REPORT OF INVESTIGATION 1

GEOLOGICAL SURVEY DIVISION
DEPARTMENT OF CONSERVATION

REGIONAL GRAVITY AND MAGNETIC ANOMALY MAPS OF THE SOUTHERN PENINSULA OF MICHIGAN

PREPARED BY THE DEPARTMENT OF GEOLOGY,
MICHIGAN STATE UNIVERSITY

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STATE OF MICHIGAN

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BY

WILLIAM J. HINZE

PREPARED BY THE DEPARTMENT OF GEOLOGY, MICHIGAN STATE UNIVERSITY

LANSING

1963

STATE OF MICHIGAN
George Romney, Governor
DEPARTMENT OF CONSERVATION
Gerald E. Eddy, Director
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William L. Daoust, Chief and State Geologist (retired)

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REGIONAL GRAVITY AND MAGNETIC MAPS

of the

SOUTHERN PENINSULA OF MICHIGAN

ABSTRACT

Regional Bouguer gravity and vertical magnetic intensity anomaly maps are presented of the Southern Peninsula of Michigan. These maps have been prepared from a peninsula-wide survey, which is discussed, plus data obtained from previous detailed surveys. Approximately 2500 gravity and 2500 magnetic observations were used in the final preparation of the maps.

The gravity and magnetic anomalies are due principally to regional changes in the lithology of and depth to the basement rocks and the lithology and structure of the sedimentary rocks overlying them. The dominating anomaly in the Southern Peninsula is a gravity and magnetic positive with adjacent negatives extending through the center of the peninsula. This positive anomaly correlates with a major structural feature of the Michigan Basin, the Howell anticline. Several other anomalies mapped warrant detailed field investigation and analysis.

INTRODUCTION

Objectives

This report summarizes information concerning the preparation and the general geological significance of the Bouguer gravity and vertical magnetic intensity anomaly maps of the Southern Peninsula of Michigan. These maps were prepared by the Department of Geology of Michigan State University as part of a continuing research program dealing with problems of petroleum exploration within the Michigan Basin.

The gravity and magnetic anomaly maps provide information on the gross features of the sedimentary rocks of the Michigan Basin and also are affected strongly by the lithology, structure, and depth of the basement igneous and metamorphic complex. Thus, they may be used to determine the tectonic framework of this area and its Precambrian geological history. This information is lacking because of the absence of outcrops of the basement complex and the paucity of subsurface data. The dominating anomaly of the gravity and magnetic anomaly maps originates in the basement complex and coincides with a major structural feature of the basin. Other structural features of the sedimentary rock of the basin also may be correlative with basement features reflected in the anomaly maps. The correlation of the dominating gravity and magnetic anomaly with the Michigan Basin suggests a possible cause and effect relationship.

The specific objectives of this phase of the program are:

(1) To map the regional magnetic and gravity anomalies of the Southern Peninsula of Michigan.

(2) To locate gravity and magnetic anomalies for future detailed study of the lithological variations, structure, and depth of the basement rocks.

(3) To study the correlation of the regional gravity and magnetic anomalies with major structures in the sedimentary rocks of the Michigan Basin.

(4) To establish gravity and magnetic base stations throughout the Southern Peninsula for purposes of tying together past and future detailed investigations.

To make the results of this phase of the program available immediately, no attempt is made in this report to make a detailed geological interpretation of the gravity or magnetic data. An interpretation of this type is in progress and will be presented elsewhere.

ACKNOWLEDGMENT

The preparation of the regional gravity and magnetic anomaly maps has been made possible through the generous assistance of many individuals and organizations. Sincere appreciation is due to the following organizations for the loan or gifts of equipment, contribution of data, and the granting of operating funds: Beard Instrument Company, Gulf Research and Development Company, Jones and Laughlin Steel Company, McClure Oil Company, Michigan Geological Survey, University of Michigan, Michigan State University All-University Research Fund, National Science Foundation Undergraduate Research Participation Program, Ohio Oil Company, Shell Oil Company, Texas Oil Company, and others who prefer to remain anonymous.

This program has been conducted under the direction of the staff of the Department of Geology of Michigan State University by students of the department. The success

of the program is directly attributable to the students' intense interest, untiring effort, intelligence, and imagination. The following students have participated in field and/or office phases of the program:

Samuel Alguire	Thomas Lawler
Charles Armstrong	James Lowden
Richard Blackwell	Joseph Mancuso
James Brett	Donald Merritt
James Carroll	Howard Meyer
John Fenton	John Norris
Donald Hill	George Secor
Warren Keith	Gary Servos
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John Klasner	John Thiruvathukal

Special acknowledgments are made to Dr. C. E. Prouty, Chairman of the Department of Geology, Michigan State University, for his support of this program; Harold M. McClure, Jr., President of the McClure Oil Company, for his continued direct encouragement of the study; and to William L. Daoust, former State Geologist of Michigan, for his efforts in obtaining publication of this report.

SOURCE OF DATA

The primary source of data for the regional gravity and magnetic maps presented in this report is a peninsula-wide survey. Observation stations were established at township corners throughout the Southern Peninsula, at intermediate points in areas of particular interest, and at strategically located elevation bench marks. Supplementary data were obtained from petroleum exploration organizations operating within the state and from theses prepared at Michigan State University and the University of Michigan. Maps obtained from petroleum exploration organizations for which the principal facts of the observations were not available or were withheld for security reasons were used as a guide in contouring.

Approximately 2500 gravity and 2500 magnetic observations were used in the final preparation of the maps.

PREVIOUS STUDIES

Little gravity information has been published from the Southern Peninsula of Michigan despite the continued use of the gravity method in petroleum exploration in Michigan from the time of its introduction into this country to the present day. The U. S. Coast and Geodetic Survey has established eight gravity base stations in the Southern Peninsula of Michigan for which they have calculated the Bouguer and isostatic anomalies (Duerksen, 1949). Jodry (1957) presented a regional gravity map of Michigan contoured on a 10 mgal interval after L. L. Logue and the Tulsa Geological Society Digest, Vol. 18, (1950). He also presented in the same paper a 2.5 mgal contour interval gravity map of portions of Muskegon, Kent, Newaygo, and Oceana counties. Jacobs, Russell, and Wilson (1959) show a Bouguer gravity anomaly map of the United States contoured at a 40 mgal interval. This map, prepared by G. P. Woollard, illustrates the gross gravity features of the state. In addition, gravity profiles associated with petroleum structures within the state have been published in technical journals.

The only published magnetic data from the Southern Peninsula of Michigan is Jenny's (1934) magnetic vector study. He has pinpointed the location of some of the major magnetic anomalies and has discussed their correlation with sedimentary structures.

INSTRUMENTS

Gravity

Three exploration gravimeters were used in this study to measure the gravity values. These were World-Wide meters no. 37 and 45 and Worden meter no. 99. They are extremely sensitive spring balance systems which measure the change in weight of a constant mass as it is moved to different locations. The change in weight of the constant mass is directly dependent on the acceleration of gravity. To achieve high sensitivity the meters consist of a complicated spring system which causes unstable equilibrium between the acceleration of gravity and the restoring force of the spring system. As a result a small change in the gravitational acceleration produces a measurable deflection of the constant mass. They are capable of measuring variations as minute as one unit in 100,000,000 of the earth's total gravity field. Such high sensitivity requires that the system be free from the effects of temperature and pressure variations which could obscure the effects of small changes in gravity. This is accomplished through temperature compensation of the mechanism and by operating it in a partial vacuum.

Magnetic

Two basic types of magnetometers were employed in this survey, the Schmidt field balance and the torsion magnetometer. Both types measure relative variations in the vertical intensity of the earth's magnetic field and have a sensitivity of approximately 2.5 gammas.

