found to dip at an angle of 15° to the northwest, while to the west of the junction point, outcrops of lava dip at 70° to 80° to the north.

Between the Northern Trap Range and the Middle Trap Range is a relative magnetic low characterized by low magnetic gradients. This low is believed to be associated with the basalt flows in the downthrown block buried beneath the Jacobsville Sandstone. In T50N, and to the east of R36W there is a positive magnetic anomaly reaching an amplitude of 500 gammas, probably due to an anticlinal flexure in the lavas. In T48N, R38 and 39W the magnetic pattern indicates a fault which may have brought lava nearer the surface.

A well-defined magnetic low of roughly 1100 gammas magnitude exists over the Iron River syncline. A still lower anomaly occurs over the Presque Isle syncline and extends northwest out of the study area. A positive anomaly of about 300 gammas surrounds the Iron River syncline from the west and north. This anomaly is correlated with a rhyolite extrusion, roughly paralleling the base of the Nonesuch Shale. In sections 5, 6, 7 and 8 of T49N, R44W, this anomaly reaches a maximum amplitude of about 1500 gammas. The high magnitude anomaly may be due to remanent polarization of the rhyolite. Another widespread positive magnetic anomaly of 1500 gammas occurs east of the Iron River syncline and centers in T50N, R42W. This anomaly has been interpreted an an upfaulted block of a previously folded anticlinal structure of the Keweenawan lavas underlying the rhyolite and the Nonesuch Shale.

A negative magnetic anomaly in T49N, R42W, within the Northern Trap Range, correlates with a rhyolite body mapped by Wright (1909). Rhyolite is found in drill holes south and within the Iron River syncline and in the Porcupine Mountains area. Miller (1966), on basis of quantitative interpretation of gravity profiles across the Porcupine Mountains area, concluded that the rhyolite is about 2000 to 3000 feet thick under the syncline, 15,000 feet thick in the Porcupine Mountains and extends for some distance to the south of the syncline. The structure in the Porcupine Mountains and the origin of the Iron River syncline could be the result of the lopolithic intrusion of rhyolite. In this case, basining has been contemporaneous with the intrusion, the overlying sediments sagging downward while masses of rhyolite are being withdrawn from the underlying magma reservoir. Billings (1959), states,

> "In fact, some geologists consider this contemporaneous basining, an essential part of the definition of a lopolith. If a large, concordant sheet injected into flat sedimentary rocks were deformed into a basin, during some later orogenic period, these geologists would use the term sill rather than lopolith."

Near the western end of the Northern Trap Range is an elongated negative anomaly of about 200 gammas centered at the border between T48N and T49N and extends across from the western border of R47W, eastward to the eastern border of R43W. This anomaly correlates with outcrops of felsite or conglomerate.

Southern Area

Lake Gogebic

Strong magnetic highs are associated with the eastern end of the Gogebic Range. They are mainly due to the Tyler Slate which includes the Ironwood Iron-formation as its lower-most member. In sections 7, 8, and 9 of T47N, R45W, the anomaly reaches its highest magnitude of about 6000 gammas. East of this location an apparent thickening of the Ironwood Iron-formation is attributed to repetition by strike faulting. The magnetic high associated with the Ironwood Iron-formation ends at the center of T47N, R43W. The magnetic anomaly associated with the Tyler Slate wraps around the nose of the east-plunging Marenisco anticline. Southwest of Lake Gogebic near Marenisco, Michigan, the magnetic anomaly associated with the upper members of the Tyler Slate disappear and the magnetic high associated with the Ironwood Iron-formation appears on the south limb of the Marenisco anticline. This anomaly lies in the center of T46N and extends from the eastern border of R43W to western border of R45W, on the upthrown side of the fault and extends across the Michigan-Wisconsin border.

To the south of the Ironwood Iron-formation anomaly, along the northern limb of the Marenisco anticline, is a negative magnetic gradient of about 250 gammas per mile extending southward for about four miles at the extreme western border of the study area. It averages about one mile in width at the eastern end of the Gogebic Range. This negative, uniform magnetic gradient is interpreted to be the result of greenstones and greenschists beneath the Tyler Slate. West of T47N, R46W, granitic rocks outcrop within the greenstones. These outcrops are not reflected on the magnetic map.

The center of the Marenisco anticline, west of Lake Gogebic is occupied by a very large number of weak magnetic anomalies that strike about N70°E. These anomalies are associated with granite and banded gneiss mapped by Fritts (1965). The boundary mapped by Fritts between the banded gneiss and the granite is apparent from the magnetic pattern east of T47N, R44W. West of that point the boundary is not apparent on the magnetic map and the two units are mapped as one.

The magnetic complexity of the Animikie rocks on the north limb of the Marenisco anticline, and east of T47N, R44W denotes a higher degree of deformation than the same rocks west of that area. According to Prinz (1967), the period of major deformation of these rocks west of T47N, R44W postdated the Keweenawan basalt flows, whereas to the east, the deformation is pre-Keweenawan.

The Tyler Slate anomaly on the south limb of the anticline is located in T46N, and extends from western portion of R41W to western portion of R43W. To the south of the Tyler Slate anomaly, a positive magnetic high of about 1500 gammas is located in the southeast portion of T46N, R42W. This anomaly is related to the iron-formation in the lower part of the metatuff and tuffaceous metagraywacke mapped by Fritts (1967). Skirting the magnetic anomaly associated with this iron-formation is a small negative anomaly of 250 gammas in some places. This anomaly is correlated with the upper parts of the metatuff and tuffaceous metagraywacke, minor quartzite and conglomerate. At the upper contact with the overlying graywacke near Banner Lake, is another narrow negative anomaly of higher magnitude ranging between 350 and 500 gammas. At the border between T46N, and T45N, R43W the discontinuity in this anomaly can be attributed to the Barb Lake fault. At the upper part of this formation, on the south side of the fault, is a magnetic high of 4000 gammas. This anomaly is correlated with the magnetic iron-formation in the upper part of the graywacke member. To the southeast it is bordered by a magnetic low and then a magnetic high. The magnetic low ranges between 300 and 500 gammas and is believed to be associated with the pillow lava and fragmental volcanic rocks. The magnetic high which has an amplitude of 200 gammas is believed to be associated with the metatuff and magnetic iron-formation. The discontinuity of these anomalies is also attributed to the Barb Lake fault which strikes east-west across the center of the Lake Gogebic area.

Clearly the principal structure to the north of the Barb Lake fault is a south-dipping monocline. North of the Barb Lake fault and in T46N and extending eastward from R40W and south of the upper contact of the metatuff formation, is a decreasing uniform magnetic gradient averaging about 500 gammas per mile. This uniform magnetic gradient is correlated with the Michigamme Slate.

