AN AEROMAGNETIC SURVEY AND GEOPHYSICAL INTERPRETATION OF THE PRECAMBRIAN FRAMEWORK AND TECTONIC STRUCTURE OF THE EASTERN LAKE SUPERIOR REGION

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ABSTRACT

AN AEROMAGNETIC SURVEY AND GEOPHYSICAL INTERPRETATION OF THE PRECAMBRIAN FRAMEWORK AND TECTONIC STRUCTURE OF THE EASTERN LAKE SUPERIOR REGION

by Norbert Wilhelm O'Hara

An aeromagnetic survey of eastern Lake Superior and Lakes Michigan and Huron, covering over 90,000 square miles, was conducted to study the relatively unknown basement geology and tectonic framework underlying the lakes. During the survey over 20,000 miles of flight lines, spaced at six-mile intervals, were recorded with a digital recording proton precession magnetometer. Approximately 6,700 miles of flight traverses, covering nearly 30,000 square miles are analyzed in this investigation of eastern Lake Superior and the eastern half of the Northern Peninsula of Michigan.

In this study a geological and geophysical interpretation of the Lake Superior trough is given, with particular emphasis on the magnetic data collected over the eastern Lake Superior region. The results of the aeromagnetic survey generally support the geological interpretation that the Lake Superior trough contains thick accumulations of flood basalts and clastic sediments. The axis of the trough extends southward across the Northern Peninsula of Michigan paralleling the basic volcanics of the Keweenaw Peninsula

which curves southward through Stannard Rock and Grand Island.

The Isle Royale thrust fault and associated volcanics parallel the general curvature of the Keweenaw Peninsula to the vicinity of Superior Shoal, where it is terminated by an en echelon zone of transverse normal faults extending from Ashburton Bay to Keweenaw Bay. A thrust fault, on the north side of Michipicoten Island continues southeastward toward Gargantua Point. To the north this fault parallels the shoreline at a distance of 10 to 15 miles. Midway between Michipicoten Island and Pic Bay the fault may either continue northward along the east side of the Port Coldwell complex or swing westward to the south of the Slate Islands toward the volcanic outcrops on the islands of Nipigon Bay.

South of Michipicoten Island the volcanics have been uplifted along transverse normal faults striking roughly east-west perpendicular to the axis of the trough. Other transverse faults produce a series of tilted blocks through the central portion of the lake. Along the southeastern margin of the trough, the volcanics appear to be discontinuous, forming a series of transverse horsts and grabens. Major areas of volcanic rock extend southwestward from Mamainse Point and the eastern margin of the Northern Peninsula of Michigan.

The structural and tectonic features in the Lake Superior trough and its extensions indicate that both compressional and tensional forces have been involved in the origin and development of a major geologic feature extending from central Kansas northeastward along the "mid-continent gravity high," through the Lake Superior trough and the Southern Peninsula of Michigan. The sinuous shape of the Lake Superior trough, the serated configuration of its southeastern shoreline, the en echelon sequence of positive gravity anomalies along the "mid-continent gravity high," and the faulting suggested by the mangetic data from eastern Lake Superior, indicate transcurrent movements. These movements have been interpreted to be the result of crustal thinning and counter-clockwise rotation of the continent. The resulting "Lake Superior Rift System" appears to have originated from tensional forces generally perpendicular to the axis of the trough. During this initial phase of the trough's development a vast amount of basic material was intruded into the upper crust layers and extruded into the central portion of the trough. As the configuration of the trough became more sinuous, compressional forces appear to have forcibly downwarped the trough. During this time a thick sequence of clastic sediments accumulated. Continued intrusions of basic mantle material into the lower crustal rocks through tension fractures at the base of the downwarped crust also increased the crustal thickening beneath the Lake Superior trough. Finally, relaxation of the shear-compression eventually resulted in isostatic adjustment which produced uplifting along the major thrust faults. Greater compressional downwarping of the western portion of the lake trough could result in proportionately greater vertical adjustment which would explain the abrupt termination of the Keweenaw and Isle Royale thrust faults along the zone of cross-faulting that appears to extend northeastward from the Keweenaw Peninsula to Ashburton Bay.

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CHAPTER I

INTRODUCTION

The Western Great Lakes Aeromagnetic Research Project

Nature and Objectives

Since Douglas Houghton's initial geological studies of the "copper country" in 1840, numerous geologists and geophysicists have labored to decipher the Precambrian framework and tectonic structure of the Lake Superior region. Motivated by the presence of rich copper and iron ore deposits, they have accumulated much information about the Precambrian structural features surrounding Lake Superior. Other geophysical studies have extended our knowledge of the basement complex beneath the Paleozoic sediments surrounding Lakes Michigan and Huron. Little attention, however, has been directed to the relatively inexcessible areas covered by the waters of the Western Great Lakes (Lakes Superior, Michigan and Huron). Consequently the lack of information regarding these areas is a severe limitation to the geological interpretation of the Great Lakes region and Interior Lowlands.

Magnetic investigations conducted over the land adjacent to the Western Great Lakes have indicated considerable magnetic relief that can be correlated with the observed geologic features. Therefore, an aeromagnetic survey was considered the most economical and rapid method of extending our knowledge of these features beneath the lakes.

The general objectives of the study were: (1) to help fill the gap in our geological knowledge caused by the lack of information on the areas beneath the lakes; (2) tie together the over-land magnetic work presently available on the areas surrounding Lakes Superior, Michigan and Huron; and (3) obtain information concerning the crustal rocks and their physical properties to correlate with the "International Upper Mantle" seismic project in Lake Superior.

The specific objectives of this study include an investigation of the following major Precambrian structural features:

1. The eastward extension of the Keweenaw, Douglas, and Isle Royale faults beneath Lake Superior.
2. The southwest extension of the Grenville front beneath Lake Huron.
3. The extent and configuration of the Lake Superior syncline.
4. The continuity and extension of the east-west Precambrian structural trends.
5. The areal and vertical distribution of Precambrian basement rocks underlying the Western Great Lakes.

Organization and Scope

To correlate the over-water aeromagnetic data with the data available from magnetic surveys of the surrounding land areas and to insure accurate navigation, this project was designed to include the land areas immediately adjacent to the lakes for a distance of about ten miles. In the western Lake Superior region additional land area was included in the survey to permit statistical analysis of the data. The survey area over land also was increased to cover the eastern half of the Northern Peninsula and the northern tip of the Southern Peninsula of Michigan. These sections were included to insure complete coverage for interpreting the extent of the Lake Superior trough and the Keweenaw fault.

The flight tracks along which useable aeromagnetic data was obtained can be seen on the Flight Traverse Map, Figure 1. Traverses also were flown around each lake, but were not plotted although the data collected along them were used in preparing the total magnetic intensity maps. The average interval between flight tracks is approximately six miles. Flight elevation was 3000 feet M.S.L. or about 2400 feet above lake level. A total of nearly 28,000 miles of useable data was obtained, covering an area of approximately 125,000 square miles.

To best accomplish the objectives of this study and to facilitate the collection and interpretation of data, the area of investigation was divided into four major overlapping

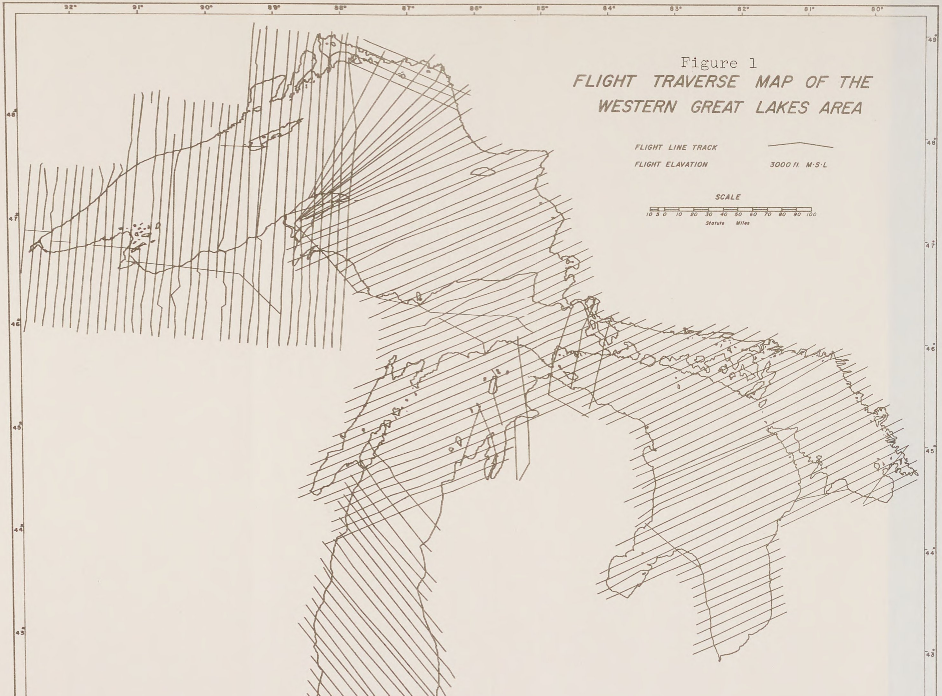


Figure 1
FLIGHT TRAVERSE MAP OF THE WESTERN GREAT LAKES AREA

4

sections: (1) western Lake Superior; (2) eastern Lake Superior; (3) Lake Michigan; and (4) Lake Huron.

The collection, reduction and interpretation of the data in the western Lake Superior section were performed by Richard Wold of the Geophysical and Polar Research Institute of the University of Wisconsin. The magnetometer used to collect the data in western Lake Superior also was employed in the other three sections. The same flight traverse interval and flight elevation was maintained in all sections of the aeromagnetic survey. The aircraft used over western Lake Superior was a Navy P2V Neptune. Flight traverses were flown in a north-south direction and the area covered in this section overlapped the eastern Lake Superior study to insure correlation. This western Lake Superior portion of the survey, covering an area of nearly 33,000 square miles, over which approximately 7,500 miles of useable data were collected along 37 flight traverses, has been recently reported by Wold and Ostenso (1966).

The three remaining sections of the aeromagnetic survey were conducted through Michigan State University. A total area of over 90,000 square miles was covered in 115 major flight traverses. Additional traverses were flown along the shoreline of each lake intersecting the main traverses. All together, approximately 20,000 miles of useable data were obtained.

The general or expected trend of the basement structures and ease of over-water navigation were the major considerations in selecting the traverse directions. The majority of the traverses across the southeastern portion of Lake Superior, Northern Peninsula Michigan, and Lake Huron bear approximately N. 65° E. In the southern half of Lake Michigan they bear generally S. 40° E. and across the northern portion of Lake Superior the direction is about S. 82° E. In the Keweenaw Peninsula area it was necessary to employ a radiating pattern of traverses to keep perpendicular to the expected structural trend and reduce the over-water flight distance to a minimum.

Specific information regarding the collection, reduction, presentation and methods of interpretation of the aeromagnetic data secured in this survey will be discussed in chapters relating more closely to the eastern Lake Superior study.

The Eastern Lake Superior Aeromagnetic Study

Area of Investigation

That portion of the Western Great Lakes Aeromagnetic Research Project included in the eastern Lake Superior section is shown on the inset map of Figure 2. The investigation covers the surveyed area beneath Lake Superior and the adjacent land, east of a line extending from Isle St. Ignace, Ontario to Houghton, Michigan to the head of Keweenaw Bay to Marquette, Michigan. The investigation also includes the Northern Peninsula of Michigan, northern Lake Michigan, and the western tip of Lake Huron, east of a line from

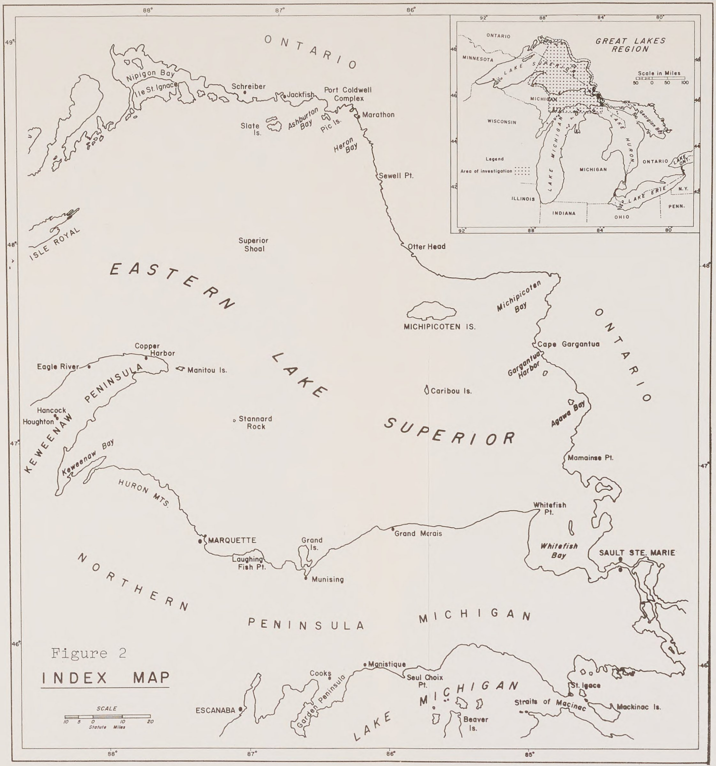


Figure 2

INDEX MAP

Marquette to a point about 15 miles south of Excanaba, Michigan. The area of study does not extend east of the eastern tip of the Northern Peninsula.

The Inde Map, Figure 2, shows the various geographical features and localities referred to in the discussion of the eastern Lake Superior section. The eastern Lake Superior section covers nearly 30,000 square miles over which approximately 6,700 miles of useable aeromagnetic data were collected.

Purpose and Objectives

Some of the most significant Precambrian features of the North American continent are located beneath eastern Lake Superior and the eastern portion of the Northern Peninsula of Michigan. The purpose of this study is to delineate and trace these features and relate them to the tectonic framework of the Lake Superior region. The lack of information regarding the Precambrian structure of this area has been a limiting factor in understanding the tectonic framework of the Great Lakes region. Some of the major objectives of the investigation in this area are listed below. Their extent and significance will be discussed in detail in following chapters.

1. The extension of the Keweenaw fault beneath eastern Lake Superior;
2. The eastward extension of the Isle Royale fault;

3. The continuity of the east-west Precambrian structural trends in the Northern Peninsula of Michigan with the east-west trends north of Lake Huron;
4. The extension of the Precambrian structural trends in Wisconsin across northern Lake Michigan into the Michigan basin;
5. The extent and structural character of the Lake Superior trough and its relationship to adjacent regions;
6. The areal extent of the magnetic basalts and the thicknesses of the non-magnetic Keweenawan sediments;
7. The areal and vertical distribution of the crust beneath Lake Superior as related to the seismic work of the "Upper Mantle" project.

Nature of Study

The study is essentially a regional examination of the extent and significance of the major geologic and tectonic features within the area of investigation. Although all available seismic and gravity data have been considered in the structural interpretations, the main source of information is the aeromagnetic data. The six mile-spacing of the flight traverses, however, limits the use of these data to an investigation of the major magnetically detectable structures. Magnetic data are especially valuable in the detection of steep faults in which displacements have placed the basic Keweenawan volcanics in juxtaposition with the younger clastic sediments. The areal extent and vertical distribution of the major basic intrusions and flows related to the Keweenawan sediments also can be determined to a great degree from aeromagnetic data.

General Geology and Physiography of the Western Great Lakes Region

The Precambrian Complex

From the General Geology Map of the Great Lakes Region, Figure 3, the relationship between the major rock units and the location of the lake basins can be observed. Precambrian crystallines and metamorphics lie exposed to the north along the shore of the North Channel and Georgian Bay of Lake Huron. To the west they nearly surround Lake Superior and extend southward into Wisconsin. South of the Canadian Shield the eroded surface of the Precambrian complex is overlapped mainly by sandstones, shales, limestones and dolomites of Paleozoic age.

The structural basins and ridges produced since the Precambrian show broad undulations of crustal warping.

The Michigan Basin

Subsidence of the Michigan basin has led to thick accumulations of sedimentary rock reaching nearly 14,000 feet in the Southern Peninsula of Michigan (Pirtle, 1932; Cohee and Landes, 1955). The Paleozoic formations dip gently toward the center of the basin. Subsequent erosion

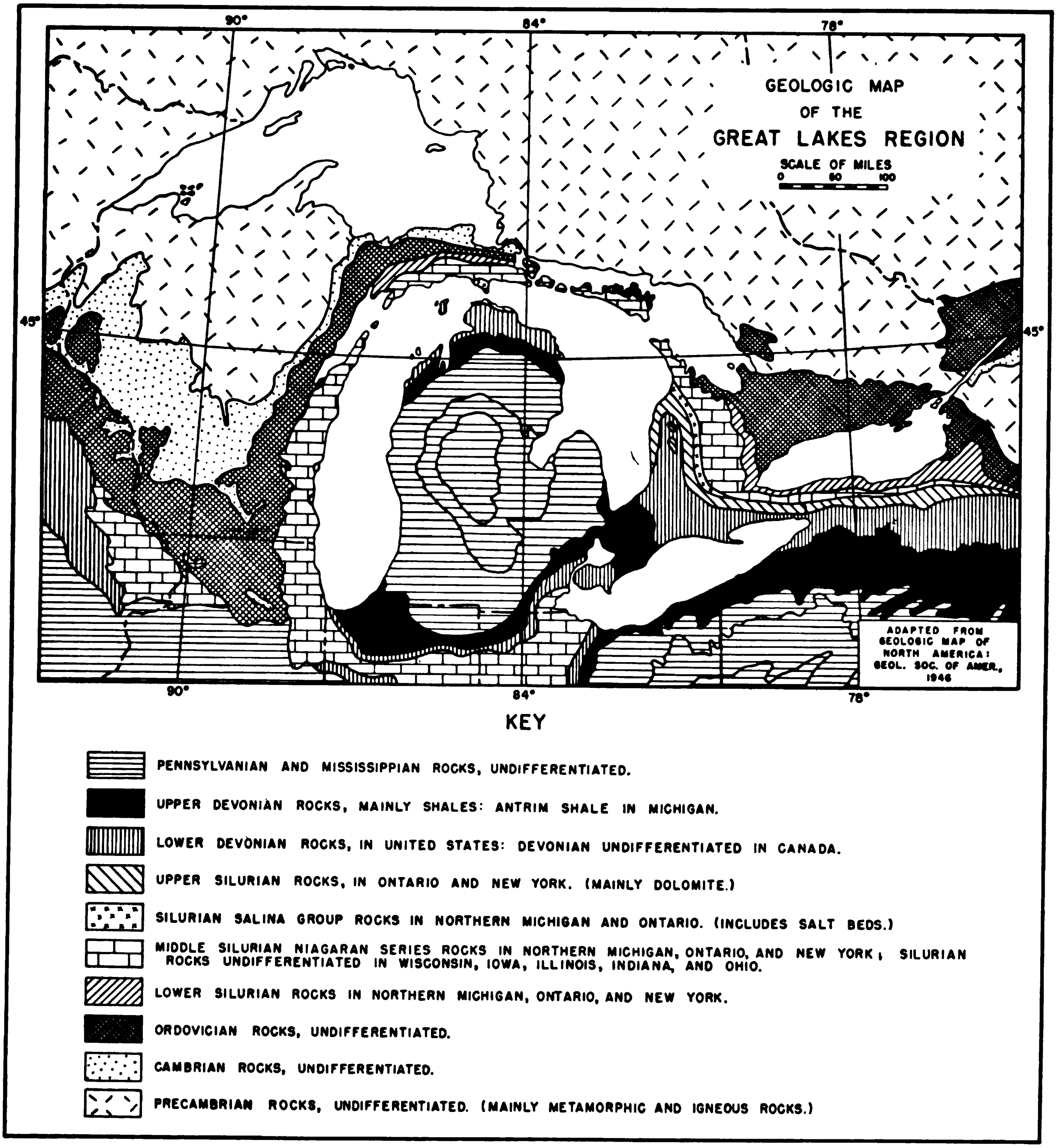


Figure 3.--General geologic map of the Great Lakes region (after Hough, 1958).

has exposed the outer edges of the underlying formations and formed numerous cuestas of the more resistant rock layers.

Lake Basins

Variations in the resistance to erosion of the Paleozoic formations is often given as the main reason for the location of the lake basins, with the exception of Lake Superior. This is only partly correct, as the structural implications of the basement rocks are often neglected. Underlying the Pennsylvanian and Mississippian formations of the Southern Peninsula of Michigan are less resistant beds of Devonian shale. Much of the area covered by Lakes Michigan and Huron is situated where these shales outcrop. Beneath the Devonian and Upper Silurian formations lie beds of resistant Niagaran dolomite. Being more resistant to erosion, the Niagaran dolomite forms the northern and western shores of Lake Michigan. These beds also form the Door Peninsula which separates Green Bay from Lake Michigan.

Extending eastward this formation forms the islands separating Lake Huron from the North Channel, and the Bruce Peninsula between Lake Huron and the Georgian Bay. It also forms the cuesta between Lakes Erie and Ontario.

Beneath the Niagaran dolomite and Lower Silurian rocks lie less resistant Ordovician shales which form the floor of Green Bay, the North Channel, Georgian Bay and Lake Ontario.

Lake Elevations and Surface Areas

The Western Great Lakes, with respect to surface area, are listed among the world's five largest fresh-water lakes. Lake Superior, the largest of these, has the greatest surface area (31,820 square miles) of any lake on earth with the exception of the saline Caspian Sea. Together the three bodies of water total 77,230 square miles. The principal dimensions of the lakes are listed in Table 1.

Lake Superior with a surface elevation of 602 feet above sea level, is 22 feet higher than Lake Huron into which it flows through the St. Mary's River. Lakes Huron and Michigan, with the same surface elevation, are connected by the Straits of Mackinaw.

Lake Depths

The Western Great Lakes each have depths extending to well below sea level. The deepest point being in eastern Lake Superior about 35 miles north of Munising. The known depth there is 1,333 feet or 731 feet below sea level. The deepest point in Lake Huron, 750 feet is 170 feet below sea level and in Lake Michigan the maximum depth, 923 feet, is 343 feet below sea level.

Bathymetry

The general bathymetry of Lakes Superior, Michigan and Huron can be seen in Figure 4. The bottom configuration of eastern Lake Superior and northern Lake Michigan are the most complex of the three lakes. An irregular north-south

TABLE 1.--Physical characteristics of the Western Great Lakes (modified after Hough, 1958).

Lake	Surface elev. (ft. above sea level)	Lowest elev. (ft. below sea level)	Max. Depth (ft.)	Length (miles)	Max. Breadth (miles)	Surface Area (sq. miles)
Superior	602	700	1,302	350	160	31,820
Michigan	580	343	923	307	118	22,400
Huron	580	170	750	206	101	23,010

Figure 4

BATHYMETRIC MAP

trending valley and ridge topography can be easily observed in these two regions. This unusually rough bottom configuration is commonly attributed to intense local scouring during glaciation. It also may reflect tectonic and structural trends. The relationship between bottom topographic features and Precambrian tectonic structures in eastern Lake Superior will be considered in view of the geophysical evidence in Chapter 4.

Glacial Influence

The present bottom configuration of the Great Lakes and the topographic features of the adjacent land are largely the product of late Wisconsin glaciation. Scouring by glacial ice of preglacial valleys is the most common explanation for the origin of the Great Lakes and the numerous smaller lakes of the Canadian Shield north of Lakes Superior and Huron. The smaller lakes over the Paleozoic rocks to the south are the result of glacial and glacio-fluvial deposits. However, the great depths below sea level of the Western Great Lakes and especially the depth of eastern Lake Superior has cast doubt on the extent to which the origin of these basins can be attributed to glacial activity alone. In this study the influence of Precambrian tectonics to the present lake configurations and bottom topography will become evident.

General Topography

Lake Superior is nearly surrounded by highlands. An elevated upland, 400 to 800 feet, directly adjacent to the lake, can be found in many places. On the Canadian side to the east elevations reach as high as 1,500 feet above lake level. Along the Keweenaw Peninsula and in the Huron Mountains area, of northern Michigan, elevations extend locally to about 1,200 feet.

To the north of Lakes Superior and Huron and in northern Wisconsin and the western portion of the Northern Peninsula of Michigan glacial deposits are thin or absent. Vertical relief of the bedrock surface varies up to 300 feet. In the eastern part of the Northern Peninsula and to the south the land forms show extensive undulating till plains having local reliefs of 10 to 50 feet. Lakes and swamps are numerous in the till plains and in the moraine areas local reliefs of 30 to 100 feet or more are abundant. The covering of glacial drift over the Southern Peninsula of Michigan exceeds 1,000 feet resulting in drift thicknesses greater than in any other section of the United States (Eardly, 1951; VerWeibe, 1957).

General Geology and Tectonics of the Lake Superior Region

Bedrock Geology

Lake Superior is situated over and nearly surrounded by outcrops of Precambrian rock. In the eastern portion of the Northern Peninsula of Michigan sedimentary formations of Paleozoic age overlap the Precambrian basement complex. In general, the western Lake Superior area is predominantly composed of Keweenawan sediments, flows, and intrusions. To the east and north of the lake the outcrops are mostly pre-Keweenawan. All available literature was compiled to produce the current Geologic Bedrock Map of the Lake Superior Region, Figure 5. The major rock units within the area were categorized according to age, type, and general magnetic properties. For the purpose of this study the rocks are divided into four age groups:

1. The oldest group contains the rocks of pre-Keweenawan age. These are mainly granites and gneisses containing some metabasic flows and intrusions, and metasediments. Iron formation is also present. The structural trend of the pre-Keweenawan units is generally east-west. Most of the highlands adjacent to Lake Superior are composed of rocks from this group.
2. The second group is composed of Keweenawan volcanics and sedimentary strata. Rocks of this age show little foliation and comprise much of the broad structural trough occupied by Lake Superior. Basic flows and intrusions, and clastic sediments are the most common rock types. Acidic flows and intrusions are present to a minor extent only.

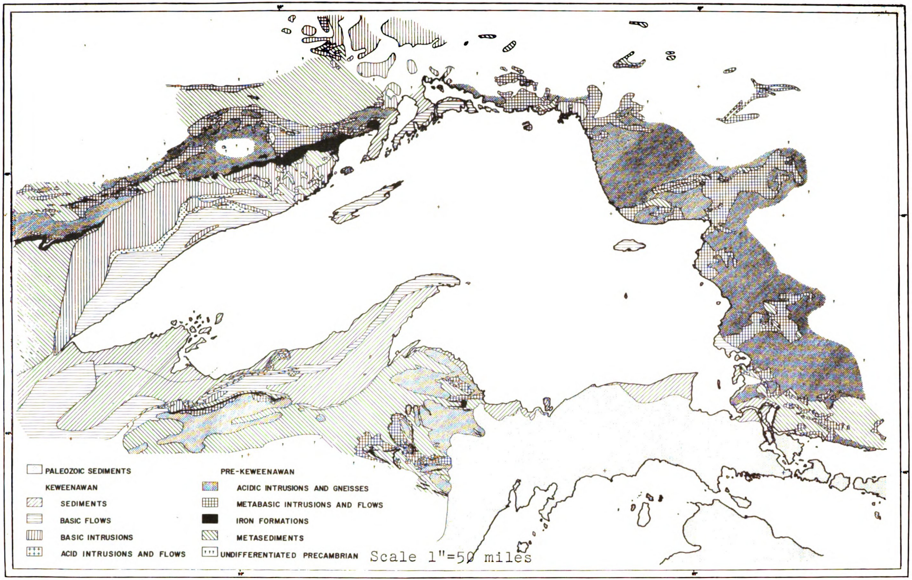


Figure 5.--Geologic bedrock map of the Lake Superior region.

Numerous faults and intrusions of Keweenawan age can be found transecting the older Keweenawan and pre-Keweenawan series. In general, the Keweenawan lavas and sediments are exposed around the margin of the trough and dip toward the lake. The geological features of this rock group can be best described by dividing them into two sub-groups:

a. The basal unit consists of thick deposits of clastics, dolomites and calcareous rock. Sediments of this unit are found on the Sibley Peninsula of Canada in the vicinity of Black and Nipigon Bays where they reach a total thickness of about 14,000 feet (Moorehouse, 1960).

b. The middle Keweenawan unit is composed mainly of basic lava flows and intrusives. The thickness of the average flow is about 50 feet. In northern Wisconsin and Michigan the total thickness of these flows is approximately 30,000 feet with estimates as high as 60,000 feet (Van Hise and Leith, 1911). In some areas the flows are interbedded with sediments and intruded by gabbro and granite. On the northwestern side of the lake a thick series of diabase is found to intrude along an erosional surface of Keweenawan age. The largest of the

Keweenawan intrusives is the Duluth gabbro with a total thickness of about 20,000 feet (Taylor, 1964). Basic lava flows also compose much of the Keweenaw Peninsula, Isle Royale, Michipicoten Island, and isolated areas along the eastern shore of the lake.

3. The upper Keweenawan unit is composed of thick beds of conglomerate, arkose, sandstone, and shale. The Copper Harbor conglomerate of the Keweenaw Peninsula is predominantly composed of rhyolite cobbles. Similar to this is the Great conglomerate of Isle Royale. These conglomerates, like all the Keweenawan sediments, are believed to have been deposited in a fresh-water environment. Above the Copper Harbor conglomerate lie about 14,000 feet of fine sandstone, siltstone, and shale forming the Freda formation in Michigan. In Wisconsin and Minnesota these rocks are known as the Oronto group. Overlying the Freda formation is a sequence of red quartzose sandstone and micaceous shale more than 2,000 feet thick known as Jacobsville sandstone in Michigan, and the Bayfield group in Wisconsin and Minnesota. Lying unconformably on the Jacobsville-Bayfield sediments to the south are the Paleozoic marine deposits of the Dresback formation and the overlying Franconia formation of the St. Croixan series.

The age of the Jacobsville-Bayfield sediments is a controversial subject. Oetking (1951) has correlated the Jacobsville sandstone in eastern Lake Superior with the Bayfield group in western Lake Superior. Thwaites (1912) places the Bayfield in the Keweenawan while Raasch (1950) considers it Cambrian. Hamblin (1958) considers the Jacobsville to be of Cambrian age while Dubois (1959) favors the Keweenawan. In this study the Bayfield and Jacobsville are considered to be upper Keweenawan in accordance with paleomagnetic evidence presented by Dubois (1959).

4. The youngest group consists of the Paleozoic marine sediments overlapping the Precambrian complex to the south of eastern Lake Superior. These sedimentary rocks cover most of the eastern portion of the Northern Peninsula of Michigan and dip gently south into the Michigan basin.

Major Structural Features

The most dominant structural feature in the western Lake Superior section is the Lake Superior trough. The axis of this asymmetrical feature, having a general northeast-southwest trend, lies between the Douglas and Lake Owen faults to the southwest of the lake. Crossing into the lake near Ashland, Wisconsin the axis of this trough parallels the Keweenaw Peninsula near the southern side of the lake and appears to swing to the southeast into eastern Lake Superior. Basic Keweenawan flows along the southern limb of the Lake Superior trough dip to the northeast with various angles ranging from 30° to 60° north of the Lake Owen fault to 70° on the northern tip of the Keweenaw Peninsula. The northern limb of the trough is characterized by flows south of the Douglas fault which dip 40° to 60° southeastward while those on the north shore in Minnesota dip 10° to 15° southeastward. In the area usually referred to as the north limb of the syncline the flows are seen to dip southward into the lake on Isle Royale and Isle St. Ignace.

A thrust fault along the northern side of Isle Royale was first suggested by Van Hise and Leith (1911) from topographic and geologic evidence.

One of the major structural features of the Lake Superior region is the Keweenaw fault. Extending from the southwest this fault bisects the Keweenaw Peninsula bringing the middle Keweenawan flows to the north into contact with the upper Keweenawan sediments to the south.

Southwest of the Keweenaw fault and possibly an extension of this fault is the northeast-southwest trending Lake Owen fault of northern Wisconsin.

To the north and generally paralleling the Lake Owen fault is the Douglas fault. This fault extends from central Minnesota to the Bayfield Peninsula, Wisconsin. It has been suggested that the Douglas fault may extend eastward into the lake south of Ashland, Wisconsin (Thwaites, 1935).

Theories on the Origin of the Lake Superior Trough

Explanations for the origin of the Lake Superior structural "basin" are numerous and varied. One of the most commonly accepted explanations was that put forth by Hotchkiss (1923). He concluded that the source of the flood basalts of middle Keweenawan age was along the axis of the Lake Superior "syncline." His conclusions were based on estimates of the original dips and directions of the Keweenawan flows which were indicated by bent "pipe" amygdules and sedimentary structures at the base of the extrusions. He further envisions a batholithic intrusion during pre-Keweenawan time located beneath the present trough. The presence of this feature produced a topographic high. During the middle Keweenawan the extrusion of flood basalts together with the escaping volatiles caused a subsidence of the crust which eventually led to a collapse of the batholithic roof.

Thwaites (1935) has suggested that the abnormal topography of eastern Lake Superior may be a result of the uneven glacial erosion of salt deposits laid down in parts of the basin. Also on glaciological evidence and downwarping of the crust during glacial times Zumberge (1964) has suggested a recent downfaulting of the Lake Superior trough as a result of isostatic adjustment following the glacial period.

The above theories exemplify the variation of ideas proposed to explain the origin of the Lake Superior trough. The structural extent, framework, and time of origin of this feature have been contemplated in many geological studies. The area has been examined on the basis of sediment dispersal patterns, configuration of bottom topography, dips and thicknesses of sediments, and tectonic structure. The significance of these studies will be discussed later in connection with aeromagnetic, gravity, and seismic evidence.

Previous Geophysical Studies

Seismic

In connection with the International Upper Mantle Project a seismic survey was conducted in the summers of 1963 and 1964. Refraction data were obtained along a line across Lake Superior from Duluth, Minnesota to Otter Cove, Ontario (Meyer, 1964; Smith, et al., 1966). A portion of the results of this survey will be discussed in connection with the interpretation of the aeromagnetic data from eastern Lake Superior.

Continuous seismic profiling was done for the first time on the Great Lakes in 1961 when approximately 250 miles of "sparker" traverses were conducted by Zumberge and Gast (1961). Results of this survey have not been published.

A "boomer" survey covering 900 miles of traverse in western Lake Superior was conducted by the University of Wisconsin Geophysical and Polar Research Center in 1965 (Wold, and Ostenso, 1966).

Gravity

In Lake Superior gravity surveys were conducted during the summers of 1963 and 1964 by the University of Wisconsin and the Dominion Observatory of Canada (Wold, 1966; Weber and Goodacre, 1966). Although relatively few stations were occupied, a Bouguer gravity map of Lake Superior and the surrounding region has been compiled by Weber and Goodacre (1966).

A Bouguer gravity map covering the midwestern states and southern Ontario has been compiled by Rudman, et al. (1965) which includes data from the Bouguer gravity anomaly map of the United States (Woollard and Joesting, 1964).

A gravity survey of the Northern Peninsula of Michigan was conducted by Bacon (1957). Various gravity profiles also were analyzed by Patenaude (1964) in the Northern Peninsula of Michigan to help in the interpretation of his aeromagnetic profiles from this area.

Magnetics

Prior to this investigation the only aeromagnetic data collected over eastern Lake Superior came from two traverses made on a reconnaissance survey by Thiel (1960). Thiel also flew two traverses across western Lake Superior. Eleven profiles were made by the U.S. Geological Survey over the far western end of Lake Superior.

In the eastern part of the Northern Peninsula of Michigan, Patenaude (1964) flew seven east-west and six north-south aeromagnetic traverses. A ground magnetic survey of the Southern Peninsula of Michigan was conducted by Hinze (1963). The State of Wisconsin also was covered by Patenaude (1966) in a regional aeromagnetic survey flown at 3,000 feet M.S.L. with a six-mile flight spacing.

The aeromagnetic data collected over western Lake Superior and Lakes Michigan and Huron as a part of the Western Great Lakes Aeromagnetic Research Project have been mentioned previously.

Case and Gair (1965) reported on an aeromagnetic study conducted by the U.S. Geological Survey over the area along the lake shore between Marquette, Michigan and Grand Island. Aeromagnetic maps published by the U.S. Geological Survey over portions of the Keweenaw Peninsula also are available.

The Geological Survey of Canada has conducted aeromagnetic surveys adjacent to Lakes Superior and Huron over Canada. In these surveys a flight traverse spacing of one-half mile was employed at an elevation of 1000 feet above ground level.

CHAPTER II

COLLECTION OF AEROMAGNETIC DATA

Field Operations

General Planning

The effective planning and successful operation of an aeromagnetic survey is dependent upon the careful consideration of numerous factors. The extensive size of this investigation, its operation across the international border between Canada and the United States, and the long over-water traverse distances produced many problems not usually encountered in a typical aeromagnetic survey.

In this section preparatory flight considerations and general field operations will be discussed. These will include the securing of State and Federal flight permits and waivers, handling of data and crew responsibilities, use of topographical and aeronautical maps, influence of weather conditions, and a summary of traverse mileage, area covered, and time involved in the survey.

In the following section of this chapter the selection of aircraft, method of navigation, operation of the magnetometer, flight altitude, flight line spacing, and traverse directions will be discussed.

Required Permits and Waivers

To install the magnetometer and recording accessories it was necessary to make certain modifications of the aircraft. Some of the modifications involved a change in weight distribution, therefore, it was necessary to obtain the approval of the Federal Aeronautical Administration. A waiver from this agency is also mandatory to tow the magnetometer's sensing head or "bird" behind the aircraft.

A flight plan should be filed when flying across the international border between Canada and the United States. A permit also is required to conduct flights over Canadian soil and assurance must be given that no unauthorized landings will be made in Canada.

Conducting flight operations across the lakes involved passing through a number of restricted zones. Flight clearance through these zones must be obtained in advance from the appropriate military authority. Prior permission also is necessary to tow the "bird" over populated areas or near major airports.

Flight Crew Responsibilities

To systematically and accurately collect and record the aeromagnetic data, a flight crew consisting of a pilot, navigator, and magnetometer operator was secured. The pilot was responsible for the safe and effective operation of the aircraft. The navigator (author) was responsible for precise navigation, plotting flight tracks, maintaining flight logs, and directing all field operations. The magnetometer operator was primarily responsible for the maintenance and operation of the aeromagnetometer. He also kept a log of all malfunctions in the magnetometer system and made sure the analog and digital output tapes were properly marked for later processing. This crew member also was assigned the task of taking driftmeter readings for use in the navigational calculations.

Map Considerations

To insure proper navigation and accurately plotted flight tracks it was important to obtain the appropriate topographic and aeronautic maps. The area of investigation lies within both the United States and Canada and because of this it was difficult to secure maps having the same projection and scale. Incongruities in any of the map characteristics made it difficult to correctly plot the proposed traverses and actual flight tracks across the lakes.

It also was necessary to correct for the map projection when plotting a constant direction. By plotting a straight line between two points on either side of Lake Superior an error of approximately two miles would be introduced toward the center of the lake on the Lambert Conformal projection used in this survey.

Although maps having a scale of 1:500,000 were employed to plot the flight traverses, it was necessary to use larger scale maps to locate landfalls especially along shorelines of low relief. The low lake level during the summer of 1964 drastically altered the shoreline configuration, making the use of large scale maps essential. With the low water level conditions it was often found that where the map would indicate the presence of a near-shore island, a peninsula would actually be observed.

Meteorological Considerations

Weather was a prime factor in planning and executing the field operations. The location of air masses and frontal systems were considered on a daily basis. Areas having unlimited visibility within reasonable range of the base of operation were given first priority. Over-water flights were not attempted during days of reduced visibility. However, areas over land were occasionally flown under these conditions when accurate navigation was possible. Poor visibility and low cloud ceilings were mainly responsible for the number of days in which no data were collected while in the field.

The Great Lakes region is a focal point through which storms and low pressure centers generally move toward the east and northeast. Cyclogenic areas to the west, southwest, and northwest in the United States and Canada produce low pressure centers which deepen over the lakes. The rapid development and variable rates of movement of these centers make weather forecasting difficult. Although severe storms are more common in November and during the winter months, weather conditions are extremely variable throughout the summer.

Days of low visibility and low cloud formation may last for a week or more anytime during middle and late summer, expecially in the Lake Superior region. During mid-summer, in the Lake Michigan area, weak centers of low pressure produce haze which is only terminated when a strong high pressure center moves through the region. The pronounced temperature lag during spring and early summer produces conditions conducive to the formation of advection fog. This fog is most evident in areas of prominent upwelling, usually found along the northeastern shores of the lakes. In Lake Superior fog is found during middle and late summer, most frequently inthe area east of Keweenaw Point and north of Au Sable Point. Foggy conditions and low visibility are extensive in the Chicago-Gary area, especially when light offshore winds prevail. Flight operations were severely limited during periods of fog and haze.

When stratus type clouds form over the lakes in summer the bottom of the cloud layer usually lies about 3500 to 4000 feet M.S.L. Flight operations were not affected unless the cloud formations lowered to the elevation of the aeromagnetic survey (3000 feet M.S.L.).

Although precipitation is generally reduced in the Great Lakes region during the summer months, the frequency of thunderstorm activity is sharply increased. The highest number of thunderstorms are found along the western and northwestern shore of Lake Michigan. The exact location of these storms is unpredictable from the limited weather information available in this area. Excellent visibility with no restricting cloud cover may be present over the eastern portion of Lake Michigan while a portion of the western side is obscured by thunderstorms. A traverse intended to pass through such an area must be terminated and reflown at a later date.

Summary of Field Operations

The aeromagnetic survey conducted over eastern Lake Superior, Lake Michigan and Lake Huron was flown between June 4 and August 14, 1964. Listed in the summary of field operations given below is the area surveyed, the approximate number of traverse miles, flight time, and days required to conduct this survey.

1. Area surveyed
    a. Eastern Lake Superior and the northern half of the Northern Peninsula . . . . 25,838 sq. mi.
    b. Lake Michigan and the southern half of the Northern Peninsula. . 31,032 sq. mi.
    c. Lake Huron, Georgian Bay and North Channel . . . . 33,217 sq. mi.
    d. Total area. . . . . 90,087 sq. mi.

2. Traverse mileage

    a. Eastern Lake Superior and the northern half of the Northern Peninsula. . . . . 6,065 miles

    b. Lake Michigan and the southern half of the Northern Peninsula . . . 6,738 miles

    c. Lake Huron, Georgian Bay and North Channel. . . . . 6,630 miles

    d. Across Southern Peninsula, Michigan . . . . 625 miles

    e. Total mileage . . . . 20,058 miles

3. Flight hours

    a. Eastern Lake Superior and the northern half of the Northern Peninsula (includes tie lines, time between airfield and traverse lines, etc.) . . . . 60 hours

    b. Lake Michigan and the southern half of Northern Peninsula (includes tie lines, time between airfield and traverse lines, etc.) . . 65 hours

    c. Lake Huron, Georgian Bay and North Channel (includes tie lines, time between airfield and traverse lines, etc.) . . . . 65 hours

d. Time lost due to breakdown of navigational and magnetometer equipment, poor weather conditions, reflying of traverses, and returning to home base for aircraft repairs and periodic inspections . . . . 52 hours

e. Total time. . . . . 242 hours

4. Days in field

a. Days in which no data were collected due to poor weather, breakdown of the magnetometer and navigational equipment, and periodic aircraft inspections . . . . 34 days

b. Days in which useable data were collected. . . . . 35 days

c. Total days in field . . . . 69 days

Magnetometer and Survey Control

The Airborne Magnetometer

It was recognized over one hundred years ago that the irregularities in the earth's magnetic field could be used as an aid in prospecting for iron ore. Since that time a number of magnetometers have been developed to measure variations in the vertical and horizontal components of the earth's magnetic field. Until approximately twenty years ago the magnetometers employed were designed for ground surveys and were not suited for operation from aircraft. Just prior to World War II members of the Gulf Research and Development Company became interested in the installation of magnetic detecting equipment in aircraft. Working on the previously developed flux-gate principle, they were able to improve the sensitivity and invent a method to stabilize it against in-flight motion. This equipment was further developed for airborne submarine detection at the Airborne Instruments Laboratory of Columbia University. A second instrument was produced and then modified for the U.S. Geological Survey at the Bell Telephone Laboratories.

