Department of Natural Resources
Geological Survey Division

STATE OF MICHIGAN
E PLURIBUS UNUM
TUEBOR
SI QUAERIS PENINSULAM AMOENAM
CIRCUMSPICE

MICHIGAN
REFERENCE ROOM
GEOLOGICAL SURVEY
DIVISION
Dept. of Natural Resources

Gravity and Aeromagnetic Anomaly Maps of the Southern Peninsula of Michigan

1971

Report of Investigation 14

The State Geological Survey collects, interprets, and disseminates basic information on the geology and mineral resources of Michigan.

Its activities are guided by public service available to all who are interested in the use or development of our resources, the protection of our environment, and sound land use management.

See page 11 for a list of other publications on geophysics and subsurface geology available from the Geological Survey.

Report of Investigation 14

Gravity and Aeromagnetic Anomaly Maps of the Southern Peninsula of Michigan

WILLIAM J. HINZE*
Department of Geosciences
Purdue University
West Lafayette, Indiana

RICHARD L. KELLOGG*
Department of Physics Luther College
Decorah, Iowa

and

DONALD W. MERRITT*
Merritt Enterprises, Incorporated
East Lansing, Michigan

Lansing 1971

**Formerly associated with the Department of Geology Michigan State University, East Lansing, Michigan*

CONTENTS

ILLUSTRATIONS

Abstract

Mapping and interpretation of gravity and magnetic data from the Southern Peninsula of Michigan reveal numerous anomalies which are primarily related to intra-basement lithologic variations. The dominant gravity and magnetic feature, called the Mid-Michigan anomaly, is interpreted as the geophysical expression of Keweenawan volcanic rocks and disturbances in deep crustal layers associated with a paleo-rift zone. Lines of weakness in basement rock associated with the paleo-rift zone are believed to be the loci for stress relief during Phanerozoic time and thus help explain deformation in overlying sedimentary rocks within the Michigan basin. Other major anomalies are associated with characteristic lithologies and structural trends of basement rock provinces within the basin. An understanding of the anomalies and their relationships to the basement rock provinces provide an insight into the geologic history of the area, and are useful in helping to locate mineral resources within the overlying sedimentary sequence.

INTRODUCTION

During the past decade, the Geophysics Section of the Department of Geology, Michigan State University, has maintained a continuing research program dealing with the problems of petroleum exploration within the Michigan basin. The major thrust of this program has been in the application of gravity and magnetic methods of geophysical exploration. An important aspect of the program was the mapping of the gravity and magnetic fields of the Southern Peninsula of Michigan on a regional basis. This report presents Bouguer gravity and total magnetic intensity anomaly maps of these fields, and summarizes information concerning their preparation and general geological significance.

The gravity and magnetic anomaly maps are strongly affected by the lithology, structure, and depth of the basement igneous and metamorphic complex. Thus, they may be used to study the tectonic framework and configuration, as well as the Precambrian geological history, of the basement complex. Direct geological information on these topics is scarce because of the absence of basement outcrops and the paucity of deep well drilling within the basin. These maps may also be used to study the correlation of regional gravity and magnetic anomalies with major structures within the sedimentary sequence of the Michigan basin. Furthermore, the maps can be used to localize detailed geophysical surveys for intensive study of specific features of the basement complex.

This report updates and replaces a previous report (Hinze, 1963) published by the Michigan Geological Survey in 1963. That report, now out-of-print, contained regional gravity and magnetic maps of the Southern Peninsula along with data on their preparation and general significance. Subsequent gravity surveys have not modified the regional Bouguer gravity anomaly map presented in the 1963 report. Therefore, that version of the map is republished unchanged as Plate 1. The regional magnetic map published in the 1963 report was based on a ground vertical magnetic intensity survey with stations located on roughly a six-mile grid. That map has now been superseded and replaced by one prepared from a peninsula-wide aeromagnetic survey of the total intensity of the earth's magnetic field. Observations were made at approximate one-eighth mile intervals along north-south flight tracks spaced at three-mile separations. The new map, Plate 2, is superior to the previously published map by virtue of the higher observation density and the elimination of magnetic effects from surface materials and cultural features. Near surface magnetic effects are negligible because the level of observation during the survey was roughly 2,400 feet (3,000 feet above M.S.L.) above the ground surface.

Some portions of the 1963 report are duplicated in this report because of the overlap in objectives and the inclusion of the 1963 version of the Bouguer gravity anomaly map. No attempt has been made to present a detailed geological interpretation of the gravity and magnetic maps. Interpretations of this type have been made by students and staff of the Geophysics Section, Department of Geology, Michigan State University. They may be found in graduate theses of the Department and in other publications.

ACKNOWLEDGMENTS

The preparation of the regional gravity and magnetic anomaly maps has been made possible through the generous assistance of many organizations and individuals. Sincere appreciation is due the following organizations for the loans or gifts of equipment, contributions of data, and the granting of operating funds: Beard Instrument Company, Consumers Power Company, Humble Oil and Refining Company, Jones and Laughlin Steel Company, Leonard Refineries, Inc., McClure Oil Company, Michigan Consolidated Gas Company, Michigan State University All-University Research Fund, Miller Brothers, Mobil Oil Company, Muskegon Development Company, Marathon Oil Company, Pan-American Petroleum Company, Shell Oil Company, Sun Oil Company, Union Oil Company, and others who prefer to remain anonymous.