The structure south of the Barb Lake fault is more complex and highly folded. Fritts (1965) reported that diamond drilling near Banner Lake indicated a synclinal flexure. The character and magnitude of the magnetic high associated with the metatuff helped in delineating the fold structures south of the Barb Lake fault. The folding of these rocks is believed to have taken place after their deposition over the erosional surface of the Wolf Lake Granite which, south of the Barb Lake fault, is considered to be the oldest rock in the area, and occurs at the center of the anticlines and associated with weak negative magnetic anomalies.

Two more broad negative anomalies occur south of the Barb Lake fault. The first occupies the center of T45N and extends from the eastern border of R43W to the center of R41W. The second occupies T44N and extends from the center of R40W to the western border of R38W. These two anomalies reach about 600 gammas and are correlated with the Michigamme Slate. The Michigamme Slate in this area is named the graywacke formation near Paulding by Fritts (1967). These magnetic lows lie along the axes of synclines.

Iron River-Crystal Falls

The Iron River-Crystal Falls area is characterized by widely contrasting magnetic anomalies. One of the most dominant features is a group of remarkably sharp, long negative anomalies cutting across all other magnetic anomalies. This group of anomalies occurs between lat 46° 15' and 46° 45' N and east of long 89° 05' W, with greatest concentration in T48N and T49N. All are related to reversely magnetized diabase dikes. These dikes intrude strata as young as Michigamme Slate, while other dikes intrude the Margeson Creek Gneiss, mainly a granitic rock generally foliated and gneissic. The age of the Margeson Creek Gneiss is believed to be Early Precambrian. Some negative magnetic anomalies associated with the diabase dikes extend through the area overlain by the Jacobsville Sandstone. These dikes may also intrude the Keweenawan lavas of the South Trap Range. They occur in T48N, R37W and western portion of R36W.

The anomalies associated with the diabase dikes west of the contact between the Jacobsville Sandstone and the pre-Keweenawan rocks have a greater wavelength than those associated with the diabase dikes east of this contact, indicating that these dikes do not reach the bedrock surface and, thus, do not intrude the Jacobsville Sandstone.

The second dominant feature in this area is a group of large positive anomalies occurring within the Michigamme Slate. One occurs in T48N, R32W. Another centers approximately on the south border of T48N, R34W. These anomalies are believed to be due to deep seated mafic rocks of unknown origin. Other anomalies of this type are located in T45, 46, and 47N, R33, 34, and 35W. Balsley and others (1949) believe they are mainly due to dark magnetic slate of volcanic origin on crests of anticlinal folds. Westward these anomalies become weaker and broader, indicating a series of west-plunging anticlines, on which the magnetic rock becomes progressively deeper.

The third group of anomalies occurs in T42, 43N and extends from the western border of R32W to the eastern border of R36W. This group of moderately strong positive anomalies reach amplitudes of 2500 gammas. The major part of the Iron River basin is located within this area. Most of these anomalies are caused by a strongly magnetic slate in the Stambaugh Formation. The slate is composed of fine-grained, intergrown chert and siderite, with abundant tiny crystals of magnetite throughout. This group of anomalies appears erratic in both trend and intensity, indicating the Stambaugh Formation is contained in tightly folded synclines of high variable trend and plunge, characteristic of the Iron River-Crystal Falls area.

Another group of positive anomalies of moderate magnitude occurs in T42N, R34, and 35W. Their source lies within the Badwater Greenstone composed of flows, tuffs, and agglomerates. The Brule River anomaly (Balsley and others, 1949) which occurs to the south of the Randville Dolomite, is associated with a belt of Brule River Greenstone exposed in a number of places in the southern part of Sections 20, 21, and 22, T42N, R35W. It is a massive metabasalt, locally agglomerate and ellipsoidal.

Another dominant magnetic feature in this area is the strong positive anomaly bordering the Amasa oval. This anomaly reaches a magnitude of 6000 gammas in several places. It is caused by the upper part of the Hemlock Formation composed mainly of volcanic breccia and basaltic flows. On the east side of the Amasa oval, the anomaly exhibits a north-south strike perhaps augmented by the Fence River Formation which is a fine-grained, magnetite-bearing quartzite. West and north of the Amasa oval, the anomaly is generally broader and discontinuous due to faulting. The Amasa Formation, chiefly a martite slate with layers of cherty iron-formation, is nonmagnetic (Wier, 1967). These anomalies are interpreted to be due to the same volcanic breccia and basaltic flow member of the upper Hemlock Formation that underlies the Michigamme Slate. The positive anomalies occurring in the center of T47, and 46N, and the northeast portion of 45N, R31, and 32W, bordering the two granitic areas are believed to have their source within the Hemlock Formation.

A large, broad negative magnetic anomaly in T46N, R31W, extends southeast along the eastern border of the Amasa oval. This anomaly correlates with the nonmagnetic graywacke of the Michigamme Slate. Within the Amasa oval, the lower members of the Hemlock Formation show two weaker magnetic zones that trend northwest. Their source may be a magnetic volcanic rock within the Hemlock Formation. Moderate to strong anomalies occur along the eastern border of the West Kiernan sill. Similar anomalies are associated with the metagabbro dikes in the area.

A broad, positive belt of magnetic anomalies extending northwest-southeast in T43N, R31W is interpreted by Bayley (1959) to be due to the magnetite-bearing volcanic schist underlying the Randville Dolomite. A broad negative magnetic anomaly roughly parallels the inferred belt of Randville Dolomite within the Amasa oval.

The magnetic anomaly associated with the Margeson Creek Granite Gneiss at the center of the Amasa oval is not as clearly defined as those associated with the two outcrops of this rock northeast of the oval. This situation can be explained by the fact that the magnetic contrast between the volcanic breccia and basaltic flows and the granitic rocks outside of the Amasa oval is much higher than that between the granite and the peripheral dolomite within the oval.

The granitic rocks north of the Marquette Range cover a large area from the center of T48N to T50N, and from R33W to the eastern border of the study area. The granite is characterized by a pattern of discontinuous highs and lows of varying orientation and of low to moderate magnitude. Apparently their magnetic character is highly affected by the Marquette Range anomaly to the south, and by the several diabase dikes. The northern contact of the granite is an erosional surface and is mapped primarily on basis of geologic information because of lack of a sharp and definite magnetic contrast between the granite and the Michigamme Slate to the north. The magnetic anomalies associated with the Michigamme Slate here exhibit a higher frequency and more irregular strike than those associated with the same formation at the center of the basin, indicating a thinning of the Michigamme Slate in this area, and also that the magnetic character of the underlying granite shows through the overlying Michigamme Slate.