In 1944 the first aeromagnetic investigation for the U. S. Geological Survey was flown by Aero Services Corporation. The flux-gate magnetometer used in that survey and variations of this magnetometer which are presently in common use are essentially mechanical in nature. Within the past ten years magnetometers requiring no mechanical stabilization and some more sensitive than the flux-gate type have been developed. One of these is the proton free-precession magnetometer used in this survey.

Principle of the Proton Free-precession Magnetometer

The method of determining the earth's total magnetic field intensity by measuring the frequency of free precession of a polarized source of protons was first reported by

Parkard and Varian (1954). In this magnetometer the sensing elements are spinning hydrogen nuclei, or protons, the source of which is usually a quarter pint bottle of water (alcohol is added under low temperature conditions). The protons acting as tiny bar magnets spinning upon their longitudinal axis have the properties of a gyroscope and a magnetized needle. They attempt to align themselves along the earth's magnetic lines of force. The rate at which this alignment, or frequency of precession, takes place is directly proportional to the magnetic field intensity. To measure the rate of precession the protons must first be polarized. Polarization is accomplished by instantaneously applying a current through a coil wound around the bottle of water. Thus a magnetic field of several hundred gauss is created at an angle to the earth's magnetic field. The coil of wire forms the detecting element. Removal of this induced polarizing magnetic field causes the protons to precess and produce a detectable e.m.f. in the coil. The signal produced from the coil is amplified and the frequency or rate of precession is measured. The rate of precession, or angular velocity (Ω) at which the protons precess is given by $\Omega = pF$ where p is constant gyromagnetic ratio of the proton and F is the strength of the earth's magnetic field. The rate of precession is proportional to the earth's magnetic field intensity. The field strength is determined by counting the cycles produced by a crystal-controlled oscillator during the time required to complete a fixed number of precession signals. For example, if the rate of precession for a field intensity of 48,000 gammas (1 oersted equals 10^5 gammas) were exactly 2000.00 cycles per second, a frequency measurement of 2000.04 c/s would mean an intensity of 48,001 gammas. The practical details of instrumentation necessary to determine the rate of precession with sufficient accuracy are given by Wold (1966).

The Elsec-Wisconsin Digital Recording Magnetometer System

The digital recording magnetometer system used in this survey was capable of accurately measuring the earth's total magnetic intensity and presenting the data in digital paper tape form. The advantage of collecting the data in digital form is that it can be fed directly into the computer with a minimum of handling. In this manner a large quantity of data are easily and quickly reduced. The system is primarily composed of a proton free-precession magnetometer to which has been added a digital paper tape punch, clock system, analog recorder and coupling unit. The magnetometer was an Elsec model manufactured by the Littlemore Scientific Engineering Company of Littlemore, England. Development of the combined system which permitted the recording of magnetic readings with reference to time in digital punch tape form was accomplished by the Geophysical and Polar Research Center, at the University of Wisconsin. The specifications for this system are given in Table 2 and a diagram showing the relationship of the component parts is presented in Figure 6. A photograph of the Elsec-Wisconsin Digital Recording Magnetometer System can be seen in Figure 7.

TABLE 2.--Digital recording magnetometer system specifications (after Wold, 1964).

Power Requirements:	28v D. C. at 9 amps. or 12v D. C. at 20 amps. or 115 v A. C., 60 ∿ at 5 amps.
Size:	Weight = 175 lbs. Height = 33 lbs. Width = 23 lbs. Depth = 20 lbs.
System Components:	Elsec proton magnetometer Elsec analog recording unit Rustrak recorder Friden tape punch Digital clock Coupling unit
Data Output:	Visual Analog Paper tape--BCD form

In the operation of the digital magnetometer system, the output from the Elsec magnetometer feeds into the recorder unit which drives a series of relays. These provide the signal for the Rustrak analog recorder and the relays operating the paper tape punch. Stepping switch S_1, through relays, sequences the information from the magnetometer-recorder to the tape punch which then automatically cycles S_1.

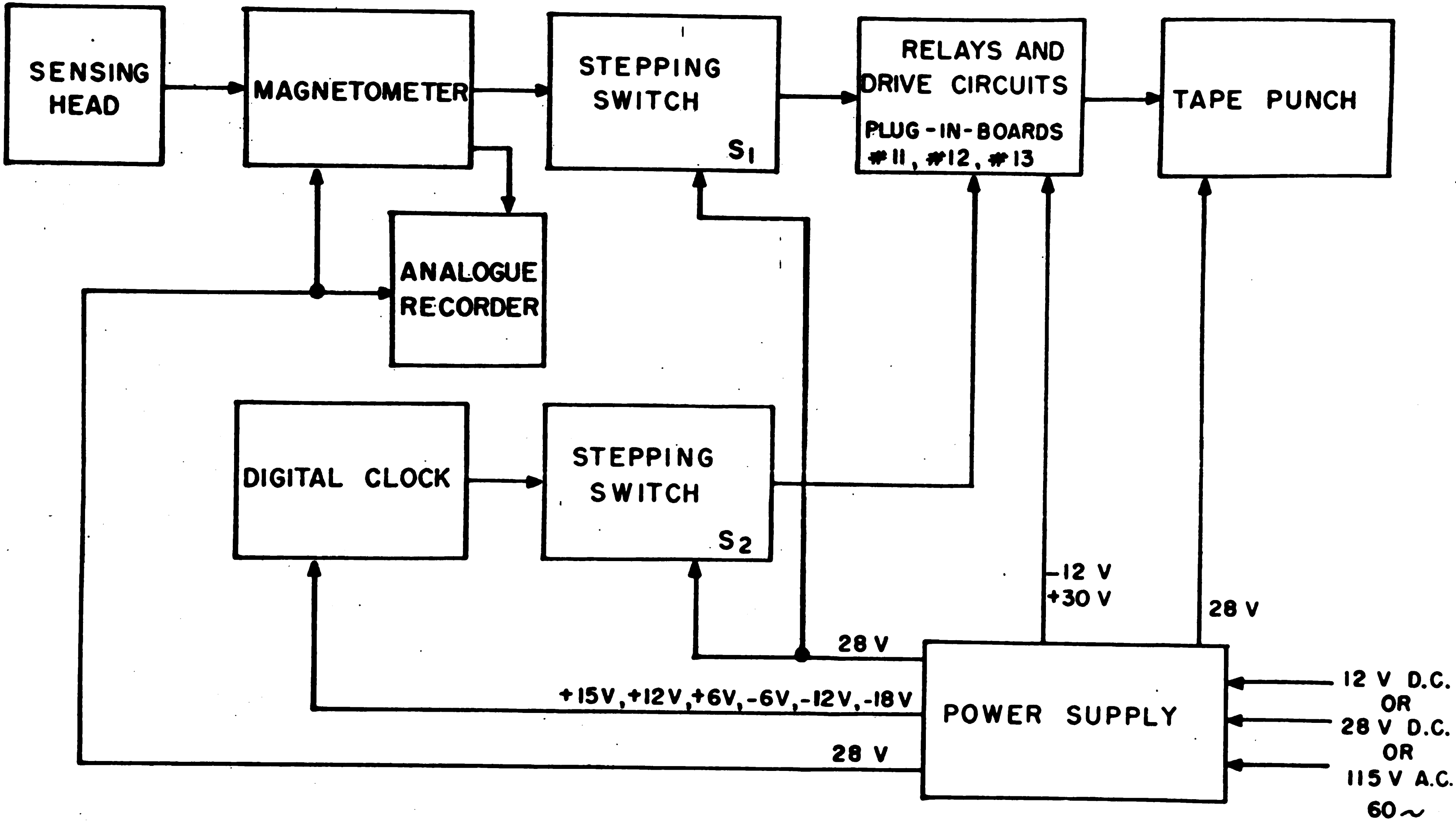
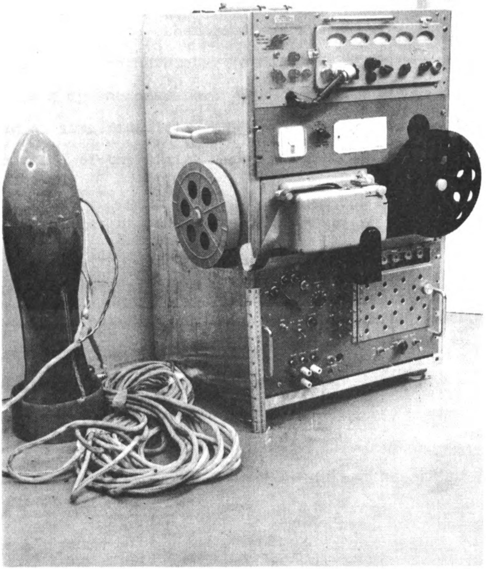


Figure 6.--Block diagram of the digital magnetometer system (after Wold, 1964).



Digital Recording Magnetometer System and "Bird"

Figure 7

The digital clock is a 24 hour clock with 1-2-4-8 BCD output. Through stepping switch S_2 the time information is sequenced to the tape punch. Time readings may be manually or automatically controlled by stepping switch S_3 and a selector switch which allows the operator to choose the time mark interval. The clock readings are punched at a specified number of magnetometer readings depending upon interval chosen by the operator. The clock also controls the placing of time fiducials on the analog record. A complete discussion of the digital recording magnetometer system is given by Wold (1966).

The advantages of the proton free-precession magnetometer are many: it is free from instrumental drift, requires no calibration, measures the total field (F), is insensitive to orientation and temperature, does not require a stable platform, and can be made rugged and portable. The Elsec type proton precession magnetometer has a range between 24,000 and 70,000 gammas and its sensitivity over gradients of 200 gammas per meter or less is ± 0.5 gammas. This magnetometer gives consistent and accurate readings over locations having magnetic field gradients as high as 800 gammas per meter with a sensitivity of ± 2 gammas.

It was not necessary to process the analog records in the conventional manner because this magnetometer system has the capability of recording data in digital form. By not having to physically pick the analog records and punch the information on computer cards, human errors are decreased and much time is saved. With comparatively little work the digital paper tape can be refined and fed directly into the computer. Accurate placing of time marks is another advantage of the digital system.

Flight Control

To gain the most accurate picture of the shape of a magnetic anomaly the flight traverse should be flown at right angles to the strike of the magnetic feature. This direction was inferred from the major tectonic features since the magnetic strike generally follows the strike of the basement rocks. Departures of up to 30 degrees from this direction are not of great significance. A second consideration in plotting the proposed flight traverse direction was over-water distance. To aid in more accurate navigation this distance was kept to a minimum. The flight traverses were planned with these two factors in mind.

Numerous considerations were involved in determining the direction of flight along each traverse. Among these were included the aircraft's range, length of traverse, and the accessibility of airports for refueling. Also of prime importance in establishing the direction of flight was the shoreline configuration. Shorelines with prominent features were approached from over the water to aid in navigation.

The reconnaissance nature of this survey did not warrant the close spacing of traverse lines required in more detailed studies.

In selecting a flight altitude a compromise must be found between the need to fly as low as possible to obtain maximum resolution of the magnetic features and the need to fly high enough to avoid the unwanted effects of small, near surface magnetic bodies. The over-water nature of the survey introduced a third consideration of primary importance, that of the necessity of higher altitude for accurate navigation. Most detailed surveys over land vary between 500 and 1500 feet. Since a detailed investigation was not the objective of this survey and because electronic aids to navigation were not available for accurate navigation at lower levels, an elevation of 2400 feet above lake level (3000 feet M.S.L.) was considered justifiable.

Each traverse was flown at a constant barometric altitude to provide a fixed datum for basement depth determinations and to help eliminate variations in ground speed. A barometric altimeter was considered adequate. The estimated variation in altitude during the survey was not greater than 100 feet. Reford and Sumner (1965) estimate that a one per cent change in altitude, above basement, will cause a change of one to two per cent in the amplitude of an intra-basement anomaly. Therefore, this altitude control was sufficient.

Data Control

To avoid recording aeromagnetic data during periods of magnetic disturbances an arrangement was made with the Fort Belvoir, Virginia Observatory to send notification of radio disturbances to the Naval Air Station at Grosse Ile, Michigan. The messages were then relayed to the flight crew. Upon receiving a message indicating a magnetic disturbance flight operations were cancelled until another message was received that the disturbance was over. As a secondary precaution records of magnetic disturbances were received from the magnetic observatory in Fredricksburg, Virginia.

A monitoring station also was operated to detect temporal magnetic activity at the Geophysical and Polar Research Center at Madison, Wisconsin. The monitor at Madison was a continuous-recording Gulf flux-gate magnetometer. The time period covered by each flight was plotted on the records received from Madison. Figure 8 is a representative sample of these records, chosen at random, covering five days of flight operations. No attempt was made to apply temporal corrections to the survey data since the records showed a magnetic variation of less than 25 gammas during the periods in which data were being collected.

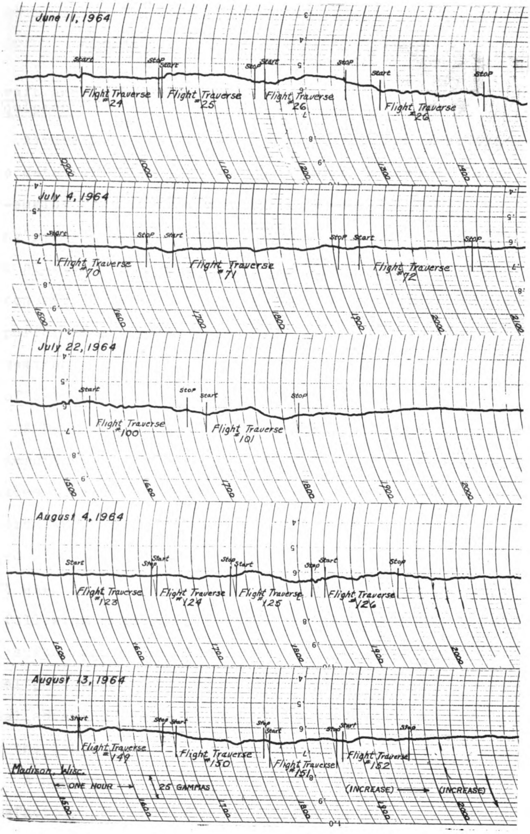


Figure 8.--Representative sequence of diurnal records recorded by a Gulf flux-gate magnetometer at Madison, Wisconsin.

Aircraft and Navigational Equipment

Aircraft and Installation of Equipment

Aircraft commonly used in the collection of aeromagnetic data vary from light single-engine Cessnas to large twin-engine Douglas DC-3's. One type commonly employed during previous years is the medium sized twin-engine Beechcraft AT-11. The choice of aircraft is primarily a matter of economics in which a balance must be reached between cost and performance. Such characteristics as speed and endurance are desirable and in the case of an over-water survey the use of twin-engine aircraft is more logical.

A Navy P2V Neptune patrol plane was used to collect the aeromagnetic data over western Lake Superior through the auspices of the Office of Naval Research. The data over eastern Lake Superior and Lakes Michigan and Huron were collected with a light twin-engine plane. A lighter type aircraft was considered adequate in this over-water survey for the following reasons: the size and weight of the magnetometer system was comparatively small, and large and heavy aerial photographic equipment was not used since no navigational advantage could be gained by using this equipment over the lakes.

A number of light planes were considered capable of satisfactory performance at a much lower cost than the larger type aircraft. In making the final aircraft selection for this investigation the following factors were considered:

(1) cruising speed, (2) refueling range, (3) usable space for recording and navigational equipment, (4) adaptability of the aircraft to the installation of equipment, (5) cost and availability, and (6) navigational equipment.

The aircraft selected was a 1961 model twin-engine Piper Apache, Figure 9. Its average cruising speed, while recording data, was approximately 145 m.p.h. The maximum flight time between refueling for this plane is about seven hours, however, no flights were extended over six hours and fifteen minutes. Most flights were planned not to exceed five hours and thirty minutes. The aircraft is designed to carry a pilot and four passengers. To secure space for the magnetometer-recording gear, the necessary navigational equipment, and an access door through which the "bird" or sensing head could be passed, two seats were removed and the magnetometer operator's seat was turned to face aft. In the space thus provided, the magnetometer was installed aft of the pilot's seat. In this position it was accessible to the operator who was seated directly behind the navigator, Figure 10. In the deck of the aircraft, just aft of the magnetometer, a ten inch opening was made to lower and retrieve the "bird." A driftmeter was installed next to this opening.

Navigational Aids

The navigational equipment and conventional electronic aids, necessary for use in the survey, were obtained with

Figure 9.--Piper Apache used to collect data over eastern Lake Superior and Lakes Michigan and Huron.

Figure 10.--Aircraft installation of digital recording magnetometer system.

the aircraft or installed to insure maximum assistance. This equipment and its significance as an aid to navigation is discussed below.

1. OMNI Receivers.--The aircraft was equipped with two OMNI receivers. However, OMNI transmitting stations are scarce in the Lake Superior region. This equipment enables an aircraft to maintain a bearing to or from a known station. Extensive use was made of the station located at Hancock, Michigan in flying the radiating traverses from the Keweenaw Peninsula to Canada. When the two OMNI receivers were used in conjunction with the transmitting stations at Hancock and Whitefish Point it was possible to establish a fix. The accuracy of the fix was dependent upon the distance and the angle between the aircraft and the two OMNI stations. The distance to which this equipment can be effectively used depends upon the altitude of the aircraft. The altitude at which this survey was flown (3000 feet M.S.L.) limited this distance to about fifty miles.
2. ADF.--ADF is a low-frequency direction finder. Although its range is greater than OMNI it is much less accurate. Little use was made of this equipment because readings were found to be unreliable if taken during the time the magnetometer was in operation.

3. Automatic Pilot.--A three-axis Mitchel type autopilot with heading lock and altitude control was used throughout the survey. Without an automatic pilot with these capabilities it would have been impossible to maintain the heading and altitude control essential for accurate navigation.

4. Compass System.--Two gyrocompasses and a magnetic compass were employed to establish course. The main gyro was operated in conjunction with the autopilot. The second gyro was installed to use in correcting the main gyro. Not being coupled to the autopilot, the second gyro was not subject to drag, but only to normal precession which is constant over a given period of time. Therefore, by resetting the gyros at regular intervals the effect of total precession was minimized. The magnetic compass also was used as a cross reference in conjunction with the gyros. Over portions of the surveyed area magnetic readings are unreliable, however, in most areas the magnetic compass with its lack of precession was quite helpful in determining initial traverse headings.

5. Driftmeter.--To more accurately plot the track of the aircraft and assure proper corrections for wind shift while over water a B-5 driftmeter was mounted aft of the magnetometer. Periodically readings were taken and reported by the magnetometer

operator, which were then used to determine wind drift and calculate course headings.

6. Binoculars.--A pair of 7 x 50mm. binoculars were used to better recognize shoreline configuration while far from land. They were was helpful in locating the point at which a flight traverse would cross the shoreline.

7. Angle Device.--A rotatable sighting tube was mounted to a 360 degree compass and attached to the aircraft console. With this device the angles between the aircraft and a series of prominent landmarks were determined. By then plotting these angles a rough fix could be calculated. This device was most effective when used between two converging shorelines during periods of excessive wind shifts.

Method and Accuracy of Navigation

Over-water Navigation Problems

The importance of good navigation can be easily seen and the effects of poor navigation are especially noticeable when data are plotted in contour form. In over-land aeromagnetic surveys the usual procedure is to plot the aircraft's position either by direct visual reference to the ground or by recording the actual flight track with a 35mm. camera. The landmarks on film are later correlated with those on a topographic map or aerial photographs.

Navigational aids are usually employed when base maps are inadequate or few landmarks exist. In most cases one or more of the sophisticated electronic aids are used, such as Doppler, Shoran, and Decca. However, the cost of using these aids was prohibitive in this survey. Therefore, one of the most difficult problems in securing the aeromagnetic data was navigating accurately on long over-water traverses. The method of navigation that was originally proposed consisted of first establishing a traverse heading over the land. This heading was established to allow for wind drift and was then held until the aircraft crossed the opposite shoreline. If a correction in the traverse heading became necessary, it was to be made only when the aircraft passed over an island or a point of land. The flight track would then be plotted by drawing a straight line between each fix. It was soon realized, however, that strong wind shifts were common over the lake and that this method of navigation would not suffice, particularly in eastern Lake Superior. The immediate offshore wind shift in many cases was opposite in direction to the wind over land. Toward the center of the lake another shift in wind would again cause the track to be deflected. Flying a traverse in this manner resulted in missing the intended point of intersection on the opposite shoreline by many miles.

Another factor which complicated plotting the traverse and navigating accurately while over the water was the inherent error in the gyro and automatic pilot system of a light twin-engine aircraft. This error was greater than had been anticipated.

Method of Navigation

To adjust for offshore wind shifts another method of navigation was devised. Additional equipment was installed in the aircraft to compensate for the inherent error in the gyro and automatic pilot system. Although it was not crucial to the investigation that the aircraft fly exactly along a proposed flight path, it was imperative that the track be plotted as accurately as possible and that this track be within reasonable proximity of the intended traverse. To accomplish these objectives the following procedures were adopted:

1. Each over-water traverse was extended inland a distance of approximately ten miles. This also helped to correlate the aeromagnetic data with existing magnetic data available over the adjacent land areas. Thus, the extension of known geologic features on land could be traced beneath the lakes. However, the primary reason for extending the traverses inland was to aid in navigation. To do this at least two features recognizable from the air, and on the topographic map, were selected. One feature was picked at a distance of about ten miles inland and at least one other was selected near the shoreline. A

course heading was established by correcting for wind velocity and direction while flying between the selected points. The automatic pilot was engaged to lock this heading and altitude. At the same time wind drift measurements were obtained. Time checks were made over the initial point on the traverse and over the shoreline. These positions were then plotted and recorded.

2. When the aircraft was over water another driftmeter reading was taken and any change relative to the established heading was calculated and the autopilot reset. Thereafter a driftmeter reading was taken at regular intervals and corrections in heading were made. The amount and time of the heading corrections were noted.
3. To reduce the error in the gyrocompass which was locked to the autopilot a second gyro was installed in the aircraft. This auxillary gyro was not subject to the drag produced by the autopilot and could therefore be used to correct the main gyro and automatic pilot system. The rate of precession of the auxillary gyro was determined and a periodic correction for precession also was applied and at the same time the main gyro was corrected.
4. Conventional methods of determining a fix in location while over water were used to the maximum extent. Dual OMNI was employed where possible,

however, few electronic aids to navigation are available in the areas of Lake Superior and northern Lakes Michigan and Huron. Significant islands, topographic features and points of land also were used to determine location.

5. Less conventional methods were employed to correct for drift and maintain course. A triangulation device was used to measure the angles between prominent shoreline features and the aircraft whenever possible. This device was used mainly as a check on the navigation and was limited to near-shore traverses. Initially, it was felt that perfect visibility would not be necessary, however, when it was decided that inflight corrections for drift must be made over the water it became evident that unlimited visibility was essential. To further aid in recognizing the intended landfall, a pair of 7 x 50 mm. binoculars were used. These aided in recognizing changes in drift at a greater distance from shore.

6. As the aircraft crossed the opposite shoreline the exact time was recorded and the position plotted on the topographic map. This same procedure was used when the aircraft passed over an island or point of land and when a reliable fix was obtained while over the water.

7. The traverse was continued inland from the shore for about ten miles where a final traverse position was established, plotted, and the exact time noted. The necessity of being able to visually identify landmarks and to establish accurate navigation restricted over-water flights to days having unlimited visibility.

Accuracy of Navigation

Using the equipment and method of navigation previously described, the plotted track of the aircraft, for an average length over-water traverse, is estimated to be within one and a half miles to either side of the actual flight path. For shorter over-water flights and flights having ground control the degree of accuracy is greater. The error in navigation for the longest over-water traverses is estimated to be less than ± 2 miles. When the navigational error was believed to exceed ± 2 miles the traverse was reflown. The degree of accuracy in plotting flight tracks is based on the analysis of various traverses over land and upon visual and OMNI fixes using islands and points of land as reference features.

In addition to the error in plotting a flight line, an error exists in locating any point along a given traverse. The location of a particular point along a traverse is dependent upon variations in ground speed, which in turn are dependent upon changes in wind velocity and airspeed. In this survey airspeed was usually maintained at 145 m.p.h. However, changes in fuel distribution and movements of the crew members would occasionally cause a change in airspeed.

To estimate the maximum and probable error to be expected in determining the location of a particular magnetic reading along any given traverse the following method of analysis was devised. From a number of selected traverses the average ground speed of each traverse was first calculated using only the time in flight and the distance between two end points.

Ground speeds were then calculated for the segments of traverse between each fix. These were found to vary between about 115 and 185 m.p.h. Ground speeds of the traverse segments deviated from the average ground speed of the whole traverse. These deviations were usually greater over shorter distances. They were also greater near shore than over the centers of the lakes or inland.

Next each traverse was marked off in ten-minute intervals based on its average overall ground speed. A second set of ten-minute interval marks also were produced along the traverse, based on the ground speeds of the individual segments of traverse.

The two sets of ten-minute interval marks were then compared. The difference in distance between corresponding time marks gave an estimate of the error which could be present on a traverse having only one fix on each end. The variation in distance between corresponding time marks was considerable. On some traverses the distance or error was small, on others it was larger, particularly over the shorter traverse segments near shore. The maximum distance was about six miles.

Although this method of estimating error indicates that a maximum error of six miles is possible on long segments of traverse having no control, it does not mean that an error of this magnitude is expected for the following reasons: (1) None of the traverse segments in this survey were as long as the overall distance between the end-points of the traverses analyzed, (2) Most of the radical variations in ground speed were located along shorelines where higher wind velocities and stronger wind shifts were present. However, in these areas all traverses have the greatest control, and (3) The traverses analyzed were selected because they had numerous fixes along them which meant they were located mainly along shorelines and over near-shore islands where greater variations in wind would cause greater deviations.

With the above considerations in mind and from an examination of only the shorter traverse segments found between islands toward the center of the lakes, the probable maximum error in locating a particular point along a traverse is within two to three miles.

CHAPTER III

COMPILATION OF MAGNETIC DATA

Magnetic Properties of Rock

General

The most significant magnetic property of a rock is its susceptibility. This property, which measures the capacity of a rock to become magnetized, varies widely, ranging from about 100×10^{-6} c.g.s. units for granite to between 1000×10^{-6} and $10,000 \times 10^{-6}$ for basic rocks. Although numerous mineralogical and geological factors influence these values, magnetic susceptibility is mainly dependent upon the magnetite content of the rock. Basic rocks generally containing more of this mineral than acidic rocks have a higher susceptibility. Sediments, excluding iron formation, are relatively non-magnetic.

The magnetic polarization of a rock unit is determined not only by its magnetic susceptibility, but also by the strength of the inducing geomagnetic field and the remanent magnetization which may be present in the rock. Changes in the magnetic intensity observed when crossing a contact between two rock units is dependent upon the contrast in these magnetic parameters. In the region of this survey the strength of the inducing geomagnetic field is about 60,000 gammas. The remanent magnetizations of most rock formations in the Lake Superior region are not well known. The remanent magnetizations have been further complicated by structural deformation within the region. The ratio of the induced and remanent magnetization is quantitatively expressed by the Konigsberger ratio.

Another magnetic parameter which may be used to characterize a given rock type is variability. Variability refers to the amplitude and width of the local anomalies superimposed on the overall magnetic intensity associated with a particular rock unit. This property had restricted use in this survey because the flight elevation tended to subdue the anomalies.

Magnetic Properties of the Rocks in the Lake Superior Region

Table 3 has been compiled to summarize the magnetic properties of the rocks in the Lake Superior region. The grouping of the rocks in this table is identical to that used in preparing the Geologic Bedrock Map presented in Figure 5. The susceptibility and Konigsberger ratio given for each rock type is a summation of the results obtained from several sources.

The variable rock types found in the pre-Keweenawan represent a time period of approximately one billion years from lower Archean to upper Hurionian. The lithologies of these rocks include geosynclinal deposits, local basinal sediments and igneous rocks varying in composition from

TABLE 3.--Summary of the magnetic properties of rocks in the Lake Superior region.

Rock Types	Susceptibility $k \times 10^{-6}$ cgs	Konigsberger Ratio $Q = I_r/kH$ H=0.6 oersted
Paleozoic Sediments	Negligible	Negligible
Keweenawan Rocks		
Sediments	Negligible	Negligible
Basic Flow	10,000 - 1,000	3.0 - 1.0
Basic Intrusions	9,000 - 2,000	2.0 - 1.0
Acid Intrusions and Flows	3,000 - 100	- - - - -
Pre-Keweenawan Rocks		
Acid Intrusions and Gneisses	3,000 - 100	Generally low
Metabasic Intrusions and Flows	4,000 - 200	2.0 - 0.5
Iron Formations	900,000 - 500	10.0- 0.0
Metasediments	200 - 0	Negligible
Undifferentiated Precambrian	Variable	Variable

acidic to ultrabasic. The rocks of this age have been altered by low to high rank regional and thermal metamorphism. As a result their magnetic properties have a broad range and are not well defined. The magnetic susceptibility of several pre-Keweenawan rock units and their average ranges are taken from a list prepared by Mooney and Bleifuss (1953). The magnetic properties of the rocks found in the Marquette syncline area were obtained from Case and Gair (1965). From the studies of Jahren (1960, 1963) and Bath

(1960, 1962) the remanent and induced magnetic properties of the pre-Keweenawan iron formation have been summarized.

The magnetic properties of the 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) have compiled the results of these studies.

DuBois (1957) has shown from thermal demagnetization curves that the principal cause of the magnetization of the middle Keweenawan volcanics is thermoremanent magnetism. DuBois also shows from the random magnetic orientation of Keweenawan volcanic boulders in the overlying Copper Harbor conglomerate that the direction of magnetization of the volcanics has not changed since Keweenawan time. By reconstructing the original dip of the Keweenawan volcanics Jahren (1965) and DuBois (1962) give an inclination of about a +45° and a declination of approximately 285° for the remanent magnetic field. Bath (1960) has analyzed two aeromagnetic traverses across these volcanics to determine the magnitude of the remanent and induced magnetization. Assuming an induced magnetization of 0.002 gauss and a remanent magnetization of 0.01 gauss he was able to calculate anomaly profiles approximating the observed profiles. The Keweenawan diabase dikes studied by Graham (1953), Strangway (1961, 1965) and Fahrig, et al. (1965) generally show a negative remanent inclination. The U.S. Geological Survey studies of the basic igneous rocks near Duluth, Minnesota show similar values of declination, inclination, and magnitude. The average susceptibility for the middle Keweenawan volcanics is 0.003 cgs.

The sediments of Keweenawan and early Paleozoic age show a very low magnetic susceptibility and a weak or non-existent remanent magnetic component.

From Table 3 and an analysis of the aeromagnetic profiles the following generalizations appear valid for the rocks of the Lake Superior region:

1. The highest amplitude anomalies are associated with iron formation and outcrops of basic Keweenawan extrusives and intrusives.
2. Pre-Keweenawan basic intrusives and flows exhibit a high level of magnetic intensity although it is generally lower than the younger Keweenawan volcanics.
3. Granitic areas show many magnetic irregularities and a generally intermediate level of intensity.
4. The sediments of all ages, including the Keweenawan sandstones, show a low level of magnetic intensity.
5. The undifferentiated Precambrian rocks show a variable level of magnetic intensity.

Data Reduction

Original Data Output

The magnetometer systems used in this survey had the capability of presenting the data in three forms. The digital form was the primary output while an analog record provided a secondary output. The third form was presented as visual output by a meter.

The digital output was recorded in binary code on paper tape by a Friden tape punch incorporated into the magnetometer system. The advantage of this system is that the data requires little handling and can be fed directly into the computer for further analysis. Magnetic readings were punched approximately every 3 or 6 seconds, depending upon the desired number of proton pulses to be counted. The count rate, therefore, determined the time interval between readings. Over most of the survey a count rate was selected that produced a 3 second interval between magnetic readings. With an average ground speed of 145 m.p.h., this time interval gave a magnetic reading approximately every one-eighth mile. After every 20 magnetic readings a time reading was automatically punched on the paper tape in conjunction with the clock mechanism.

The analog output was recorded on a Rustrak unit, set to move the recording paper at a speed of about 1 inch per minute. The paper width represented a range of 2,500 gammas in a field of 60,000 gammas. Fiducial time marks were produced every 5 minutes. During the collection of the data the analog records were used as a check on the digital output. Tape punch malfunctions in recording the magnetic and time readings could be distinguished from magnetometer malfunctions by referring to the analog record. The most important use of the analog data, however, was as a supplement to the digital output. Along those portions of a traverse where the tape punch failed, the analog record was analyzed and the data substituted. This eliminated the necessity to refly the traverse. The scale of the analog record made it possible to pick magnetic values to approximately the nearest 15 gammas. Almost ten per cent of the entire survey data has been taken from these records.

While the magnetic data were being recorded the meter readings served as a visual check on the operation of the tape punch and analog recorders.

Transposing Paper Tape to Magnetic Tape Images

The first step in reducing the aeromagnetic data was to delete the useless magnetic readings recorded between traverses and on traverses that had been reflown due to magnetometer malfunctions and errors in navigation. The data along each traverse was isolated by locating the first and last magnetic readings from corresponding time punches on the paper tape and the times recorded in the navigator's log. The paper tapes were then cut to include only the useful data collected along each traverse. A date, traverse number, and the beginning and ending times of the flight were added to the paper tapes. These were punched in binary form and then spliced together. The paper tapes were then fed into the CDC 160-A computer with program PAMAG which converted the paper tape images to magnetic tape images for further processing by the CDC 3600 computer. During this operation the binary form of the data was not altered. The computer programs used in the data reduction are given in the Flow Diagram, Figure 11.

Converting Binary Frequency Counts to Total Magnetic Intensity Values

The second step in reducing the aeromagnetic data was to change the binary frequency counts originally read by the magnetometer to total magnetic intensity values read in gammas. This was accomplished by feeding the magnetic tape generated by program PAMAG into the CDC 3600 computer with program CONVERT. To compute the total magnetic intensity value each magnetic reading was divided into a constant.

$$\text{Total intensity } (\gamma) = \frac{\text{constant}}{\text{magnetometer reading X } 10^5}$$

The value of the constant is dependent upon the number of proton pulses counted over a given period of time.

Correcting Errors in Magnetic and Time Readings

The results from program CONVERT were output in graphic form for each traverse. A printout also was made of the time and magnetic readings. By analyzing the graphic output,

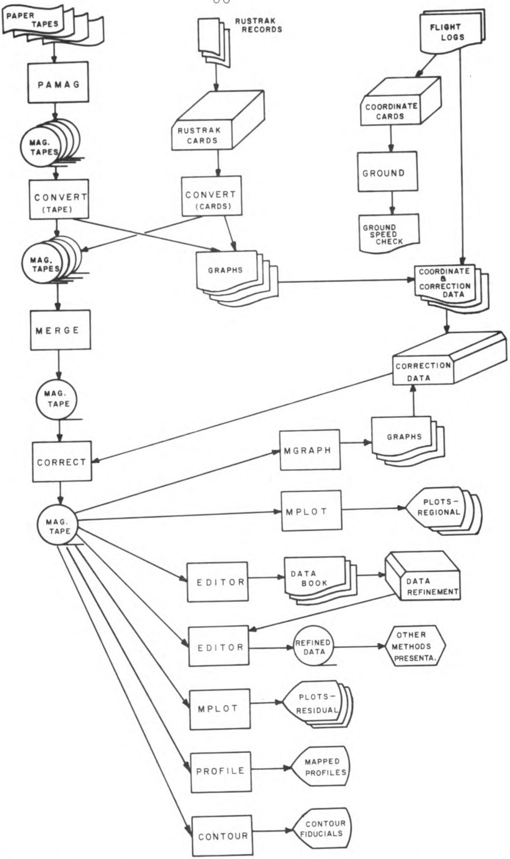


Figure 11.--Flow diagram of data processing.

it was then possible to determine whether or not the digital output should be supplemented with data from the analog record. When it was necessary to make this substitution the information was picked in the conventional manner from the analog records and put in punch card form. Using this data and program CONVERT, a graphic and magnetic tape output was again secured and analyzed in the same manner as the digital data. Figure 12 shows an example of the graphic output and the digital and analog records from which it was derived.

Mispunched magnetic and time readings were corrected with program CORRECT. Each spurious magnetic reading was changed with a punch card noting the correct value interpolated from the magnetic readings on either side and positioned by referring to time readings on the graph. The time over each navigational position also was added by punch cards referenced to the graph times. Wold (1966) describes a mathematical method developed at the University of Wisconsin to filter noise and erroneous observations caused by electrical disturbances and malfunctions in the recording system.

Prior to using program CORRECT, program MERGE was employed to compile all the computer tapes produced from the analog and digital data onto one magnetic tape. This made it possible to quickly locate the data from any particular traverse for individual analysis by the computer.

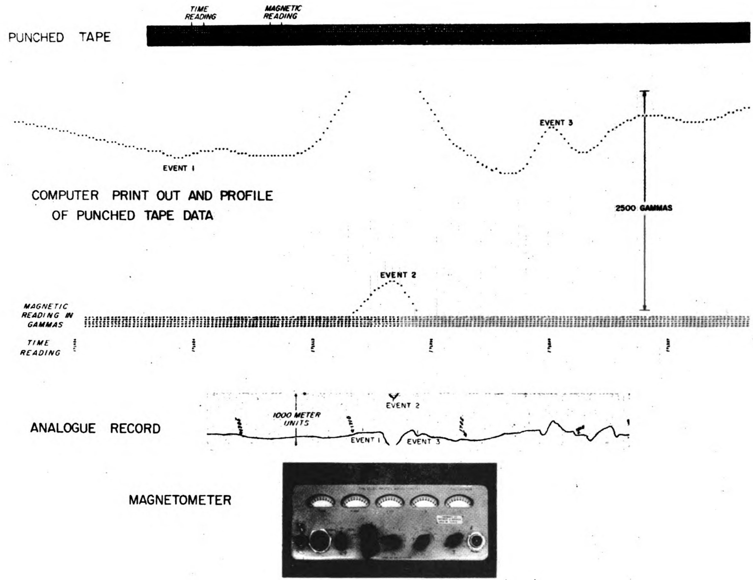


Figure 12.--Types of data output.

Correlating Magnetic Data with Geographic Positions

To correlate the magnetic readings with geographic position it was first necessary to determine the magnetic reading taken over a known ground position. This was done by observing the time recorded in the navigators log over a given fix. With this time it was possible to interpolate between the appropriate time marks recorded by the magnetometer system to determine the corresponding magnetic reading. Once the time and magnetic reading over a given fix had been correlated the coordinates of the fix could be related. Punch cards were used to relate the time and coordinates of a navigational fix to the appropriate magnetic readings. Through program CORRECT the data were then incorporated onto the magnetic tape.

To describe the position of a given fix either geographic coordinates (latitude and longitude) or grid coordinates (x-y points) can be used. However, the computer can more satisfactorily employ the linear relationships which exist in a grid coordinate system. Therefore, if a fix is given in geographic coordinates, it must be converted to grid coordinates. A complete discussion of the program used to make this conversion is given by Wold (1966). However, to eliminate converting the geographic coordinates to grid coordinates, the map upon which each fix had been plotted was overlaid with a grid system and all geographic positions were described directly in grid coordinates.

Ground Speed Check

A method was needed to check the previous operations for errors before proceeding to the next step because a number of manual operations were involved in reducing the data to this point. The errors of greatest concern were those introduced in picking the x-y grid coordinates, correlating time with the magnetic readings, changing incorrect time fiducials, isolating individual traverses, and transposing information from the maps and graphs to punch cards. To recognize these errors a method was devised to statistically analyze the ground speeds along each traverse. The use of ground speed data was an outgrowth of the method previously described to help determine the maximum possible error when plotting the location of any given magnetic reading along a flight traverse.

The ground speed analysis was accomplished through program GROUND on the CDC 3600 computer. Using the recorded time over each fix and its grid coordinates, this program was designed to generate and printout the following information for every traverse:

1. Mileage, flight time, and ground speed for the entire traverse.
2. Mileage, flight time, and ground speed for each segment of traverse between fixes.
3. Standard deviation of the ground speed of each segment of traverse from the ground speed of the entire traverse.

A traverse was analyzed when the ground speed of a segment of that traverse deviated significantly from the average traverse ground speed. The source of a large deviation in ground speed was usually attributed to an error in one of the following: plotting grid coordinates, recording time over fixes, determining correlations of time and magnetic readings, and transposing information to computer cards.

Not all large deviations in the ground speed of various segments of traverse were the result of error. By comparing the abnormal ground speeds found on segments of various traverses with corresponding segments of adjacent traverses it became apparent that many of the large deviations were due to high velocity winds. In numerous cases a deviation in ground speed could be attributed to winds having velocities of over 40 knots. Proof of these conditions could be observed by comparing a traverse with a high ground speed flown in one direction to an adjacent traverse with a correspondingly low ground speed flown in the opposite directions on the same day.

Presentation of Data

Presenting the Observed Data

In reducing the aeromagnetic data to the presentation stage the digital paper tapes and supplementary analog records were first refined and recorded on magnetic computer tapes through program PAMAG. Next the binary form in which the data were originally recorded was transposed into decimal form through program CONVERT and output as graphs with magnetic readings in gammas and time readings in hours, minutes and seconds. The graphs were then used to correct erroneous readings and to correlate the magnetic data with navigational positions using program CORRECT. The results of this step were again output in graphic form through program MGRAPH. The graphs were then used in conjunction with the output from program GROUND to make final corrections. Program CORRECT was again employed to incorporate the final corrections on the magnetic tape and all tapes were combined through program MERGE to facilitate future operations.

At this point all the observed total magnetic intensity data were ready to be presented in profile and contour form. Through program MPLOT, two sets of magnetic profiles were graphed on a ten-inch plotter for each traverse at a horizontal scale of 1:500,000. One set of profiles was plotted at a vertical scale of 1 inch equal to 2500 gammas and the other set at 1 inch equals 400 gammas. Those profiles having a vertical scale of 1 inch equals 2500 gammas were plotted directly onto a map along their respective flight lines to produce the Total Magnetic Intensity Profile Map, Figure 13. The profiles with a vertical scale of 1 inch equals 400 gammas were picked to produce isogam fiducial marks at an interval of 50 gammas. These fiducial marks were then plotted on a second map along the appropriate flight line. The data were first contoured at a 100-gamma

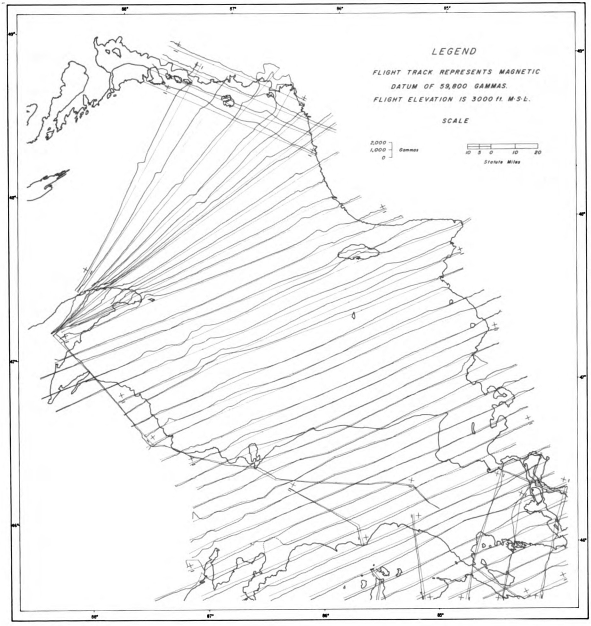


Figure 13.--Total magnetic intensity profile map of the eastern Lake Superior region (observed data).

interval. Areas of low gradients where more detail was advisable were contoured on a 50-gamma interval, Figure 14. This same procedure was used to present the observed aeromagnetic data for Lakes Michigan and Huron. In presenting the observed data from western Lake Superior in profile and contour form, programs PROFILE and CONTOUR were successfully developed by Wold (1966) for the CDC 1604 computer located at the University of Wisconsin. The use of these programs enables the data to be plotted directly through the computer, thus saving many man-hours of work in transcribing and contouring.