This study was performed by students of the Geophysics Section, Department of Geology, Michigan State University under the direction of the staff. The success of the study is directly attributable to the students1 intense interest, untiring effort, and ability. The following students have participated in the field and office phases of the program:

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

Special acknowledgments are made to Dr. C. E. Prouty, former chairman of the Department of Geology, Michigan State University, for his support of this program and to Harold M. McClure, Jr., president of the McClure Oil Company, for his continued direct encouragement of the study.

PREVIOUS STUDIES

Little gravity information has been published about 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 Bouguer Gravity Anomaly Map of the United States (Woollard and Joesting, 1964) shows the regional ten milligal (mgal) anomaly contours of Michigan based at least in part on data used to prepare the gravity map of this report. In addition, numerous local gravity maps and profiles associated with petroleum structures within the state have been published in technical journals. Hinze and Merritt (1969) have discussed the geological implications of the gravity and magnetic maps of the Southern Peninsula, particularly as they relate to the basement complex. Thiruvathukal (1963), Meyer (1963), Lowden (1964), Klasner (1964), Roth (1965), Servos (1965), Keith (1967), Merritt (1968), Peebles (1969), and Ibrahim (1970) have presented gravity anomaly maps of various portions of the state and discussed their geological implications in unpublished graduate theses of the Department of Geology, Michigan State University.

Previously published magnetic studies of the Southern Peninsula of Michigan include Jenny's (1934) magnetic vector study of portions of the peninsula, Hinzefs (1963) vertical magnetic intensity study of the Southern Peninsula, and Patenaude's (1964) aeromagnetic survey of the central portion of the Michigan basin. Unpublished graduate theses dealing with magnetic investigations of portions of the Southern Peninsula are: Hunt's (1952), Kinder's (1954) and Behren's (1958) theses at the University of Michigan, and Brett's (1960), Meyer's (1963), Stevenson's (1964), Shaw's (1971) and Kellogg's (1971) theses at Michigan State University. Kellogg's thesis gives an in-depth analysis of the basement geology of the Southern Peninsula based on the aeromagnetic map presented in this report.

THE GRAVITY SURVEY

Instrumentation

Three exploration type gravimeters, capable of being read to the nearest 0.01 mgal, were used in this study. 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. The meters 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.

Survey Procedure

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. Approximately 2500 gravity observations were used in the final preparation of the Bouguer gravity anomaly map. In addition, detailed maps of certain areas were available as an aid in contouring.

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. Also, 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 the survey.

Reduction of Data

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 absolute gravity through observations at base stations which were tied by repeated observations to a primary gravity base. The primary base 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-Astronomy Building, formerly the Physics and Math Building. The observed gravity of this station is 980.3498 gals with an error of no greater than +0.1 mgal. The adjusted values were then converted into gravity units, milligals, by multiplying by the calibration constant of the gravimeter. The calibration constants of the meters were checked against each other and were found to agree with the values provided.

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, which is:

$$g\varphi = 978.049\ (1+0.0052884\sin^2\varphi) - 0.0000059\sin^2\varphi)$$

where $g\varphi$ 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. The 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 the elevation of the station. The gravity anomaly map accompanying this report (Plate 1) was prepared by employing a density of 2.67 g/cc. The combined correction constant for this density is 0.06 mgals per foot. A density of 2.67 g/cc was assumed so that this map would be consistent with other regional maps which are generally prepared by 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) by using the corrections previously discussed. The equation used in the calculation is:

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

Accuracy: The accuracy of the Bouguer gravity anomaly 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 which were 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. Only 12 percent of the stations of the survey have barometric altimeter elevations. For a Bouguer reduction density of 2.67 g/cc 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 ranged from 580 to 1380 feet, a span of 800 feet. Thus, the Bouguer anomaly values of the stations at the higher elevations may be as much as 6 mgals too low. This source of error cannot be eliminated until data are obtained on the distribution and density of the entire geologic sequence and the glacial drift of the Southern Peninsula.

THE MAGNETIC SURVEY

Instrumentation

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 Company, Oxford, England. The instrument measures the reciprocal of the frequency of precession of protons contained in a bottle of water. The frequency of precession is directly proportional to the total intensity of the ambient earth's magnetic field. This reciprocal reading magnetometer is provided with analog recording facilities in the form of a chart recorder. The instrument has a sensitivity of approximately three gammas. As used in this survey, observations were made at a rate of about eight per mile. The electronics package and recorder were installed in a Cessna 182 single engine aircraft and the sensing unit, contained in an aerodynamically stabilized housing, was trailed approximately 100 feet behind the aircraft during flight operations. For a complete description of the principle of the reciprocal reading proton precession magnetometer the reader is referred to P. Hood (1969), Magnetic Survey Instrumentation - A Review of Recent Advances.