A large positive magnetic anomaly of 8,000 gammas occurs in the center of T48N, R31W. This anomaly is associated with the Negaunee Iron-formation and related sediments at the western end of the Marquette Range. Two distinct positive magnetic anomalies occur immediately west of the margin of the outcrop of the Lower Precambrian granite and gneiss. They are believed to be due to basic igneous rocks and perhaps iron-formation in part. Several small, positive anomalies occurring in T50N, R32W are associated with basic igneous rocks.

Depth Determinations

A variety of techniques were applied to the magnetic data to determine the depth to the magnetic anomaly sources. Where applicable the half-width method (Nettleton, 1942) Smellie's method (1956), Peters' slope method (1949) and Vacquier and others' method (1951) were used to determine depths on a total of 129 anomalies. All of the methods are based on the assumption that the magnetization is only induced. As a result, the depth determinations may be in error because most basic igneous rocks and iron-formations of the area have a strong remanent magnetic component.

Northern Area

Within the Keweenawan area the lavas of the Northern Trap Range occur at or near the surface along its entire length. However, they may be buried to depths of 1400 to 2500 feet at the southern border of the Iron River syncline. South of the Keweenaw fault, in the central and western portions of the study area, a narrow band of Keweenawan rocks of the northern Trap Range appear to be covered by a thin wedge of sediments.

The volcanics of Middle Trap Range are buried beneath 1250 to 2500 feet of Jacobsville Sandstone. However, they outcrop in the Silver Mountain area. This variation in depth to the Middle Range is believed to be due to several cross faults with considerable vertical displacement.

The South Trap Range is exposed continuously west of Lake Gogebic. East of Lake Gogebic it outcrops occasionally along its extension while in some other parts is covered by 3,000 to 5,000 feet of Jacobsville Sandstone.

Southern Area

Magnetic depth determinations indicate that the Michigamme Slate contains more than one level of source anomalies. Those causative masses that are near the surface could be either a magnetite-rich slate member or outcropping basic intrusives. Another group of anomalies has a depth range between 1500 and 4000 feet. The source of these anomalies is believed to be due to basic intrusives and extrusives that lie at the base of the Michigamme Slate.

The metatuff and metavolcanic rocks occurring around Lake Gogebic are mostly outcropping or at few hundred feet from the surface. However, due to local structure these rocks produce anomalies which originate at depths up to 1500 feet from the surface.

The source of anomalies in the Hemlock Formation and Badwater Greenstone either outcrop or are very near the surface. However, in the Hemlock Formation some anomalous sources occur at a depth of 1400 to 2000 feet. The Fortune Lake Slate seems to include a deep magnetic source ranging between 2500 and 4500 feet.

Magnetic Trend Analysis

Studying the "character" of a magnetic map, is a common quantitative approach to magnetic interpretation. This technique is based upon study of wavelength, amplitude, grouping of anomalies, and their magnetic trend pattern. Trend patterns can be used to define magnetic provinces which reflect tectonic provinces (Affleck, 1963).

The area of this report was divided into two parts, the northern area and the southern area. On the basis of magnetic properties of rocks, depth determinations, and examination of the aeromagnetic maps, the magnetic anomalies in the study area were classified according to amplitude, and their correlative rock types, as follows:

First order anomalies -- amplitudes greater than 2500 gammas,

Pre-Keweenawan basic intrusives and extrusives

Pre-Keweenawan iron-formations.

Second order anomalies -- amplitudes between 500 and 2500 gammas,

Keweenawan acidic and basic extrusives

Near surface pre-Keweenawan basic intrusives.

Third order anomalies -- amplitudes less than 500 gammas,

West-trending, reversely-magnetized diabase dikes of Keweenawan age

Keweenawan extrusives buried beneath Keweenawan sediments

Basement gneisses, intrusive greenstones and near-surface, slightly magnetic rocks of pre-Keweenawan age.

The rock type ascribed to each anomaly group is necessarily generalized. Anomalies associated with specific rock types may fall within more than one group due to varying depths, magnetization, or volume of the source.

In general, the anomalies align themselves along definite axes, forming "trends". The trends for the three groups of anomalies were traced out and marked according to the above classification. A simple and standard method of portraying the two-dimensional magnetic trend patterns is to construct a frequency plot showing the number of elements lying in various direction ranges (Miller and Kahn, 1962). The study area was divided into squares of two miles on a side. The squares serve to define "elements" of the pattern. The number of elements is equal to the number of squares in which a particular trend occurs. The direction of the element was measured as an azimuth, clockwise from north, and each element contributed a separate measurement of azimuth. An element that changed its azimuth by more than 5 degrees along its length was broken into two or more separate elements. The number of elements within each area and amplitude group, in each 5 degrees of azimuth, was tabulated and their frequency percentages calculated. The frequency percentage of the total number of elements in the entire survey area as well as in the northern and southern areas for each 5 degrees of azimuth also was calculated. The relationships and the comparisons between areas are shown in figures 3-5. The elements of magnetic trend patterns associated with Keweenawan diabase dikes were tabulated with other elements of the Keweenawan (northern) area, though most of these dikes occur within the pre-Keweenawan (southern) area.

Clearly an east-west trend is dominant through the study area for all groups of anomalies. This east-west trend can be regarded either as a basic tectonic trend or as an overprinted pattern on previous ones. Figure 3-C shows two subsidiary peaks on either side of the major east-west peak associated with the southern area. They occur roughly at N72°E and N102°E and are comparable to two shear planes, suggesting that the stress acting on these rocks at the time of their formation or right after was probably of nonrotational nature (pure shear). Assuming the rocks were ductile, as evidenced by folding, the direction of the principal stress axis is concluded to be north-south.

Figure 5-B shows the subsidiary peak at N72°E more developed than the other subsidiary peak, indicating perhaps that the stress acting during Keweenawan time was rotational (simple shear) due to a shear couple. Figure 3-B shows a gradual increase in frequency of magnetic elements with azimuth between 40 and 85 degrees resulting in asymmetry of the major east-west peak for the northern (Keweenawan) area. This may reflect a gradual shift in both time and space of the shear couple.