The unaltered magnetic characteristics of the area can be determined from the observed data which is presented in the total magnetic intensity profile and contour maps. The next step in reducing the magnetic data was to remove the normal geomagnetic effect and again present the resulting data in profile and contour form. From these residual maps, Figures 15 and 16, the magnetic anomalies produced by geological variations in the underlying bedrock can be more easily recognized. Also an estimate of the normal geomagnetic effect can be determined by directly comparing the residual and observed data in profile and contour form.

Removal of the Regional Magnetic Field

The regional magnetic field correction is designed to remove the broad effects caused by the earth's normal magnetic field. Two methods are available for applying this

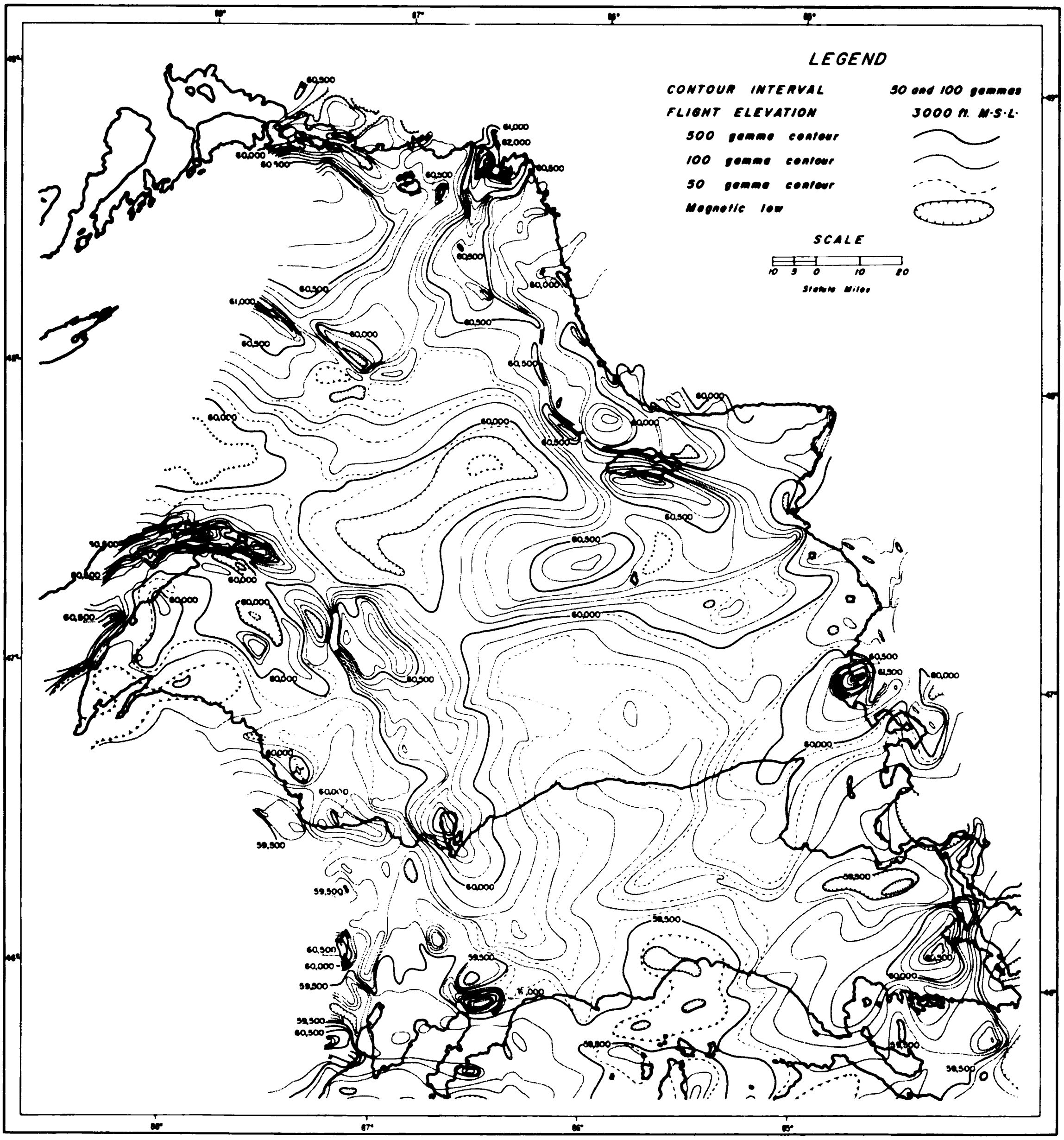


Figure 14.--Total magnetic intensity contour map of the eastern Lake Superior region (observed data).

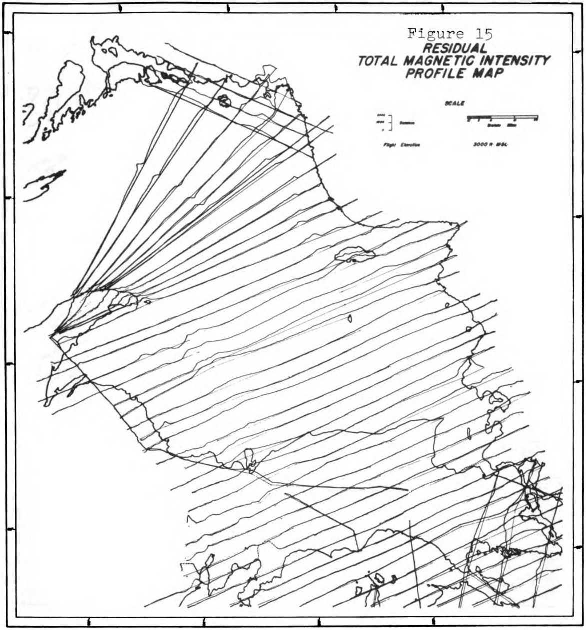


Figure 15
RESIDUAL
TOTAL MAGNETIC INTENSITY
PROFILE MAP

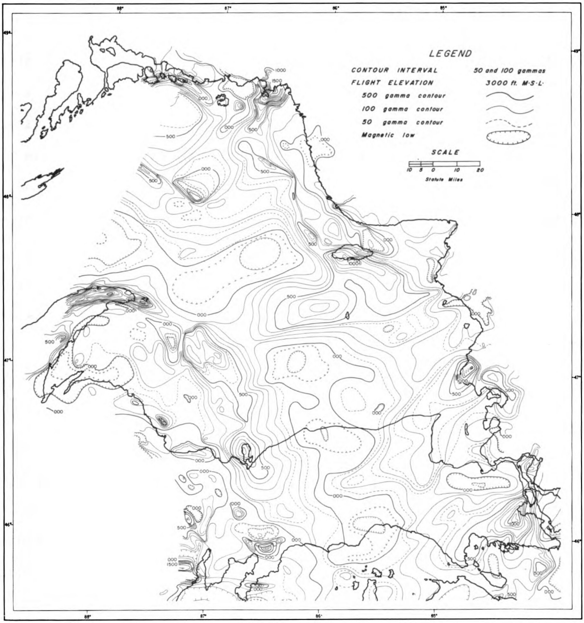


Figure 16.--Residual total magnetic intensity contour map of the eastern Lake Superior region.

correction. The standard method of removing the geomagnetic field is to consult the Total Intensity Chart of the United States published at ten-year intervals by the U. S. Coast and Geodetic Survey. Since the existing chart was made for the year 1955, it was first necessary to extrapolate the field to mid-summer 1964, when this survey was conducted, by applying the secular variation correction. From the total intensity contours produced, the regional field was determined and picked for each grid coordinate at which a fix had been established. By linear interpolation between traverse coordinates the regional field was determined and then subtracted from each magnetic reading through use of the computer.

A second and more satisfactory method of removing the regional effect has been developed and programmed by J. C. Cain at NASA, Goddard Space Flight Center. In applying Cain's program the main geomagnetic field is computed for any desired latitude, longitude, altitude, and date by spherical harmonic expansions. Based on the spherical harmonic coefficients determined by Cain, et al. (1965) smoother contours are produced for the geomagnetic field than can be found on standard world magnetic charts and, therefore, are considered to better represent the actual geomagnetic field. The NASA program determines the regional field for a navigational position through geographic coordinates. Since each fix was described in x-y grid coordinates, it was necessary to incorporate into the program a system to convert these coordinates to geographic coordinates. A complete description of this relationship and the equations used to make this conversion are given by Wold (1966). After the regional field at each fix has been determined through the NASA program, the field is then calculated by interpolating between these coordinates and subtracting the regional value from each observed magnetic reading along the traverse. A complete description of this program, including a program listing, is given by Cain, et al. (1964).

The advantages of using the NASA program rather than the Total Intensity Chart of the United States are:

1. The geomagnetic field is more accurately represented.
2. The secular variation correction necessary to extrapolate the 1955 data to the time of the survey need not be made.
3. Physically determining the regional value at each fix and then transposing this data onto punch cards for computer analysis is not necessary.

Although both methods described above were applied to the data collected in this survey only the results obtained from the NASA program were used in the final presentation.

CHAPTER IV

INTERPRETATION OF DATA

Methods of Interpretation

General Procedures

The primary objectives in the interpretation of magnetic data are to draw inferences about the attitude, depth, configuration, and lithology of the subsurface structures. To accomplish this, information must be obtained about the regional geology, and the induced and remanent magnetization of the underlying basement complex. The observed magnetic data must be reduced, the geomagnetic field correction should be made, and the resulting data presented in profile and contour form.

In this section the various qualitative and quantitative methods of analysis used to interpret the aeromagnetic data collected over eastern Lake Superior are discussed. Where gravity data are available the information has been incorporated into the qualitative analysis of the magnetic data to more accurately determine the configuration, extent, and development of the structural features. The interpretation of the gravity data in conjunction with the magnetic data also is discussed in this section.

Qualitative Methods

The empirical analysis of data is always performed whether or not additional quantitative methods are applied. The general geologic structure of an area can usually be determined from an inspection of the residual total magnetic intensity profile and contour maps. Assuming that the overlying sediments show no magnetic effect, the large magnetic anomalies can be interpreted as reflecting changes in the composition of the igneous and metamorphic basement rocks. In general, the boundaries of magnetically contrasting rock units can be determined by following the bands of steep gradients represented on a magnetic map by closely spaced contour lines. By observing the shape and extent of the profiles over a contact between two rock units, together with the known regional geology, such features as faults, extrusives, and intrusives can frequently be identified. Structural trends also can be determined from the general magnetic trends of the area. Abrupt shifts of the magnetic contour pattern is often an indication of faulting.

Based on the previously discussed magnetic properties of the rocks in the Lake Superior region, the following interpretations have been generally applied to the analysis of positive magnetic anomalies. Depending upon amplitude, configuration, extent, and location, positive anomalies are indicative of:

1. Accumulations of Keweenawan volcanics or intrusives,
2. Faulting or pinching out of Keweenawan extrusives,
3. Iron formation,
4. Accumulations of pre-Keweenawan basic intrusives and extrusives.

Negative magnetic anomalies depending upon their characteristics are attributed to:

1. Accumulations of Keweenawan sedimentary rocks or a near surface subcropping of non-magnetic pre-Keweenawan rocks,
2. Faulting or the sudden pinching out of the Keweenawan extrusives.

Another consideration affecting the interpretation of the aeromagnetic data is the influence of the remanent magnetization. For example, the dip of the Keweenawan volcanics will affect the amplitude of the magnetic anomaly because in the Lake Superior region the intensity of the remanent magnetization having an azimuth of 285° and a dip of about +45° is as great as three times the induced magnetization. This can be observed in the magnetic anomalies produced over the Douglas and Lake Owen faults at the western end of Lake Superior (Wold, 1966). Both faults and the associated Keweenawan volcanics strike perpendicular to the remanent magnetization. The extrusives associated with the fault dip 30° to 60° northwestward, thus the remanent and induced magnetization reinforce each other to produce positive anomalies. In contrast, the volcanics associated with the Douglas fault dip southeastward causing the remanent and induced magnetization to oppose each other, resulting in a negative anomaly over the fault.

An empirical analysis of the aeromagnetic data can be improved by including the results from a gravity study of the area. Basically the interpretation of the Bouguer gravity data is based upon the densities of the rocks. Therefore, these data aid in determining the type of rock and structural configuration. The rock types found in the Lake Superior region are usually accepted to have the following densities (White, 1966):

1.	Keweenawan basic rock	2.90 gm/cc
2.	Keweenawan sedimentary rock	2.35 gm/cc
3.	Pre-Keweenawan rock	2.67 gm/cc.

In making a Bouguer gravity interpretation using the rock densities listed above, it should be remembered that crustal density variations are strongly suspected within the Lake Superior trough.

Relatively high gravity anomalies are generally attributed to one of the following sources:

1. Accumulations of Keweenawan extrusives and near surface intrusives,
2. Intrusions of dense subcrustal or crustal rocks into the pre-Keweenawan complex.

Broad scale variations in both negative and positive gravity values may reflect density variations in the mantle as well as variations in crustal thickness.

When it is possible to analyze the gravity and magnetic data together and both indicate positive anomalies, the interpretation is usually made that accumulations of Keweenawan basic rock lie close to the surface.

If the magnetic and gravity results both indicate negative anomalies one of the following conditions may be suggested:

1. Keweenawan basic rocks are thin or absent and/or thick accumulations of Keweenawan sediments are present,
2. Relatively non-magnetic and low-density masses of pre-Keweenawan rocks occur near the surface.

Areas showing positive magnetic and negative gravity anomalies may be interpreted as indicating a relatively thin near surface sequence of Keweenawan basic extrusions associated with a thick sequence of Keweenawan sediments or pre-Keweenawan rocks.

When the more unusual case exists in which negative magnetic and positive gravity anomalies are associated, the explanation may be found by assuming one of the following conditions:

1. Intrusions of dense subcrustal rocks into the pre-Keweenawan complex. Keweenawan extrusives may be absent.

2. Remanent magnetization of the Keweenawan volcanics may oppose the induced magnetization.

In all of the above explanations for the observed magnetic and gravity data the anomalies are dependent primarily on contrasts between the physical properties of the associated rocks. Interpretation, therefore, is dependent to a large extent on determining the structural situation in which a greater or lesser degree of contrast exists between the densities and susceptibilities of two or more associated rocks. The limiting factors are the physical properties of the rocks of the region and the geological feasibility of the proposed structural explanation. In all cases the explanation must be commensurate with the known or possible geologic structure of the area.

Quantitative Methods

The quantitative treatment of aeromagnetic data is carried out in two basic ways. One approach is to analytically study the anomalous magnetic features in profile form while the other approach involves the application of mathematical processes to the magnetic data in contour form. The methods used to analyze magnetic anomalies in the profile form are designed to determine, through model studies, the depth of the rock unit causing the anomaly and to estimate its size, configuration, and magnetic properties. Those analytical methods employed to interpret the magnetic data in contoured map form are primarily designed to delineate the true areal extent and relief of the anomalies.

Although the results of this aeromagnetic survey have generally been interpreted using qualitative methods of analysis, the interpretation of the data is based upon theoretical models produced over variously shaped magnetic bodies with different susceptibility contrasts and remanent magnetizations. A more satisfactory interpretation can be made by studying theoretical anomalies calculated from quantitative estimates of the magnetic properties of the rocks within the area of investigation. The use of prismatic and dike models are particularly applicable. Vacquier, et al. (1951) present a complete description of prismatic models. In this analysis total intensity anomalies are computed for prismatic bodies with various length-to-breadth dimensions at uniform depths of burial with different magnetic inclinations. The resulting data are presented in the form of theoretical contour maps. The observed anomalies from the contoured intensity maps can then be compared to these models and the best fitting model chosen. Estimates of the depth of burial, as well as an evaluation of the possible susceptibility contrast giving rise to the anomaly, can then be made from the parameters given for the chosen model. The prismatic bodies from which the theoretical anomalies are computed are rectangular in plan and bottomless with vertical sides and uniform magnetization. The magnetization vector is assumed to be in the same direction as the induced field. Although this assumption is valid in some cases in the Lake Superior region, departures from this, due to the additional component of remanent magnetization, are known to occur and must be taken into consideration.

To further facilitate the interpretation of the data from this survey, dike models were computed in profile form using the previously discussed magnetic susceptibility and remanent magnetization properties for the rock of the Lake Superior region. In calculating the magnetic anomalies over these models the direction of the remanent magentization vector was assumed to be constant. A zero dip was also assumed for the volcanics. Although these assumptions do not accurately reflect the actual conditions, the model studies were valuable in making a first order estimation of the observed magnetic anomalies. A dike model is a two dimensional body assumed to be of infinite strike length, extending to a great depth, having parallel sides and a horizontal top. The models were calculated and plotted through a computer program developed by Heirtzler, et al. (1962) for two dimensional structures of arbitrary shape. Seventy-two theoretical dike models were calculated and the anomalies produced from them were plotted in profile form. To produce these models eight magnetic bodies were first calculated with strikes of N 0° E, N 45° E, and N 90° E having the following inclinations and widths:

1. 15°, 16 miles,	5. 20°, 8 miles,
2. 30°, 8 miles,	6. 30°, 8 miles,
3. 30°, 16 miles,	7. 40°, 4 miles,
4. 70°, 4 miles,	8. 70°, 8 miles.

A profile was then plotted for each of the 24 sets of data at a calculated depth of 1500 feet, 3000 feet, and 4500 feet. Figures 17, 18, 19, 20, and 21 represent the magnetic anomalies produced over various dike models. In each figure the variable and constant factors are listed together with their induced and remanent magnetizations. In each figure models have been combined to show the variations produced in the anomaly profiles when three of the four variables are held constant and the fourth is changed.

In Figures 17 and 18 the dip, depth, and width are the same for each model, but the strike has been varied. The three profiles in Figure 17 are calculated over a dike having a 30° dip, and show considerably more similarity than the three profiles in Figure 18, where the dip was 70°.

The two models represented in Figure 19 compare the effects produced by a change in the dip of the dike when its depth, width, and strike are held constant. From Figure 20 the difference in the amplitude of the anomaly change in depth of the dike, can be easily observed. Similarly, a comparison of the two models in Figure 21 show the different anomalous effect produced when the width of the dike is varied and the strike, dip, and depth remain the same.

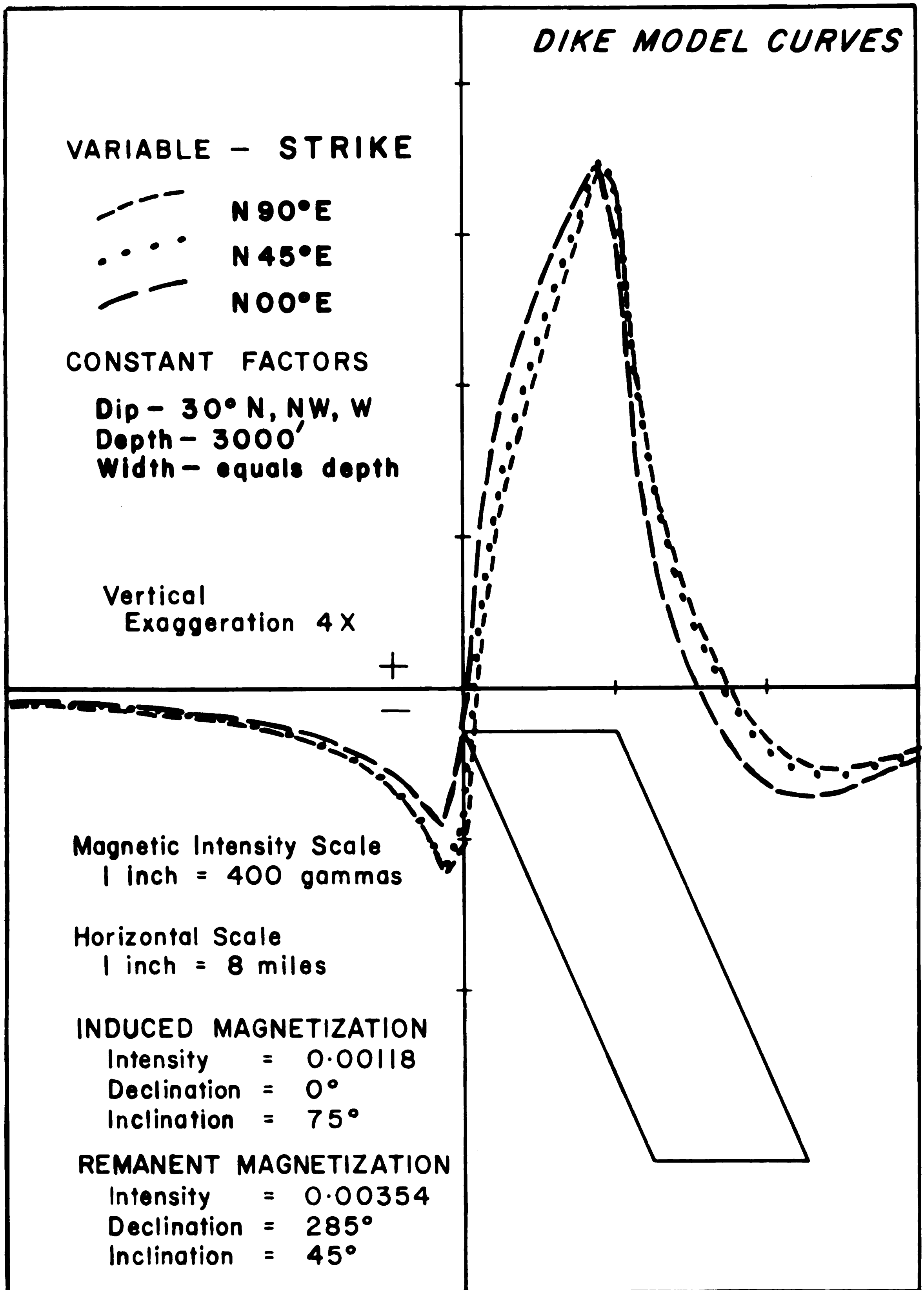


Figure 17.--Dike model with variable strike (dip 30°).

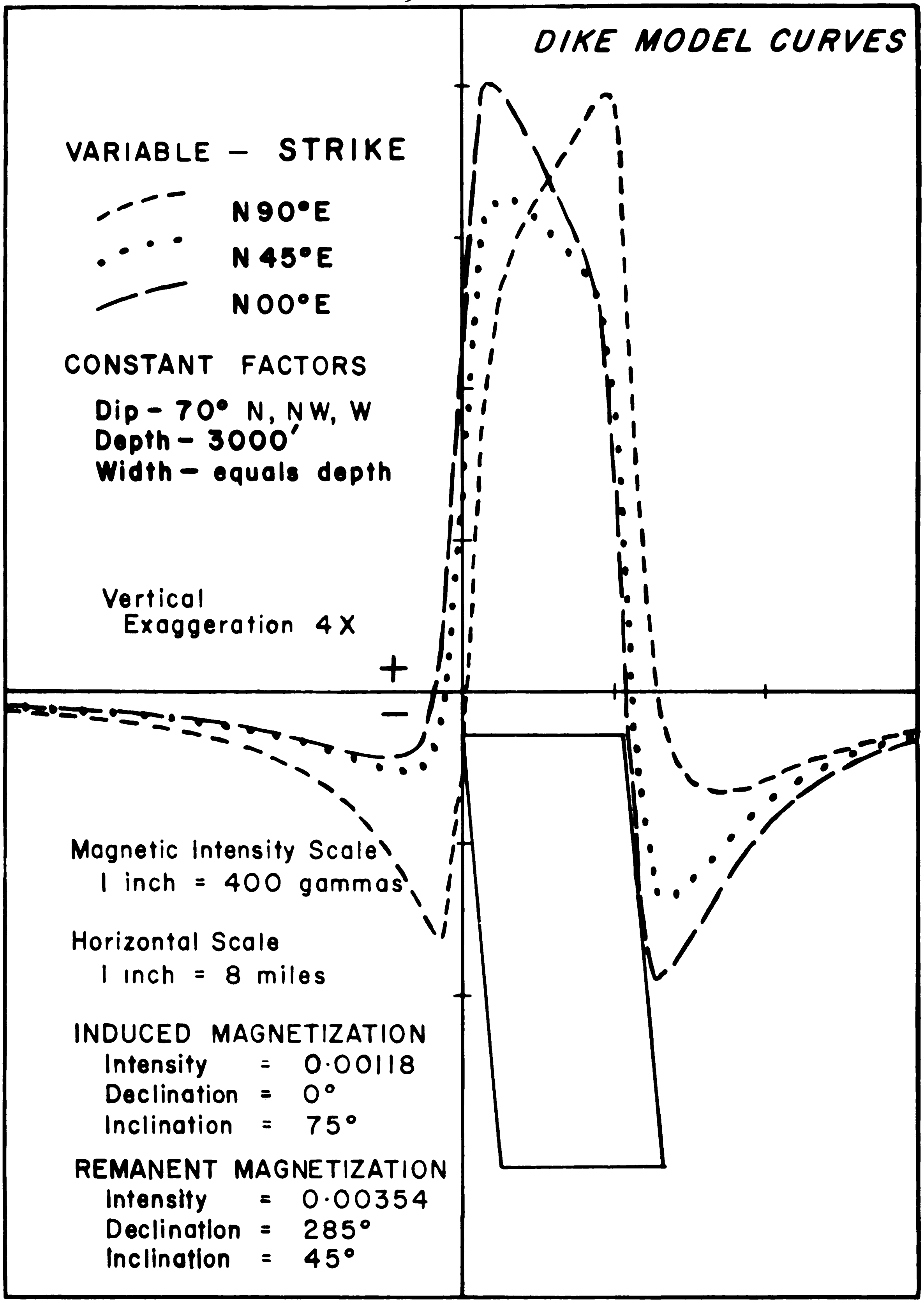


Figure 18.--Dike model with variable strike (dip 70°).

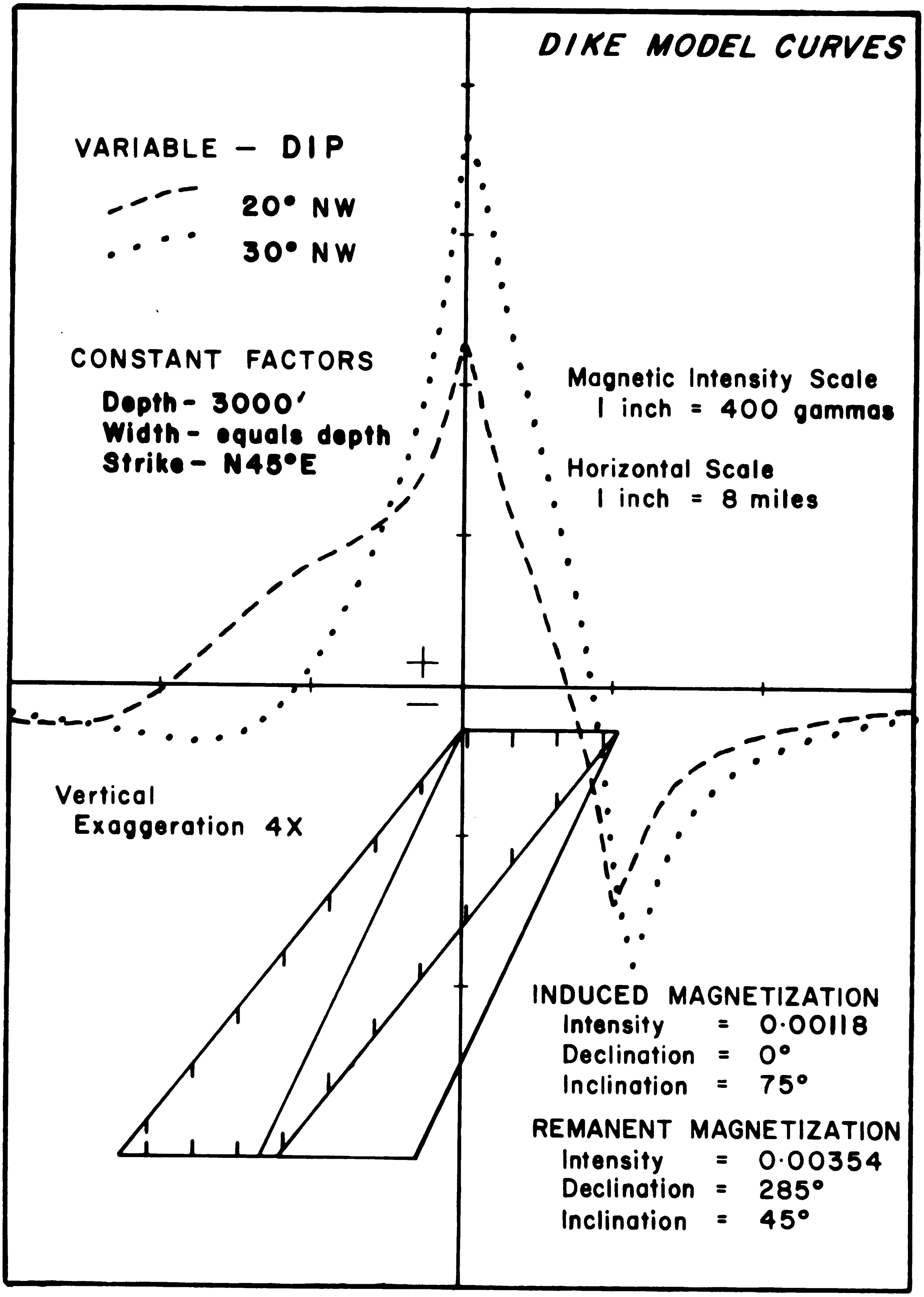


Figure 19.--Dike model with variable dip.

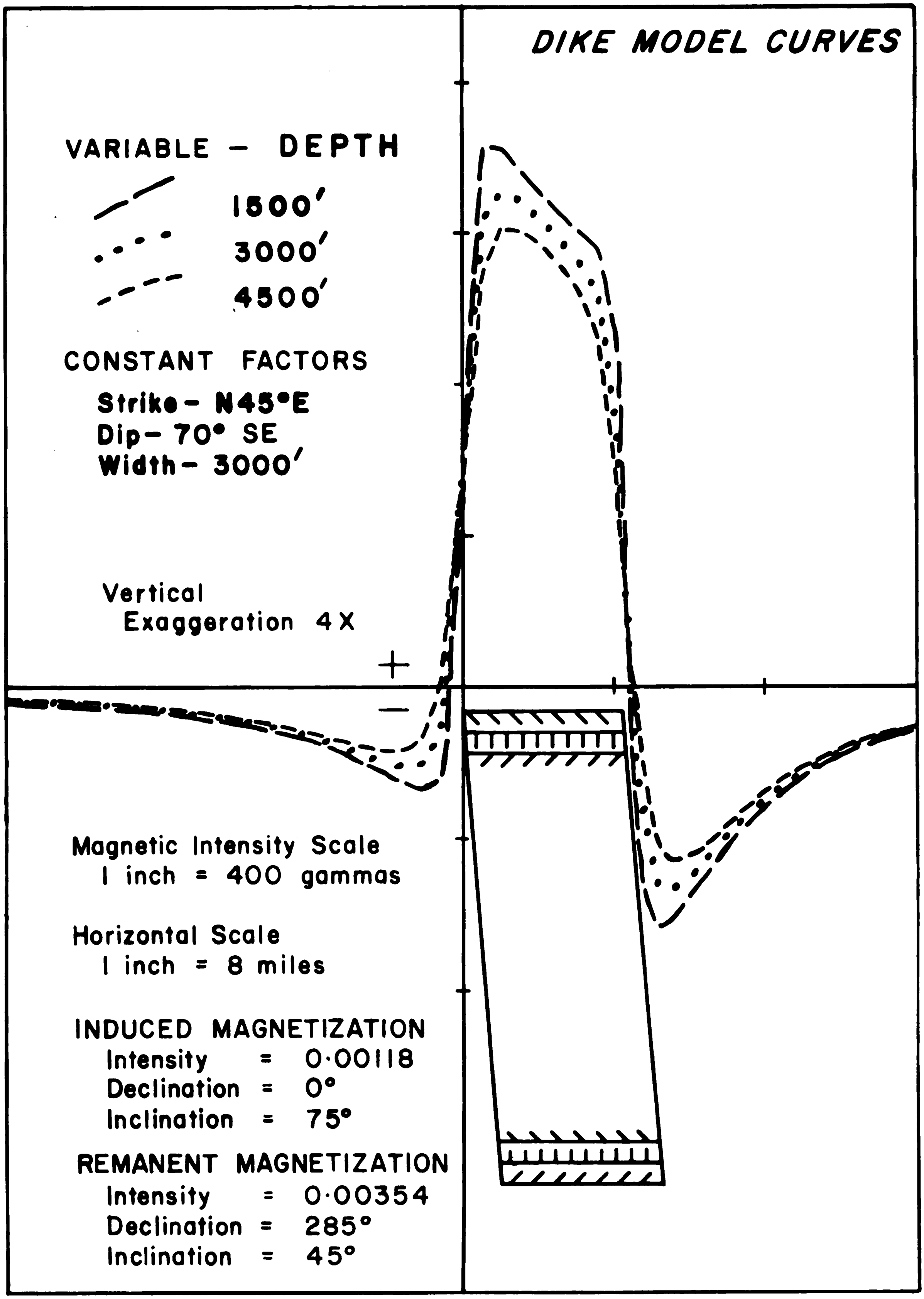


Figure 20.--Dike model with variable depth.

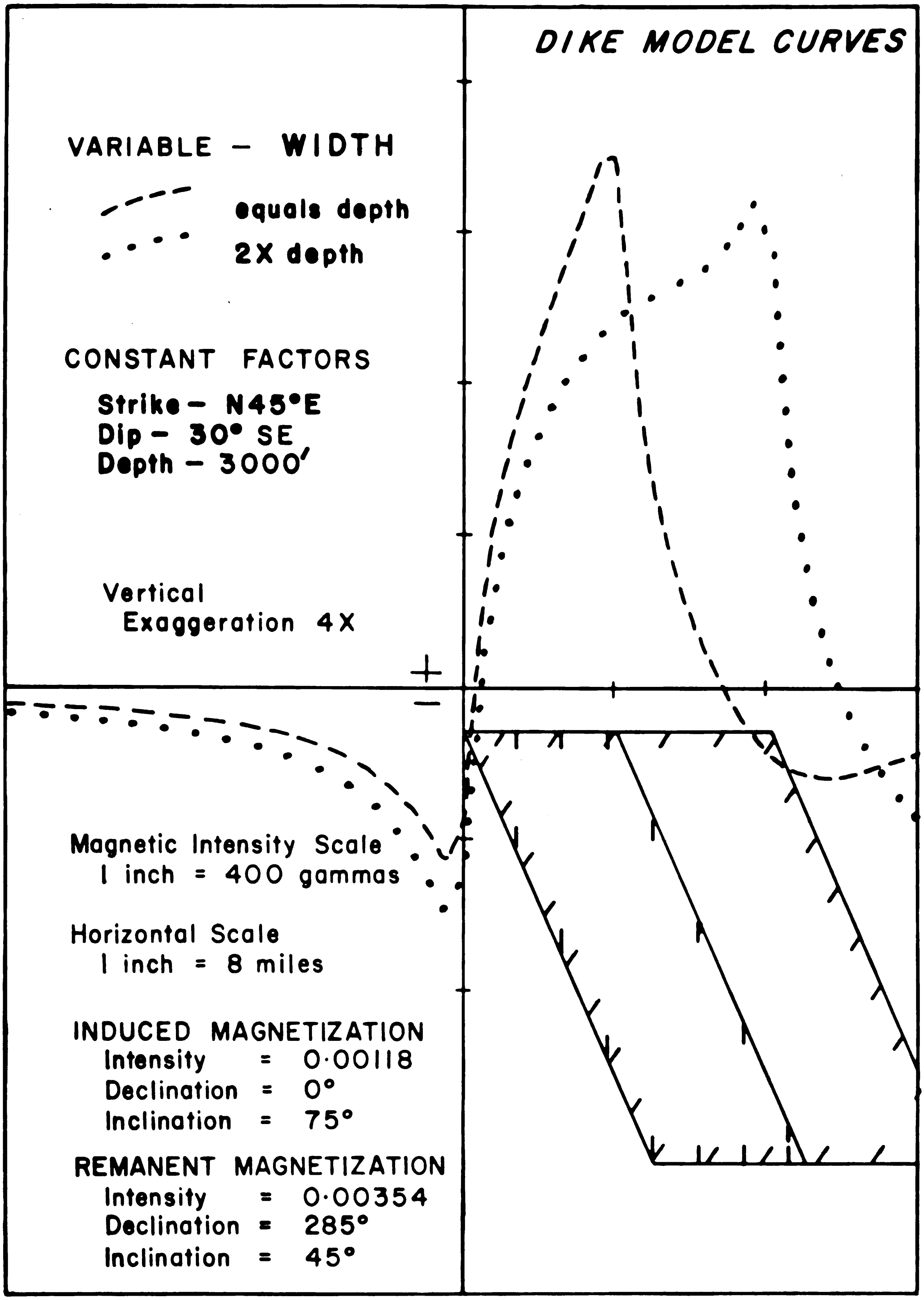


Figure 21.--Dike model with variable width.

Although quantitatively derived, the dike and prismatic models were used mainly as a basis for the qualitative analysis of the aeromagnetic data. Additional theoretical model studies were used to quantitatively interpret the data from this investigation. In these studies magnetic profiles either were taken directly from observed anomalies along a flight traverse or from profiles constructed across the traverses after the data were put in contour form. These profiles also were analyzed using the computer program developed by Heirtzler, _et al_. (1962). Geologically feasible models representing the underlying structure were constructed. Susceptibility contrasts, and remanent and induced magnetic properties for the rock bodies were based on the magnetic properties of rock data compiled for the Lake Superior region, shown in Table 3. The magnetic effect produced from the inferred structure was then computed and machine plotted. The theoretical results were compared with the actual residual magnetic anomalies. Corrections were then made in the inferred structure and replotted until a more satisfactory fit between the calculated and observed data was obtained. The results of these model studies are given in a later section of this chapter.

Description of the Major Aeromagnetic Anomalies

General Statement

In this section the amplitude and extent of the major aeromagnetic anomalies are described. The possible source of the anomalies and any indications of faulting are considered. To aid in this phase of the interpretation, the magnetic effects produced over idealized bodies were compared with the observed magnetic profiles. The previously mentioned dike model studies were helpful in suggesting the source and presence of associated faulting.

The magnetic variations in eastern Lake Superior and the eastern portion of the Northern Peninsula of Michigan can be observed from the Residual Total Magnetic Profile and Contour Maps, Figures 15 and 16. However, to facilitate the description of the individual magnetic anomalies, each has been marked on the contour map to produce the Magnetic Anomaly Map, Figure 22. Negative anomalies below zero gammas and positive anomalies above 300 gammas were selected for consideration and have been labelled according to the sequence in which they are considered in this section. Only a brief description of the significant anomalies and the possible geologic source of each anomaly are given in this section.

The magnetic profiles are generally smooth over the central portion of the lake and the eastern portion of the Northern Peninsula of Michigan. Elsewhere, they are

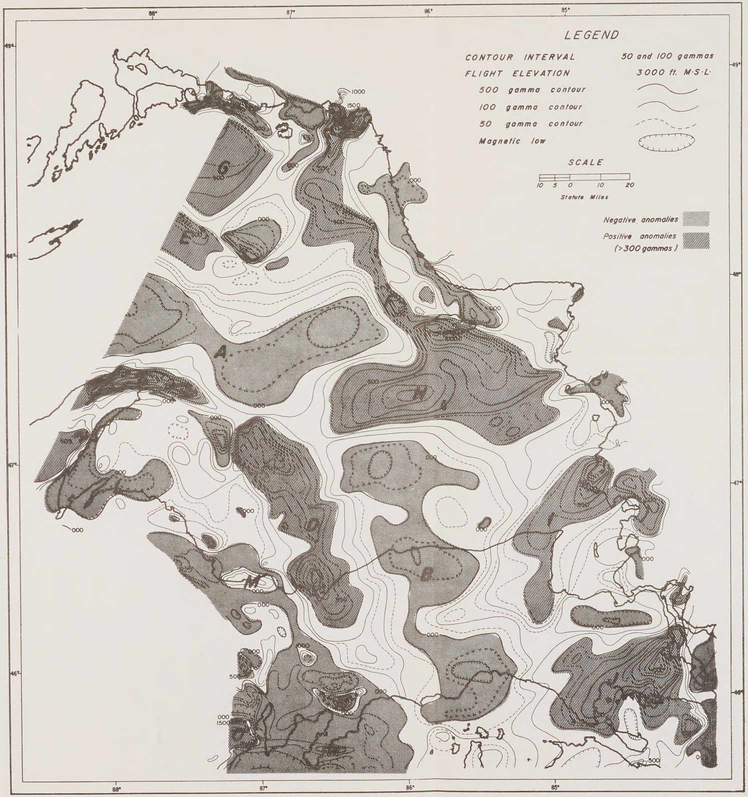


Figure 22.--Magnetic anomaly map of the eastern Lake Superior region.

commonly irregular. Negative anomalies usually do not exceed an amplitude of minus 100 gammas, while the broad positive anomalies range in amplitude from 500 to 100 gammas and locally exceed 1000 gammas.

Anomaly A

This is a negative magnetic anomaly having a maximum amplitude of about minus 150 gammas. To the east of the Keweenaw Peninsula the magnetic minimum narrows and then broadens again to strike northeast across the lake. The source of the anomaly may be interpreted as being primarily due to accumulations of non-magnetic Keweenawan clastic sediments.

Anomaly B

This anomaly is similar in form and magnitude to Anomaly A, but is separated from it by the positive Anomaly H which cuts across eastern Lake Superior. The source of Anomaly B also is assumed to be a wedge of Keweenawan clastic sediments similar to the source responsible for Anomaly A.

Anomaly C

This positive magnetic anomaly is an expression of the middle Keweenawan basic volcanic flows outcropping on the Keweenaw Peninsula. The anomaly is nearly symmetrical, having a relatively high amplitude. The Keweenaw fault extends along the southern margin of the volcanics and interbedded clastics. The amplitude is further increased by the northwestward dip of the volcanics which increases the effect of the remanent magnetization. Detailed total intensity aeromagnetic maps of this anomaly have been published by the U.S. Geological Survey.

Anomaly D

Anomaly D appears to be a continuation of Anomaly C, being separated from it by a decrease in amplitude southeast of Maintou Island. The anomaly is broader and has a slightly lower amplitude than Anomaly C. It is generally asymmetrical with steeper gradients on the western side and it decreases in amplitude from the south shore of Lake Superior to the north shore of Lake Michigan. This decrease may be partly due to an increasing depth of burial. The structural significance of Anomaly D makes it one of the most important anomalies mapped in this survey. Although the anomaly is probably caused by basic Keweenawan volcanics, a question exists as to whether the exact source can be described as an extrusive or intrusive feature. It is also debatable whether vertical displacement has taken place along the western margin and if so, is this faulting a continuation of the Keweenaw fault.

Anomaly E

This is an asymmetric positive anomaly having a correlative magnetic low to the north, and is a continuation of the anomaly associated with the Keweenawan basic volcanics on Isle Royale. The steep gradients on the northern side and the shallow gradients on the southern side of the anomaly suggest that the basic lavas dip southwestward and that the northern edge is cut by a fault. The fault is an extension of the Isle Royale fault originally postulated by Van Hise and Leith (1911).

Anomaly F

This anomaly is similar in nature to Anomalies E and G. It extends from near Gargantua Harbor, Ontario, through Michipicoten Island, then northward to the vicinity of Pic Bay. It then merges with Anomaly K which is produced by the Port Coldwell complex. The association of Anomaly F with the basic Keweenawan volcanic rocks of Michipicoten Island and its configuration suggests that the source is a sequence of basic volcanics dipping into the basin. The steeper gradients extending along the eastern side of the anomaly are indicative of faulting. Midway between Michipicoten Island and Pic Bay the anomaly and associated fault appear to either swing from a northerly to a northwesterly trend or to continue northward along the eastern margin of Anomaly K. The northwestern portion of the anomaly is cut off from the broad Anomaly G by a magnetic low extending southward from Jackfish Bay and the Slate Islands. This magnetic negative is associated with a zone of cross faults which may extend to the southwest toward the Keweenaw Peninsula. The magnetic minimum located between Anomaly F and the shoreline suggests faulting in this location, but it also may indicate an erosional dip slope. If this is a fault, it continues to the southeast where it joins the main fault associated with Anomaly F to the east of Michipicoten Island. To the northwest it strikes parallel to the shoreline until it intersects the shoreline in the vicinity of Heron Bay. The fault may continue inland and associate with the Pic River linear. In Lake Superior this magnetic minimum indicates the northeastern edge of the basic Keweenawan volcanics.