Survey Procedure

Magnetic observations were made at a constant barometric elevation of 3000 feet above sea level along north-south flight lines spaced at three mile intervals over the entire Southern Peninsula. Data from approximately 17,000 miles of north-south traverses were used in the preparation of the aeromagnetic map (Plate 2). An additional 4000 miles of data were recorded along six east-west traverses spaced at approximately 50 mile intervals. These data were used to tie together the data observed along the north-south traverses.

Navigation was accomplished by visual fixes on cultural and natural features which were keyed and labeled on the magnetic chart and noted on maps for later data compilation. Navigational fixes were established at approximately five mile intervals along the flight track. Study of repeatedly flown test traverses indicated that the error in the positioning of the aircraft along the traverse was no greater than 600 feet. The error in positioning perpendicular to the marked flight track is difficult to evaluate because of the visual navigation procedure, but it is estimated to be of the same order as the error along the traverse. Locally, within the northern portion of the survey area, limited cultural features necessitated a combination of dead-reckoning and sighting on natural features such as the shorelines of lakes to establish the traverse position. As a result, actual flight tracks may have deviated from the intended straight line traverses and errors in navigation are anticipated because of unknown variations in airspeed and wind direction between navigational fixes.

Time or "diurnal" variations in the earth's magnetic field were eliminated by using data obtained from the east-west control traverses and by repeated flights over established test traverses. High gradient, large amplitude time variations known as magnetic "storms" are impossible to eliminate from observed aeromagnetic data. Therefore, flights were discontinued during the "storm" periods. Notification of impending "storm" activity was received from the Space Disturbance Laboratory of the ESSA Research Center at Boulder, Colorado. In addition, the flight crew monitored the magnetic field on the ground for several minutes prior to commencing flight operations. Only six hours of flight operations, out of 250 total hours, had to be repeated because of traverses run during severe magnetic disturbances.

Reduction of Data

Essentially all the steps in the processing of the aeromagnetic data, from compilation of the data to the final contouring of the total magnetic intensity anomaly map, were performed with the digital computer. A series of computer programs were thus developed to process the data. Initially, the magnetograms were machine digitized and the relative position of the navigational fixes of each flight line were flagged in the digitized data. The navigational fixes positioned on maps were hand digitized and these coordinates were then converted to latitude and longitude by use of a suitable computer program. After adequate checks had verified the accuracy of both the machine and hand digitization processes, the two sets of data were merged and the reciprocals of the frequency of precession of protons in the earth's magnetic field, obtained from the magnetograms, were then converted to the total intensity of the earth's magnetic field in gammas. Each digitized value of the magnetogram was assigned a latitude and longitude by linear interpolation between the adjacent navigational fixes of the flight line.

Time or "diurnal" variations in the magnetic field occurring during the observation of the data of the survey were determined from a control net of doubly flown east-west flight lines tied together with a doubly flown north-south flight line in the center of the state. Total magnetic intensity values corrected for time variations were assigned to critical navigational fixes on each traverse separated by no more than thirty minutes of flying time. Corrections were applied to all data points by using linear interpolation of distance between successive critical navigational fixes.

The next step in the reduction process was calculation of the total magnetic intensity anomaly by eliminating the normal variation of the earth's magnetic field from the corrected total magnetic intensity values. The total intensity of the earth's normal magnetic field was calculated at 3000 feet above sea level for September, 1968 (the approximate mid-point of the data collection), by using a computer program developed by Cain, et al. (1968). The program, which is based on eight degrees of spherical harmonic expansions of the geomagnetic potential, used a series of coefficients determined by Daniels and Cain (1964) to calculate the normal geomagnetic field at each data point. The calculated normal field, illustrated in Figure 1, was subtracted from the data points to obtain the total magnetic intensity anomaly values. These values were then blocked into sets of data of convenient size for computer processing. After a final check of the data, the total magnetic intensity anomaly map was machine contoured by using a machine contour package developed by California Computer Products, Incorporated. Additional details of the magnetic data reduction process have been published by Kellogg (1971).

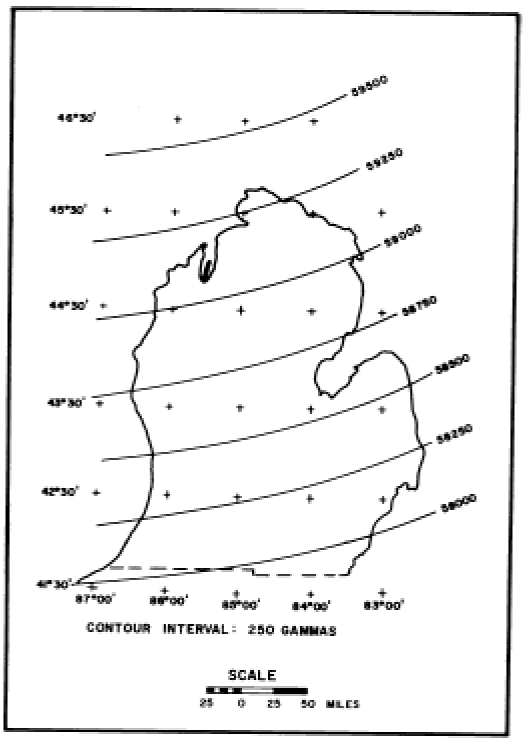

Figure 1. Normal Geomagnetic Field of the Southern Peninsula of Michigan

GEOLOGICAL SIGNIFICANCE OF ANOMALY MAPS

Source of Anomalies

The gravity and magnetic anomaly contour maps, Plates 1 and 2, are also shown as machine drawn relief models as seen along a N.30°W. line of sight at an inclination of 45° (Figures 2 and 4). These maps and models are pictorial representations of geological conditions. They illustrate 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. Magnetic susceptibility and remanent magnetization are the pertinent physical properties in magnetics.