Aeromagnetic and Geologic Profiles

For making quantitative interpretations, fourteen profiles across the area were prepared (plate 3). Their location is plotted on the bedrock map (plate 1). These profiles were laid out as closely as possible at right

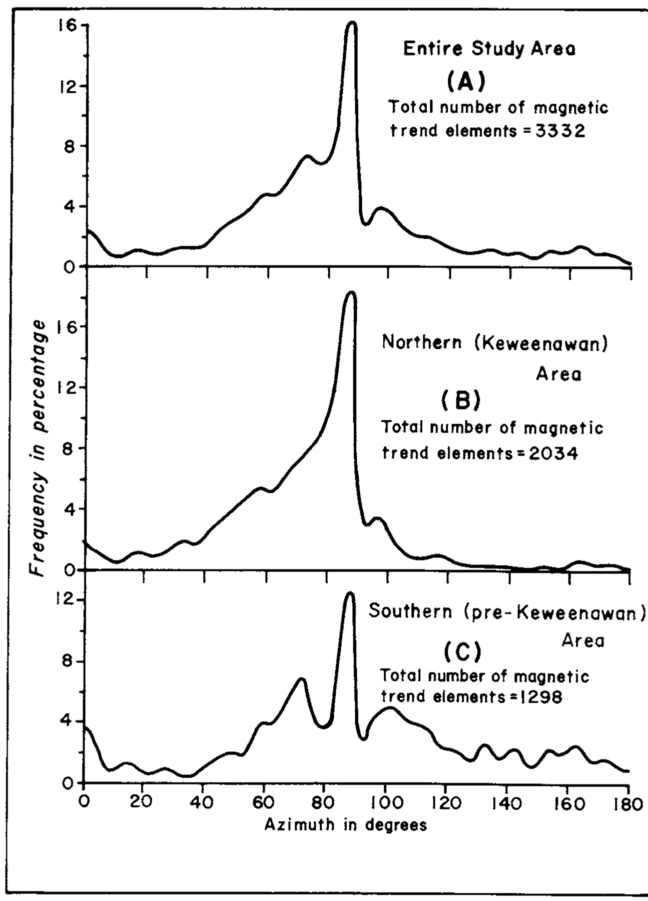

Figure 3 -- Comparison of magnetic trend elements between areas.

angles to known major geological features. Surface topography was taken from U.S. Geological Survey topographic maps.

The general purpose of the quantitative magnetic interpretation was to determine the geology in the cross-sections. In particular, the quantitative interpretation was used to study the geology along the Keweenaw fault and to determine the structure of the Keweenawan lavas of the Middle Trap Range below the Jacobsville Sandstone.

Many of the geologic bodies and structure in the area of investigation are horizontally linear and thus can be approximated by the two-dimensional form of analysis. A two-dimensional magnetic program devised by Talwani, Worzel, and Landisman (1959) was set up for the Michigan State University C.D.C. 3600 computer. This program is based on the assumption that the boundary of the vertical cross-section of a two-dimensional body can be approximated by a polygon. Accuracy can be increased by increasing the number of sides of the polygon. The total magnetic intensity due to the polygon can be obtained at any given point and there are no limits on the size or position of the body.

Initially several trials were conducted to compute anomalies from bodies of assumed geometric configuration and magnetic polarization contrasts to fit the observed anomalies along three of the fourteen profiles. The assumed forms of these bodies were selected on the basis of available geologic information. All other available information concerning the parameters of the bodies such as depth, length, dip and magnetic polarization also were used in the calculations. Unfortunately, little success was achieved in matching theoretical anomalies with the observed magnetic profiles perhaps due to the complexity of magnetic rock properties.

As a result, a qualitative approach was made to the interpretation of the profiles using surface geology, depth determinations, second vertical derivative magnetic map, Bouguer gravity map (Bacon, 1957), plus the results of one profile, H-H' in which a reasonable match was obtained between the theoretical and observed anomalies.

Profile A-A'

The magnetic gradient at the northern end of profile A-A' is related to the dip of the Keweenawan lavas into the Lake Superior basin and the thickening of the Keweenawan sediments. A low magnitude positive anomaly of about 150 gamma amplitude lies over the outcrop of Copper Harbor Sandstone. This anomaly may be due to a conglomeratic member of the Copper Harbor Sandstone which contains abundant basalt pebbles. To the immediate south of this anomaly

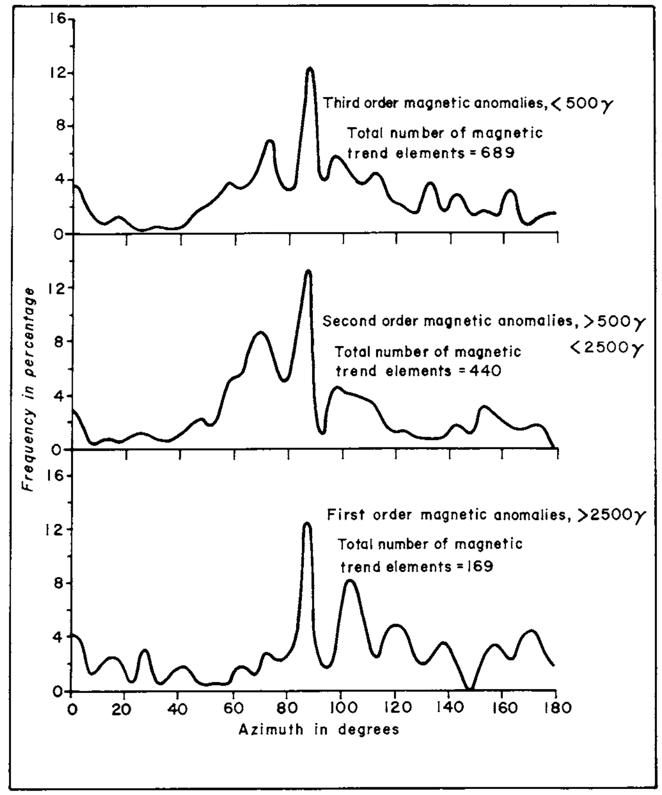

Figure 4 -- Distribution of magnetic anomalies within southern (pre-Keweenawan) area.

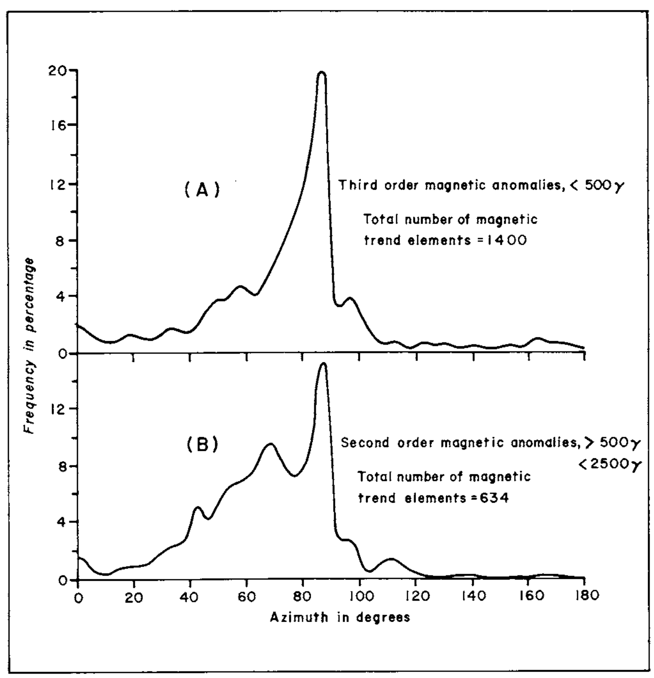

Figure 5 -- Distribution of anomalies within northern (Keweenawan) area.

are two positive peaks separated by a large negative anomaly. The two positive peaks reach an amplitude of about 500 gammas and are related to the Keweenawan lavas of the Northern Trap Range. The negative anomaly reaches an amplitude of about 400 gammas and is associated with a felsitic, concordant intrusion within the Northern Trap Range. A negative anomaly occurs to the immediate south of the positive anomaly associated with the Northern Trap Range lavas. This negative anomaly is believed to be attributed to loss of magnetism of the lavas near the Keweenaw fault or to the complications of remanent magnetization in the neighborhood of the fault. Hemming (1965) in a typical section across the Keweenaw fault near Portage Lake mapped the Keweenaw fault at a distance of about one mile to the south of the positive anomaly associated with the Keweenawan lavas. Accordingly, the Keweenaw fault throughout the study area has been mapped at the center of this negative anomaly at the southern margin of the Northern Trap Range.

The Jacobsville Sandstone to the south of the Keweenaw fault yields a magnetic low. At the southern margin of the Jacobsville Sandstone a magnetic high of about 2400-gamma magnitude is associated with the outcropping lavas of the South Trap Range. Although the width of the outcrop of the South Trap Range is less than that of the Northern Trap Range, the South Trap Range anomaly has a much higher amplitude. This may be attributed to the higher angle of dip along this profile and/or greater magnetic polarization of the South Trap Range lavas.

To the immediate south of the South Trap Range anomaly a positive anomaly of 5000-gamma amplitude is associated with the Ironwood Iron-formation. The anomaly associated with the greenstone underlying the iron-formation seems to be partially masked by the local strong regional effect resulting from the iron-formation anomaly. The granite and banded gneiss at the center of the Marenisco anticline is associated with a magnetic low that includes narrow positive anomalies having amplitudes generally less than 100 gammas. To the south of the granite is a magnetic high of about 1500-gamma amplitude associated with the iron-formation on the south limb of the Marenisco anticline. The contact between the granite and this iron-formation is considered to be an unconformity, as evidenced by the erosion of the greenstone on the south limb of the Marenisco anticline. To the south, the iron-formation is overlain by metatuff and tuffaceous metagraywacke associated with a magnetic low.

Profile B-B'

The prominent feature at the northern portion of profile B-B' is the positive magnetic anomaly associated with the rhyolite outcrop. This anomaly is higher than the anomaly associated with the Northern Trap Range lavas, perhaps because of strong magnetic polarization of the rhyolite due to a remanent component. The negative anomaly associated with the felsite intrusion within the Northern Trap Range also occurs on this profile. The negative anomaly immediately south of the positive anomaly associated with the Northern Trap Range lavas suggests southerly dip of the contact between these lavas and the Jacobsville Sandstone. Two positive anomalies occur within the outcrop area of the Jacobsville Sandstone. The anomaly situated immediately south of the Keweenaw fault has a steeper magnetic gradient than the one further south. The latter is interpreted as a horst associated with the Middle Trap Range.

The anomaly immediately south of the Keweenaw fault is interpreted as a block of Keweenawan lavas separated from the main body of the Northern Trap Range by faulting. This anomaly continues for about fifty miles across the study area and lies immediately south and parallel to the interpreted position of the Keweenaw fault, indicating the origin of this block is associated with the thrusting of the Northern Trap Range along the Keweenaw fault. Several explanations of the origin of this block are suggested but all lack geologic evidence.

One is based on the assumption that faulting took place across the southern portion of the Northern Trap Range (fig. 6-B). Due to the thrust with rotation along the Keweenaw fault, the wedge of sediment north of the fault has been brought nearer to the surface (fig. 6-C). Differential erosion followed and resulted in separation of the smaller block of lava from the main body of the Northern Trap Range (fig. 6-D). Still later a younger sandstone formation was deposited (fig. 6-E) leading to the present geologic structure.

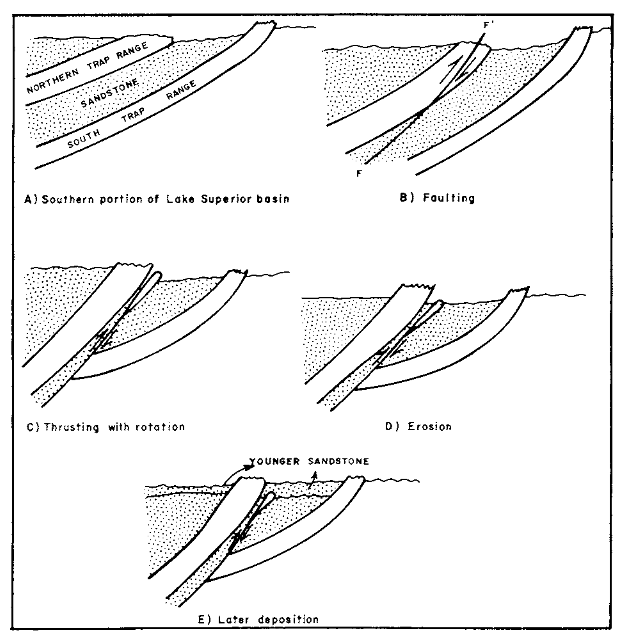

Figure 6 -- First explanation of development of structure along Keweenaw fault.

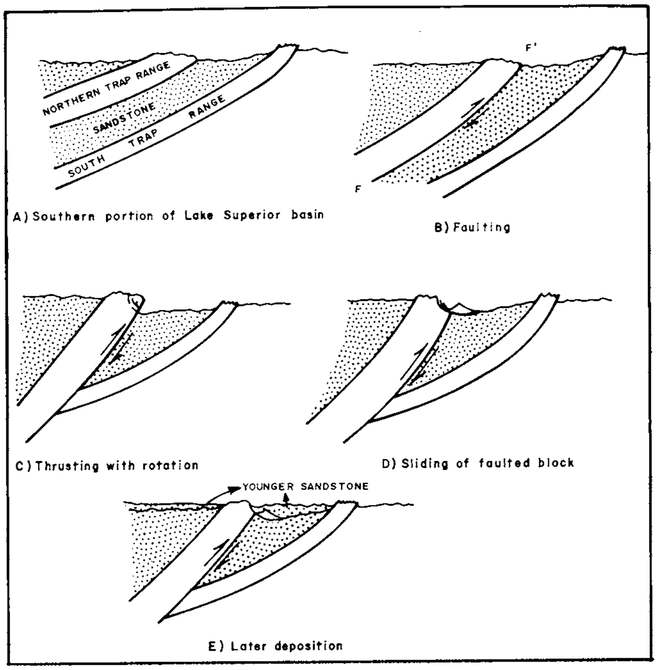

Figure 7 -- Second explanation of development of structure along Keweenaw fault.

Another explanation is based upon the assumption that faulting took place along the contact of the sandstone and the lavas of the Northern Trap Range or parallel to it. As illustrated in fig. 7-C, a cross fault developed within the Northern Trap Range lavas approximately at right angles to the Keweenaw fault plane and sliding of the faulted block took place (fig. 7-D). The cross-faulting and/or sliding may have been facilitated by insufficient support of the Northern Trap Range lavas by the underlying sandstone. Later deposition of a younger sandstone formation followed, leading to the present geologic structure (fig. 7-E).

Results obtained from quantitative magnetic interpretation substantiates the configuration along the Keweenaw fault shown in fig. 7-E. Also Miller (1966), as result of his gravity investigation of the Porcupine Mountains area, concluded that the southern margin of the lavas in contact with the sandstone dips to the south rather than the north as previously postulated. He reached this conclusion as a result of quantitative interpretation of gravity profiles across the Keweenaw fault.

A third explanation of the positive anomaly immediately south of the Keweenaw fault, is that it is an intrusion into the sandstone. This seems unlikely due to the persistence of this feature for a distance of about fifty miles. The solution to the source of this anomaly must await further detailed geological and geophysical studies.

The anomaly associated with the South Trap Range reaches an amplitude of about 2000 gammas and is separated from the iron-formation anomaly on the northern limb of the Marenisco anticline by a magnetic low. This low is associated with the upper member of the Tyler Slate which is nonmagnetic. The anomaly associated with the greenstone along this profile is more pronounced than that shown on the previous profile and reaches an amplitude of 500 gammas. The positive magnetic anomaly associated with the iron-formation on the south limb of the Marenisco anticline reaches an amplitude of about 1000 gammas.

South of the Marenisco anticline is a syncline that includes rocks of the Upper Animikie series. A graywacke slate formation occurs at the center of this syncline and is correlated with the Michigamme Slate to the east. The graywacke slate formation is associated with a magnetic low and overlies the slightly magnetic metavolcanics and metasediments near Blair Lake. Near Banner Lake the metavolcanics and metasediments are underlain by the graywacke which includes a magnetic iron-formation in its upper part.

The two anomalies associated with the metavolcanics and iron-formation member of the graywacke at the northern limb of the syncline merge into one anomaly that reaches about 200-gamma magnitude. The low magnitude and breadth of this anomaly can be attributed to the small angle of dip of these formations. The graywacke is underlain by the metatuff and tuffaceous metagraywacke which thickens along this profile due to repetition by faulting. At the extreme southern portion of the profile the granitic basement rocks of Early Precambrian age outcrop at the surface.

Profile C-C'

The northern portion of profile C-C', associated with the Keweenawan rocks, is similar to the corresponding portion of profile B-B'. However, the Northern Trap Range anomaly includes more magnetic lows. These lows are attributed to a number of felsitic conglomerates in the Great Conglomerate and Outer Conglomerate (Upper Keweenawan) estimated by Butler and Burbank (1929) to have maximum thicknesses of 2200 and 3500 feet respectively.

In the pre-Keweenawan (southern) area the anomaly associated with the iron-formation at the base of the Tyler Slate on the south limb of the Marenisco anticline is not present, probably as result of faulting. Further to the south is a large positive anomaly of about 3500 gammas associated with the iron-formation in the upper series of the graywacke near Banner Lake. The anomaly over the metavolcanic and metasedimentry rocks divides into a magnetic low and a magnetic high. The magnetic low is situated immediately south of the iron-formation anomaly and is associated with the pillow lavas and fragmental volcanic rocks.

The magnetic high attains a magnitude of about 500 gammas and is associated with the metatuff and magnetic metasedimentary rocks. The granitic basement rocks outcrop at the extreme southern portion of this profile.

Profile D-D'

Along profile D-D' the Northern Trap Range anomaly reaches its maximum amplitude of 2000 gammas, and the magnetic gradient north of it reflects a thickening of the sediments over the center of the Iron River syncline. The steep-gradient anomaly to the south of the Keweenaw fault and the anomaly associated with the Middle Trap Range lavas are shown on this profile as in previous profiles. The South Trap Range does not outcrop along this profile and is assumed to underlie Lake Gogebic.

A small positive magnetic anomaly of about 200-gamma magnitude is associated with the iron-formation at the base of the metatuff and tuffaceous metagraywacke. Further to the south, an asymmetrical anomaly of about 600-gamma magnitude occurs along this profile and is related to the combined effect of the outcropping metavolcanics and metasediments and the underlying iron-formation in the upper part of the graywacke near Banner Lake. The steeper gradient on the northern side is attributed to the Barb Lake fault. The gentler slope of the southern side reflects the low angle of dip of the magnetic formations. Another small positive anomaly of 200-gamma magnitude associated with the outcrop of the metavolcanics and metasediments is situated at the southern limb of the syncline. At the southern portion of this profile and within the granitic basement rocks, are two positive anomalies associated with two outliers of metavolcanics and metasediments.

Profile E-E'

The portion of the profile E-E' associated with the Keweenawan rocks is similar to the corresponding portion of the profile D-D'. However, the South Trap Range anomaly is present along this profile and reaches a magnitude of about 500 gammas. Immediately to the south of the South Trap Range volcanics, the metatuff and tuffaceous metagraywacke outcrops and is intruded by a younger granite, probably of late Animikie age. This younger granite outcrops along the profile and in several other places south of Lake Gogebic and north of the Barb Lake fault. South of this granite is a broad magnetic low associated with the upper members of the metatuff and tuffaceous metagraywacke, the graywacke near Banner Lake, and the metavolcanic member of the younger rocks. Four positive magnetic anomalies are associated with the outcrops of the metatuff and magnetic iron-formation on both sides of the Barb Lake fault. The magnitude of these anomalies differs because of local thickening and minor folding. The two magnetic lows situated immediately south of the Barb Lake fault and at the southern portion of the syncline are associated with the graywacke-slate formation. The central negative magnetic anomaly is due to local thinning of the metatuff and magnetic iron-formation. At the southern portion of this profile and within the granitic basement rocks, a broad positive anomaly of about 250-gamma magnitude is associated with an outlier of the metavolcanics and metasediments.

Profile F-F'

The magnetic gradient at the northern end of profile F-F' reflects a doming of the buried Keweenawan lavas. This doming is mainly related to folding. A sharp decrease in the magnetic gradient at the northern end of this profile is attributed to faulting of the Keweenawan lava. The steep-gradient positive anomaly immediately south of the Keweenaw fault reaches its maximum amplitude of about 850 gammas along this profile.

The positive magnetic anomaly associated with the South Trap Range lavas reflects a thinning of these lavas due to erosion along its outcrop. South of the South Trap Range anomaly is a sharp positive anomaly of about 600-gamma magnitude associated with the iron-formation which occurs in the upper part of the graywacke near Banner Lake. This anomaly is followed by a broader and stronger positive anomaly associated with the outcrop of the metavolcanics and metasediments. The Michigamme Slate on the downthrown side of the Barb Lake fault is associated with a magnetic low. The granitic basement rocks outcrop along the southern portion of the profile on the upthrown side of the Barb Lake fault. Several positive magnetic anomalies of varying amplitudes are associated with outliers of metavolcanics and metasediments in the granitic basement rocks.

Profile G-G'

The anomalies associated with the Keweenawan rocks along profile G-G' are generally similar to the corresponding anomalies along profile F-F'. However, the magnetic gradient at the northern portion of the profile reflects a thickening of the Keweenawan sediments along this profile as result of the disappearance of the domal uplift encountered along the previous profile. The South Trap Range is associated with a negative anomaly along its outcrop reflecting a change in the magnetic polarization of the South Trap Range lavas. The negative anomaly is emphasized by the positive anomaly immediately south of it and associated with the metavolcanics and metasediments. The gentler gradient on the south side of the positive anomaly is attributed to a lower angle of dip of the metavolcanics and metasediments and due to thickening of the Michigamme Slate toward the center of the syncline. The granitic basement rocks outcrop immediately to the south of Barb Lake fault and are associated with a small positive magnetic anomaly. South of the Barb Lake fault, a strong positive magnetic anomaly of 5500-gamma amplitude is associated with the outcrop of the metavolcanics and metasediments on the northern limb of the syncline. The outcrop of the same formation on the south limb of the syncline is associated with another anomaly of much lower magnitude. This decrease in amplitude is attributed to thinning and gentler angle of dip of the metavolcanics and metasediments at the south limb of the syncline. Another positive magnetic anomaly at the southern end of this profile is related to metavolcanics and metasediments at or very near the surface.

Profile H-H'

The portion of profile H-H' associated with the Keweenawan rocks has been interpreted quantitatively. Separate body configurations were utilized to approximate the Northern Trap Range, and the combined Middle and South Trap Ranges.

The magnetic program used in the quantitative interpretation is based on calculating the combined induced and remanent field vector. Both vectors are resolved into orthogonal components which are then added algebraically. The sums specify the coordinates of the end point of the combined field vector. The combined angles of declination and inclination are then calculated. An inclination of $+45^{\circ}$, a declination of 285°, and a total magnetic intensity of 0.00354 c.g.s. units were used for the remanent magnetization vector of the Keweenawan volcanics. These are the approximate values given by Dubois (1962) and Jahren (1965) for the remanent magnetic polarization vector of the basic Keweenawan plutons and extrusives. These values are given for the remanent magnetic vector assuming that the lavas lie in a horizontal position. A structural correction of 50° dip was applied to the remanent vector applied for the Northern Trap Range body; and a correction of 20° dip was applied for the remanent vector used for the other body representing the Middle and South Trap Ranges. Consequently, the resultant magnetization vector for each body was calculated by the vector summation of the induced and remanent magnetization values. A magnetic inclination of $+71^{\circ}$, a magnetic declination of 0°, and a total field intensity of 59,500 gammas were the magnetic elements utilized for the induced vector in the calculations. The resultant magnetic vector used in the calculations of the magnetic effect for the Northern Trap Range body has a magnetic inclination of $+74^{\circ}$, a magnetic delination of 143°, and a combined field intensity of 527 gammas. The resultant magnetic vector used for calculating the magnetic effect for the other body has a magnetic inclination of $+63^{\circ}$, a magnetic declination of 127°, and a combined field intensity of 513 gammas. The value of magnetic susceptibility used for the combined vector for both bodies was unity and the combined intensity was read, in gammas, into the computer in place of the total magnetic field. The dimensions of the bodies, the flight elevation (500), and station spacing (200), were in feet. The assumption has been made in the magnetic program that the inclination and declination do not vary as the magnitude of the anomaly increase. This assumption allows the summations of the effects of individual bodies along the profile.

Repeated trials with reasonable configurations bringing the Keweenaw fault to the surface greatly distorted the theoretical anomaly as compared to the observed anomaly. However, a reasonable match between the theoretical and the observed anomalies was achieved over this portion of the profile by assuming the configuration shown for the Northern Trap Range body in profile H-H'. The steep gradient anomaly to the south of the Keweenaw fault is not present along this profile. A close correlation over the Middle Trap Range is obtained between the theoretical anomaly and the observed magnetic profile. The estimated depth from the quantitative interpretation for the Middle Trap Range is about 2000 feet. This value is in close agreement with the value of 2300 feet obtained from a borehole drilled at latitude 46° 31' N and longitude 89° 16' W through sandstone (Bacon, 1966) about 2.7 miles west of this profile. No match for the negative anomaly associated with the outcrop portion of the South Trap Range is evident from the theoretical profile. This necessitates the assumption of a different magnetic polarization for the South Trap Range, which, in turn, casts suspicion on the configuration of the Middle Trap Range anomaly determined by the calculation. The thickness of the Keweenawan lavas below the Jacobsville Sandstone is not predictable from the magnetics. However, a minimum thickness of about 2000 feet is reasonable to assume.

Immediately south of the South Trap Range anomaly, an asymmetrical positive magnetic anomaly is associated with the outcropping portion of the metavolcanics and metasediments. The gentle gradient on the south side is attributed to the thickening of the overlying nonmagnetic Michigamme Slate toward the center of the syncline. The granite outcrop to the south is associated with a magnetic low. At the southern portion of this profile another asymmetrical positive magnetic anomaly is associated with another metavolcanic outcrop to the south of the granitic basement rocks.

Profiles I-I' and J-J'

The profiles I-I' to N-N' are primarily aimed toward the discussion of the Keweenawan geology in the northeastern portion of the study area. This is justified by the fact that the Precambrian geology to the southeast of these profiles, has been investigated in detail by the U.S. Geological Survey. The results of these studies are published by Wier and others (1953), Gair and Wier (1956), Bayley (1959), and Wier (1967).

Due to the general similarities, profiles I-I' and J-J' are discussed together. The Northern Trap Range in both profiles is associated with a multiple-peak positive anomaly which decreased in magnitude due to the thinning of the lava flows. The southernmost peak is smaller amplitude and separated from the main Northern Trap Range anomaly by a negative anomaly related to felsitic intrusions within the Northern Trap Range. Possibly the smaller amplitude anomaly to the south of the negative may be due to the continuation of the block of volcanics along the south edge of the Keweenaw fault.

The Middle Trap Range is cut by three normal faults which bring the volcanics nearer the surface. Along profile J-J' is a peculiar negative anomaly associated with the Middle Trap Range. This negative anomaly is attributed to tilting of the faulted blocks of the Middle Trap Range. Also, no South Trap Range anomaly is present along the southern margin of the Keweenawan rocks on profile J-J' or profiles to the northeast, probably because the lavas occur only as a thin sheet which gradually wedges out beneath the sandstone. The thinning shown on the profiles is highly schematic.

Along the southern portion of these profiles diabase dikes cut through the older formation. The most northwesterly dike along these profiles is believed to cut through the erosional wedge of the South Trap Range, but does not continue through the overlying Jacobsville Sandstone. This is evidenced by the broader negative anomalies associated with these dikes compared to the dikes outcropping in the southeastern portion.

Profiles K-K' to N-N'

Profiles K-K' to N-N' are discussed together because of their general similarity. The Northern Trap Range anomaly along these profiles varies from 250 to 1000 gammas reflecting local change in the volume of lava. The steep-gradient positive anomaly immediately south of the Keweenaw fault is not present. A very broad positive anomaly of low magnitude lies over the Jacobsville Sandstone outcrop south of the Keweenaw fault. This anomaly is attributed to a deep anticlinal flexure of the Keweenawan lavas. The Middle Trap Range anomaly attains a maximum amplitude of about 750 gammas and its steepest gradient along profile K-K' where it appears to be very near the surface. The outcrop at Silver Mountain supports this observation. The Middle Trap Range anomaly is not present along profile N-N' because this profile passes north of an east-west cross fault terminating the Middle Trap Range. In all of these profiles no magnetic anomaly is associated with the erosional wedge of the South Trap Range lavas.

Several diabase dikes along the southeastern portion of these profiles cut across pre-Keweenawan formations. None of these dike anomalies cut across the erosional wedge of the Keweenawan volcanics. A positive magnetic anomaly of about 2500 gammas occurs along the southeastern portion of the profile K-K'. This anomaly is related to an anticlinal flexure of the metavolcanics and metasediments beneath the Michigamme Slate. Several other positive anomalies of smaller amplitude along the southeastern portion of the profile are associated with local anticlinal flexures in the metavolcanics and the metasediments.

The portion of the magnetic profile overlying the Michigamme Slate levels off in an easterly direction from profile K-K' to profile N-N'. This is mainly attributed to the thinning of the metavolcanics and metasediments, possibly due to erosion before the deposition of the younger Michigamme Slate.

# # #

CONCLUSIONS

This study has shown conclusively that aeromagnetic interpretation is an extremely useful tool in determining the regional structure of Precambrian terrane consisting of widely diverse magnetic formations. However, the complexity of the magnetic rock properties restricts the interpretation to a semi-quantitative approach based upon the integration of the surface geology, Bouguer gravity anomalies, and the results of analytical studies of the magnetic data. Analytical studies useful in the interpretation include magnetic depth determinations and trend analysis, second vertical derivative total magnetic intensity anomalies, and correlation of theoretical magnetic anomalies with the observed magnetic data.

Magnetic interpretation confirmed some geological relations and suggested new solutions to major structural problems in the western Upper Peninsula of Michigan. The near-surface contact between the Keweenawan lavas of the Northern Trap Range and the Jacobsville Sandstone appears to dip southerly west of long 89° 20' W. This dip probably originates from cross faulting and/or sliding to the south of a block of Keweenawan lavas over the Jacobsville Sandstone after the major thrust of the Northern Trap Range lavas along the Keweenaw fault.

A time break in deposition of the Jacobsville Sandstone is suggested, dividing it into two major series of sandstone. The lower series is believed to have been deposited before extrusion of the Northern Trap Range lavas, whereas the upper series was deposited after the extrusion of these lavas. This postulated break in deposition during the period of tectonism associated with the Keweenaw fault may be the main reason for the present ambiguity about the age of the Jacobsville Sandstone. Evidently the lower sandstone series is not older than Middle Keweenawan age, while the upper series can be either of late Keweenawan or Early Cambrian age, depending on the magnitude of the disconformity separating the two series.

The thickness of the Northern Trap Range lavas in the Porcupine Mountina area is due to local structural relations. The structure in the Porcupine Mountains and the origin of the Iron River syncline are interpreted to be the result of a lopolithic intrusion of rhyolite. The sagging of the overlying sediments is believed to be contemporaneous with the withdrawal of the rhyolite from the underlying magma reservoir.

The structure of the Middle Trap Range is interpreted as a lava horst. Other than the Silver Mountain outcrop, the volcanics of the Middle Trap Range generally are buried beneath 1250 to 2500 feet of Jacobsville Sandstone. The variation in depth to the Middle Range is believed to be due to several cross faults of considerable vertical displacement. The Keweenawan lavas in the graben between the Northern Trap Range and the northern portion of the Middle Trap Range exhibit an anticlinal flexure paralleling the strike of the Middle Trap Range. A thinning of the Jacobsville Sandstone in the central portion of Houghton County is indicated from quantitative interpretation of the aeromagnetic map. This thinning suggests another anticlinal flexure of Keweenawan lava. The lavas of the Middle Trap Range are interpreted as younger members of the South Trap Range lavas separated from the South Trap Range east of long 89° 50' W. The older members of the South Trap Range lavas extend along the contact between the older Animikie rocks and younger Keweenawan rocks. The South Trap Range lavas occasionally outcrop, but in general these volcanics are buried beneath 3000 to 5000 feet of sandstone.

The Wolf Lake Granite south of the Barb Lake fault, assigned to Late Animikie age by Fritts (1967), is believed to be Early Precambrian associated with the granitic basement rocks in the center of the Marenisco anticline. The basement rocks are believed to have been tilted to the north during early Precambrian time and subjected to erosion, thus resulting in a greater angular unconformity between the basement and the overlying sediments. The northerly tilt of the basement rocks resulted in a thickening of the sediments toward the north. This fact is evident in the study area where younger Animikie metavolcanics and metasediments exposed south and west of Watersmeet lie unconformably on granitic basement rocks, while the older Tyler Slate lies unconformably on granitic basement rocks outcropping near Marenisco.

The magnetic strata of the Marenisco Range as mapped by Fritts (1967) are interpreted as the Ironwood Iron-formation of the Tyler Slate series on the south limb of the Marenisco anticline.

The volcanic breccia and basaltic flows in the upper part of the Hemlock Formation, associated with a group of strong positive anomalies surrounding the Amasa oval, are believed to underlie the Michigamme Slate basin. The depth of this basin varies between 1500 and 4000 feet.

The magnetic trend analysis results suggest that the stress acting on the pre-Keweenawan rocks was non-rotational, and that the principal stress axis was north-south. However, the stress acting on the Keweenawan rocks is believed to be rotational due to a shear couple shifting in time and space during Keweenawan tectonism.

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