Anomaly G

Anomaly G is the eastern extension of a positive anomaly located between the Isle Royale fault and the north shore. It is associated with a narrow sharp-gradient negative anomaly to the north. This negative anomaly can be correlated with the northern margin of the Keweenawan extrusives and sediments outcropping on the islands in Nipigon Bay and is interpreted to indicate faulting. The source of both anomalies is probably the basic volcanics which dip toward the center of the lake. These volcanics are interrupted to the south by the Isle Royale fault.

Anomaly H

This is a positive anomaly with an east-west trend, lying south of Michipicoten Island. On the eastern side it merges with Anomaly F. To the west it extends across the lake nearly to Anomaly D, separating the two negative

Anomalies A and B. Since the aeromagnetic flight lines are approximately parallel to the strike of the anomaly, the magnetic gradients on the northern and southern margins are not well defined. The source of this anomaly is probably Keweenawan basic rock of either an intrusive or extrusive nature. The aeromagnetic data appears to indicate associated faulting along the sourthern and northern borders and possibly the eastern margin.

Anomaly I

Like Anomaly H, this positive anomaly lies at an angle to the main trend of the Lake Superior trough. It reaches a maximum of 2000 gammas over Mamainse Point and, with decreasing amplitudes, extends to the southwest through Whitefish Point into the central portion of the eastern part of the Northern Peninsula of Michigan. The anomaly correlates with the Keweenawan volcanics and interbedded sediments outcropping on Mamainse Point. Its limited extent suggests that faulting may have occurred adjacent to the anomaly.

Anomaly J

This positive anomaly occurs over the Paleozoic sediments at the eastern end of the Northern Peninsula of Michigan. Its configuration, extent, trend, and probably its source are similar to Anomaly I. A volcanic center near the eastern end of Anomaly J could account for the maximum amplitude of over 1000 gammas. The decrease in amplitude toward the southwest may indicate a thickening of the sediments over the basic volcanics and/or a decrease in the thickness of these volcanics. The source of this anomaly and its limited extent also suggest adjacent faulting.

Anomaly K

Anomaly K is a positive anomaly located at the north-eastern corner of Lake Superior near Marathon, Ontario. Its high amplitude and sharp gradients indicate that the source is at or very near the ground surface. The anomaly has been well defined by the aeromagnetic mapping program of the Geological Survey of Canada (Geophysics Paper 7088, Geological Survey of Canada, 1965). It is correlated with the Port Coldwell complex (Puskas, 1960). Faulting also may be associated with this feature.

Anomaly L

This is a small amplitude negative anomaly centered over Keweenaw Bay. Its source is interpreted as a wedge of Jacobsville sandstone between the Keweenaw fault to the north and the pre-Keweenawan rocks outcropping to the south.

Anomaly M

This is a low amplitude positive anomaly with an east-west strike located on the southern shore of Lake Superior between Marquette, Michigan and Laughing Fish Point. It appears to be related to the east-west striking, pre-Keweenawan, metamorphic rocks outcropping to the west of the anomaly.

Anomaly N

Anomaly N occurs over the Paleozoic sediments near Cooks, Michigan. It is observed on only one aeromagnetic traverse, but may be associated with minor magnetic fluctuation found on adjacent traverses. Although the geographic extent and strike of this positive anomaly are questionable, a general east-west strike has been indicated. Its source is probably associated with either an east-west striking iron formation or with a pre-Keweenawan or Keweenawan basic intrusive.

Anomaly O

This high amplitude positive anomaly is located near Escanaba, Michigan. Its southern peak continues eastward across the Garden Peninsula and into Lake Michigan. The anomaly correlates with two magnetic bands of iron formation that Allen (1914) has traced from the Menominee Iron Range near Waucedah to Escanaba, Michigan. Drilling operations at Escanaba have encountered iron formation under 800 feet of Paleozoic sediments, thereby supporting an interpretation that the anomaly is derived from magnetic iron formation.

Magnetic Model Studies

Procedure

The major magnetic anomalies were described in the previous section. The geologic source of each anomaly and any indications of associated faulting were suggested from analysis of the configuration, amplitude, extent, and location of the anomalous features.

To determine if the interpretations given in the previous section were magnetically feasible, a number of theoretical models were produced over seven of the most significant anomalies. The calculated anomalies generated over the models are based on the two-dimensional method derived by Heirtzler, et al. (1962). This method was programmed for the CDC 3600 computer and the calculated magnetic profiles were plotted directly on the ten-inch plotter. A brief description of the computer programs is included in Appendix A and a description of the computer and decks is given in Appendix B. The structural significance and the indications derived from each magnetic model are considered in this section.

In the model studies it has been assumed that the positive anomalies are produced by Keweenawan basaltic flows and that the negative anomalies are the result of thick accumulations of non-magnetic sediments.

It was determined in the model studies that the thickness of the volcanics has little effect on the calculated magnetic profiles. Therefore, to simplify the model studies it has been assumed that the positive magnetic profiles reflect the general topography of the basic basement rocks. White (1966a) and Wold (1966) have made a similar assumption in their investigations of the aeromagnetic data from western Lake Superior. They suggest that a magnetic horizon near the top of the volcanics be considered the source of the anomalies. By making a similar assumption about the models illustrated in this section, only the upper trace of the basement complex is shown. Where the magnetic profiles show negative anomalies the basement rocks are assumed to be deeply buried by clastics. However, no assumption is made in the final interpretation regarding the existence or thickness of the volcanics beneath the clastic sediments. For this reason no attempt has been made in the illustrations to produce an actual geological cross-section.

The values discussed previously for the magnetic properties of rocks in the Lake Superior region which were used to produce the dike models, Figures 17-21, also were employed to construct the theoretical models being considered here. A constant remanent magnetization vector was assumed throughout the area. It is realized that this assumption has introduced some error in the calculated anomalies because structural deformation has not been uniform in this region.

The location of each magnetic model has been indicated on the Magnetic Anomaly Map, Figure 22. From a number of models prepared along each profile, one was selected in which the calculated anomaly either best approximated the observed anomaly or provided the most useful information to aid in the interpretation of the structural feature. The models do not in all cases produce a magnetic anomaly closely fitting the observed anomaly. However, despite the actual fit of the calculated and observed magnetic profiles, the models were helpful in the final interpretation of the tectonic and structural features in eastern Lake Superior.

Each magnetic model, Figures 23-29, was plotted with a horizontal scale of one inch equal to eight miles. The vertical exaggeration was four times the horizontal scale. A rough estimate of the thickness of the clastics and the depth to the underlying basement complex can be obtained from the models. The reliability of these estimates, however, is poor because the models were constructed with the assumption that in all cases the basement complex underlying the clastics is composed of volcanic rock. This may be particularly significant where the magnetic anomalies reach a negative amplitude. Another factor limiting the reliability of the depth estimates is the unknown effect of the remanent magnetization in many parts of the Lake Superior trough.

Magnetic Model Along Profile A-B

Profile A-B strikes approximately north-south across magnetic Anomaly C, Figure 22. The magnetic model, Figure 23, is based on the known geology of the northern portion of the Keweenaw Peninsula and generates a calculated magnetic profile comparable to the observed anomaly. The model corroborates the presence of the Keweenaw thrust fault and the basic volcanics known to outcrop in this area. A comparison of the fit between the calculated and observed

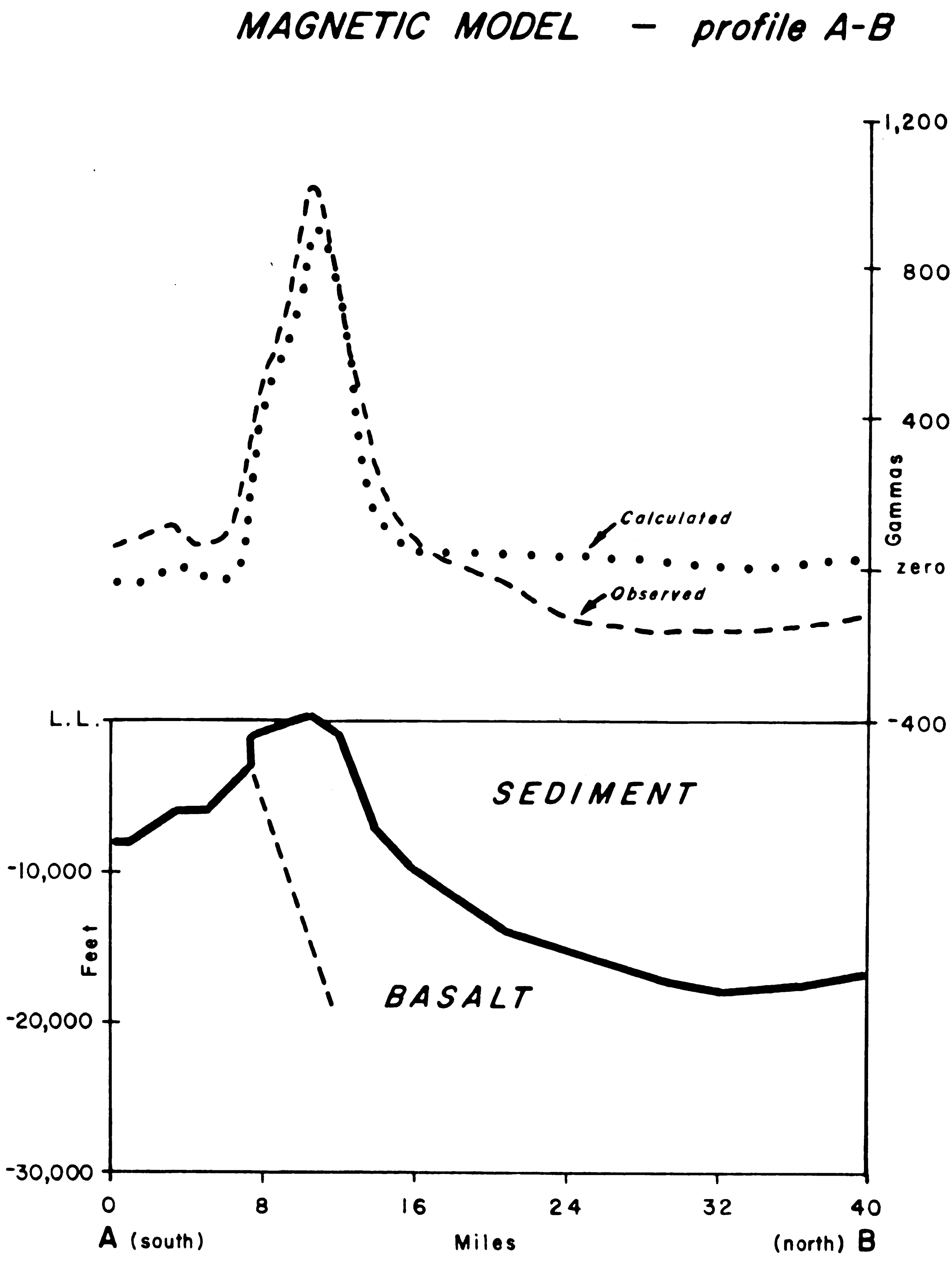


Figure 23.--Magnetic model along profile A-B.

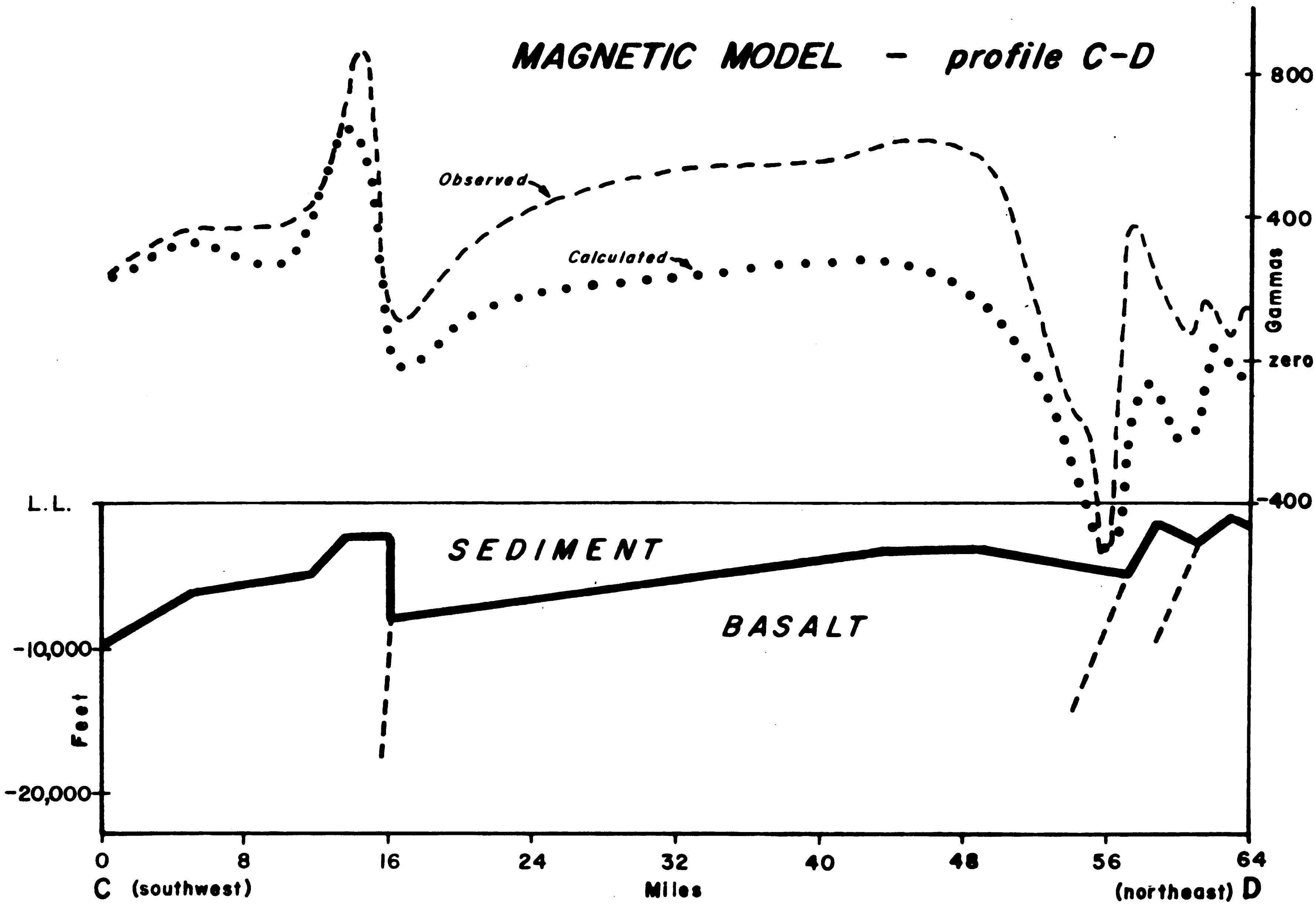


Figure 24.--Magnetic model along profile C-D.

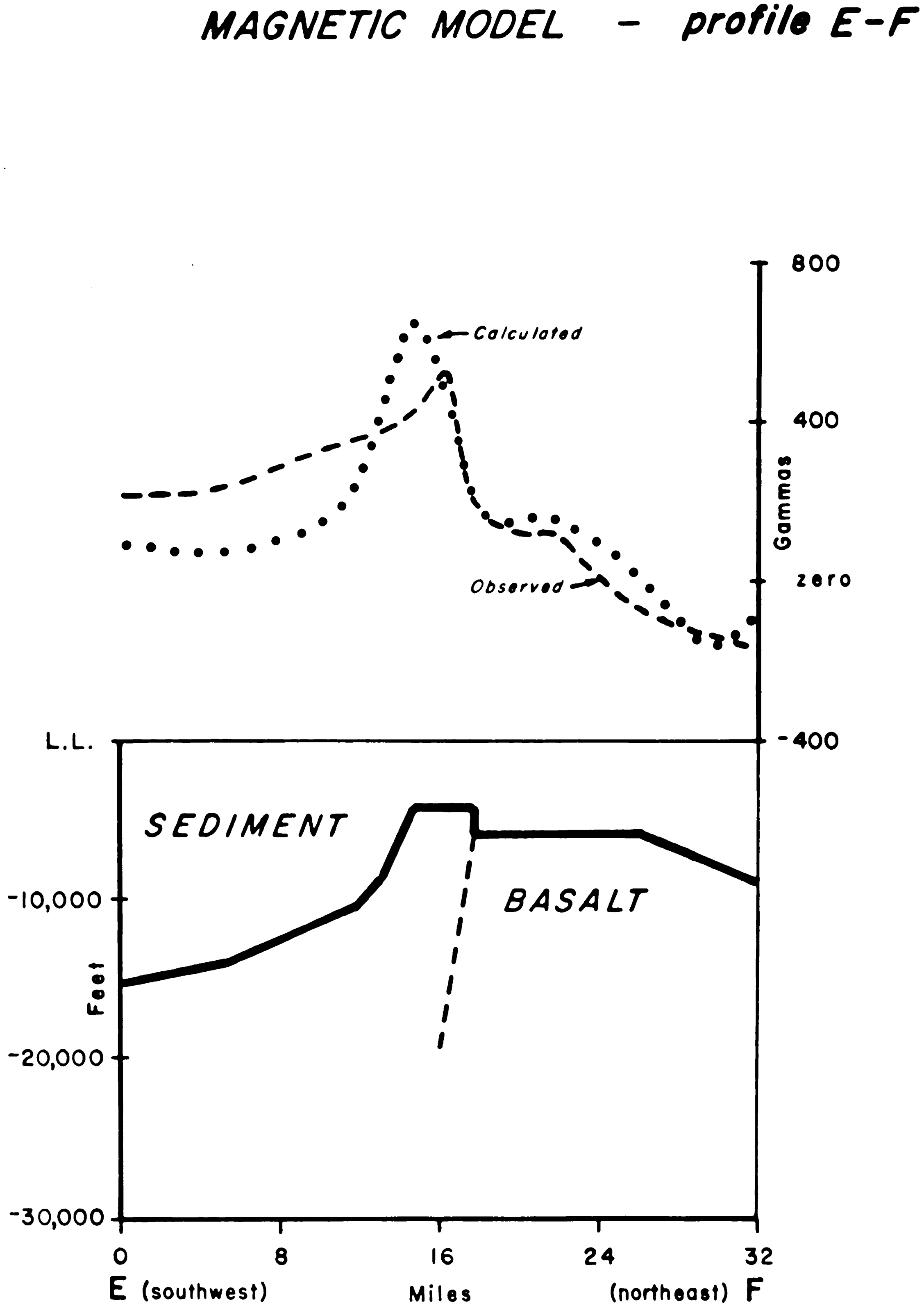


Figure 25.--Magnetic model along profile E-F.

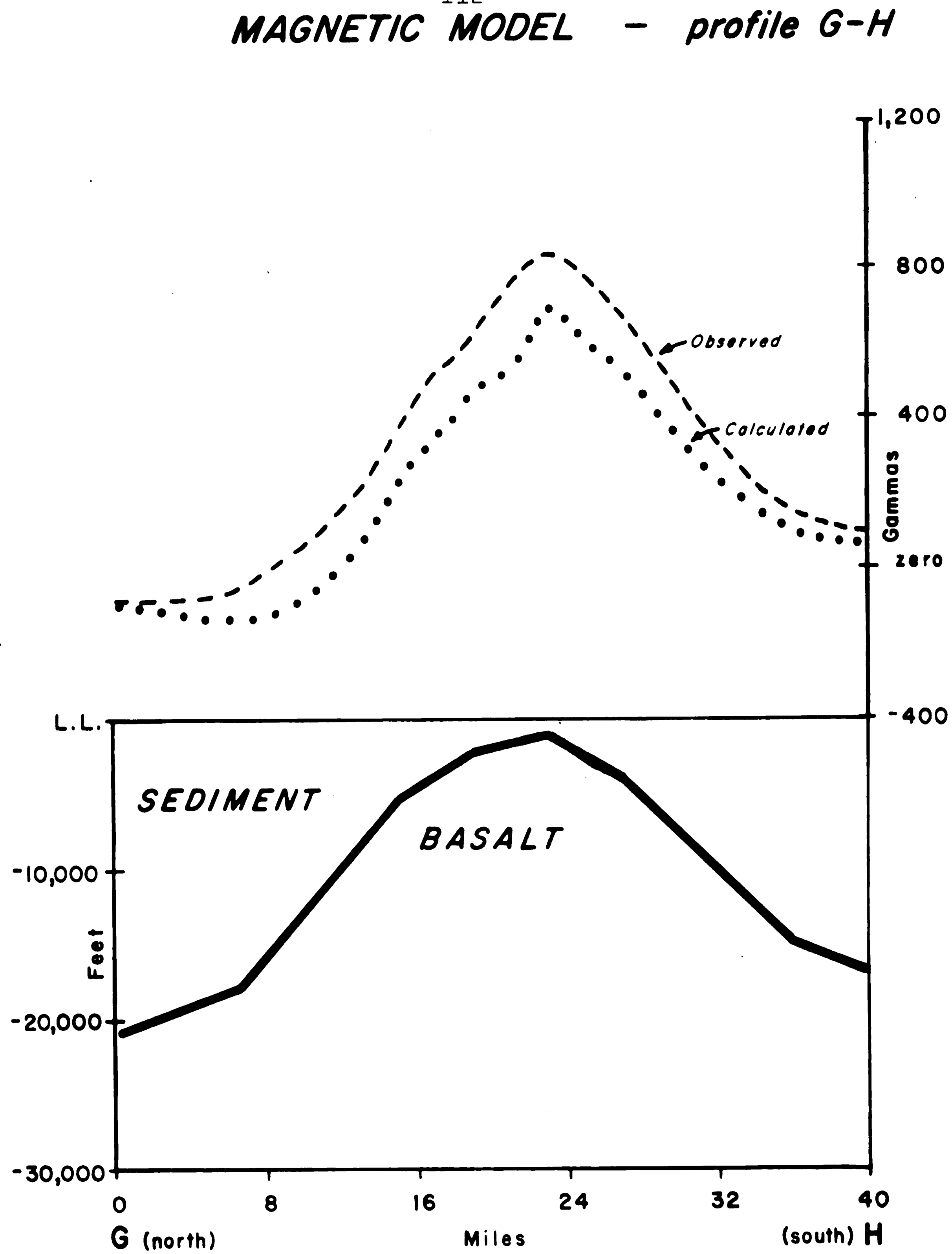


Figure 26.--Magnetic model along profile G-H.

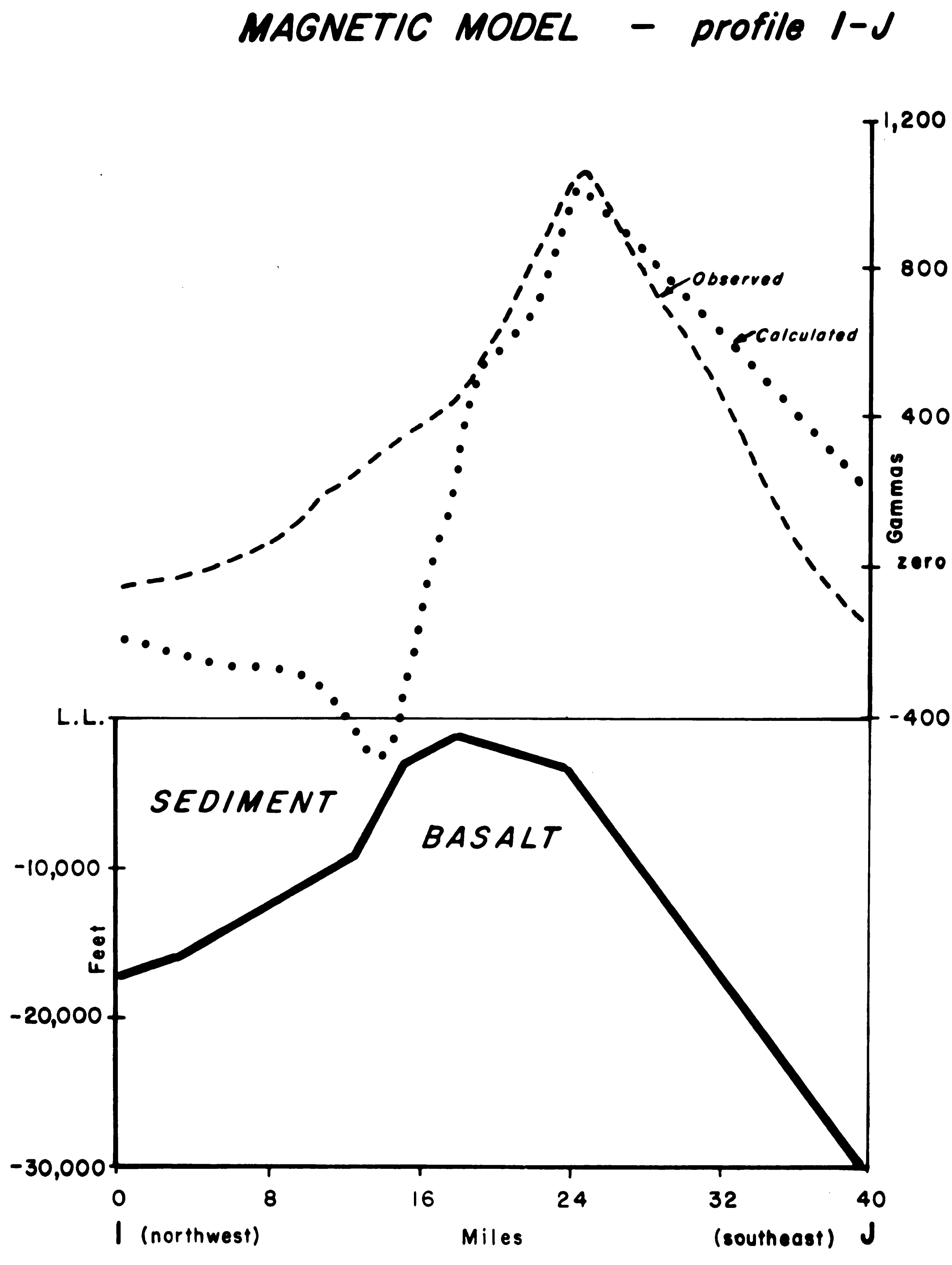


Figure 27.--Magnetic model along profile I-J.

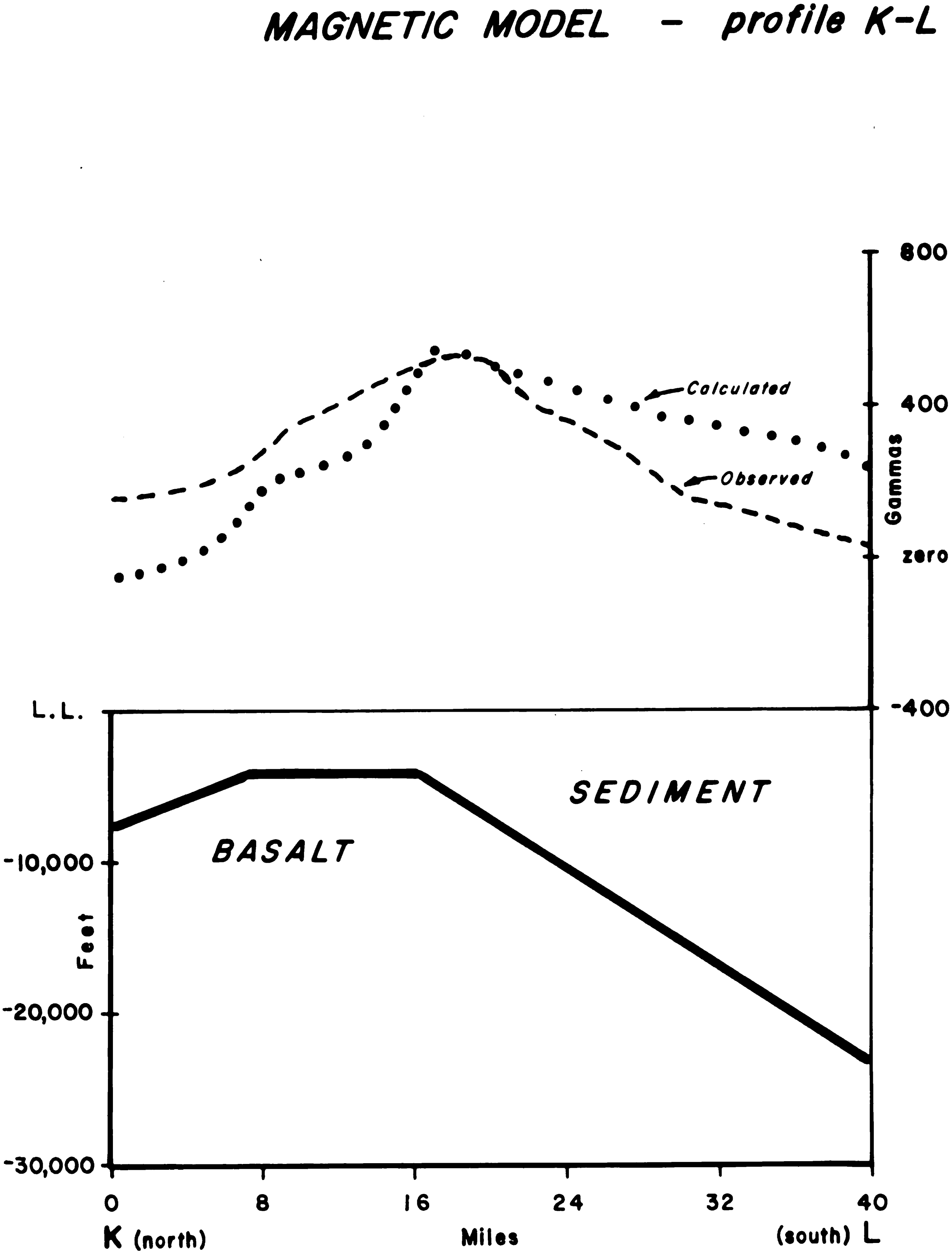


Figure 28.--Magnetic model along profile K-L.

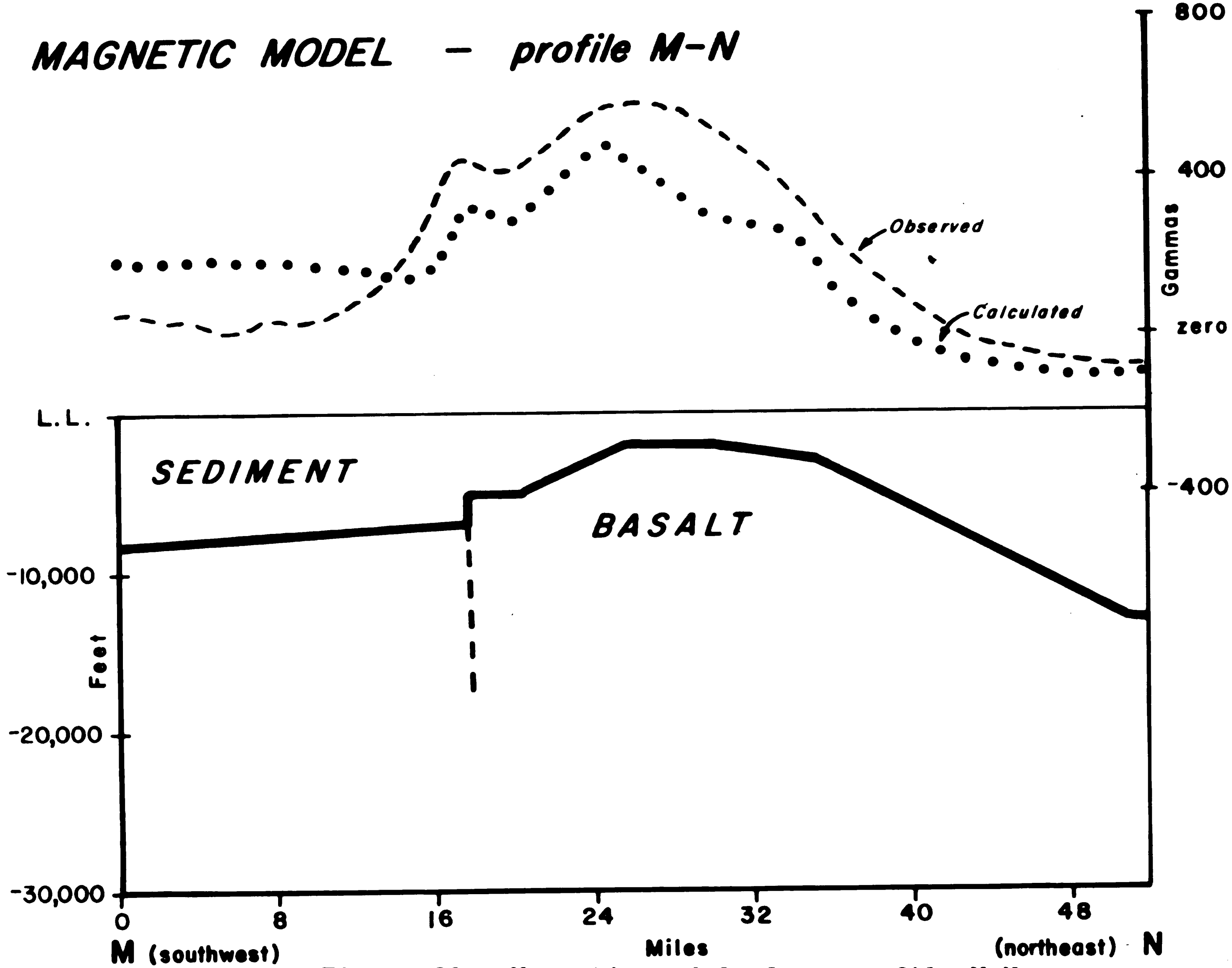


Figure 29.--Magnetic model along profile M-N.

anomalies indicates that the bedrock beneath Keweenaw Bay may lie closer to the surface than illustrated by the model. It further indicates that if volcanics are present beneath Keweenaw Bay they may be irregularly distributed and tilted as a result of faulting and that the Keweenawan clastics increase in thickness toward the south. The model also indicates an increasing thickness of clastics to the north of the Keweenaw Peninsula. Toward the center of the lake the observed anomaly has a lower amplitude than the calculated anomaly, suggesting a thicker accumulation of clastics in this area than illustrated by the model. It may also indicate that the volcanics are pinching out beneath the sediments.

Magnetic Model Along Profile C-D

Profile C-D strikes approximately northeast-southwest across magnetic Anomalies E and G. Figure 22. The amplitude of the calculated anomaly over this model, Figure 24, is consistently lower than the observed anomaly. This was true for all the models produced along this profile regardless of how close to the surface the model was constructed. The lower magnetic amplitude of the calculated anomaly is attributed to an incorrect estimation of the remanent magnetization of the underlying bedrock. Another reason for this phenomenon which cannot be ruled out at this time is that possibly the correction for the earth's normal magnetic variation has been incorrectly calculated in this area.

The model does indicate, however, that the basic volcanics and the associated Isle Royale thrust fault extend eastward toward Superior Shoal and that the upthrown side of the fault is to the south. The volcanics appear to have a relatively low southward dip for a limited distance toward the center of the lake. They then appear to plunge more steeply toward the axis of the trough indicating an increased thickening of the overlying Keweenawan clastics. To the north in the vicinity of Anomaly G the volcanics are close to the surface. A normal fault and possibly a pinching out of the volcanics is indicated near the northern shore of the lake.

Magnetic Model Along Profile E-F

This magnetic model, Figure 25, represents the structural configuration of the rocks beneath Anomaly F along profile E-F, Figure 22, which has a general northeast-southwest strike. Upthrusting of the volcanics is indicated in the center of the model. A comparison of the calculated and observed anomalies supports this interpretation. Although the fit of the two anomalies is not good toward the southwest, some conclusions can nevertheless be drawn about this feature. The dip of the volcanics toward the southwest is probably much less inclined than illustrated in the model. Therefore, the thickness of the Keweenawan clastics also is much less than indicated. This explanation may account for both the steeper gradient and higher amplitude of the calculated anomaly.

To the northeast a normal fault or an erosional pinch-out of the volcanics or both are indicated by the model. In either case this area represents the eastern-most extension of the volcanics in the northeastern portion of Lake Superior.

Magnetic Model Along Profile G-H

Profile G-H strikes generally north-south through Anomaly H, Figure 22. The calculated anomaly over this magnetic model, Figure 26, is lower in amplitude than the observed anomaly. The close proximity of the model to the surface again suggests that the lower amplitude is the result of an error in the estimated remanent magnetization of the underlying rocks. The model supports the interpretation that Keweenawan volcanics are the source of the observed magnetic anomaly. Although it is not clearly indicated in the model, faulting may exist to the north and south along either side of the volcanics. The trace of the magnetic profiles collected over this anomaly closely parallel these suspected east-west striking faults. The poor magnetic gradients which result make the detection of faulting difficult. The depth to which the basement complex appears to dip on both sides of this structure indicates that the volcanics are buried by vast accumulations of clastics. Also the volcanics may pinch out beneath these sediments.

Magnetic Model Along Profile I-J

Profile I-J strikes approximately northwest-southeast across Anomaly J, Figure 22. The fit between the calculated and observed anomalies over this model, Figure 27, is poor. However, some indications may be observed about the structure producing this anomaly. Along the southeastern side the dip of the volcanics is considerably steeper than indicated by the model, suggesting the presence of a normal fault with the downthrown side to the southeast. On the northwestern side the calculated and observed anomalies again have little in common, indicating that the volcanics have a much more shallow dip then illustrated by the model. Along the northwestern margin the volcanics appear to dip beneath a thick accumulation of clastics.

Magnetic Model Along Profile K-L

Profile K-L across Anomaly I, Figure 22, has a general north-south strike. The relationship between the calculated and observed anomalies over this magnetic model, Figure 28, is similar to that produced over the model along profile I-J. Although the fit between the observed and calculated anomalies is again poor, the same general conclusions can be obtained. The dip of the volcanics is steeper to the south than indicated by the model. This steep dip and the great depth to which the volcanics appear to extend suggests that normal faulting has occurred with the downthrown side to the south. To the north the volcanics dip less steeply beneath the overlying clastics than is illustrated by the model.

Magnetic Model Along Profile M-N

Profile M-N strikes generally northeast-southwest across Anomaly D, Figure 22. The magnetic model, Figure 29, has been constructed to show a fault along the western margin. Although the shape of the calculated anomaly does not closely fit the observed anomaly to the southwest beneath Keweenaw Bay, the general shape of the two curves appear to support the interpretation that a fault with some vertical displacement may be present. The higher amplitude of the calculated anomaly beneath Keweenaw Bay suggests that the volcanics, if present, dip more steeply to the southwest or pinch out beneath thicker accumulations of clastics than the model indicates.

The consistently lower amplitude of the calculated anomaly over the model to the northeast may again indicate an error in the estimation of the remanent magnetization.

Sublacustrine Bottom Topography

Procedure

In this section the bottom topography of eastern Lake Superior is considered. The structural implications previously drawn from the topographic features are reviewed and the prominent features are compared with the magnetic data for possible correlation. The various studies on the origin of the deep valleys in eastern Lake Superior and northern Lake Michigan also are summarized.

Previous Studies

Thwaites (1935) prepared the first topographic map of the Lake Superior basin. From this map and the known geology of the Lake Superior region, he attempted to interpret its structure. Figure 30 shows this structural interpretation illustrated with cross-sections.

Parker (1964) has recently prepared a more detailed map of eastern Lake Superior from the additional data provided over the years by the U.S. Lake Survey. From this map, the known geology, and samples collected in scattered portions of the lake, Parker also has attempted to interpret the structure of eastern Lake Superior, Figure 31.

Thwaites recognizes the possible southeastward extension of the Keweenaw fault and the eastward extension of the Isle Royale thrust fault. He further suggests that a fault extends along a line striking northeastward from east of the Keweenaw Peninsula to the vicinity of Superior Shoal and that the eastern and western parts of Lake Superior form two separate structural features. Parker also postulates a northeastward striking fault in this same vicinity. However, he extends the fault southward east of the Keweenaw Peninsula to the north shore of the Northern Peninsula of Michigan.

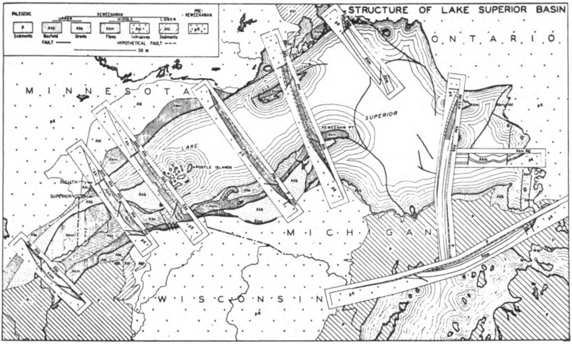


Figure 30.--Lake Superior structural map (according to Thwaites, 1935).

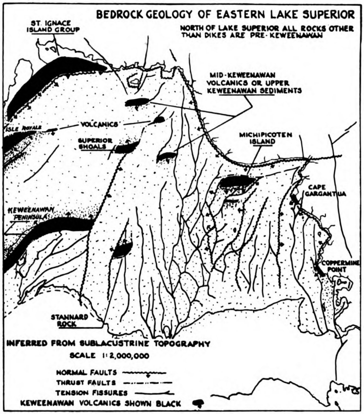


Figure 31.--Bedrock geology of eastern Lake Superior (according to Parker, 1964).

Thwaites and Parker both recognize the sharp drop in elevation that exists along much of the northern and eastern margin of the lake. Thwaites attributes this elevation difference to both faulting and an erosional dip slope of the volcanics while Parker suggests only normal faulting. The steep escarpments along the east and west sides of Michipicoten Island are attributed, by Parker, to normal faulting. A thrust fault also is recognized along the north side of the island.

Parker has suggested numerous "tension" fissures having a north-south strike throughout the eastern portion of Lake Superior. The location of several volcanic rocks observed within the lake also are represented on Parker's map. These include the volcanics from Stannard Rock, Superior Shoal, three areas lying north and to the east of Superior Shoal, and those on Michipicoten Island. He has suggested thrust faulting between Superior Shoal and the volcanics indicated to the northeast. To the west of Stannard Rock a normal fault has been indicated with a north-south strike.

The numerous north-south striking fissures and faults indicated by both Parker and Thwaites are based primarily on the deep valleys present in eastern Lake Superior. Some of these valleys are more than 600 feet from rim to floor with a width of two to four miles. Zumberge and Gast (1961) have analyzed six cores obtained in western Lake Superior and report 40 to 60 feet of lacustrine sediment overlying a red glacial till. From "sparker" and "boomer" surveys conducted by the University of Wisconsin, the thickness of this till has been determined to be, in many cases, several hundred feet (Wold, personal communication). Parker (1964) states that no great vertical displacement occurs across these valleys.

Relationship Between Aeromagnetic Data and Bottom Topography

Recently the bathymetric map compiled by Parker for eastern Lake Superior has been integrated with the bathymetric data of the U.S. Lake Survey to produce an accurate representation of the Lake Superior bottom topography (Farrand and Zumberge, 1966). By referring to the eastern portion of this map, Figure 32, and the Magnetic Anomaly Map, Figure 22, many correlations can be seen. Examples are listed below:

1. A ridge on the topographic map extending north-northeastward from the Keweenaw Peninsula, closely approximates a line along which Anomalies C, E, and G terminate and Anomaly A appears to narrow. This ridge clearly divides the Lake Superior basin.
2. The northeastward striking ridge in the vicinity of Superior Shoal, represented on the topographic map, shows some correlation with the northeast striking small positive anomaly in this area.

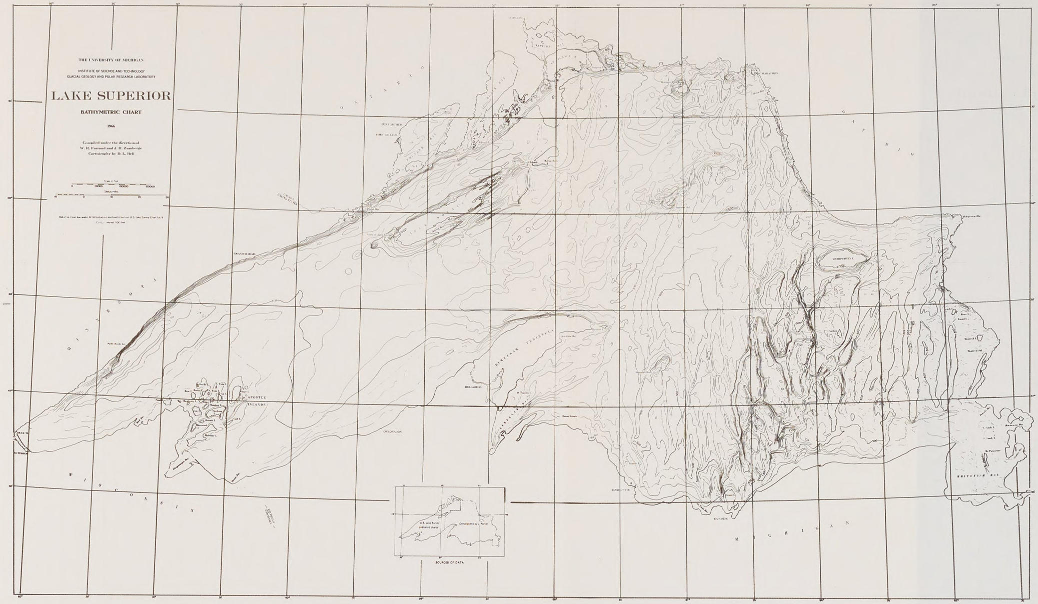


Figure 32.--Lake Superior bottom topography map.

3. The north-south lineation of the ridges and valleys shown on the topographic map compare with the general north-south trending magnetic anomalies.
4. The valley to the east of Keweenaw Point is comparable to the position of the magnetic low separating Anomalies C and D.
5. The northeastward strike of the eastern portion of Anomaly A is comparable to the general topographic trends shown in the Superior Shoal area on the topographic map.

Previous Views on the Origin of the Lake Superior Bottom Topography

Parker (1964) attributes the origin of the deep valleys in eastern Lake Superior to glacial modification of the structural bedrock features. He further believes "that all the topographic evidence suggests that the sublacustrine valleys, and most of Lake Superior, owe their present form principally to erosion by Pleistocene ice sheets."

Thwaites (1935) suggests that the valleys beneath eastern Lake Superior are a result of uneven glacial scouring of the underlying Paleozoic evaporities during the Pleistocene. Hough (1958) also has attributed the valleys, at least in northern Lake Michigan, to a similar origin.

Zumberge,(1964) from a review of the literature, believes that in addition to stream and glacial erosion and damming by glacial drift that recent downfaulting of the entire basin may be involved. He suggested that if this is so, the valleys could have been eroded by streams above sea level.

The above views on the origin of the Lake Superior bottom topography all suggest modification of the bedrock as a result of glacial activity. In most cases it is implied that these topographic features reflect structural trends in the underlying bedrock.

Review of the Results of Pertinent Geological and Geophysical Investigations

The Lake Superior trough was considered by Hotchkiss (1923) to be the result of a collapsed roof of an intrusive body. Thwaites (1935) considered it "an 'inner lowland' similar to several others in the Great Lakes region except that it extends back into the highlands of pre-Cambrian rocks." Although for many years the lake trough was suspected to be a geosynclinal feature, more recently its origin has been associated with that of the "mid-continent gravity high." As a result there is a growing belief that this structure may be due to rifting.

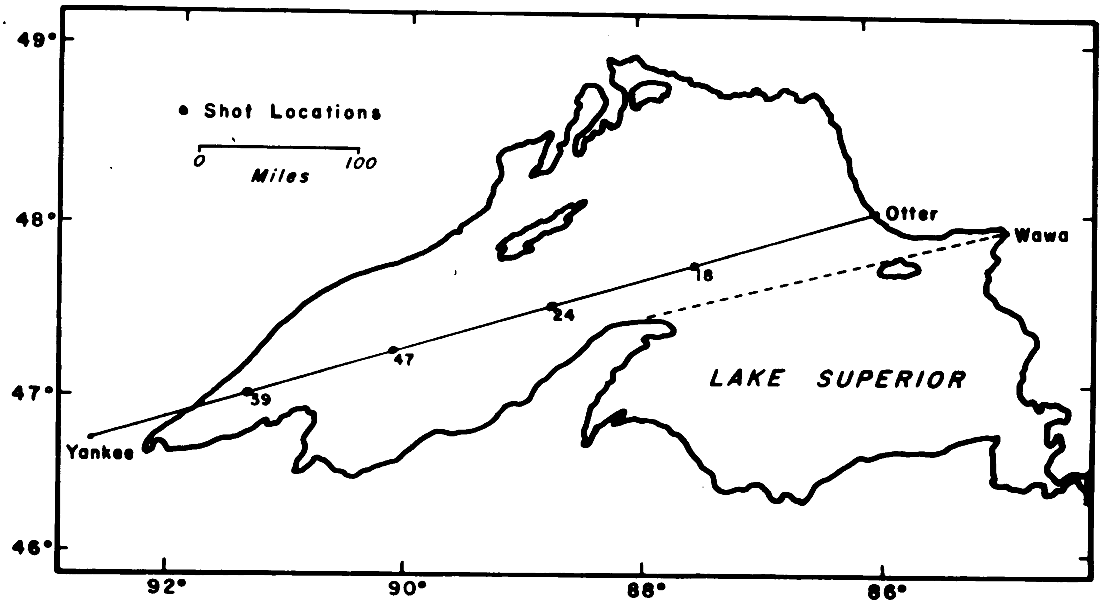
For years it has been known that a vast accumulation of Keweenawan volcanics and sediments exist in the Lake Superior region. Van Hise and Leith (1911) estimate the thickness of the middle Keweenawan volcanics in northern Wisconsin and Michigan to range from 30,000 to 60,000 feet. Thwaites (1912) estimates the thickness of the upper

Keweenawan sediments to be at least 25,000 feet in northern Michigan and Wisconsin. In the Delaware quadrangle on the Keweenaw Peninsula the middle Keweenawan volcanics are known to be 15,000 feet thick (Cornwall, 1954) and to be overlain by an additional 15,000 feet of upper Keweenawan sediments. Based upon the down-dip extrapolation of these rocks, White (1966a) has estimated the thickness of the Keweenawan volcanics and sediments beneath Lake Superior to be between 35,000 and 50,000 feet.

Thiel (1956) has attempted to correlate the low Bouguer gravity values obtained on the Bayfield Peninsula with the thick accumulations of upper Keweenawan sediments. Thiel also correlated the high gravity values obtained over the "mid-continent gravity high" in Douglas County, Wisconsin with thick accumulations of middle Keweenawan volcanics. From his interpretations Thiel states, "The correlation of gravity and geology . . . is striking. The positive anomalies occur over the dense basic rocks, either basaltic lava flows or gabbro. The negative anomaly over the Bayfield Peninsula is associated with the downwarped Lake Superior syncline which has been filled with low-density sandstones and shales of the upper Keweenawan." Thiel also attempted to quantitatively determine the thickness of the volcanics producing the "mid-continent gravity high" in Douglas County. In his calculations Thiel assumes that the lava mass has a density of 2.90 gm/cc and that the pre-Keweenawan rocks have a uniform density of 2.67 gm/cc. From his calculations these volcanics were estimated to be 33,000 feet thick.

A seismic investigation of Lake Superior has been conducted as a part of the United States and Canadian programs in the Upper Mantle Project (Smith, et al., 1966). The results of this study indicate that a high-velocity crust (6.67 km/sec) exists beneath 4 to 6 km of Keweenawan sediments and volcanics. The depth of the M discontinuity was found to vary from about 20 km in the area just west of the lake to 55 km or more in eastern Lake Superior. From this seismic study the hypothesis of Van Hise and Leith (1911) that Lake Superior is a compressional feature of Precambrian tectonics has been questioned. Smith, et al. (1966) have suggested instead that Lake Superior may be a tensional feature. They attribute the high seismic velocities to the intrusion of basic material derived from the underlying mantle. The results of this investigation are illustrated in Figure 33.

The Bouguer Gravity Map of the Lake Superior Region, Figure 34, has been compiled by Weber and Goodacre (1966) from available data and the gravity survey conducted by the Dominion Observatory of Canada. On this map a broad trend can be observed to extend southeastward across the eastern portion of the lake, reaching a low of minus 40 milligals south of Michipicoten Island. Other gravity anomalies of the same amplitude can be observed in the Superior Shoal



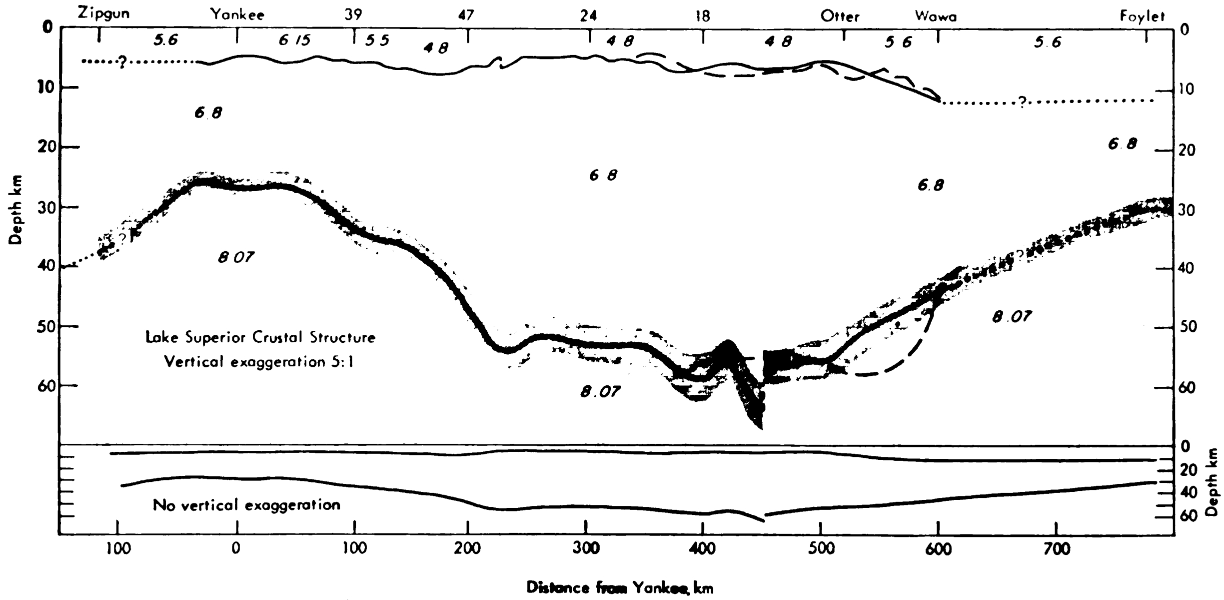


Figure 33.--Seismic profile across Lake Superior (after Steinhart, <u>et al.</u>, 1966).

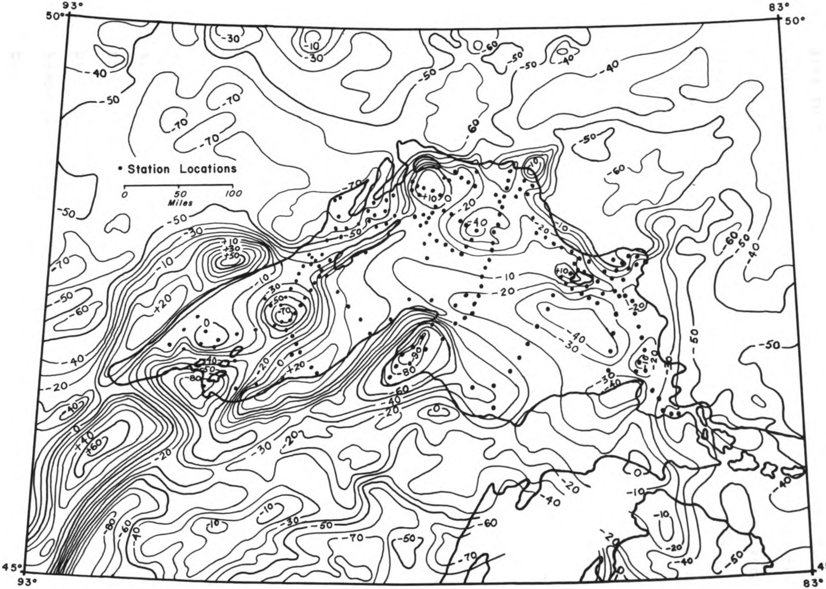


Figure 34.--General Bouguer gravity map of the Lake Superior region (after Weber and Goodacre, 1966).

area to the northwest and the Whitefish Point area to the south. A distinct gravity low also is centered over the Keweenaw Bay area. Relative gravity highs are indicated over the area south of Isle St. Ignace, the northeast corner of Lake Superior, Michipicoten Island, and the south-eastern portion of the Northern Peninsula of Michigan. A relatively low gravity high also can be observed to extend southeastward from the tip of the Keweenaw Peninsula.

Although the Bouguer gravity data illustrated in Figure 34 has been incorporated into the structural interpretation of eastern Lake Superior, it should be noted that the stations are sparcely spaced throughout much of the area. For this reason the data is used only as a first order approximation.

Weber and Goodacre (1966), in their investigation of Lake Superior, have conducted model studies based upon the crustal thicknesses determined from seismic evidence. From these studies they have concluded that the normal crustal rocks beneath Lake Superior have been largely replaced by dense basic material. They further state that, "The abrupt changes in structure required to explain the gravity field are consistent with the hypothesis of crustal rifting during the development of Lake Superior." They also conclude that positive Bouguer anomalies generally occur over the middle Keweenawan basic flows and that the negative anomalies prevail over the upper Keweenawan and Cambrian sediments and Archean granitic rocks. The relatively higher positive gravity anomalies are interpreted to indicate the presence of basic material underlying most of the lake. They further state that,"Although low-density sedimentary rocks and/or massive granitic rocks may suitably account for the negative gravity field, there still remains the uncertainty about how much of the anomaly may be due to deepseated effects."

In contrast to the most recent hypothesis that crustal rifting is responsible for the development of Lake Superior, White (1966b) states, "Thicknesses and lithofacies of the Keweenawan rocks suggest that the basin was formed primarily by downwarp of the crust, either by loading when mafic lavas were extruded in great volume, or by crustal compression."

Major Structural and Tectonic Features

Procedure

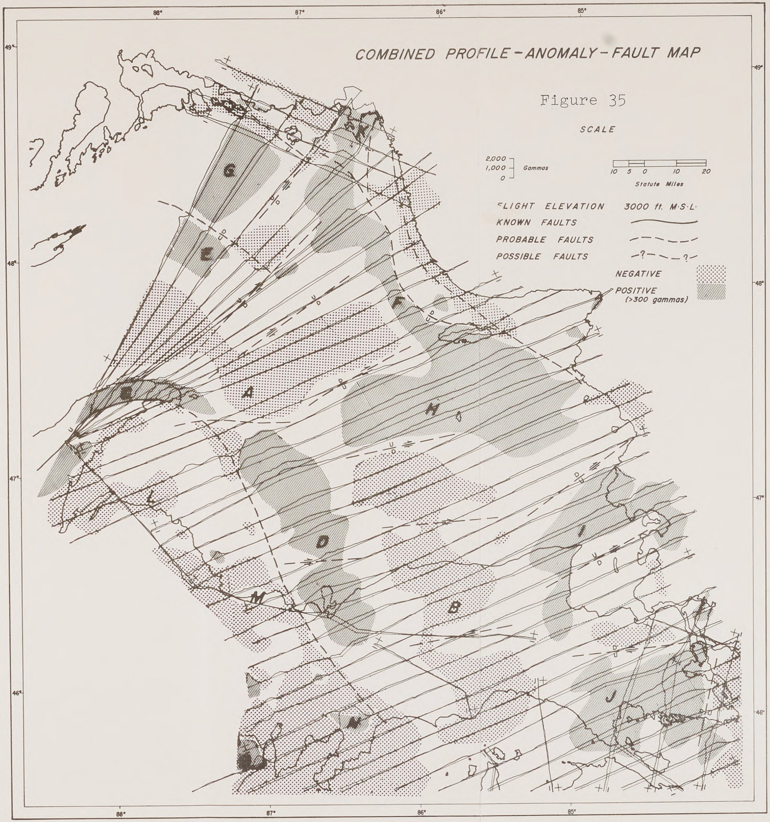
In this section an attempt is made to interpret the Precambrian framework and tectonic structure of eastern Lake Superior and the eastern portion of the Northern Peninsula of Michigan. Structurally significant and magnetically identifiable features in eastern Lake Superior are related to each other and to their tectonic movements. Pertinent geological and physiographical observations are integrated with the aeromagnetic, gravity, and seismic data.

The central portion of the lake producing the negative magnetic anomalies is considered first. The axis of the

Lake Superior trough is traced by this magnetic minimum from western Lake Superior through the Northern Peninsula of Michigan. A number of transverse features also are noted. The differences which appear to exist between the eastern and western parts of the lake are mentioned next. The region separating the two halves of Lake Superior is then discussed, along with the structural and tectonic features extending into this region from the west. The southwestern portion of the study area, including the Keweenaw Bay area, is examined next and related to the structures previously analyzed. The tectonic and structural features along the northeastern and southeastern margin of Lake Superior are compared and related to the rest of the trough. Finally, the eastern part of the Northern Peninsula of Michigan is considered with the southeastern margin of the lake.

To help illustrate the structural features and tectonic movement within the area of investigation two summary maps have been compiled. One map, the Combined Anomaly-Profile-Fault Map, Figure 35, illustrates the major residual magnetic anomalies overlayed on the Residual Total Magnetic Intensity Profile Map. The trace of the major faults referred to in this section also are shown in Figure 35.

The second summary map referred to in this section is the Geologic Cross-section Map of Eastern Lake Superior, Figure 41. Qualitative cross-sections have been drawn across seven of the more significant magnetic anomalies.


COMBINED PROFILE - ANOMALY - FAULT MAP
SCALE
2,000
1,000
0
Gammas
10 5 0 10 20
Statute Miles
FLIGHT ELEVATION 3000 ft. M·S·L·
KNOWN FAULTS
PROBABLE FAULTS
POSSIBLE FAULTS
NEGATIVE
POSITIVE (>300 gammas)
88°
87°
86°
85°
49°
48°
47°
46°
A
B
D
E
F
G
H
I
J
K
L
M
N
Figure 35

The cross-sections are located along the same lines illustrated in the magnetic model studies. Although all available geological and geophysical data have been referred to in constructing them, they are primarily based on the model studies, Figures 23-29. The geologic bedrock surrounding eastern Lake Superior also is shown in Figure 41.

Central Portion of the Eastern Lake Superior Trough

The magnetic minimums, Anomalies A and B, Figure 35, are interpreted to indicate relatively thick accumulations of upper Keweenawan sedimentary rock. Anomaly A is the eastern extension of the magnetic low which can be traced to the Bayfield Peninsula in western Lake Superior, Figure 36. Wold (1966) suggests that this broad negative anomaly indicates the axis of the Lake Superior "syncline" through the western portion of the lake. The exact thickness of the clastics beneath the magnetic minimum cannot be accurately predicted at this time. Also, it is not possible to determine the thickness of the middle Keweenawan volcanics generally believed to underly the clastic sediments. Although the down-dip extrapolation of the volcanics on the Keweenaw Peninsula appears to indicate thick accumulations of extrusives beneath the sediments, no geophysical or direct geological evidence actually confirms their existence. The main reason for this uncertainty is that the density and composition of the underlying crustal rock is not accurately

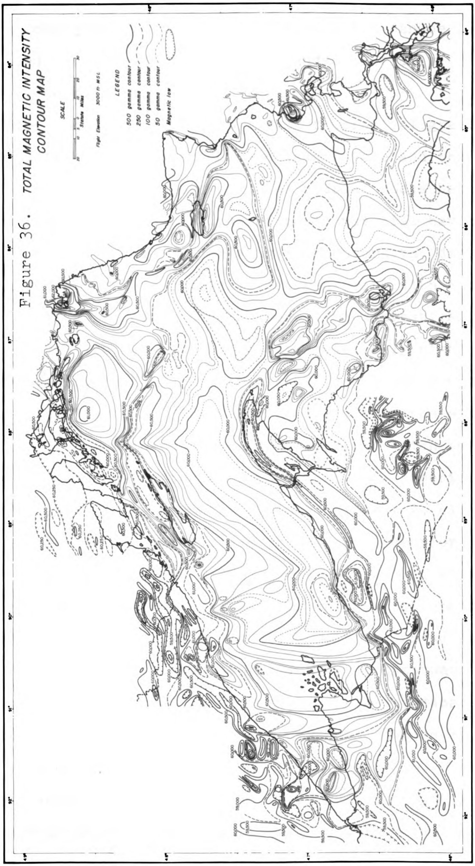

TOTAL MAGNETIC INTENSITY
CONTOUR MAP
SCALE
Statute Miles
Flight Elevation 3000 ft. M.S.L.
LEGEND
500 gamma contour
250 gamma contour
100 gamma contour
50 gamma contour
Magnetic low

Figure 36.

known. Consequently, the gravity effect which can be attributed to the clastic sediments and/or extrusive flows cannot be determined.

Weber and Goodacre (1966), from theoretical gravity model studies of the crust between Isle Royale and the Keweenaw Peninsula, suggest that the crustal rocks beneath this region are composed mainly of basic material having a density of 2.97 g/cc. The relatively high crustal density value appears to be isostatically commensurate with the crustal thickness determined in the seismic investigations reported by Smith, et al.(1966). The relatively high Bouguer gravity feature, referred to by Weber and Goodacre (1966) as the "Keweenaw High," Figure 34, may be the eastward extension of the "mid-continent gravity high" which extends from central Kansas to the western tip of Lake Superior.

The axis of the magnetic minimum, Anomaly A, closely parallels the form-line contours of the Lake Superior trough prepared by Irving (1883) and White (1957), Figure 37. However, these form-lines representing the general configuration of the trough depict a more southeasterly trend to the east of Keweenaw Point than shown by the northeastward striking magnetic anomaly. Hamblin (1965) also prepared form-lines from sediment dispersal patterns, Figure 38, which show a change in curvature in the eastern part to a more east-west alignment closely resembling the strike of the magnetic anomaly. It should be noted, however, that

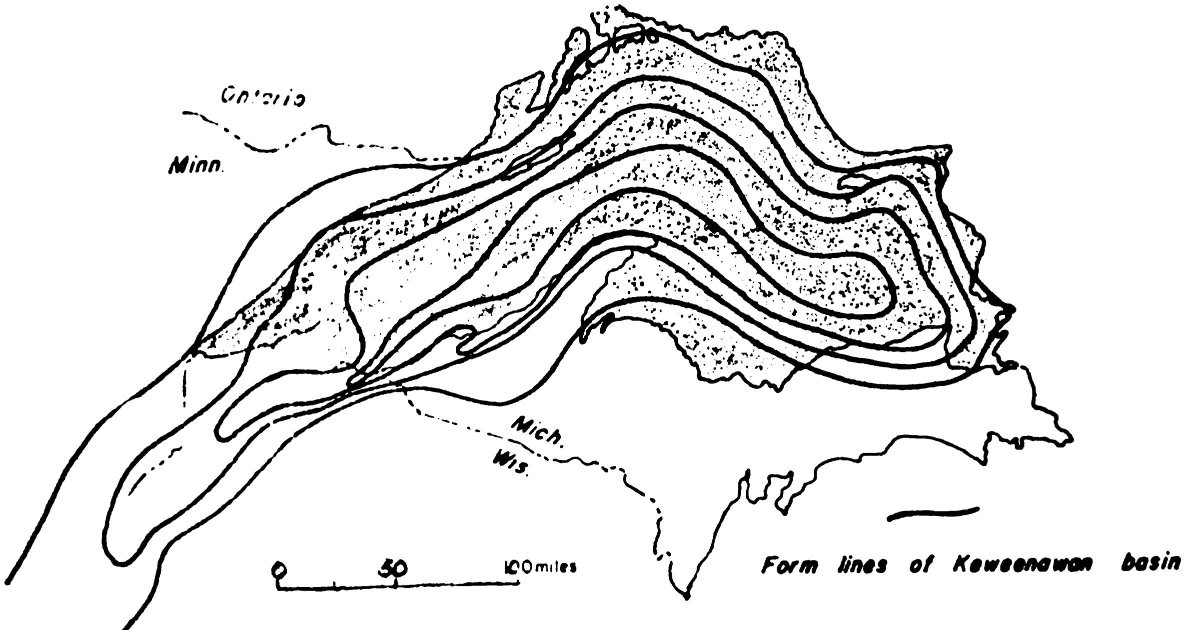


Figure 37.--Configuration of Keweenawan trough based on stratigraphic thickness (according to Irving, 1883).

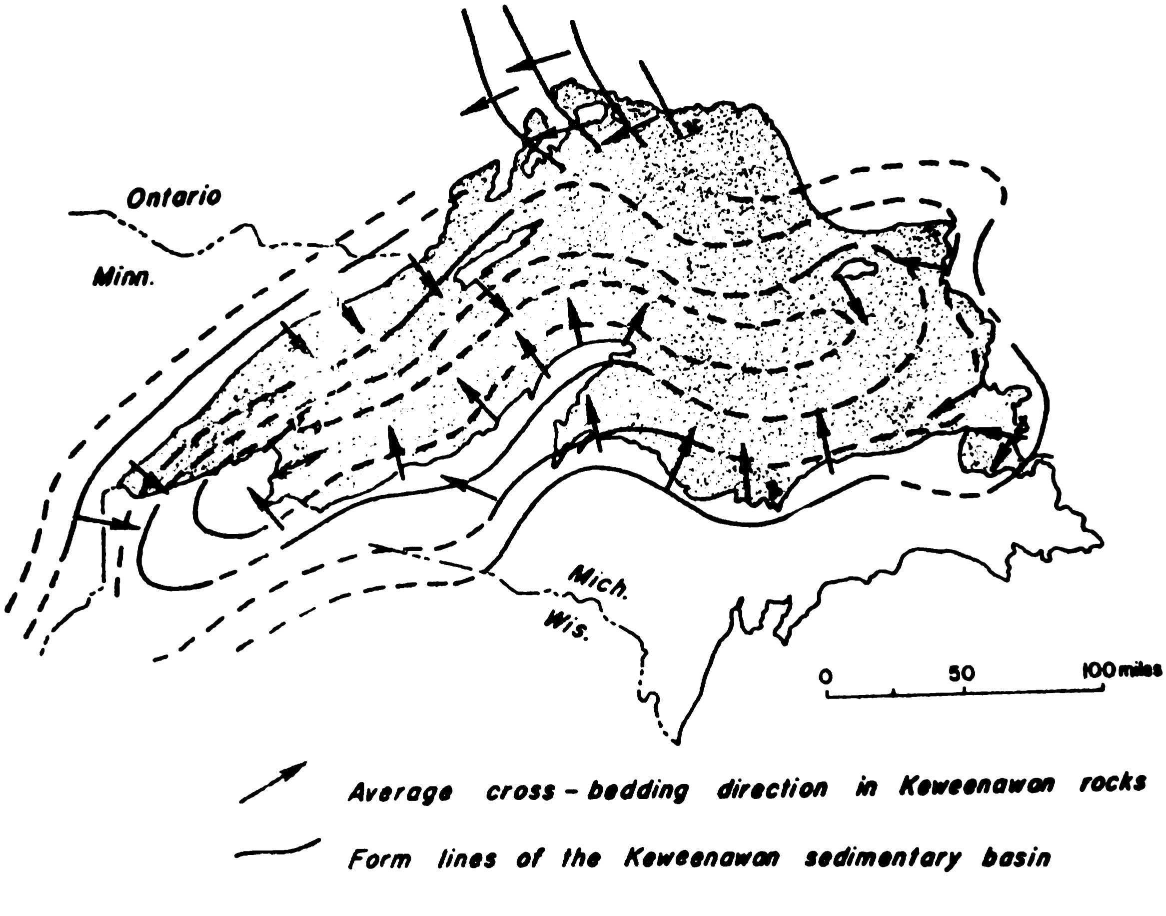


Figure 38.--Configuration of Keweenawan trough based on sediment dispersal patterns (according to Hamblin, 1965).

the eastern portion of the anomaly is located north of the axis of Hamblin's form-lines.

Although Anomalies A and B are separated by a northeasterly striking positive magnetic anomaly, they are interpreted to represent similar structural features. Originally these structural features may have been continuous. Anomaly B, therefore, is interpreted to represent the southeastern extension of the axial tract of the Lake Superior trough.

Irving (1883) suggested that the trough extends into the Whitefish Bay area. On the basis of geological evidence, Thwaites (1935) extended the trough into the eastern portion of the Northern Peninsula. Hamblin (1965) shows middle and upper Keweenawan sediment dispersal patterns on the eastern shore of Lake Superior pointed toward the Northern Peninsula which substantiates this conclusion. However, on the basis of sediment dispersal patterns in the Jacobsville sediments (considered as upper most Keweenawan in this study) Hamblin concludes that the direction of sediment transport was to the north on the southern shore of Lake Superior during this period. This indicates that the eastern portion of the Northern Peninsula of Michigan was a highland during Jacobsville time either as a result of uplift by faulting or arching of the Northern Peninsula or by differential sinking of the region beneath eastern Lake Superior.

The southward extension of the magnetic minimum across the eastern portion of the Northern Peninsula suggests that the Lake Superior through may have originally extended farther south into the Southern Peninsula of Michigan. From the Bouguer Gravity Map, Figure 39, and the Vertical Magnetic Intensity Map, Figure 40, of the Southern Peninsula (Hinze, 1963), the axis of the Lake Superior trough may be observed to extend southward from the Straits of Mackinaw to the center of the Southern Peninsula and then southeastward toward Lake St. Clair. However, in the Southern Peninsula of Michigan the axis of the trough is represented by a high gravity anomaly and a high magnetic anomaly, both of which separate lower anomalies. This relationship is opposite to that observed beneath eastern Lake Superior where low gravity and magnetic anomalies separate two higher anomolous features. The relationship of the gravity results in the Southern Peninsula more closely resemble the results along the "mid-continent gravity high" and from western Lake Superior than the results observed from eastern Lake Superior. The relationship of the magnetic results in the Southern Peninsula also more closely resemble those along the "mid-continent gravity high" than the results observed over both eastern and western Lake Superior.

Numerous transverse structural and tectonic features, striking perpendicular to the general axial trend of the Lake Superior trough, can be observed from the aeromagnetic data. Topographic and geologic features within and adjacent to eastern Lake Superior indicate transverse structures. Traverse faulting may be indicated by what appears to be a

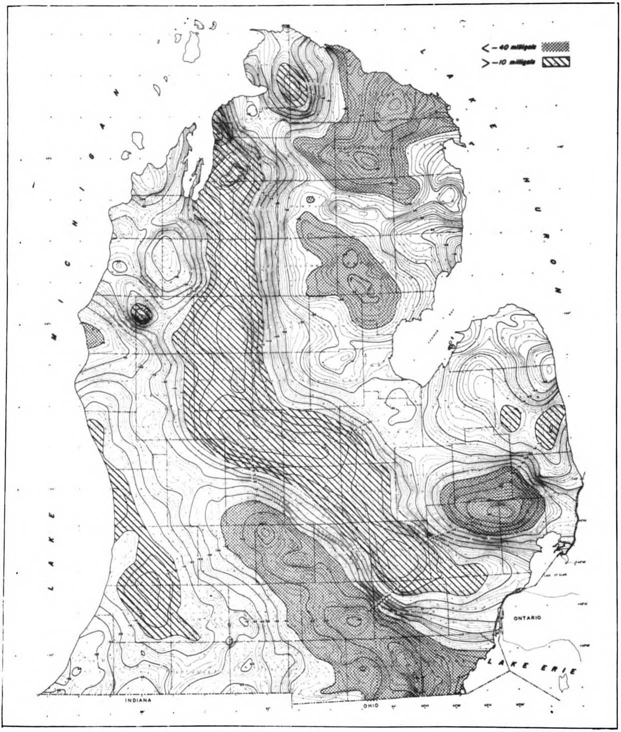


Figure 39.--Bouguer gravity map of the Southern Peninsula of Michigan (after Hinze, 1963).

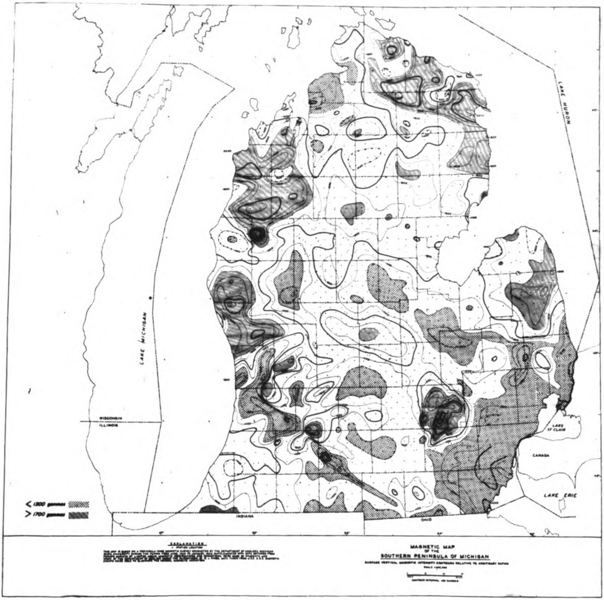


Figure 40.--Vertical magnetic intensity map of the Southern Peninsula of Michigan (after Hinze, 1963).

southern offset of the eastern portion of Anomaly A and the apparent pinching of the isogams outlining this anomaly to the northeast of Keweenaw Point. The pinched appearance of the isogams of Anomaly B in two places are interpreted to indicate transverse faulting parallel to the north shore of the Northern Peninsula of Michigan. To the east of the lake the general northeastward trend of many dikes and faults from Michipicoten Bay south to Sault Ste. Marie, Michigan indicates a fault system at right angles to the long axis of eastern Lake Superior. Corroborating evidence for the interpretation that transverse faults exist beneath southeastern Lake Superior comes from a recent "sparker" profile obtained by the University of Wisconsin. This profile, made along one of the deepest north-south trending valleys, indicated that numerous faults striking roughly east-west are present in the area (Wold, personal communication).

The presence and orientation of the positive magnetic Anomaly H separating Anomalies A and B and the nearly parallel orientation of the eastern portion of Anomaly A further exemplify the transverse nature of the structural features.

From the above indications of transverse tectonic activities the central portion of eastern Lake Superior is interpreted to be a series of tilted blocks. The faults producing these blocks strike roughly perpendicular to the axis of the lake trough. The tilted blocks appear to have produced a basin and range type structure. A similar series of tilted blocks, or horsts and grabens are indicated along the eastern margin of the lake, and along Anomaly D. The nearly east-west striking transverse faults along Anomaly B appear to be offset from the transverse faults along the structural features paralleling Anomaly E. This suggests that right-lateral slippage may parallel the axis of the trough and Anomalies B and D. The deep valleys located in southeastern Lake Superior also may reflect this north-northwestward faulting.

Differences Between the Eastern and Western Portions of the Lake Superior Trough

Thwaites (1935) suggested, on the basis of the Lake Superior bottom topography, that the eastern and western portions of the lake were structurally different and that the two basins were divided by a topographic ridge which can be observed to strike northeastward across the lake from the eastern tip of the Keweenaw Peninsula, Figure 32. The recent seismic data of Smith, et al. (1966) tends to confirm this hypothesis. From Figure 33 it can be observed that the greatest depth to the mantle is located between the eastern and western portions of the lake. The thickness of the crust is about 55 km, making it the thickest crustal section in North America. A fault can be seen to extend into the mantle in this same area. The seismic velocities for the region of the crust just below the P_1 time-term depths are determined to be 6.64 ± 0.01 km/sec in the western half of the Lake and 6.69 ± 0.02 km/sec in the eastern half.

The gravity survey conducted by Weber and Goodacre (1966) also tends to suggest that the two portions of the lake are structurally different. The decreasing amplitude of the Bouguer gravity anomaly toward the southeast in the eastern part of the lake, Figure 34, considered with the higher seismic velocity, suggests that the upper Keweenawan clastics beneath the central portion of southeastern Lake Superior may be much thicker than the sediments between Isle Royale and the Keweenaw Peninsula. However, it also may indicate a thinner sequence of middle Keweenawan extrusives beneath southeastern Lake Superior.

Further evidence that the eastern and western portion of the lake may differ structurally can be observed from the aeromagnetic data. In western Lake Superior the magnetic anomalies, Figure 36, appear to be more continuous parallel to the axis of the lake trough than they are in the eastern portion of the lake. This indicates that while both eastern and western Lake Superior have developed continuous structural features parallel to the axis of the Lake Superior trough, the eastern portion of the lake also has developed perpendicular structures.

Other differences between the two halves of the lake trough are indicated by the geological evidence. The greater transverse width of eastern Lake Superior and the presence of prominent thrust faults in western Lake Superior suggests that the western portion of the lake trough was originally subjected to greater downwarping which eventually resulted in greater isostatic adjustment and uplifting.

Region Separating Eastern from Western Lake Superior

In the area separating eastern from western Lake Superior the general trend of the Keweenaw Peninsula changes. The Keweenaw thrust fault extending the length of the peninsula forms the southern margin of the Portage Lake volcanics and interbedded clastics which are overlain by the Copper Harbor conglomerate. These rock units dip steeply to the north in the northern part of the peninsula. Uplifting along the thrust fault brings them into juxtaposition with younger Keweenawan clastics to the south. Like the Keweenaw Peninsula, the trend of the volcanics and associated fault changes from northeast to southeast as they continue eastward. From Anomalies C and D, Figure 35, the volcanics may be separated by faulting to the east of the peninsula.

The volcanics on Isle Royale and the associated thrust fault to the north trend generally northeastward and dip gently to the southeast. To the east, in a manner similar to the Keweenaw fault and volcanics, the trend of the Isle Royale fault and volcanics curves toward the southeast where it appears to either abruptly terminate or change strike toward the northeast near Superior Shoal, as shown by the positive Anomaly E. The positive Anomaly G to the north also reflects a similar change in the trend of the volcanics and normal fault producing this magnetic feature.

The apparent termination of the volcanics and the associated faults indicate that traverse faulting perpendicular to the axis of the Lake Superior trough has taken place from the general area of Asburton Bay and the Slate Islands to a point just east of the Keweenaw Peninsula, Figure 35. The higher magnetic amplitude producing the narrowing of Anomaly A indicates that the basement complex just west of the fault is not so deeply buried by clastic sediments, and that the upthrown side is to the west in this area.

The lower Bouguer gravity anomaly, Figure 34, and low magnetic anomaly to the north of the Isle Royal fault immediately west of the transverse fault suggest that the basement rocks are more deeply buried by clastic sediments. From the above indications it appears that the northern portion of the trough has been stretched parallel to the axis of the trough producing a graben or tilted block structure which suggests that the transverse faults are tensional features. The same condition appears to exist between Anomalies C and D to the east of the Keweenaw Peninsula and beneath the Keweenaw Bay. The relatively high magnetic and gravity anomalies, across the central portion of the fault in the area where Anomaly A narrows to the west of the fault, reflect the eastward extension of the "Keweenaw High" referred to by Weber and Goodacre (1966). The Isle Royale fault may cut across this main transverse fault in the Superior Shoal area and then strike northeastward, Figure 35.

From the seismic data obtained by Smith, et al. (1966) a fault is indicated to extend into the mantle near Superior Shoal, Figure 33. The location of this deep fault closely corresponds to the transverse fault zone interpreted from the aeromagnetic data. The seismic results, however, have been interpreted to indicate that the downthrown side is to the west of the fault in this area rather than to the east as indicated by the aeromagnetic data. If this seismic interpretation is correct it may be a further indication that the western part of the lake trough was subjected to more compressive downwarping than the eastern portion. Greater compression of the trough on the western side of the transverse faults found in this area may have caused proportionately greater isostatic adjustment. This may have resulted in greater uplifting of the western trough and explain the abrupt termination of the Keweenaw and Isle Royale thrust faults along the zone of cross faults. It also may explain why the seismic velocities in the upper crustal layers are lower in the western portion of the lake trough. Possibly this greater compressional downwarping inhibited the intrusion of basic material into the upper crustal layers more than in the eastern portion of the trough, resulting in slightly lower rock velocities.

Southwestern Portion of the Eastern Lake Superior Trough

It is suggested that a fault exists along the western margin of magnetic Anomaly D, Figure 35. This fault may be an eastward extension of the Keweenaw thrust fault. Right-lateral slippage may be present along this fault. It is also suggested that the fault continues southeastward across the Northern Peninsula of Michigan. Some vertical displacement along the fault is indicated from the magnetic model study, Figure 29. Although the structural feature represented by Anomaly D can be observed on the Bouguer Gravity Map, Figure 34, no faulting is indicated from the gravity data. However, geological evidence can be found on the northern shore of the Northern Peninsula of Michigan in the area of Au Train Bay and Grand Island. Oetking (1951) reports minor thrust faults in the Jacobsville sandstone on the eastern side of Laughing Fish Point, Au Train Island and in the southeastern corner of Au Train Bay. Patenaude (1964) also points out that a nearly vertical fault of unknown displacement striking N 70° W on Au Train Island may be a continuation of the Keweenaw fault. The suggestion that the Keweenaw fault extends into this area was first made by Thwaites, (1935) on the basis of bottom topographic studies. Although evidence is weak, the faulting in the Au Train Bay area appears to extend to the southwest, where small scale faulting near Seul Choix Point has been found along the projection of a northwestward trending anticline developed in Silurian dolomite (Patenaude, 1964).

The position and characteristics of Anomaly D strongly suggest that its source is a continuation of the basic volcanics on the Keweenaw Peninsula. If Anomaly D does represent volcanic rock, the flow appears to have an eastward dip. Irving (1883) suggests that felsite taken from Stannard Rock is from the same horizon as the Mount Houghton felsite of Keweenaw Point.

The separation of Anomalies C and D may be a result of faulting along the transverse fault indicated in Figure 35. The magnetic minimum between these two anomalies could reflect either thick accumulations of clastic sediment or an absence of the volcanics, or an alteration of the magnetic to a non-magnetic mineral along the fault zone.

The abrupt termination of Anomaly C and the irregular bottom topography of Keweenaw Bay, Figure 32, suggests that a branch of the transverse fault may continue through one or more of the deep valleys beneath the bay. Faulting parallel to the deep valleys is suggested in the magnetic model, Figure 23.

There is little magnetic or gravity evidence that volcanics extend to the west of Anomaly D beneath Keweenaw Bay. The negative Bouguer gravity anomaly over the bay. indicates a thick deposit of clastic sediments in this area. These data may be partially explained by thinning of or complete absence of the volcanics. The qualitative geological cross-sections through Anomaly D and the Keweenaw Peninsula,

Figure 41, illustrate one possible structural configuration for this region.

On the Northern Peninsula of Michigan the magnetic data suggest that the volcanics are at best very thin and probably missing to the west and that the upper Keweenawan sandstones are thinner than under the lake. It should also be noted that Anomaly D has a rather discontinuous configuration which closely corresponds to that observed for Anomaly B. The discontinuous configuration of these anomalies indicates that faults, trending nearly east-west, may exist parallel to the north shore of the Northern Peninsula.

Northeastern Portion of the Lake Superior Trough

Situated in the northeastern corner of Lake Superior in the vicinity of Marathon, Ontario is the Port Coldwell Complex which is responsible for Anomaly K, Figure 35. From aeromagnetic data, Lilley (1964), has interpreted this feature as an inverted intrusive cone approximately 2.5 miles deep with an associated feeder pipe. From the results of this survey, however, it can be observed that the anomaly extends a considerable distance into Lake Superior where it merges with the anomaly associated with the northwest-southeast trending volcanics. Therefore, the Port Coldwell complex is elliptical, having a north-south orientation, rather than circular in cross-section. This intrusive feature consists of olivine gabbro, augite syenite, and alkali-rich rocks.