The anomaly values are the summation of all departures from horizontally homogeneous physical properties within the subjacent earth. The effect of individual geologic features at a point on the surface of the earth is a complex function of the distance to the feature, both horizontally and vertically, the size and configuration of the source, and the physical property contrast between the feature and the surrounding formations. As a result, the gravity and magnetic maps consist of a complex array of anomalies, commonly overlapping, which are derived from a variety of geological sources.

Sources of gravity and magnetic anomalies within the Michigan basin, and their respective anomalies for a hypothetical basin similar in gross characteristics to the Michigan basin, are shown in Figures 3 and 5. The size, depth, configuration and physical properties of the anomaly sources are representative of the geology of the Michigan basin. Sources of gravity anomalies indicated in Figure 3 are the overall effect of the basin, bedrock topography, sedimentary structure, basement topography, and basement lithology. Additionally, short wavelength and low amplitude anomalies are caused by density contrasts within the glacial drift and long wavelength anomalies of variable amplitude are produced by regional facies changes within the sediments, deep crustal or upper mantle density contrasts, and variable thickness crustal layers.

The broad negative gravity anomaly associated with the basin reflects the lower density of the sedimentary rocks in comparison to the underlying basement rocks. The density assigned to the basement rocks is typical of densities encountered in the igneous and metamorphic complex of the Precambrian Shield where it outcrops to the north. The density of the sediments is based on the results of measurements made on an 1100 foot vertical section of the sedimentary rocks within the basin by Secor, et al. (1963). Gravity anomalies derived from bedrock topography and sedimentary structures such as reefs and fracture zones have short wavelengths and positive and negative amplitudes of less than one mgal and are commonly less than 0.5 mgal. The station spacing of the gravity survey is too great to map anomalies derived from these sources. Gravity anomalies arising from relief of the basement surface vary considerably in wavelength and amplitude. But, as shown in Figure 3, these anomalies will be less than five mgals in amplitude, except for those derived from the largest magnitude basement relief. The largest amplitude anomalies, and thus those that dominate the gravity anomaly map, are derived from intra-basement lithologic variations. The effect of depth (to the top of the source) on the amplitude and gradients of gravity anomalies is well illustrated in Figure 4. The effect can be further seen by observing the anomalies, caused by the same source, positioned at 50 and 100 miles. The top of the source is 4000 feet deeper for the anomaly centered at 100 miles.

The effect of basement lithology on magnetic anomalies as illustrated in Figure 5 is even more striking than in the case of gravity. The sources of anomalies are primarily the effect of gross basin configuration, basement topography, and intra-basement lithologic variations. But, assuming a primarily granitic basement, the magnetic effect of the basin is negligible in terms of the mapped magnetic anomalies. The magnetic effect of basement topography is an order of magnitude less than the effect of basement lithology. Thus, the primary sources of major gravity and magnetic anomalies within the Southern Peninsula of Michigan are intra-basement lithologic variations.

The effect of depth to the top of anomalous bodies on the amplitude and gradients of magnetic anomalies is also illustrated in Figure 5, as shown by the differences in the anomalies positioned at 50 and 100 miles. These anomalies are derived from the same source, but the top of the source is 4000 feet deeper at the anomaly located at 100 miles. The amplitude and gradients of the anomaly from the deeper source are less, in fact considerably less than the relative change in the gravity anomalies from these two sources as shown in Figure 3. This illustrates the greater sensitivity of magnetic anomalies to depth. It is also significant in Figure 5 to note that magnetic minimums are associated with positive anomalies. These minimums are caused by the dipolar nature of the magnetic phenomenon. In the absence of remanent magnetism the relative position, amplitude, and areal extent of the minimums with respect to the positive anomalies are a complex function of the geometry and depth extent of the sources and the inclination of the earth's magnetic field. Steeply dipping magnetic bodies in Michigan are marked by magnetic maximums displaced somewhat to the south of the center of the source body, and relatively much weaker minimums to the magnetic north.

Interpretation of the principal gravity and magnetic anomalies in terms of their sources and intra-basement lithologic variations involves reversing the procedure used in preparing Figures 3 and 5. The configuration, depth, and lithology of causative bodies, for example, are determined from the observed anomalies. This is a difficult process, and has a double source of ambiguity, because the physical property contrasts are uncertain and little is generally known about the configuration of the causative bodies. Even when it is possible to assign a configuration to a source of an anomaly from geologic knowledge and the characteristics of the anomaly, the calculated physical property contrast does not lead directly to the lithology because the densities and magnetic susceptibilities of rocks generally overlap. The problem may be further complicated by improper isolation of the gravity and magnetic anomalies from the regional background. The inability to uniquely isolate an anomaly for the analysis greatly decreases the value of the interpretation. Interpretation may be further complicated by remanent magnetic polarization which may drastically alter the intensity and direction of magnetic polarization. As a result lithologies which, on the basis of their magnetic susceptibility, are expected to produce magnetic highs, may cause magnetic lows or highs.

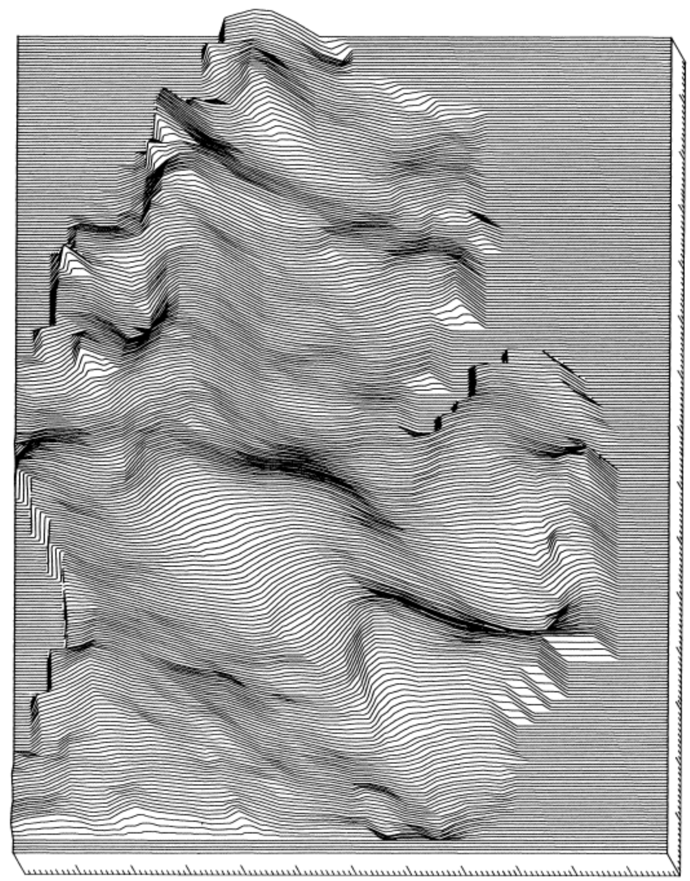

Figure 2. Relief Model of the Bouguer Gravity Anomaly Field of the Southern Peninsula of Michigan as Observed Along a Line of Sight of N 30° W and an Inclination of 45°.

In spite of the difficulties of relating specific lithologies to gravity and magnetic anomalies, certain generalizations are possible in interpreting the gravity and magnetic anomaly maps of the Southern Peninsula. These generalizations are based upon correlation of gravity and magnetic anomalies with mapped geology of the adjacent Precambrian Shield. Mafic intrusives and extrusives are generally associated with positive gravity and magnetic anomalies. Locally, however, both mafic intrusives and extrusives may produce negative magnetic anomalies due to remanent magnetism. Granite intrusives commonly cause negative gravity anomalies and either negative or positive magnetic anomalies, depending on the nature of the country rock. Granitic belts and highly altered gneisses correlate with magnetic and gravity positives. Relatively weakly metamorphosed sedimentary-volcanic belts and low grade gneisses are generally associated with magnetic and gravity minimums. These general regional relationships are useful as a starting point in mapping basement lithology from gravity and magnetic anomaly maps. But they must be used cautiously because of possible exceptions and because the source of the anomalies, particularly in the case of the gravity anomalies, may be deep-seated and thus do not reflect the basement surface lithology.

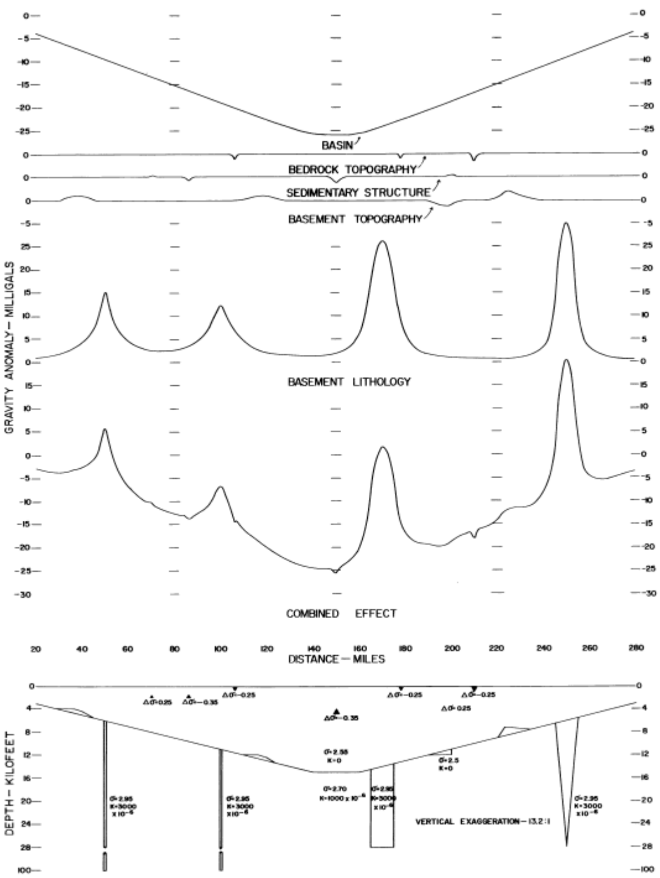

Figure 3. Theoretical Gravity Anomalies from a Simulated Michigan Basin

Hinze and Merritt (1969) used these principles to prepare a regional basement lithology map of the Southern Peninsula from the Bouguer gravity anomaly and vertical magnetic intensity anomaly maps. They, and Kellogg (1971), also used this information together with anomaly characteristics and the extrapolation of known basement geology by geophysical anomalies to prepare a basement province map of the Southern Peninsula. The basement province map also shows predominant basement structural trends. Four basement provinces are recognized, each with its characteristic lithologies and structural trends.

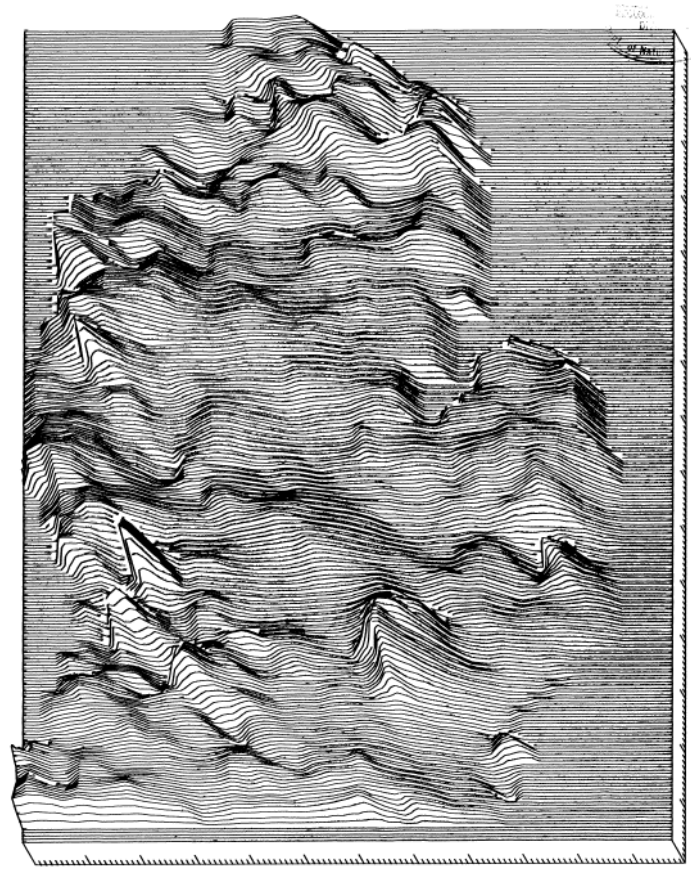

Figure 4. Relief Model of the Total Magnetic Intensity Anomaly Field of the Southern Peninsula of Michigan as Observed Along a Line of Sight of N 30° W and an Inclination of 45°.

DISCUSSION OF SELECTED ANOMALIES

Consideration of the sources of gravity anomalies within the Southern Peninsula of Michigan suggests that the Bouguer gravity map (Plate 1) should show a broad gravity minimum associated with the sedimentary rocks of the Michigan basin. This is not the case, however. Instead, the gravity map is dominated by a positive gravity anomaly called the Mid-Michigan anomaly, extending across the peninsula from Wayne County in the southeast to Grand Traverse Bay in the northwest. South of 44° North latitude, a positive magnetic anomaly (Plate 2) coincides with the gravity anomaly, thus confirming an origin due to intra-basement lithologic variations. North of 44° North latitude, the amplitude of the magnetic anomaly decreases and the anomaly is lost in a regionally higher magnetic level. In the Grand Traverse Bay region the magnetic anomaly associated with the Mid-Michigan anomaly becomes negative, thus suggesting remanent magnetic polarization effects in the basement rocks. The Mid-Michigan anomaly has been shown to connect, geophysically, with the Mid-Continent gravity high through Lake Superior. It has been interpreted by Hinze and Merritt (1969) as having its source in a Keweenawan paleo-rift zone which is expressed locally as a basalt trough, and generally as a disturbance of the deep crustal layers by intrusion and upwarp. The gravity and magnetic minimums flanking the Mid-Michigan anomaly south of about 43°30' North latitude have been explained by Hinze and Merritt (1969) and Kellogg (1971) as originating primarily from downwarp of deep crustal layers.

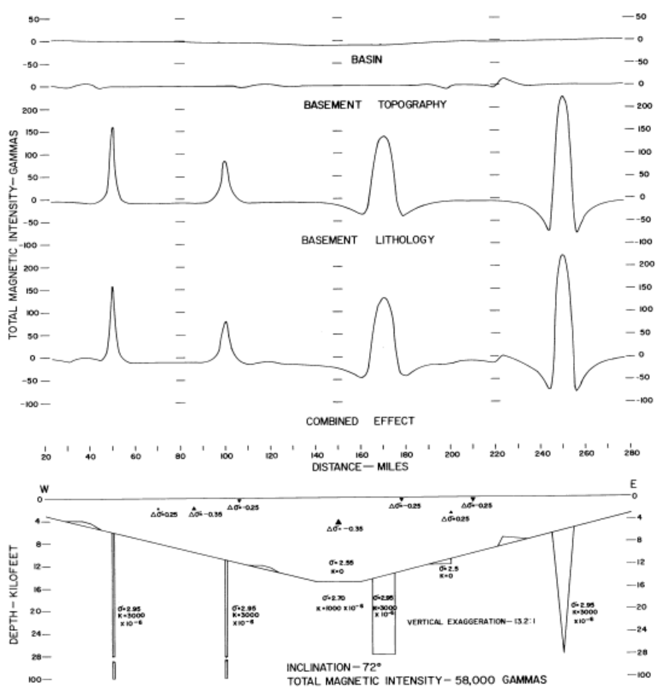

Figure 5. Theoretical Magnetic Anomalies from a Simulated Michigan Basin.

The signs of the gravity and magnetic anomalies of the Southern Peninsula are in general, directly related. One exception is the major negative gravity closure centered around 44°15' North and 84°15' West in Ogemaw County and associated with a broad magnetic positive. The gravity minimum may originate from thickening of Silurian and Devonian evaporites as previously discussed by Hinze (1963). It may also be caused, in part, by a depression of the Precambrian surface which resulted in an increased thickness of Cambrian sediments as was encountered in the Brazos, et al. No. 1 State-Foster well (Sec. 28, T.24N., R.2E.) in northern Ogemaw County. Another major exception to the direct relationship in anomalies is the broad positive gravity anomaly transecting the southwestern part of the peninsula. Except for the northern part of this anomaly, only occasional positive magnetic anomalies occur along this gravity positive. Hinze and Merritt (1969) suggested that this anomaly may be associated with a paleo-rift zone and related disturbances of deep crustal layers. Still another prominent exception is the linear, magnetic minimum which attains maximum amplitude in Calhoun County. This anomaly, which corresponds at least in part with a positive gravity anomaly, has been discussed by Hinze (1963) and ascribed to a dike or swarm of dikes in the basement rock.

Particularly strong local magnetic anomalies occur in northwestern Lake County and central Kent County. The Lake County anomaly, which correlates with a gravity high, was studied by Meyer (1963). He concluded that the source of the anomaly is a mafic intrusive stock in the basement. The amplitude of the Kent County magnetic anomaly is similar to the Lake County anomaly, but the gravity anomaly is only one-tenth as large. As a result, Stevenson (1964) concluded that the source of the Kent County anomaly is probably mafic extrusives with strong remanent magnetic polarization and an associated feeder pipe.

The role of the basement rock in the origin of structures within the sedimentary rocks of the Michigan basin has been the subject of considerable discussion. The gravity and magnetic maps, which to a large degree reflect basement geology, provide an opportunity to evaluate this role. Furthermore, these maps may be used to locate unknown structures within the Michigan basin. The dominant trend of the anticlinal structures and faults in the Paleozoic rocks of the basin is northwest-southeast. The magnetic anomalies, and particularly the gravity anomalies, exhibit a marked northwesterly trend south of 44°30' North latitude and closely parallel the trend of the intra-basin structures. The most conspicuous example is the association of the Howell anticline with the Mid-Michigan anomaly. It is reasonable to conclude, therefore, that the dominant northwesterly intra-basin structural trend reflects lines of weakness in the basement, perhaps associated with the rift zone interpreted as the source of the Mid-Michigan anomaly. Rejuvenation of movement along these zones of weakness during the sinking of the basin, or by externally applied stress fields, may have caused the basin structures. Other structures may be related to basement surface relief, developed over particular lithologies or in association with structures. Rudman, et al. (1965) gave examples of this from the Midwest.

Coons, et al. (1967) found that the occurrence of Paleozoic structures along lines of weakness associated with the Mid-Continent gravity high is common. Thus, by analogy and evidence of the trend of structures in the Michigan basin, undiscovered folds and faults which are not reflected in the upper Paleozoic formations may occur along the Mid-Michigan anomaly.

The prolific Albion-Scipio oil field strikes northwest through Hillsdale, Jackson and Calhoun Counties for more than 35 miles, and has an average width of less than one mile.

Ells (1962) has speculated that the linear trend of the field is controlled by slight lateral movement along a basement fault. Basement control for this linear, fracture zone feature is also suggested by Rudman, et al. (1965) on the basis of regional gravity anomaly trends. Merritt (1968) has noted a marked change in the regional gravity gradient at the Albion-Scipio oil field. He relates this change to basement topographic relief along a fault in the basement complex, the fault having been reactivated in Paleozoic time. Movement along the fault caused fracturing of the overlying competent rocks, thus leading to the present structure of the field.

The foregoing brief discussion of the possible significance of a few major gravity and magnetic anomalies was not meant to be comprehensive. The main intent was to show how the published anomaly maps can be used to provide information on the geological history of the Southern Peninsula of Michigan, and how the data may be used as an aid in locating new economic mineral deposits such as gas and oil.

REFERENCES

Behrendt, J. D., and Woollard, G. P., 1961, An evaluation of the gravity control network in North America: Geophysics, v. 26, no. 1, p. 57-76.

Behrens, E., 1958, An extension and re-interpretation of a regional magnetometer survey of part of southeastern Michigan: Unpublished M. S. thesis, University of Michigan, Ann Arbor.

Brett, J. W., 1960, A vertical magnetic intensity survey of a portion of south-central Michigan: Unpublished M. S. thesis, Geol. Dept., Michigan State University, East Lansing.

Cain, J. C., Hendricks, S., Daniels, W. E., and Jensen, D. C., 1968, Computation of the main geomagnetic field from spherical harmonic expansions: NASA Data Users Note NSSDC 68-11, 45 p.

Coons, R. L., Woollard, G. P., and Hershey, G., 1967, Structural significance and analysis of Mid-Continent gravity high: Am. Assoc. Petroleum Geologists Bull., v. 51, no. 12, p. 2381-2399.

Daniels, W. E., and Cain, J. C., 1964, An evaluation of the spherical harmonic coefficients for the geomagnetic field (abs.): Trans. Am. Geophys. Union, Vol. 45, p. 39.

Dobrin, M. B., 1960, Introduction to Geophysical Prospecting: McGraw-Hill Book Company, N.Y., 446 p.

Ells, G. D., 1962, Structures associated with the Albion-Scipio oil field trend: Michigan Geol. Survey, 86 p.

Hinze, W. J., 1963, Regional gravity and magnetic anomaly maps of the Southern Peninsula of Michigan: Michigan Geol. Survey, Rept. Inv. 1, 26 p.

Hinze, W. J., and Merritt, D. W., 1969, Basement rocks of the Southern Peninsula of Michigan: Michigan Basin Geol. Soc. Guidebook, Studies of the Precambrian of Michigan, ed. H. B. Stonehouse, p. 28-59.

Hood, P., 1969, Magnetic surveying instrumentation - a review of recent advances: Geol. Survey of Canada Rept. 26, Mining and Groundwater Geophysics, ed. L. W. Morley, p. 3-31.

Hunt, H. B., 1952, A regional magnetometer survey of the Pinckney area, Michigan: Unpublished M. S. thesis, University of Michigan, Ann Arbor.

Ibrahim, Abdedwahid, 1970, The application of the gravity method to mapping bedrock topography in Kalamazoo County, Michigan: Unpublished Ph.D. thesis, Geol. Dept., Michigan State University, East Lansing.

Jenny, W. P., 1934, Magnetic vector study of Kentucky and southern Michigan: Am. Assoc. Petroleum Geologists Bull., v. 18, no. 1, p. 97-105.

Keith, Warren E., 1967, A gravity study of Big Hand and Columbus-Niagaran reef fields in St. Glair County, Michigan: Unpublished Ph.D. thesis, Geol. Dept., Michigan State University, East Lansing.

Kellogg, Richard L., 1971, An aeromagnetic investigation of the Southern Peninsula of Michigan: Unpublished Ph.D. thesis, Geol. Dept., Michigan State University, East Lansing.

Kinder, A. S., 1954, Regional vertical magnetometer survey of Livingston County, Michigan: Unpublished M. S. thesis, University of Michigan, Ann Arbor.

Klasner, John S., 1964, A study of buried bedrock valleys near South Haven, Michigan, by the gravity method: Unpublished M. S. thesis, Geol. Dept., Michigan State University, East Lansing.

Lowden, James E., 1964, A combined geologic and gravity analysis of Walker field, Michigan: Unpublished M. S. thesis, Geol. Dept., Michigan State University, East Lansing.

Merritt, Donald W., 1968, A gravitational investigation of the Scipio oil field in Hillsdale County, Michigan, with a related study for obtaining a variable elevation factor: Unpublished Ph.D. thesis, Geol. Dept., Michigan State University, East Lansing.

Meyer, Howard J., 1963, A combined magnetic and gravity analysis of the Sauble anomaly, Lake County, Michigan: Unpublished M. S. thesis, Geol. Dept., Michigan State University, East Lansing.

Patenaude, R. W., 1964, Results of regional aeromagnetic surveys of eastern upper Michigan, central lower Michigan, and southeastern Illinois: University of Wisconsin Geophysics and Polar Research Center Rept. No. 64-2.

Peebles, Roger W., 1969, Gravity studies of buried bedrock topography in northwest Oakland County, Michigan: Unpublished M. S. thesis, Geol. Dept., Michigan State University, East Lansing.

Roth, John N., 1964, A gravitational investigation of fracture zones in Devonian rocks in portions of Arenac and Bay Counties, Michigan: Unpublished M. S. thesis, Geol. Dept., Michigan State University, East Lansing.

Rudman, R. J., Summerson, C. H., and Hinze, W. J., 1965, Geology of basement in Midwestern United States: Am. Assoc. Petroleum Geologist Bull., v. 49, no. 7, p. 894-904.

Secor, G. B., Meyer, H. J., and Hinze, W. J., 1963, A density determination by underground gravity measurements in Michigan: Geophysics, v. 28, p. 663-664.

Servos, Gary B., 1964, A gravitational investigation of Niagaran reefs in southeastern Michigan: Unpublished Ph.D. thesis, Geol. Dept., