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AN AEROMAGNETIC INVESTIGATION OF THE SOUTHERN PENINSULA OF MICHIGAN

By

Richard L. Kellogg

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ABSTRACT

AN AEROMAGNETIC INVESTIGATION OF THE SOUTHERN PENINSULA OF MICHIGAN

By

Richard L. Kellogg

Only fragmentary direct information is available on the basement complex underlying the Phanerozoic sediments of the Michigan Basin because of the limited and poorly distributed basement drill tests. To supplement this information, a regional aeromagnetic survey has been conducted of the Southern Peninsula. Approximately 17,000 miles of total magnetic intensity data were recorded along north-south flight lines spaced at three mile intervals, and flown at 3,000 feet MSL.

A basement configuration map prepared from magnetic depth estimates and basement drill tests confirms that the basement surface under the Southern Peninsula has the form of an oval depression reaching a maximum depth of approximately 15,000 feet below sea level on the western shore of Saginaw Bay. A basement high underlies the Howell anticline in Livingston County and a roughly north-south striking regional basement trough plunges into the basin from the

common boundary point of Indiana, Ohio and Michigan to the vicinity of 42° 30'N. The map shows a broad basement platform striking northwest in the extreme southwest corner of the Peninsula.

Interpretation of the residual aeromagnetic map in conjunction with geologic and other regional geophysical data from the Southern Peninsula and adjacent areas indicates that the basement of the Michigan Basin has had a complex geologic history. Four basement provinces are delineated on the basis of magnetic and gravity anomalies, isotope ages of samples obtained from basement drill holes, and extrapolation of known Precambrian geology from the margin of the Basin. The Penokean province can be traced from northern Michigan and Wisconsin into the northern portion of the Southern Peninsula by means of several regional magnetic anomalies. In the Southern Peninsula, this province is characterized by east-southeast striking anomalies. Central and southwestern Michigan is underlain primarily by felsic rocks correlating with the Central province.

Basement rocks in southeastern Michigan, which strike generally north-northeast are interpreted as metamorphosed intrusives and extrusives and mafic and felsic gneisses of the Grenville province. The western boundary of this province strikes south-southwest from Saginaw Bay to west of the Howell anticline and then due south to the Michigan-Ohio boundary. A Keweenawan rift zone characterized by mafic intrusives, extrusives and uplifted gneisses transects the Peninsula from the Grand Traverse Bay area to southeastern Michigan. Keweenawan igneous activity may also occur southwest of the Keweenawan rift zone where several local magnetic anomalies occur along northwest striking trends. These trends parallel the regional gravity anomaly pattern.

The geology of the Keweenawan rift zone was investigated by matching observed magnetic and gravity anomalies with theoretical anomalies derived from models based on geological and geophysical interpretation of the Mid-Continent and Kapuskasing gravity anomalies. The observed anomalies can be derived from a variety of possible geological sources. An interpretation based on a rift zone containing volcanics, gneisses and intrusives differentially uplifted against granite, gneisses and metasediments of adjacent provinces is favored for the origin of the magnetic anomaly. The gravity anomaly may be explained by these lithologies plus associated modification of deep crustal layers.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure		Page

CHAPTER I

INTRODUCTION

The Aeromagnetic Survey of the Southern Peninsula of Michigan

Nature and Objectives

The Michigan Basin, centered in the Southern Peninsula of Michigan covers the basement with an estimated maximum 15,000 feet of Phanerozoic sediments. The basement, which is the object of this study, is defined as the first igneous or metamorphic rocks found under the unmetamorphosed sedimentary cover. The basement complex of the entire Midwest has been the subject of considerable recent interest not only for the purpose of determining the Precambrian geologic history, but also because of the increasing awareness of the role of the basement on the sedimentation and structure of the overlying Phanerozoic sediments. Exploration for oil and other natural resources has provided a wealth of information about the shallow formations of the Michigan Basin; however, the deeper sediments and the basement itself have largely remained untouched by the drill. Therefore, limited direct geologic information is available.

To augment the available geologic data, a number of regional geophysical studies have been undertaken. These studies indicate that the basement in the Midwest is complex and contains many interesting structural and lithologic features. Magnetic investigations conducted in adjacent states and Canada where Precambrian structures are exposed have indicated considerable magnetic relief that can be correlated with these geologic features. Magnetic studies of the Southern Peninsula also show many interesting magnetic anomalies. However, magnetic coverage is limited to a reconnaissance vertical intensity survey with a station spacing of approximately six miles (Hinze, 1963) which is inadequate to define the magnetic anomalies for anything but the most regional of interpretations. Thus, an aeromagnetic survey was conceived as an economical and rapid means of improving our knowledge of the regional configuration, lithology and structure of the basement of the Michigan Basin.

Specifically, the objectives of this study are to:

1. determine the configuration of the basement surface and prepare a structure contour map of this surface from the magnetic and well control data;
2. delineate the structural trends and basement provinces of the Southern Peninsula and particularly the Grenville Front;

3. quantitatively investigate the possible sources of the major positive gravity and magnetic feature known as the Mid-Michigan gravity and magnetic anomaly crossing the State from Lake St. Clair to the Grand Traverse Bay region.

Scope and Organization

Continuous observations of the magnetic field were made along north-south traverses flown at three mile intervals. Magnetic observations were made with a proton precession magnetometer and navigation was by visual fixes to cultural features. A series of east-west flight lines provided a network into which all flight lines were tied. Nearly 22,000 line miles of data were recorded, of which 17,000 north-south line miles were finally incorporated into the aeromagnetic maps.

Flight elevation for the survey was 3,000 feet above mean sea level or roughly 2,000 to 2,400 feet above the ground surface. The selection of the traverse separation was largely dictated by economic factors; however, the flight elevation was chosen to be consistent with aeromagnetic surveys previously flown in the upper Midwest (Patenaude, 1964, Hinze et al., 1966).

To facilitate the collection of data and to reduce access time to a minimum, the area of investigation was divided along latitude 44°00'N into two overlapping sections. The base of operations for the southern section was East Lansing, and the base for the northern portion was located at Pellston, near the northern tip of the Southern Peninsula.

Observed total intensity aeromagnetic data were correlated with navigational data and computer processed to produce a residual total intensity map of the Southern Peninsula.

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

General Geology of the Southern Peninsula

Previous Basement Studies and Precambrian Geology

Direct geologic investigation of the basement of the Southern Peninsula has been restricted because of the paucity of deep drill holes; however, information from the available basement tests (Figure 1) has been supplemented by the extrapolation of geologic data from outcrops exposed on the Precambrian shield to the west, north and east of the Michigan Basin. In addition, numerous drill holes have penetrated basement in nearby Wisconsin, northern Illinois, Indiana and Ohio, and southern Ontario. Several authors have recently studied the basement provinces in the vicinity of the Southern Peninsula. Lidiak *et al.* (1966) studied provincial

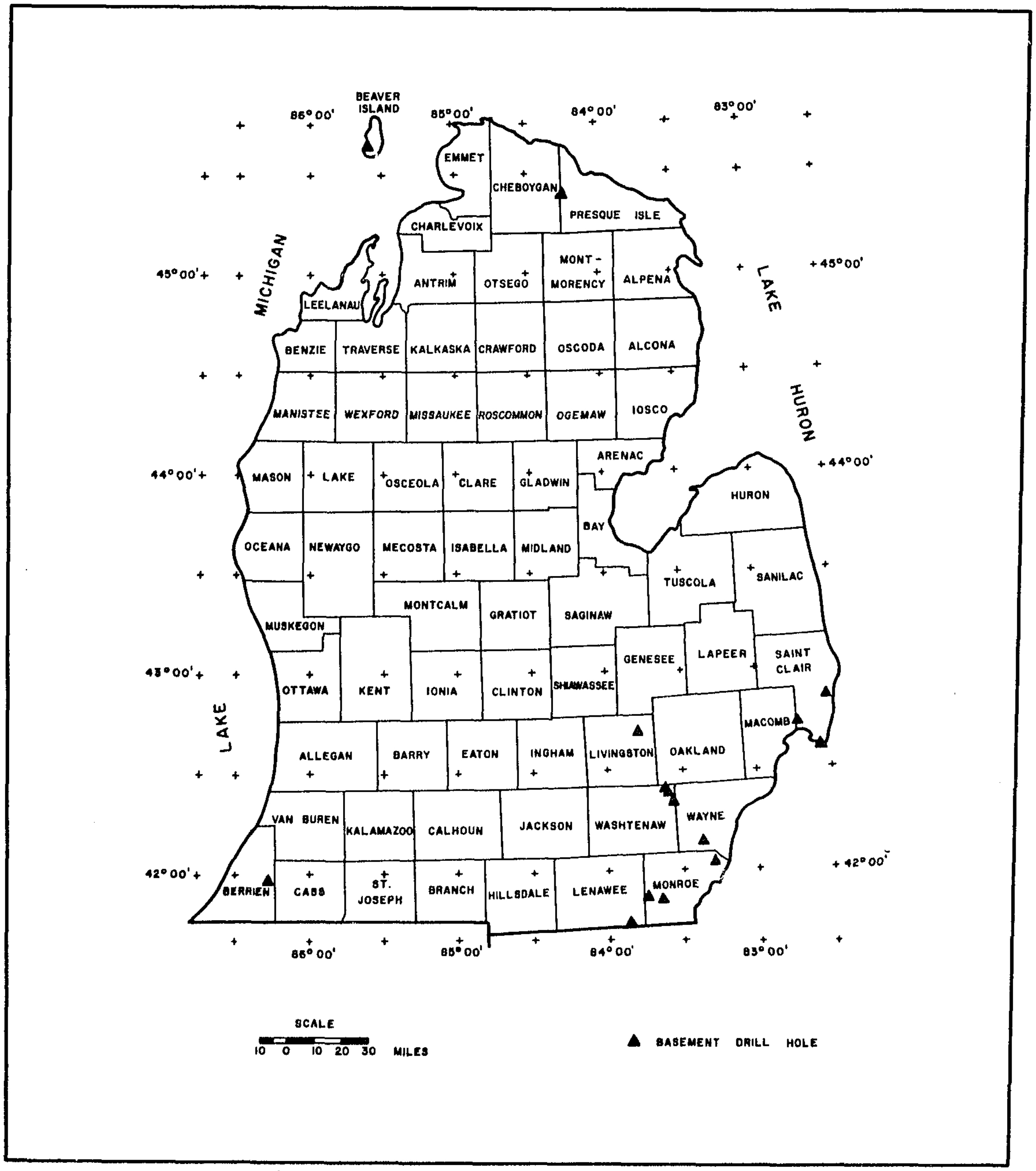

Figure 1.--Basement Drill Holes, Southern Peninsula of Michigan.

boundaries on the basis of geochronology in the Midcontinent region. Following Hinze (1963), they show a belt of Keweenawan mafic igneous rocks transecting the Southern Peninsula. These rocks extend from the Grand Traverse Bay region to a point roughly 35 miles west of Lake St. Clair, where they are abruptly terminated by the western margin of the Grenville province. They suggest that "the supracrustal Keweenawan rocks terminate near Lake Erie, possibly as a result of erosion during uplift of the intracrustal Grenville rocks, or because of nondeposition of these rocks beyond southeastern Michigan" (Lidiak et al., 1966, pg. 5429).

Muehlberger et al. (1967) also reviewed the structural provinces underlying the Michigan Basin. The boundary between the Central province (1.2-1.5 b.y.) and the Penokean province (1.6-1.8 b.y.) was drawn just north of the northern tip of the Southern Peninsula. Most of the Southern Peninsula was considered to be underlain by rocks of the Central province except for the transecting Keweenawan rift zone discussed above and the Grenville province in the eastern portion of the Thumb area.

Hinze and Merritt (1969) show much the same picture as Muehlberger et al. except that the boundary between the Penokean and Central provinces was drawn so as to roughly divide the Southern Peninsula along latitude 44°00'N. Hinze and Merritt also assigned lithologies to the basement rocks, on the basis of geophysical anomalies, basement tests and regional geology.

Cohee (1945) published a basement configuration map of the Southern Peninsula based on four basement tests plus extrapolation from known geology. He depicted the basement as elliptical in plan with regularly spaced contours, and little or no expression of intrabasin structures. Rudman et al. (1965) revised the basement surface map by taking into account subsequent basement tests. Again, the picture obtained was one of regularly spaced contours. Bayley and Muehlberger (1968) show essentially the same map as Rudman et al.; however, their map shows a broadening of the basement depression into the southern extremity of Lake Michigan.

Hinze and Merritt (1969), assuming major basement relief to be reflected in shallower horizons, prepared the most detailed map of the basement surface to date. They utilized an Ordovician Trenton structure contour map and available well control and published magnetic depths in the preparation of their map. Their map is characterized by a maximum depth of 14,000 feet below sea level in Bay, Midland, and Gladwin counties, a topographic ridge associated with the Howell anticline, and a general elongation of the basin to the southwest. In addition, they hypothesize a fault-line scarp to exist in the basement in Hillsdale, Calhoun, and Barry Counties, associated with the Albion-Scipio oilfield.

Many other papers, aimed primarily at studying the basement rocks in the upper Midwest have been published. Among the more important are aeromagnetic investigations of eastern Lake Superior, Lake Huron and Lake Michigan, by Hinze et al. (1966), Secor et al. (1967), and Hinze and O'Hara (1971) respectively. Aeromagnetic studies of Wisconsin and Indiana have been undertaken by Patenaude (1966), and Henderson and Zietz (1958) respectively. A gravity survey of the eastern portion of the Northern Peninsula of Michigan has been completed by Oray (1971). Nwachukwu et al. (1965) have conducted shipborne magnetic work over Lake Huron, Georgian Bay, and adjacent areas of southwestern Ontario, Manitoulin Island, and eastern Michigan.

Rudman (1963) and McGinnis (1966) have studied the basement surface in Indiana and Illinois, respectively utilizing the seismic method. However, there are no published accounts of the use of the seismic method in studying the configuration of the basement surface in the Southern Peninsula. This can probably be attributed to the absence of a well defined acoustical boundary between the weathered basement surface and the overlying Cambrian arkoses and sandstones. No crustal refraction seismic investigations have been reported from the Southern Peninsula although considerable work has been undertaken in the Lake Superior region to the north and west (Cohen and Meyer, 1966, Smith et al., 1966, Steinhart et al., 1966 and Mooney et al., 1970).

Additional local gravity and magnetic surveys aimed primarily at investigating specific anomalous areas of the basement of the Michigan Basin are reported by Brett (1960), Meyer (1963), Stevenson (1964), Patenaude (1964) and Shaw (1971).

The Tectonic Framework of the Michigan Basin

Midwestern United States is a stable area characterized by prominent sedimentary basins and somewhat less well defined arches. The Michigan Basin is bordered on the north by the Precambrian shield complex of igneous and metamorphic rocks (Figure 2). The western boundary is the Wisconsin Arch, while to the southwest, the Michigan Basin is separated from the Illinois Basin by a discontinuous structural high, generally referred to as the Kankakee Arch. The Kankakee Arch joins the Findlay Arch near the Indiana-Ohio boundary. North of this junction lies the Indiana-Ohio Platform generally assumed to be the northern extension of the broad Cincinnati Arch (Green, 1957). Woodward (1961) has identified an anticlinal structure lying about 60 miles east and subparallel with, the Findlay Arch which he named the Waverly Arch.

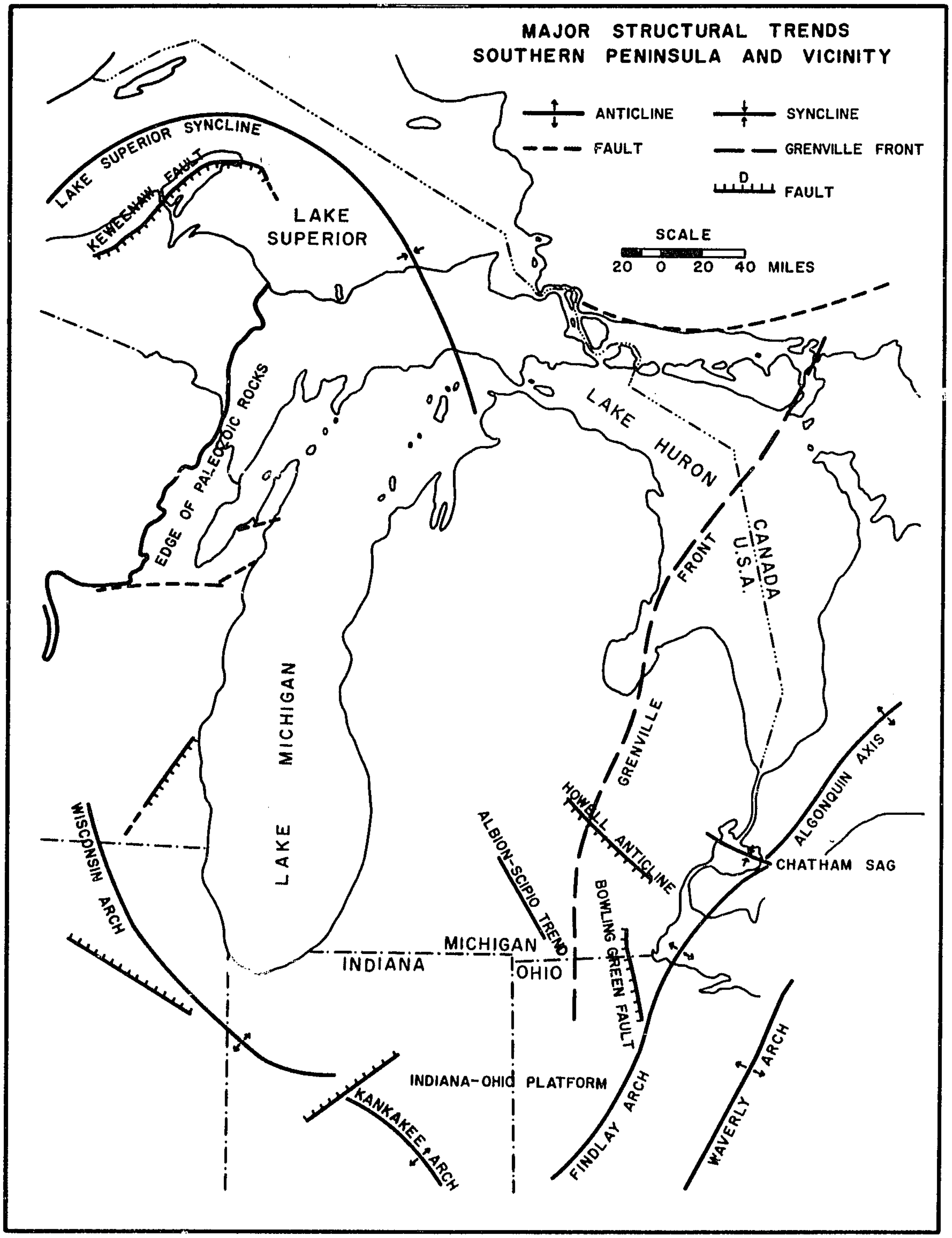

Figure 2.--Structure in the Vicinity of the Michigan Basin.

The Algonquin Axis of southeastern Ontario appears, at first glance, to be a continuation of the Findlay Arch although the two features are not on trend and apparently are not related (Sanford and Quillian, 1958). Hamblin (1958) has identified an east-west trending highland in the Northern Peninsula of Michigan, on the basis of sediment dispersal studies.

Basement Lithologies

The lithology of the basement is important in defining basement provinces. Direct information on basement lithology in the Southern Peninsula is confined to fifteen poorly distributed basement tests (Figure 1) whose lithologies are described in Table 1. Samples obtained from these basement tests often lack a comprehensive description; in addition, they show evidence of contamination from overlying sediments. However, the descriptions listed are compatible with descriptions of basement samples from surrounding areas (Rudman et al., 1965;Lidiak et al., 1966 and Muehlberger et al., 1967). The majority of the tests are in the southeastern portion of the Southern Peninsula and have encountered both granite, granite gneiss and more mafic gneisses.

The age and lithologic relationships for the basement test in Presque Isle County are uncertain. Bass (1968) believes the rocks encountered in this well are

TABLE 1.--Basement Drill Holes in the Southern Peninsula of Michigan.[1]
(Modified from Hinze and Merritt, 1969)

County	Location: Sec.	Twn.	Rnge.	Precambrian Surface Below Sea Level (Ft)	Lithology
Berrien	10	6S	17W	3802	Granite Gneiss[2]
Charlevoix	6	37N	10W	3988	Granite
Lenawee	32	8S	5E	3150	Granite & Granite Gneiss[3]
Livingston	11	3N	5E	6179	Intermediate Gneiss[5]
Monroe	29	5S	10E	2745	Granite
Monroe	19	7S	7E	2926	Granite
Monroe	16	7S	6E	2951	Granite Gneiss
Presque Isle	29	35N	2E	4902	Quartzite & Greenstone
St. Clair	31	4N	15E	3989	Granulite
St. Clair	17	2N	16E	3436	Plagioclase-Quartzite Gneiss
St. Clair	26	5N	16E	4065	Biotite Gneiss[4]
Washtenaw	27	1S	7E	5185	Chlorite Schist[3]
Washtenaw	16	1S	7E	5459	Gneiss[4]
Washtenaw	12	2S	7E	4852	Gneiss[4]
Wayne	16	4S	9E	3360	Granite Gneiss

[1]Data from Michigan Geological Survey, except as noted.

[2]Yettaw (1967).

[3]Summerson (1962).

[4]Lidiak *et al.* (1966).

[5]Laaksonen (1971).

Keweenawan basalts subjected to alteration either subsequent to or in late Keweenawan time. Other workers (Bradley, 1971) (personal communication) have reported a much younger age for the greenstone based on K-Ar determinations.

Paleozoic Features Associated with the Michigan Basin

The Tectonic Map of Canada shows numerous folded areas and major faults at the northern edge of the Michigan Basin and similar features occur in northern Michigan and Wisconsin bordering the Basin. We can therefore presume that the basement of the Michigan Basin is characterized by comparable features.

Several structures have been identified within the Michigan Basin. In southeastern Michigan, there are three major Paleozoic features trending northwest-southeast, all of which may be associated with faulting (Fisher, 1969). The Howell anticline (Figure 2) trends northwest across Livingston County. The southwest flank of this structure shows evidence of fault control (Newcombe 1928, 1933), although Ells (1969) has mapped this area as a flexure. Regional considerations, based on the Trenton (Middle Ordovician) datum suggest that this anticlinal trend may continue northwesterly through the southeastern part of Clinton County before losing identity (Ells 1969). A recent basement test (Howard J. Messmore No. 1, Mobil

Oil Corp., 1970) located in Sec. 11, T3N, R5E, about six miles northeast of the axis of the Howell anticline confirmed the long held belief that this structure is reflected in the basement surface, as shown on a previous basement map (Hinze and Merritt, 1969).

Bowling Green fault has been mapped in Ohio (Figure 2). This fault may extend into the Southern Peninsula where it is associated with the Lucas-Monroe monocline along the southern half of the Monroe-Lenawee County line.

The Albion-Scipio oilfield which trends northwest across Hillsdale and Calhoun Counties is also considered to be fault controlled (Ells, 1962). Wells drilled into Ordovician Trenton and Black River formations show no vertical displacement; thus, the fault is believed to be primarily strike slip (Fisher, 1969). However, Merritt (1968) has attributed a change in the regional gravity gradient occurring in the vicinity of the Albion-Scipio field to basement topographic relief. He further suggests that this topographic feature represents either a fault or fault-line scarp having several hundred feet of relief.

Ells (1962) has pointed out that the dominant trend of other Paleozoic structures and faults throughout the Basin is northwest-southeast. Regional geophysical data also confirm the northwest-southeast trend of these features south of roughly 43°30'. Thus the dominant northwesterly intra-basin structural trend strongly suggests lines of weakness along which Paleozoic structural features later developed.

Development of the Michigan Basin

The Michigan Basin is a roughly circular structural basin (Figure 3). It includes the Southern Peninsula and eastern portion of the Northern Peninsula of Michigan, eastern Wisconsin, northeastern Illinois, northern Indiana, northwestern Ohio, and southwestern Ontario. The basin includes an area of 122,000 square miles, part of which is covered by Lakes Michigan, Huron and St. Clair, and is estimated to contain more than 14,000 feet of Phanerozoic sediments.

The time of initial subsidence of the basin has been debated in the literature. Pirtle (1932) and Newcombe (1933) are of the opinion that the basin began to form in Keweenawan time. Subsequent folding took place parallel to the major axis of the downwarp which in turn parallels the direction of the Kankakee and Wisconsin Arches. Lockett (1947) has suggested that a very early mountain chain extended from Ontario through western Ohio and that the reflection of this belt may be found in the Paleozoic sediments as the Cincinnati and Findlay Arches. During the Paleozoic era, the dominant structural movement was thought to be subsidence of the intervening basin areas.

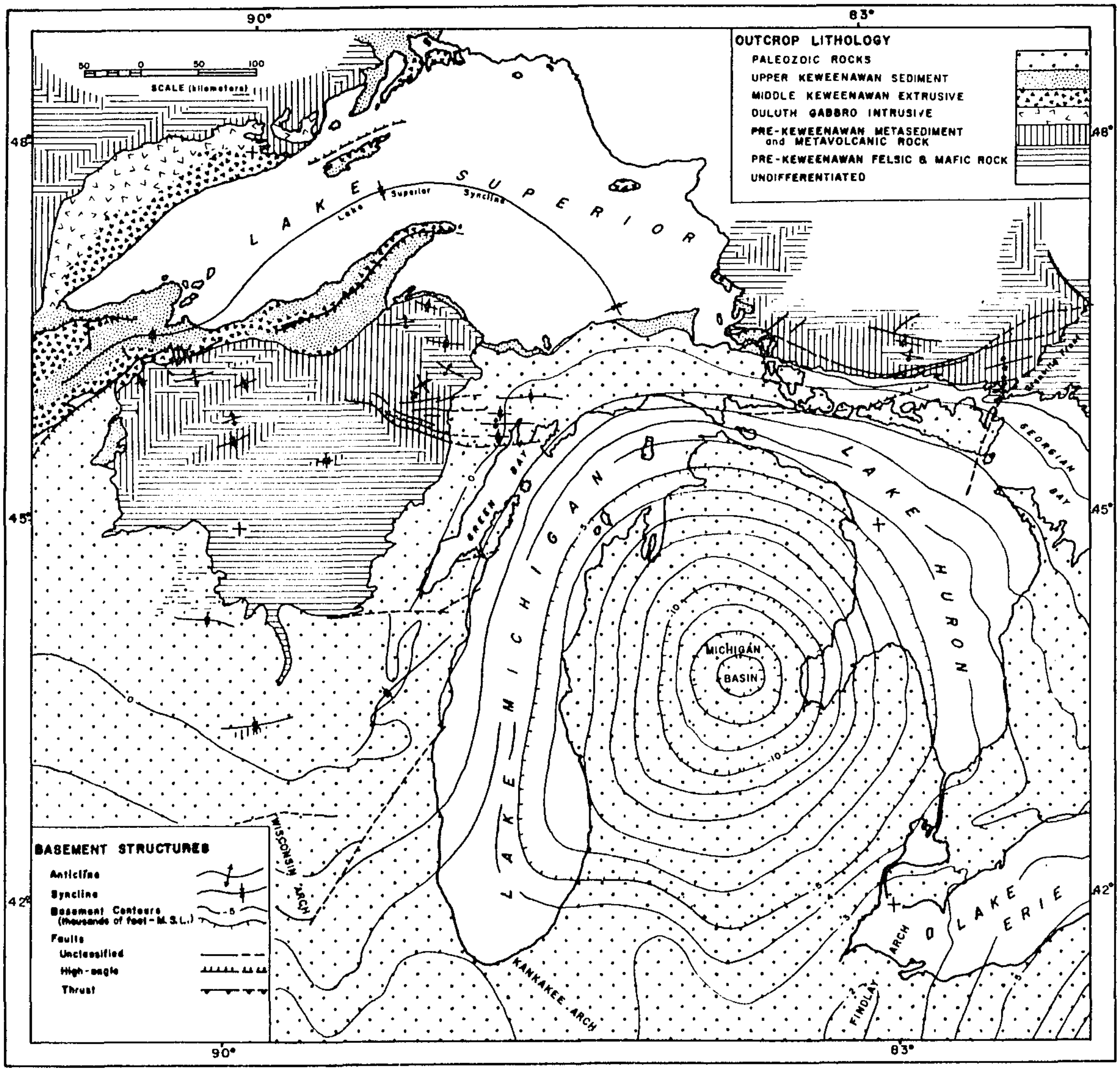

Figure 3.--Regional Structure and Structure Contours on the Basement Complex of the Michigan Basin.

Green (1957) assigned a late Silurian time to the inception of subsidence in the Michigan Basin. He also invoked the idea of Basin subsidence rather than uplift of the structural features between basins to explain the origin of the positive features. Fisher (1969) on the basis of isopach studies of the Ordovician sediments believes the Basin, as it is known today, was created during Ordovician time.

Deposition of Paleozoic marine sediments in the Michigan Basin, to the best of our knowledge, did not begin until late Cambrian time when the sea transgressed from the south. Sand from the weathered Precambrian surface to the north and northwest formed a thick blanket sandstone over the area of the Michigan Basin. Cambrian deposits accumulated to an average thickness of about 2,600 feet of sandstone, dolomite and shale (Cohee, 1965). Two depositional centers separated by an intervening high are shown by Fisher (1969). Fisher correlates the high with the Mid-Michigan gravity high (Hinze, 1963) inferring that the feature responsible for the gravity anomaly was a structural or topographic high during Cambrian time.

Sedimentation was continuous from late Cambrian through early Ordovician time. Clastic sediments were deposited around the margins of the basin. A profound unconformity separates lower Ordovician rocks from the overlying middle Ordovician rocks. Both the Kankakee and Findlay Arches are slightly positive during the late Ordovician.

Lower Silurian rocks consist largely of shales and carbonates. By Middle Silurian time a massive barrier reef had grown around the margin of the basin reaching a maximum thickness of over 900 feet in the northern part of the Southern Peninsula.

The single greatest episode of sinking occurred during Salina (Late Silurian) time with the accumulation of over 2,800 feet of evaporites, carbonates, and shales with a depocenter near the southwest end of Saginaw Bay.

Devonian rocks, which are about 3,500 feet thick, are largely dolomite, sandstone, salt and anhydrite in the lower part and limestone and shale in the upper part. Evidence that the Devonian depocenter shifts with time has been suggested by Prouty (1971).

More than 2,100 feet of Mississippian sandstone and shale outcrop almost entirely within the Southern Peninsula of Michigan. Most of the folding in the central part of the basin is late Mississippian in age. About 750 feet of Pennsylvanian sandstone and shale occupy the central part of the basin. Overlying Pennsylvanian rocks in the western part of the central basin area are a few erosional remnants of the Jurassic period, the only known Mesozoic rocks in Michigan. Pleistocene glacial deposits cover the bedrock surface ranging in thickness up to 1,000 feet.

Influence of Basement Topography on the Paleozoic Sediments in the Midwestern United States

The role of the basement in shaping the major structural and tectonic features in the Midwestern United States has already been considered (see also Figure 3). A more detailed examination is required if some relations between local basement scarps, ridges, sedimentary folds, and faults within these major structural and tectonic divisions are to be established, and related to the Michigan Basin.

A prominent semi-continuous east-west basement scarp extends from south-western Illinois into western West Virginia. This scarp, which underlies the Rough Creek and Kentucky River fault systems influenced primarily Cambrian and Ordovician sedimentation, but was also a zone of structural movement during late Paleozoic time and, in places, is still active. Apparent vertical displacements as great as 5,000 feet have been measured along this fault system (Summerson, 1962, Rudman *et al.*, 1965).

A north-south basement ridge has been correlated with the LaSalle anticline in Illinois, and apparently controlled the structural development of the anticline during Paleozoic time. Again the influence of the ridge was felt mainly during early Paleozoic time.