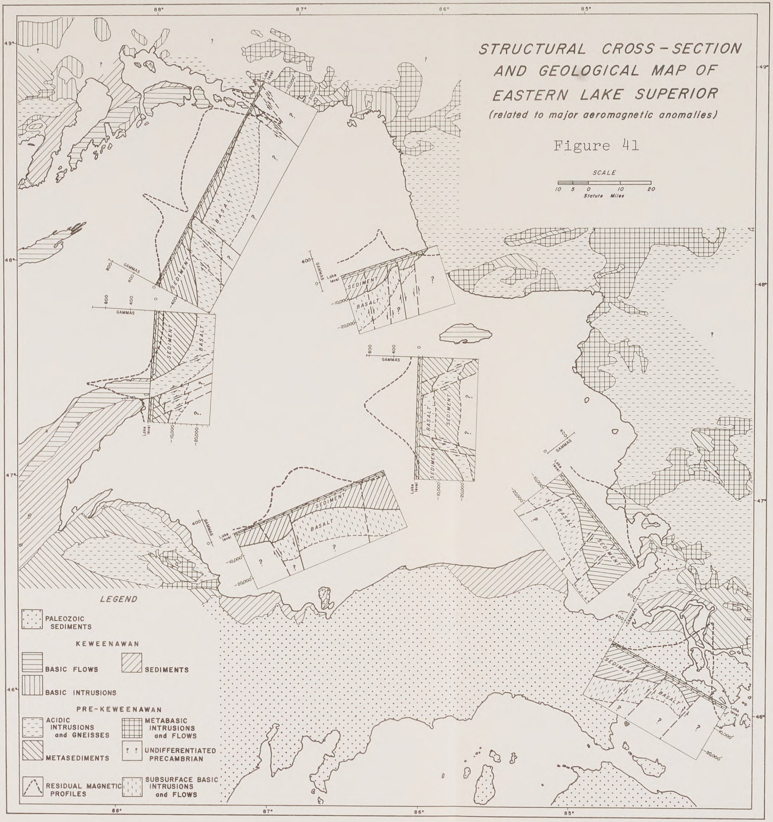

STRUCTURAL CROSS-SECTION AND GEOLOGICAL MAP OF EASTERN LAKE SUPERIOR
(related to major aeromagnetic anomalies)
SCALE
10 5 0 10 20
Statute Miles
LEGEND
PALEOZOIC SEDIMENTS
KEWEENAWAN
BASIC FLOWS
SEDIMENTS
BASIC INTRUSIONS
PRE-KEWEENAWAN
ACIDIC INTRUSIONS and GNEISSES
METABASIC INTRUSIONS and FLOWS
METASEDIMENTS
UNDIFFERENTIATED PRECAMBRIAN
RESIDUAL MAGNETIC PROFILES
SUBSURFACE BASIC INTRUSIONS and FLOWS
SEDIMENT
BASALT
GAMMAS
Lake level
88°
87°
86°
85°
49°
48°
47°
46°

Figure 41

A thrust fault is believed to be present on the eastern side of the volcanics, represented by Anomaly F, Figure 35. The fault may extend northward along the eastern margin of the Port Coldwell complex, or it may swing to the south of the intrusive feature and extend westward toward the normal fault associated with Anomaly G. If the fault extends westward it may be interrupted by the transverse fault zone extending southward toward the Keweenaw Peninsula.

To the south the Anomaly F fault merges with the thrust fault on the northern side of Michipicoten Island. The aeromagnetic data indicate that this fault extends southeastward, almost to Gargantua Harbor, Figure 35. The magnetic minimum between the thrust fault and the northeastern shore represents the pinching out of the volcanics and probably also a normal fault. A qualitative geological cross section with a general northeast-southwest strike has been attempted through this structural feature, Figure 41. The cross section located to the northwest of Michipicoten Island is primarily based on the magnetic model, Figure 25.

Although a gravity high appears to coincide with the magnetic positive over Michipicoten Island, no geological or gravity data reflect the existence of the structure producing the magnetic Anomaly H. The lower amplitudes of the gravity anomaly over this feature and the poor indications of faulting provided by the aeromagnetic data to the south and north of the anomaly suggest that this transverse feature may be a result of differential sinking of the basins on either side. It is suggested that the source of the magnetic anomaly is a thin sequence of flows overlying a thicker accumulation of possibly lower Keweenawan clastic sediments and/or less dense pre-Keweenawan rocks.

The above interpretation for the structural feature producing Anomaly H has been qualitatively illustrated in Figure 41. Faulting may or may not exist to the north and south of this feature. The lack of magnetic gradient control, to help in determining the possibility of faulting, is a result of the flight line pattern.

The negative magnetic anomalies to the north and south of Anomaly H have been interpreted to indicate thicker accumulations of sediment which collected in deeper basins to either side of a transverse "arch." In western Lake Superior a similar structural feature may exist. From the Bouguer Gravity Map, Figure 34, and the Total Magnetic Intensity Contour Map, Figure 36, a transverse "arch" striking roughly perpendicular to the Lake Superior trough can be observed in the vicinity east of the Apostle Islands. Distinct basins appear to have developed to either side of this structure. Similar transverse "arches" also may be responsible for the separation of the uplifted elongated grabens located along the "mid-continent gravity high." The eastern portion of the Northern Peninsula of Michigan may be another transverse "arch" separating the Lake Superior trough from the elongated structural trough extending through the Southern Peninsula of Michigan.

An explanation for the series of discontinuous basins or elongated grabens extending the length of the "mid-continent gravity high," through the Lake Superior trough, and southeastward into the Southern Peninsula of Michigan, may possibly be found by attributing them to the curvature of the earth's surface. Holmes (1965) attributes the discontinuous basins observed in the western portion of the East African Rift Valley System to this origin in the following manner: by considering an arc of 3 degrees, which represents a length of 207 miles on an undeformed surface, it can be seen that a straight line (chord) joining the two ends of the arc will be shorter than the arc itself. Thus, a difference in height of 7,167 feet at the middle of the arc, above the straight line, will be present. Therefore, if a rift block 207 miles long subsides along the arc, it will be thrown into compression along its length which will produce transverse arches of great amplitude.

Southeastern Margin of the Lake Superior Trough

The basic Keweenawan volcanics found along the southeastern margin of the lake have a limited distribution. The most important of the basic flows are located in the Mamainse Point area and to the south of Sault Ste. Marie, Michigan. The thickness of the volcanic sequence and interbedded sediments on Mamainse Point is over 12,000 feet. The flows have an average dip of 30° toward the basin (Thompson, 1953). The limited distribution of this sequence is indicated by Anomaly I, Figure 35. Normal transverse faulting probably exists along the northwestern and southeastern margins of the anomaly. The suggested faults have produced a series of horsts and grabens similar to the series of tilted blocks previously discussed for the center of the lake. The serated configuration of the eastern shoreline of the lake strongly indicates wrench faulting which has produced normal faults along the shoreline. The flat character of the magnetics over Michipicoten, Agawa, and Whitefish Bays contrasts with the positive anomalies between the bays. This may indicate that the volcanics are more deeply buried beneath the bays as a result of differential downfaulting during the development of the wrench faults along the eastern shoreline.

The Bouguer Gravity Map, Figure 34, shows a minimum over Whitefish Point which suggests that the volcanics producing magnate Anomaly I thin to the southwest or become more deeply buried by sediments.

The volcanics associated with Anomaly J, Figure 35, to the south of Sault Ste. Marie are interpreted to have an origin similar to the volcanics on Mamainse Point. The faulting in this area appears to have a more north-south orientation to the southeast than the transverse faults to the north.

Patenaude (1964) interprets the magnetic maximum associated with the volcanics to the south of Sault Ste.

Marie to be faulted on the northern side by a north-south striking fault which extends southward into Lake Huron with the upthrown side to the west. This interpretation is based on an associated 8 mgal positive Bouguer gravity anomaly. He also suggests that an east-west trending negative gravity anomaly to the north may be indicative of an east-west trending fault system.

Based on the geological, gravity, and magnetic models, Figures 27 and 28, qualitative geological cross-sections have been attempted to illustrate the structure of the volcanic features along the southeastern margin of the lake, Figure 41.

Origin and Tectonic Development of the "Lake Superior Rift System"

Extent of Tectonic Development

From the combined geological, topographical and geophysical evidence, the eastern Lake Superior region constitutes a key segment of a major geologic feature. Extending from central Kansas this structural system may be traced along the "mid-continent gravity high," through the Lake Superior trough, and southeastward into the Southern Peninsula of Michigan.

Two Major Hypotheses

Most of the geologists and geophysicists presently working on various segments of this structural feature attribute its origin and development to one of two hypotheses. The first hypothesis, according to White (1966b), suggests "that the basin was formed primarily by downwarp of the crust, either by loading when mafic lavas were extruded in great volume, or by crustal compression."

The second and recently more favored hypothesis suggests that crustal rifting has taken place during the accumulation of the flood basalts and sediments presently filling the trough. Smith, et al. (1966) conclude from their seismic profile across Lake Superior that the thick crust beneath the lake resulted from isostatic adjustment to the high-density basic material which appears to have intruded the crustal rocks.

Both hypotheses can be supported to a limited degree. The belief that crustal downwarping has resulted from vast accumulations of basalt and clastic rock is strongly supported by the geological evidence. This evidence indicates that the lake trough has been filled with lava and sediment.

The suggestion that compressional forces are responsible for downwarping of the crust appears to be supported by the upthrusting of numerous major faults such as the Keweenaw and Isle Royale faults. Supposedly, the thrusting resulted from a relaxation of the compressional forces after the flood basalts and clastic sediments accumulated.

The high density of the crustal material beneath the lake is attributed to intrusions of dense mantle rock along tensional fissures developed in the lower crust through downwarping. The main disadvantage of this suggestion is that tension developed in the lower part of the crust would produce compression in the upper crust and stop the extrusion of basalt along the fissures. Therefore, crustal downwarping which suggests compressional forces, does not appear to be compatible with the extrusion of basaltic material which indicates that tensional forces are involved. White has attempted to explain the crustal intrusions and downwarping by suggesting that they are the result of crustal undulations. Although this suggestion would explain the downwarping and possibly the intrusion of magma into the lower crust, it does not provide an explanation for the passageways necessary for the magma to reach the surface. The passageways would have to be formed beneath the lake trough because geological evidence has indicated that the lavas came from the immediate area and not an adjacent region.

The second hypothesis suggesting crustal tension also is discussed by White (1966b). In this discussion he considers three models illustrating two possible origins for the Lake Superior trough. The first two models suggest an origin in which a graben or half-graben has been produced by normal faulting. White's major criticism of the rift models is that the Keweenaw and related faults could not have been the boundary faults of a graben system. Aside from the fact that they are thrust faults, the volcanic origin of pebbles in the conglomerate beds on the Keweenaw Peninsula indicate that the edge of the lava flows lie far to the south. White points out that if the thrust faults also were the boundary faults, a narrow belt of fanglomerate would be expected along their margins similar to the ones occurring along the Triassic boundary faults of eastern United States. Also the trend of the Keweenaw fault varies greatly in some areas to the marginal trend of the trough. Although convincing geological evidence appears to support the view that the Keweenaw and related faults could not have been the boundary faults of a graben system, other boundary faults not as yet recognized may be present to the north and/or south.

White dismisses the formation of grabens and half-grabens as an explanation for the origin of the lake trough mainly because they do not appear to explain the later uplifting of the central part of the basin relative to the margins along the Keweenaw and Douglas faults.

The above disadvantages of attributing the origin of the lake trough to rifting apply to all rifts in which graben structures form. When the lake trough is compared to the East African Rift Valley System, as illustrated in White's model, or to uplifting which can result from vertical tectonics, a more serious disadvantage can be suggested. Uplifting of the crust produces normal faulting along which basic material may move upward along the marginal faults. The amount of basic material which moves upward beneath the rift in this manner is debatable. Once the boundary faults break through the crust and the "Keystone" block subsides compression is produced and the passageways along the faults become closed. The East African rifts, which are believed to have developed in this way as a result of uplifting, produce gravity minimums which do not suggest the intrusion of dense basic material into the upper crust. The relatively small amount of volcanic material found within these rift valleys also indicates little upward movement of magma beneath the graben. It should be noted that the graben-type rifting discussed above refers to rifting produced by vertical tectonics and not by crustal separation resulting from horizontal movements.

The fairly uniform thickening of the stratigraphic units north of the Keweenaw fault may indicate a gradual tilting of the basin before the development of the thrust faults. This suggests subsidence resulting from crustal tension produced by horizontal movement. This model is most commensurate with the geological and geophysical data. It appears to explain the intrusion of basic materials from the mantle producing the flood basalts and dense upper crustal rocks. It also eliminates the necessity to show the boundary faults of a graben system.

Indications of Compression and Tension

From the above discussion it appears that the Lake Superior trough and its related extensions are the result of tension and compression. Structural features indicating that compressional forces were involved in the development of the trough are shown by the geological data while the tension forces are indicated best by the geophysical data.

East of the Keweenaw Peninsula compression perpendicular to the axis of the trough similar to the Keweenaw and Isle Royale thrusting, is indicated by the thrust fault along the northeastern margin of the lake and possibly by general north-south faulting in the southeastern portion of the lake. Tension also is indicated by the normal faulting suggested along the southeastern shoreline of the lake and by the series of tilted block structures believed to extend along the central axis of the trough. This indicates that two directions of tension exist, nearly at right angles. Two sets of dikes striking perpendicular to each other to the east of the lake basin corroborate the two tensional directions. From these indications it appears that both tensional and compressional forces were developed along a parallel direction perpendicular to the axis of the trough. Although two perpendicular directions of tension may be produced simultaneously, parallel tension and compression cannot exist at the same time. The geological evidence conclusively proves that the thrust faults developed after the basaltic extrusions and deposition of clastic sediments. Therefore, the compressional forces perpendicular to the axis of the trough must have developed after the tensional forces.

Transcurrent Movements

It is suggested that the Lake Superior trough and its apparent extensions are the result of crustal separation and transcurrent faulting. The suggestion that transcurrent movements have been involved in the formation of this structural system comes primarily from the indication that both compressional and tensional forces were present during its development. The en echelon pattern of the structures producing the "mid-continent gravity high," the serated configuration of the eastern shoreline of Lake Superior, and the sinuous configuration of the lake trough, all strongly indicate transcurrent movements. The indications of slip-faulting in the southeastern portion of the lake and the thrusting along most of the major faults paralleling the axis of the Lake Superior trough are particularly convincing.

Previously it was suggested that the Northern Peninsula of Michigan and several other "arches" may be attributed to the curvature of the earth's surface. Although this suggestion does explain the origin of these structural features, they also can originate as a result of transcurrent faulting. The arching may be a consequence of uplifting caused by tensional forces paralleling the axis of the trough. The relief of pressure at the base of a crustal block liberated by tension faults may result in the vertical uplift of a horst-type structure. The broad base of a horst would provide a greater area upon which the ascending materials could exert pressure. The arching also may be the result of greater downwarping of the adjacent basins.

Many similarities appear to exist between the Red Sea and Gulf of Aden rift, and the Lake Superior trough. For example, both features show essentially the same general configuration. Both also have rift extensions from the closed end of the structure. Girdler (1964) concludes from his investigation that at least two directions of tension are responsible for the origin of the Red Sea and Gulf of Aden rift. Geologic evidence clearly indicates that the southern side of this rift has moved eastward relative to the northern side as the result of transcurrent faulting probably produced by continental movement.

Sequence of Events

The following sequence of events is suggested to have occurred during the origin and development of the "Lake Superior Rift System."

During the early Keweenawan and possibly before, the crust beneath Lake Superior began to thin. The crustal thinning may have been the result of uneven counterclockwise rotation of the continent or vertical uplifting to the north. As stretching of the crust proceeded, transcurrent movement was introduced and a trough formed. As stretching continued and transcurrent movement developed, the trough beneath Lake Superior subsided. The orientation of the trough was much less sinuous than presently observed.

The decreased pressure on the underlying mantle rock led to the formation of magma. As lower Keweenawan sediments began to collect in the trough downwarping was initiated. Through the tension fractures which developed in the lower boundary of the crust, parallel to the axis of the trough, magma began to migrate upward. Fractionation of the magma may have produced both acidic and more basic material. One of the early intrusions may have produced the more basic Duluth gabbro near the beginning of the middle Keweenawan. Differentiation of the lower crustal rocks and assimilation by the magma may have initially provided more acidic, less dense upper crustal intrusions, accounting for the earlier rhyolite flows.

As the crust continued to thin, lavas began to extrude along the tension fractures in the trough causing increased subsidence. With increasing crustal density, isostatic adjustment caused the trough to sink deeper into the mantle. Stretching of the crust toward the north, accompanied by transcurrent faulting, then produced a more sinuous configuration to the trough.

The central portion of the trough may or may not have developed normal faults wich completely penetrated the crust to form grabens. If graben-type rifts did form during the early stages, a thinner crust probably existed at that time which would suggest that the boundary faults were produced close to the axis. This may mean that the central "Keystone" block occupies a rather narrow strip beneath the present lake trough in the area represented by the negative magnetic anomalies. The downfaulting of the rift block may have tended to close the passageways along which the magma was extruded into the trough. Flood basalts may then have begun to extrude from tension fractures developed along the margins of the trough. This suggests that a time span existed between major extrusions of lava. During this intervening period thicker accumulations of sediments may have been deposited in the central portions of the trough. Flood basalts which extruded along the margins may have later covered some of these thick clastic deposits. This may partly explain why the uplifted geological structure represented by the positive magnetic Anomaly H, Figure 35, has an associated negative gravity anomaly. Possibly a thick layer of sediments covered by thin marginal flows would produce a magnetic positive and a gravity negative. An interpretation of this structural feature is illustrated in Figure 41.

With continued crustal stretching, transcurrent faulting became increasingly more pronounced. Eventually the tension fractures along the trough's margins were closed by compressional stresses which developed perpendicular to the axis of the trough as its configuration became more sinuous. In addition, the increased sinuousity of the trough probably caused tension fractures to develop to the north in the vicinity of Lake Nipigon. Tensional stress probably existed in this area throughout the development of the Lake Superior trough, resulting in large accumulations of flood basalts. With the cessation of the basaltic extrusions the middle Keweenawan came to a close.

The compressional forces developing perpendicular to the axis of the trough, as the result of transcurrent movements, produced continued downwarping during the upper Keweenawan. The increasing sinuosity of the trough, produced by compression, caused uplifting to the south. This upwarped region supplied much of the upper Keweenawan clastics which eventually filled the Lake Superior trough.

As transcurrent movements became increasingly more prominent and the trough more sinuous, faults developed perpendicular to the trough's axis. This transverse faulting developed most conspicuously in eastern Lake Superior. Some acidic extrusives resulting from the initial magmatic fractionation may have accompanied this faulting. However, the volcanic activity was held to a minimum, possibly because the normal faults producing the horsts, grabens, and tilted block structures sealed the avenues along which the magma must pass.

The formation of these transverse normal faults gave rise to uplifting of the horst structures and downwarping of the basins to either side, producing the transverse "arches," such as the Northern Peninsula of Michigan. The Northern Peninsula is known to have supplied sediments to the southeastern portion of the Lake Superior trough during Jacobsville time, as indicated by Hamblin's (1961) sediment dispersal studies. Therefore, this "arching" must have developed after the extrusion of flood basalts, but before the close of the upper Keweenawan.

The right-lateral slipfaults, paralleling the trough in the southeastern portion of Lake Superior, may be reflected in the deep topographic valleys striking north-northwest. These faults probably formed about the same time as the transverse faults. Along the southeastern margin of the lake, this wrench faulting also produced the serated shoreline and the downfaulted areas beneath Whitefish, Agawa, and Michipicoten Bays.

The transverse fault zone extending across the Lake Superior trough from Ashburton Bay to Keweenaw Bay appears to have developed toward the close of the late Keweenawan. The transcurrent movement producing the shear-stress probably stopped shortly thereafter. However, faulting may have continued into the Paleozoic.

Relaxation of the compressional shear-stress, originally responsible for the formation of the Isle Royale, Keweenaw, and related faults, occurred some time after the close of the late Keweenawan. The offshore thrust fault extending from the northeastern portion of the lake to the vicinity of Gargantua Point probably developed about this same time. Therefore, the thrust faults were not developed until after the transverse faulting and the deposition of the upper Keweenawan clastics. White (1966b) concludes from the geological evidence and Hamblin's (1961) study that, "The Keweenaw fault had no conspicuous surface expression in Jacobsville time; Jacobsville sandstone immediately adjacent to the fault was deposited by northward-flowing streams, as shown by cross-stratification measurements."

With the relaxation of the compressional forces produced by the transcurrent movement, the forcibly downwarped crust adjusted isostatically to the thick deposits of less dense clastic sediments which had accumulated since the close of the middle Keweenawan. White (1966b) also believes, "The uplift simply represents a restoration of isostatic equilibrium when forcible depression of the crust was relaxed."

The "Lake Superior Rift System" may have continued to develop for a considerable time after the uplifting along the major thrust faults. Although the configuration probably has not changed appreciably since this time, the thickening of the crust may have continued well into the Paleozoic. Basaltic material may have continued to ascend from the mantle and attach itself to the base of the crust or it may have been transferred by currents in the mantle from beneath the adjacent areas. This second possibility might explain the relatively thin crust found beneath the Wisconsin Arch. Regarding the origin of the thick crust beneath the Colorado Plateau, Gilluly (1964) states, "Several other features of western geology seem also to suggest currents in the mantle and perhaps even to permit our considering the somewhat unorthodox idea of subcrustal erosion and deposition." Another explanation for this crustal thickening, advanced in the previous section, suggests that shear-compression has caused downwarping of the crust which has resulted in the intrusion of basic mantle material into the lower crust. These intrusive masses are in addition to the intrusions of basic material into the upper crustal rocks during the earlier stages of crustal thinning.

CHAPTER V

CONCLUSIONS

The aeromagnetic survey of eastern Lake Superior and the eastern half of the Northern Peninsula of Michigan has confirmed some previous geological concepts and brought to light new ideas on the tectonics of the Lake Superior structural trough. Although the geophysical interpretation of the magnetic data is subject to error because of the inherent ambiguity of a magnetic analysis and the effects of remanent magnetization, the conclusions presented here serve as a first order approximation. By integrating the available gravity and seismic results with the aeromagnetic data the reliability of the structural interpretation has been increased significantly.

The geological interpretation that the Lake Superior trough contains middle Keweenawan basic volcanics overlain by upper Keweenawan clastic sediments is supported by the magnetic data from eastern Lake Superior. The trough also can be observed to extend southward across the eastern part of the Northern Peninsula of Michigan with diminished structural intensity, thereby supporting the suggestion that this feature extends into the Southern Peninsula of Michigan.

The Lake Superior trough is divided into two main structural basins which are separated by an en echelon zone of transverse faults extending from the Keweenaw Bay area northeastward to the area of Ashburton Bay. Some right-lateral slippage may exist along these faults. However, they appear to be primarily normal faults with the upthrown side to the west. Near Superior Shoal these transverse faults terminate the basic volcanics and associated fault which extends eastward from Isle Royale paralleling the general curvature of the Keweenaw Peninsula.
faults also terminate the volcanics and the associated fault to the north of the Isle Royale fault. Similarly, the Keweenaw volcanics and associated fault have been interrupted by one of these cross faults to the east of Keweenaw Point.

The change in trend of the Keweenaw Peninsula, the Isle Royale volcanics, and the volcanic feature to the north, all indicate that the Lake Superior trough became increasingly more sinuous during its development. The sinuous configuration of the trough, together with the en echelon sequence of positive gravity anomalies along the "mid-continent gravity high," and the serated configuration of the eastern shoreline of Lake Superior, are interpreted as indications of transcurrent movement. This movememt, however, may be a result rather than the cause of the trough's initial formation.

At least two directions of tension and one of compression further suggest that shear forces have been involved in the development of the "Lake Superior Rift System." Tensional forces perpendicular to the axis of the trough probably produced the original thinning of the crust which initiated the lake trough during the early Keweenawan. As the configuration of the trough became more sinuous, a second system of shear-tension fractures developed perpendicular to the axis of the trough. Faulting along these fractures produced a series of tilted block structures through the central portion of eastern Lake Superior. The normal faults separating the tilted blocks are closely related to the zone of transverse faults extending from the Asburton Bay area toward Keweenaw Bay.

The first major extrusions and intrusions of basic material were the result of the tensional forces that caused the crustal thinning during the early part of the middle Keweenawan. Rifting along the central axis of the trough may have supplied the first lavas. Fractionation of the magma intruding the upper crustal rocks could have produced the Duluth gabbro and the rhyolite flows. A later extrusion of lava may have developed near the margins of the trough as downwarping became increasingly more prominent. As the trough developed a more sinuous configuration, shear-compression closed the passageways originally formed by the tensional forces which caused the initial thinning of the crust. The development of this shear-compression brought to a close the middle Keweenawan and the vast accumulations of flood basalt. Shearing continued to create a compressional component perpendicular to the axis of the trough. This produced forcible downwarping of the lake trough. Great thicknesses of upper Keweenawan sediments then accumulated. At the same time the shearing also produced the tensional forces paralleling the axis of the trough which were responsible for the series of tilted block structures that formed across the central portion of eastern Lake Superior.

The nearly east-west trending volcanics to the south of Michipicoten Island were "uplifted" mainly by downwarping of the basins on either side along normal faults. In a similar manner, the Northern Peninsula of Michigan was partially elevated by the downwarping of the trough to the north and south. This uplifting separated the Lake Superior trough from the trough extending southward through the Southern Peninsula. The curvature of the earth's surface also may have been partly responsible for the "arching" of the Northern Peninsula.

The basic volcanics along the eastern margin of the lake trough were faulted into a discontinuous series of transverse horsts and grabens. The basic volcanics extending southwestward from Mamainse Point and the eastern end of the Northern Peninsula follow the strike of two horsts which trend perpendicular to the axis of the trough.

The serated configuration of the southeastern shoreline of Lake Superior also reflects wrench faulting. An en echelon series of tension faults first developed along the southeastern shore of Michipicoten, Agawa, and Whitefish Bays as the result of right-lateral shear-stress along the eastern shoreline. As the stress continued, the faults became connected, producing a series of "S" shaped faults which later formed the bays and points of land. The development of this serated shoreline is closely related to the transverse faulting which produced the discontinuous series of horsts and grabens along the southeastern margin of the trough. With the increasing sinuous configuration of the trough, right-lateral movement probably developed along each of the transverse faults.

Right-lateral slip faulting also may have developed parallel to the axis of the trough as its configuration became more sinuous. At this stage in the trough's development the faulting parallel to its axis resulted from shear-compression rather than the initial tension which had been caused by crustal thinning. An undetermined number of faults belonging to this system are probably reflected by the deep topographic valleys found in southeastern Lake Superior which have a general north-northwestern trend. The valleys may be the result of structural alignment along these faults.

As the shear-compression continued to develop the trough to its present sinuous configuration, the western portion became increasingly more downwarped. Major compression faults, paralleling the axis, may have developed along the present margins of the trough. After the close of the late Keweenawan and the deposition of the Jacobsville sandstone the transcurrent movement stopped. The compressional shear-stress responsible for the forcible depression of the trough relaxed and isostatic adjustment of the more depressed central section caused the trough to be uplifted along the previously formed compressional faults. This uplifting produced the major thrusting observed along the Keweenaw, Isle Royale, Douglas, and Lake Owen faults in western Lake Superior.

In eastern Lake Superior a thrust fault also developed to the north of the volcanics on Michipicoten Island. This fault extneds southeastward toward Gargantua Point and northward paralleling the shore at a distance of 10 to 15 miles. It may then continue farther north along the eastern margin of the Port Coldwell complex or it may turn northwestward about 20 miles southwest of Pic Bay and continue south of the Slate Islands toward the volcanics outcropping on the islands of Nipigan Bay. It may be interrupted by the zone of northeast striking transverse faults extending from Ashburton Bay toward Keweenaw Bay. These transverse faults also may extend northeastward and offset the thrust fault at a number of places along its strike to the northwest of Michipicoten Island. One or more of the transverse faults also may extend to the southwest and be responsible for the development of Keweenaw Bay. An extension of this normal transverse faulting appears to separate the volcanics on the Keweenaw Peninsula from the volcanics to the east of the bay.

The Keweenaw thrust fault may extend along the western margin of the volcanics to the east of Keweenaw Bay. However, the amount of uplifting along this southeastern portion of the fault may be considerably less than along the Keweenaw Peninsula. The western Lake Superior trough appears to have been downwarped to a greater extent than the eastern portion. Therefore, less isostatic adjustment in the eastern half of the lake trough may have resulted in less vertical displacement along the southeastern portion of the fault.

APPENDIX A

PROGRAM DESCRIPTIONS

APPENDIX A

PROGRAM DESCRIPTIONS

Introduction

Software Configuration

With the exception of Program PAMAG, all programs in this series were written for operation under SCOPE 5.2, the systems operating program used at Michigan State University at this time. In most cases FORTRAN was the language used. FORTRAN under the SCOPE system is called 3600 FORTRAN, which is about the same as FORTRAN IV. Occasionally, COMPASS, the 3600 assembly language, was used for some of the more unusual problems which were too cumbersome or time consuming to perform in FORTRAN. These special routines are so noted and in all cases remain under control of the SCOPE system.

Program PAMAG was written for the satellite computer CDC 160-A and therefore is written in OSAS (One-Sixty-Assembly-System).

Hardward Configuration

Unless otherwise noted, all of the programs in this series were written for and run on the facilities of the Computer Laboratory at Michigan State University. These computer facilities include the following:

1. Control Data Corp 3600 computer with 32,768 words, 48 bits per word for data.
   This computer is operated in a tape-oriented system with 10 CDC 606 tape drives serving as I/O.
2. Control Data Corp 160-A computer, with 8,192 words, 12 bits per word.
   This computer is operated as I/O for the CDC 3600 computer and may also be used as a satellite.
   Devices normally attached:
   a. 2 - CDC 606 tape drives
   b. 1 - CDC 501 printer (1000 lines per minute)
   c. 1 - CDC 405 card reader (1000 lines per minute)
   d. 1 - IBM 523 card punch (100 lines per minute)
   e. 1 - CDC 350 paper tape reader (350 characters per second)
   f. 1 - Teletype BRPE - 11 paper tape punch (110 characters per second)
   g. 1 - IBM 731 typewriter
   h. 1 - Calcomp plotter (10 inches wide)

With the exception of Program PAMAG all programs were for the CDC 3600, assuming I/O offline on the CDC 160-A which is normally done with this installation.

General Notes and Techniques

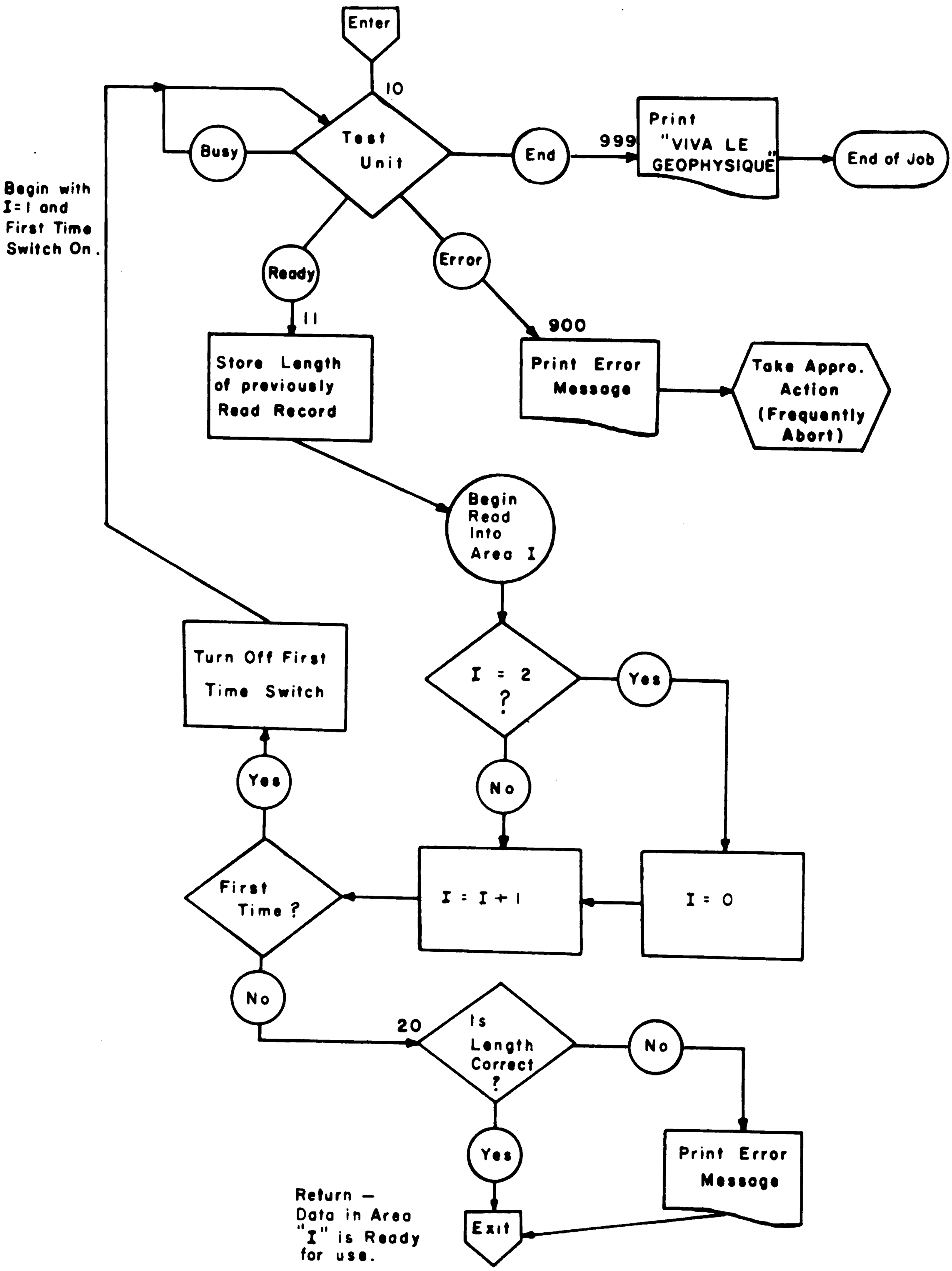
Since most of the programs and routines used in this project were written by the same person, there are many similarities between them. It will be helpful, therefore, to note some of these similarities and general characteristics before proceeding to the individual routines.

All data is stored on reels of magnetic tape and is inputed and outputed, therefore, via magnetic tape routines. Card input is restricted to control and/or to editing information.

All magnetic tapes are written in large blocks of binary words, usually with variable length records. These tapes are written and read, using buffer statements, directly into or from core memory. Each program has a routine to accomplish this buffering operation. Buffering allows input/output to occur at the highest possible speed, independent of the main program (usually while the main program is being used elsewhere), thereby giving the greatest overall efficiency.

To understand this buffering procedure, refer to the block diagram of a typical buffered input routine and the associated FORTRAN coding, Figure 1 and Figure 2 of this section. A doubly subscripted array is used for an input area. To buffer, data is first read into column 1 of the array. When this operation is completed, the tape reading circuits may read data into column 2 of the array while the program uses the data in column 1 of the array. The next block of data is obtained by reversing the columns.

In practice, buffering is achieved with a procedure similar to that shown in Figure 2. The tape drive unit is tested for status. If the unit is still busy with the



Appendix Figure 1.--Typical Buffer Routine.

Appendix A--Figure 2

IBM FORTRAN Coding Form

X28-7327-5
Printed in U.S.A.

PROGRAM: ATYPICAL BUFFER ØPERATIØN

PROGRAMMER | DATE | PUNCHING INSTRUCTIONS: GRAPHIC / PUNCH | PAGE OF | CARD ELECTRO NUMBER*

STATEMENT NUMBER | CONT. | FORTRAN STATEMENT | IDENTIFICATION SEQUENCE

```
      SUBRØUTINE READ
      COMMON MAGDATA (1526)
      DIMENSIØN INPUT (1526,2)
      DATA (I=1),(K=0)
  900 FØRMAT(33HOTAPE PARITY ERRØRS, JØB ABØRTED.)
  901 FØRMAT(29HOLENGTH ERRØR ØN THIS RECØRD.)
  999 FØRMAT(21H-VIVA LE GEØPHYSIQUE.)
   10 IF(UNIT,1) 10, 11, 99, 90
   11 LENGTH = LENGTHF(1)
      BUFFER IN (1,1) (INPUT(1,I),INPUT(1526,I))
      IF(I.EQ.2) I=0
      I = I + 1
      IF(K) GØ TØ 20
      K = 1 $ GØ TØ 10
   20 IF(LENGTH-INPUT(26,I)-26) PRINT 901
      DØ 21 J = 1, LENGTH
   21 MAGDATA(J) = INPUT(J,J)
      RETURN
   90 PRINT 900 $ STØP
   99 PRINT 999 $ REWIND 1 $ STØP
      END
```

*A standard card form, IBM electro 888157, is available for punching statements from this form

previous read operation, the program retests status, in this manner it "waits" for ready condition. If the unit has sensed an error in the previous tape read, appropriate action may be taken, usually aborting the job. If the unit has sensed an end-of-file mark on the previous read, the job is completed.

If the unit is ready for further action, the number of words read on the previous read operation is stored for checking against word counts within the data. Then the next read operation is initiated into the column just used by the program. The column index is changed and the program may now use the data previously read from the tape unit.

When the first tape read is initiated there is no data in the opposite column for use by the program, therefore, a "first-time" check must be made to allow the tape read circuits to advance one cycle ahead of the program.

In most cases, data is transmitted from the read/write routine to other routines of the program via a singly subscripted array in common. Although this is not necessary and in fact costs a few milliseconds to transfer one column of data to this common array, the convenience of a singly-subscripted array elsewhere in the program usually justifies this slight expenditure. Core storage available is sufficient for such an operation.

An output operation is similar, except that there is no test for error or end-of-file. Care must therefore be taken to insure that the last block is written out.

Data Formats

Data will be found on magnetic tape reels in one of the following three formats: Raw, Time and Coordinate.

1. Raw Format: Data in this format is essentially an image of the original paper tape. Each computer word contains 4 paper tape frames, 12 bits per frame. Each frame is right-justified in its 12 bit byte (word segment). Each magnetic tape record is 500 words in length (2000 paper tape frames).

   The first frame of each flight traverse line is found as the first byte (leftmost) of the first word of a record. Should the traverse end short of the record, the remaining bytes are packed with 0177_8. More than one record per traverse is allowed.

   The paper tapes were spliced with Scotch brand "Magic Tape," in accordance with the Computer Laboratory's recommendation. However, it was later found that the CDC 350 paper tape reader would not reliably read through these splices, therefore, many frames were lost.

2. Time Format: This tape is produced by program CONVERT when converting the above "Raw formated" tapes from frequency count to magnetic intensities. Each control number, time, magnetic value, etc. is contained in a separate, single computer word. All data is in integer binary form.

Word Number	Description
1	traverse number
2	segment of traverse
3	date of data collection
4	count constant x 10_6
5	N = number of magnetic values in this record
6	record number
7	total number of magnetic values thus far
8 & 9	unused
10	time
11 - N + 10	magnetic values (maximum allowed 500)

3. Coordinate Format: This tape is produced by program CORRECT, by assigning data to coordinate point segments. Each segment consists of the data between two coordinate points. Each control number, etc. is contained in a separate, single computer word, in integer binary form.

Word Number	Description
1	traverse number
2	date of data collection
3	count constant x 10^6
4	flight direction flag
5	average magnetic value for this segment

6	minimum magnetic value for this segment
7	sequence number
8	segment number of sequence
9	maximum magnetic value for this segment
10	time of beginning coordinate point
11	X value beginning coordinate point
12	Y value beginning coordinate point
13	longitude beginning coordinate point
14	latitude beginning coordinate point
15	altitude beginning coordinate point
16	regional beginning coordinate point
17	connection at beginning coordinate point
18	time of ending coordinate point
19	X value of ending coordinate point
20	Y value of ending coordinate point
21	longitude of ending coordinate point
22	latitude of ending coordinate point
23	altitude of ending coordinate point
24	regional of ending coordinate point
25	connection at ending coordinate point
26	N number of values in this segment

27 - N + 26 magnetic values in this segment (maximum allowed 1500)

Program CONVERT

Purpose

Input data from magnetic tape in Raw format (see general notes), convert magnetic frequency counts to magnetic intensities and output in three forms:

1. magnetic tape in Time format,
2. printed tabular record of all data,
3. printed graph of all data for ease of visual review.

A second version of this program accepts punch card input for recovery of data from Rustrak recording, whenever paper tape proves unusable.

Method

The main program controls three subroutines for input and two forms of output, while printing the tabular records directly.

A call to routine INPUT returns one value from the input file, either magnetic tape or cards depending on the version in use. Only time values and magnetic intensity readings are allowed as a returned value indicated by a zone value (N ZONE), anything else will cause abortion with an error message, "INVALID ZONE RETURNED BY INPUT ROUTINE xxxxxxxx." Where the x's will be replaced by this invalid zone.

When N ZONE indicates magnetic intensity, the value of the magnetic intensity is temporarily stored by the main program, sent to subroutine MGRAPH for printer graphing, and sent to subroutine OUTPUT for packing in the output block. When N ZONE indicates a time value, all magnetic intensities which were temporarily stored are printed in tabular form, the time value is sent to subroutine GRAPH for subsequent graphing and subroutine OUTPUT is instructed to output the previous block of data and begin another with this time value.

When subroutine returns end-of-data (as indicated by N SWITCH bit 1 on numerical value 2), subroutines OUTPUT and GRAPH are closed and the operation is informed of the volume of graphing on the auxiliary print tape.

Subroutine INPUT

There are two subroutines with this name for use with program CONVERT. One is for use with cards and one is for use with tape input. The main program is slightly modified for these two versions, so two completely separate programs CONVERT exist; CONVERT-CARDS and CONVERT-TAPE.

1. Subroutine INPUT for TAPE.--Subroutine INPUT is written in COMPASS, the CDC 3600 assembly language. The subroutine reads magentic tape in Raw format and de-blocks, byte-by-byte, into individual frames of paper tape. These frames are then condensed into values according to zone information.

Upon entry to subroutine INPUT, the zone bits of the byte now being used are tested. If they do not indicate either magnetic reading, time, traverse number or end code (177_8), another byte is requested through a jump to GET, and zone testing is repeated.

When the zone bits indicate a magnetic count reading, a jump to MAG occurs. At MAG, VALUE is set to zero. VALUE is multiplied by 10 and the digit bits of this byte are added to VALUE. This is repeated with successive bytes (by jumping to GET) until 5 digits have been added to VALUE. This VALUE is then divided into the appropriate constant and rounded, yielding the magnetic intensity, which is returned to the main program. Should another zone be encountered before 5 digits are added to VALUE, zero is returned to the main program.

When the zone bits indicate a time reading, a jump to TIME occurs. The procedure at times is very similar to MAG, except any number of digits up to 6 digits is allowed. If the time is 6 digits long, the first digit is stored and used as the first digit of all subsequent time readings less than 6 digits. The reading is then returned to the main program.

When the zone bits indicate a traverse beginning, a jump to TRAVERSE occurs. Three digits are used to develop the traverse number, which must be between 0 and 1000. Using this traverse number as an index, the constant and date for this traverse are loaded into common. Sense lights are set to flag the beginning of a new traverse line and control returns to the zone test at the beginning of subroutine INPUT.

When the zone bits indicate an endcode, a jump to ENDCODE occurs. If the next 3 bytes are also endcodes, the next block of input data is read in. Control returns to the zone test at the beginning of subroutine INPUT.

GET is a routine within a routine. It de-blocks the input data byte-by-byte and separates the zone bits and digit bits into two computer words. The first word of each block is tested against control words read from cards to provide a means of using only part of the input file. The header label is bypassed. GET begins with word 0 of the input block and pulls out the leftmost 12 bits as the first byte, then right-justifies these bits into DIGIT and ZONE. DIGIT and ZONE are masked for the appropriate bits. The byte index is incremented automatically for the next byte until the fourth byte is used. At this time the byte index is reset and the word index is incremented. When the word index equals 500, a jump to READ occurs.

At READ, a buffered input read operation occurs. This operation is very similar to that described under general notes in FORTRAN except, of course, that it is written in COMPASS.

2. Subroutine INPUT for CARDS.--Subroutine INPUT will return values to the main program in precisely the same manner, either from CARDS or TAPE. The difference lies in the nature of the input. From cards, the input consists of a string of pairs of numbers for each traverse. The first number of the pair is time, the second is magnetic frequency count as picked from Rustrak recording at that time. Whenever the time field is blank, the pair is ignored.

An operation, a time-count pair is read by the subroutine and sufficient count values are interpolated on a straight line with the previous time-count pair to maintain a ratio of 20 magnetic counts per minute. Thus the i^{th} count of the interpolation is calculated:

$$m_i = \frac{(m_1 - m_0)\, i}{(t_1 - t_0)\, 20} + m_0$$

where m_0 = previous magnetic count

m_1 = this magnetic count

t_0 = previous time

t_1 = this time

Each m_i is divided into the appropriate constant before being returned to the main program. When a new traverse was encountered, the entire procedure was cleared and begun anew, with appropriate flags for the new traverse condition.

Subroutine OUTPUT

Magnetic intensity values are accepted from the main program and packed, one per word, in the output block. When a new time or traverse is received, the block is buffered out, using techniques discussed in the general notes. The first 10 words of each outputed block contain control information. The number of magnetic values in a block (word 5) dictates the length of the written record; only sufficient words for the record are outputed. The output format is that of Time.

Subroutine GRAPH

Subroutine GRAPH produces a second print tape. This print tape is in every way similar to the standard output (produced by such statements as PRINT 100,A, B, C) and is handled by computer personnel as such. It produces the effect of having two printers attached to the computer at once, each printer serving a different function. Due to the volume of printing produced by this auxiliary print tape, it is produced by a buffered statement and a COMPASS formating routine, to maintain some degree of speed.

Subroutine GRAPH works in 4 steps. Step 1 blanks the previous line of graph from the memory work area and inserts fiducials. If the magnetic value to be graphed is equal to zero, the word "MISSING" is placed at the edge of the paper. Step 2 calculates the print position needed to graph this value. Each value is graphed at two scales, 200 gammas-per-inch in asterisks and 400 gammas-per-inch in periods. To calculate these positions, the following formula is used:

$$p = (m - b)/(s/10)$$

where m = magnetic value

b = base value for the graph (here 58000)

s = scale

p = print position

These print positions are tested to be sure that the graph will not exceed the upper or lower limits of the paper. If so, 110 (width of graph area in print positions) is either added or subtracted to bring the graph back within limits. This is called "wrap-around." Subroutine SYMBOL is called to actually perform the graphing. Step 3 inserts the magnetic value (and time when appropriate) in the margin of the graph line work area in memory. An ENDCODE statement accomplishes this. ENDCODE works exactly like PRINT except that a section of memory is referenced, instead of some output device. Step 4 causes the entire graph line work area to be written on the auxiliary print tape, using a buffered statement. This procedure avoids a lengthy FORMAT and PRINT combination which is time consuming.

Whenever the routine is entered with the control parameter, k, equal to 3, a new page is begun with appropriate headings.

Subroutine SYMBOL

To avoid the time consuming PRINT and FORMAT combination, subroutine SYMBOL was written, using COMPASS language to translate the M^{th} print position into indexes for the proper word, and byte of that word, in the graph line work area. The graph line work area is all blanks, and the desired symbol is lain over the M^{th} print position.

To calculate the word index,

$IW = M/8$, in integer arithmetic.

That is, no fractions are allowed and no rounding occurs. Thus $7/8 = 0$, $25/8 = 3$, etc. If the remainder, R, of the above division, equals zero, then

$IW = m/8 - 1$, and the byte index, $IB = 0$.

If $R \neq 0$, then

$IB = 48 - 6\ R$

An asterisk is loaded into the appropriate byte for M, and a period for N.

Program GROUND

Purpose

The purpose of this program is to calculate the ground speed of the aircraft used in the aeromagnetic survey by using x - y map coordinates and the logged times for these coordinates. By inspecting these ground speeds, considerable editing of logged times and navigation is possible.

Input

Each input card contains the traverse number in the first three columns, followed by five points: (1) hour, (2) minute, (3) second, (4) x coordinate in hundredths of inches, (5) y coordinate in hundredths of inches.

Output

All output is printed. Each segment (from one coordinate point to another) produces a single line which consists of the beginning time and coordinates, the ending time and coordinates, the elapsed time, the calculated distance and the calculated ground speed. At the end of each traverse, the total time elapsed, distance spanned and total speed is printed, followed by the mean speed and standard deviation of speeds for that traverse.

Method

Programming is straightforward. The data is read as card image into memory and stored. Thus, by using the DECODE statement, this card may be "reread" as many times as desired, with as many different formats as desired. Once two adjacent coordinate points for one traverse have been located, the calculation proceeds normally:

$$ds = 7.8914141 \sqrt{(x_1 - x_o)^2 + (y_1 - y_o)^2}$$

where x_o, y_o are the coordinates of the beginning of the segment and x_1, y_1 are the coordinates of the ending of the segment.

$$dt = 60(h_1 - h_o) + (m_1 - m_o) + (s_1 - s_o)/60$$

where h_o, m_o, s_o is the time in hours, minutes and seconds of the beginning of the segment and h_1, m_1, s_1 the time of the ending, then

Speed = ds/dt x 60

and Mean Speed = $\left(\sum_{i=1}^{n} ds_i/dt_i \right) \times 60/n$

and Standard Deviation = $\sqrt{\dfrac{n\sum_{i=1}^{n} (ds_i/dt_i)^2 - \left(\sum_{i=1}^{n} ds_i/dt_i \right)^2}{n^2}}$

Program CORRECT

Purpose

The purpose of this program is to accept data in Time format, editing information from cards, and produce output data in Coordinate format (see general notes). At this time, x - y map coordinates are tied to segments of data, bad data are corrected or eliminated and most editing is performed.

Input/Output

Data are inputed on logical unit number 1 (tape drive) and editing information comes from cards (see instructions for preparing cards for format). Output is to logical unit number 2 (tape drive) and to standard output tape (printer). Data output is in Coordinate format. Printer output consists of a running record of editing performed and flags of error conditions.

Method

See instructions for preparing cards for a description of the function of each of the various types of card input. These cards initiate a string of calls to input and output routines which result in the desired action.

To understand the operation of this program, one can visualize three files of magnetic data: (1) tape input, (2) car input, (3) tape output. These three files can work independently of one another but are all controlled by information from the card file. Data transfers from either input file to the output file one magnetic value at a time, but always advancing the file involved forward. No file can back up. The card file provides master control but, the input tape file is controlled by the time on the input, and the output file is controlled by the coordinates on the output. Thus, the card file can cause data to transfer from input tape file to output tape file (advancing input tape file and ouput tape file together); stop the input tape file to insert some data from the card file (advancing only the output tape file) and then resume transference (advancing both again).

A highly important technique used in this program is that known as "zeroing a value." During the data transference operation, any value desired may be changed to zero (including data being inserted from cards). The output file routine accepts this in the output area along with all other data for a given segment. When the output routine receives the next x-y coordinate point, these stored values are scanned for any values equal to zero. When one is found, an interpolation is performed on the nearest non-zero values before and after the zero value, and the resulting calculated value inserted in place of the zero. Then the entire block is buffered out onto magnetic tape (see general notes for discussion of buffering). This provides an easy means for the geological reviewer to correct obviously erroneous readings.

As indicated above, the input tape file is controlled by time. Since there are usually about 20 values of magnetic data associated with each time reading, specific magnetic readings are determined by a count of the number of readings beyond a specified time. In other words, a time of 150530 and a count of 10 will cause the input routines to pass all values through the transfer word up to the 10th value beyond time 150530 and stop with the 10th value in the transfer word. Whether the values just passed were outputed depends, of course, on other conditions established by this particular control card. Time reference can be to the last time referenced (as the counter is now based on it) or to the time now in the input area (as the counter can be switched to it). Reference can also be made to a time not yet reached on the input tape file (reading and data transference will take place until the specified time is reached). Reference may not be made to times already passed on the input tape file (no file may back up).

The output file is controlled by x - y coordinate points. This implies that no reference may be made which depends upon data outputed in the last x - y segment, or on the next segment to be processed.

Main Program

The control cards are read and the first eight characters are compared as one word to a stored table of code words to determine the nature of editing action indicated by that card. This is accomplished by using a DO loop and an IF statement to compare the word from the card to each word of the table. When the two compare exactly, a jump outside the loop occurs. The loop index now can be used as a code number for control. It generates a jump to the appropriate routine through the use of a calculated GO TO statement.

Each of the routines call subroutines SEARCH, READ, WRITE, OUTPUT in the required order and the required number of times to effect data transference, deletion, insertion, changes, etc. as requested on the control card. They are too numerous to outline in detail; description can best be made by describing each of the subroutines mentioned and then referring the reader to the program listing for the order in which these subroutines are called for each of the control card types.

Subroutine SEARCH

Subroutine SEARCH uses three parameters; k, the time reference; N, the number beyond that time reference; and M, the control of transference. If M is non-zero, the magnetic values are transferred to the output file just as read in; if M is equal to zero, the magnetic values are deleted, that is, they are not transferred to the output file.

When k, the time reference, is the same as in the previous use of this subroutine, control goes to the counter. When it is not, subroutine INPUT is called again and again (with calls to subroutine OUTPUT if M is non-zero) until k is found. Then the counter is reset to k. Should the end of this traverse occur, as indicated by L(5) or L(6) being on, an error return to the main program occurs.

Once the time reference has been established, INPUT is called (with OUTPUT if requested) until the counter of the number beyond k is equal to N. Note that the count of magnetic values associated with any time begins with the 0^{th} value.

Subroutine INPUT

This subroutine reads the input tape file (see general notes on buffering) and returns values to the calling routine one-at-a-call. Some data manipulation is performed to compensate for data collection difficulties known to have occurred. When the end of the traverse is sensed, L(4) is tested. If L(4) is on, the next traverse is read as though it were a part of the previous traverse. If L(4) is off, L(6) is turned on to flag other routines of possible error. When the end of the tape occurs L(5) is turned on and the tape is rewound to allow another pass of the data. This is costly in time, but occasionally will allow the job to recover itself after some error has caused the input and output files to get "out-of-step."

READ is an entry to this subroutine which allows entire blocks to be read without returning values one-per-call. This is usually done when the program is searching for some traverse number.

All data communication into and out of this subroutine is through common.

Subroutine OUTPUT

Subroutine OUTPUT accepts values one-at-a-call and stores them in the output area. When WRITE is called (WRITE is an entry point to OUTPUT), the values stored are scanned, interpolated, and outputed, using a buffered output statement. The format of the output is by coordinates now, and each record represents one segment, the data between two coordinate points.

When WRITE is called, the data is scanned for zero values. When one is found, it is replaced by an interpolated value between the nearest non-zero values before and after the zero value. Exceptions are the first and last value of a segment, it is replaced by the nearest non-zero value. In the case of the first value of a segment, an interpolation is made between the last value of the previous segment and the nearest non-zero value. Of course, in the case of the first segment of a traverse, this first value is treated like a last value.

When the n^{th} value is not the first or last value of a segment and is discovered to be zero, the program searches for the next non-zero value, the k^{th} value. The previous non-zero value is the m^{th} value. Then

$$mag_n = \frac{(n - m)\ (mag_k - mag_m)}{(k - m)} + mag_m$$

While going through this scanning and interpolation process, the minimum, maximum,and sum of all values is noted. Then when the block is complete, the mean or average value is calculated and stored in control word 5, and the block of control words and magnetic values is buffered out. Only sufficient words are output to contain the block as specified by control word 26 (count of magnetic values contained in the block). The maximum block size is 1526 words, but typically, block size is between 100-500 words in length.

Program MERGE

Purpose

To read successively any number of input tapes as specified by control cards and write them all onto one output tape.

Input/Output

No change is made to the data or format as transference from input to output occurs. Either Time format or Coordinate format will be accepted (see general notes).

Method

A three-column input-output area is used with a 3-way buffer-in operation and a 3-way buffer-out operation (see general notes for a discussion of buffering). This maximizes buffering abilities, minimizes input/output interaction and allows complete freedom for program use of data.

The program begins with the first input tape already mounted on unit 1. As each tape reaches its end-of-file, the next control card is read to determine the physical number of the next reel desired. A message requesting this number reel is outputed to the operator and the computer is stopped. When the operator presses start, it is assumed that he has made the requested change of reels. The time between Stop and Start is noted and the total operator time is printed at the end of the job.

As each tape is transferred, its physical number is printed, followed by the traverse numbers (word 1 of the I/O columns) with the times for each block (word 10 of the I/O columns). This provides a compact record of the location of any segment of data, in the order of appearance on the output tape.

Program COORT

Purpose

An empirical test of a method of converting from x - y coordinates as used on the aeromagnetic project to latitude-longitude on a Lambert Conformal Projection map.

Input/Output

Input is a card for each test case. On the card is punched the x coordinate, y coordinate, latitude, and longitude of a test point. Output is a printed page showing the actual data, calculation therefrom, and the error between them.

Method

Basically, the problem is treated as one in plane analytical geometry, where a cartesian coordinate system is to be changed to a polar system. It is necessary to translate, transform and then rotate.

Reading directly from the map, it is seen that the north pole is at a point (33.0, 422.6) in the cartesian system. Therefore, first a translation is made to that point (33,422.6). Colatitude is simply distance from this point divided by 8.7 inch/degree. Longitude is an arctangent function which must be rotated 6°. Since the computer subroutine for arctangent returns values between $-\pi/2$ to $\pi/2$, it is necessary to add 180° whenever $x - 33$ is negative.

Then

$$\text{latitude} = 90° - \frac{\sqrt{(x - 33)^2 + (y - 422.6)^2}}{8.7}$$

and $$\text{longitude} = -57.295777 \arctan (.9031 \frac{y}{x} + C(180°) - 6°.$$

$$\text{where } c = 1 \text{ when } x - 33 < 0.$$

$$c = 0 \text{ when } x - 33 \geq 0.$$

The adjustment to the tangent ratio y/x is an empirical correction. It was found to improve overall accuracy by several tenths of a degree.

Accuracy using this conversion is well within 0.1° for both latitude and longitude, over the region for which the survey was taken. This will result in errors in the calculated regional magnetics of less than 20 gammas. This error is less than the resolution of the plotter at the scales planned, therefore, this routine is quite adequate for the survey's needs.

Program TEST

Purpose

To try subroutine GFIELD, which was obtained from the University of Wisconsin who in turn had obtained it from NASA.

Output

The regional magnetic field of the earth was calculated and printed for each intersection of whole degrees of latitude and longitude over the region of the survey. This was then compared to a regional map of the same area and found to be quite reasonable.

Program TREG

Purpose

To prove the combination of techniques involved in conversion from x - y coordinates to latitude-longitude, and then, using NASA's subroutine GFIELD, to calculate the regional magnetic field.

Output

The x and the y coordinates,calculated latitude, calculated longitude, calculated north, east and vertical components as well as the calculated total intensity, were printed for several representative points of the Great Lakes region.

Program MGRAPH

Purpose

The purpose of this program is to provide a means of graphing desired traverses on the printer.

Input/Output

Input is data in Time format (see general notes). Output is on the standard output (printer) and is in the form of printed graphs.

Method

The program is essentially subroutine GRAPH with the associated subroutine SYMBOL as described in program CONVERT, isolated as a program in its own right. The routine has been changed slightly to output on the standard output (printer), rather than producing an auxiliary print tape. An output routine is attached to feed data to GRAPH. This routine is almost exactly that described in the general notes as an example of buffering.

The program begins by reading a group of control cards which list the traverses to be graphed. These cards comprise a series of 4-column fields which contain the numbers, one-to-a-field right-justified. The first number is the physical reel number for record purposes. The second field is the number of traverses to be graphed. The third field determines if these traverses are to be selected by traverse number or sequence number (1 for traverse number, 7 for sequence number). The remaining fields, on as many cards as necessary (20 fields/card) are the requested traverses or sequence number. These are stored in a table and as the program reads data, the data is checked against the table. If the appropriate control number is not in the table, that data is bypassed.

Program MPLOT

Purpose

To read data from magnetic tape in Coordinate format (see general notes) and produce a plotted profile at two magnetic scales, one for analysis and one for transference to maps, with distance scaled to maps.

Input/Output

Input data is from magnetic tape files in Coordinate format. Control information is read from punched cards. Traverses to be plotted are specified in a list, along with (or without) the regional effect. Magnetic scales and bases for plotting are specified.

Output is primarily on the plotter. Each profile is plotted at two scales, with fiducials and coordinate points spaced to fit maps. Secondary output is from the printer, which provides a check on the coordinates. For each line segment (data between two coordinate points), beginning and ending times and coordinates are printed, along with elapsed time, distances spanned, calculated ground speed, and station/plot ratio. The station/plot ratio represents the number of observed stations (individual magnetic intensity readings) plotted per 0.01 inch. This number represents the "packing" of the data, and is usually in the range 0.30 to 0.80.

Control Cards

Card #1.--This "card" can be any number of physical cards and is comprised of 4 digit integer fields, all right-justified.

Field #1 - KTAPE: The physical number of the input tape--for information only.

Field #2 - LL: Regional/residual control. When LL = 0, regional profiles are plotted. When LL ≠ 0, residual profiles are plotted.

Field #3 - IL: Number of plots requested. This field determines the number of cards read by this section of the program.

Field #4 - IJ: Control index. If IJ = 1, traverses will be selected by traverse number. If IJ = 7, traverses will be selected by sequence number.

Fields #5 through (IL + 5): Either traverse number or sequence numbers of traverses to be plotted, depending on IJ.

Card #2.--This card specifies bases and scales for plotting the profiles.

Field #1 - BASE 1 - F7.0: Base for first profile, usually the analytic scale, e.g., 58200.

Field #2 - SCALE 1 - F5.0: Scale for first profile, e.g., 400.

Field #3 - BASE 2 - F7.0: Base for the second profile, usually for mapping. By setting this base low, e.g. 40350, this profile appears high on the page.

Field #4 - SCALE 2 - F5.0: Scale for second profile, e.g. 2500.

Field #5 - BASE L - F7.0: Value of base line to be drawn by plotter for convenience of draftsman, e.g., 59100.

Method

The main program begins by reading in and then printing a record of all control data. KTAPE is included to provide a record of the number of the physical reel used but is not used in any way. LL determines whether regional (e.g. observed data) or resigual (e.g. after removing regional field) will be profiled. IL determines the number of lines which will be plotted. IJ determines if these lines will be selected via traverse or sequence numbers. The traverse or sequence numbers of the lines requested are stored in a table.

Data is read by calling subroutine READ. As each segment (data between two coordinate points) is returned, it is checked against the table of requested traverses. If it is not listed, the data segment is bypassed.

When the traverse number changes, a call to subroutine FIDUCIAL produces the terminal set of fiducials to the previous traverse, the plotter paper is advanced two inches, the pen is shaken 10 times to aid ink flow, and the beginning set of fiducials is produced with another call to subroutine FIDUCIAL.

The length of each segment is calculated from the beginning and ending coordinates. DY is this length in miles, floating point. M is this length in hundredths of an inch, fixed point. When M = 0, or M > 3000 (indicating a segment more than 240 miles in length), an error message is printed and plotted, and the segment bypassed.

$$M = \sqrt{(x_1 - x_o)^2 + (y_1 - y_o)^2}$$

where (x_o, y_o) is the beginning point in 10^{-2} in, fixed point, and (x_1, y_1) is the beginning point in 10^{-2} in, fixed point.

$$DY = \frac{M \times 7.8914141}{100}$$

The input data is interpolated from N points, where N is the number of observed magnetic intensity readings in the segment, to M points, where M is calculated above.

$$Pi = \{[\frac{(N-2)i}{(M-2)} + 1] - k\} (Mag_{k+1} - Mag_k) + Mag_k$$

for i = 2, . . . , M - 1

and where

$$k = \frac{(N - 2)\, i}{(M - 2)}$$

is truncated to the nearest lower integer. Having prepared the data for the best plotter resolution (.01 inch), a call to subroutine XYPOINT causes a "+" to be plotted along the lower edge of the plot, with the digits of the coordinates, at the coordinate point.

If LL $\neq$ 0, two calls to subroutine REGION provide the regional field of the beginning and ending points, R0 and R1. From these, the regional effect is removed from the data, P_i as calculated above, with another interpolation process:

$$Pr_i = P_i - (R_1 - R_o)\,\frac{i}{M} - R_o \text{ for } i = 1, \ldots, M$$

Finally, the data is plotted twice by first a call to subroutine SCALE and then to subroutine PLOT for each P_i, i = 1, . . . , M. On the second return trip for the plotter pen, a line is drawn at BASEL.

One line of print is produced for each segment; times, coordinates, distance, ground speed and the ratio N/M (station/plot ratio). Lastly, the ending coordinate point is plotted with another call to subroutine XYPOINT.

Subroutine FIDUCIAL

This subroutine uses five parameters, K, L, LSEQ, LTRAV, KR. Upon entry to the subroutine, the present pen position is reestablished as zero, the pen moved to the edge and made zero once more. Then the pen is caused to move across the paper, make a "+" every inch. If K = 0, control returns to the calling program.

If K $\neq$ 0, several words are plotted along the top edge of the paper. First, the word "REGIONAL" if L = 0, or the word "REDIDUAL" if L $\neq$ 0. Next, LSEQ, the sequence number of this profile, and LTRAV, the traverse number of this profile, are plotted. Finally, if KR $\neq$ 0 the word "REVERSED" is plotted. Then control returns to the calling program.

Subroutine XYPOINT

This routine produces an "+" to mark a coordinate point at the lower edge of the plot paper. A check against the previous call to this subroutine is made and if more than 0.5 inches have been plotted, the x and y coordinates are plotted below the "+".

Subroutine READ

This routine is almost identical to the example of buffering given in the general notes.

Subroutine SCALE

The parameters to this subroutine are X, Y, P, B, and S. Plotter pen position, in inches, is calculated from the value to be plotted, P; the base value, B; and the scale, S.

$$x = -(P - B)/S$$

The negative value is necessary as the y - axis is considered the long orientation of the paper. Since 0 is along the bottom edge of the plot, the profile always occurs along the x - axis.

If $x < 0$ or $x > 10$ (outside the limits of the plot width), the pen is lifted and moved to the appropriate edge of the plot to reflect "wrap-around."

Subroutine REGION

This subroutine embodies the conversion from x - y coordinates to latitude-longitude as described in program COORT and uses the latitude-longitude for a call to subroutine GFIELD, which returns the regional field of the earth at that coordinate point. The only change is to calculate east longitude as required by subroutine GFIELD.

Subroutine GFIELD

This program was obtained from the University of Wisconsin, which in turn had received it from NASA. It is described elsewhere. Given a point on the earth in latitude-longitude (east), the subroutine will return the theoretical magnetic field of the earth at that point, along with component vector values.

FORTRAN Subroutine READ

Purpose

To provide the user a means of inputing selected traverses and/or selected map areas from a data tape in Coordinate format (see general notes) without the necessity of complex tape-handling statements.

Input

Data enters the routine via magnetic tape in Coordinate format, and is transmitted to the calling program via common. Controls enter the routine via parameter. An entry point INITREAD initiates the read routine and causes card read (if necessary) of a list of desired traverses and/or the limits or boundaries of a desired map area.

Formats of Control Cards

1. Traverse List.--This card(s) is a sequence of 4 column fields, each an integer, right-justified.

   Field #1: Traverse of sequence control requested. If = 1, traverse number control is used; if = 2, sequence number control is used.

   Field #2: Number of traverse requested. This number determines the number of 20 field cards to be read.

Field #3: List of traverses, either by traverse number or sequence number, as dictated by Field #1, to be read.

2. Boundaries Card.--This card specifies the boundaries of a given map area. Any data occurring within these boundaries will be transmitted; any occurring outside these boundaries will be bypassed. The card consists of four floating-point 4 digit fields, with two implied decimals (4F4.2).

   Field #1: East boundary

   Field #2: West boundary

   Field #3: South boundary

   Field #4: North boundary.

Method

There are two entry points to the program, INITREAD and READ, and one parameter, KK.

When INITREAD is entered with KK = 1, the Boundary card will be read, stored, printed and the boundary-selective switch, KAR, turned on. When INITREAD is entered with KK = 2, the list of desired traverses will be read, stored, printed and the traverse-selective switch, KSEL, turned on. Entry to INITREAD is required, but it is not necessary to request either type of data selection. If KK = 0, neither selection will occur. If INITREAD is entered twice, once with KK = 1 and once with KK = 2, both types of data selection will occur. Order of the control cards in this case depends on the order of entrys to INITREAD.

The standard entry to READ causes a buffered input in a manner very similar to that described in the general notes. When KAR is on, the position of each data point is calculated and tested against the boundaries. Only those lying within these boundaries will be transfered to common. When KSEL is on, the table of stored traverse requests is searched and compared against the traverse or sequence number, as instructed, of each segment. Only those requested will be transfered to common. If neither KAR or KSEL are on, then all data will be transfered to common. The various modes of selection may be used or not, in any combination.

Should either a parity error or a read length error occur on the input tape, the job is aborted with an appropriate message.

When the end-of-file is reached on the input tape, KK is set $\neq 0$. On other returns, KK = 0.

Examples of calls:

CALL INITREAD (1) causes area selection

CALL READ (K)

IF (K) GO TO end statement

Program PROFILE

Purpose

To read data in Coordinate format (see general notes) and produce magnetic profiles oriented by coordinates, that is, on a map.

Input/Output

Data is read from magnetic tape in Coordinate format. One control card is read to specify the boundaries of the map area. The format of this card is (4F4.2).

Field #1: West boundary (x coordinate)

Field #2: East boundary (x coordinate)

Field #3: South boundary (y coordinate)

Field #4: North boundary (y coordinate).

Output consists of plotter paper, ten inches wide and as long as the north-to-south boundaries' distance. These represent strips of the map area, working from west to east until the area is completely plotted.

Method

All the data is read for each strip. The program establishes the limits of one map strip and then reads all data, testing the coordinates of each point as it is read. When the point lies within the map strip, it is plotted. When it is outside the map strip, it is bypassed. When all data has been read, the data tape is rewound, the limits of the next strip are established, and the process repeated.

When the requested area has all been plotted, the program comes to an end.

Data is read by a call to subroutine READ, which returns a traverse segment (data between two coordinate points). The data for this segment is interpolated for greatest plotter resolution in precisely the same manner as in program MPLOT. The regional effect also is removed in the same manner as in program MPLOT.

After preparing the data for the plotter, the direction of the segment is calculated:

$$dx = x_1 - x_o$$

$$dy = y_1 - y_o$$

$$r = \arctan dy/dx$$

where (x_o, y_o) and (x_1, y_1) are the beginning and ending points of the segment, respectively; and r is in radians.

The data is scanned twice, once to plot the path of the aircraft, and the second time to plot the profile along that path. As the data is scanned, the position of each data point is calculated and checked against the limits of the map strip now being plotted:

$$x_i = \frac{i}{M}dx + x_o \qquad \text{where } i = 1, \ldots, M$$

$$\qquad\qquad M = \text{number of plotter data points}$$

$$y_i = \frac{i}{M}dy + y_o \qquad dx,\ dy,\ x_o,\ y_o \text{ as above.}$$

When $x_w < x_i < x_e$ and $y_s < y_i < y_n$, where

x_w = west boundary,

x_e = east boundary,

y_s = south boundary, and

y_n = north boundary, the point is plotted.

If the above inequality is not satisfied, the point, and its data, are bypassed.

On the first pass the pen is caused to move from points (x_i, y_i) to (x_{i+1}, y_{i+1}), creating a line representing the path of the aircraft. On the next pass, the pen is offset from each (x_i, y_i) where

$d = P_{i/s}$ $\quad$ P_i = residual magnetism at point i

$\quad$ s = scale factor, e.g. 2500.

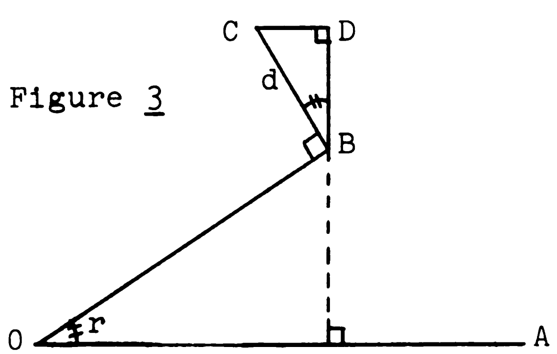
To achieve this offset, the point (x_c, y_c) is calculated:

$$x_c = x_i - d \sin r$$
$$y_c = y_i - d \cos r$$

where r is defined above.

To justify this calculation, consider Figure 3.

Figure 3



$\overline{OB}$ is the flight path.

$\overline{OA}$ is the x - axis.

$\overline{BC}$ is a vector of length d at right angles to line $\overline{OB}$.

$\overline{CD}$ is the x - component of $\overline{BC}$.

$\overline{BD}$ is the y - component of $\overline{BC}$.

Since $\overline{BC} \perp \overline{OB}$ and $\overline{BD} \perp \overline{OA}$, then $\angle BOA = \angle CBD$.

Since $\angle AOB = r$ and $\overline{BC} = d$, then $\overline{CD} = d \sin r$ and $\overline{BD} = d \cos r$.

Therefore, the coordinates of point C are as follows:

$$x_c = x_B - d \sin r$$

$$y_c = y_B + d \cos r$$

Plotting successive points (x_c, y_c) produces a profile along the flight path.

Subroutine LIMITS

This subroutine establishes the boundaries of one strip of the area to be mapped. These boundaries are communicated to other routines of the program through common.

When the routine is entered through a call to LIMITS, the boundary control card is read and stored. The eastern boundary of the first strip is obtained by simply adding 10 to the western boundary of the entire area. A "+" is plotted in the lower two corners of the strip by calls to subroutine CROSS. Routine then returns to the calling program.

When the routine is entered through LIMUP, the upper two corners of the strip are identified by calls to CROSS. Then the western and eastern strip boundaries are increased by 10. If the eastern strip boundary exceeds the eastern boundary of the entire area, the eastern strip boundary is reduced to that of the entire area. When the western strip boundary equals or exceeds the eastern boundary of the area, the job is complete.

After testing the boundaries and finding more area to plot, the lower corners of the next strip are marked by calls to CROSS and control returns to the calling program.

Subroutine CROSS

There are three parameters to this subroutine, x, y, K. The x and y are the coordinates of the point to be marked by a "+", and K determines which corner of the plot strip is being marked.

When K = 1, the x and y for this call are accepted as the "zero" reference coordinates and calls to subroutine PLOT set the plotter as such. This will be the southeast corner.

When K = 2, 3, or 4, the x and y are adjusted by the "zero" cordinates established above, and then the cross is plotted appropriately. As used here, K = 2 determines the southwest corner of the strip, K = 3 determines the northeast corner, K = 4 determines the northwest corner. When k = 4, this is considered the last corner of the strip to be marked, so the plotter paper advances 3 inches to space for the next strip.

The x and y are printed by the plotter pen for convenience. When K = 1 or 2, x and y are printed below the cross; when K = 3 or 4, above.

Subroutine READ

This routine is typical of any buffered read (see general notes). When the end-of-file occurs, the data tape is rewound and a call to subroutine LIMITS is made through LIMUP.

Subroutine REGION and GFIELD

These subroutines are exactly as described under MPLOT.

Program CONTOUR

Purpose

To read data in Coordinate format (see general notes) and produce contouring fiducials on a map.

Input/Output

Input, both data and control cards, is identical to program PROFILE. Output is in the form of map strips, just as with program PROFILE, but instead of profiles along the flight paths, fiducial marks are made at each contour (isogam) intersection.

Method

Data reading, interpolation, searching, etc. is accomplished with exactly the same procedure as with program PROFILE. Instead of calculating d for a residual, however, d is 0.05 inch and a fiducial mark is made by moving the pen a distance d at right angles to the path as the first and only pass of the pen is made.

To determine when a fiducial point is needed, each data point is compared to the data point immediately previous.

If $[P_{i/k}]_T - [P_{i-1/k}]_T \neq 0$, where k is the contour interval, then a fiducial is made at point P_i, and $[\,]_T$ indicates integer arithmetic, that is the division is truncated to the nearest lower integer.

$$K = (\max \{[P_{i/k}]_T, [P_{i-1/k}]_T\}) \times k$$

K is the value of the isogam just crossed. K is stored, and, after 10 successive values of K have occurred, are printed on the printer to provide assistance in contouring.

$$\text{If } \left(\left[\frac{K}{200}\right]_T - \left[\frac{K + 100}{200}\right]_T\right) \neq 0,$$

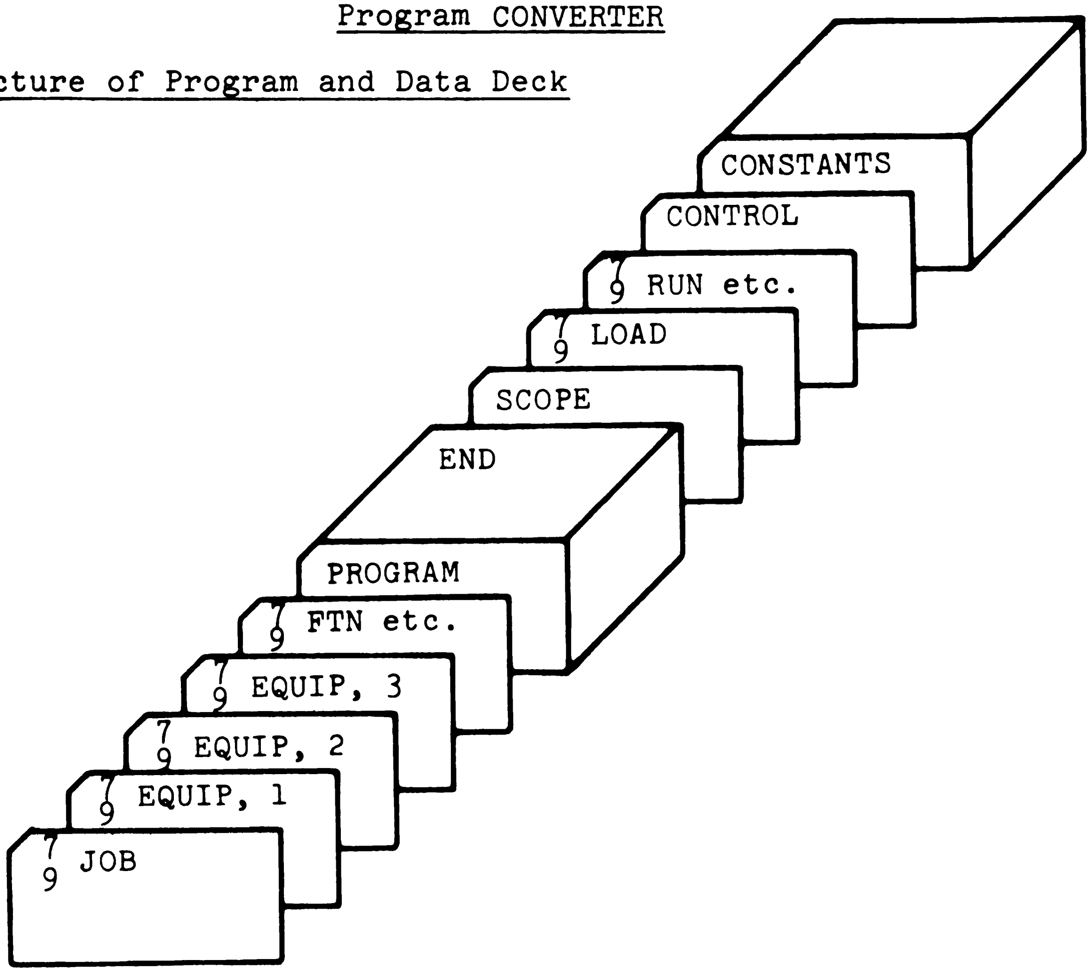
the value of K is in odd hundreds and d is made - 0.05. When K is in even hundreds, d is made + 0.05. The exception is the tenth successive value of K, for which d = ± 0.10 and the corresponding value of K on the printer has a plus sign following it.

APPENDIX B

DECK STRUCTURES

Program CONVERTER

Structure of Program and Data Deck



Card Descriptions

The JOB, SCOPE, LOAD, and RUN cards are normal scope control cards. The equip cards should be:

$\begin{smallmatrix}7\\9\end{smallmatrix}$ EQUIP, 1 = RO, HI, SV,** (input tape - in Raw format)

or $\begin{smallmatrix}7\\9\end{smallmatrix}$ EQUIP, 1 = BY (used when using card version (RUSTRAK))

$\begin{smallmatrix}7\\9\end{smallmatrix}$ EQUIP, 2 = RW, HI, (AUX PRINT), PR (auxiliary printer

$\begin{smallmatrix}7\\9\end{smallmatrix}$ EQUIP, 3 = MT20, SV (output tape - in Time format)

The CONTROL card specifies the beginning and ending point of desired data--simply write in octal the first word of the desired data block and the first word following data block. These words must be first words in their respective blocks.

Word 1: Columns 1-16

Word 2: Columns 17-32

The following example of a CONTROL card will cause all data to be used as there are no such words:

```
1                16   17               32
0000000000000000       7777777777777777     unused
```

The CONSTANTS cards specify the count constant and data of each traverse. Any traverse for which there is no CONSTANTS card will automatically be assigned a constant of 12025.5 and a date of 080164 (August 1, 1964).

Traverse number:	Columns 1 - 3
Date:	Columns 4 - 9
Constant:	Columns 10-15 (no decimal)

Columns 16 through 19 must be blank or zero.

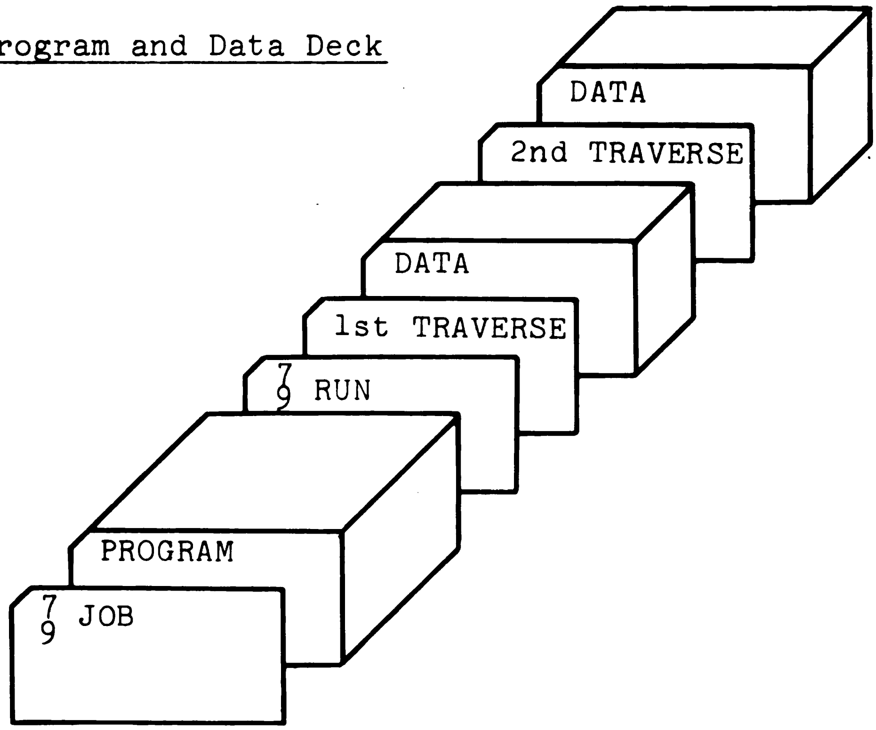
Example for traverse 93, June 23, count constant of 12025.5:

```
1 34    9 10     15 16       19
093062364 1 20255                unused
```

It is not necessary that there be a CONSTANTS card for each traverse, if the constant and date which are automatically assigned are acceptable.

Program CONVERT for Cards

Structure of Program and Data Deck



Card Descriptions

The scope control cards and program deck are the same as with the tape version of the program CONVERT except for the first equip card, which should now be:

$^{7}_{9}$ EQUIP, 1 = BY

The data is broken into groups by traverse, each preceded by a traverse heading card:

1 3 TRAVERSE NUMBER	4 9 DATE FLOWN	not used	20 27 HEADER ^ ^	not used

The data is laid out in successive time and rustrak readings:

1 3 TRAVERSE NUMBER	4 9 TIME #1 IN HRS, MINS, SECS	10 14 COUNT FROM RUSTRAK	15 20 TIME #2	21 25 COUNT #2

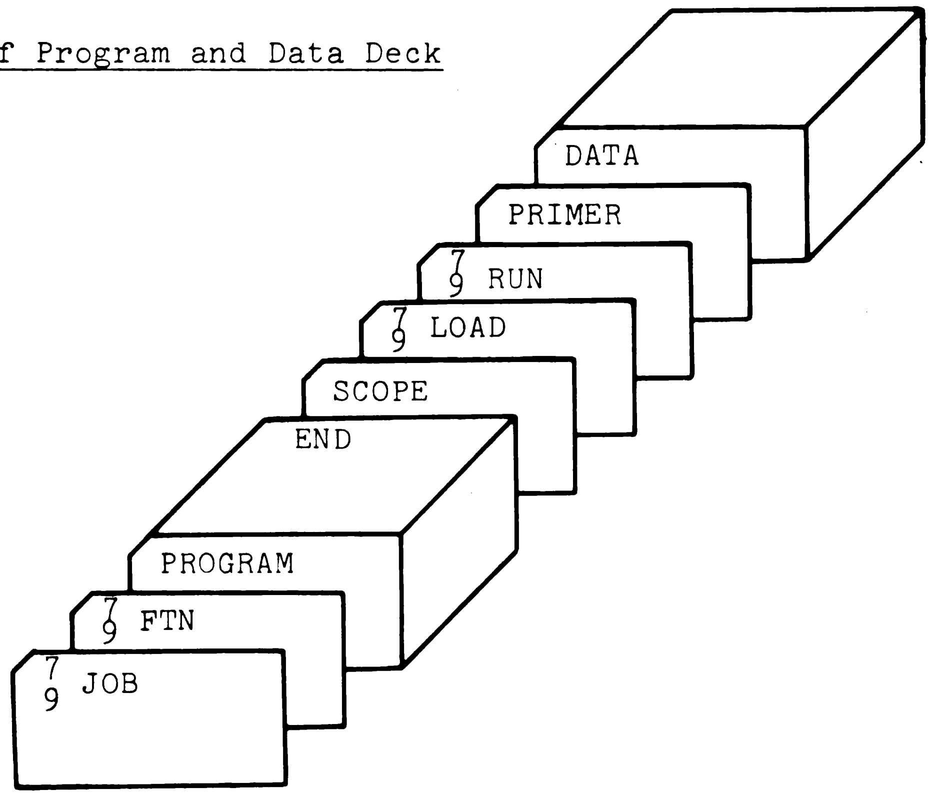
=

=

75 TIME #7	76 80 COUNT #7

Program GROUND

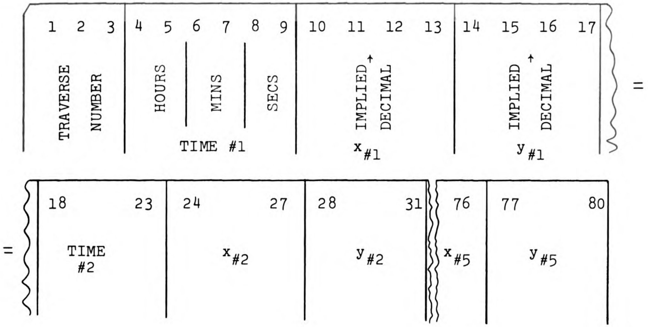
Structure of Program and Data Deck



Card Descriptions

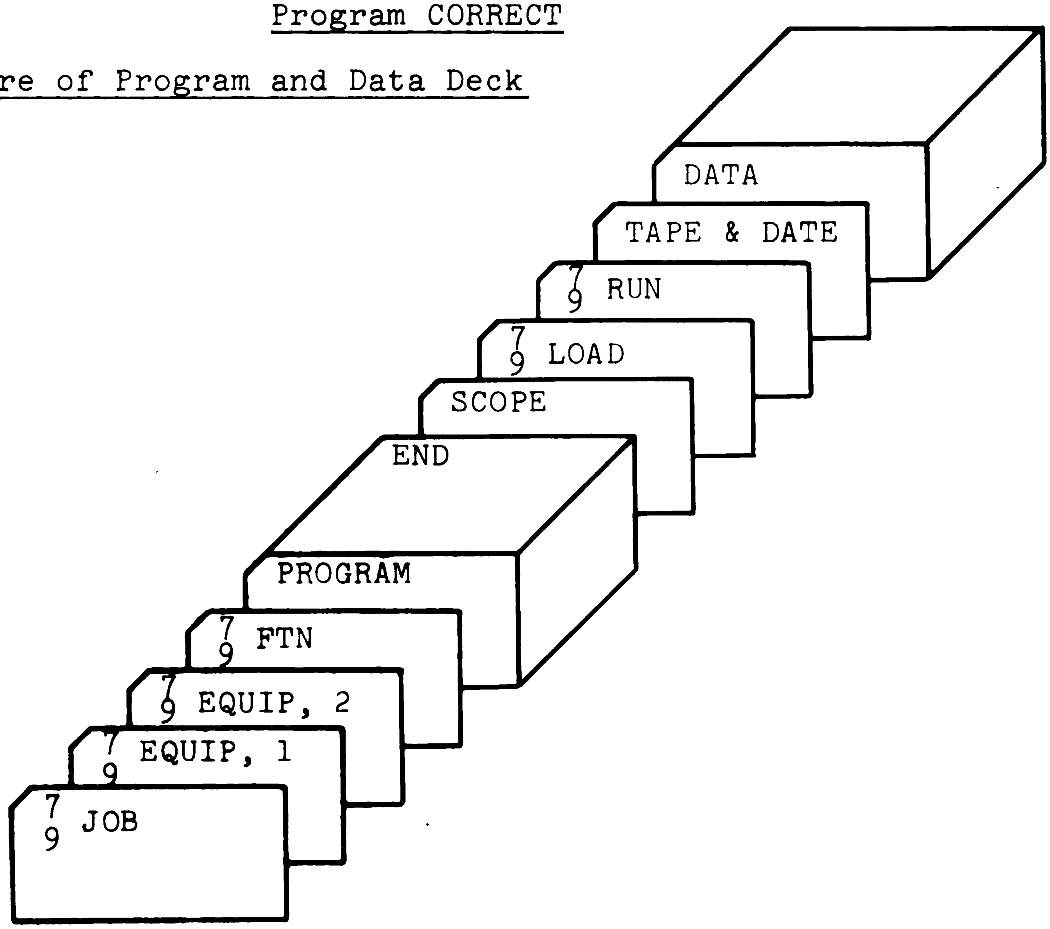
All scope control cards are conventional.

The first data card consists of only the traverse number of the first traverse in the job. This card serves only to "prime the pump." The number is punched in columns 1-3 (just the traverse number of the first traverse). The data cards are each made up of a traverse number followed by 5 time-coordinate triples.


1 2 3
TRAVERSE NUMBER
4 5 6 7 8 9
HOURS
MINS
SECS
TIME #1
10 11 12 13
IMPLIED DECIMAL
x #1
14 15 16 17
IMPLIED DECIMAL
y #1
=
=
18 23
TIME #2
24 27
x #2
28 31
y #2
76
x #5
77 80
y #5

Program CORRECT

Structure of Program and Data Deck



Card Descriptions

The scope control cards are conventional. The equip cards are: $^7_9$ EQUIP, 1 = RO, (MERGED INTENSITIES, 1, 1), SV

$^7_9$ EQUIP, 2 = RW, **, MT20, SV

The TAPE and DATE card is for reference only. It must be present but need not be punched.

Columns 1 - 8: Submission date, e.g. 06/30/65 (alphabetic field).

Columns 9 -14: Physical reel number of input, right-justified.

The data deck has been described elsewhere.

Brief Description of Card Formats

The following cards are designed to allow the geological reviewer to edit the output data from program CONVERT of the aeromagnetic project. See attached copy of card formats, Figure 3.

TRAVERSE Card:

This card is placed at the beginning of each traverse deck. It alerts the program to search for the traverse named on this card, and assigns it the proper sequence number and flight order. An altitude field also is provided.

NAME Card:

This card is used only when the traverse number is erroneous or missing. It causes the program to rename the traverse. This card must follow a SPLIT card when a traverse is being split.

DATE Card:

This card is used only when the date is erroneous. It should usually accompany a NAME card.

XY POINT Card:

This card identifies a navigational point. All output will be in terms of these navigational points, that is, all magnetic readings will be given with reference to a navigational point. Most of this data was punched onto cards to enable a study of the ground speeds. Time as found on the graphs was then inserted onto these cards. The only additional cards necessary were the "dummy" points necessary for

Appendix B--Figure 3

IBM FORTRAN Coding Form

X28-7327-5
Printed in U.S.A.

PROGRAM: CARD FØRMATS FØR PRØGRAM CØRRECT

PROGRAMMER | DATE | PUNCHING INSTRUCTIONS: GRAPHIC / PUNCH | PAGE OF | CARD ELECTRO NUMBER*

STATEMENT NUMBER | CONT. | FORTRAN STATEMENT | IDENTIFICATION SEQUENCE

STATEMENT	T_1	T_2	N_1	N_2	R_1	R_2	R_3	etc.	
TRAVERSE	traverse nø	sequence nø	altitude	ørder					
NAME	corrected nø								
DATE	corrected date								
XY PØINT				real or dummy	X-cørdinate	Y-cørdinate	Longitude	Latitude	altitude
BEGIN					values tø insert				
INSERT		corrected time	number	number	values tø insert				
DELETE	time as	(may be blank)	of values	of values					
CHANGE	føund øn		beyønd	tø be acted	values tø change				
ZERØ	graph		time	upøn					
ADD					additive factør				
TIME									
SPLIT									
JØIN									

Nøt used

*A standard card form, IBM electro 888157, is available for punching statements from this form

adjustment of count rates. These dummy point cards were identified by a "1" in column 28. Times were taken from these cards.

BEGIN Card:

This card identifies the first point from the graph to be used as output. The program will begin with the reading at $T_1 + N_1$ when $N_2 \geq 0$. When $N_2 > 0$, the program will first insert N_2 values from input cards, it will then continue with the reading at $T_1 + N_1$.

INSERT Card:

This card inserts N_2 values from the input cards before the reading at $T_1 + N_1$.

DELETE Card:

This card deletes N_2 values beginning with the reading at $T_1 + N_1$. (Note that these readings are deleted, not zeroed or changed, even the positions they occupied are deleted. See ZERO card description).

CHANGE Card:

This card changes N_2 values beginning with the reading at $T_1 + N_1$. That is, the reading at $T_1 + N_1$ is changed to R_1, the reading at $T_1 + N_1 + 1$ is changed to R_2, . . . , to R_{N2}.

ZERO Card:

This card changes N_2 reading to zero, beginning with the reading at $R_1 + N_1$. Any reading which is found to be zero, upon outputing by the program, was interpolated linearly, by the program, between the nearest non-zero readings. Two or more successive zero readings are permissible. That is, the user may change any reading to zero. When the program attempts to output these zero readings, it detects them as zero and interpolates between the last non-zero reading to be outputed and the next non-zero reading to be output. Should the zero readings occur either at the beginning or end of a traverse, so that interpolating is impossible, the zero readings is changed to equal the nearest non-zero reading.

ADD Card:

This card changes the additive factor. All readings are adjusted by this additive factor when outputed by the program and hence the user can adjust readings between traverses for amounts indicated by tie-lines, diurnals, etc. This additive factor is set to zero at the beginning of each traverse. A plus factor will increase all magnetic readings thereafter; a minus factor will decrease all magnetic readings thereafter.

TIME Card:

This card changes the time reading. It should be seldom needed as output will not depend on times.

SPLIT Card:

This card is used to divide one continuous sequence of magnetic readings into two traverses, beginning with the reading at $T_1 + N_1$. The card immediately previous must have been the last XY POINT card of the previous segment and the card immediately following must be a NAME card for the next segment. BEGIN, etc. cards are the same as with a normal traverse.

JOIN Card:

This card signals the program to ignore the beginning of the next input traverse and continue the present traverse with the data of that next traverse. To be joined with this card, two segments of a traverse must be directly adjacent on the input tape (follow one another on the graphs). Two widely separated input segments (such as Numbers 112 and 115) can be joined by appropriate use of NAME cards and sequence fields of TRAVERSE card.

END Card:

This card defines the last reading to be outputed for a traverse. The immediately previous card must be the last XY POINT card for the traverse.

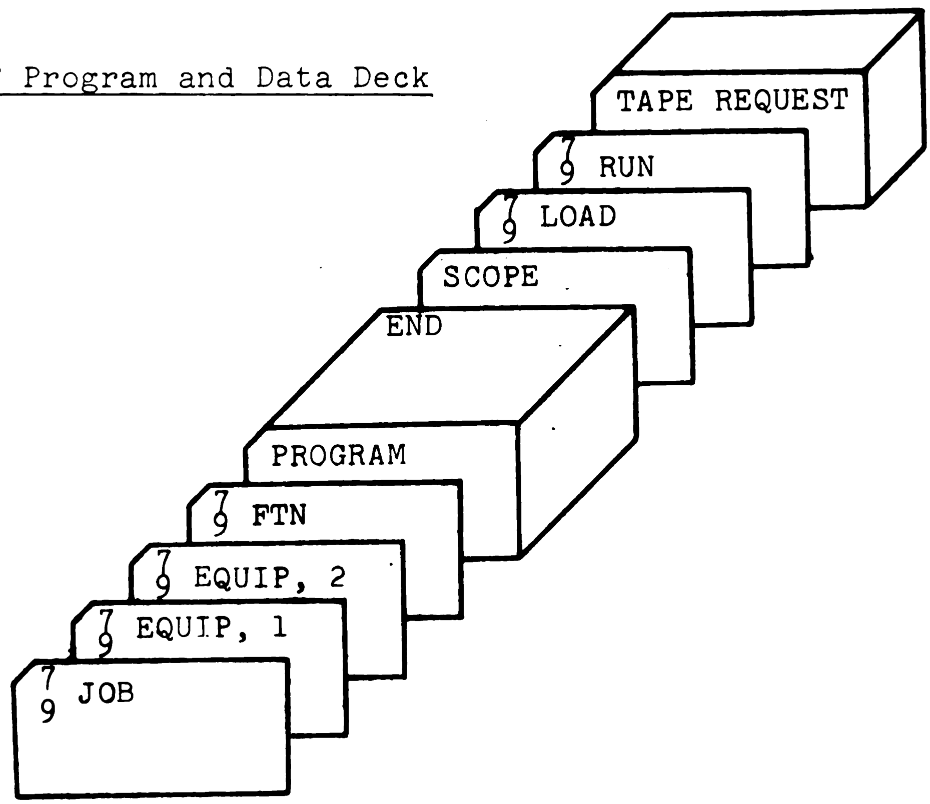
Program CORRECT reads the above cards along with the data tapes outputed by program CONVERT (graphing program). The output is a printed record of all changes made and a magnetic tape of the corrected data.

A change in data control occurs at this point in the system. The input data is controlled by the time readings and is blocked in terms of all readings following each time reading. The output data is controlled by the X-Y points and is blocked in terms of all readings between each pair of X-Y points. The traverses can now be properly named, sequenced and ordered.

Because of the change in data control, it is not necessary to correct all time readings. Input data can be referenced by the times existing on the graphs and output data can be referenced by the X-Y points. Therefore, X-Y times are the only ones which need to be corrected. A means of correcting these times is provided on the XY POINT card.

Program MERGE

Structure of Program and Data Deck



Card Descriptions

The scope control cards are conventional. The equip cards depend on the nature of the tapes being merged.

Merging Time format tapes for CORRECT:

$^{7}_{9}$ EQUIP, 1 = RO, (*03, , 01), SV

$^{7}_{9}$ EQUIP, 2 = (MERGED INTENSITIES, 1, 1), SV, DA

Merging Coordinate tapes:

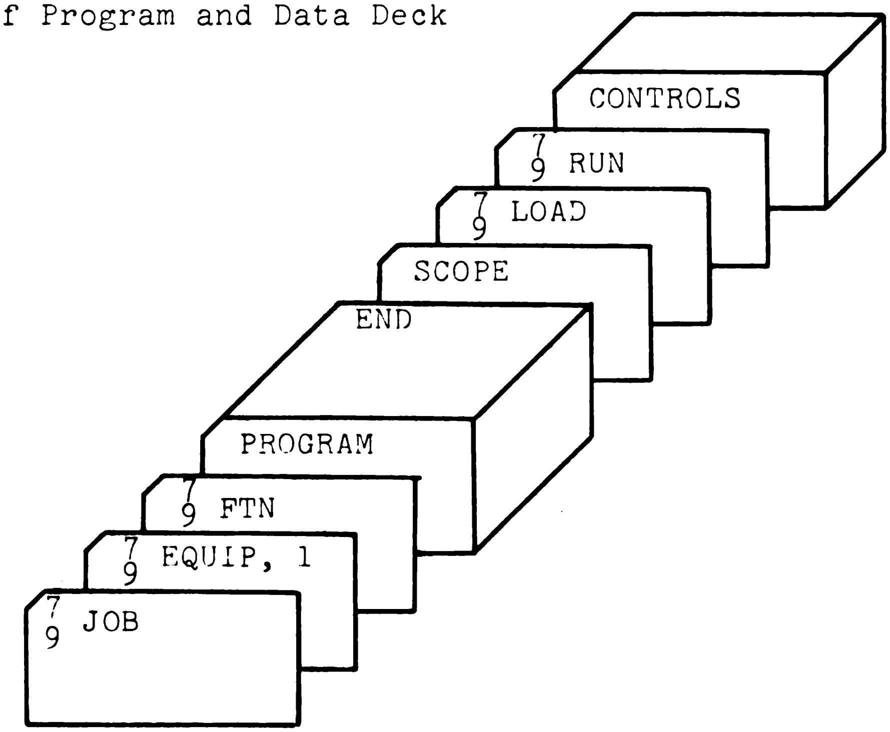
$^{7}_{9}$ EQUIP, 1 = RO, **, SV

$^{7}_{9}$ EQUIP, 2 = RW, MT20, **, SV

Tape request cards: The physical reel number of each reel to be merged is punched, one to a card, in the first 3 columns of the card, right-justified. These may be in any order desired.

Program MGRAPH

Structure of Program and Data Deck



Card Descriptions

The scope control cards are conventiona. The equip card should be: $\frac{7}{9}$ EQUIP, 1 = RO, SV, **

The controls may be any number of cards, each consisting of 20 fields of 4 digits, right justified, beginning with card 1:

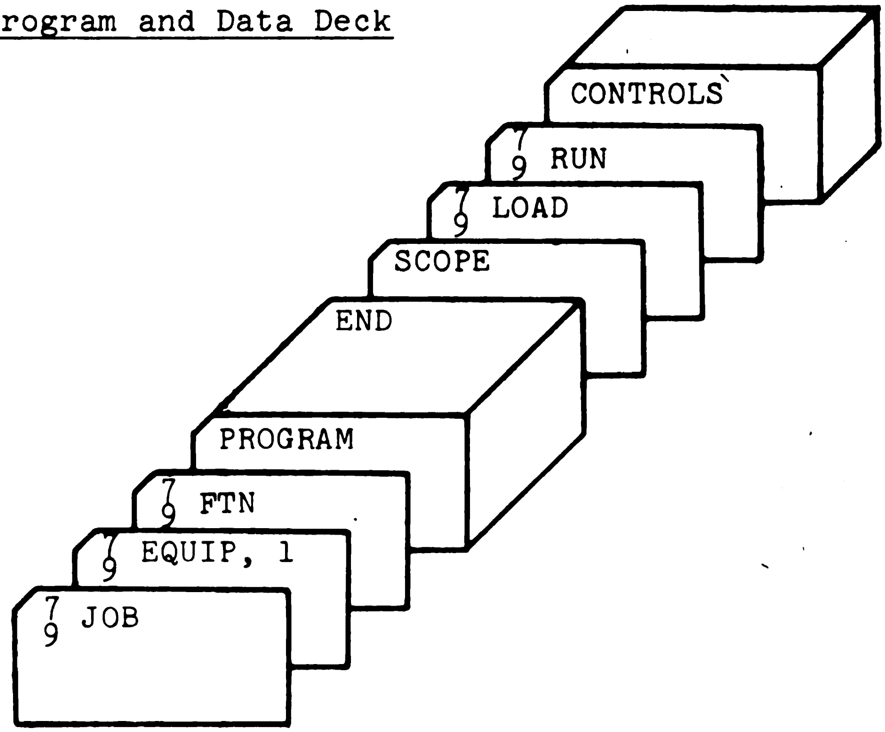
Columns	Description
1 - 4	Physical reel number for reference
5 - 8	Number of graphs being requested
9 - 12	Traverse/sequence control:
	if 1, lines will be selected by traverse number
	if 7, lines will be selected by sequence number
13 - 16	Traverse or sequence number of line requested
17 - 20	Traverse or sequence number of line requested
	Etc.

Continue on second card, etc. as needed.

(Note: This packet of controls constitutes a table and has no bearing on the order of graphs produced. Traverses are graphed in the order they appear from the input data tape, if and only if the control for that traverse is present in the table.

Program MPLOT

Structure of Program and Data Deck



Card Descriptions

The scope control cards are conventional. The equip card should be: $\frac{7}{9}$ EQUIP, 1 = RO, SV, **

The controls may be any number of cards, each consisting of 20 fields of 4 digits, right-justified.

Columns	Description
1 - 4	Physical reel number for reference
5 - 8	Regional/Residual; if non-zero, the regional field will be removed before plotting
9 - 12	Number of plots requested

13 - 16 Traverse/Sequence number control:

if 1, traverse numbers are used for selection

if 7, sequence numbers are used for selection

17 - 20 Request traverse or sequence number for plotting

Etc.--continue on second, third, etc. cards.

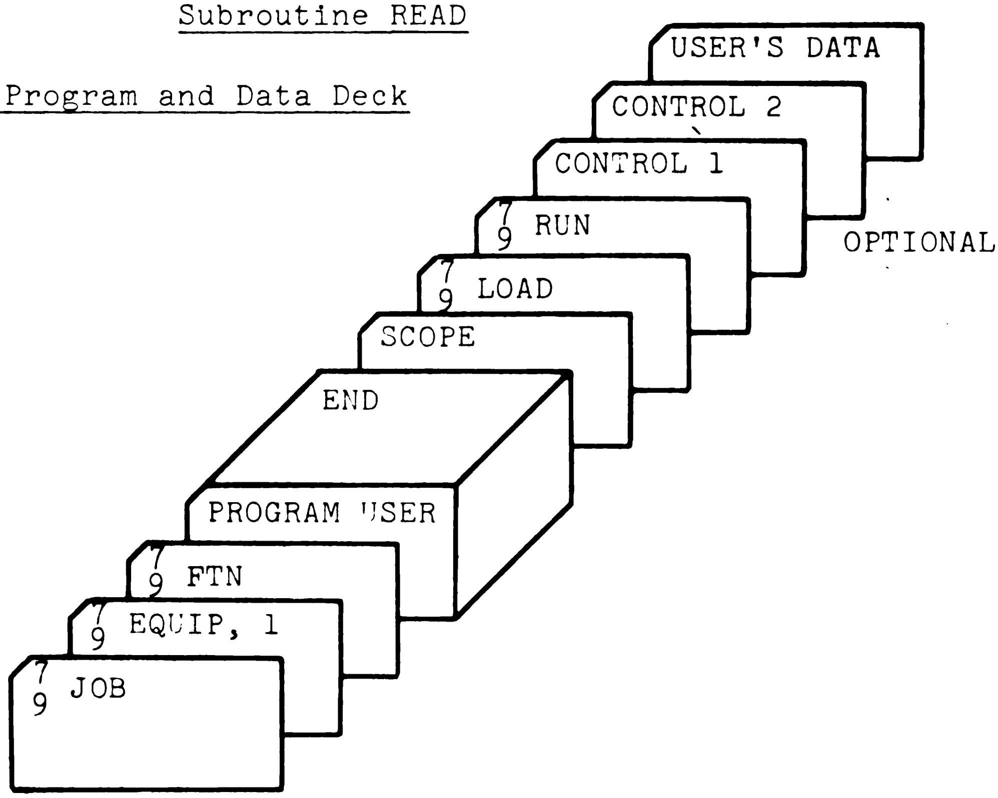
(Note: This packet of control cards has no bearing on the order of plotting. Traverses are plotted in the order of appearance on the input data tape, if and only if the traverse control number appears on this card(s).)

CARD #2	Columns	Residual Control
BASE 1	0 - 7	Base level for large-scale plot, e.g. 1200 gammas
SCALE 1	8 - 12	Scale for 1, e.g. 400 gammas/in.
BASE 2	13 - 14	Base level for Small-scale, e.g. -18750.
SCALE 2	20 - 24	Scale for 2, e.g. 2500 gammas/in.
BASE LEVEL	25 - 31	For Straight line, e.g. 0 for Residual, 59100 for Regular

CARD #2	Regular Control
BASE 1	58200
SCALE 1	400
BASE 2	40350
SCALE 2	2500
BASE LEVEL	59100

Subroutine READ

Structure of Program and Data Deck



Card Descriptions

The scope control cards are conventional. The equip card should be: $\overset{7}{9}$ EQUIP, 1 = RO, **, SV

Control cards 1 and 2 are optional, and appear in the order dictated by the user's program when requested (see the subroutine READ discussion). These control cards specified either or both, a limited area or the particular traverses of interest. They are quite similar in description to the limit cards of programs PROFILE and CONTOUR, and the table of specified traverses in programs MPLOT and MGRAPH.

The control card for a limited area (fields have F4.2 format) is:

Columns	Description
1 - 4	Eastern boundary of desired area
5 - 8	Western boundary of desired area
9 - 12	Southern boundary of desired area
13 - 16	Northern boundary of desired area

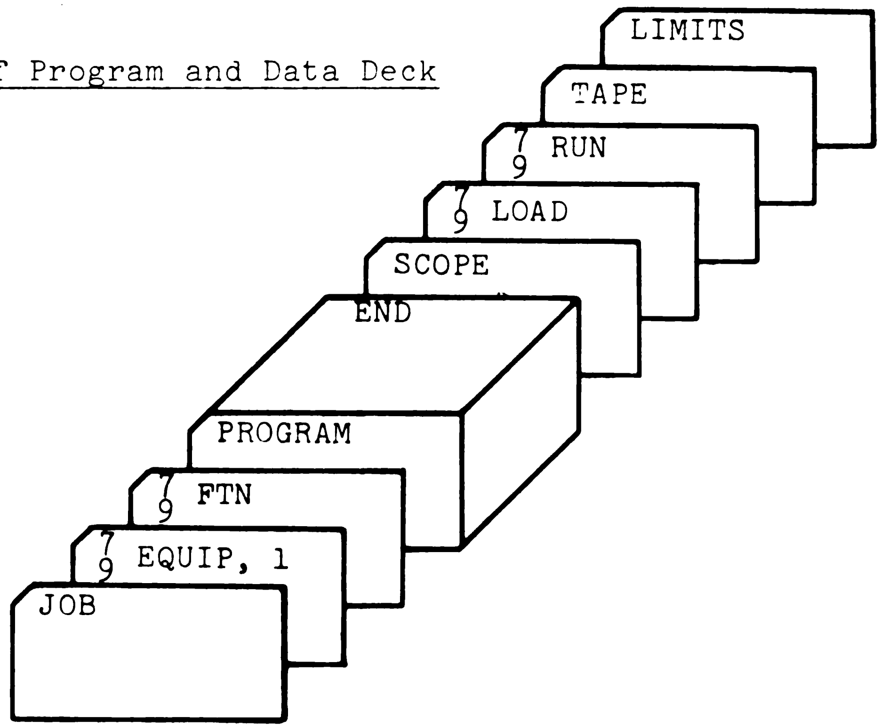
The control card(s) for specified traverses (20 fields per card, 4 digits, right-justified) are:

Columns	Description
1 - 4	Traverse/sequence control:
	If = 1, control is by traverse numbers
	If = 2, control is by sequence numbers
5 - 8	Number of traverses requested--Count of TRAVERSE TTOT
9 - 12	1st requested traverse or sequence number
13 - 16	2nd requested traverse or sequence number
	Etc.

Continue on as many cards as needed.

Programs CONTOUR and PROFILE

Structure of Program and Data Deck



Card Descriptions

The scope control cards are conventional. The equip card is: $\begin{smallmatrix}7\\9\end{smallmatrix}$ EQUIP, 1 = RO, **, SV

The TAPE card consists of three fields, right-justified:

Columns	Description
1 - 4	Physical reel number for reference
5 - 8	Beginning traverse number. If blank, the program begins at the beginning of the tape.
9 - 12	Ending traverse number (one beyond desired traverse). If blank, the programs are read to end of the tape.

The LIMITS card consists of 4 fields, F4.2 format in X-Y Coordinate.

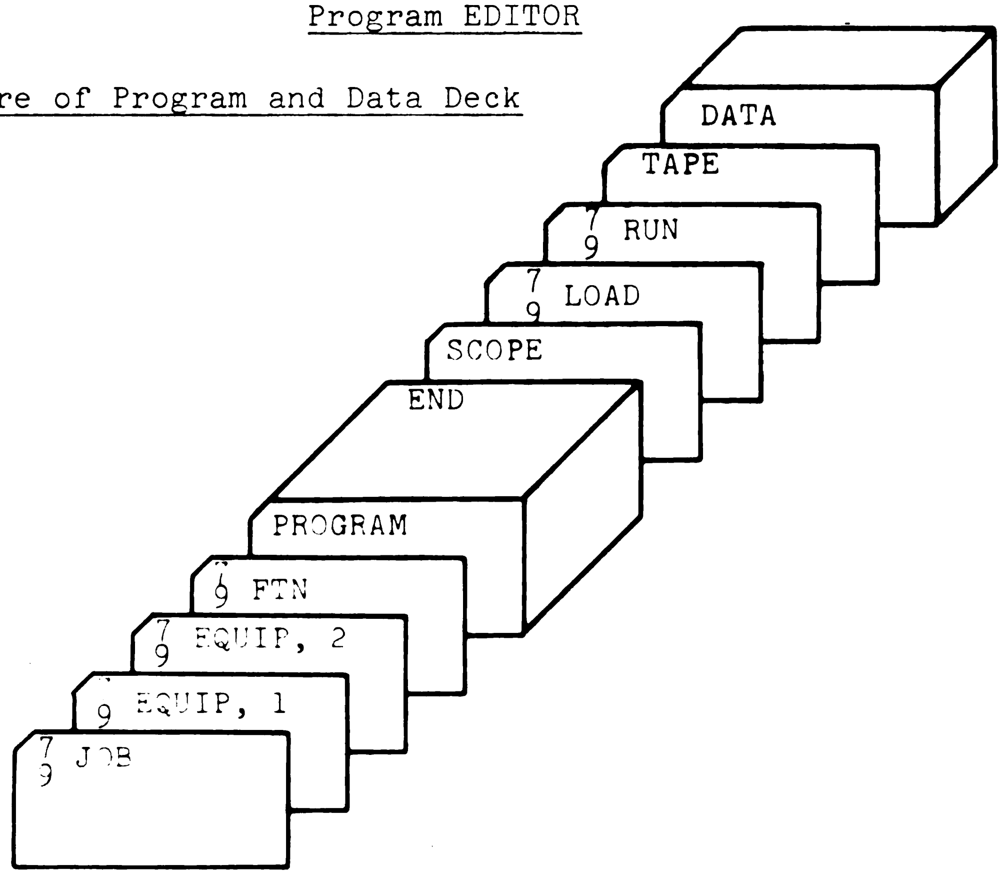
Columns	Description
1 - 4	Eastern boundary of area desired
5 - 8	Western boundary of area desired
9 - 12	Southern boundary of area desired
13 - 16	Northern boundary of area desired

Example, for x from 5.00 to 35.00 and y from 40.00 to 67.00.

1			4	5			8	9			12	13			16	not
0	5	0	0	3	5	0	0	4	0	0	0	6	7	0	0	used

Program EDITOR

Structure of Program and Data Deck



Card Descriptions

The scope control cards are conventional. The equip cards should be:

$\frac{7}{9}$ EQUIP, 1 = RO, **, SV

$\frac{7}{9}$ EQUIP, 2 = RW, MT20, **, SV

The first control card, TAPE, determines the job that program EDITOR will do.

Columns	Description
1 - 8	The date of submission (e.g. 06/30/65). Alphabetic field
9 - 16	The physical reel number for reference, right-justified
17 - 24	If non-zero, no editing takes place. The input tape, unit 1, is printed in book form for easy reading. If zero, data cards are expected which will cause editing.

Editor Cards

The format of the data cards for editing is indicated by the attached coding sheets, Figure 4. Note that the coding sheets show only 9 fields, whereas the actual data cards may use 10, the tenth being columns 73-80.

The first 26 forms of data cards are for changing one of the control words in a segment of a data tape in Coordinate format. That is "TRAVERSE" will cause the traverse number to be changed, "Y COOR Z" will cause the y coordinate for the ending point of the segment to be changed. Note that these changes affect only the one segment to which they refer. Field 2 contains the new value of the control word.

A segment is specified with a "PAGE" card. Field 2 is the page number. Field 3 of the "PAGE" card specifies the traverse number, field 4 the sequence number and field 5 the segment number. All must be correct for a successful locate.

The "PUBLISH" card may be inserted anywhere in the job. It causes EDITOR to publish a new version of the data book, for future reference, after all editing is completed. Field 2 of the "PUBLISH" card specifies which unit to publish (1 for the old tape, 2 for the new, edited tape). Field 3 is optional, and specifies the physical reel number of the tape being published for reference. The "CHANGE" card may be used to change one value of magnetic data within a segment. Field 2 specifies the data word number (which is printed to the left of each magnetic work in the published book), and field 3 is the new value. A before-and-after record is printed of the change.

The "DELETE" card will cause the deletion of any number of magnetic values in a segment. Field 2 specifies the number of values to be deleted, and field 3 specifies the data word number of the first magnetic value to be deleted.

The "INSERT" card will cause the insertion of any number of values. Field 2 specifies the number of values to be inserted, field 3 specifies the data word number before which these new values are to be inserted, and the new values begin in field 4 and continue through field 10. Continuation cards begin in field 2.

When using program EDITOR, it is important that "PAGE" requests be made in ascending order. The program will abort if this is not done. The order of all other cards is immaterial, so long as they each refer to the last "PAGE" card.

Appendix B--Figure 4

IBM

FORTRAN Coding Form

X28-7327-5
Printed in U.S.A.

PROGRAM EDITØR CARDS - Used only to change a field	PUNCHING INSTRUCTIONS	GRAPHIC	PAGE OF
PROGRAMMER / DATE		PUNCH	CARD ELECTRO NUMBER*

STATEMENT NUMBER (1–5)	CONT. (6)	FORTRAN STATEMENT (7–72)	IDENTIFICATION SEQUENCE (73–80)

```
1  TRAVERSE
2  DATE
3  CØNSTANT
4  REVERSE
5  AVERAGE
6  MINIMUM
7  SEQUENCE
8  SEGMENT
9  MAXIMUM
10 TIME 1
11 X CØØR 1
12 Y CØØR 1
13 LØNG. 1
14 LAT. 1
15 ALT. 1
16 REG. 1
17 CORR. 1
18 TIME 2
19 X CØØR 2
20 Y CØØR 2
21 LØNG. 2
22 LAT. 2
23 ALT. 2
24 REG. 2
```

FIELD 2 FIELD 3 FIELD 4 FIELD 5 FIELD 6 FIELD 7 FIELD 8 FIELD 9 FIELD 10

*A standard card form, IBM electro 888157, is available for punching statements from this form

Appendix B--Figure 4 (continued)

IBM FORTRAN Coding Form

X28-7327-5
Printed in U.S.A.

PROGRAM	PUNCHING INSTRUCTIONS	GRAPHIC	PAGE OF
PROGRAMMER / DATE		PUNCH	CARD ELECTRO NUMBER*

	STATEMENT NUMBER	K1	K2	K3	K4	NEW(1)	NEW(2)	NEW(3)	NEW(4)	IDENTIFICATION SEQUENCE
25	CORR. 2									
26	NO. OF M									
27	PUBLISH	Lun	tape No.							
28	PAGE	Page No.	traverse No.	sequence No.						
29	CHANGE	Data Word No.	Data (New Value)							
30	INSERT	No. of Values	start -1	Values →						
31	DELETE	No. of Values	start -1							
	CHANGE	No. of Values	starting With							

*A standard card form, IBM electro 888157, is available for punching statements from this form

BIBLIOGRAPHY

Allen, R. C. 1914. Relative to an Extension of the Menominee Iron Range Eastward from Waucedah to Escanaba, Michigan. Econ. Geol., 9, pp. 236-238.

Bath, G. D. and G. M. Schwartz. 1960. Magnetic Anomalies and Magnetization of Main Mesabi Iron Formation (abstract). Inst. on Lake Superior Geology, Madison, Wisconsin, p. 27.

Bath, G. C. 1962. Magnetic Anomalies and Magnetizations of the Biwabik Iron Formation, Mesabi Area, Minnesota. Geophysics, 27, pp. 627-650.

Bacon, L. O. 1957. Relationship of Gravity to Geologic Structure in Michigan's Upper Peninsula. Inst. on Lake Superior Geology, Houghton, Michigan, pp. 54-58.

Cain, J. C., S. J. Hendricks, W. E. Daniels, and D. C. Hensen. 1964. Computation of the Main Magnetic Field from Spherical Harmonic Expansions. Goddard Space Flight Center Report X-611-64-316.

Cain, J. C., S. J. Hendricks, W. E. Daniels, and D. C. Jensen. 1965. An Evaluation of the Main Geomagnetic Field 1940-1962. J. Geophys. Res., 70 (15), pp. 3647-3674.

Case, J. E. and J. E. Gair. 1965. Aeromagnetic Map of Parts of Marquette, Dickinson, Barage, Alger and Schoolcraft Counties, Michigan and its Geologic Interpretation. U. S. Geol. Surv. Geophy. Inv. Map GP467.

Cohee, G. V. and K. K. Landes. 1955. Oil in the Michigan Basin, Habitat of Oil. Amer. Assoc. Pet. Geol., pp. 473-493.

Cornwall, H. R. 1954. Bedrock Geology of the Delaware Quadrangle, Michigan. U.S. Geol. Surv. Geologic Quadrangle Map, GQ 51.

Cox, A. and R. R. Doell. 1960. Review of Paleomagnetism. Geol. Soc. Amer. Bull., 71, pp. 645-768.

Dubois, P. M. 1957. Comparison of Paleomagnetic Results for Selected Rocks of Great Britain and North America. Adv. Physics, 6.

Dubois, P. M. 1959. Correlation of Keweenawan Rocks of Lake Superior District by Paleomagnetic Methods. Proc. Geol. Assoc. Canada, 11, pp. 115-128.

Dubois, P. M. 1962. Paleomagnetism and Correlation of Keweenawan Rocks. Bull. Geol. Surv. Canada, 71, 75 pp.

Eardley, A. J. 1951. Structural Geology of North America. Harper and Row, New York.

Fahrig, W. F., E. H. Gaucher, and A. Larochelle. 1965. Paleomagnetism of Diabase of the Canadian Shield. Canadian J. Earth Sciences, 2, pp. 278-297.

Farrand, W. F., J. H. Zumberge, and J. Parker. 1966. New Bathymetric Map of Lake Superior and Some Geological Implications (abstract). Inst. on Lake Superior Geology, Sault Ste. Marie, Michigan, p. 6.

Geological Survey of Canada, Geophys. Paper 7088, 1965.

Gilluly, J. 1964. Volcanism, Tectonism, and Plutonism in the Western United States, Geol. Surv. Amer., Memoir No. 80.

Graham, J. W. 1953. Changes of Ferromagnetic Minerals and their Bearing on Ferromagnetic Properties of Rocks. J. Geophys. Res., 58, pp. 243-260.

Hamblin, W. K. 1958. The Cambrian Sandstones of Northern Michigan. Mich. Geol. Surv. Publ. 51, 145 pp.

Hamblin, W. K. 1961. Paleogeographic Evolution of the Lake Superior Region from Late Cambrian Time. Geol. Soc. Amer. Bull., 72, pp. 1-8.

Hamblin, W. K. 1965. Basement Control of Keweenawan and Cambrian Sedimentation in the Lake Superior Region. Bull. Amer. Assoc. Pet. Geol., 49, pp. 950-958.

Heirtzler, J. R., G. Peter, M. Talwani, and E. G. Zurfluch. 1962. Magnetic Anomalies Caused by Two-Dimensional Structure: Their Computation by Digital Computers and Their Interpretation. Lamont Geol. Observ. Tech. Rep. No. 6.

Hinze, W. J. 1963. Regional Gravity and Magnetic Anomaly Maps of the Southern Peninsula of Michigan. Rept. Invest. 1, Geol. Surv. Div., Dept. Conservation, State of Michigan.

Holmes, A. 1965. Principles of Physical Geology. Ronald Press Co., New York.

Hotchkiss, W. O. 1923. The Lake Superior Geosyncline. Geol. Soc. Amer. Bull., 34, pp. 669-678.

Hough, J. L. 1958. Geology of the Great Lakes. University of Illinois Press, Urbana.

Irving, E. 1964. Paleomagnetism and its Application to Geological and Geophysical Problems. John Wiley and Sons, Inc., New York.

Irving, R. D. 1883. The Copper-Bearing Rocks of Lake Superior. U.S. Geol. Surv. Mon., 5.

Jahren, C. E. 1960. Magnetizations of Iron Formations and Igneous Rocks of Northern Minnesota (abstract). Inst. On Lake Superior Geology, Madison, Wisconsin, p. 28.

Jahren, C. E. 1963. Magnetic Susceptibility of Bedded Iron-Formation. Geophysics, 28, pp. 756-766.

Jahren, C. E. 1965. Magnetization of Keweenawan Rocks Near Duluth, Minnesota. Geophysics, 30, pp. 858-874.

Leith, C. K., R. J. Lund, and Andrew Leith. 1935. Precambrian Rocks of the Lake Superior Region. U.S. Geol. Surv. Profess. Paper 184, 34 pp.

Lilley, F. E. M. 1964. An Analysis of the Magnetic Features of the Port Coldwell Intrusive, M. Sc. thesis, University of Western Ontario.

Meyer, R. P. 1964. North American seismic group experiment (abstract), Proceedings of the 36th Annual Meeting of the Eastern Section of the Seismological Society of America.

Mooney, H. M., and R. Bleifuss. 1953. Magnetic Susceptibility Measurements in Minnesota, 2, Analysis of field results, Geophysics, 18, pp. 383-393.

Moorehouse, W. W. 1960. Gunflint Iron Range in the Vicinity of Port Arthur. Ontario Dept. of Mines, 69 (7), 40 pp.

Oetking, P. F. 1951. The Relation of the Lower Paleozoic to the Older Rocks in the Northern Peninsula of Michigan, Unpublished Ph.D.thesis, University of Wisconsin.

Parkard, M., and Varian, R. 1954. Free Nuclear Induction in the Earth's Magnetic Field. Phys. Rev., 93:941.

Parker, Jack. 1964. Sublacustrine Topography of Eastern Lake Superior, M. Sc. thesis, Michigan Technological University, 63.

Patenaude, R. W. 1964. Results of Regional Aeromagnetic Surveys of Eastern Upper Michigan, Central Lower Michigan, and Southeastern Illinois. The University of Wisconsin Geophysical and Polar Research Center, Research Report Series 64-2, 51 pp.

Patenaude, R. W. 1966. A Regional Aeromagnetic Survey of Wisconsin. Geophy. Mono. No. 10, Amer. Geophys. Union, pp. 111-126.

Pirtle, G. W. 1932. Michigan Structural Basin and Its Relationship to Surrounding Areas. Amer. Assoc. Pet. Geol., 16.

Puskas, F. P. 1960. Preliminary Map No. P-114, Port Coldwell Area. Ontario Dept. Mines.

Raasch, G. O. 1950. Current Evaluation of the Cambrian-Keweenawan Boundary, Illinois Acad. Sci. Trans., 43, pp. 137-150.

Reford, M. S. and J. S. Sumner. 1964. Aeromagnetics. Geophysics, 29, pp. 482-516.

Rudman, A. J., C. H. Summerson, and W. J. Hinze. 1965. Geology of Basement in Midwestern U. S., Amer. Assoc. Pet. Geol. Bull., 49, pp. 894-904.

Smith, T. J., J. S. Steinhart, and L. T. Aldrich. 1966. Lake Superior Crustal Studies: A Comparison of Several Techniques. J. Geophy. Res., 71 (4), pp. 1141-1172.

Stockwell, C. H. 1965. Structural Trends in Canadian Shueld. Amer. Assoc. Pet. Geol. Bull., 49, pp. 887-893.

Strangeway, D. W. 1961. Magnetic Properties of Diabase Dikes. J. Geophy. Res., 66, pp. 3021-3032.

Strangeway, D. W. 1965. Interpretation of the Magnetic Anomalies Over Some Precambrian Dikes. Geophysics, 30, pp. 783-796.

Thiel, E. C. 1956. Correlation of Gravity Anomalies With the Keweenawan Geology of Wisconsin and Minnesota, Geol. Soc. Amer. Bull., 67, pp. 1079-1100.

Thiel, E. C. 1960. Geologic Interpretation of Airborne Magnetometer Profiles Across Lake Superior (abstract). Inst. on Lake Superior Geology, Madison, Wisconsin, 32.

Thomson, J. E. 1953. Geology of Mamainse Point Copper Area. Annual Report, Ontario, Dept. of Mines, 62 (4), 25 pp.

Thwaites, F. T. 1912. Sandstone of the Wisconsin Coast of Lake Superior. Wisc. Geol. Nat. Hist. Surv. Bull., 25, 117 pp.

Thwaites, F. T. 1935. Sublacustrine Topographic Map of the Bottom of Lake Superior. Kansas Geol. Soc. Guidebook, Ninth Ann. Field Conf., pp. 226-228.

Vacquier, U., N. Steenland, R. G. Handerson, and I. Zeitz. 1951. Interpretation of Aeromagnetic Maps. Geol. Surv. Amer., Memoir No. 47.

VanHise, C. R. and C. K. Leith. 1911. The Geology of the Lake Superior Region. U.S. Geol. Surv. Mono. 52. 641 pp.

VerWibe, W. A. 1957. North American Petroleum, Edwards Brothers, Ann Arbor, Michigan.

Weber, J. R. and A. K. Goodacre. 1966. A Reconnaissance Underwater Gravity Survey of Lake Superior. Geophy. Mono. No. 10, Amer. Geophys. Union, pp. 56-65.

White, W. S. 1957. Regional Structural Setting of the Michigan Native Copper District. Inst. on Lake Superior Geology, Houghton, Michigan, pp. 3-16.

White, W. S. 1960. The Keweenawan Lavas of Lake Superior, an Example of Flood Basalts. Amer. Jour. of Sci., 258-A, pp. 367-374.

White, W. S. 1966a. Tectonics of the Keweenawan Basin, Western Lake Superior Region. U. S. Geol. Surv. Profess. Paper, 424-E, 23 pp.

White, W. S. 1966b. Geologic Evidence for Crustal Structure in the Western Lake Superior Basin. Geophy. Mono. No. 10, pp. 28-41.

Wold, R. J. 1964. The Elsec Wisconsin Digital Recording Proton Procession Magnetometer System. The University of Wisconsin, Geophysical and Polar Research Center, Research Report Series, 64-4, 83 pp.

Wold, R. J. 1966. The Elsec Wisconsin Digital Recording Proton Procession Magnetometer System and a Geophysical Interpretation of Western Lake Superior, Ph.D. thesis, University of Wisconsin.

Wold, R. J. and N. A. Ostenso. 1966. Aeromagnetic, Gravity and Sub-Bottom Profiling Studies in Western Lake Superior. Geophy. Mono. No. 10, Amer. Geophys. Union, pp. 66-94.

Wollard, G. P., and H. R. Joesting. 1964. Bouguer Gravity Anomaly Map of the United States, U. S. Geol. Surv. Spec. Map.

Zumberge, J. H., and Paul Gast. 1961. Geological Investigations in Lake Superior, Geotimes, 6 (4), pp. 10-13.