Approximately 75 percent of the stations were observed with a torsion magnetometer manufactured by the Askania-

Werke. This instrument employs a magnet provided with a fiber axis in which the torsion of the fiber is a measure of the vertical component of the earth's magnetic field. This component is measured indirectly by the movement of a calibrated knob which applies counter-torque to the fiber to bring the magnet to a null position. The remaining 25 percent of the stations were observed with Schmidt field balances which consist of a permanent magnet pivoted on a horizontal knife edge. A balance is achieved between the gravitational torque and the magnetic torque acting on the moving system. Changes in the magnetic field cause a deviation in the system which is measured by means of an autocollimation telescope. The vertical component alone acts upon the magnet when it swings in a plane perpendicular to the magnetic meridian.

SURVEY PROCEDURE

Gravity

Station Network

A basic station network was set up with observation sites located at approximately six mile intervals throughout the Southern Peninsula. Wherever possible the stations were established at township corners. In many cases, however, the stations were established as much as two miles from these positions because township corners were inaccessible to vehicular traffic or because known elevations were available nearby. In addition, the exact station locations had to be free from marked local relief and vibration and easily identifiable both on the site and on maps.

Stations were also established at selected elevation bench marks and in areas of particular geologic interest. Additional data at three mile intervals were obtained from previous surveys and incorporated into the final map. Detailed maps of certain areas were also available as an aid in contouring.

Drift Control

Gravimeters are subject to "drift," or time variations in readings in a constant field. These variations are caused largely by the effect of temperature changes and by creep effects in the mechanism of the meter. In addition, the gravity field varies with time due to the tidal effects of the moon and the sun. These effects were eliminated with data obtained from repeated readings at a base station at intervals from two to four hours. The accuracy achieved with this time interval is adequate for the purpose of this survey.

Base Stations

Gravity base stations were established throughout

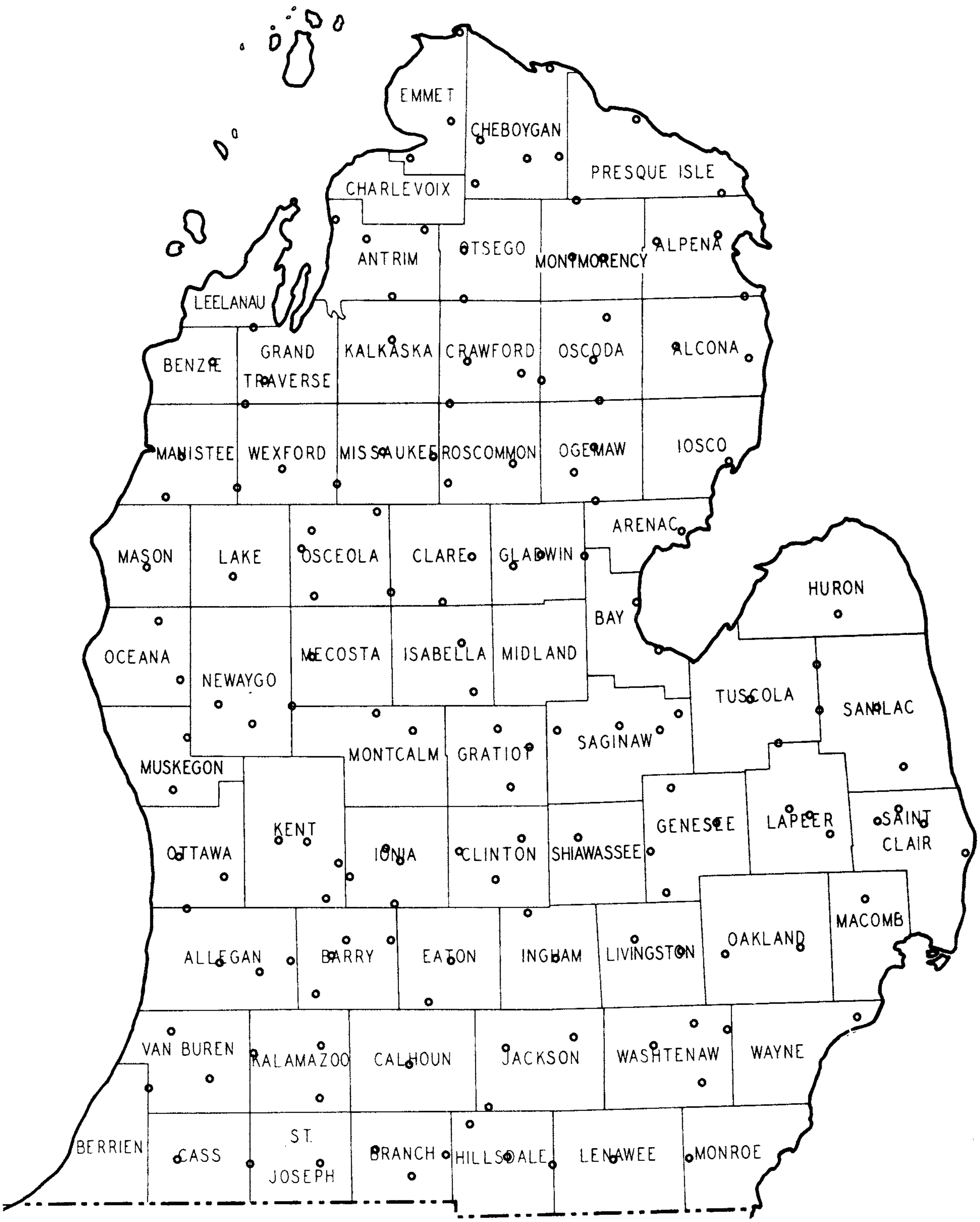

Fig. I GRAVITY BASE STATIONS

the Southern Peninsula by the method of "looping." The purpose of these stations is to set up control points to tie together the observations of this survey as well as to establish stations to which future surveys may be tied. All base stations were tied to a primary gravity base which was established by Behrendt and Woollard (1961) on the campus of Michigan State University. This station is designated WU 17, East Lansing, Michigan and is located at the curb in front of the main entrance of the Physics and Math Building. It is given an observed gravity of 980.3498 gals. with an error no greater than ± 0.1 mgal.

The locations of the base stations are indicated in Figure 1. The descriptions of these stations with maps showing their precise locations are on file at the Department of Geology, Michigan State University and copies are available on request.

Magnetic

Station Network

The gravity and magnetic surveys usually were made together, thus the general locations of most magnetic and gravity stations coincide. Occasionally, a site free from extraneous magnetic fields was unavailable near the gravity station, therefore, another nearby magnetic station location was selected. In the metropolitan areas sites free from extraneous magnetic fields were unavailable, hence magnetic stations were not established. The exact magnetic station locations were selected so as to be free from the magnetic effects of steel fences, tramp iron and steel, pipe lines, iron and steel structures, et cetera. At each site two observations were made at a separation of roughly 50 feet and a third observation was made at 50 feet on a right angle offset. The purpose of the multiple reading method is to aid in the evaluation of the magnetic effects of the surface formations and to permit selection of a representative magnetic reading at the site free from surface disturbances. If two of the three readings did not check within approximately 5 gammas, readings were continued at 50 foot intervals until this consistency was obtained. Some sites had to be abandoned altogether because of the wide dispersion of the readings.

As in the case of the gravity station network additional data were obtained from previous surveys and detailed maps of certain areas were also available as an aid in contouring.

Drift Control

The earth's magnetic field undergoes daily variations due to extraterrestrial causes. These variations are great enough so that the magnetic readings must be corrected for them. Inasmuch as these variations cannot be predicted it is necessary to determine each daily variation or the "drift" of the magnetic field. Magnetic drift control was obtained from the U. S. Coast and Geodetic Survey daily magnetograms from Fredricksburg, Virginia and by repeat observations at base stations at approximately two hour intervals. Observations generally were not taken during periods of magnetic storms, but those stations which were unknowingly observed during these periods were re-established at a later time to insure accurate readings.

Base Stations

Magnetic base stations were established throughout the Southern Peninsula in the same manner as the gravity base stations. The purpose of these stations is to set up control to tie together the observations of this survey and to establish stations to which future surveys may be tied. All of the stations were tied to an arbitrary base, the Clinton County base station. The magnetic observations are, therefore, all relative to one another, but are not tied into an absolute datum.

REDUCTION OF DATA

Gravity

Observed Gravity

The gravimeter readings at each station were converted to observed gravity by first correcting for observed instrumental drift and then adjusting the readings to a base station previously tied to the primary base. These values were then converted into gravity units, milligals, by multiplying by the calibration constant of the gravimeter. The calibration constants of the meters as provided by the manufacturer were checked against each other and were found to agree.

Station Elevations

The elevation correction is the most significant factor in the reduction of gravity observations. For this reason, every effort was made to obtain the most accurate elevation of each station. To achieve the maximum precision, gravity observations were made at known elevations, level line stations, bench marks or elevated road junctions, or at locations, the elevations of which could be interpolated from contour maps having a maximum interval of 20 feet. Barometric altimeters were used to determine elevations where other control was not available. The barometric drift was monitored by a base altimeter and all precautions were taken to achieve maximum precision. Elevations determined in this manner were checked for discrepancies against the 50 foot elevation contours of the U. S. Geological Survey 1:250,000 topographic map series. In selecting the gravity stations to be used in preparing the final map, stations with elevations established by altimeters were eliminated wherever possible. Only 12 percent of the stations have barometric altimeter elevations. Where it became necessary to use these stations to achieve the desired coverage, the final gravity values were checked against private detailed gravity maps for possible errors. Previous studies (Hinze, 1959) indicate that errors in altimeter elevations can be held to ± 10 feet.

Station Locations

The stations were plotted on 1:250,000 U. S. Geological Survey topographic maps and the latitude and longitude coordinates of the stations were determined from these plots to the nearest 0.1 minute. A comparison of latitudes determined from the 1:250,000 maps to the nearest 0.1 minute and 1:62,500 maps to the nearest 0.01 minute for a group of randomly selected stations indicated a maximum difference of only 0.08 minutes.

Bouguer Gravity Anomaly

Observed gravity measurements can be utilized in the interpretation of geologic structures by comparing them with theoretical values of gravity. The difference between the observed gravity and the calculated theoretical gravity value at any observation site is called a "gravity anomaly." Specifically, the gravity anomaly is termed a "Bouguer gravity anomaly" if the theoretical value includes the effects of the shape and rotation of the earth, the elevation of the observation site, and the local terrain departures.

The theoretical gravity at sea level at each station was determined from the International Gravity Formula of 1930,

$$g_\phi = 978.049\ (1 + 0.0052884\ \sin^2\phi - 0.0000059\ \sin^2 2\phi)$$

where g_ϕ is the sea level gravity at latitude ϕ. This formula takes into account the change in gravity at sea level of 5 gals from the equator to the poles due to the shape and rotation of the earth. This effect is of the order of magnitude of 1.5 mgals per minute of latitude at the latitude of this survey.

The effect of the elevation of the observation site above sea level is determined by calculating the Free-air (effect of elevation) and Bouguer (effect of included mass) reductions. The Free-air reduction accounts for the decrease in gravitational attraction with increased elevation because of the greater distance from the center of the earth. The effect is 0.09406 mgals per foot.

The Bouguer correction factor which accounts for the gravitational acceleration due to the mass of material between sea level and the station elevation is 0.01276 σ mgals per foot where σ is the mean density of the included rock mass. This correction is opposite in sign to the Free-air correction. The Free-air and Bouguer corrections were combined into a single constant which is multiplied by elevation of the station. The combined correction factor was calculated for densities of the included rock mass of 1.89, 2.12, 2.40, 2.50, 2.60, 2.67, and 2.80. The gravity anomaly map accompanying this report was prepared employing a density of 2.67. The combined correction constant for this density is 0.06 mgals per foot. A density of 2.67 was assumed so that this map would be consistent with other regional maps which are generally prepared using this factor.

In areas of reasonably level topography the Bouguer correction gives a sufficiently accurate approximation of the mass effect for regional surveys, but where rugged topography is present a correction is required to compensate for local relief. This terrain correction accounts for the deviation of the topography from the horizontal slab of infinite extent assumed in the Bouguer correction. Terrain corrections were not calculated for this survey because of the rather gentle topography in the Southern Peninsula and because local terrain was eliminated as a source of error by judicious selection of the station locations.

The Bouguer gravity anomalies were calculated in the usual manner (Dobrin, 1960) using the corrections previously discussed. The equation used in the calculations is:

> Bouguer gravity anomaly = observed gravity - theoretical gravity at sea level + combined Free-air and Bouguer correction + terrain correction.

The actual calculation of the theoretical gravity at sea level, the combined Free-air and Bouguer correction, and the Bouguer anomalies assuming seven different densities for the included rock mass between sea level and the observation site were made with a digital computer. The principal facts for each station are available either in printed form or on punched cards. The information given for each station includes the survey from which it was obtained, station number, county, latitude and longitude, elevation, source of the elevation, observed gravity, theoretical gravity at sea level, Free-air gravity anomaly which excludes the Bouguer and terrain corrections, and the Bouguer gravity anomaly for seven different densities.

Accuracy

The accuracy of the Bouguer gravity anomaly calculations is a function of the possible errors in each phase of observing and reducing the data. The accuracy of the observed gravity can be judged from the results of readings made at the same station on different days using normal surveying procedures. The standard deviation of a group of 65 repeated gravity observations is 0.17 mgals.

The error in the theoretical gravity at sea level is dependent on the accuracy of the determination of the latitude of the station. The standard deviation of these measurements is estimated to be approximately 0.1 minute which is equivalent to 0.15 mgals in the latitude range of the survey.

Errors in the combined Free-air and Bouguer corrections originate from incorrect elevations. Elevations of stations obtained from bench marks, level lines, road corners, and interpolation between contours on topographic maps are estimated to have a standard deviation of approximately 3 feet. The standard deviation of the barometric altimeter elevations may be as great as 10 feet. For a Bouguer reduction density of 2.67 the 3 foot and 10 foot errors will produce errors respectively of 0.18 mgals and 0.60 mgals, assuming negligible error due to omission of the terrain correction.

The net standard deviation of the errors is 0.5 mgals or the probable error, assuming a normal population distribution, is approximately 0.3 mgals except for stations whose elevations were determined by barometric altimeter. The net standard deviation of errors for those stations is 0.92 mgals or the probable error is 0.62 mgals. These values represent maximum figures for most parts of the state because in many areas one station was selected for the final map as representative of a number of nearby stations. Also, the final map was checked against private detailed gravity maps for possible errors.

Another source of error is the use of an incorrect combined Free-air and Bouguer correction factor due to an improper selection of the representative density of the rock material between sea level and the station. The error depends on the amount of topographic relief involved because the correction factor is multiplied by the elevation of the individual stations. The sign of the anomaly error is a function of the sign of the error in density. In the case of an assumed density which is greater than the true rock density the Bouguer anomaly will be decreased and vice versa. The magnitude of the error is 0.00128 mgals per foot for each 0.1 g/cc error in density. The full significance of this error is difficult to evaluate because of inadequate knowledge of the distribution and density of the subsurface formations. The error due to the glacial drift, however, can be approximated. Assuming that the glacial drift has a density of 2.17 g/cc, the error in the assumed density (2.67 g/cc) is 0.5 g/cc. Elevations in this survey range from 580 to 1380 feet, a span of 800 feet. Thus, the Bouguer anomaly values of the stations at the higher elevations may be up to 5 mgals too low. This source of error cannot be eliminated until data are obtained on the distribution and density of the rocks and glacial drift of the Southern Peninsula.

Magnetic

Observed Magnetic Intensity

In calculating the observed magnetic intensity, a representative instrument reading was first determined from the multiple observations at a site. Where the readings were nearly equal, the average of all the readings was selected as the representative reading. However, where one or more readings differed widely from a group of nearly equal readings, the representative reading was based only on the average of the group. A more truly representative reading was obtained in this manner. No attempt was made to correct for diurnal magnetic drift during the multiple observations at a station location because the observations normally were completed within 10 minutes or less.

The selected representative reading was converted into magnetic units, gammas, by multiplying by the calibration constant of the magnetometer. The calibration constants were determined and frequently checked with a Helmholtz coil calibration apparatus. The readings were then converted to observed magnetic intensity by correcting for magnetic diurnal drift and adjusting the readings to a base station previously tied to the primary base. A temperature correction was unnecessary because the magnetometers were temperature compensated.

Normal Magnetic Correction

The earth's normal magnetic field varies over the surface of the earth. The vertical component varies from zero at the magnetic equator to approximately 65,000 gammas at the magnetic poles. Over the surface of the Southern Peninsula of Michigan the total variation in the vertical intensity is roughly 2000 gammas. The principal variation is with latitude, approximately 7 gammas per mile, while only a minor variation exists with longitude, reaching a maximum of slightly over one gamma per mile. The normal variation at each station was interpolated from a contour map of these variations prepared from data taken from U. S. Coast and Geodetic Survey magnetic charts. This map was ad-

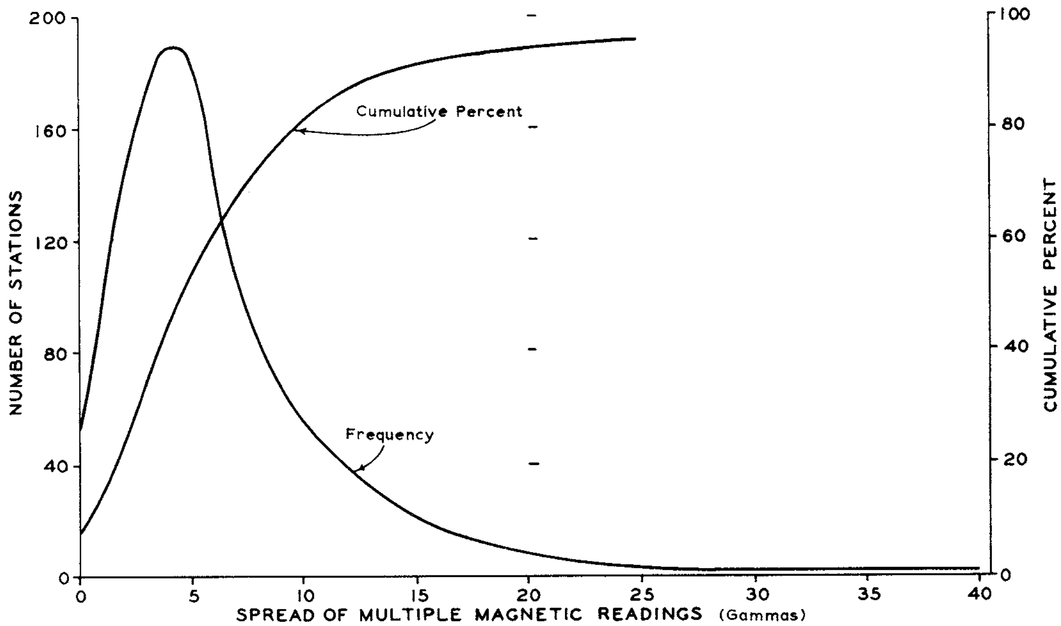

Fig. 2 FREQUENCY AND CUMULATIVE PERCENT GRAPHS OF THE SPREAD BETWEEN MULTIPLE MAGNETIC READINGS AT A STATION.

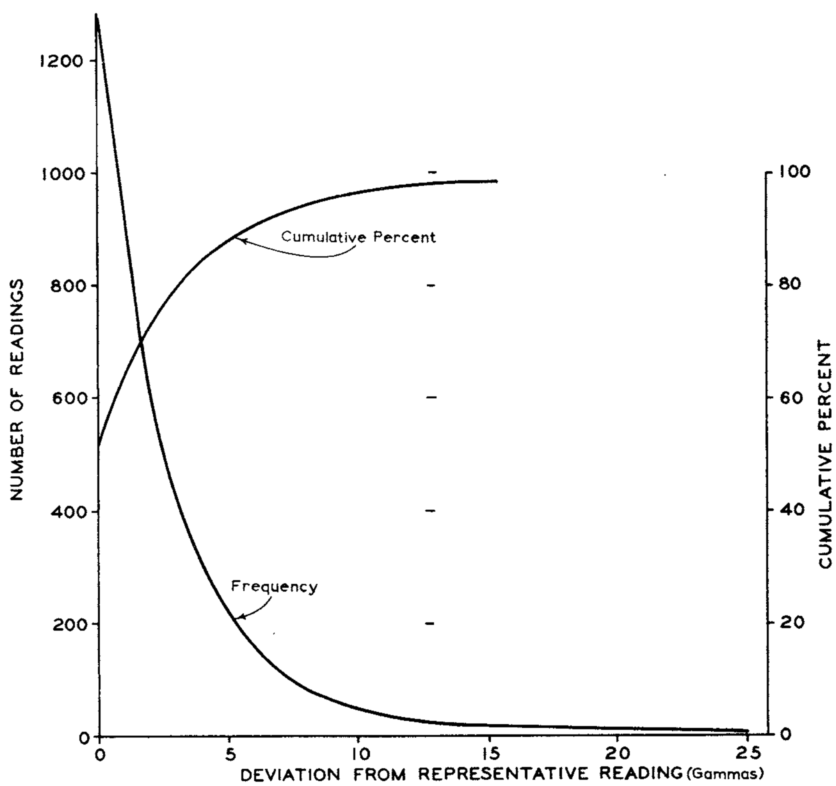

Fig. 3 FREQUENCY AND CUMULATIVE PERCENT GRAPHS OF THE DEVIATION OF MULTIPLE MAGNETIC READINGS FROM THE REPRESENTATIVE READING AT A STATION CORRECTED FOR READING ERROR.

justed to take into account the time at which the observations were made to eliminate the effect of secular variations in the earth's magnetic field.

Vertical Magnetic Anomaly

The vertical magnetic anomaly, in a manner analogous to the gravity anomaly, refers to the difference between the observed and the theoretical vertical intensity of the earth's magnetic field. Theoretical intensity is referred to as the normal magnetic correction and is determined from regional observations made by the U. S. Coast and Geodetic Survey as discussed in the previous section. The magnetic anomaly is the difference between the observed magnetic intensity corrected for diurnal magnetic drift and this theoretical intensity. The anomaly indicates horizontal variations in the magnetic susceptibility or remanent magnetization of the underlying rock formations.

Accuracy

The accuracy of the magnetic anomaly, like that of the Bouguer gravity anomaly, is a function of the errors in each phase of observing and reducing the data. In glaciated areas a primary source of error in ground magnetic observations is local disturbances due to concentrations of magnetic minerals in the glacial drift. Normally, the magnetic effects from these concentrations would not produce measurable anomalies if they were buried a few hundred feet below the surface. Where they occur at or very near the plane of observation, however, they can cause appreciable anomalies which distort or even mask geologically significant anomalies. The possible origins of these concentrations have been discussed elsewhere (Hinze, 1961; Lawler, 1962). To evaluate the magnetic effect of the glacial drift from the multiple magnetic observations at a station, the deviation of each observation was determined from the reading selected as representative for that station. The frequency with which the spread between multiple readings at a station occurs is shown in Figure 2. The maximum frequency occurs at twice the least count of the magnetometer or approximately 4.6 gammas. The spread of roughly 50 percent of the stations is less than this value and 80 percent of the stations have a spread of 10 gammas or less. Figure 3 is a plot of the frequency of the deviation from the selected reading, corrected for reading error, as determined from repeat observations at base stations. The mean deviation of the observations from the selected reading neglecting nine extreme variations above 53 gammas is 2.8 gammas. The cumulative percentage curve also given in Figure 3 indicates that 50 percent of the observations are free from magnetic effects from the glacial drift, that 75 percent of the observations are affected by no more than the least count of the Askania torsion magnetometer, 2.3 gammas, and that 90 percent have a deviation of no more than 4 gammas.

The accuracy of the observed vertical magnetic intensity can be appraised from the results of repeat readings at the same station on different days using standard surveying procedures. The standard deviation of a group of 93 repeated magnetic observations is 13 gammas. There is no standard criterion for judging the accuracy of the normal magnetic correction. However, adjacent stations are estimated to be in relative error by no more than 5 gammas because of the limited variation in this effect, but over the entire Southern Peninsula the error could be several times this value. In summary, the relative error of adjacent stations may be of the order of magnitude of 20 gammas, but the error between stations in widely separated parts of the peninsula may be twice this value.

GEOLOGICAL SIGNIFICANCE

Source of Anomalies

Gravity and magnetic anomaly maps are pictorial representations of geological conditions. They show the mathematical differences between the observed values and the expected or theoretical values of a force field. These differences are caused by horizontal variations in the physical properties of the underlying rock formations. In the case of gravity this physical property is density and in the case of magnetics this physical property is magnetic susceptibility and remanent magnetization.

The anomaly values are the summation of all departures from horizontally homogeneous earth conditions. They include effects from rocks directly below and adjacent to the observation point from the surface to the center of the earth. The Bouguer gravity anomaly map of the Southern Peninsula of Michigan, therefore, represents the total effect due to variations in the 1) lithology, degree of water saturation, and thickness of the glacial drift, 2) lithology, thickness, and structure of the sedimentary rocks, 3) lithology, and structure of the basement rocks, and 4) lithology and thickness of the deeper rock layers. Horizontal density variations may occur and thus gravity anomalies may originate throughout the entire Michigan geological rock column. The source of magnetic anomalies is more limited in the Southern Peninsula of Michigan. The magnetic properties of most rocks are directly dependent on their magnetite content. The source of magnetic anomalies, therefore, is restricted to the glacial drift and the basement igneous and metamorphic rocks, the only formations containing sufficient magnetite for their effects to be measurable at the surface. Possibly sandstones locally contain appreciable quantities of magnetite, but their effect at the surface would probably be negligible. The effect of the magnetite in the glacial drift was largely eliminated in the observational procedure, therefore, the magnetic anomalies reflect variations in the depth to the basement rocks and the lithology of these rocks.

Inasmuch as the anomaly maps are the summation of effects from such a large number of sources, particularly the gravity map, the difficulties of resolving anomalies due to individual sources becomes apparent. Even where it is possible to isolate an anomaly from a single source, it is theoretically impossible to arrive at a unique source for the anomaly on the basis of measurements of a single force field. The geometry--size, shape, and depth--and the variation in the relevant physical property of the anomalous feature may take on an infinite number of variations to account for the anomaly. The only limits are that the causative body is always narrower than the resulting anomaly and that it cannot be deeper than a certain value that can be determined from the anomaly. It is necessary, therefore, in determining the source of an anomaly to place limits upon the interpretation from geological information or the results of other geophysical measurements.

The anomalies mapped in this study, because of the widely separated observation sites, are limited to those originating from major regional features and/or from features that are deeply buried. No attempt was made to map those anomalies directly originating from petroleum reservoir structures. Anomalies on the maps should not be interpreted as representing effects from sedimentary structures without making additional geophysical measurements and detailed quantitative interpretation based upon the limits imposed by the local geology. The anomalies are principally due to regional changes in one or more of the following geological parameters: 1) lithology of the sedimentary rocks of the Michigan Basin; 2) depth to the basement rocks; and 3) lithology of the basement rocks.

Discussion of Selected Anomalies

Disregarding the structure and lithology of the basement rocks, negative gravity and magnetic anomalies would be expected to be associated with the Michigan Basin due to the generally less dense, non-magnetic sediments filling the basin as compared with the enclosing basement rocks. Cohee and Landes (1958) state that the volumes of sedimentary rocks in the Michigan Basin are: carbonate rock, 47%; sandstone, 23%; shale, 18%; and evaporites, 12%. Even considering that the carbonate rock would not contribute to the gravity anomaly, a negative gravity anomaly would be expected. However, this is not the case. In fact the principal anomaly on both the gravity and magnetic maps is a positive anomaly, generally with bordering negative anomalies, extending through the center of the basin (Figures 4, 5, 6, and 7). This anomaly extends from Wayne County northwest to Gratiot County, then west-northwest into Montcalm County, and then due north to Lake

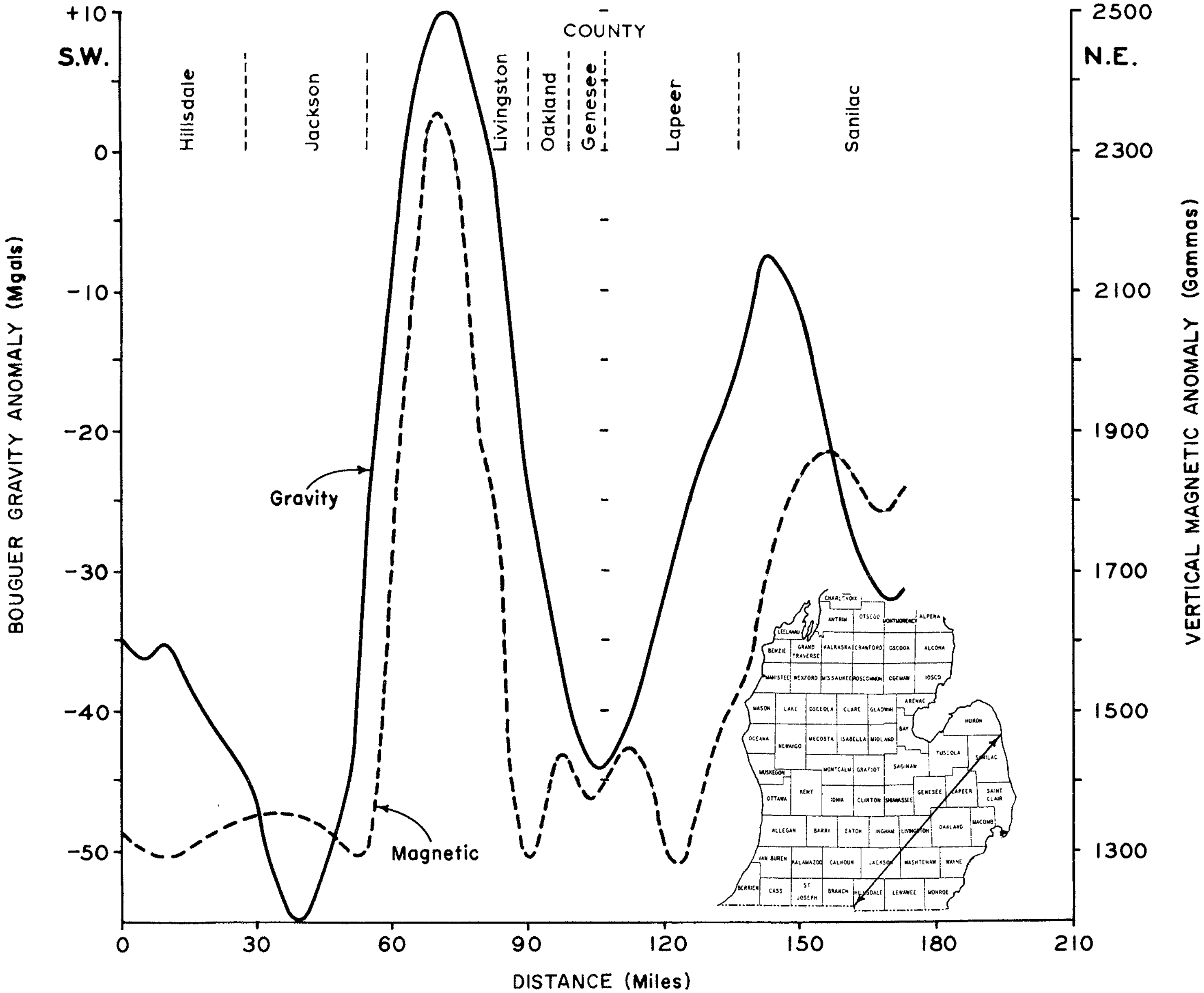

Fig. 4 GRAVITY AND MAGNETIC PROFILE BETWEEN HILLSDALE AND SANILAC COUNTIES

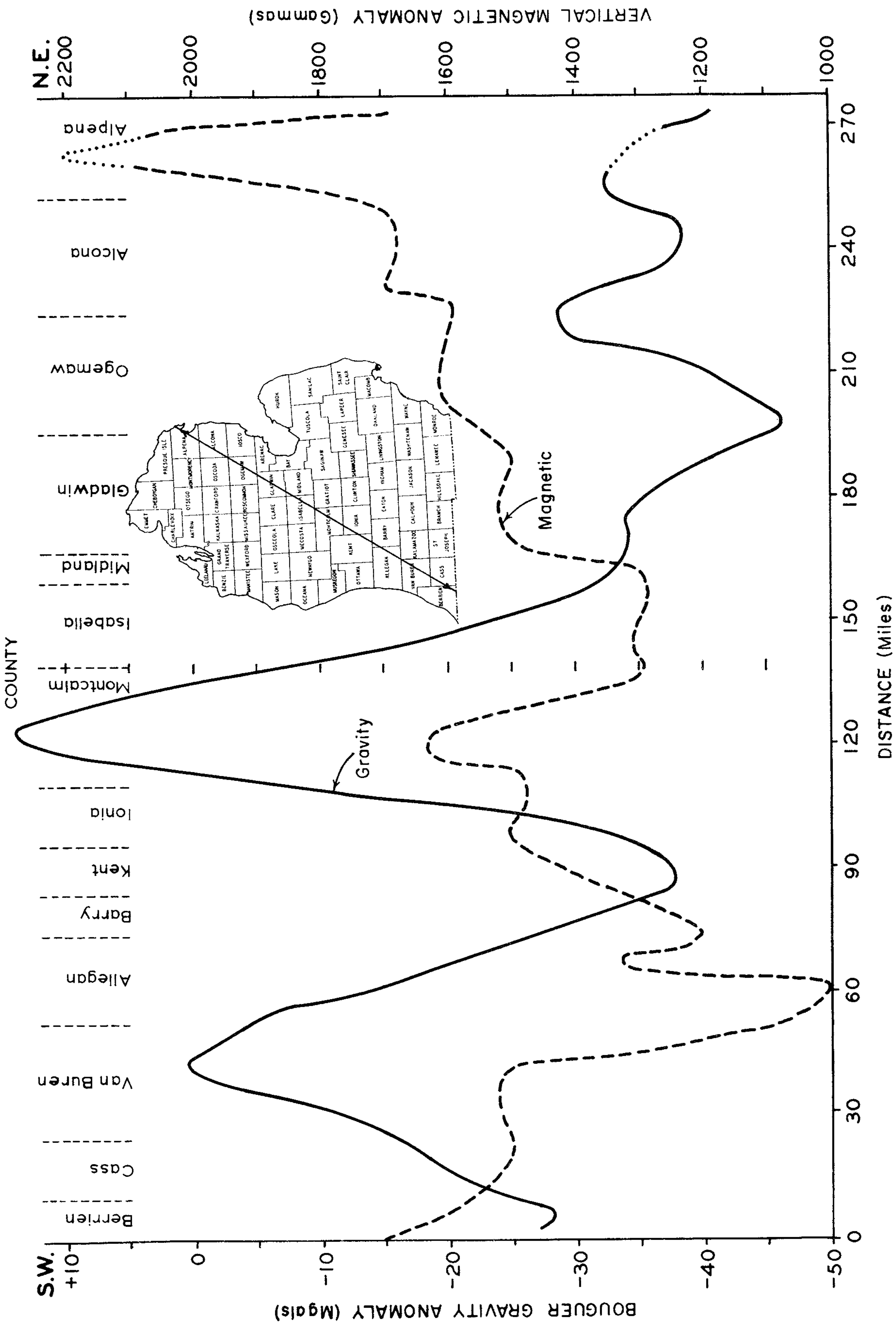

Fig.5 GRAVITY AND MAGNETIC PROFILE BETWEEN BERRIEN AND ALPENA COUNTIES

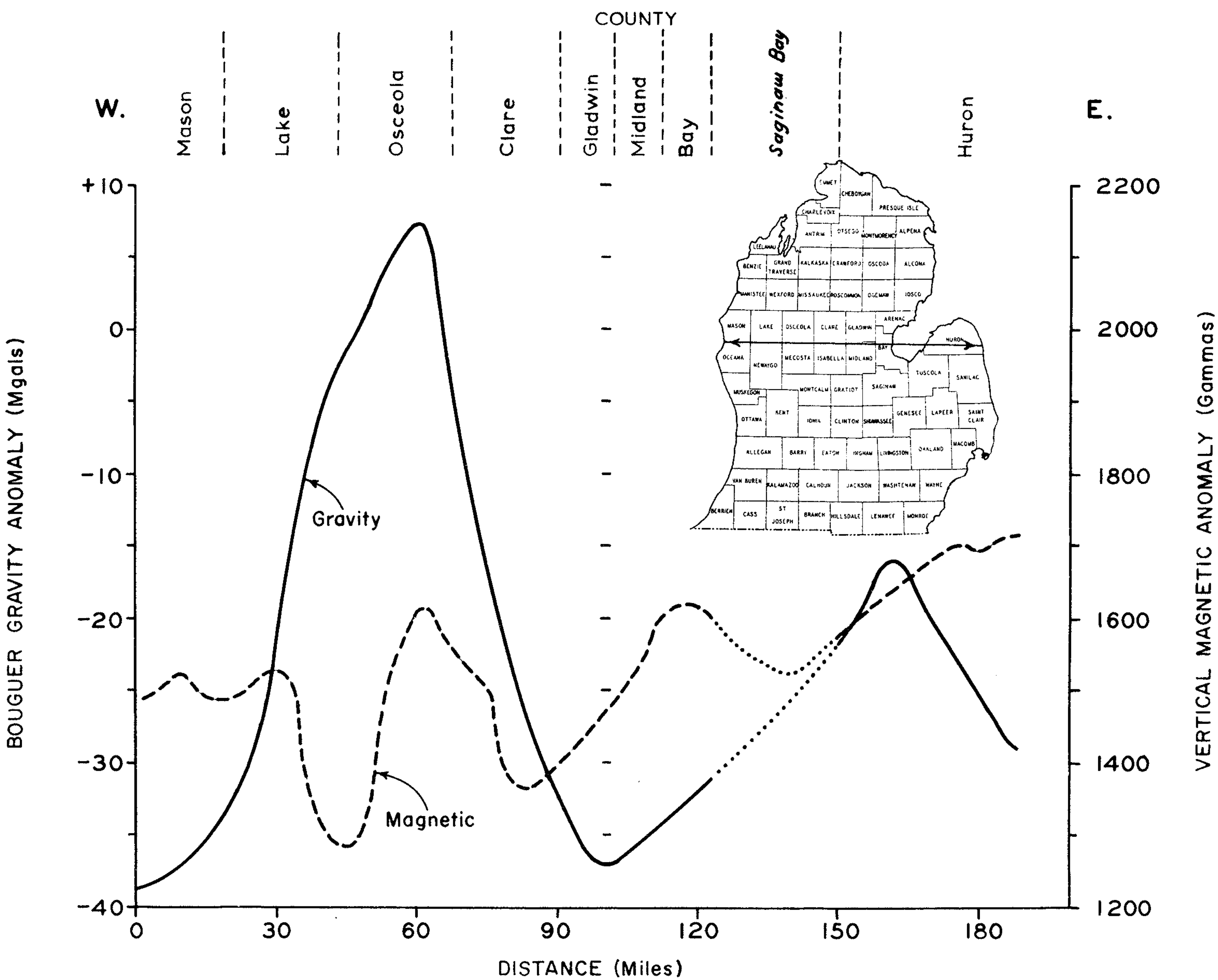

Fig. 6 GRAVITY AND MAGNETIC PROFILE BETWEEN MASON AND HURON COUNTIES

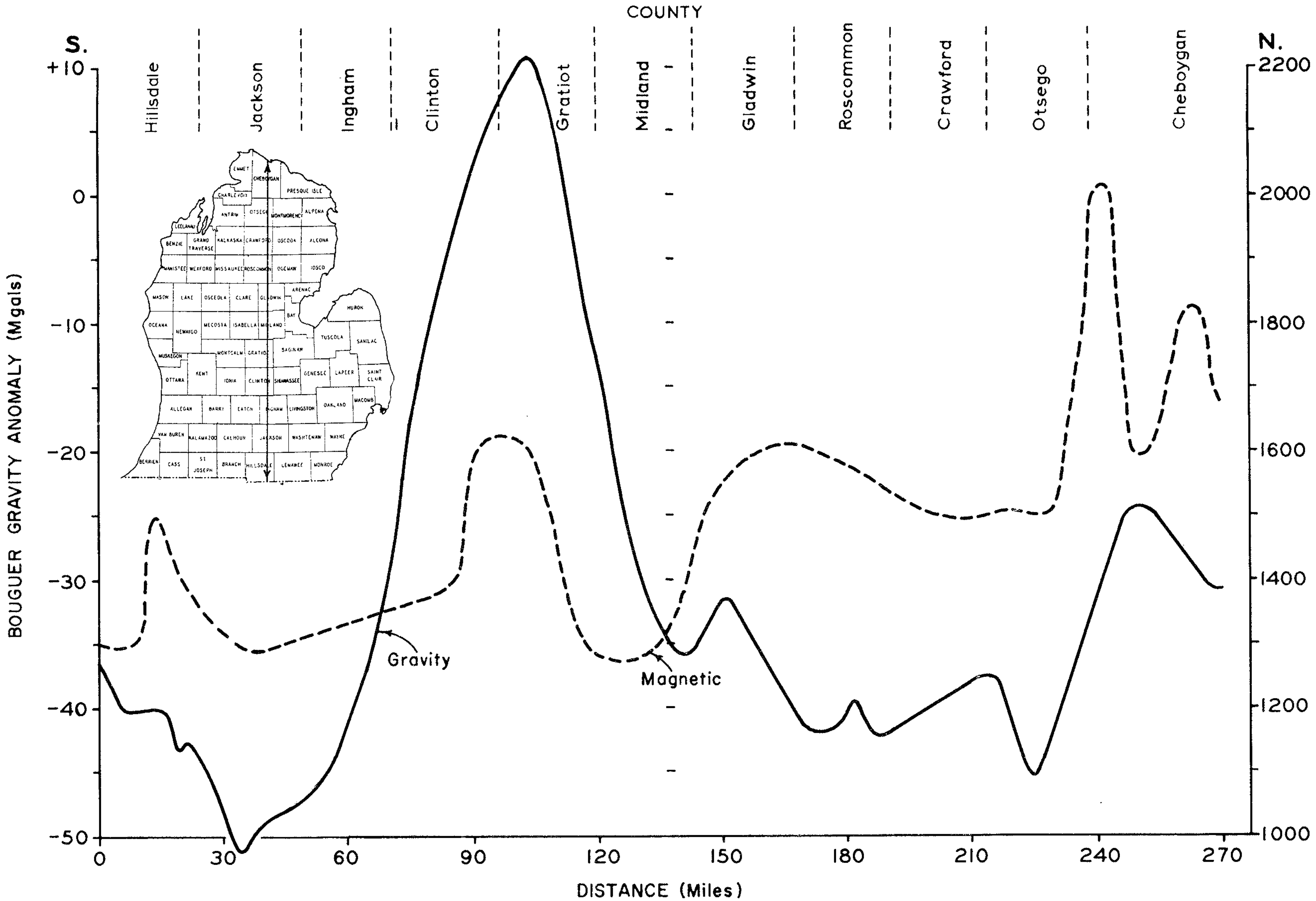

Fig. 7 GRAVITY AND MAGNETIC PROFILE ALONG 84°30′ LONGITUDE

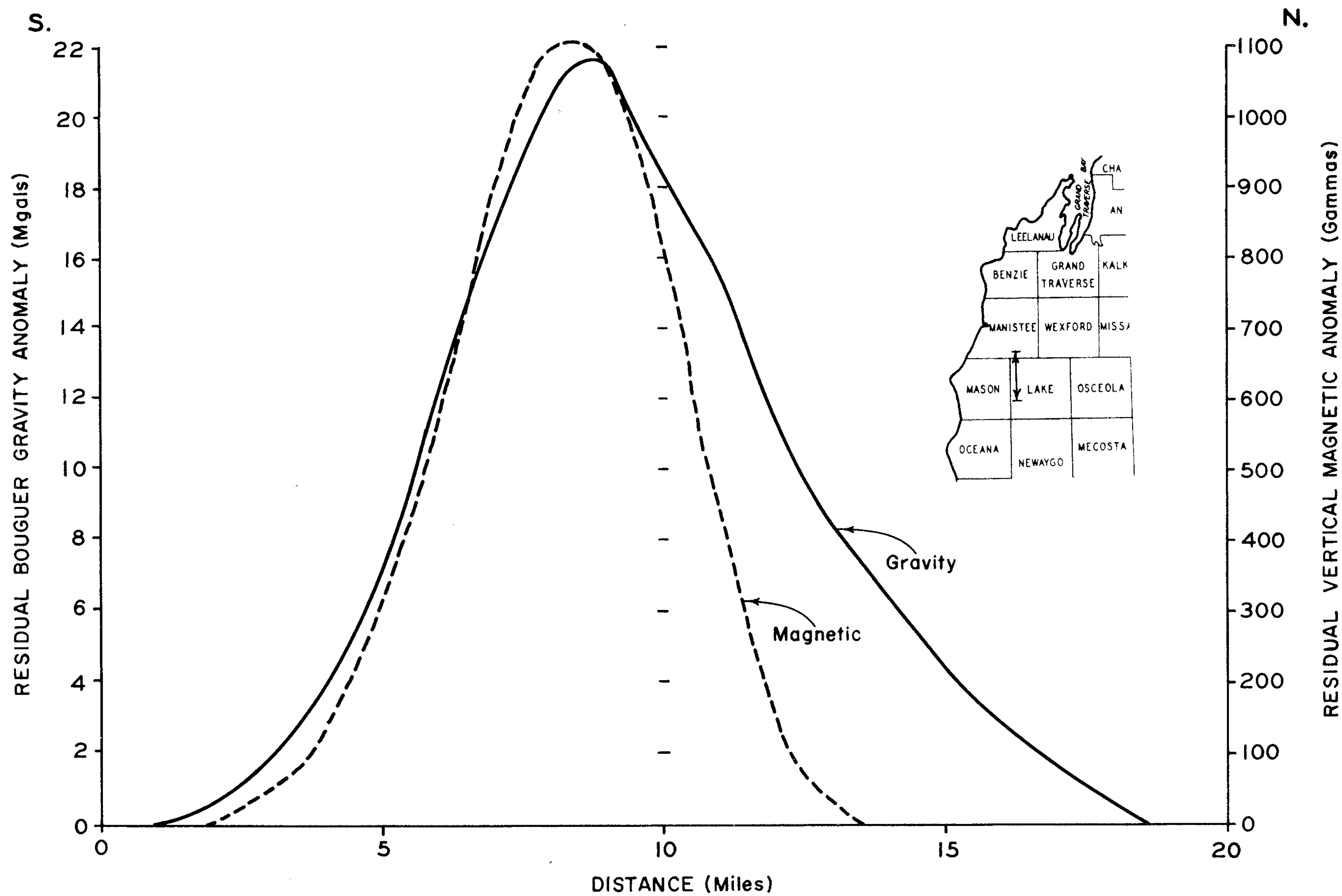

Fig. 8 RESIDUAL GRAVITY AND MAGNETIC PROFILE OF THE SAUBLE ANOMALY, LAKE COUNTY

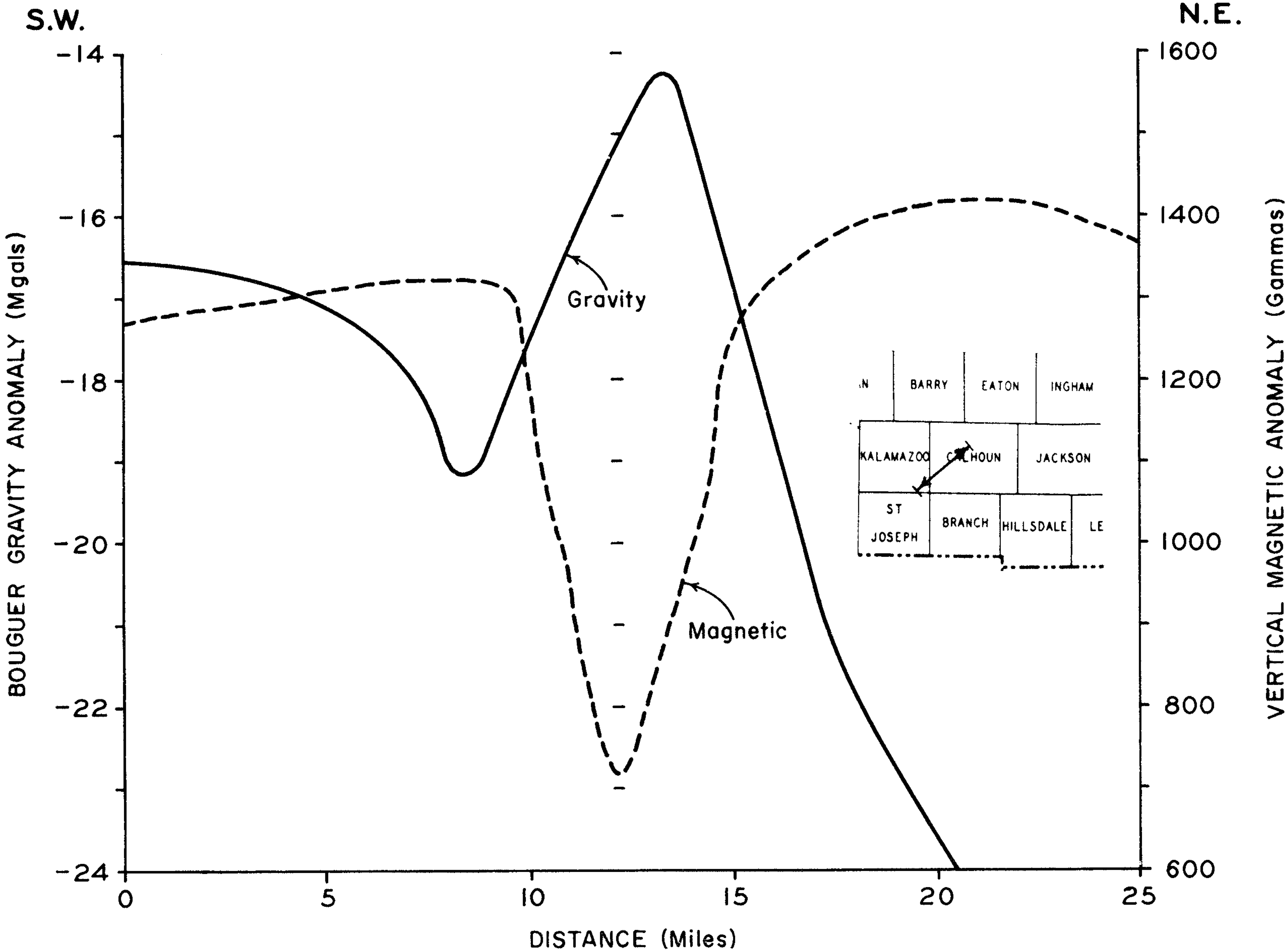

Fig. 9 GRAVITY AND MAGNETIC PROFILE OF THE CALHOUN COUNTY ANOMALY

Michigan. It coincides with the Howell anticline in Livingston County, a major structural feature in the sedimentary formations of the Michigan Basin. The gravity high correlates extremely well with the magnetic high in the southern and central portion of the basin. The magnetic high, however, becomes less distinct in the northern part where it encounters regionally higher magnetic values. The magnitude of the anomalies and the excellent correlation between the gravity and magnetic highs suggest a basic rock in the basement complex as the origin of the anomalies. The manner in which this anomaly cuts other trends extending from adjacent Precambrian areas suggests a late Precambrian age, possibly a Keweenawan age, for the causative mass. This in turn suggests a possible relationship between the Lake Superior geosyncline and the Michigan Basin as advocated previously by Irving (1883), Robinson (1923), and Newcombe (1934). This also points up the possibility of Keweenawan sediments in the Michigan Basin, possibly correlating with the negative anomalies bordering the gravity and magnetic highs. Keweenawan sediments in this area have been postulated by Pirtle (1932) and Newcombe (1934).

The correlation of the positive anomalies with the Michigan Basin opens up the possibility that they may be related and that the Michigan Basin may have originated from isostatic sinking in response to the added mass of the basic rocks in the basement complex. Although a gross simplification of a complicated phenomena, this hypothesis offers a possible explanation for the origin of the Michigan Basin. The form and magnitude of this major gravity and magnetic anomaly is similar to the anomalies of the Mid-Continent gravity high (Black, 1954) extending from Kansas to Lake Superior. It is possible that the Michigan positive anomalies are an extension of this feature. It is also interesting to note that Lyons (1959) has suggested that the basins associated with the Mid-Continent gravity high may have developed by isostatic sinking.

The only major negative gravity anomaly in the Southern Peninsula of Michigan without a corresponding negative magnetic anomaly is centered in Ogemaw County northwest of Saginaw Bay and has a northwest strike. This anomaly correlates very closely both in position and strike to the maximum thickness, 3000 feet, of the Salina group in the Michigan Basin (Burns, 1963). The fact that the Salina group is the principal evaporite formation in the Michigan Basin together with the lack of a negative magnetic anomaly strongly suggests that the gravity anomaly originates from a thickening of the less dense Silurian evaporite deposits. The Devonian evaporite deposits which attain a maximum thickness in the same general area (Landes, 1951) also may contribute to the negative gravity anomaly.

The maximum vertical magnetic intensity anomaly recorded in the Southern Peninsula of Michigan occurs in Lake County associated with a nearly circular positive magnetic and gravity anomaly. These anomalies were studied in detail by Meyer (1963). The residual anomalies have a maximum amplitude of 1130 gammas and 22 mgals. A typical residual gravity and magnetic profile through the center of the anomaly is shown in Figure 8. Geological interpretation of the anomaly indicates that the causative mass is a very basic intrusive stock in the basement rocks and that the depth to the top of the feature is from 8,000 to 9,000 feet below sea level.

An unusual relationship exists between the gravity and magnetic anomalies centered in Calhoun County. A negative magnetic anomaly coincides with a positive gravity anomaly. The magnetic anomaly reaching a maximum amplitude of a negative 700 gammas in Calhoun County, has been traced by detailed magnetic observations almost continuously for 100 miles along a northwest strike. As illustrated in Figure 9 a positive 8 mgal Bouguer gravity anomaly coincides with the maximum magnetic anomaly. The gravity anomaly has not been traced the full length of the magnetic anomaly. The inverse relationship between the gravity and magnetic anomalies is interpreted as due to reversed remanent magnetization of an intermediate composition dike or group of dikes.

This is only a brief discussion of some selected anomalies shown on the Bouguer gravity and vertical magnetic anomaly maps. Several other anomalies warrant detailed field investigation and further quantitative analysis. A more comprehensive, quantitative analysis of these maps is in progress.

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