Highly localized basement features are also known to influence Paleozoic sedimentation and structure. Workman and Bell (1948) noted a correlation between early Paleozoic sedimentation and a small anticline in western Illinois. A sudden change in dip of basement rocks and overlying sediments occurs at the Mt. Carmel fault in west-central Indiana. Coons et al. (1967) list nine Paleozoic anticlinal structures along the trend of the Mid-Continent gravity high. They note that Paleozoic deformation appears to be nearly continuous along Precambrian faults which extend from Kansas to Lake Superior, and are associated with the gravity high. Ells (1962) has pointed out that the dominant trend of anticlinal structures and faults in the Michigan Basin is northwest-southeast. Hinze and Merritt (1969) noted that "the anomalies of the vertical magnetic intensity map and particularly the Bouguer gravity anomaly map show a marked northwesterly trend south of the 44°30'N latitude closely paralleling the trend of the intra-basin structures." Noting the correlation of the Howell anticline with the Mid-Michigan anomaly in Livingston and adjacent counties, they concluded that the north-westerly intra-basin structural trend reflects lines of weakness perhaps associated with a rift zone interpreted as the source of this major anomaly.

CHAPTER II

COLLECTION OF AEROMAGNETIC DATA

Instrumentation

Continuous observations of the total intensity of the earth's magnetic field were made with an Elsec type 592J proton precession magnetometer manufactured by Littlemore Scientific Engineering Co., Oxford England. The instrument measures the reciprocal of the frequency of precession of protons in the earth's field. The frequency of precession is directly proportional to the intensity of the earth's magnetic field. This reciprocal reading magnetometer system is provided with analog recording facilities in the form of a chart recorder. As used in this survey, the instrument has a sensitivity of approximately 3 gammas.

A sensing unit, contained in an aerodynamically stabilized housing is trailed about 100 feet behind the aircraft during flight operations.

For a complete description of the principle of operation of the proton precession magnetometer, the reader is referred to Hood (1969).

The output of the instrument is displayed in the form of reciprocal frequency counts on an 8 inch chart recorder. These records, along with navigational information, are the basic data of the survey. Figure 4 is a representative record from the survey. One magnetometer unit on this record equals 2.8 gammas. Recording parameters and airspeed (which was maintained at 120 m.p.h.) were established so that a horizontal distance of one inch on the chart represents a distance of approximately one mile on the ground. About eight readings were obtained per mile giving semi-continuous coverage along the flight path. Variations in ground speed due to winds aloft caused the number of readings per mile to fluctuate, but never by more than two or three per mile.

Flight Crew and Aircraft

A three man crew, consisting of a pilot, navigator and magnetometer operator was utilized in survey operations. The pilot was responsible for keeping the aircraft directly over the intended traverse at the proper flight elevation. The navigator was responsible for plotting flight traverses, identifying and recording navigational data on the flight maps and supervising all field operations. Finally, the magnetometer operator was primarily responsible for the operation and maintenance of the magnetometer system. In addition, he kept a log of all take-offs and landings and recorded all magnetometer malfunctions.

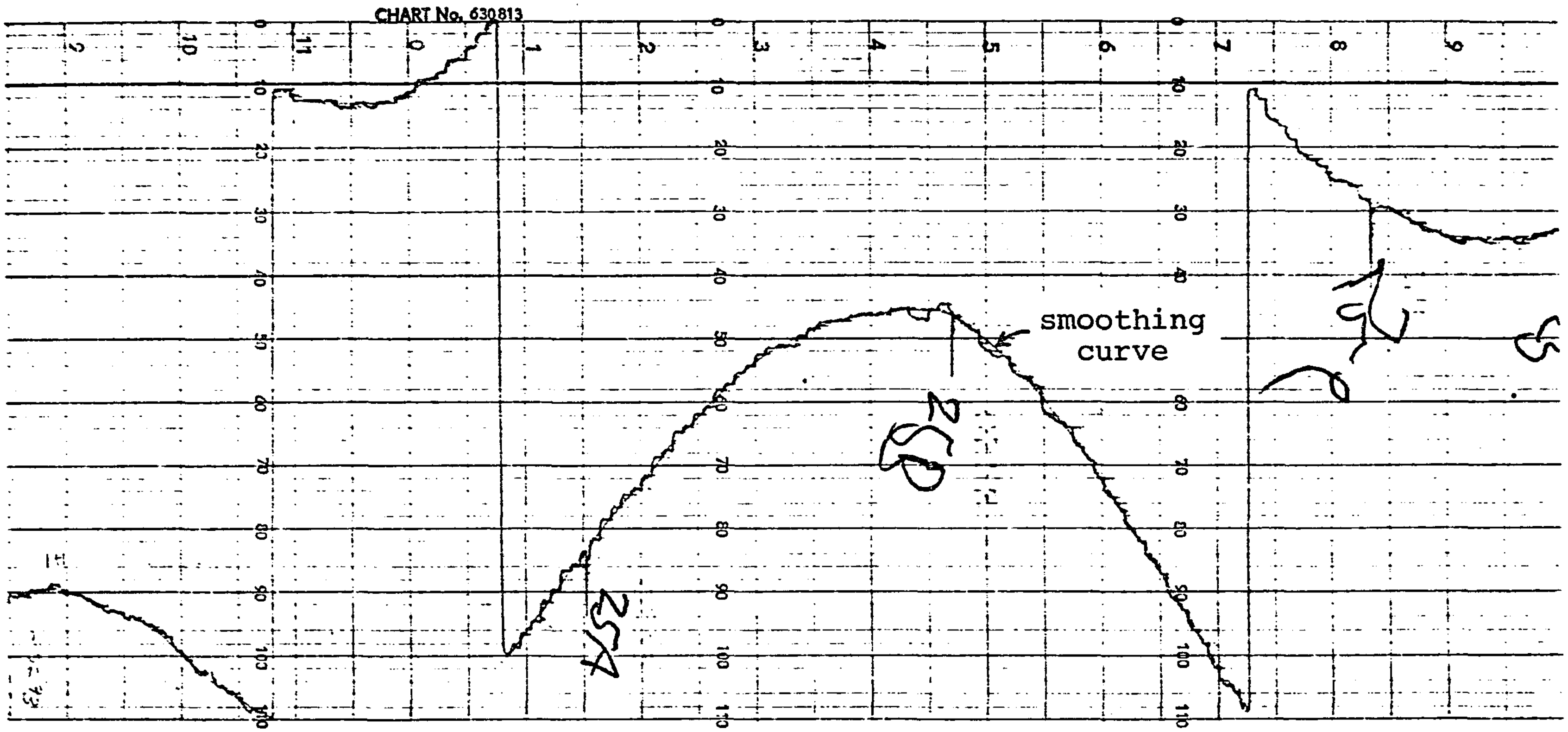

Figure 4.--Representative Magnetogram

A Cessna 182 single engine aircraft was selected for the survey. This aircraft has a five hour range and was operated at a constant airspeed of 120 m.p.h. The magnetometer system was installed behind the pilot in the place of a passenger seat. This resulted in minor modifications to the aircraft which required the approval of the Federal Aeronautical Administration.

Survey Procedures

The regional nature of this survey did not warrant close spacing of flight lines. One consideration in choosing a flight line separation is the expected depth to basement. The depths to basement in the Southern Peninsula vary between approximately 3,500 and 15,000 feet below mean sea level. A commonly used rule of thumb in regional aeromagnetic studies holds that the flight line separation should not exceed the distance from the disturbing body to the magnetometer. This assumes a dipolar magnetic source giving rise to a circular anomaly; however, most anomalies have widths appreciably greater than their lengths. Therefore, a compromise traverse separation of three miles was selected taking into consideration the objectives and the available financial resources.

Each traverse was flown at a constant barometric altitude of 3,000 feet MSL or roughly 2,000 to 2,400 feet above the ground surface. This provides a fixed datum for basement depth determinations and is compatible with previous aeromagnetic surveys flown in the vicinity of the Southern Peninsula. A barometric altimeter calibrated prior to each take off was considered adequate for elevation control.

In selecting a flight line direction, two considerations are necessary. The first is the desirability of maintaining the lines of flight at right angles to the strike of the disturbing bodies, because the most useful and informative picture of a magnetic anomaly is obtained when flight traverses are oriented in this manner. A second consideration is the navigational control. In this survey navigation was achieved primarily by visual observations of cultural features, particularly the road and section line network. Roads in the Southern Peninsula are laid out along a rectangular grid and generally coincide with north-south and east-west section lines. In laying out the flight paths, it was therefore necessary to choose between a north-south and an east-west direction. Both were considered, but the north-south direction was finally chosen because flight lines oriented in this direction take maximum advantage of the general tendency of most magnetic anomalies in the Southern Peninsula to possess a marked east-west component.

Navigation was accomplished by visual fixes to cultural features such as road intersections or railroad tracks. Occasionally, natural features such as lake shores were used. Flight lines were ruled on county highway maps prepared by the State of Michigan before any flights were attempted. Once in the air, the pilot was directed by the navigator to the preselected flight traverse above a road or section line. As each navigational fix was approached (generally a road or section line at right angles to the traverse), the instrument operator was alerted by the navigator. At the precise moment when the aircraft passed over the desired fix, the observer, on command from the navigator, triggered a fiducial marker located on the front panel of the chart recorder. The location of the navigational fix was then carefully marked on the map and a number was assigned to both the map location and the fiducial on the chart. In addition, the time at which the observation was made was recorded. Navigational fixes were established, on the average, every 5 miles.

Another factor which must be considered in laying out the survey is time variations in the magnetic field. Accurate surveys are impossible unless time or "diurnal" variations are properly removed. Particularly important is the early detection of large amplitude time variations known as magnetic storms. Ordinarily it is necessary to repeat traverses flown during these storms; therefore, a system of identifying these disturbances in advance of flight operations is desirable to eliminate the need for costly reflights. Arrangements were made with the Space Disturbances Laboratory of the ESSA Research Center at Boulder, Colorado to notify the flight crew of impending disturbances of the earth's magnetic field. It generally became the practice, towards the end of the survey, to call the Space Disturbances Lab prior to commencing each day's operations to obtain the daily forecast. Only 6 hours of flight operations out of 250 total hours had to be repeated because flights were conducted during magnetic disturbances, and none after the initiation of regular calls to the Space Disturbances Laboratory.

The problem of eliminating the smaller scale diurnal variations was achieved by flying a network of control lines east-west across the north-south traverses. Six control lines were flown averaging about 50 miles apart. An attempt was made to establish control lines in areas having low magnetic relief; however, this was not always possible, particularly in the northern portion of the Southern Peninsula where magnetic gradients are steep.

In addition to the network of control lines and the daily call to the Space Disturbances Laboratory, a number of procedures were initiated to reduce or eliminate the need for reflights and to insure that equipment was functioning properly. Prior to each takeoff, the sensing head or "bird" was removed from the aircraft and placed in a convenient location about 100 feet from the aircraft and as far as possible from extraneous metallic material. The instrument was then turned on and the signal monitored for a period of several minutes. By this procedure, it was possible to detect magnetic disturbances already in progress. The sensing head was located in the same place each day prior to beginning the test. An identical test was also conducted at the termination of each day's operations.

A second test was also conducted on a daily basis to provide a further check on diurnal conditions and to insure that the instrument was functioning properly. A test traverse, about five miles long, was selected in an area convenient to the base of operations and doubly flown. This traverse was located along a prominent road or highway, in an area having gentle magnetic relief, and was flown at the beginning and end of each day's flight operations. The data from this test, in addition to providing a check on the equipment and diurnal conditions, were later used in the diurnal reduction process (Chapter III), and in evaluating the accuracy of navigation.

Accuracy of Navigation

The accuracy of navigation in this survey is difficult to assess except in a qualitative manner. Because flight traverses were conducted over cultural features, particularly roads, navigational control and accuracy is best where these features are in greatest abundance. This condition is best satisfied south of latitude 44°00'N. However, it was usually possible to follow section lines in the northern portion of the area so that lack of road coverage was not a critical factor affecting navigation.

Locally, within the northern portion of the survey, there were areas having a paucity of navigational features. One such area, covering 2,500 square miles occurs in Montmorency, Alpena, Oscoda and Alcona Counties in the northeastern portion of the Southern Peninsula. Both marked section lines and roads are infrequent in this area; thus, it became necessary to rely on a combination of dead reckoning and sighting on natural features such as the shores of lakes and ponds to establish the traverse position. The use of lake shores as navigational fixes caused the actual flight paths to deviate from the intended straight line traverses. Unknown factors affecting this type of navigation are variations in airspeed and wind velocity between navigational fixes.

Navigational accuracy is dependent on the pilot's ability to keep the aircraft directly over the intended traverse. In addition, accuracy is critically dependent on the navigator's ability to determine the exact instance at which the aircraft passes directly above a navigational fix, such as a road intersection. Only then can the navigational data be properly correlated with the magnetic data. Errors of this type were evaluated in the following manner: a series of short test traverses were selected and doubly flown. These test traverses were previously discussed under survey procedures. Ratios of distances on the records were then compared for both flight directions. These distances agreed, on the average, to within one cycling of the magnetometer chart recorder. During one cycling of the magnetometer (about 3 seconds), and assuming an airspeed equivalent to ground speed the aircraft will have moved about 600 feet. Therefore, assuming no errors caused by straying of the aircraft right or left of the intended traverse, the north-south accuracy is better than 600 feet.

Accuracy of the magentic observations can also be evaluated in terms of chart recorder units from the same repeated flights over short test traverses. These errors include the inherent sensitivity error of 3 gammas of the instrument. Test results indicated errors of the order of three or six gammas in low gradient areas and from six to twenty or more gammas in steep gradient areas.

A serious problem which cannot be tolerated is the mislocation on the flight line maps of cultural features used as navigational fixes. An improperly located road intersection may produce a "herringbone" pattern on the aeromagnetic map. This is especially true in high gradient areas. Errors from this source were eliminated in the following manner: the ratios of distances between pairs of points on the records and on the flight line maps were visually compared. Any points which deviated from a relatively constant ratio were then deleted from the data. In this manner, serious navigational errors were detected before data processing began.

Meteorological Considerations

Weather conditions strongly influenced the timing and execution of the field operations. Prior to each days operations, the local Flight Service Station of the FAA was consulted about the location of air masses, frontal systems, visibilities, ceilings and winds aloft. This information was then used to plan the day's flights. Areas having good visibility and within easy reach of the base of operations were assigned first priority.

On many summer days, however, extensive fog and haze covered most of the Southern Peninsula, reducing visibility to four miles or less. These conditions commonly preceded afternoon thunderstorms. Flight operations were severly limited during these periods, often having to be curtailed for several days or more.

Turbulent conditions, due to rising pockets of warm air, were almost a daily occurrence on this survey. These pockets, or "thermals," usually reached the flight elevation of the aircraft about 10:00 AM and persisted until about 4:00 PM. Repeated flights over test strips indicated turbulent conditions were not a source of error in making the magnetic measurements. "Turbulent air prevents successful flights more from conditions of safety than from the appearance of noise on the record" (Reford and Sumner, 1965).

Summary of Field Operations

The aeromagnetic survey was flown between the dates of July 25, 1968 and March 14, 1969. However, the majority of the survey was completed by October 1, 1968.

Flights conducted subsequent to this date replaced data flown during diurnally disturbed periods and data having questionable navigation. Listed below is the approximate area surveyed, approximate number of traverse miles, and days required to conduct the survey.

1. Area surveyed: 41,000 square miles
2. Traverse mileage:
    a. north-south traverse mileage: 17,000 miles
    b. east-west control line mileage: 4,000 miles
    c. access mileage: 1,000 miles
    d. total mileage: 22,000 miles
3. Flight hours:
    a. north-south traverse time: 194 hours
    b. east-west control line time: 45 hours
    c. access time: 11 hours
    d. total time: 250 hours
4. Days in field (days on which operations were attempted): 40
    a. days on which useable data were collected: 28
    b. days on which no data were collected due to poor weather, breakdown of the magnetometer, breakdown of the aircraft, and periodic aircraft inspections: 20
    c. total days in field: 48

CHAPTER III

COMPILATION AND REDUCTION OF MAGNETIC DATA

Introduction

Before the magnetic data can be presented in the form of a residual total intensity contour map for interpretation, they must be corrected for diurnal variation and the effect of the earth's normal field. At the time this survey was conceived, the decision was made to compile, reduce, and present the data, as much as possible, through computer reduction. The decision to machine contour the data entailed the preparation of several computer programs. In addition to providing for the removal of diurnal and normal field variations, these programs merged navigational and analog data and prepared the magnetic data for input into a machine contouring package. The role of each of these programs is briefly discussed in the following section.

The method of data reduction is explained through the use of Figure 5, a flow chart illustrating the steps involved.

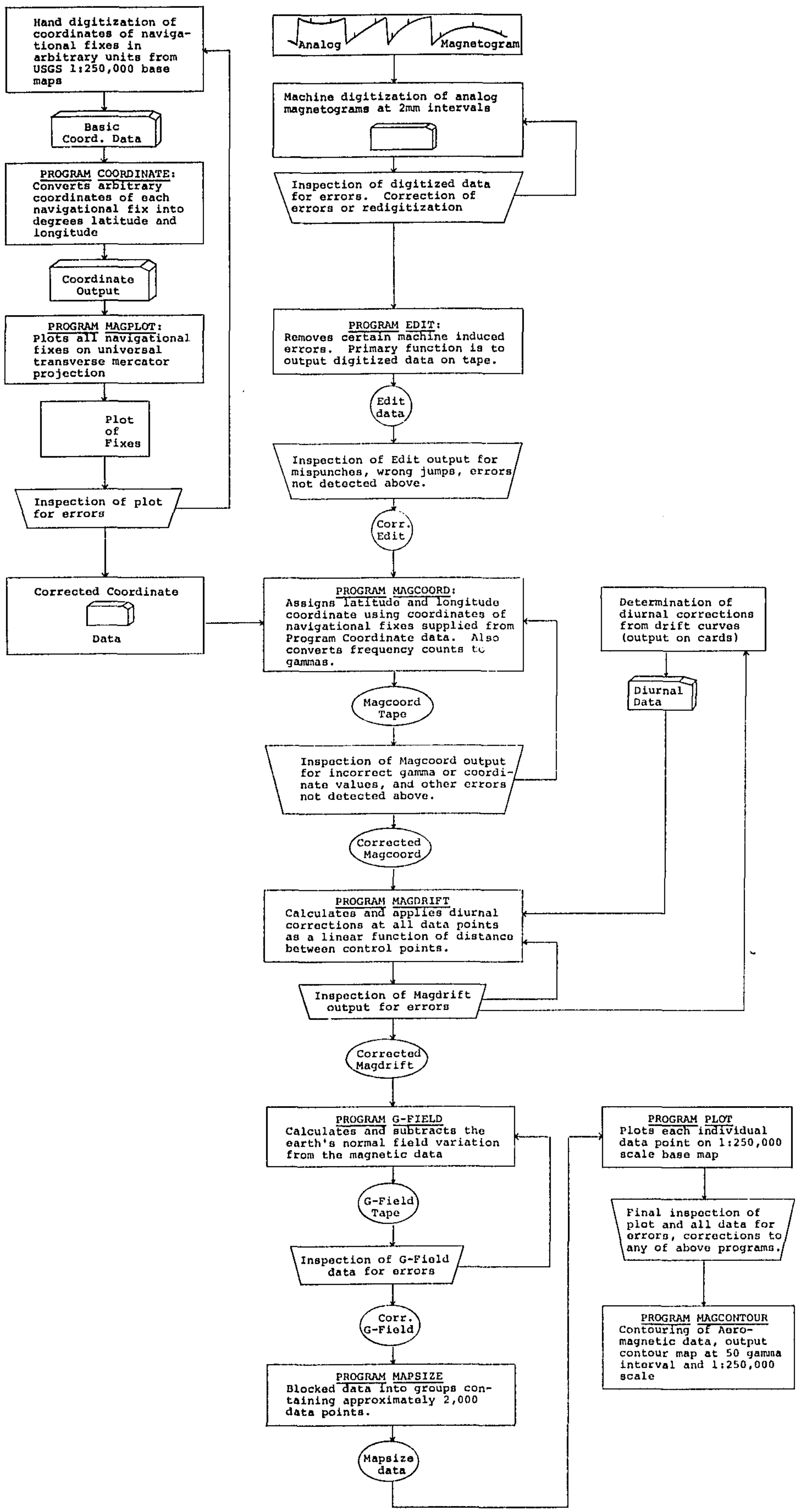

Figure 5.--Flow Diagram Illustrating Sequence of Data Reduction Steps.

Digitization of Navigational Fix Data

Following a data gathering flight, navigational fix data were plotted on U. S. Geological Survey maps at a scale of 1:250,000. The coordinates of each navigational fix and the beginning and end of each flight line were then measured from these maps in arbitrary units from a single arbitrarily chosen origin. These data were keypunched for digital processing (Figure 5).

The next step was to convert the coordinates measured above to degrees latitude and longitude. This was accomplished with program COORDINATE. The output of COORDINATE consisted of punched cards containing the navigational fixes, and their coordinates in degrees of latitude and longitude, to five decimal places.

To insure that each navigational fix was in its proper geographical location, i.e., that no errors were committed in the hand digitization process, the following procedure was adopted:

1. The COORDINATE data became the input to program MAGPLOT which plotted all fixes on a Universal Transverse Mercator projection at the same scale as the U. S. Geological Survey base maps (1:250,000).
2. Errors in the COORDINATE data were detected by overlaying these computer plotted navigational fix maps on the base maps.

3. Misplaced navigational fixes detected by this technique were remeasured and steps (1) through (3) were repeated until all of the navigational fix data were in their proper geographical location.

Digitization of Analog Records

Another major data reduction step was the machine digitization of the analog magnetograms (see Figure 5). Prior to digitization, occasional erratic values caused by instrumental problems were eliminated by hand smoothing of the magnetograms. This process involved drawing a smooth line through the magnetic values (Figure 4). In addition, all navigational fixes were uniquely identified on the magnetograms.

An X-Y machine digitizer was utilized for the digitization. The sequence of processing steps and procedures adopted to insure that the data were free of errors is outlined below.

1. Each traverse was machine digitized; a separate deck being prepared for each line. A header card contained pertinent information about the traverse. Data were digitized at 2mm intervals, or roughly the separation between readings on the magnetogram. Navigational fixes were encoded in the data as they were encountered on the magnetograms.

2. The digitized data were then inspected for human or machine induced errors, such as misplaced alphabetic characters, dropped digits or other obvious mistakes.
3. Corrected data were then input into program EDIT (Figure 5). The function of this program was to remove certain machine induced errors and to output the corrected data on tape.
4. The output from EDIT was inspected for further errors, and steps 3 and 4, and where necessary, 1 and 2 were repeated until all of the data were in proper form for further processing.

Merger of Navigational Data and Digitized Magnetograms

Until this point, navigational and magnetic data were treated individually (Figure 5). The function of program MAGCOORD is to merge the navigational data with the machine digitized magnetograms and to convert the frequency counts to gamma values. The input to this program is the output deck from program COORDINATE consisting of navigational fixes, with their associated geographical coordinates in degrees latitude and longitude, and the output from program EDIT, a tape containing the digitized data keyed to the navigational data. Program MAGCOORD assigned a latitude and longitude coordinate to each data point on the EDIT tape utilizing the coordinates of navigational fixes supplied from the COORDINATE data. In addition, this program converted the frequency counts associated with each data point to gamma values. Thus, the output of program MAGCOORD is a tape containing the data points described in terms of their latitude, longitude and gamma values.

Preparation of the Diurnally Corrected Data

The object of the diurnal correction is to remove the time variations in the earth's magnetic field from the magnetic data. The sequence of steps developed to accomplish this goal are outlined below.

1. A north-south master control line was doubly flown along the approximate geographical center of the State. This line crossed all east-west control lines.

2. A drift curve was prepared for this line by referring all values to a single point at the intersection of this master control line with the southernmost east-west control line. This was necessary to remove time variations in the magnetic field which occurred while the north-south control line was being flown. The test strip data recorded at the beginning and end of the day provided additional information about the rate of drift for the day.

3. Drift curves were then similarly prepared for each doubly flown east-west control line and all values were referenced to the common tie point with the north-south line. Finally, a small correction equal to the difference between adjusted values at the intersection of the east-west and north-south control lines was added to all navigational fixes on the east-west control line. This was necessary to bring the level of observation of these points into coincidence with the level observed at the master control point of the north-south control line.

4. Having established a control net, the values of all diurnally corrected navigational fixes including fixes at the beginning and end of each line together with their associated latitude and longitude values were obtained from the curves and coordinate information and keypunched (Figure 5). These data, and the output tape from program MAGCOORD were the input to program MAGDRIFT. This program calculated and applied the diurnal corrections at all data points. Corrections were applied as a linear function of distance between control points and between a control point and the beginning or end of a traverse.

Removal of the Earth's Normal Magnetic Field

Before a residual total magnetic intensity map can be prepared, it is necessary to remove the earth's regional or normal field from the magnetic data. Over the surface of the Southern Peninsula of Michigan, the variation of the total intensity is roughly 1,300 gammas as determined from maps prepared by the U. S. Naval Oceanographic Office. The normal gradient, which varies chiefly with latitude, is 4 gammas per mile.

The earth's normal field was removed utilizing a program developed by Cain _et al._ (1968) (Program G-Field, Figure 5). The program uses 8 degrees of spherical harmonic expansions of the geomagnetic potential, and treats only the main internal field. The coefficients used in this program were determined by Daniels and Cain (1964). The earth's normal magnetic field was calculated for an elevation of 3,000 feet MSL and for September, 1968. A contour map showing the normal geomagnetic field variations is presented in Figure 6. The regional geomagnetic field values are given in Table 2.

Preparation of the Corrected Data for Machine Contouring

Several programs were developed to group the data into blocks of 15 minutes latitude by 15 minutes longitude, each containing approximately 2,000 data points. Only every third data point was utilized because of restrictions imposed by the available computer facilities. This

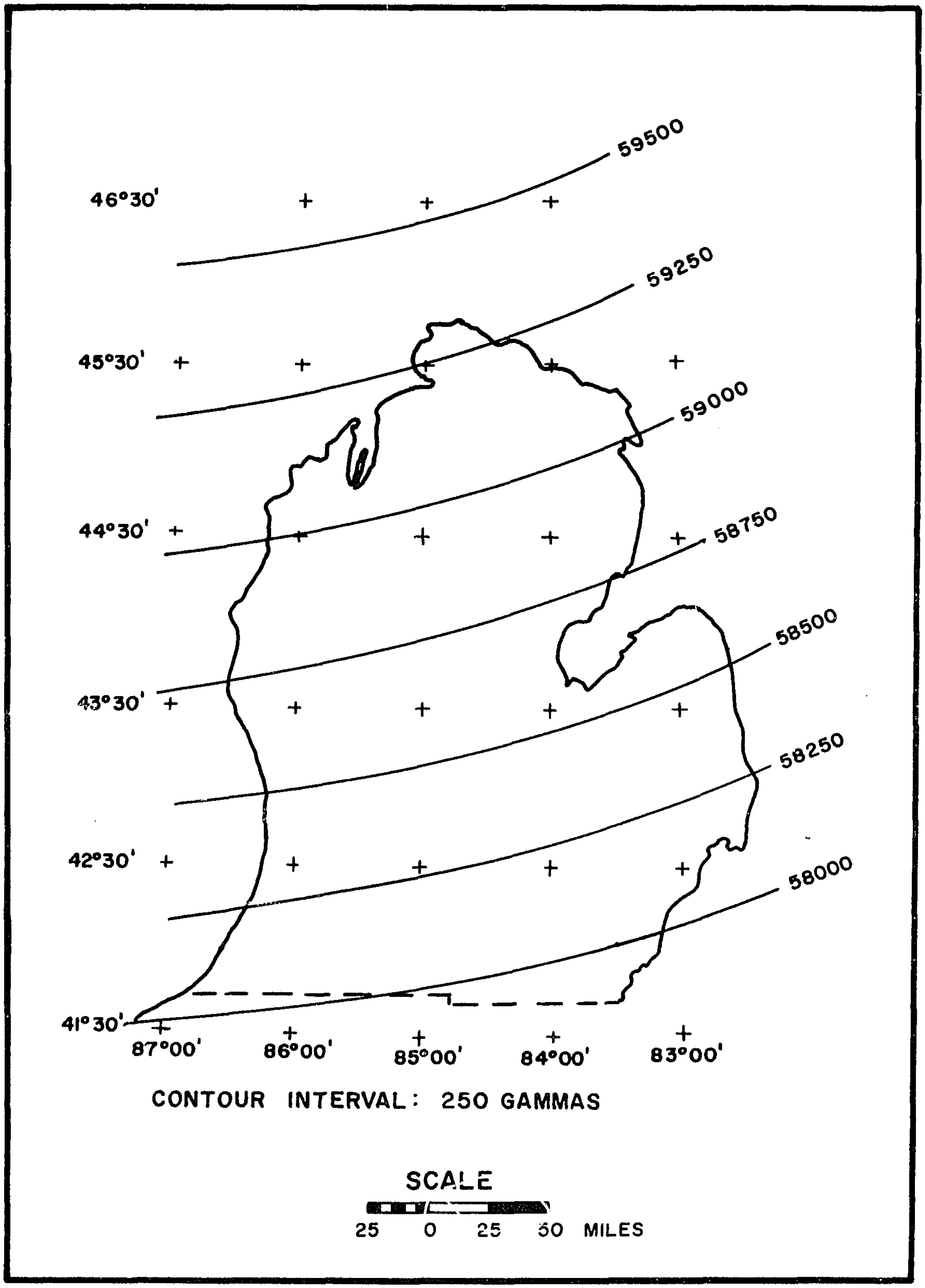

Figure 6.--Normal Geomagnetic Field over the Southern Peninsula of Michigan.

TABLE 2.--The Earth's Normal Total Magnetic Intensity in the Vicinity of the Southern Peninsula of Michigan.

Latitude	Longitude	Gamma Value	Latitude	Longitude	Gamma Value
41° 30'	87° 00'	57,964	44° 30'	87° 00'	59,059
	86° 00'	57,922		86° 00'	59,005
	85° 00'	57,870		85° 00'	58,940
	84° 00'	57,806		84° 00'	58,865
	83° 00'	57,732		83° 00'	58,780
42° 30'	87° 00'	58,355	45° 30'	87° 00'	59,371
	86° 00'	58,308		86° 00'	59,313
	85° 00'	58,252		85° 00'	59,245
	84° 00'	58,184		84° 00'	59,167
	83° 00'	58,106		83° 00'	59,078
43° 30'	87° 00'	58,720	46° 30'	86° 00'	59,595
	86° 00'	58,669		85° 00'	59,523
	85° 00'	58,609		84° 00'	59,442
	84° 00'	58,537			
	83° 00'	58,455			

set of programs is combined on the flow chart (Figure 5) under program MAPSIZE.

The output of MAPSIZE was recomposited and used to plot a 1:250,000 scale base map showing the location of all data points. This map was superposed on the U. S. Geological Survey base maps for a final check of the navigational data before machine contouring of the data.

Contouring of Aeromagnetic Data

A machine contour package developed by California Computer Products Inc. was used to contour the aeromagnetic data. This computer package determines the contours and presents them in a form suitable for display on an X-Y plotter. The program is capable of generating a contour map from arbitrarily spaced data points. Contours can be annotated with labels, hachures and heavy lines as necessary. The surface to be contoured is specified by data points arranged along flight lines. However, it is necessary to estimate the values at the mesh points of a rectangular array before contouring. The contour package then operates on the gridded data points to generate the contour map.

Gridded data are generated from flight line data in the following manner: A plane is passed through each data point, determined by the gradient from nearby data points and the data point under consideration. This plane is derived as a least squares function of these values, weighted according to their distance from the data point. The plane passes through the data point and agrees as closely as possible with the selected data points surrounding it. The intersection of the plane with a vertical line passing through a desired grid point is an approximation of the magnetic field at that point. In this study, the weighted average of the intersections of the planes determined from the nearest 50 data points was used to approximate the field at the grid point. Grid points are evaluated sequentially, starting from one corner of the map.

In this survey, the grid spacing is one-half mile. The smallest rectangles of the grid are called cells. These cells are in turn, subdivided into even smaller cells, called subcells. The purpose of this division is to remove angularity or "herringbone" from the magnetic data by increasing the number of intermediate interpolation points.

Contours are generated from the interpolated function values at the mesh points of the subgrid. This interpolation, which preserves the gradient of the function across cell boundaries, is third order in X and Y.

The contour maps were plotted on a 30 inch CALCOMP drum plotter. Because of the large scale and dimensions of the final map (1:250,000), three runs were made and the results assembled to produce the final maps.

CHAPTER IV

INTERPRETATION OF AEROMAGNETIC DATA

Configuration of Basement Surface

Introduction

The basement of the Michigan Basin is commonly depicted as an oval depression with little or no modifying topographic relief. Unlike the Michigan Basin, the Illinois Basin, which resembles the Michigan Basin in area and maximum depth, is illustrated as having prominent topography that is reflected in the overlying lower Paleozoic sediments. With additional control information, localized basement topography of the Michigan Basin may be found to resemble that of the Illinois Basin. Depths obtained from aeromagnetic studies are a valuable supplement to basement drill holes in determining the configuration and topography of the basement surface.

Only fifteen poorly distributed basement tests have been made in the Southern Peninsula (Figure 1 and Table 1). While the basement is estimated to attain a depth of over 14,000 feet below sea level, only three drill holes, all located in the southeastern corner of the state, intersect the basement surface at depths greater than 5,000 feet and none are at depths greater than 6,200 feet. In addition, only two basement tests are located north of 43° 00' N.

Basement depths obtained from well cuttings may be uncertain because of contamination of the samples by chips from overlying formations. In addition, it may be difficult to distinguish the lowermost sediments (commonly an arkosic sandstone) from the weathered surface of basement granitic rocks on the basis of cuttings (Yettaw, 1967). Thus, discretion is necessary in interpreting depths obtained from well cuttings.

Both gravity and magnetic data are available for the Southern Peninsula of Michigan. Magnetic methods are preferred to gravity methods when making depth determinations primarily because magnetic anomalies originating from within the basement are not distorted by anomalies from the overlying sediments as are gravity anomalies. Sediments are essentially non-magnetic, hence structure or facies changes within them will not give rise to magnetic anomalies. However, these same variations will usually cause horizontal density changes and thus gravity anomalies. In addition, gravity anomalies are broader and less definitive than magnetic anomalies originating from the same sources. One of the factors controlling the amplitude and sharpness of the gravity or magnetic anomaly, the distance from the source, varies inversely one power faster for magnetic anomalies than for gravity anomalies.

Thus magnetic anomalies have a higher resolving power than gravity anomalies. Finally, gravity anomalies may be more distorted by deep seated intra-crustal structural or lithologic variations than magnetic anomalies, which increases the problem of isolating gravity anomalies for depth determinations.

Depth determinations by magnetic methods are, however, subject to a number of assumptions regarding the configuration and magnetic properties of the source. In particular, the effect of remanent magnetization is difficult to predict with certainty. Despite these limitations, an average error of less than 10 per cent can be obtained under favorable conditions by a trained interpreter (Steenland, 1963). The precision of magnetic depth determinations is strongly influenced by the anomalies selected for analysis. Anomalies chosen should originate from a single source. Thus, in so far as possible, anomalies free of effects from adjacent anomalies should be selected for analysis. Also, the direction of the line connecting the maximum and minimum of the magnetic anomaly should be parallel to the declination. If not, remanent magnetization may be suspected (Vacquier et al., 1951). However, few anomalies are sufficiently isolated to permit the unrestricted application of this principle. Finally, anomalies with a prominent minimum should be avoided; at the magnetic latitude of this survey, a prominent minimum may be indicative of remanent polarization effects, a restricted depth extent or dip of the anomaly source. These factors will result in errors if the anomaly is interpreted according to standard theory.

Selection of Depth Determination Techniques

Numerous magnetic depth determination techniques have been developed and their advantages and disadvantages discussed in the literature (Reford and Sumner, 1964 and Riddell, 1966). In general, methods based on the higher amplitude portions of the anomaly curve and not on its total amplitude are less subject to error arising from overlapping anomalies and definition of the zero level of the anomaly. The magnetic depth determination methods developed by Vacquier *et al.* (1951), Bean (1966), and Peters (1949) were applied to critically selected magnetic anomalies located near basement tests to "calibrate" the techniques and determine their usefulness in this study. Of these methods, Peters' half-slope and the straight slope technique of Vacquier *et al.* proved to be the most accurate in determining depths from magnetic anomalies adjacent to drill holes. Table 3 summarizes these results.

While the average per cent error for these determinations appears to be large, the control wells are located a minimum of 4.3 miles and range to a maximum of 12.2 miles from the site of the measurement. The

TABLE 3.--Comparison of Magnetic Depth Determinations with Basement Drill Depths.

Well Control County, Location	Distance of Magnetic Measurement From Control Well (Miles)	Depth of Basement From Control Well (Feet)	Bean Depth/ % Error	Vacquier/1.0 Depth/ % Error	Peters Depth/ % Error
Berrien 10-6S-17W	9.4	3,802	No Fit	2,460/-55%	4,650/+22%
Monroe 16-7S-6E	11.3	2,951	No Fit	3,780/+22%	3,900/+32%
Monroe 29-5S-10E	4.3	2,745	5,900/ +115%	2,800/+2%	3,120/+12%
Wayne 16-4S-9E	4.5	3,360	5,900/ +75%	2,800/-20%	3,120/-8%
Livingston 11-3N-5E	12.2	6,179	8,750/ +29%	5,100/-17%	6,850/+11%
Average Error W/0 Regard to Sign:				23%	17%

correlation of the results possibly would improve considerably if the magnetic depths could be compared with basement depths from hypothetical wells located at the site of the depth determination.

Half-slope lengths obtained from Peters' method were generally divided by a factor of 1.6 which applies when the width of the body is equal to twice the depth of burial (Peters, 1949). However, other factors were used when the dimensions of the anomaly suggested a markedly broader or narrower source.

In the method of Vacquier et al. the horizontal extent of the steepest gradient of the north flank of the total intensity curve is measured (the G index). This value is an approximate depth, uncorrected for the shape of the body. In this method, the shape of the body is expressed in terms of units of depth to its upper surface. To obtain the depth corrected for shape, the G index is divided by a factor between 1.0 and 1.3 for sources located at the magnetic latitude of this study. This factor is determined from theoretical magnetic anomalies of idealized prismatic sources. For bodies elongated in the north-south direction, this factor is approximately 1.0. For bodies elongated in the east-west direction, the factor is variable, reaching a maximum of 1.3 when the east-west extent is roughly 3 times the north-south. In this study, all G indices were divided by a constant factor of 1.0. This was justified because use of a variable index failed to improve depth estimates made adjacent to control wells over estimates made with a constant index. In addition, depth indices average close to 1.0 for many body shapes at the magnetic latitude of this survey.

The selection of anomalies for depth determinations proceeded in the following manner. Detailed total intensity maps at a scale of one inch equals eight thousand feet and a contour interval of 20 gammas were used to select anomalies for analysis, on the basis of the criteria previously discussed. Depth estimates were then made from the original magnetograms to avoid problems of interpolation in construction of the magnetic contour maps and profiles.

Only magnetograms which intersected the anomaly at roughly right angles to its strike were used in the analysis. Finally, with few exceptions, only the north flanks of the anomalies were analyzed.

The regional or normal field generally was not taken into account when making the depth determinations. This was justified because the depth determination techniques used in this study are applied to only a relatively short horizontal distance of the anomaly curve (one or two miles). The effect of the regional gradient is generally negligible over this distance considering the other sources of error. This was substantiated by tests which indicate that depths obtained from regionally corrected anomaly curves are not significantly different from depths obtained from uncorrected curves.

Generally, values from Peters' and Vacquier's methods were averaged (Table 4) to arrive at the depth to be utilized in preparing the basement configuration map (Figure 7). Occasionally, unreasonable values obtained from one method were rejected. In addition, average values based on widely different depths were downgraded when making the final interpretation.

Although 56 depths are listed in Table 4, only 44 anomalies were analyzed. Thus, several anomalies have more than one depth estimate. Multiple depths obtained from a single anomaly are marked in Table 4.

The number of anomalies suitable for making depth determinations is greater in the southern and northern thirds of the Peninsula. This reflects, in part, the greater depth to basement in the middle third, but also could reflect a change in the character of the anomalies in the central portion of the Basin. Thus, the reliability of the contours decreases in the central portion of the state.

The construction of a detailed basement configuration map was not justified because of limited data and the potential errors in making magnetic depth determinations. Regional contours were therefore drawn, permitting local errors of several hundred feet in some areas.

TABLE 4.--Magnetic Depth Determination Results.

County	Location	Depth from Straight Slope Method (Feet BMSL)	Depth from Peters Half Slope Method (Feet BMSL)	Average Depth	Comments on Determination by the Straight Slope Method	Comments on Determination by Peters Half Slope Method	Multiple Depths on One Anomaly
Berrien	41°50'N 86°20'W	2,460	4,650	3,555			
Cass	41°47'N 86°11'W	3,740	3,250	3,495			
Cass	41°52'N 85°49'W	3,200	4,280	3,740			
St. Joseph	41°52'N 85°46'W	2,725	3,300	3,012[a]			}
St. Joseph	41°50'N 85°35'W	3,320	--	3,320			}
Branch	41°59'N 84°53'W	4,025	6,050	5,037			
Lenawee	41°53'N 83°57'W	3,780	3,900	3,840			
Wayne	42°7'N 83°15'W	2,750	2,960	2,855			}
Wayne	42°6'N 83°18'W	2,800	3,120	2,960			}
Jackson	42°21'N 84°21'W	5,900	7,000	6,450			
Calhoun	42°13'N 84°43'W	11,500	9,500	10,500[a]			
Kalamazoo	42°7'N 85°35'W	4,440	7,500	4,440			
Kalamazoo	42°21'N 85°42'W	3,750	4,900	4,325			}
Kalamazoo	42°21'N 85°45'W	4,025	6,725	4,025			}
Van Buren	42°20'N 86°10'W	5,330	6,100	5,715[a]	b		}
Van Buren	42°23'N 86°6'W	4,150	3,000	3,575			}
Van Buren	42°22'N 86°10'W	3,500	3,150	3,325			}
Allegan	42°30'N 85°53'W	3,260	4,525	3,890			
Barry	42°28'N 85°8'W	4,750	5,100	4,925[a]			
Eaton	42°36'N 85°4'W	7,800	8,800	8,300			}
Eaton	42°35'N 85°1'W	4,400	5,600	5,000[a]			}

TABLE 4.--Continued.

County	Location	Depth from Straight Slope Method (Feet BMSL)	Depth from Peters Half Slope Method (Feet BMSL)	Average Depth	Comments on Determination by the Straight Slope Method	Comments on Determination by Peters Half Slope Method	Multiple Depths on One Anomaly
Eaton	42°38'N 84°53'N	5,050	6,250	5,650[a]			
Eaton	42°33'N 84°43'W	6,050	6,800	6,425			
Eaton	42°34'N 84°40'W	6,950	12,200	6,950			
Livingston	42°40'N 84°4'W	5,100	6,850	5,975			
Oakland	42°52'N 83°7'W	6,050	5,500	5,775			
Ionia	42°46'N 85°10'W	5,300	6,850	6,075[a]			}
Ionia	42°47'N 85°13'W	6,450	8,700	7,575			}
Ionia	43°2'N 85°18'W	14,300	14,800	14,550[a]	c		
Kent	43°00'N 85°43'W	7,800	--	7,800		d	
Ottawa	42°49'N 86°7'W	5,100	6,100	5,600			
Ottawa	43°2'N 86°11'W	5,500	8,150	6,825		d	
Ottawa	42°45'N 85°53'W	7,100	--	7,100[a]		d	
Gratiot	43°16'N 84°46'W	18,800	--	18,800[a]		d	}
Gratiot	43°16'N 84°43'W	14,700	--	14,700[a]		d	}
Saginaw	43°34'N 84°6'W	15,000	--	15,000		d	
Saginaw	43°21'N 84°3'W	9,700	--	9,700		d	
Tuscola	43°20'N 83°7'W	9,150	8,100	8,625			
Sanilac	43°30'N 82°47'W	5,650	6,500	6,075			
Huron	43°49'N 83°12'W	10,200	14,400	12,300			
Bay	43°41'N 84°3'W	15,200	15,400	15,300		b	
Bay	43°47'N 84°3'W	13,900	13,900	13,900			
Oceana	43°30'N 86°15'W	6,900	--	6,900			

TABLE 4.--Continued.

County	Location	Depth from Straight Slope Method (Feet BMSL)	Depth from Peters Half Slope Method (Feet BMSL)	Average Depth	Comments on Determination by the Straight Slope Method	Comments on Determination by Peters Half Slope Method	Multiple Depths on One Anomaly
Lake	44°3'N 86°2'W	6,600	10,500	8,550			
Roscommon	44°13'N 84°27'W	11,550	--	11,550[a]		d	
Alcona	44°33'N 83°23'W	7,550	9,950	8,750			
Alcona	44°44'N 83°48'W	5,350	8,800	8,800	e		
Benzie	44°33'N 86°4'W	4,950	8,000	6,475		d	
Alpena	45°4'N 83°51'W	5,850	9,100	5,850		d	
Otsego	44°58'N 84°42'W	9,000	--	9,000			
Otsego	44°59'N 84°40'W	7,050	10,700	8,875			
Antrim	44°57'N 85°23'W	8,700	14,000	8,700		d	
Antrim	44°56'N 85°20'W	9,200	14,700	9,200		d	
Antrim	44°57'N 84°53'W	8,400	--	8,400			
Emmett	45°23'N 85°1'W	4,900	6,350	5,625			
Emmett	45°33'N 84°50'W	4,300	5,140	4,720			

[a]Depth value which deviates more than 10 per cent from value indicated by contours.

[b]This determination made on south flank of anomaly.

[c]South Flank of anomaly analyzed only.

[d]Unable to accurately pick tangent to lower portion of anomaly curve.

[e]Straight slope part of anomaly curve slightly distorted.

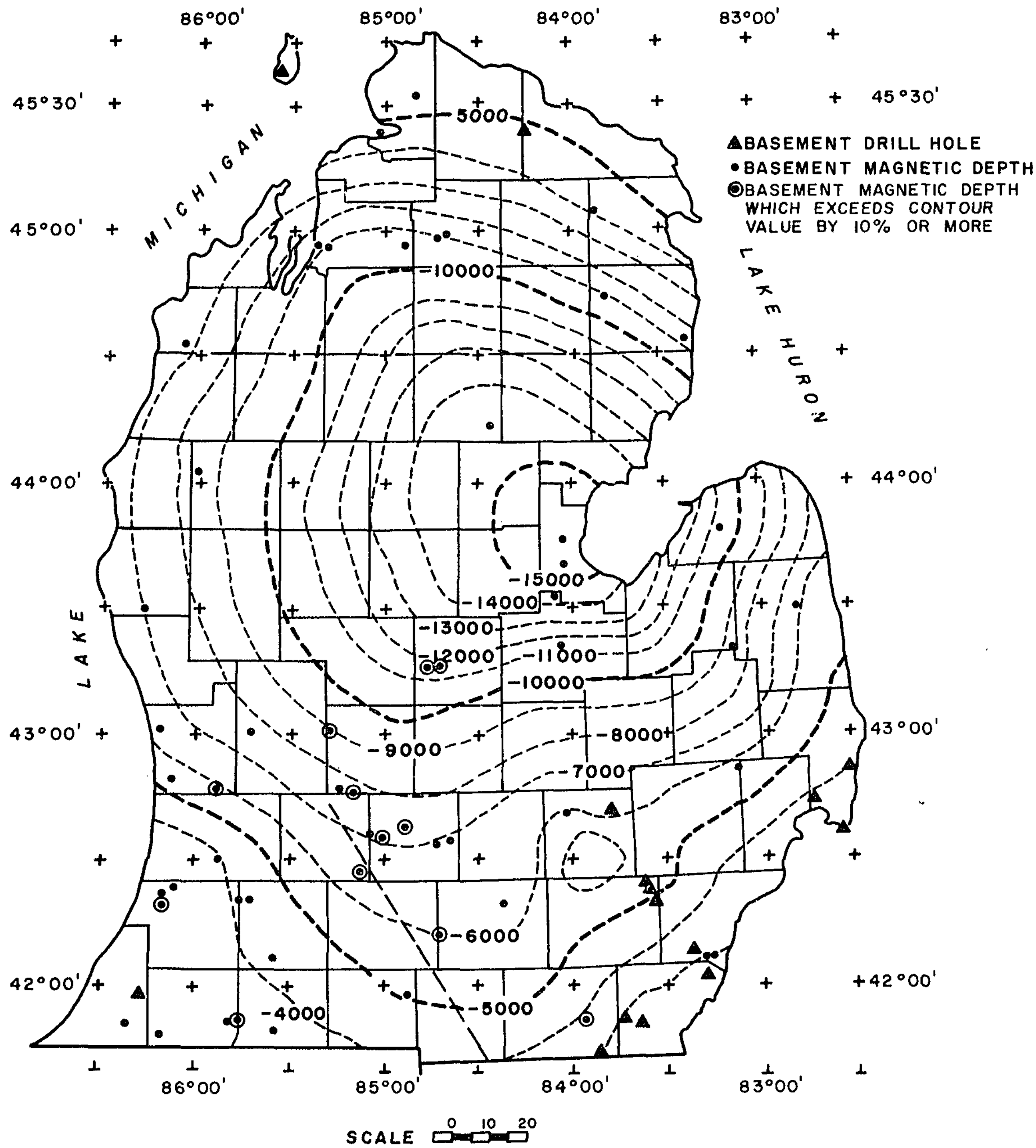

Figure 7.-- BASEMENT SURFACE CONFIGURATION MAP OF THE SOUTHERN PENINSULA OF MICHIGAN

Datum Sea Level

Contour Interval 1000 feet

Discussion of the Basement Configuration Map

The basement configuration map is presented in Figure 7. Datum for the map is mean sea level and the contour interval is 1,000 feet. The smooth, regional nature of the contouring has downgraded the role of depths shown in Table 4 which are inconsistent with the great bulk of the data. Depth estimates which deviate from the contour values indicated in Figure 7 by more than 10 per cent, are marked on the Figure and in Table 4. However, these depths are included in the table for completeness. The map includes a fault in the south-central part of the state inferred from gravity data by Merritt (1968).

The basement configuration map confirms that the basement surface of the Southern Peninsula of Michigan has the form of an oval depression reaching a maximum depth of approximately 15,000 feet below sea level on the western shore of Saginaw Bay. Following Hinze and Merritt (1969), it shows a minor topographic depression in the northwest which plunges southeast into the Basin. A similar depression exists in the structure contour map of the Ordovician Trenton formation (Hinze and Merritt, 1969).

A basement high is depicted in the southeast underlying the Howell anticline in Livingston County. The areal extent of this feature is clearly open to question; however, well control in Livingston and Washtenaw Counties and adjacent magnetic depths suggest a basement closure of perhaps 1,000 feet.

To the west of the Howell structure, a broad trough plunges to the north-northwest into the Basin. The existence of this feature is postulated solely on the basis of magnetic depth determinations as no basement wells are located in this area. A similar trough has been shown by Bayley and Muehlberger (1968).

The southwestern portion of the Southern Peninsula is characterized by a broad basement platform. This feature, which has not been discussed in connection with previous basement maps strikes northwest and may indicate a northward broadening of the Kankakee Arch into the extreme southwest portion of Michigan. Eight depths from magnetic anomalies provide the control for this feature.

Sources of Anomalies

Geological and geophysical studies indicate that the Precambrian rocks of the upper Midwest are lithologically complex. Gravity and magnetic maps are particularly useful in deciphering this complex pattern where the Precambrian surface is buried beneath Phanerozoic sediments. Basement lithologic variations are generally associated with density and magnetic susceptibility changes. Further, it can be shown that gravity and magnetic anomalies originating from intra-basement lithologic and structural variations are an order of magnitude greater than anomalies originating within the overlying sediments. This is illustrated in Figures 8 and 9 (after Hinze and Merritt, 1969) which depict cross sections of a hypothetical basin, similar in gross characteristics to the Michigan Basin. The anomaly sources include basement lithology and topography, structures within the sediments, bedrock topography and the overall effect of the basin. Also presented are the theoretical gravity (Figure 8) and magnetic (Figure 9) anomalies for each of these groups of bodies and their combined effect. The conclusion reached from an examination of these diagrams is that the prominent gravity and magnetic anomalies are derived from intra-basement lithologic variations. Not included in Figure 8 are the effect of lateral facies changes in the sediments and deep crustal or upper mantle density variations giving rise to long wavelength anomalies of a regional nature.

In Figures 8 and 9 the gravity and magnetic effects of idealized subsurface bodies were computed. In interpreting gravity and magnetic maps where the subsurface structure is unknown, one attempts to reverse this procedure, i.e., to determine the configuration and lithology of the causative bodies from the observed anomaly maps and profiles. However, the process involves a double source of ambiguity because both the physical property contrasts

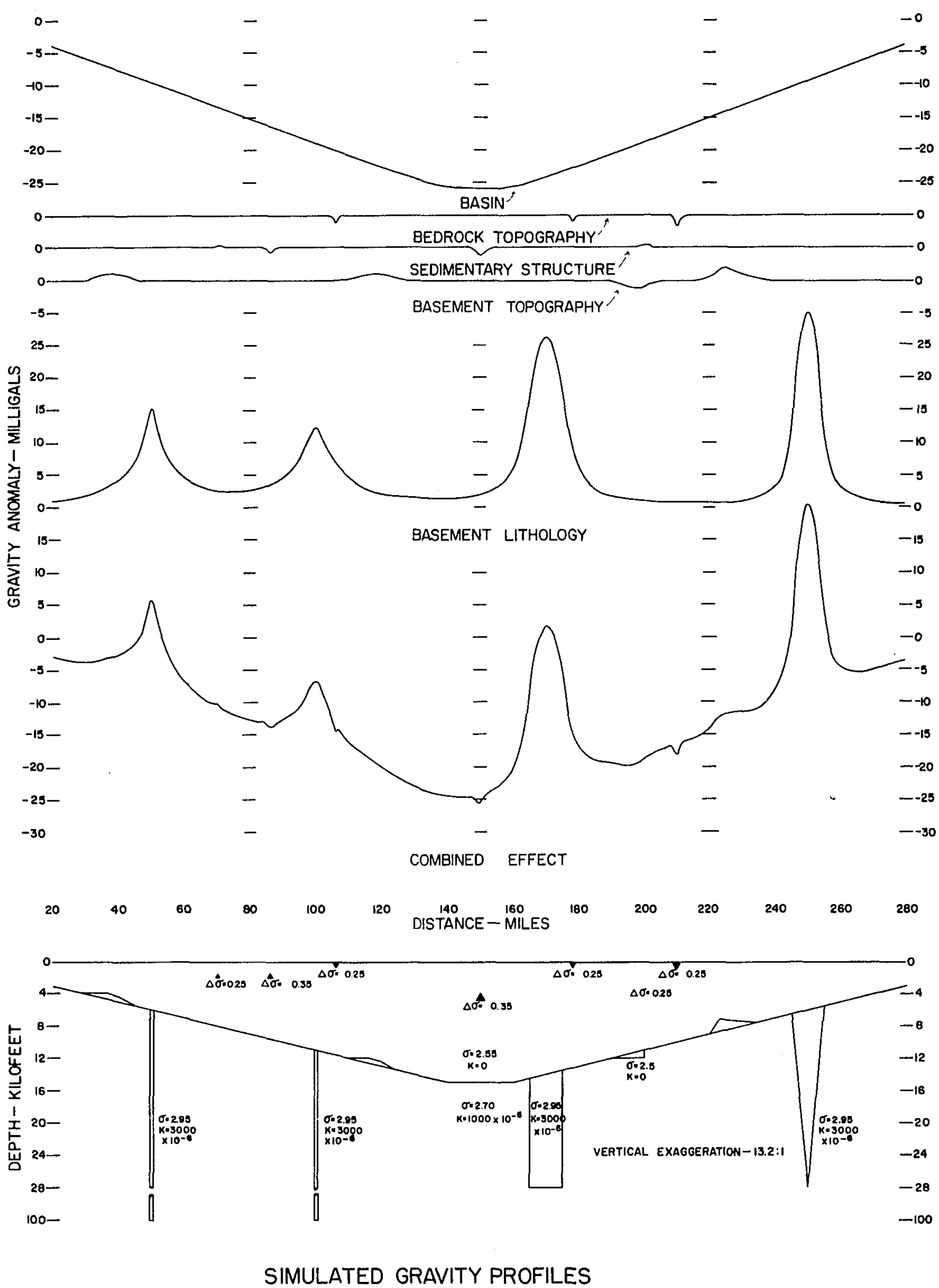

Figure 8.--Simulated Gravity Profiles (after Hinze and Merritt, 1969).

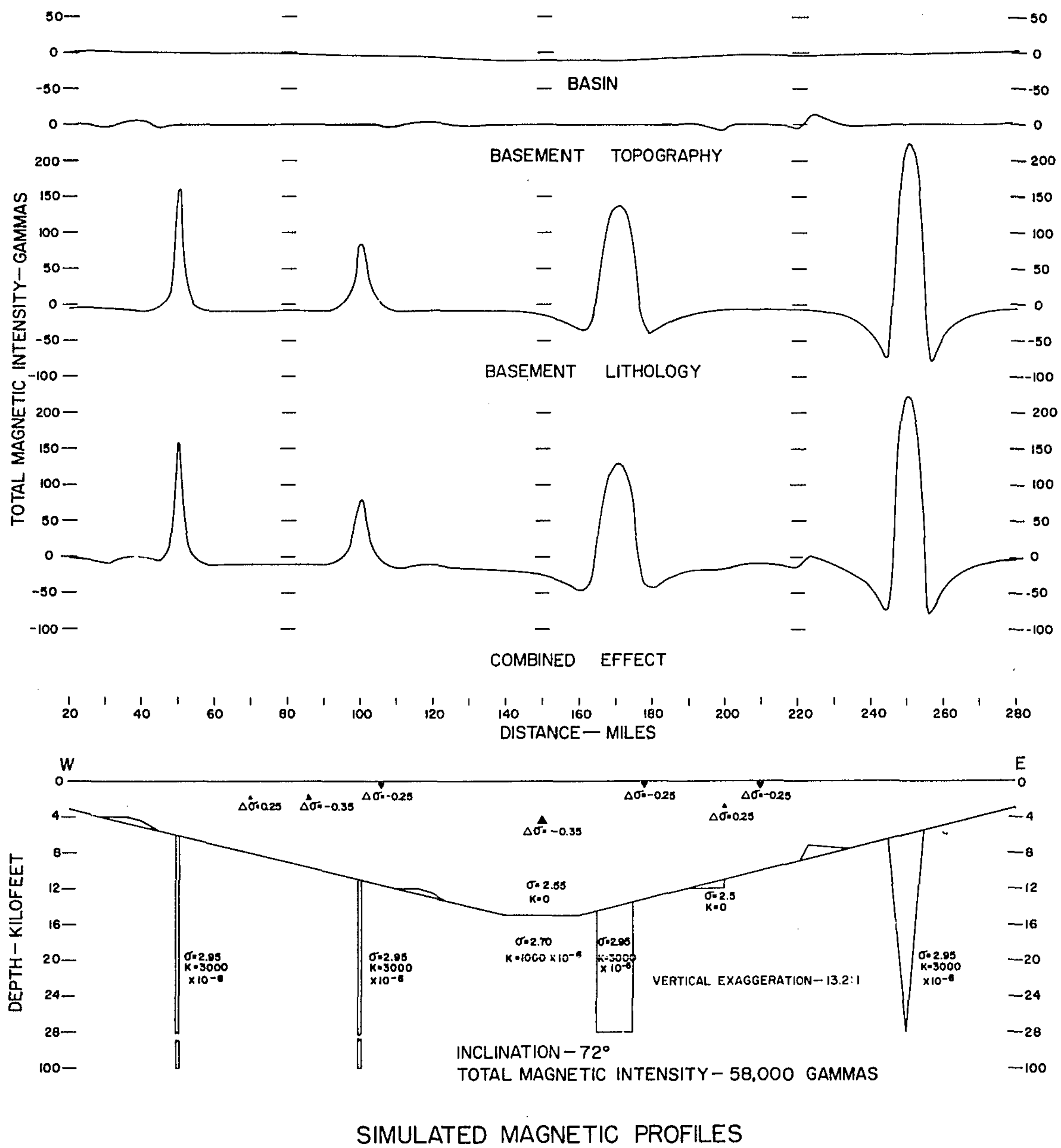

Figure 9.--Simulated Magnetic Profiles (after Hinze and Meritt, 1969).

are uncertain and little is generally known about the configuration of the causative bodies. Even if the physical properties are known, the configuration of the anomalous mass is still unknown except that if a prominent magnetic anomaly is present than the source resides within the basement rocks. Conversely, if the source can be delineated by geologic knowledge and the characteristics of the anomaly, it is still usually impossible to uniquely determine the lithology of the source because the specific gravities and magnetic susceptibilities of rocks generally overlap (Grant and West, 1965). The problem may be further complicated by improper isolation of the gravity or magnetic anomaly from the regional background. The inability to uniquely isolate an anomaly for analysis greatly decreases the value of the interpretation. Finally, there exists the uncertain contribution of remanent magnetic polarization, which may be difficult or impossible to correlate with lithology.

In spite of the difficulties of assigning specific lithologies to intra-basement features, certain generalizations are possible. These generalizations are the result of geophysical studies conducted over the vast exposures of igneous and metamorphic rocks of the Canadian Shield. Thiel (1956) and Craddock, Thiel and Gross (1963) have found that large positive gravity and magnetic anomalies are associated with the great thicknesses of Middle

Keweenawan basalt and gabbro found in the western Lake Superior Basin. Gravity and magnetic anomalies and scattered control well information indicate that these lavas can be traced beneath Paleozoic cover as far south as southern Kansas. This feature was designated the Mid-Continent gravity high by Thiel. Thiel showed that lavas in the center of the structure have been thrust upward as a horst and, in places, juxtaposed against upper Keweenawan, low density clastic sediments. Strong negative gravity and magnetic anomalies are associated with these sediments. White (1966) and Cohen and Meyer (1966) attribute a portion of the minimums flanking the Mid-Continent feature to regional downwarping of the crust-mantle boundary caused by the great weight of the overlying volcanics. Farther south, astride the Kansas-Nebraska border, Muehlberger et al. (1967) have found from petrographic studies that, generally, the Mid-Continent gravity high can be correlated with basalt; however, a portion of the gravity high is not underlain by basalt but rather is underlain by granite and gneiss of average specific gravity. Zietz et al. (1966) show a positive magnetic anomaly in part correlative with this portion of the gravity high. Thus, the presence of an intra-basement mafic mass must be inferred to account for the portion of the gravity high which overlies the granite and gneiss. Keweenawan basalt flows are also responsible for the gravity and magnetic highs east of the Keweenaw fault and at other localities in the Northern Peninsula of Michigan (Bacon, 1966, Meshref and Hinze, 1970).

Locally, in the Lake Superior area, both Keweenawan mafic intrusives and extrusives may produce negative magnetic anomalies due to remanent magnetization (Case and Gair, 1965, Corbett et al., 1967, Meshref and Hinze, 1970).

Elsewhere, granite intrusives generally are associated with negative gravity anomalies (Weaver, 1967, Gibb and McConnell, 1969), and either negative or positive magnetic anomalies depending on the nature of the country rock (MacLaren and Charbonneau, 1968). MacLaren and Charbonneau find that "granitoid rocks and highly altered gneisses generally correlate regionally with magnetic highs and belts of sedimentary and volcanic rocks and low grade gneisses generally correlate with magnetic lows, although the latter may have numerous narrow magnetic highs within the broad belt."

In Ontario, a linear positive magnetic anomaly has been correlated with a complex horst consisting of amphibolite, pyroxene, garnet, feldspar granulite by Bennett et al. (1967). This feature, known as the Moose River magnetic high extends northeastward over 300 miles from Chapleau, Ontario east of Lake Superior to Moosonee on James Bay. The magnetic high is located along the eastern flank of a positive gravity anomaly, the Kapuskasing gravity high. The surface rocks associated with the gravity high are primarily massive granites which do not contribute to the gravity anomaly (Figure 15). Innes et al. (1967) concluded that the gravity anomaly can be accounted for by a local rise in the Conrad discontinuity.

Dutton and Bradley (1970) have reviewed the Precambrian geology of Wisconsin and discussed its relationship to gravity and magnetic anomalies. An inspection of their map shows a zone of metasedimentary rocks, chiefly quartzites, associated with relative gravity and magnetic lows. Positive magnetic anomalies are frequently associated with massive granites. Some of these belts can be traced eastward into Lake Michigan by their magnetic character.

The regional relationships given here are useful in mapping lithology, but they are subject to uncertainty, especially in the case of gravity anomalies because of the unknown contribution of deep seated lithologic variations to the anomalies.

In summary, it is possible to assign a lithologic type to a gravity or magnetic anomaly only in the most general sense, because of overlapping physical property parameters among rock types and the ambiguity of potential field methods. However, it has been found that granitic rocks and metasediments are commonly associated with negative Bouguer gravity anomalies while mafic intrusives and extrusives are frequently characterized by positive

Bouguer gravity anomalies. Metasediments and low grade gneisses are often accompanied by magnetic lows while granitic rocks, highly altered gneisses and mafic intrusives and extrusives are frequently associated with magnetic highs. These relationships are particularly dependent on the nature of the surrounding country rock, and in the case of the magnetic anomalies, on remanent magnetization.

Characteristics of Magnetic Anomalies in the Southern Peninsula of Michigan

Interpretation of aeromagnetic maps generally begins with a qualitative approach which consists of noting trends and inspecting gradients, amplitudes and shapes of anomalies. The deepest portions of sediment filled basins, for example, are generally reflected magnetically by broad, long wavelength, low amplitude anomalies due to the relatively greater distance from source to magnetometer. An examination of the Total Magnetic Intensity Map of the Southern Peninsula (Figure 10) shows an extensive area, centered west of Saginaw Bay, having relatively broad low amplitude anomalies. These anomalies reflect the greater depth to basement in this area. The periphery of the map, on the other hand, is characterized by an abundance of anomalies having relatively high amplitudes and steep gradients. These anomalies occur within the shallower portions of the Basin.

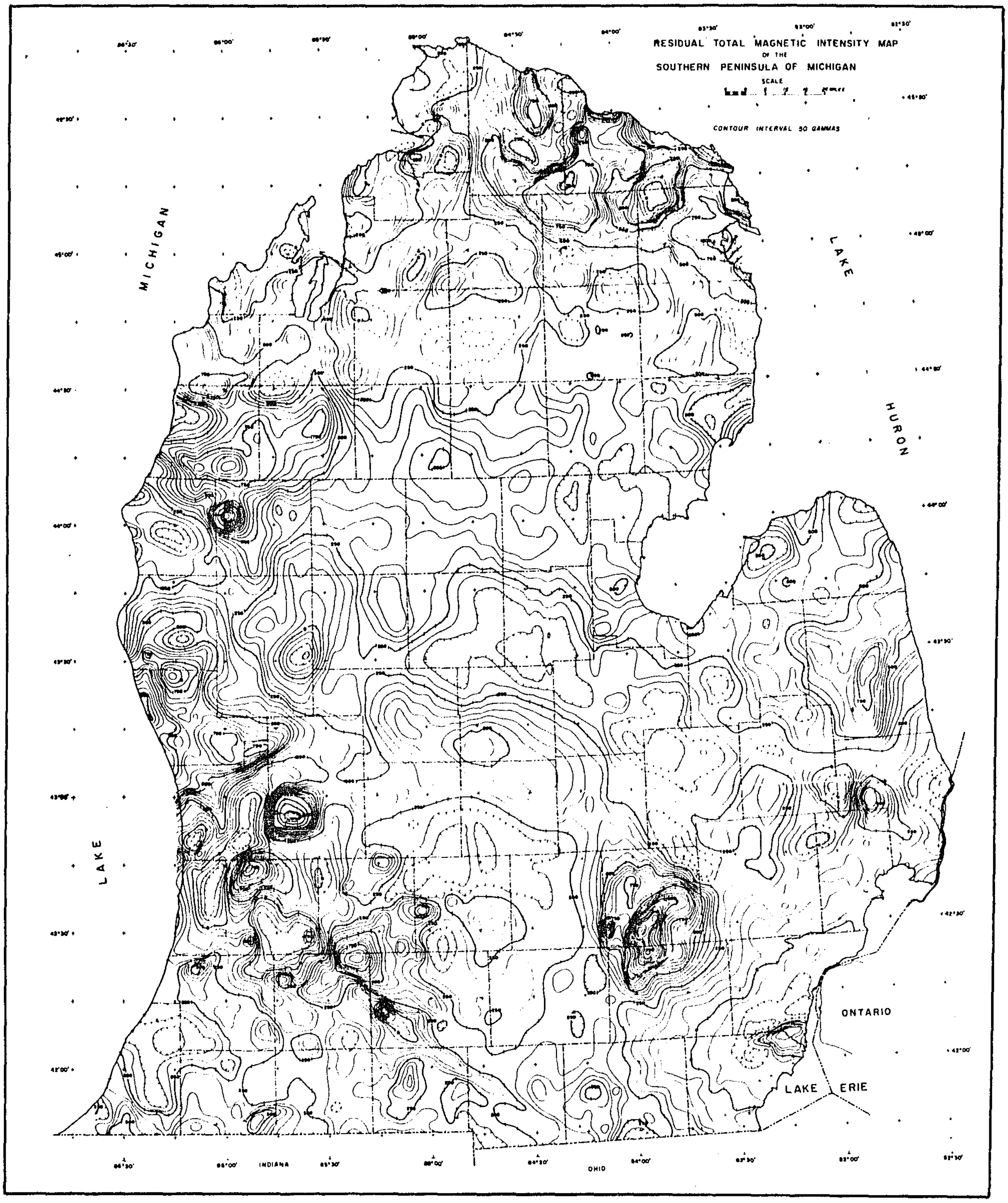

Figure 10.--Residual Total Magnetic Intensity Map of the Southern Peninsula of Michigan.

Magnetic anomalies in the Southern Peninsula are generally elongated, that is, they are characterized by a length which is two or more times the width of the anomaly. However, many high amplitude circular to subcircular anomalies are found in southwestern Michigan (Figure 10).

The strike of magnetic anomalies varies over the State. Southeastern Michigan, east of a line extending from southern Saginaw Bay to the boundary of Michigan and Ohio at 84° 30'W, is characterized by north to northeast trending anomalies. Anomalies falling within this category include the north-south striking anomaly in western Lenawee County, the intense north to northeast striking anomalies in Livingston County and several anomalies in the Thumb area of Michigan. In addition, the regional trend of the total magnetic intensity contours strikes northeast in this area, although these contours are cut near 43° 00'N by a large southeast trending minimum (Figure 10). With the exception of the Livingston County anomaly, the amplitudes of magnetic anomalies in southeastern Michigan range from 250 to approximately 800 gammas. The Livingston County anomaly, reaches an amplitude of approximately 1,250 gammas above the regional magnetic level. Extreme southeastern Michigan in Monroe and Lenawee Counties, is associated with a rather broad northeast trending minimum.

Throughout the remainder of the Southern Peninsula, magnetic anomalies vary from an east-west to a northwest-southeast strike. The latter class of anomalies is best developed in southern Michigan roughly south of 43° 30'N and is truncated on the east by the previously discussed suite of northeast trending anomalies. A particularly good example of this class of anomalies is the broad positive centered in Gratiot County which reaches an amplitude of roughly 300 gammas. This anomaly is continuous with a broad anomaly in Livingston County on which several north-northeast trending anomalies appear to be superimposed.

South and west of the Livingston and Gratiot County anomalies a large number of circular to sub-circular anomalies of limited areal extent are found. The sharp gradients, limited size, and intense amplitude of some of these anomalies generally reflect the shallower depth to basement in this area. One anomaly, located in Kent County, reaches 1,500 gammas in amplitude while several others exceed 800 gammas.

The northern tip of the Southern Peninsula, roughly north of 45° 00'N, is the most complex area, magnetically, in the Southern Peninsula. East-southeast trending anomalies in this area are characterized by steep gradients and amplitudes ranging up to 1,000 gammas or more. Magnetic anomalies in the northern tip of the Southern Peninsula appear to reflect both a shallower basement and the relatively greater complexity of the basement geology. This follows from an examination of the Residual Total Intensity Anomaly Map, (Figure 10) together with the Basement

Configuration Map (Figure 7). Nowhere else in the Southern Peninsula, at comparable depths, are magnetic anomalies found which resemble the complex pattern present north of 45° 00'N.

South of 43° 30'N, gravity anomalies strike northwest-southeast, paralleling the trend of the magnetic anomalies (Figures 10 and 11). However, north of this latitude, gravity anomalies frequently strike north-south, while magnetic anomalies generally assume a more east-west strike. However, an east-southeast trending gravity anomaly is noted in Oscoda County (Figure 11) and several anomalies having similar trends are apparent on a residual Bouguer gravity anomaly map prepared by Hinze and Merritt (1969), and presented in Figure 13.

The signs of gravity and magnetic anomalies are generally directly related in the Southern Peninsula. However, several important magnetic anomalies are inversely related to gravity anomalies. One example is centered in Ogemaw County (44° 15'N and 84° 15'W) where a northwest trending negative gravity closure is associated with a broad magnetic positive. The gravity minimum may originate from thickening of Silurian and Devonian evaporites as discussed by Hinze (1963). However, the unexpected large accumulation of Cambrian sediments encountered in the Foster No. 1 well in northern Ogemaw County (28, 24N, 2E) was cited by Hinze and Merritt (1969) as evidence for a

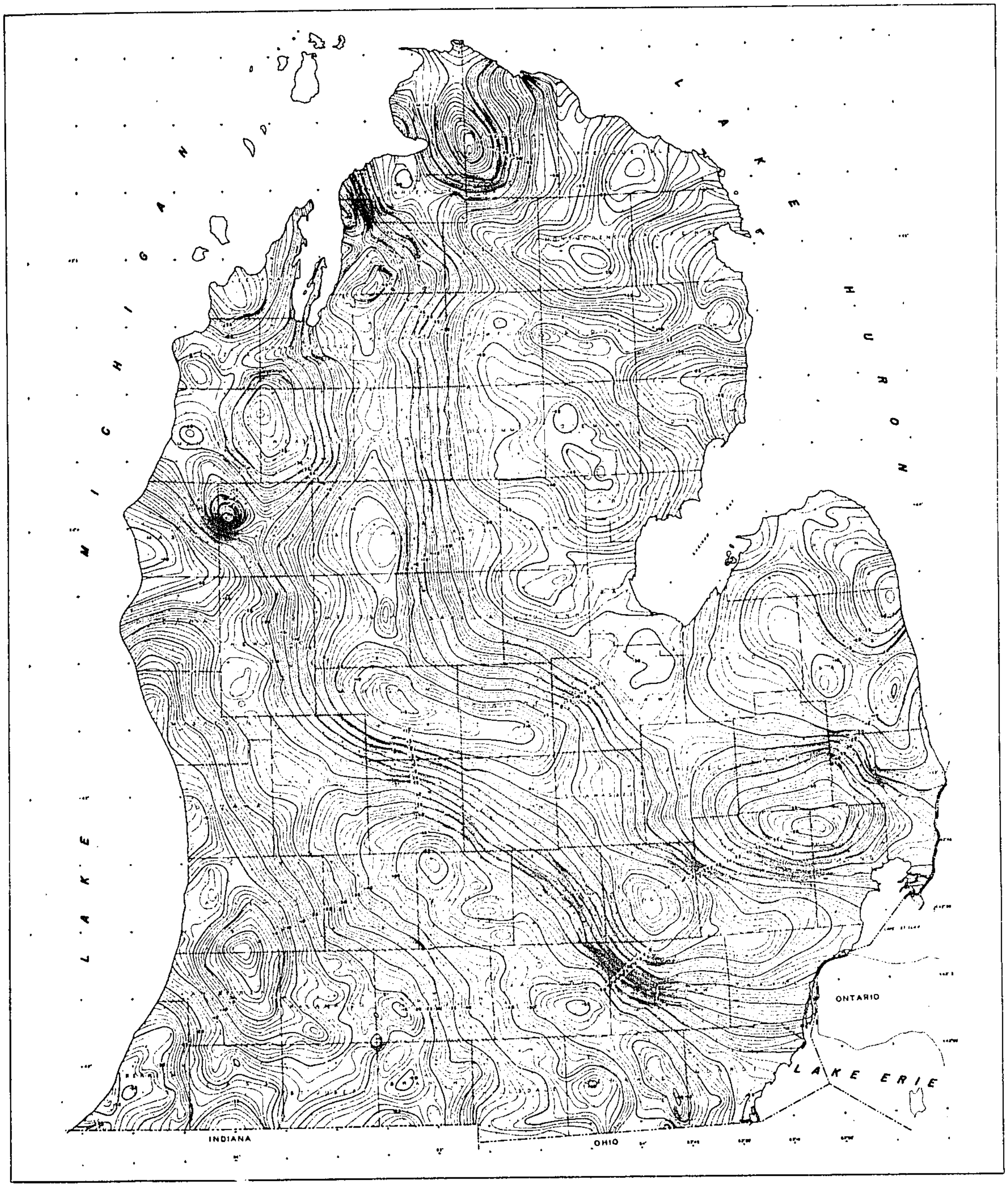

Figure 11.--Residual Bouger Gravity Anomaly Map of the Southern Peninsula of Michigan.

depression in the Precambrian surface. The existence of this depression cannot be confirmed or denied on the basis of magnetic depth determinations undertaken in this study because none of the determinations falls within Ogemaw County (Figure 7).

An inverse relationship also exists in southwestern Calhoun County where a strong negative magnetic anomaly coincides with a positive gravity anomaly. The magnetic anomaly has an amplitude of a negative 600 gammas while the gravity anomaly reaches a positive 8 mgals. The negative magnetic anomaly can be traced for more than 50 miles along a northwest-southeast strike; however, the gravity anomaly is confined to Calhoun County.

Finally, an important inverse correlation is noted between the gravity and magnetic anomalies in the vicinity of Grand Traverse Bay. In this area, a large gravity anomaly (the Mid-Michigan gravity high [Hinze, 1963]) correlates with a marked negative (-400 gammas) magnetic anomaly. The Mid-Michigan gravity high transects the entire Peninsula from the Grand Traverse Bay region to Lake St. Clair and is the most important anomaly on the Bouguer Gravity Anomaly Map (Figure 11). The variable relationship of the gravity anomaly to the magnetic anomaly along the length of this important feature, will be considered in detail in subsequent sections.

Basement Structure and Lithology

Introduction

Four basement provinces have been postulated to exist in the basement underlying the Southern Peninsula of Michigan. Nowhere else on the earth, to the best of our knowledge, has the identification of so many provinces been made in such a small geographical area. Geophysical data, particularly gravity and magnetic anomaly maps, have been indespensable to an understanding of basement provinces. This is true because anomalies associated with basement provinces can be extended beneath the sedimentary cover on the basis of their character.

Basement provinces of shield areas are defined on the basis of a series of related geological events, and may be recognized by isotope ages, coordinated tectonic patterns and lithologies and associated geophysical anomalies. The effects of diastrophism are generally manifested in common geologic features and trends which further aid in defining the basement provinces in the shield area (Stockwell, 1965). Extensive areas of the North American Precambrian Shield are characterized by ages representing the latest tectonic activity in the area.

Isotope dating of samples from basement drill holes in the sediment covered portions of the Midwest affords the opportunity to extend the provinces of the exposed Shield into this area and to arrange chronologically the geological events of the hidden basement rocks. Considerable caution is necessary when interpreting ages from a few scattered samples. This is true, because local post-orogenic metamorphic activity may have affected only portions of a province; thus ages obtained from isotope analysis may represent the last period of local change in the rock rather than its regional metamorphic or crystallization age. In addition, older rocks or minerals involved in orogenic activity may not have been sufficiently recrystallized to remove all daughter products of the radioactive elements, resulting in an older age for a sample than the date of the latest orogenic activity. In summary, single isotope ages may not truly reflect the thermal events which produce the features characteristic of a basement province. Other ages may reflect minor orogenic "post province" activity. Goldich et al. (1966) find that most age determinations using the Rb-Sr and K-Ar dating methods "do not appear to be related to belts of tectonic deformation or to known orogenic cycles. They date igneous events and their metamorphic effects on the older basement rocks."

The geochronology of the eastern Midcontinent region has been studied by Lidiak et al. (1966). In the Southern Peninsula of Michigan they find rocks dated at 0.8 to 1.0 b.y. and interpreted as belonging to a subsurface extension of the Grenville province of the Canadian Shield. The western boundary of this province has been extended into southeastern Michigan and into western Ohio.

On the north shore of Lake Superior and in northern Michigan and Wisconsin, Goldich et al. (1966) find that the Penokean orogeny (1.6-1.8 b.y.) and Keweenawan activity (1.05-1.15 b.y.) are superimposed on rocks affected by the earlier Algoman event (2.5 b.y.). Lidiak et al. (1966) find that west of the Grenville Front in Ohio, volcanic activity is about 1.2 to 1.3 b.y. old. This date is also associated with igneous activity in Indiana, Illinois, and Iowa. In southern Wisconsin, isotope ages vary from 1.2 to 1.5 b.y. and are considered to be contemporaneous with the same thermal event identified in Iowa, Illinois, and Indiana (Lidiak et al. 1966).

Table 5 presents information on the six basement tests in the Southern Peninsula of Michigan which have been isotopically dated. The dates from these wells fall within the rather narrow range of 0.8 to 1.1 b.y. The four dates from southeastern Michigan are correlated with Grenville activity. The date from the Beaver Island test is typical for Keweenawan igneous activity. This basement test is located just west of the northward extension of the Mid-Michigan gravity and magnetic anomaly which has been correlated with Keweenawan igneous activity by Hinze

TABLE 5.--Isotope Age Dates (Modified from Hinze and Merritt, 1969).

County	Location	Lithology	Sample	Age b.y. Rb-Sr	Age b.y. K-Ar
Charlevoix	6-37N-10W	granite	biotite feldspar	1.04	1.09
Lenawee	32-8S-5E	granite		0.89-0.97	
St. Clair	26-5N-16E	biotite gneiss	biotite	0.9	0.97
Washtenaw	16-1S-7E	gneiss	biotite	0.84	
Washtenaw	12-2S-7E	gneiss	biotite	0.92	
Presque Isle	29-35N-2E	greenstone			0.38

and Merritt (1969) and Oray (1971). This age may reflect thermal metamorphism of an older granite or it may be a granite emplaced during Keweenawan time. The basement drill hole in Presque Isle County is reported to have penetrated quartzite or perhaps vein quartz and then bottomed in greenstone. The greenstone has been dated at 0.38 b.y. (Bradley, 1971).

The Total Intensity Magnetic Anomaly Map (Figure 10) and Bouguer Gravity Anomaly Map (Figure 11) of the Southern Peninsula have been used in conjunction with the geophysical maps and Precambrian geology and isotopic ages to develop a Basement Province Map of the Southern Peninsula (Figure 12). Provinces shown on this map were delineated on the basis of isotope ages and lithologies of basement drill samples and the extrapolation of known basement geology around the perimeter of the Michigan Basin utilizing magnetic and gravity anomalies. As a result of the limited number of basement drill tests in the Southern Peninsula of Michigan, the geophysical maps are particularly significant. Identification of basement provinces from magnetic and gravity anomaly maps is possible because basement provinces are characterized by anomalies reflecting prevailing structural trends and lithologies. Regional magnetic anomaly maps have proven to be particularly useful in mapping basement provinces of the Canadian Shield (MacLaren and

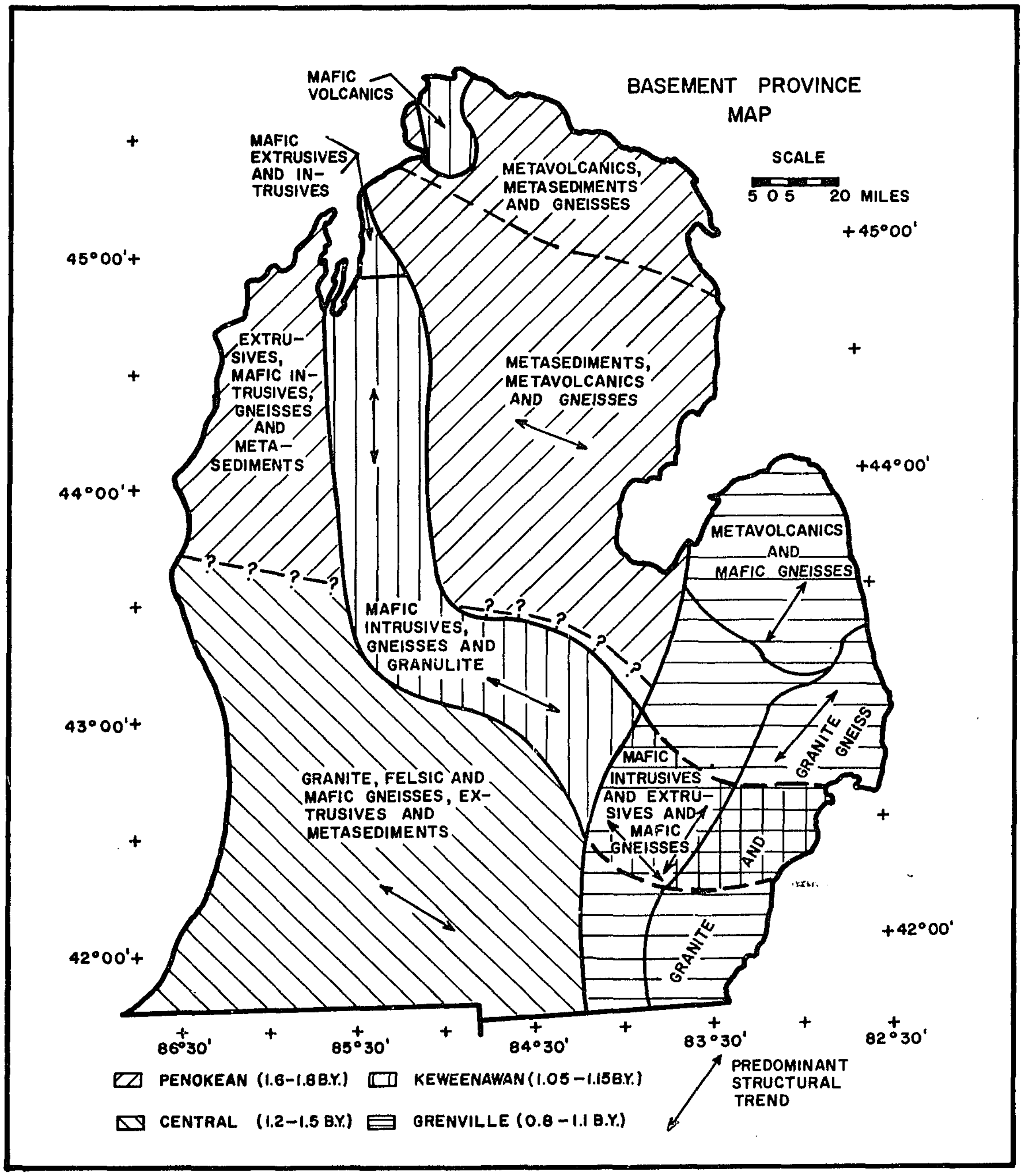

Figure 12.--Basement Province Map of the Southern Peninsula of Michigan.

Charbonneau, 1968). The value of the Residual Total Intensity Magnetic Anomaly Map of the Southern Peninsula was enhanced because it was used in association with magnetic maps of adjacent areas to extrapolate basement anomalies from Precambrian exposures and basement drill holes in these areas into the Southern Peninsula. The Bouguer Gravity Anomaly Map of the Southern Peninsula of Michigan (Figure 11) and the Residual Gravity Anomaly Map prepared by Hinze and Merritt (1969), (Figure 13), are also valuable supplements to the magnetic map in basement province delineation. The latter map was prepared using a double Fourier analysis developed by James (1966). Wavelengths of anomalies in excess of 113 miles in the north-south direction and 95 miles in the east-west direction have been eliminated from the map.

The recent aeromagnetic surveys of Lakes Michigan (O'Hara and Hinze, 1971), Huron (Secor et al. 1967) and eastern Lake Superior and the eastern portion of the Northern Peninsula of Michigan (Hinze et al. 1966) have provided the opportunity to extrapolate magnetic anomalies from the perimeter of the Michigan Basin into the Southern Peninsula. Trends of magnetic anomalies are shown in Figure 14 by means of double ended arrows. Positive trends are depicted by solid arrows while negative magnetic trends are represented by dashed arrows. Correlatable trends selected for discussion are numbered in Figure 14.

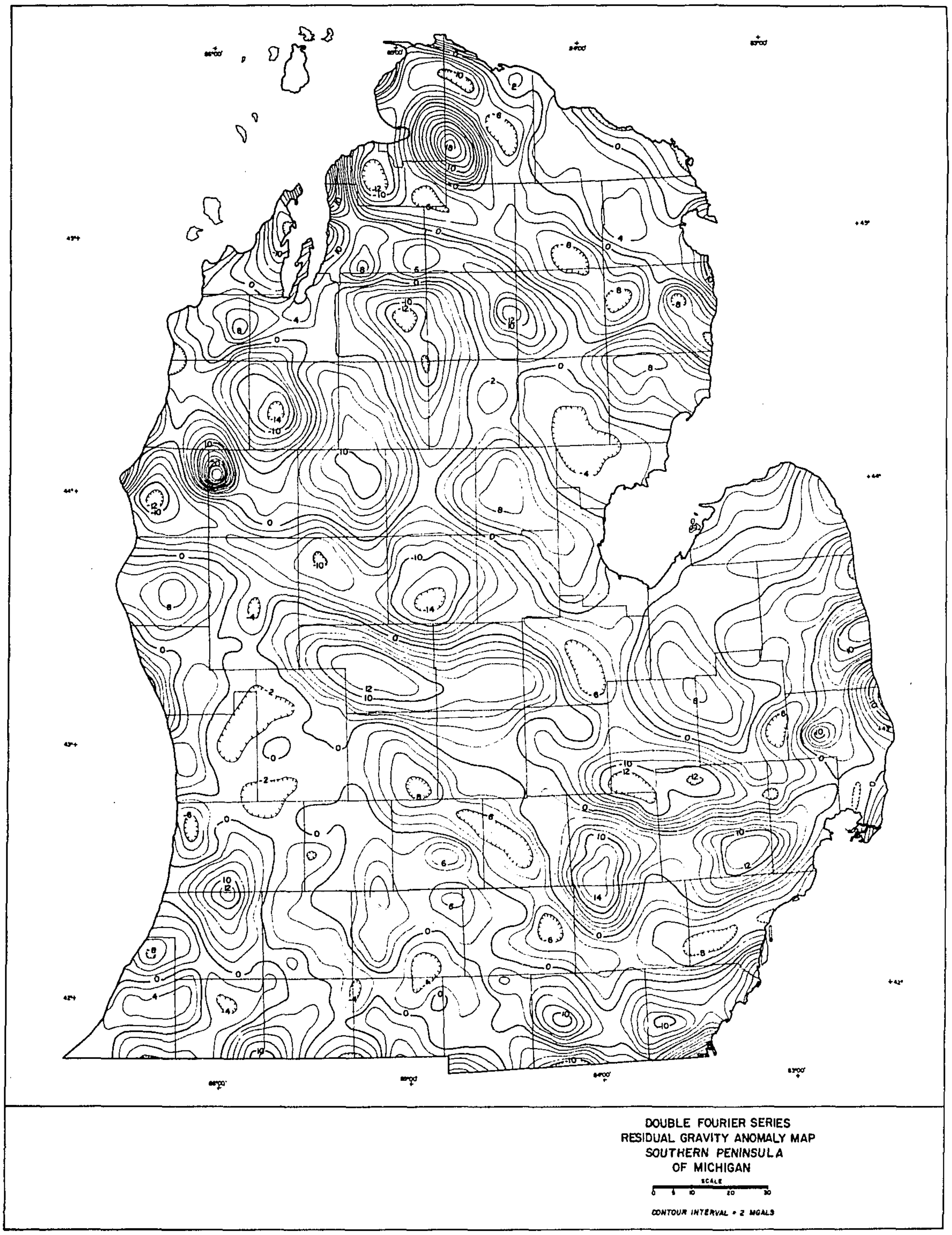

Figure 13.--Double Fourier Series Residual Gravity Anomaly Map of the Southern Peninsula of Michigan (after Hinze and Merritt, 1969).

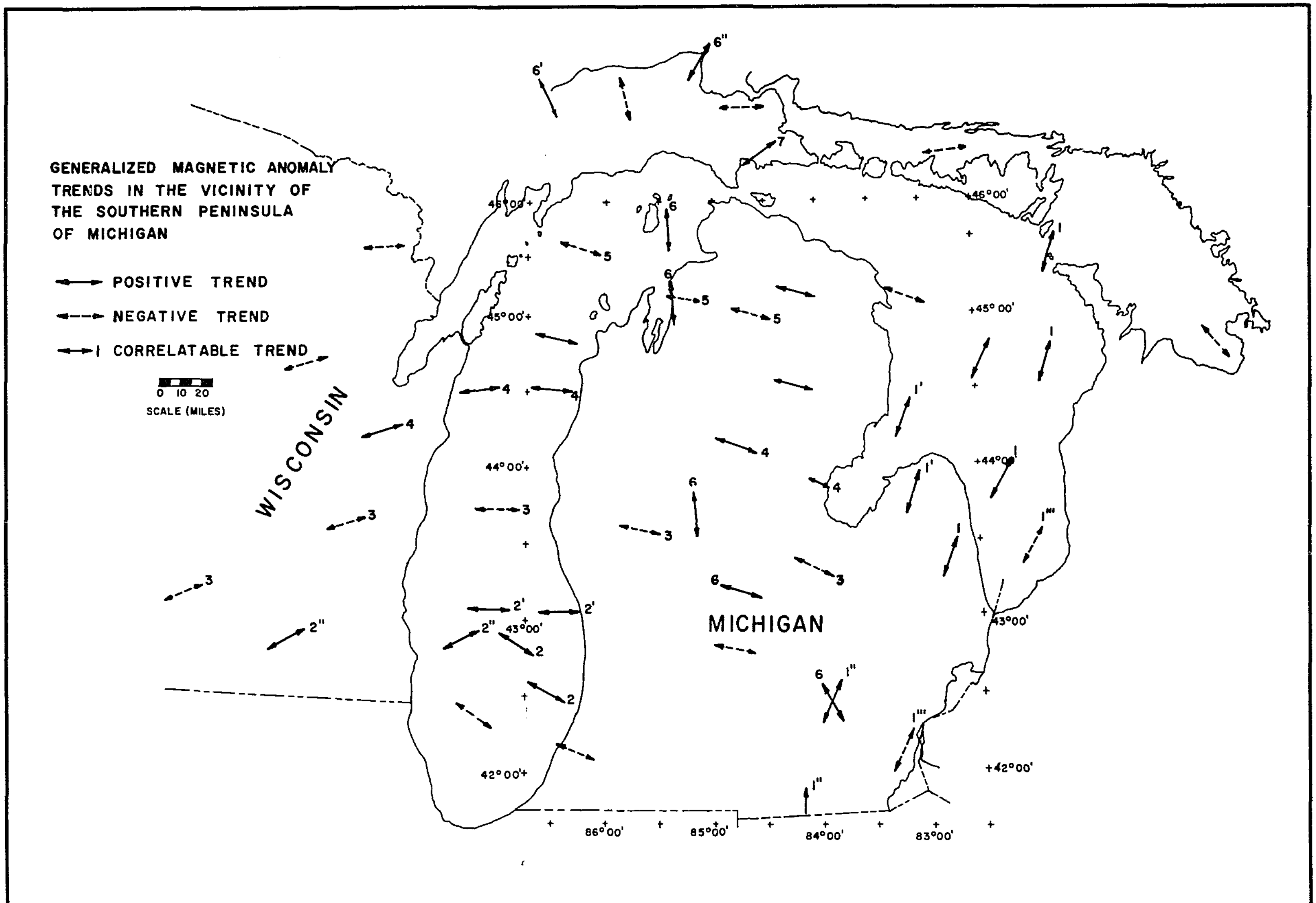

Figure 14.--Magnetic Trend Map, Southern Peninsula and Vicinity.

Four major structural provinces are shown on Figure 12. These include the Grenville province in southeastern Michigan which is dated at 0.8 to 1.0 b.y.; the Penokean (1.6 to 1.8 b.y.) and Central (1.2 to 1.5 b.y.) provinces, and the Keweenawan rift zone (1.1 ± 0.1 b.y.). The boundaries between these provinces are not equally distinct. This is especially true of the Central and Penokean province boundary. Further, they are subject to modification as more information becomes available.

Grenville Province

The Grenville province (Figure 12) is identified on the basis of distinctive isotopic ages, lithologies from basement drill tests and structural patterns reflected in the magnetic and gravity anomaly maps. As stated previously, rocks common to this province frequently are dated at 0.8 to 1.0 b.y. Structures within the Grenville province tend to have irregular, curvilinear trends (Stockwell, 1965); however, Nwachukwu *et al.* (1965) show a predominant northeast alignment of magnetic trends in Lake Huron and adjacent portions of Ontario and Michigan (trends 1 through 1'" Figure 14). These trends are parallel to the trend of basement lineaments in the Grenville rocks of Southwestern Ontario. Central Lake Huron is characterized by intense magnetic anomalies ranging from 600 to 900 gammas, attributed to amphibolites, pyroxenites and mafic gneisses such as are encountered elsewhere in the Grenville province (MacLaren and Charbonneau, 1968). Local anomaly values rise to 2,400 gammas and are attributed to intra-basement intrusives (Nwachukwu et al. 1965). These northeast trending anomalies can be traced into the Thumb area of Michigan where they are associated with a positive gravity anomaly and several northeast trending magnetic anomalies (Secor et al. 1967). South and east of this area, drill tests and geophysical data suggest a granite gneiss subprovince. The Bruce Peninsula has dominant northeast magnetic trends and overlies the granite gneiss subprovince in Ontario (Hinze and Merritt, 1969).

The north and west limit of the Grenville province is known as the Grenville Front. The Grenville Front has been described by Wynne-Edwards (1967) as a "metamorphic transition zone, a fault and a shear zone in different places, and is a major linear tectonic feature that separates high-grade metamorphic rocks of the Grenville province from low grade metamorphic rocks to the northwest."

Secor et al. (1967) have shown on the basis of their aeromagnetic study of Lake Huron that the Grenville Front can be traced by magnetic anomalies southwest from the vicinity of Killarney, Ontario, through the east end of Manitoulin Island and then south to the Thumb of Michigan. The location of the Front was drawn separating the predominantly northeast magnetic trends in southwestern Ontario, central Lake Huron, and the Michigan Thumb from the east-southeast trends that dominate the magnetic pattern of northwestern Lake Huron and Saginaw Bay. The latter are interpreted to reflect the Penokean fold belt.

The Front is shown entering the Southern Peninsula in southern Saginaw Bay on the basis of the criteria previously discussed and then trends southwest, entering Livingston County at 84°00'W.

The position of the Front has been located west of the northeast trending cross magnetic anomaly in Livingston County (Figure 10). This anomaly is on trend and similar in character to the suite of northeast trending magnetic anomalies investigated by Secor and Nwachukwu and used to establish the location of the Front in Lake Huron. From this point, the Front is extended due south on trend with a smaller north-south striking anomaly near the Michigan-Ohio boundary at approximately 84° 15'W. This position is compatible with the location of the boundary in Ohio as shown by isotope dating of basement drill samples.

The origin of the broad positive anomaly in the Thumb of Michigan is attributed to a southwestward extension of the volcanics and/or amphibolites discussed by Nwachukwu *et al.* No basement drill holes occur in this area.

Magnetic anomalies in the Grenville subprovince in southeastern Michigan are predominantly negative, except in St. Clair County and near the Monroe and Wayne County boundary adjacent to Lake Erie. This area is interpreted as the southwestward extension of the granite gneiss subprovince of Nwachukwu et al. (Figure 12). Southeastern Michigan also correlates in part with large gravity lows and the Mid-Michigan gravity high which extends eastward into this area (Figure 11). Similar relationships are noted for relic lithologies in exposed portions of the Grenville province by Stonehouse (1969). He reports that lithologies belonging to the Superior and Penokean provinces can be found extending into the Grenville province in several areas.

Several drill holes have penetrated the basement in the vicinity of the Howell anticline (Figure 1), and elsewhere in southeastern Michigan as discussed above. These tests provide an opportunity to correlate lithology with magnetic expression. The Livingston County well (11-3N-5E), located on the northeast flank of the large Livingston County gravity and magnetic anomaly (Figures 10 and 11) encountered an intermediate composition gneiss (Laaksonen, 1971). Laaksonen found that magnetic susceptibility values of cuttings obtained from this well have values of approximately 50 emu/cc. These values are surprisingly low considering the location of the well. However, Laaksonen found evidence of recrystallization of mineral grains and the possible oxidation of magnetite to hematite. Thus, it is reasonable to assume that the low susceptibility may reflect local environmental conditions and may not be truly representative of the susceptibility of the rocks responsible for the Mid-Michigan magnetic anomaly in this area.

Considerably higher values (approximately 2,000 emu/cc), were found from cuttings from the well in northeastern Monroe County (29-8S-5E), which encountered granite. This well is located on a small magnetic high. A well located a few miles to the north in southern Wayne County, (16-4S-9E) encountered granite gneiss but samples obtained from this well were not tested for magnetic susceptibility. The high susceptibility in the Wayne County well (29-8S-5E) may reflect a magnetite rich granite.

Central and Penokean Provinces

The Central province (Engel, 1963) is widespread throughout the upper Midwest. Granites, rhyolites, metasediments and granite gneiss dated at between 1.2 b.y. and 1.5 b.y. have been found or interpreted in southern Wisconsin, northern Illinois, Indiana and western Ohio (Goldich et al. 1966). However, Stonehouse (1969) cites several acid intrusives along the north shore of Lake Huron which have been dated at between 1.4 and 1.5 b.y. and may be associated with the Penokean orogeny. Thus, considerable caution is warranted when interpreting the presence of the Central province in an area from isotope age dates alone.

On the basis of available geophysical maps, a single basement test in Berrien County, and extrapolation of the basement rocks of southern Wisconsin and northern Illinois beneath Lake Michigan, Hinze and Merritt (1969) concluded that the Central province extends into Michigan and is associated with granites and granite gneisses and subsidiary mafic rocks and perhaps metasediments.

The location of the boundary separating the Central province from the older Penokean province to the north has been placed in a variety of locations from near the tip of the Southern Peninsula (46° 00'N, Eardley, 1962, and Muehlberger *et al.* 1967), to a south central location at 43° 00'N (Stonehouse, 1969). An examination of the most recent information in Wisconsin (Dutton and Bradly, 1970) including geophysical maps, isotope ages of basement samples, lithologies and structural trends, indicates a sharp provincial boundary does not occur in Wisconsin. Rather, a transition zone occurs which is characterized by overlapping isotope ages ranging from 1.2 b.y. in southern Wisconsin to more than 1.7 b.y. at several locations in northern Wisconsin. Thus it is difficult to be specific about the contact between the Central and Penokean provinces. The position of the contact shown in Figure 12 designates a boundary north of which Penokean trends predominate. However, Penokean trends may occur well south of this boundary.

Rocks of the Penokean thermal event (1.6-1.8 b.y.) are exposed in several areas in Wisconsin and occur as infolded remnants in the early Precambrian gneiss complex in the Northern Peninsula of Michigan and northern Wisconsin. Where exposed, they are generally arenaceous metasediments and felsic extrusives as well as gneisses and intrusives.

Animikean metasediments, metavolcanics and gneisses, strongly folded during the Penokean orogeny, may occur within a subprovince which encompasses the northern portion of the Southern Peninsula (Figure 12). This interpretation is based on the marked change in gradients, amplitudes and number of anomalies north of approximately 45° 00'N. These anomalies, while complex, generally trend southeast and are similar magnetically to anomalies associated with Animikean lithologies in the Northern Peninsula (Zietz and Kirby, 1971). An intervening zone of gentle magnetic relief, centered in northern Lake Michigan, separates these anomaly belts.

A large gravity high which is not associated with a single magnetic anomaly also occurs in this area (Figure 11). Oray, (1971), has suggested that this high may reflect Keweenawan volcanics or mafic intrusives.

Both the Central and Penokean provinces are transected by the Keweenawan rift zone. This belt generally cuts older Penokean trends north of latitude 43° 30'N at nearly right angles. South of this latitude, the predominant trend of geophysical anomalies is parallel to the rift zone.

O'Hara and Hinze (1971) show that Lake Michigan is characterized by alternating bands of positive and negative magnetic anomalies which can be traced westward into Wisconsin and eastward into the Southern Peninsula of Michigan. The southernmost positive band (Number 2', Figure 14) strikes northwest across the Lake from 42° 00'N to 43° 30'N. This anomaly belt contains three somewhat overlapping magnetic trends in Lake Michigan. One trend strikes northeast in the western half of the Lake (Number 2", Figure 14), while a second strikes east-west in the eastern portion of the Lake and continues into the Southern Peninsula in Muskegon and Oceana Counties (Trends 2', Figure 14). A third magnetic trend observed in this positive anomaly zone strikes southeast from the central portion of the Lake and continues into southwestern Michigan as a series of isolated magnetic anomalies (Trend 2, Figure 14). This trend is roughly parallel to the broad regional Bouguer gravity positive transecting southwestern Michigan and which occurs in northeastern Indiana and northwestern Ohio. In northeastern Indiana, Bayley and Muelhberger (1968) indicate Keweenawan type rocks underlie a portion of the anomaly.

North of this complex high, in Lake Michigan, a broad magnetic minimum strikes east-west across the Lake at 44° 00'N (Trend 3, Figure 14). This belt is a continuation of a magnetic minimum which trends northeast across Wisconsin from the southwest corner of the state into Lake Michigan. Bouguer gravity anomaly contours in Wisconsin generally parallel the magnetic minimum; however, no specific anomaly is related to the magnetic minimum. Basement tests and outcrops in Wisconsin indicate that the minimum generally correlates with quartzites of the Baraboo, Waterloo, and Fond Du Lac ranges which overlie a primarily felsic basement (O'Hara and Hinze, 1971). In the eastern half of Lake Michigan, the trend of this minimum changes to a southeast strike and extends into the Southern Peninsula (Trend 3, Figure 14). The trend can be followed by way of a broad magnetic minimum centered in Newaygo County to the large gravity and magnetic minimum lying on the northern margin of the Mid-Michigan gravity high. On this basis, the broad magnetic minimum north of the Mid-Michigan structure is interpreted to have originated during the Penokean or an earlier orogeny. This trend may have undergone modification during Keweenawan activity in the Southern Peninsula.

A predominantly positive magnetic zone strikes northeast across Wisconsin north of the magnetic minimum discussed above, and enters Lake Michigan between 44° 00'N and 45° 00'N (Number 4, Figure 14). The magnetic high correlates with a gravity high in eastern Wisconsin. Scattered outcrops in Wisconsin reveal a granitic basement with occasional patches of quartzites and mafic rocks. As noted in the case of the two previously discussed magnetic anomaly zones the strike of this magnetic anomaly becomes southeast in Midlake. The anomaly enters the Southern Peninsula at roughly 44° 30'N as a relatively positive magnetic and gravity zone, and can be traced southeast to the vicinity of western Saginaw Bay on the Residual Total Magnetic Intensity Map of the Southern Peninsula, (Figure 10) and a residual gravity map prepared by Hinze and Merritt (1969) (Figure 13). This anomalous trend is also interpreted to reflect basement lithologies dating back at least to the Penokean period.

A large east-west trending magnetic minimum (Trend 5, Figure 14), occurs north of the anomaly discussed above and extends from the western shore of Green Bay to south of Beaver Island. The anomaly is on strike with felsic rocks of the Mountain-Amberg area of Wisconsin which is also characterized by magnetic and gravity minimums. In the eastern portion of Grand Traverse Bay, an intense magnetic low occurs on trend with the minimum in Lake Michigan. Significantly, this magnetic minimum also occurs along the axis of the Mid-Michigan gravity high.

This can be explained by assuming that Keweenawan volcanics associated with the gravity high have been affected by remanent magnetization. However, at least a portion of the Grand Traverse Bay magnetic low may be due to an extension of Penokean felsic rocks of the Mountain-Amberg area of northeastern Wisconsin. This interpretation is supported by the tendency for the northerly trending Mid-Michigan gravity high to become constricted and of reduced amplitude at the point where it encounters the extension of the Mountain-Amberg minimum. North and south of the constriction, the gravity high once again assumes Bouguer gravity anomaly values in excess of +5 mgal. East of the Mid-Michigan anomaly, the minimum reappears as a series of local minimums and strikes east-southeast to Lake Huron (Trend 5, Figure 14). A well defined residual gravity minimum correlates with the magnetic minimum (Hinze and Merritt, 1969).

Keweenawan Rift Zone and Related Activity

As stated above, the dominant feature of the Bouguer Gravity Anomaly Map (Figure 11) is the Mid-Michigan anomaly. A Keweenawan age for this feature has previously been suggested (Bacon, 1957 and Hinze, 1963). This anomaly will be considered quantitatively in the following section.

The Mid-Michigan feature can be divided into several portions based on the relationship of the positive gravity to the magnetic anomaly within each segment. Southeastern Michigan, east of Livingston County is overlain by a positive Bouguer gravity anomaly. No magnetic anomaly is associated with the gravity anomaly in this area (Figure 10). The Livingston County area has both a positive gravity and a strong positive magnetic anomaly (Trend 6, Figure 14). North and west of Livingston County, a generally subdued magnetic anomaly correlates with the Mid-Michigan gravity high to approximately 44° 00'N. North of 44° 00'N, to approximately 44° 45'N the gravity anomaly persists; however, the magnetic anomaly is no longer discernable. Finally, in the Grand Traverse Bay area, the Mid-Michigan gravity anomaly correlates with a marked negative magnetic anomaly (Figures 10 and 11).

The boundaries between these segments are perhaps fault contacts. The marked change in strike of the anomalies just north of the Livingston County anomaly and again at 43° 30'N is suggestive of faulting.

Flanking the Mid-Michigan anomaly south of approximately 43° 30'N are gravity and magnetic minimums. The magnetic and gravity minimum on the north flank of the Mid-Michigan high and its correlation with Penokean trends was considered above. The magnetic and gravity minimum on the south flank of the gravity high may also reflect Animikean lithologies which underwent structural deformation during the Penokean orogenic event. However, the lack of distinct anomalies in Wisconsin and Lake Michigan which can be correlated with this low precludes a definitive interpretation. Furthermore, the magnetic pattern south and west of the Mid-Michigan high is complicated by southeasterly trends that are believed to be associated with Keweenawan tectonic and igneous activity.

North of the Grand Traverse Bay area the Mid-Michigan anomaly can be traced to the eastern side of Beaver Island (Trend 6, Figure 14). At this point, the anomaly bifurcates, with one limb extending to the northwest (Trend 6', Figure 14) where it joins the anomaly associated with middle Keweenawan basalts on the Keweenaw Peninsula (Hinze et al. 1966). The eastern limb trends north-northeast by way of the eastern portion of the Northern Peninsula through Whitefish Point to Mamainse Point, Ontario where it correlates with Keweenawan volcanics and interbedded sediments (Trend 6", Figure 14). To the south, the magnetic anomaly abruptly terminates east of the Howell anticline, while the gravity anomaly extends a short distance into Ontario before dying out.

The positive gravity anomaly at the northern tip of the southern peninsula, south of the Straits of Mackinac, has been discussed above. This anomaly may be the southward extension of a large positive gravity and magnetic anomaly in the easternmost portion of the Northern Peninsula of Michigan (Trend 7, Figure 14). Oray (1971) has investigated the anomaly in the Northern Peninsula and attributed it to Keweenawan volcanics with an associated feeder pipe.

Several other anomalies may have a Keweenawan origin. A particularly strong magnetic anomaly was mapped in Kent County by Stevenson (1964). The magnitude of the Kent County anomaly, as previously discussed, exceeds that of any other feature on the total intensity map. However, only a two mgal residual positive gravity anomaly is found to be associated with the magnetic anomaly. Stevenson conclude that the source of the anomaly is mafic extrusives with an associated feeder pipe. He also concluded that the extrusives have been affected by remanent magnetization. Several additional positive magnetic anomalies occur north of the southwestern Michigan gravity high which parallels the Mid-Michigan high. Two particularly important anomalies are centered in north-central Allegan and northeastern Kalamazoo Counties. Neither anomaly correlates with a significant gravity anomaly. The origin of these anomalies is probably similar to the Kent County anomaly. Moreover, the centers of these anomalies can be connected by a line which strikes roughly parallel to the Mid-Michigan high. Other less prominent subcircular to circular magnetic anomalies occur south and west of the Mid-Michigan gravity high. All of these anomalies may have originated during the development of the Mid-Michigan high along parallel zones of weakness, perhaps as volcanoes or extrusives of limited depth extent.

Meyer (1963) investigated the strong positive magnetic and gravity anomaly in northwestern Lake County. Unlike the circular anomalies discussed above, this feature correlates with a 22 mgal residual gravity anomaly. Meyer attributed the anomaly to a basic intrusive stock in the basement, possibly of Keweenawan age.

The linear magnetic minimum centered in Calhoun County can be traced for more than 50 miles and roughly parallels the Mid-Michigan anomaly. This feature has an associated positive gravity anomaly only in Calhoun County. The correlation of the positive gravity anomaly with the strong negative magnetic anomaly in Calhoun County suggests that the source of the anomaly there is a basic stock reversely polarized due to remanent magnetization. Elsewhere, the magnetic anomaly may be attributed to a reversely polarized dike or swarm of dikes trending northwest and southeast from the parent stock. Its subparallel alignment with the Mid-Michigan feature suggests the possibility that this body was emplaced during Keweenawan time.

Support for a Keweenawan age for some of these anomalies may be obtained from paleomagnetic studies of

Keweenawan rocks in the Lake Superior region. Paleomagnetic studies in the Northern Peninsula by Dubois (1962) show that the average inclination and declination of the total field vector in Middle Keweenawan time were approximately I = +45° and D = +285°. Assuming subsequent structural deformation in the Southern Peninsula has not appreciably altered this orientation, significant negative anomalies would be expected to occur on the northwest flanks of the magnetic positives associated with Keweenawan rocks having strong remanent magnetization components. To some extent, this is observed, e.g., the Kent County and Lake County anomalies, and the anomaly in north-central Allegan County (Figure 10). Therefore, these anomalies are tentatively assigned a Keweenawan age on the basis of their parallel alignment with the major Mid-Michigan high and their possible association with Keweenawan remanent magnetization.

Other circular anomalies which may reflect Keweenawan volcanism or intrusives occur along the border between Oceana and Muskegan Counties and in southern Manistee County.

The general parallelism of the anomalies attributed to Keweenawan activity including the Mid-Michigan gravity and magnetic high, with the anomalies associated with Penokean or older events south of 44° 30'N suggests that Keweenawan features were emplaced along pre-existing zones of weakness. North of 44° 30'N, the Keweenawan rift zone transects the Penokean and older trends nearly at right angles.

Interpretation of the Mid-Michigan Anomaly

Mid North American Paleo-Rift Systems

The Mid-Michigan anomaly, which has been discussed previously, is the dominant gravity feature and a significant magnetic anomaly of the Southern Peninsula of Michigan. The Mid-Michigan anomaly, in some areas, transects pre-existing basement trends and has been interpreted as a paleo-rift feature by Hinze and Merritt (1969). Other features in the central North American Continent have also been alluded to as paleo-rift zones. The most prominent is the Mid-Continent gravity and magnetic high which extends from the Lake Superior region to Kansas (Zietz, 1969). The parallel gravity and magnetic minimums generally associated with this feature recall those flanking the Mid-Michigan anomaly south of 43° 30'N. The Kapuskasing gravity and Moose River magnetic feature have also been likened to a paleo-rift structure (Innes *et al.* 1967) (Figure 15). Both of these postulated paleo-rift zones can be correlated with exposed basement geology and therefore provide valuable insight into the possible geological interpretation of the Mid-Michigan anomaly. Continuity of gravity and magnetic

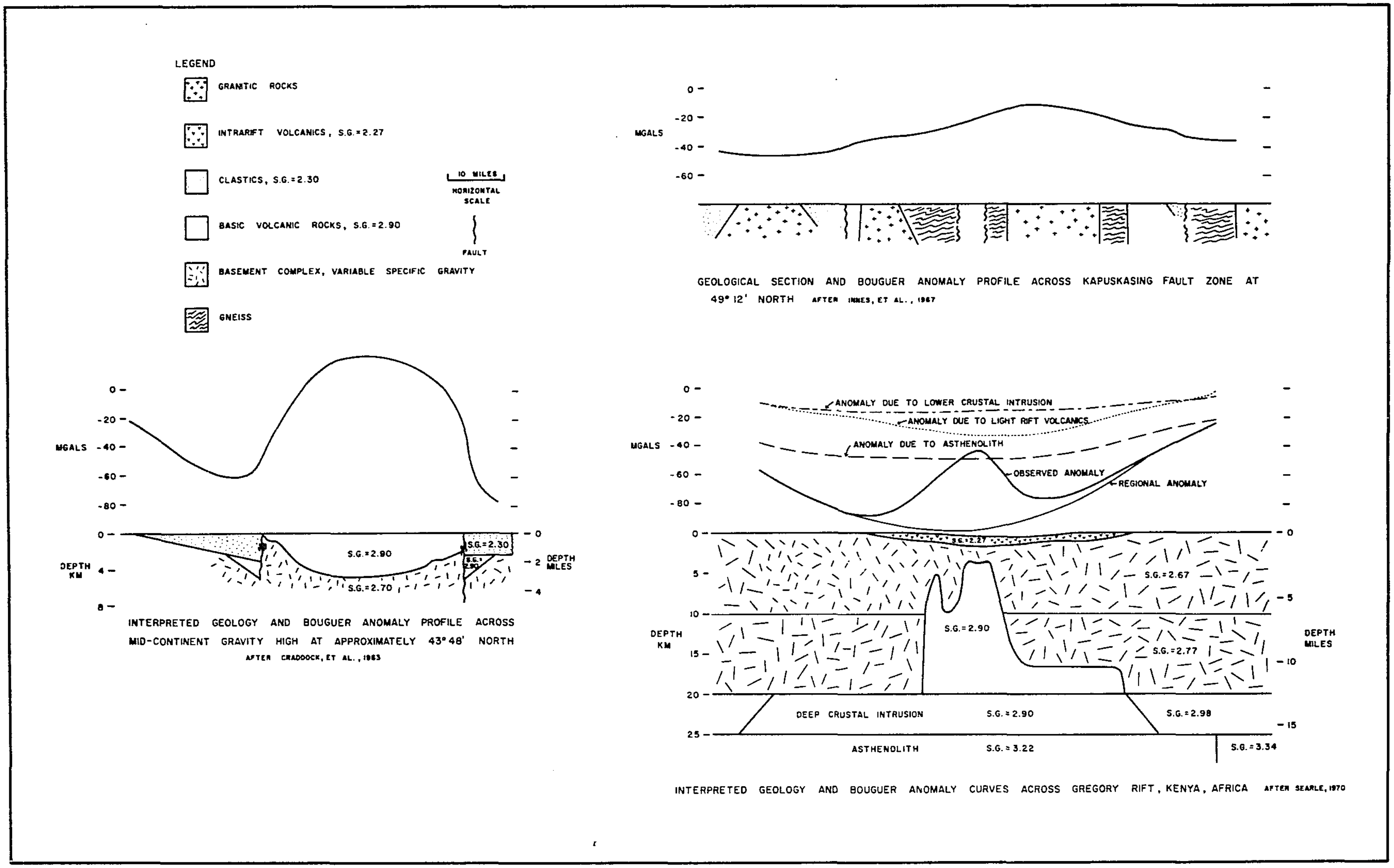

Figure 15.--Typical Cross Sections, East African and Mid-America Rift Systems.

anomalies shows that the Mid-Michigan feature is an extension of the igneous activity of the Lake Superior Basin (Hinze et al. 1966). The Lake Superior structures, in turn, have been correlated with the Mid-Continent gravity high (Thiel, 1956). The Mid-Continent feature has been interpreted as a horst, composed of Middle Keweenawan basalts, gabbro and interflow sediments thrust into juxtaposition with marginal sedimentary basins. The basins are filled with low density Upper Keweenawan clastic rocks. Prominent gravity and magnetic minimums overlie the marginal sedimentary basins. White (1966) and Cohen and Meyer (1966) on the basis of geologic, gravity and seismic evidence, suggest that the gravity minimums flanking the Mid-Continent feature are derived only in part from clastics in the marginal troughs. Cohen and Meyer have further shown that the crust is thicker than normal under the Mid-Continent gravity high in northern Wisconsin and Minnesota, thereby attributing a portion of the gravity lows to crustal downwarp.

Alternatively, Innes and Goodacre (1967) have suggested on the basis of similarity in anomaly patterns, that the Mid-Michigan anomaly may be a southward extension of the Kapuskasing gravity high and Moose River magnetic anomaly belt in Ontario. The gravity anomaly trends northeastward for over 300 miles from Chapleau, Ontario, east of Lake Superior, through Kapuskasing to Moosonee on James

Bay. The surface rocks underlying the gravity anomaly are primarily granites; thus, the source of the gravity anomaly must lie at depth. Innes and his coworkers (1967) believe that the gravity anomaly can be accounted for by a local rise of the Conrad discontinuity with an amplitude of about 8 km along the major rift feature. Bennett et al. (1967) show that the magnetic anomaly which discontinuously parallels the gravity high 20 to 30 miles to the east is caused by a highly faulted and structurally complex horst, consisting of high grade metamorphic rocks, primarily granulites. The granulites, possibly of Archean age, were faulted into place in late Precambrian time. A minimum age of 1.2 b.y. has been suggested by Bennett et al. for the faulting which occurs within and to the west of the granulite zone.

The tendency for the north to northeast trending rift zone associated with the Moose River anomaly to transect easterly trending Archean volcanic-sedimentary rocks recalls the relationship, previously discussed, between the Mid-Michigan anomaly and the Penokean trends. In addition, the Mid-Michigan and Kapuskasing features are roughly on trend and have similar gravity anomaly patterns. Therefore, the Canadian rift system and the Mid-Michigan structures may be related. However, the Gravity Map of Canada (Innes and Gibb, 1969) indicates that the Kapuskasing gravity high does not extend south of 48° 00'N. Thus, although the lithology and structure of the Mid-Michigan feature may locally resemble the Kapuskasing-Moose River belt, the two are not contiguous and perhaps developed independently of one another.

The East African Rift System

The East African Rift System has been recognized as a continental extension of the world rift system (Baker and Wohlenberg, 1971). Thus geophysical and geological studies of this system are pertinent to the interpretation of the Mid-Continent and Mid-Michigan rift systems. However, until recently, gravity surveys revealed that negative Bouguer gravity anomalies were invariably associated with the rifts (Bullard, 1936). Recently, Searle (1970) has conducted a gravity survey over a portion of the East African Rift System in Kenya (the Gregory Rift Valley), and has shown that a positive Bouguer anomaly generally flanked by adjacent parallel lows occurs over the rift system from 0.25°N to 1.25°S. The anomaly is between 40 and 80 km wide and has an amplitude of 30 to 60 mgal. This pattern is similar to the Mid-Continent and Kapuskasing anomalies. Searle analyzed the positive and negative portions of this anomaly separately. On the basis of geological criteria, he finds that the positive anomaly cannot completely be accounted for by a shallow mass distribution model such as a basalt filled trough. Searle finds that the geological and geophysical data are best satisfied by an intrusion of gabbro, perhaps 20 km wide with an upper surface less than 3 km below the land surface, and extending to a depth of about 20 km (Figure 15).

The work of Sowerbutts (1969) and Girdler et al. (1969) who studied the long wavelength negative Bouguer anomalies associated with the rifts, indicates that the negative portion of the anomalies can be explained by an asthenolith or body of low density material (s.g. 3.22) in the upper mantle. This low density material is thought to extend under the whole of the East African Plateau, but is shallowest beneath the rifts themselves (Figure 15). This conclusion is substantiated from studies of S_n propagation in East Africa by Gumper and Pomeroy (1970). Searle finds that an additional intrusion of material of specific gravity 2.90 into the base of the crust is necessary to completely satisfy the negative anomaly. These two features are then overlain by the gabbroic intrusion with positive specific gravity contrast. A small portion of the negative anomaly is attributed to low specific gravity (2.27) intra-rift volcanics.

There are several dissimilarities between the interpreted geology of the Mid-Continent rift system in northeastern Minnesota and northwestern Wisconsin and the Gregory Rifts of East Africa; however, these may reflect the stage of development of the East African system and not inherent differences in the mode of formation of the features. The most important difference is the source of the positive portion of the gravity anomalies as discussed above. There are also differences in the origin of the negative anomalies and the depth of the crust, as well as the direction of displacement along the marginal faults. The intrusive feature of the Gregory Rift described by Searle more closely resembles the Kapuskasing rift despite their obvious surficial differences. In particular, the local topographic rise associated with the Conrad layer suggested by Innes et al. (1967) for the Kapuskasing feature alternatively may be interpreted as a basic intrusion, derived from the mantle and caused by crustal separation. On this basis, the Kapuskasing belt may represent the deeply eroded counterpart of the Gregory Rifts in Kenya. In addition, it is possible that intrusions of basic material into the crust occur within the Mid-Michigan and Mid-Continent paleo-rifts. As more data is accumulated, the structure beneath these rift systems may be found to resemble the Gregory Rifts as well. Smith, Steinhart and Aldrich (1966) have reported unusually high seismic crustal velocities beneath Lake Superior which may reflect intra-crustal basic intrusions.

Quantitative Study of the Mid-Michigan Anomaly

Quantitative studies of the Mid-Michigan anomaly have previously been undertaken by Thiruvathukal (1963) and Hinze and Merritt (1969). The total magnetic intensity map of the Southern Peninsula provides the additional data for refining these previous studies and suggesting additional interpretations. The models obtained from matching observed and theoretical anomalies are suggestive only and are not unique, even for the presented geological interpretation. No attempt has been made to precisely match calculated and observed anomaly profiles because of the inherent ambiguity in the methods.

Specific gravities and magnetic susceptibilities used in the models were obtained from published measurements and estimates of presumed rock types. Table 6 presents a brief summary of this information. Remanent as well as induced magnetic polarization was used in the calculation of the magnetic effect of the Keweenawan basalts. Approximate values given by Dubois (1962) for the remanent magnetic polarization vector of basic Keweenawan plutons and volcanics were vectorially combined with the induced vector, to arrive at the resultant magnetic polarization vector. The results are summarized in Table 7.

TABLE 6.--Specific Gravity and Magnetic Susceptibility Data.

Specific Gravity Data

Rock	Location	No. of Samples	Mean Specific Gravity	Source
Basic Rocks				
Middle Keweenawan Basic Volcanics	NW Wisconsin	50	2.90 ± 0:10	(1)
Middle Keweenawan Basic Flows	N. Peninsula Michigan	214	2.88	(2)
Basalt	Allen Cnty. Indiana	20	2.90 ± 0.30	(3)
Acidic Rocks				
Granite	LaSalle Cnty. Illinois	18	2.70 ± 0.10	(3)
Granitic Rocks	Northern Manitoba	486	2.62 ± 0.04	(4)
Metamorphic Rocks				
Granulite	Northern Manitoba	214	2.73 ± 0.15	(4)
Metasediments	Lawrence Cnty. Indiana	5	2.63 ± 0.02	(3)

Magnetic Susceptibility Data

Rock	Location	No. of Samples	Mean Susceptibility	Source
Basic Rocks				
Middle Keweenawan Basic Flows	N. Peninsula Michigan	4	1561 (range 1220-1773)	(5)
Middle Keweenawan Basic Intrusives	N. Peninsula Michigan	6	5683 (range 1881-9730)	(5)
Basalt	Shelby Cnty. Ohio	7	2000	(4)
Diabase	St. Francois Mts. Missouri	10	2700	(6)
Acidic Rocks				
Keweenawan Acidic Intrusives	Northern Peninsula Michigan	2	43 (range 31-56)	(5)
Keweenawan Acidic Flows	Northern Peninsula Michigan	5	436 (range 143-1000)	(5)
Granite	Wayne Cnty. Indiana	4	260	(3)
Rhyolite	St. Francois Mts. Missouri	38	2800	(6)
Metamorphic Rocks				
Greenstone Flow	N. Peninsula Michigan	75	1580	(2)
Metasediments	Howard Cnty. Indiana	9	300	(3)
Metamorphosed Iron Formation	N. Peninsula Michigan	1	4230	(4)

(1) Thiel, E. 1956. Correlation of Gravity Anomalies with Keweenawan Geology of Wisconsin and Minnesota: Geol. Soc. Am. Bull., V. 67, pp. 1079-1100.

(2) Bacon, L. O. 1966. Geologic Structure East and South of the Keweenaw Fault on the Basis of Geophysical Evidence: Am. Geophy. Un., Geophy. Mon. 10, pp. 42-55.

(3) Rudman, A. J. and Blakely, R. F. 1965. A Geophysical Study of a Basement Anomaly in Indiana: Geophysics, V. 30, pp. 740-761.

(4) Gibb, R. A. 1968. A Geological Interpretation of the Bouguer Anomalies adjacent to the Churchill-Superior Boundary in Northern Manitoba: Can. Jour. Earth Sciences, V. 5, No. 3.

(5) Meshref, W. M. and Hinze, W. J. 1970. Geologic Interpretation of Aeromagnetic Data in Western Upper Peninsula of Michigan: Mich. Geol. Surv. Rpt. Inv. 12, 25 p.

(6) Allingham, J. W. 1964. Low Amplitude Aeromagnetic Anomalies in Southeastern Missouri: Geophysics, V. 29, pp. 537-552.

TABLE 7.--Parameters of Induced, Remanent and Combined Magnetic Polarization Vectors.

Component	Magnetic Polarization	Inclination	Declination
Induced	0.00091 emu/cc	+72°	0°
Remanent	0.00354 emu/cc	+45°	285°
Combined	0.00425 emu/cc	+53°	292°

Calculation of the combined vector was made assuming no rotation of the remanent vector of the Keweenawan lavas due to deformation.

Two representative profiles of observed Bouguer gravity and total intensity magnetic anomalies, trending at right angles to the strike of the Mid-Michigan anomaly, were selected for quantitative investigation. The profile shown in Figures 16, 17 and 19 extends from the Michigan-Indiana border in southeastern Branch County and trends northeast to 44° 00'N and 82° 30'W. The profile passes between the two high amplitude magnetic anomalies in Livingston County which are superimposed on the regional north-northwest striking high (Figure 10). The profile shown in Figure 18 was constructed from the Indiana border at the junction of Cass and St. Joseph Counties northeast to Thunder Bay near Alpena. The location of the profiles is shown on the small inset maps on Figures 16 through 19.

Gravity and magnetic effects of basement structures based upon geological and geophysical evidence from the Mid-Continent gravity high and the Kapuskasing anomaly were computed using standard two dimensional theory developed by Talwani et al. (1959). The configuration of the source was then modified as necessary to achieve a match with the observed anomalies.

Figure 16 closely duplicates the geologic conditions interpreted for the Mid-Continent gravity high by Thiel (1956). A basalt trough is shown flanked by marginal clastic basins. The basins are generally underlain by downfaulted blocks of basalt which thin away from the axis of the basalt trough. This model also has been investigated by Hinze and Merritt (1969).

The Bouguer gravity anomaly profiles match well, but the calculated magnetic profiles show appreciable deviations with the observed curve at several locations. Magnetic anomaly curves are generally more difficult to match than Bouguer gravity anomaly profiles because of the presence of remanent magnetization effects which are uncertain at best. To fit the observed anomalies at the northeastern end of the profile, a block of higher specific gravity mafic gneiss and metavolcanics was positioned within the basement rocks and low grade metamorphics.

The structural picture presented here suggests that during Keweenawan time, a great outpouring of basalts

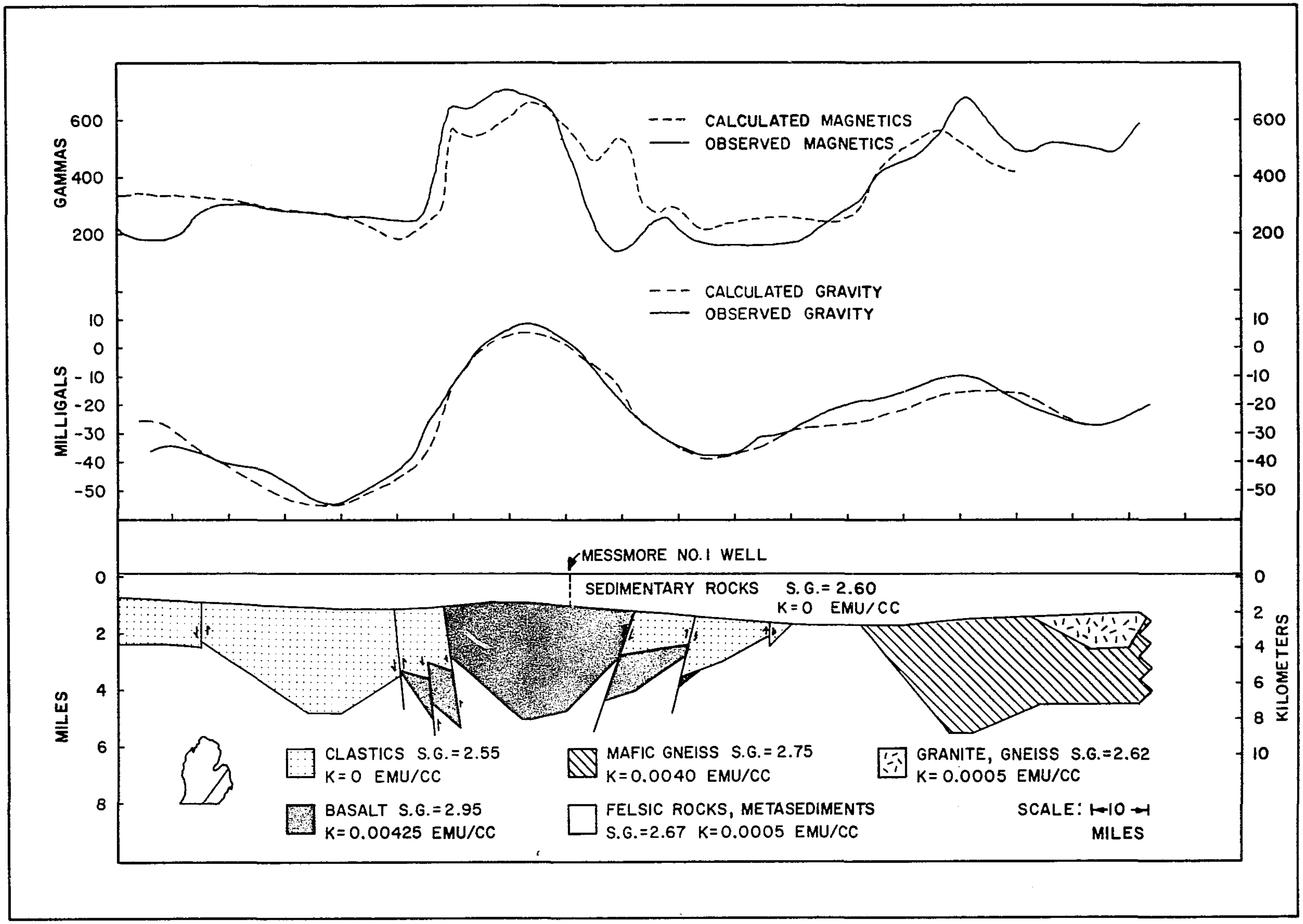

Figure 16.--Observed and Computed Bouguer Gravity and Total Magnetic Intensity Anomaly Profiles across the Howell Anticline Area, Illustrating Basalt Trough Model.

occurred in a rift zone perhaps bounded by marginal faults. In response to the load of outpouring basalts, the crust progressively sagged beneath their weight. Clastics accumulated in the downwarp, perhaps to a thickness of 15,000 feet or more. The final event in the history of this model is the uplift of the central rift zone, bringing the basalts into juxtaposition with low density clastic rocks.

The basement drill hole in Livingston County (11-3N-5E) was extrapolated into the plane of the section utilizing the magnetic contours as a guide (Figure 16). This well encountered an intermediate composition gneiss. It is significant that this test encountered the basement, well within the confines of the postulated basalt trough. The absence of volcanics in this well is strong evidence for disregarding the basalt trough concept as presented in Figure 16. However, the effect of the Grenville orogeny, including metamorphism, faulting and uplift on the basement undoubtedly has complicated and altered the basement geology to a point where the basalt, at least locally, is not present.

The most important difficulty with the basalt trough hypothesis is its failure to provide a satisfactory explanation for the marginal gravity and magnetic minimums flanking the positive portion of the Mid-Michigan anomaly. Basement tests in Lenawee and Monroe Counties (Figure 1) which are located in the gravity minimum bottomed in granite or granite gneiss and did not encounter an excessive thickness of clastic rocks nor an abnormally deep basement.

Another objection to the basalt trough model is the lack of a magnetic anomaly correlative with the Mid-Michigan anomaly between 44° 00'N and 44° 45'N and at its southeastern extremity. The strong induced and remanent magnetization of Keweenawan basalts in the Lake Superior region and the general association of marked magnetic anomalies with these extrusives, suggests that magnetic anomalies should be related to the gravity high in the Southern Peninsula. The only exception to this correlation would occur in the unlikely event that the induced magnetic polarization was exactly compensated by the remanent effects.

Between 43° 00'N and 44° 00'N the Mid-Michigan magnetic anomaly can be correlated with the gravity expression as a subdued, although positive anomaly. The relationship of the gravity and magnetic anomalies in this portion of the Mid-Michigan high suggests a source which would produce a limited magnetic disturbance, while producing a large positive gravity anomaly. The basalt trough concept could be adapted to fit the Mid-Michigan magnetic anomaly in this area. A source consisting of relatively thin, gently dipping volcanics may explain the subdued magnetic relief. This model would not account for the large positive gravity anomaly; therefore, an additional source must be hypothesized to account for the gravity anomaly. Thus, although the basalt trough model may occur locally along the Mid-Michigan high such as in Livingston County and/or the Grand Traverse Bay area, an alternative geologic model is needed to satisfy the observed geological and geophysical evidence elsewhere.

An alternative geologic model based on geological relationships observed for the Kapuskasing-Moose River belt in Ontario is illustrated in Figure 17. The magnetic anomaly is due to high grade metamorphic rocks (perhaps granulites) uplifted in the rift zone, whereas the gravity anomaly is due to both the high grade metamorphics and uplifted high specific gravity rocks within the rift. Marginal minimums are attributed to local structural depressions. These depressions may be partially filled with metasediments, as previously suggested in the discussion of the Penokean province. The second profile (Figure 18) using the same geological approach and constructed from the Indiana border at the junction of Cass and St. Joseph Counties northeast to Thunder Bay near Alpena, Michigan also satisfies the observed geological and geophysical relationships over the Mid-Michigan anomaly to the north and west of Livingston County. However, this

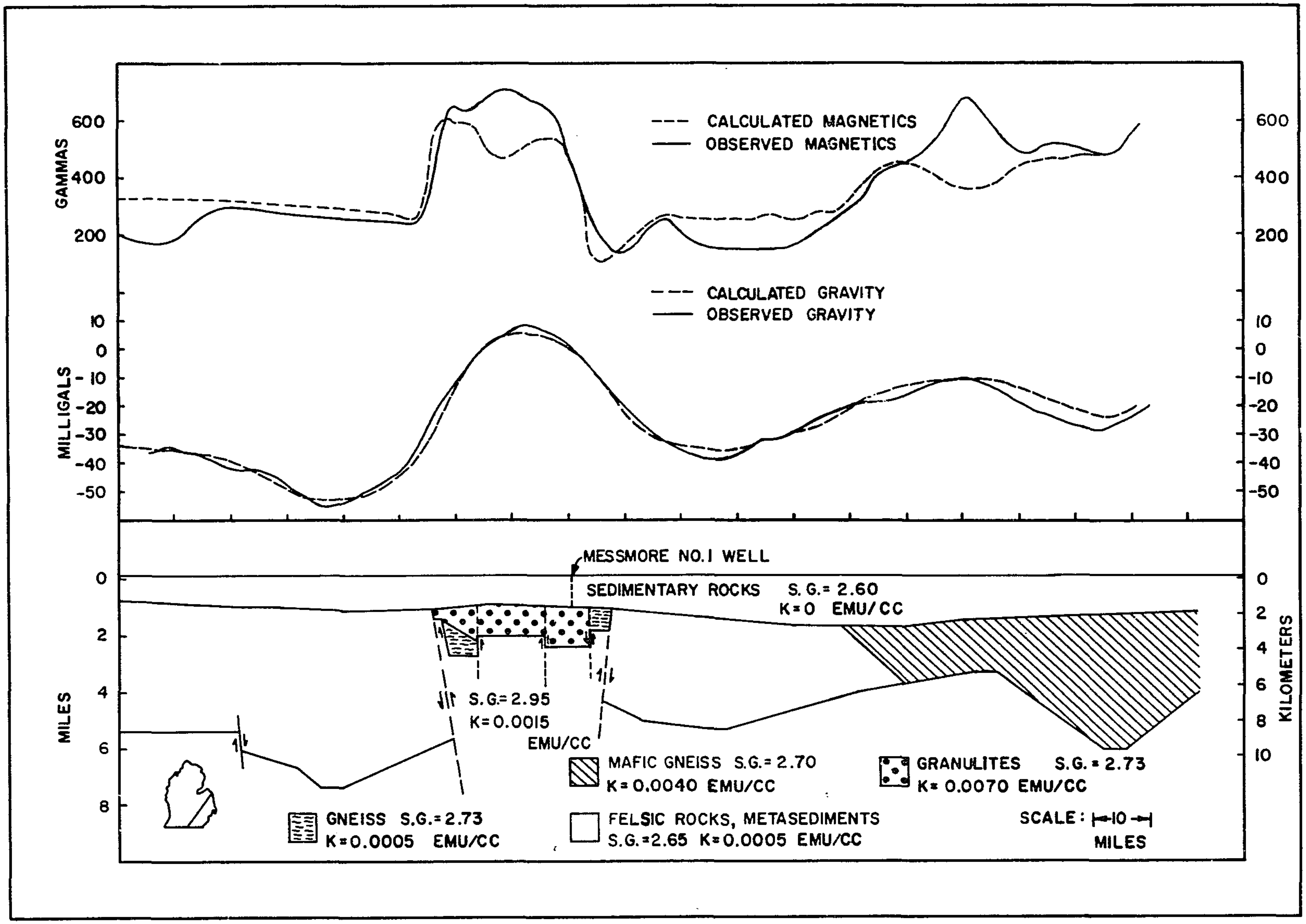

Figure 17.--Observed and Computed Bouguer Gravity and Total Magnetic Intensity Anomaly Profiles across the Howell Anticline Area, Illustrating High Grade Metamorphics Model.

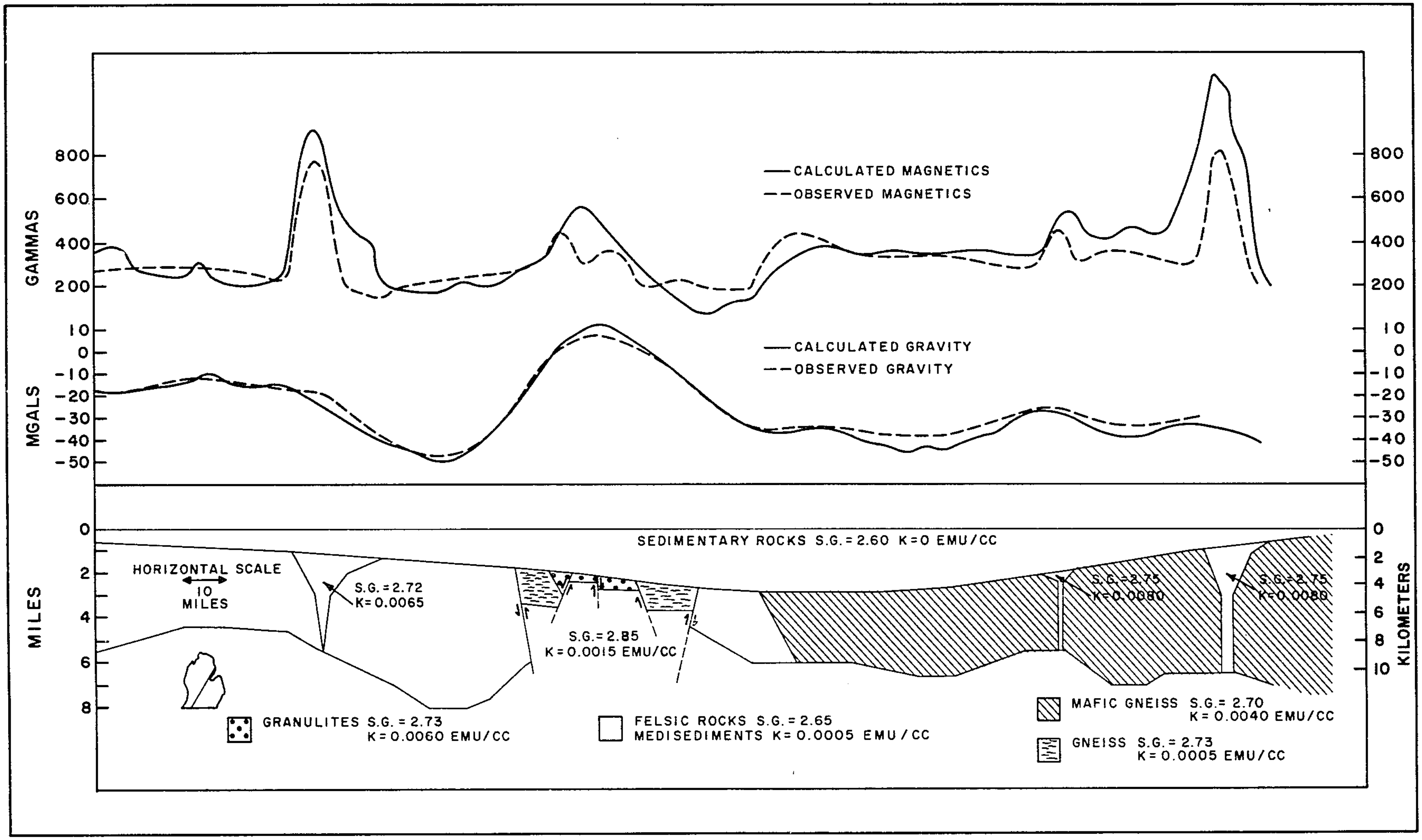

Figure 18.--Observed and Computed Bouguer Gravity and Total Magnetic Intensity Anomaly Profiles from St. Joseph County to Thunder Bay Area Illustrating High Grade Metamorphics Model.

excludes the strong negative in the Traverse Bay region. The variable magnitude of the Mid-Michigan magnetic anomaly along its length can be explained by assuming differential uplift of high grade metamorphic rocks or variations in magnetic susceptibility of the metamorphic rocks of the rift.

Figure 19 shows a cross section constructed on the basis of some of the geological aspects of both the Mid-Continent and Kapuskasing anomalies. The interpreted geology exterior to the Mid-Michigan belt has been omitted from the diagram. Although only the southeasternmost profile crossing the Livingston County anomaly is considered, the model could be adapted to the St. Joseph-Thunder Bay profile as well. The Mid-Michigan anomaly is attributed to the combined effect of a basalt trough and the structure associated with deep crustal layers. Marginal basins occur on the flanks of the basalt trough. In addition, the overall effect of the Moho, based on the work of Cohen and Meyer (1966) for the Mid-Continent gravity high in northeastern Minnesota and northwestern Wisconsin has been superimposed on the other gravity effects. Cohen and Meyer's analysis is based on loading of the crust, and its subsequent deformation, by a two dimensional body (Heiskanen and Vening Meinesz, 1958, pp. 231-232). The model assumes that the crust behaves like an elastic beam,

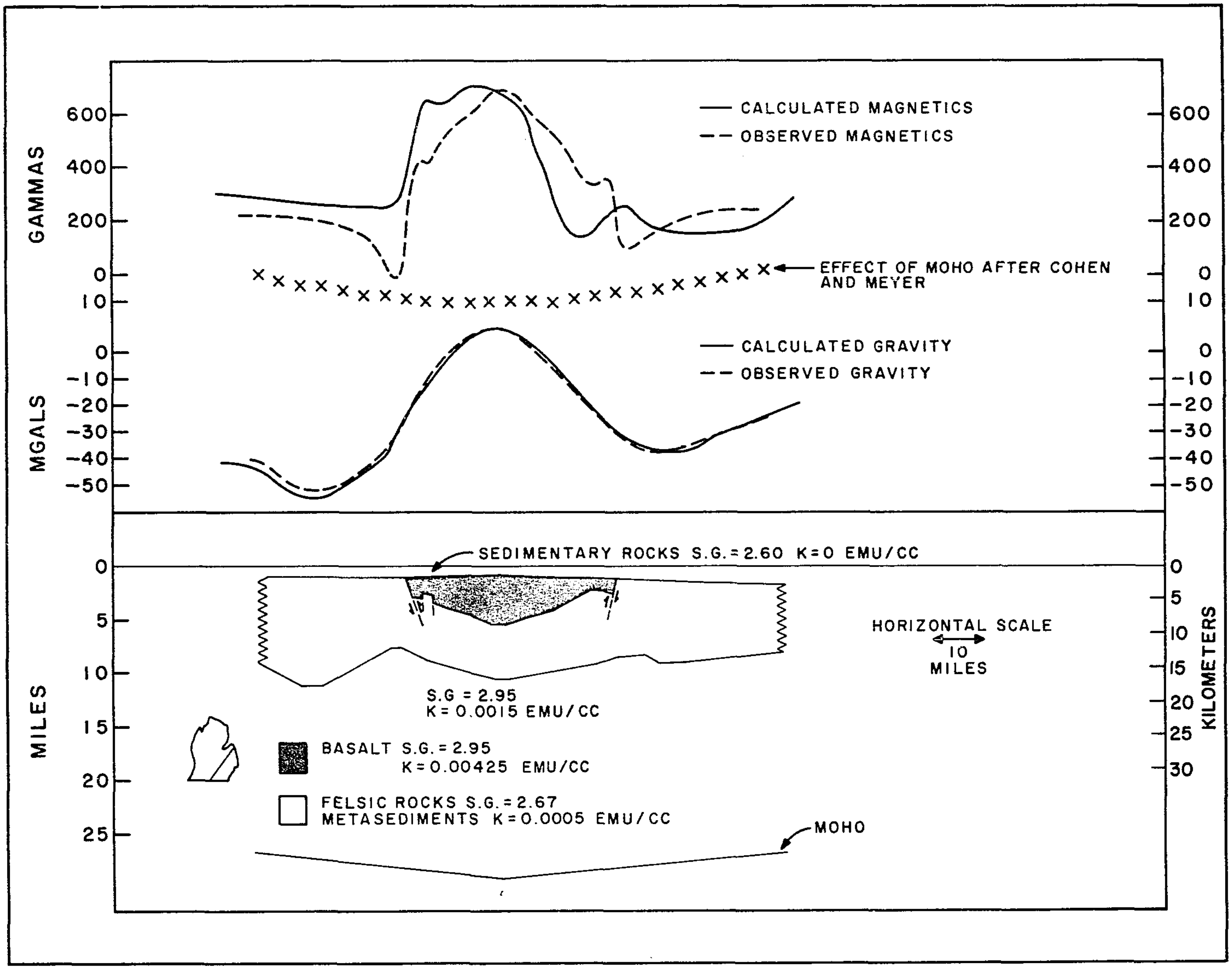

Figure 19.--Observed and Computed Bouguer Gravity and Total Magnetic Intensity Anomaly Profiles across the Howell Anticline Area, Illustrating Basalt Trough and Deep Crusted Layer Model.

while conserving isostatic balance. The gravitational effect of the Moho structure is plotted in Figure 19, along with the observed and calculated gravity anomalies. In the vicinity of the Mid-Michigan anomaly, the gravity gradient attributed to the downwarped Moho is only 0.2 mgal per mile. The conclusion reached from an examination of the diagram is that the downwarped Moho can account for only a small portion of the negative anomaly associated with the Mid-Michigan high, the remainder coming from density contrasts within the crust. Similarly, the inclusion of the gravitational effect of the Moho in the other models would not significantly alter the geological interpretation.

The deep crustal layer illustrated in Figures 17 through 19 may be a discrete boundary; however, it also may be represented by the cumulative effect of several layers, or a specific gravity gradient. This layer may also reflect intra-crustal intrusions, beneath the Mid-Michigan high.

Crustal seismic refraction studies of the Mid-Michigan high are needed to augment available geophysical and geological data and to assist in the evaluation of the models proposed in this paper and elsewhere (Hinze and Merritt 1969, Oray 1971), or to suggest additional ones.

All of the models considered have advantages as well as disadvantages. On the basis of the character of the magnetic and gravity anomalies at various locations and the lithologies encountered in basement tests, the model illustrated in Figure 19 is favored for the Mid-Michigan anomaly. Variable accumulation of volcanics, differentially affected by reversed remanent polarization, combined with flexures of deep crustal layers and perhaps intrusions, is necessary to explain the relationship of the magnetic anomaly to the gravity anomaly along its length. Flanking magnetic and gravity minimums are attributed to structural depressions, perhaps partially filled with low specific gravity metasediments.

Alternatively, the Mid-Michigan anomaly may resemble the model proposed in Figure 17 and Figure 18. Various stages of uplift could explain the changing nature of the Mid-Michigan magnetic high along its length.

Additional models consisting of combinations of the ones proposed may also be matched to the observed anomalies. A more precise interpretation must await the accumulation of additional geological and geophysical data.

Relationship of the Keweenawan Rift Zone to the Grenville Province in Southeastern Michigan

The intersection of the interpreted Keweenawan rift zone with the Grenville province in southeastern Michigan makes it possible to inter-relate these two important basement provinces (Figure 12). In Livingston County and to the east, the Keweenawan rift zone, as interpreted from both magnetic and gravity data, transects the Grenville province. This suggests that the Keweenawan structure, at least in this area, was developed after the Grenville orogeny. This interpretation is supported from isotope age dates of basement samples from two wells (Table 5) in northeastern Washtenaw County, which occur on the southern flank of the Mid-Michigan gravity anomaly. Samples obtained from these wells are dated at 0.84 and 0.92 b.y. by the Rb-Sr method. Thus, they fall within the range of typical Grenville activity (Goldich et al. 1966) rather than older Keweenawan igneous activity. In addition, the intense cross magnetic anomaly in Livingston County which appears to be composed of north-northeast striking anomalies is on trend with similar, but less intense anomalies in the Thumb area of Michigan. These anomalies can be traced into central Lake Huron where they are interpreted to be derived from Grenville amphibolites, pyroxenites, intercalated gneisses and perhaps volcanics belonging to the Grenville province by Nwachukwu et al. (1965) and Secor et al. (1967). Thus, the cross magnetic anomalies, in Livingston County reflect Grenville activity.

An alternative interpretation is that the Keweenawan rift zone pre-dates the Grenville event and thus exists only as a relic structure. Evidence favoring a pre-Grenville age for the rift structure is the age of the granite encountered in the basement beneath Beaver Island and the age dates of Keweenawan intrusives in the Lake Superior region. These dates are older than the isotope age dates of the Grenville province in southeastern Michigan. However, the absence of basement drill holes confirming a Keweenawan age for the Mid-Michigan feature precludes the positive identification of this structure as Keweenawan in southeastern Michigan. In addition, the evidence discussed above strongly suggests that, at least locally, Grenville rocks are present in Livingston County.

The magnetic anomaly in Livingston County may be the key to understanding the age relationships of these two provinces in southeastern Michigan. In addition to the intense northeast trending anomalies which have been correlated with Grenville activity, the Livingston County anomaly appears to be composed of a broad regional positive which is continuous with the Mid-Michigan magnetic high to the north and west (Figure 10). This positive may reflect a Keweenawan relic structure, originally composed of extrusives and intrusives, which was subjected to metamorphism, uplift, deformation, and erosion prior to and during the Grenville orogeny. Uplifted deep crustal layers together with the Keweenawan intrusives and extrusives are capable of satisfying the gravity anomaly in Livingston County (Figure 19). Finally, the northeast striking magnetic anomalies in Livingston County may be the result of local metavolcanics which were emplaced along the Grenville Front (MacLaren and Charbonneau, 1968), during the Grenville orogeny. These volcanics probably were erupted along faults which cut the postulated rift zone relic structure at nearly right angles to its strike, and developed along lines of weakness parallel to the Grenville Front. These lines of evidence, taken together, suggest that the Keweenawan rift zone preceded the Grenville event.

The Mid-Michigan high continues east of Livingston County before dying out a short distance into Ontario. In this area, the Mid-Michigan gravity anomaly may reflect the uplifted deep crustal layers within the rift zone. However, near surface igneous activity associated with the rifting and responsible for the magnetic anomaly in Livingston County has been eliminated perhaps by alteration and erosion following uplift during the Grenville Orogeny.

The sequence of events discussed above is suggestive only and a more definitive interpretation must await the slow accumulation of additional data.

CHAPTER V

CONCLUSIONS

This study has shown that interpretation of aeromagnetic data is a useful tool in studying the basement geology beneath the sediments of the Michigan Basin, despite their great thickness. However, the complexity of the magnetic rock properties restricts the interpretation to a semi-quantitative approach based upon the integration of the drill hole information, extrapolation of magnetic and gravity trends from surrounding outcrops into the Basin, and analytical studies of the magnetic data. Analytical techniques used in this study include magnetic depth determinations and correlation of theoretical magnetic anomalies with the observed magnetic data.

Magnetic depth determinations confirm that the basement of the Southern Peninsula has the form of an oval depression reaching a maximum depth of 15,000 feet below sea level. A basement high having an estimated closure of perhaps 1,000 feet was found to underlie the Howell anticline in Livingston County. West of the Howell structure, a broad trough plunges north-northwest into the Basin. Southwestern Michigan is characterized by a basement platform which may indicate a northward broadening of the Kankakee Arch into the extreme southwest portion of the Southern Peninsula.

Interpretation of the residual aeromagnetic map in conjunction with other regional geophysical data and drill hole information suggests that four basement provinces underlie the Southern Peninsula of Michigan. These include the Grenville province in southeastern Michigan, the Penokean province generally north of 43° 30'N latitude, the Central province generally south of this latitude and a Keweenawan rift belt which transects all of the other provinces.

The Grenville province in southeastern Michigan is identified on the basis of isotope ages and characteristic magnetic anomaly patterns which can be traced from Lake Huron and southern Ontario. The Grenville province is further divided into two subprovinces dominated by mafic lithologies in the northwest and granite gneiss in the southeast, respectively. The north and west boundary of this province, the Grenville Front is drawn separating the north-northeast magnetic anomaly trends of the Grenville province from the east-southeast trends which occur elsewhere in the Southern Peninsula. The Front trends southwest from southern Saginaw Bay and enters Livingston County at 84° 00'W, west of the Livingston County anomaly. The

Grenville Front is then extended due south on trend with a north-south striking anomaly near the Michigan-Ohio boundary at approximately 84° 15'W.

The Central province is interpreted to occur in southwestern Michigan, where it is associated with the granites, granite gneiss and metasediments found in southern Wisconsin, northern Illinois, Indiana and western Ohio. Several circular anomalies within this province have limited gravity expression and occur along trends which strike subparallel to the Keweenawan rift province. They are interpreted as extrusives which erupted along lines of weakness subparallel to the Keweenawan rift province in southern Michigan.

An examination of geophysical maps, isotope ages of basement samples, lithologies and structural trends in Wisconsin indicates that a sharp boundary does not occur between the Central and Penokean provinces. By extrapolation, a precise boundary probably does not occur in the Southern Peninsula. Penokean (or older) trends can be traced from the outcrop in Wisconsin by way of Lake Michigan into the north and central portions of the Southern Peninsula where they have a general east-southeast strike. The residual total intensity anomaly map is dominated by these trends north of 43° 30'N latitude. The Bouguer gravity anomaly map, on the other hand, is dominated by the younger north and east striking Keweenawan rift zone. This Keweenawan feature transects the entire Peninsula and can be traced geophysically to the vicinity of Beaver Island where it joins the southern terminus of the Lake Superior basin. South of 44° 30'N, the Keweenawan belt appears to have been emplaced along pre-existing zones of weakness which strike east-southeast.

The Keweenawan province in the Southern Peninsula has been likened to a paleo-rift system. Three other linear gravity anomaly belts flanked by parallel minimums have also been attributed to crustal rifting. These include the Kapuskasing gravity anomaly belt of central Ontario, the Mid-Continent gravity high of the central United States, and the Gregory Rifts from 0.25°N to 1.25°S in Kenya, Africa. These features can be correlated with exposed basement geology and therefore provide valuable insight into the possible geological interpretation of the Mid-Michigan anomaly. Calculated gravity and magnetic anomalies of models based on the geology of these rift zones can be matched with the Mid-Michigan observed anomaly curves.

A model which combines some of the geological aspects of both the Kapuskasing and the Mid-Continent features explains what is known of the Keweenawan basement geology of the Southern Peninsula. This model combines a basalt trough with a variable depth crustal layer or layers to explain the observed positive geophysical anomalies. Variable uplift of segments of the rift which are bounded by cross faults explains the changing nature of the Mid-Michigan magnetic anomaly along its length. Downwarp of deep crustal layers forming basins filled with low specific gravity rocks explains the flanking gravity minimum, especially south of 44° 00'N. Metasediments, some of which can be traced magnetically from the outcrop in Wisconsin, probably exist in the downwarps and contribute to the gravity minimum. They are believed to be primarily responsible for the magnetic minimums.

The gravitational effect of the Moho underlying the negative and positive portions of the Mid-Michigan gravity anomaly is of the order of 10 mgals assuming the geological parameters established seismically for the crust-mantle boundary in Wisconsin. This effect is too small to explain the large gravity minimums flanking the Mid-Michigan gravity high.

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APPENDIX

Any finite function of distance, such as a magnetic anomaly profile, can be represented by the sum of a series of sine and cosine waves of specific amplitudes and frequencies. The summation is expressed mathematically for a one dimensional periodic waveform, f(x), by the Fourier expansion:

$$f(x) = \frac{Ao}{2} + \sum_{n=1}^{\infty} (A_n \cos n\omega x + B_n \sin n\omega x)$$

where,
$$A_n = \frac{2}{\tau} \int_{-\tau/2}^{\tau/2} f(x) \cos n\omega x dx \quad n = 0,1,2,3, \ldots$$

$$B_n = \frac{2}{\tau} \int_{-\tau/2}^{\tau/2} f(x) \sin n\omega x dx \quad n = 0,1,2,3, \ldots$$

$$Ao = \frac{2}{\tau} \int_{-\tau/2}^{\tau/2} f(x)\ dx$$

and, τ = fundamental period

$\omega = \frac{2\pi}{\tau}$ = fundamental angular frequency

x = independent variable

The plots of A_n and B_n as functions of frequency ω, consist of a number of discrete spectral lines occurring at a constant spacing of $\omega = 2\pi/\tau$. To obtain the Fourier amplitude spectrum, which depicts the amplitudes of various frequency components in the original signal, the values of A_n and B_n are squared, summed, and the square root of the resulting expression is plotted against the frequency ω.

In this study, several magnetic profiles were constructed from the residual data and their Fourier amplitude spectra were computed utilizing a program prepared by Sederlund (1971). The location of profiles selected for analysis is presented in Figure 1. The profiles are plotted in the distance domain in Figures 2 through 5. These profiles were interpolated from large scale (1" = 8,000') maps having a contour interval of 20 gammas. The profiles were then sampled at intervals of 4,000 feet, taking into account the smallest anomalies on the Residual Total Intensity Map (Figure 10 of text), which have wavelengths of the order of five miles. Thus, the shortest wavelength anomalies were sampled at least five times, eliminating the possibility of bias due to frequency aliasing.

For purposes of analysis, the plots were divided into two groups. Group 1 consists of all north-south or northeast trending lines and group 2 comprises all east-west lines (Figure 1). Members of group 1 are plotted in the distance domain in Figures 2 through 4 and members of group 2 are plotted in Figure 5.

The Fourier transforms of these plots were obtained in the wavelength domain (Figures 6 through 14). The plots of each group were compared by superimposing them in pairs on the same graph and noting significant differences in amplitude which persist over a range of wavelengths of several tens or hundreds of thousands of feet. Thus, extreme variations in amplitude which occur over a narrow band of wavelengths are not considered significant as far as this study is concerned. Wavelengths shorter than 30,000 feet and greater than the maximum length of each line were established as outer bounds and are not considered in the interpretation. The wavelength corresponding to the maximum length of each line is marked in Figures 6 through 14 by an arrow.

All of the curves in Figures 6 through 14 are characterized by relatively low amplitude, short wavelength components. A gradual increase in amplitude is noted with increasing wavelength. This may be due to bodies deep within the crust which would be reflected in the plots only at the long wavelength end of the spectrum, due to attenuation of the high frequency components. Also, long wavelength components from near-surface sources, contribute to the amplitude of the long wavelength portion of the spectrum. Significant differences in amplitude between the curves may have several origins. These include the geometry, number and depth of the sources, and variations in magnetic polarization of the sources. These factors will, in turn, produce variations in magnetic anomaly gradients, amplitudes and shapes of anomalies which will be reflected in the Fourier spectra. The direction of the profile with respect to the strike of the magnetic anomaly is also a factor affecting the amplitude of the resultant curves. Idealy, the direction of the profile should intersect the anomalies at nearly right angles to their strike.

The profiles are compared in Figures 6 through 14. Figures 6 through 11 apply to the lines of group 1, (the northeast and north-south trending lines), whereas the lines in group 2 are shown in Figures 12 through 14.

The Fourier spectrum of line 1 is compared with line 2 in Figure 6. These lines are parallel and roughly eight miles apart and cross the Mid-Michigan anomaly in the vicinity of Livingston County (Figure 1). Although the profiles from which the plots were obtained are similar in appearance (Figure 2) and location (Figure 1), the relative amplitude of many peaks and troughs of the resulting spectral plots (Figure 6) are different, and occasionally are offset with respect to wavelength. Thus, local variations, which occur over a short range of wavelengths, are not considered to be significant as far as this study is concerned.

The Fourier spectrum of line 2 is compared with line 3 in Figure 7. Line 2 strikes northeast across the Livingston County anomaly, whereas line 3 trends northeast and passes over the deepest portion of the basin (Figure 1). The plots are very similar; however, line 2 displays slightly higher amplitudes than line 3 at both the short and long wavelength ends of the spectrum. Wavelengths ranging from 50,000 feet to roughly 350,000 feet (10 to 70 miles), show little variation between the two curves. The absence of significant variations in the curves over this wide band of wavelengths suggests that the eastern and central portions of the Southern Peninsula have similar basement geology. However, line 3 samples a much broader range of basement depths than line 2. Thus, the results shown in Figure 7 may reflect a tendency for the depth factor to offset changes in basement geology.

Line 2 is compared with line 9 in Figure 8. Line 9 is located in the western portion of the Peninsula (Figure 1) and crosses several of the high amplitude, short wavelength anomalies. As in the case of the previous diagrams, the amplitudes of the curves shown in Figure 8 are comparable throughout most of the spectrum. Only at the shorter wavelengths (between 30,000 and 55,000 feet) do the curves show a marked difference in amplitude. The indication of differences in amplitude of short wavelength components shown in both Figures 7 and 8 may be geologically significant; however, the ambiguity of the method prohibits a positive statement concerning the geological significance of these variations.

Line 9 is compared with line 5 in Figure 9. Line 5 is coincident with the 84°30'W meridian and transects the entire Peninsula (Figure 1). Once again the comparison does not show any major differences, although line 9 generally shows higher amplitudes at the long wavelength end of the spectrum.

To examine the effect of depth on the spectral plots, line 9 was compared with line 10, (Figure 10) a segment of line 5 which crosses the deepest portion of the basin (see Figure 1 for location and Figure 4 for the profiles in the distance domain). Despite the large difference in depth, (see Figure 7, text, for depth-to-basement map), the curves are generally similar. However, the amplitude of the short wavelengths (40,000 to 90,000 feet) of line 10 are lower than those of line 9, perhaps reflecting the greater attenuation of these wavelengths with distance from the source in the case of line 10. This comparison was carried one step further by upward continuing line 9 a distance of two miles using a 17 point upward continuation formula developed by Hinze (1960). This allows the profiles to be compared at roughly the same level from the sources (15,000 feet from the basement surface). The wavelength-amplitude spectra of the upward continued profile was computed and plotted on the same graph as the spectra of line 10 (Figure 11). An inspection of Figure 11 shows the relatively high amplitude wavelengths in the 40,000 to 90,000 feet band present on line 9 (Figure 11) are diminished by the upward continuation process, and the curves are now similar in overall amplitude, except at very short wavelengths. This comparison suggests a broad similarity in the geology of the western and central portions of the basement.

A close comparison of Figures 10 and 11 indicates that certain short wavelengths in the 20,000 to 30,000 feet range are amplified rather than attenuated by the upward continuation process. This result probably stems from the nonlinearity in the upward continuation process.

In summary, the examination of the plots of group 1 fail to confirm the existence of appreciable differences in basement geology (i.e., geometry, number of sources, and depth of the sources).

A difference in the amplitude response among the lines of group 2 was noted. Group 2 includes all east-west trending lines (lines 7, 4 and 8, Figure 1). Line 8 is compared with line 4 in Figure 12. Line 4, which strikes east-west across the Peninsula at 44°00'N generally has higher amplitudes than line 8 throughout both the distance (Figure 5) and wavelength (Figure 12) domains. An even greater difference is noted in Figure 13 which is a comparison of lines 7 and 8 (see Figure 1 for locations). For reference, lines 4 and 7 in the northern tip of the Southern Peninsula are plotted together in Figure 14 and have similar amplitude responses.

The large difference in amplitudes at all wavelengths noted in Figures 12 and 13 probably reflects a difference in geology between the southernmost portion of the Peninsula and its northern tip as interpreted in Chapter IV and Figure 12 of the text.

In conclusion, the results of this limited study indicate that Fourier spectral plots of magnetic anomaly profiles can be useful in delineating basement provinces where the magnetic anomalies have distinctly different characteristics. However, the effect of complicating factors such as variable depth and strike impose serious limitations on the interpretational process. More detailed studies are needed to evaluate the usefulness of Fourier spectral plots in mapping basement provinces. These studies should be undertaken initially, in areas of exposed basement rocks, so that the method can be calibrated against known basement geology.

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HINZE, W. J. 1960. Downward Continuation of Two-Dimensional Gravity and Magnetic Anomalies: Address Mich. Acad. Sci., Arts and Letters.

SEDERLUND, E. 1971. Personal Communication.

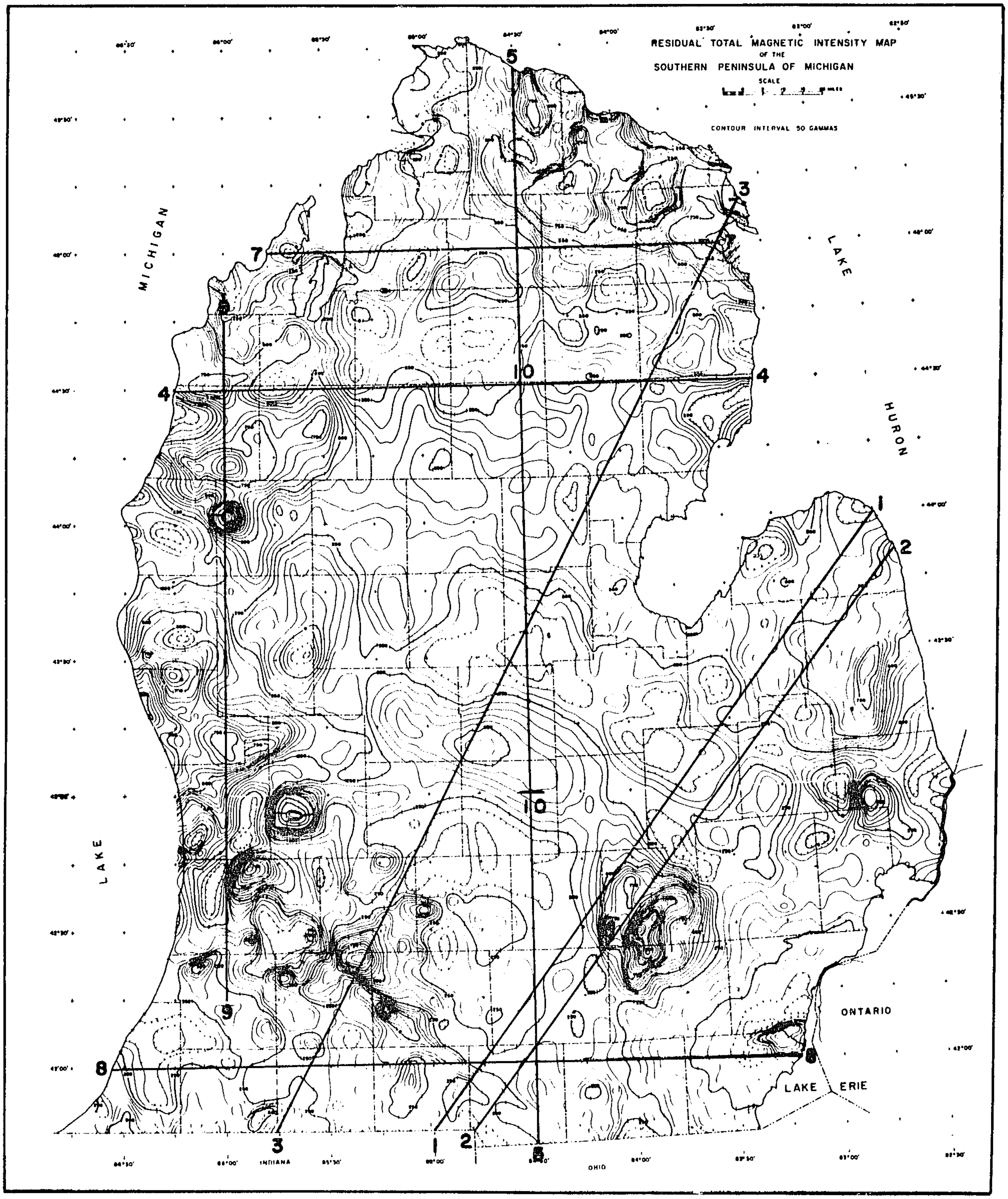

Figure A-1.--Location of Profiles Selected for Analysis.

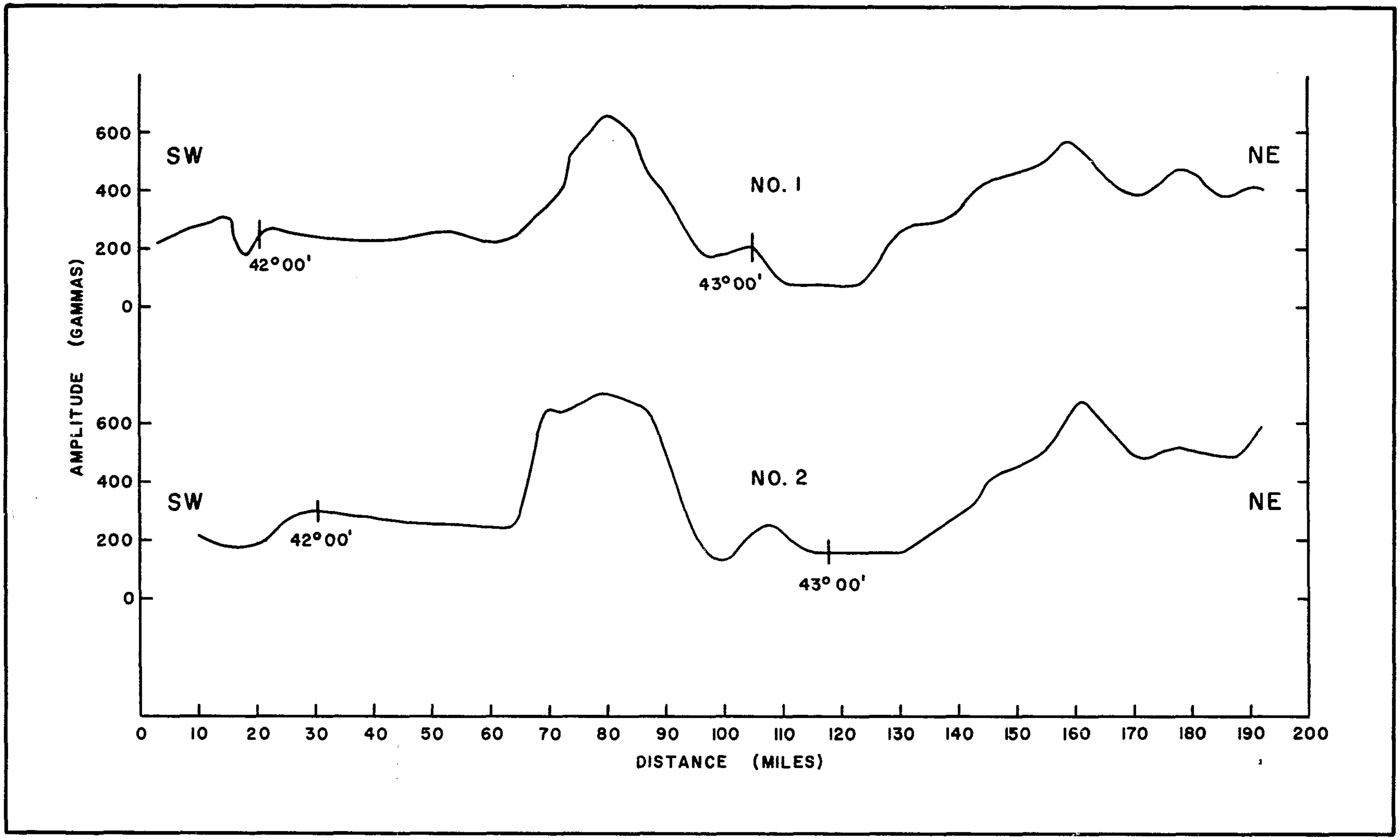

Figure A-2.--Magnetic Anomaly Profiles 1 and 2.

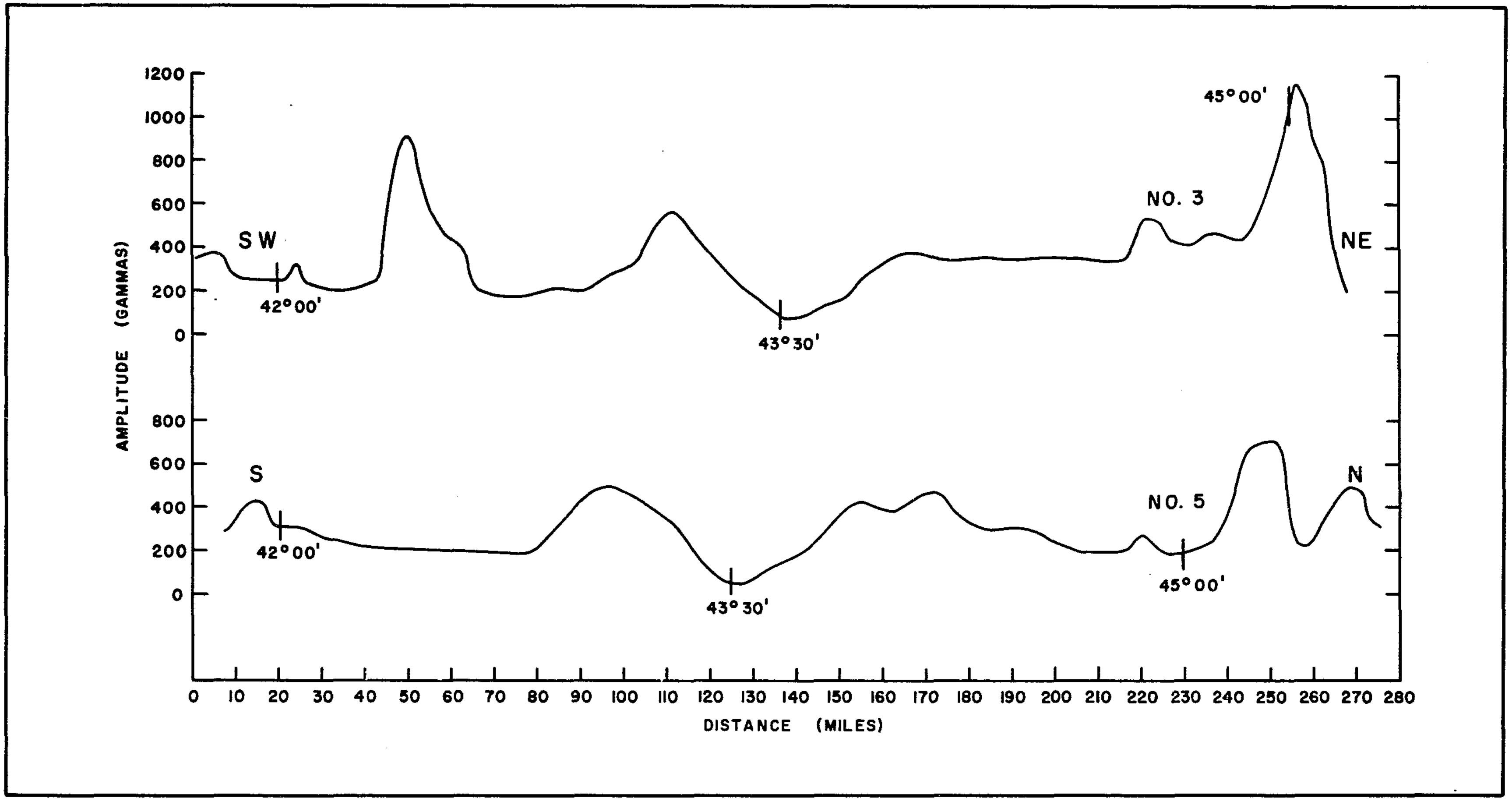

Figure A-3.--Magnetic Anomaly Profiles 3 and 5.

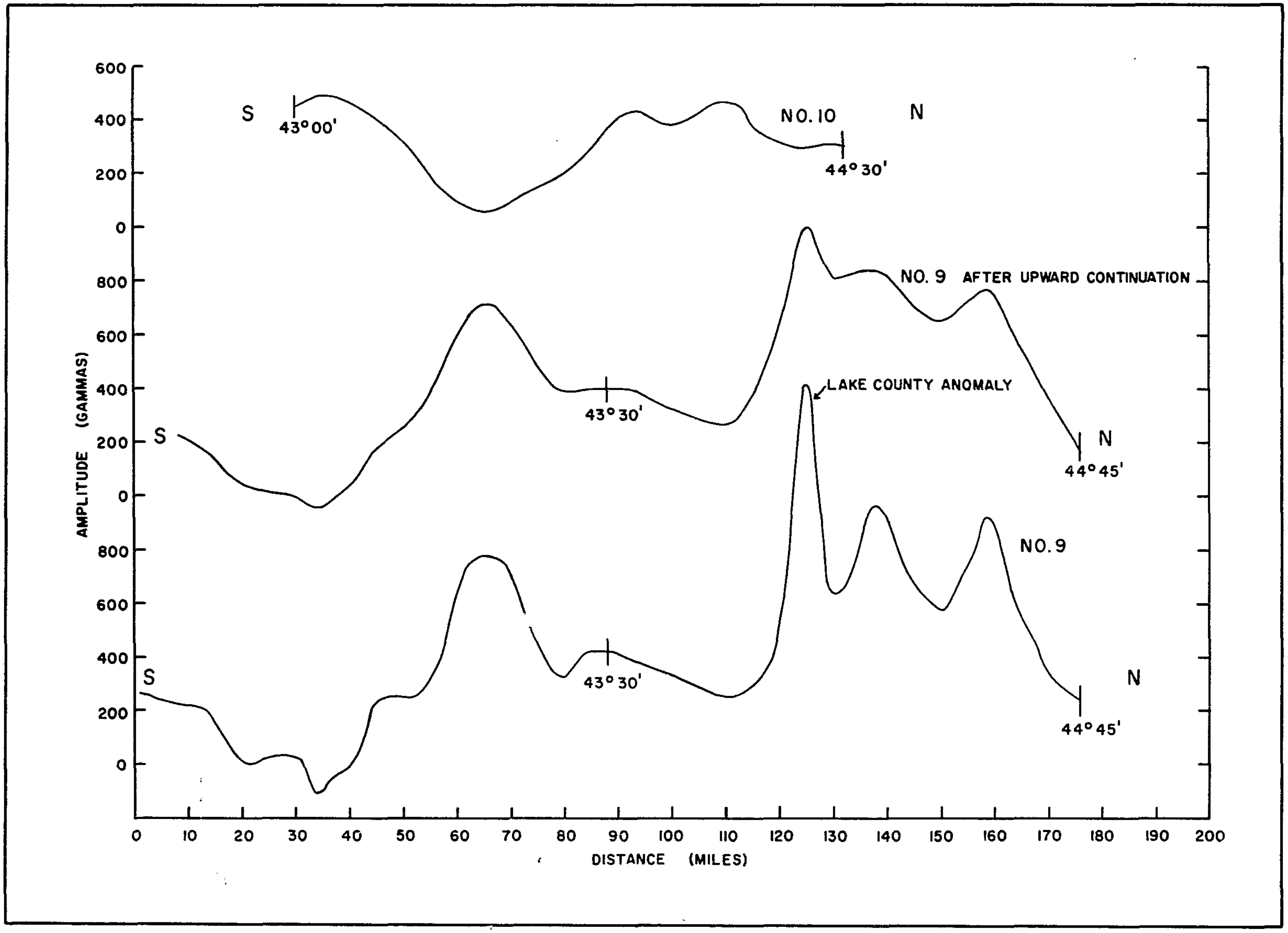

Figure A-4.--Magnetic Anomaly Profiles 9, 9 U. C., and 10.

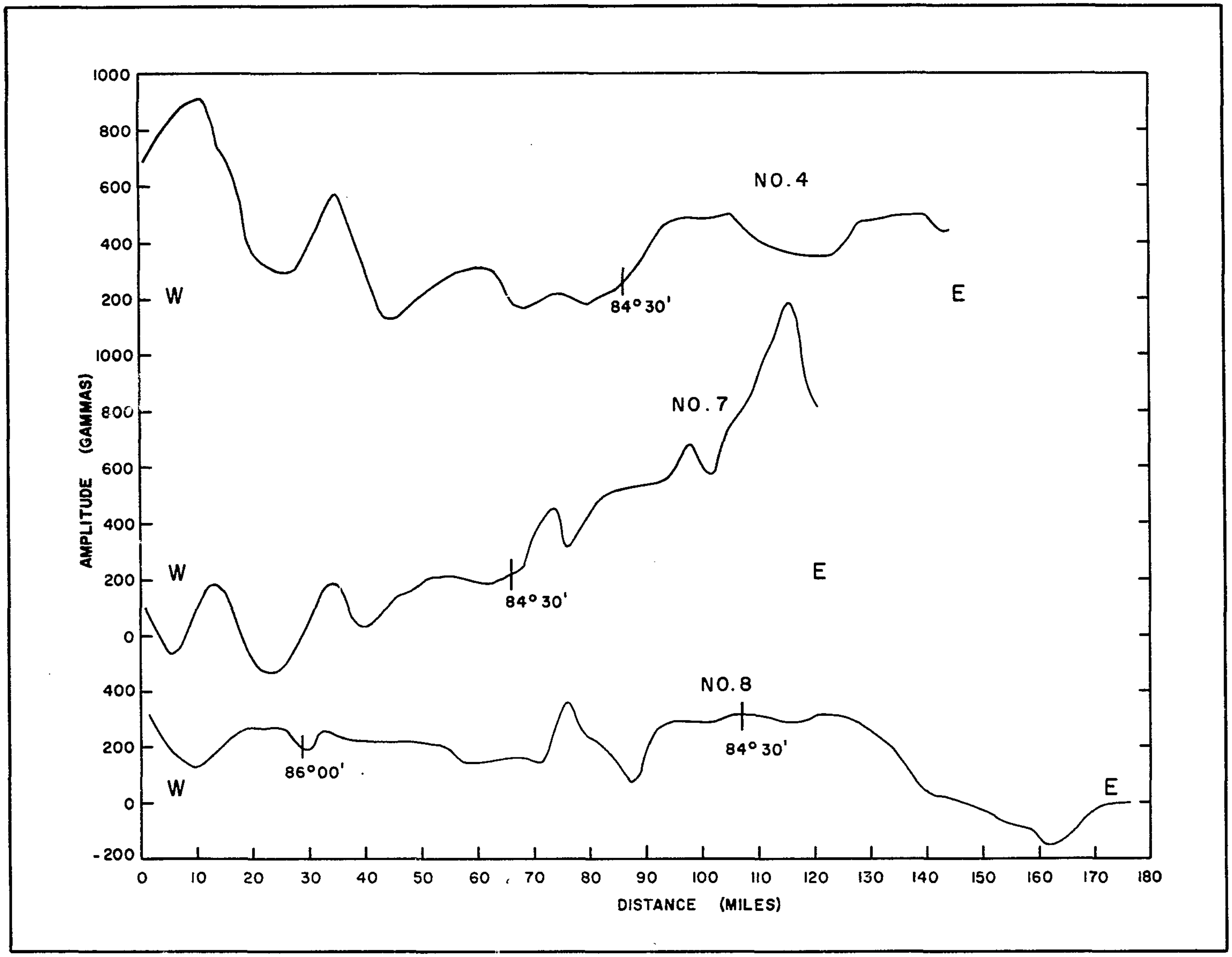

Figure A-5.--Magnetic Anomaly Profiles 4, 7 and 8.

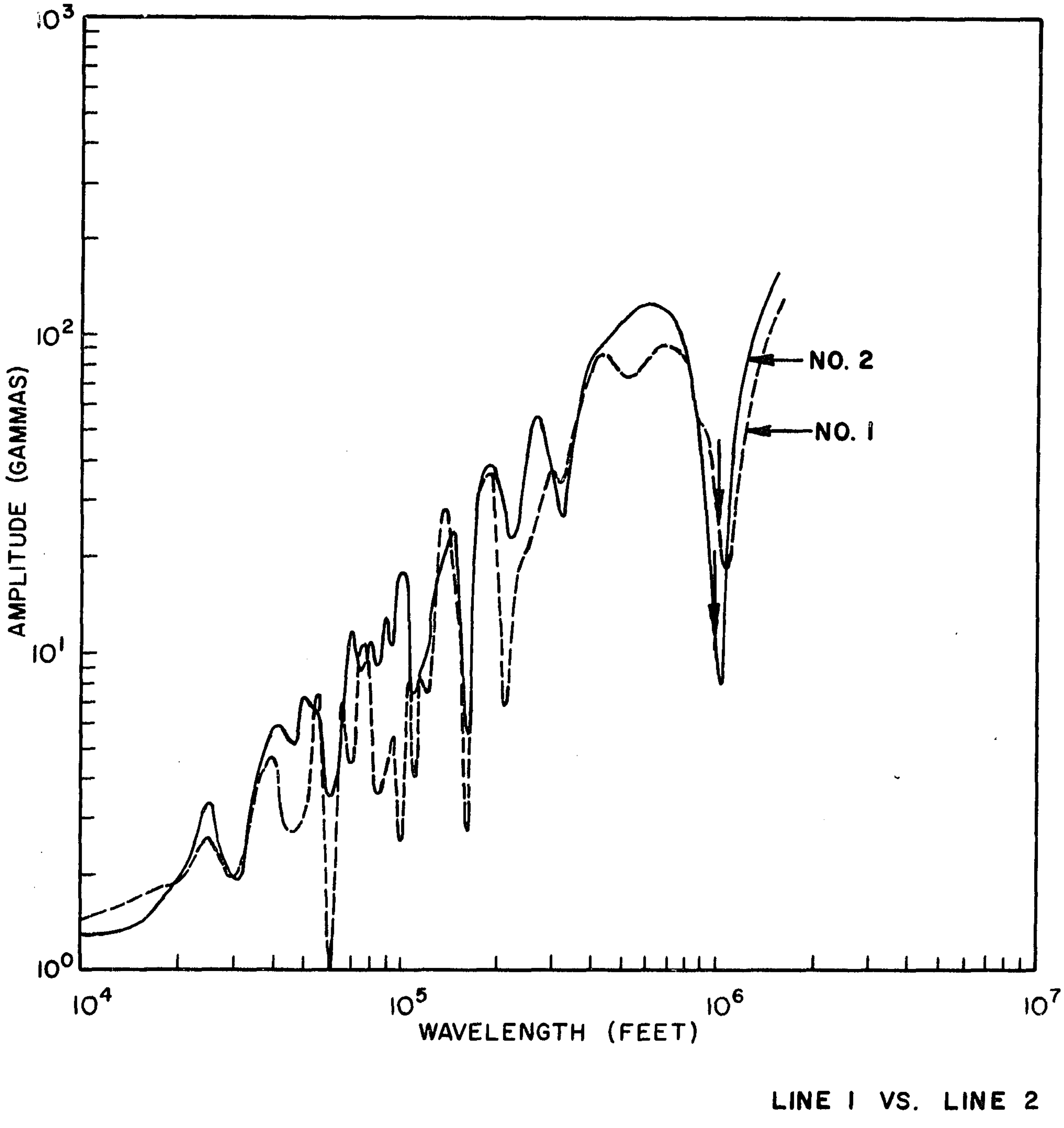

Figure A-6.--Comparison of Fourier Spectra of Profiles 1 and 2.

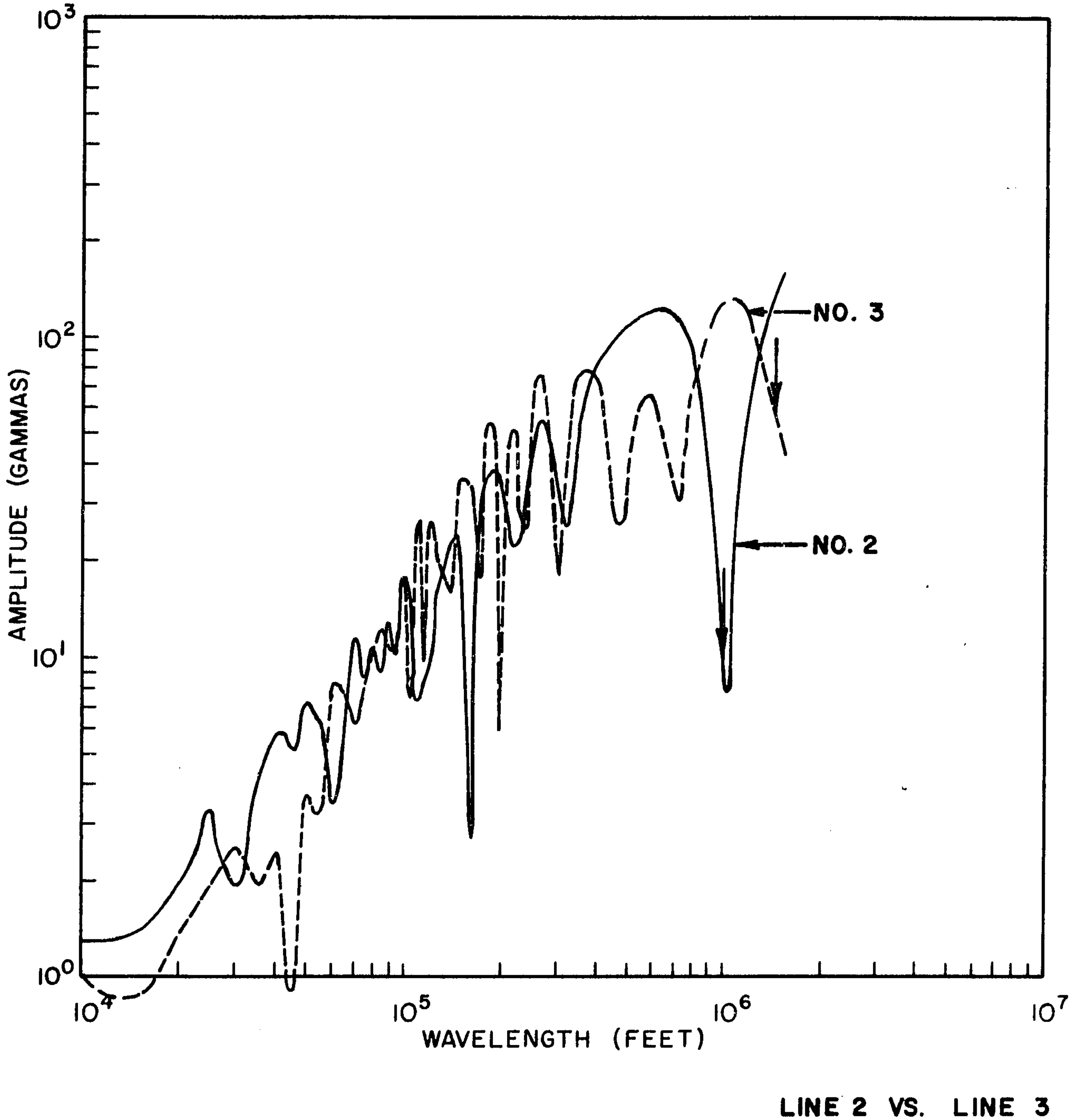

Figure A-7.--Comparison of Fourier Spectra of Profiles 2 and 3.

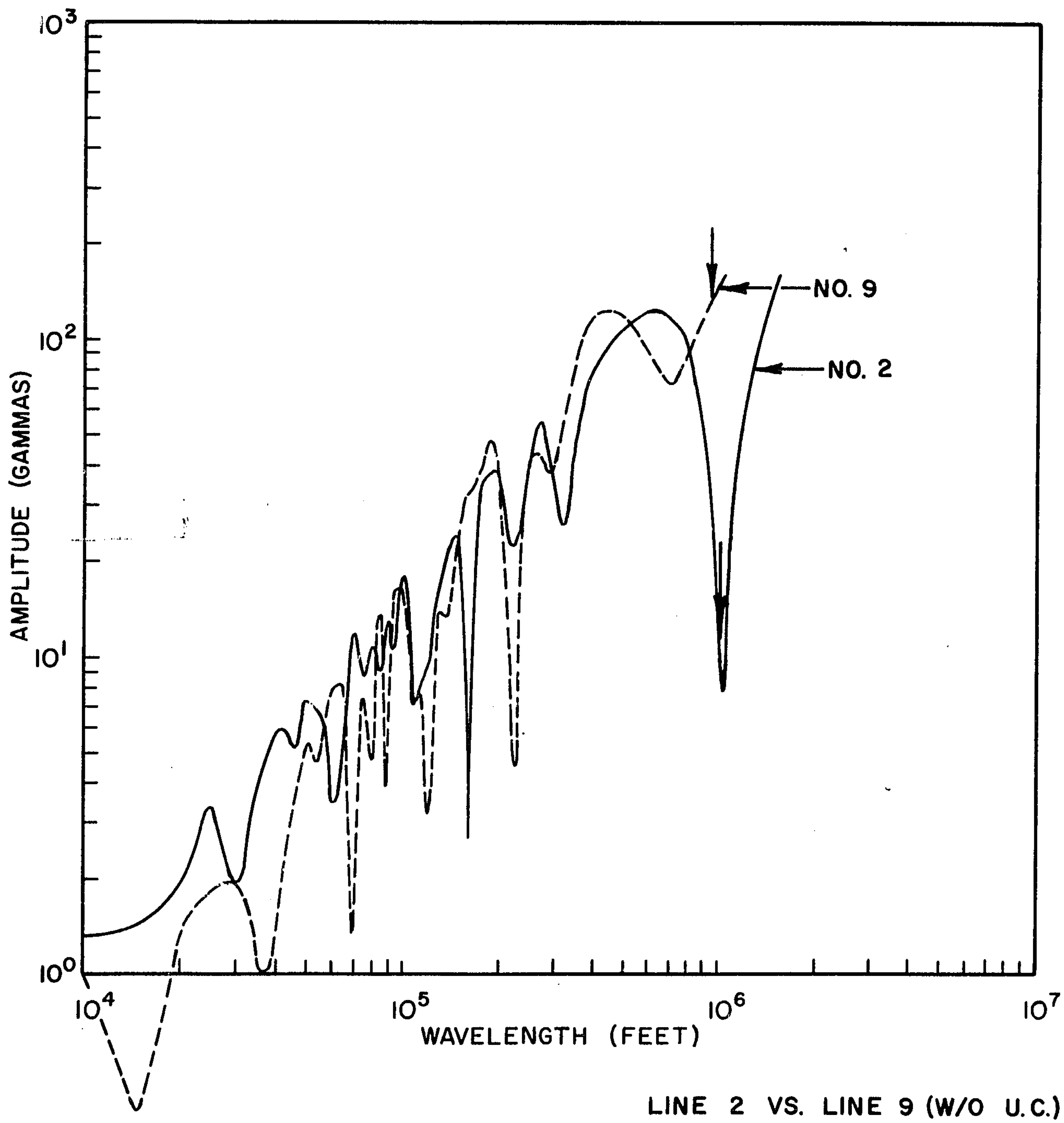

Figure A-8.--Comparison of Fourier Spectra of Profiles 2 and 9.

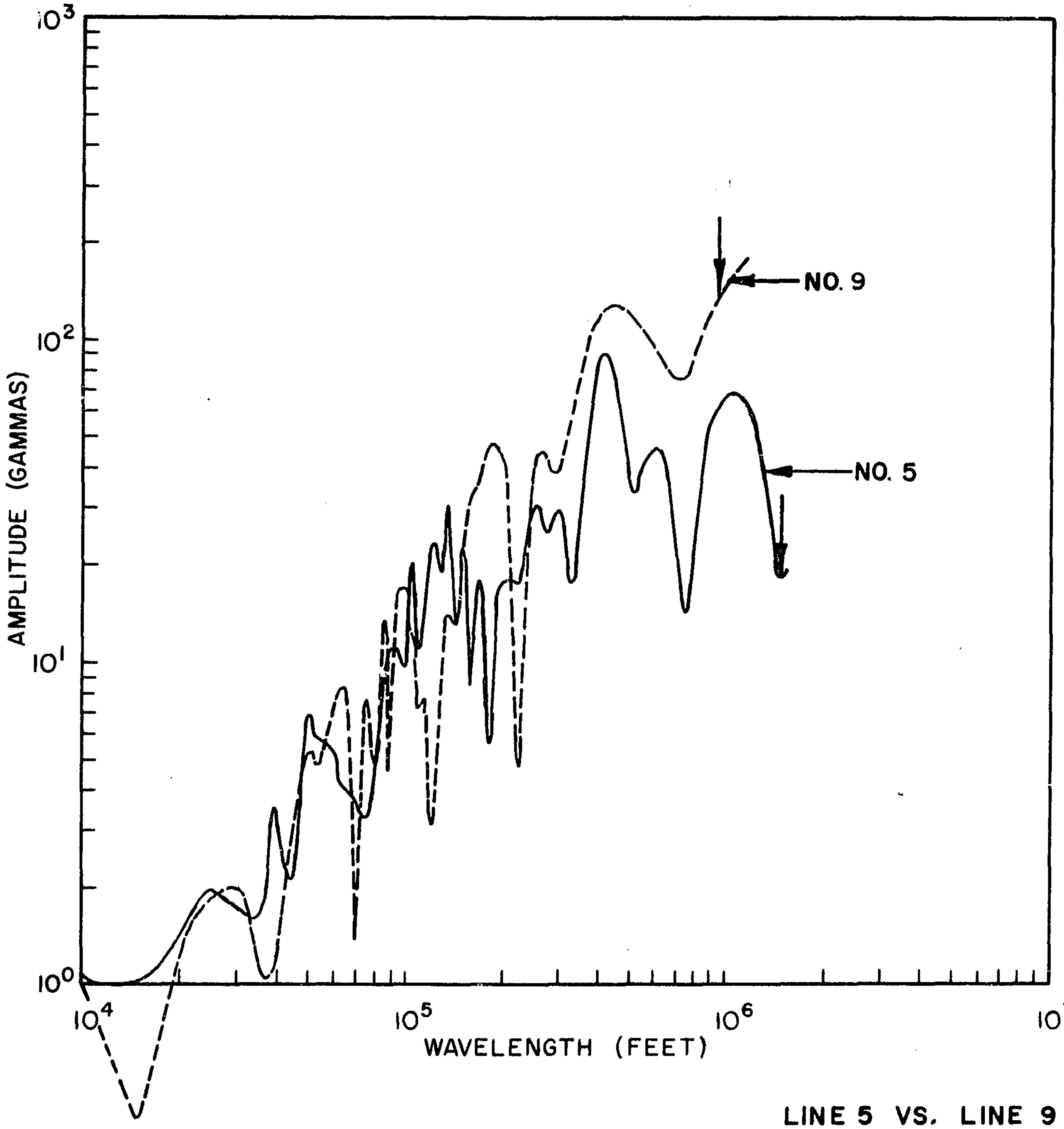

Figure A-9.--Comparison of Fourier Spectra of Profiles 9 and 5.

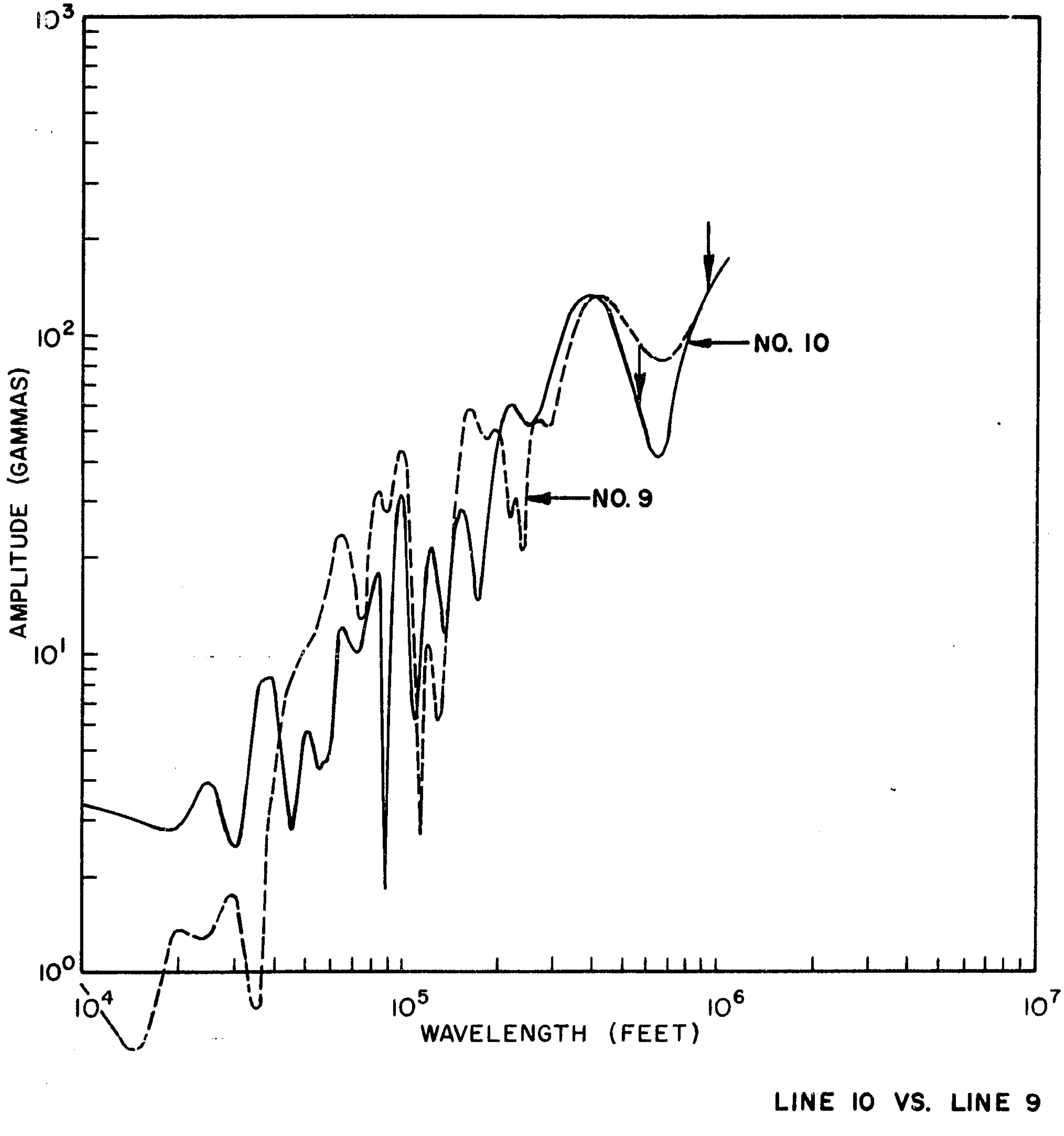

Figure A-10.--Comparison of Fourier Spectra of Profiles 9 and 10.

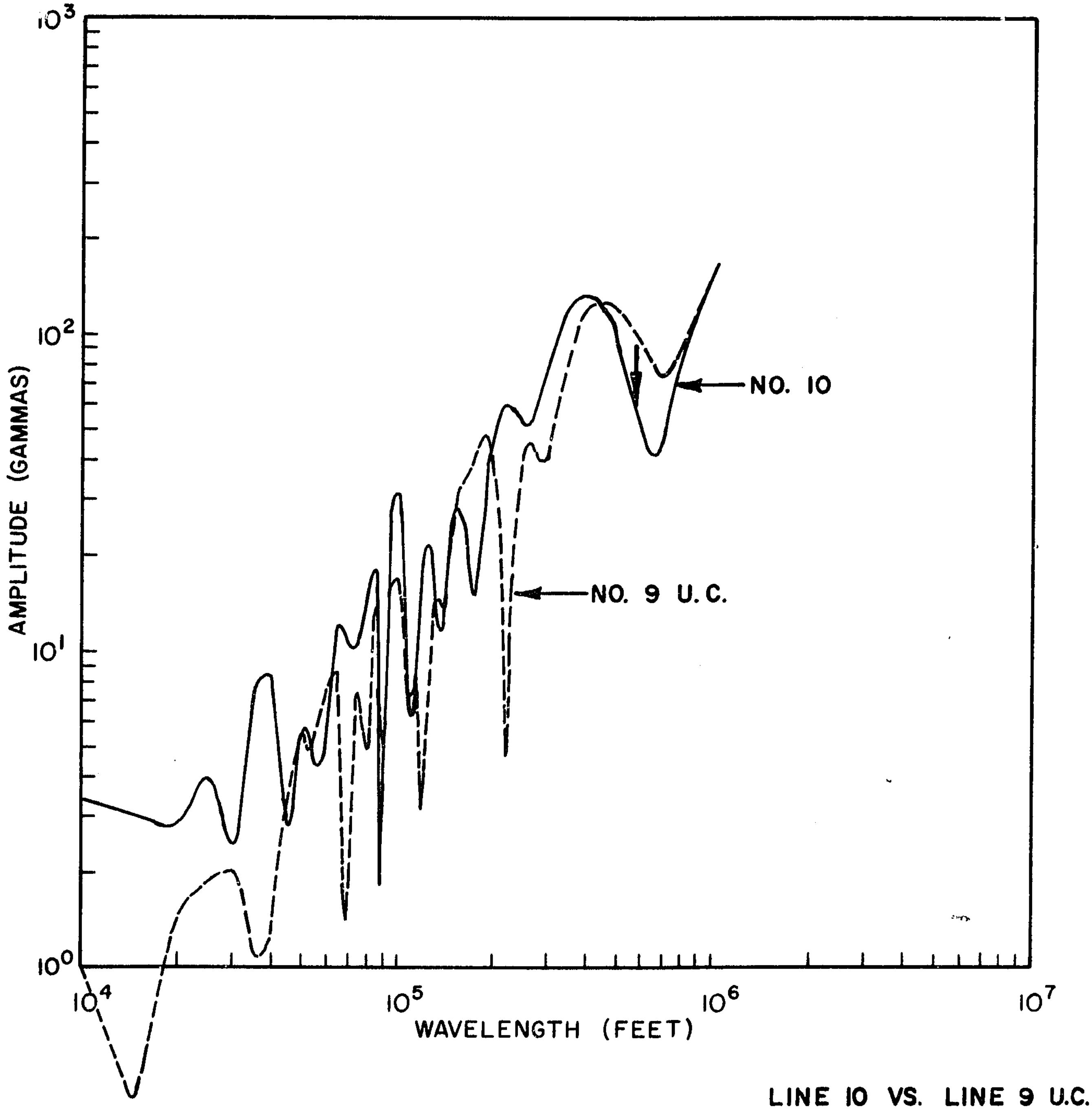

Figure A-11.--Comparison of Fourier Spectra of Profile 9, Upward Continued and Profile 10.

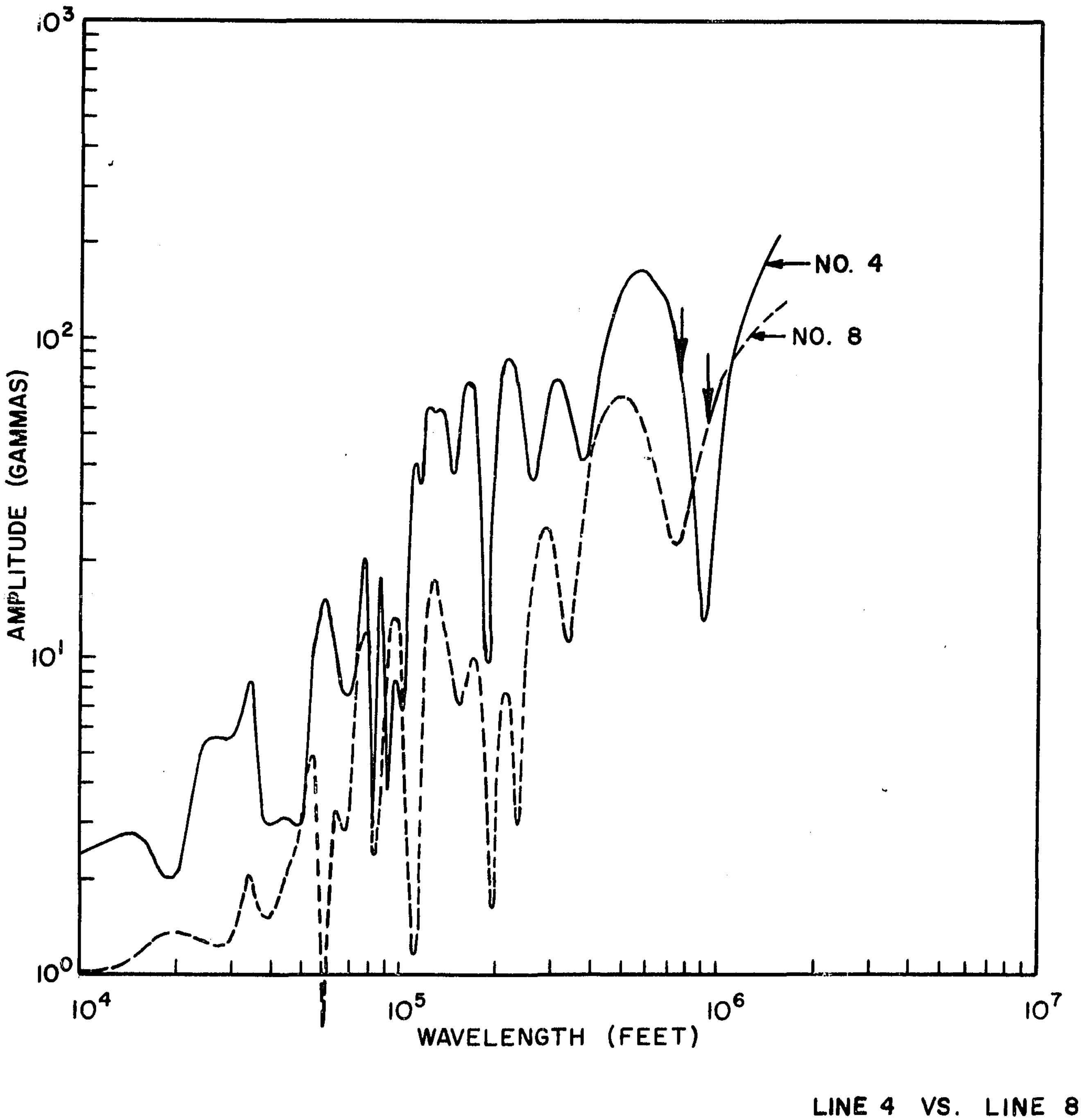

Figure A-12.--Comparison of Fourier Spectra of Profiles 8 and 4.

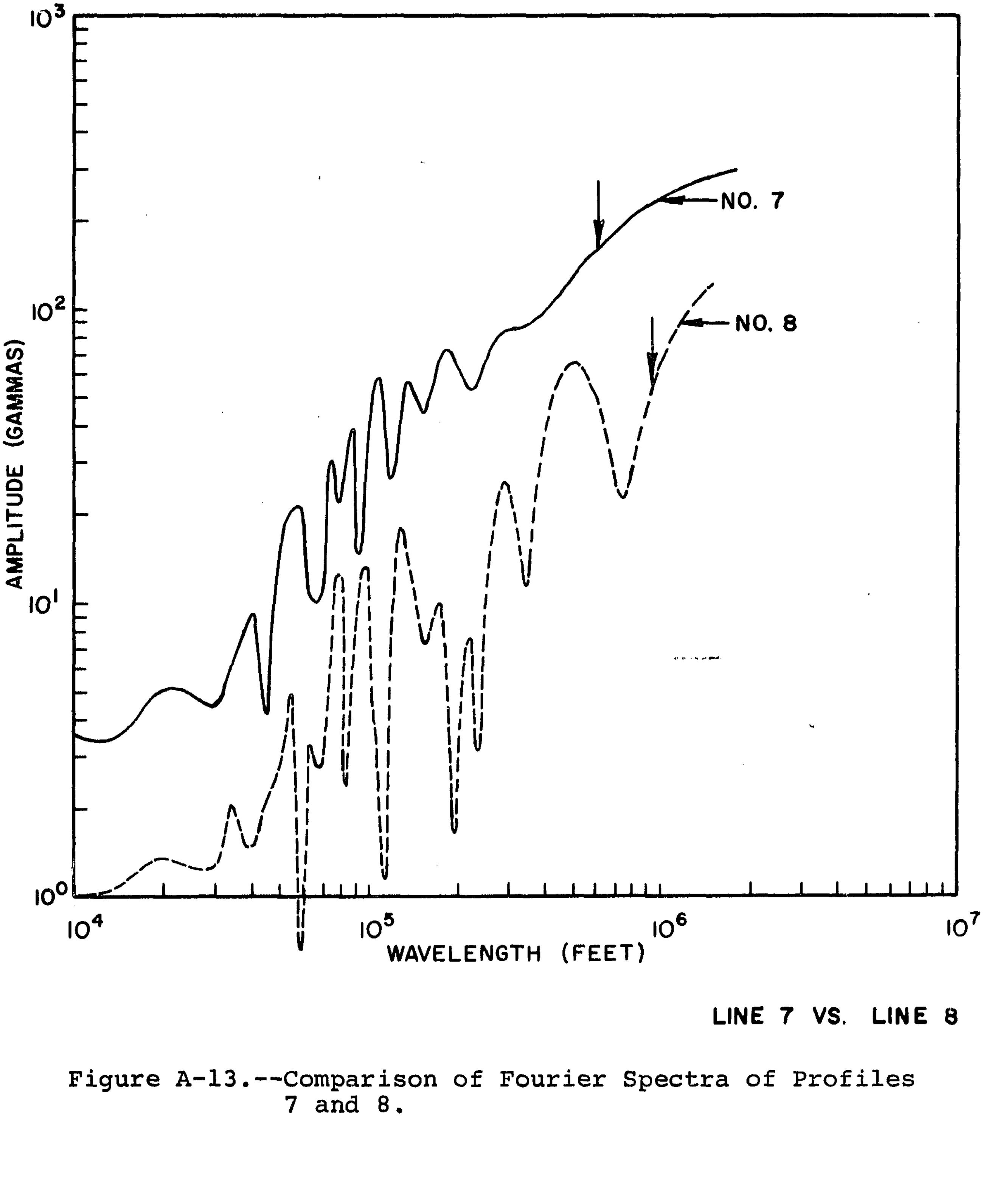

Figure A-13.--Comparison of Fourier Spectra of Profiles 7 and 8.

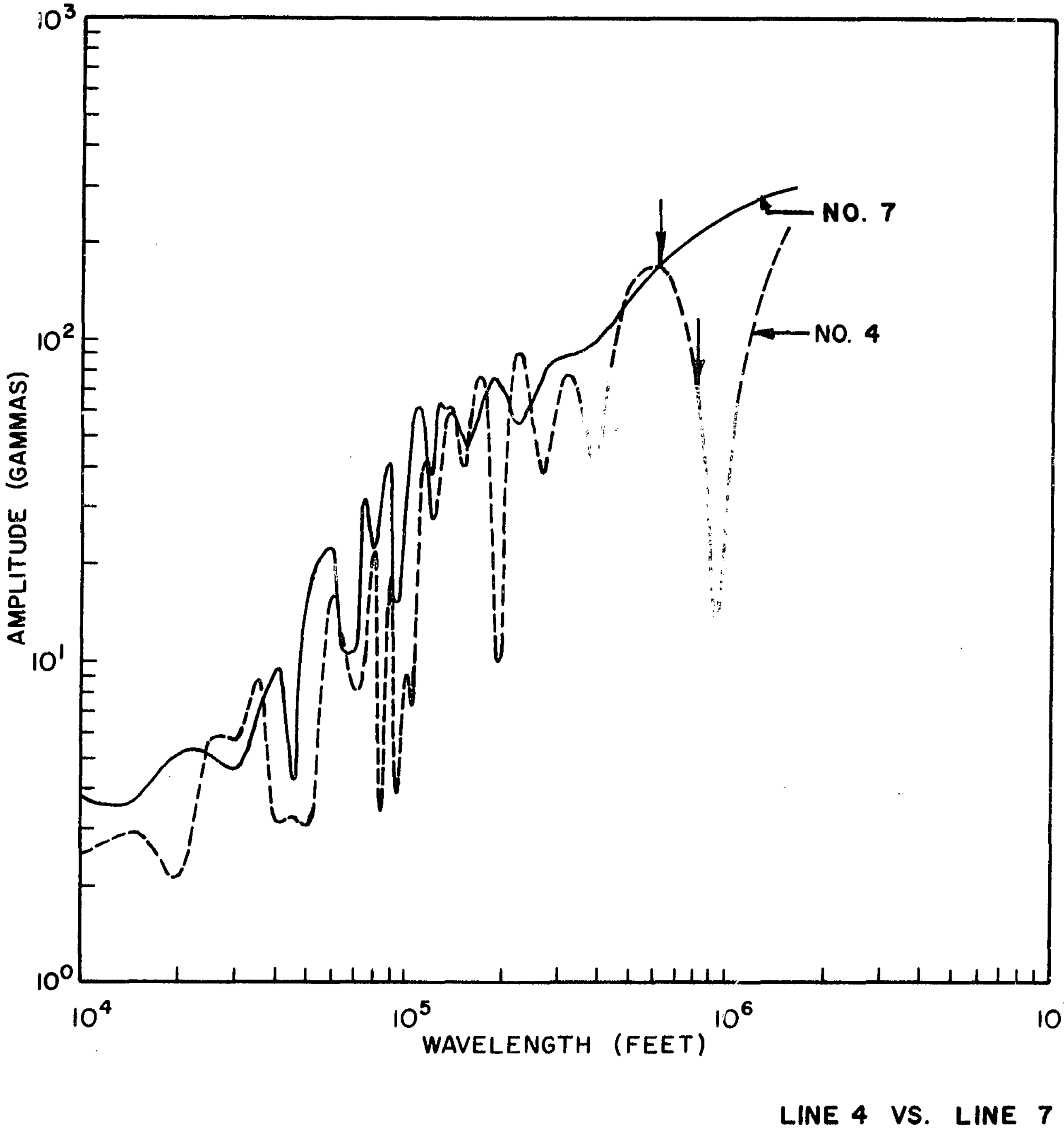

Figure A-14.--Comparison of Fourier Spectra of Profiles 4 and 7.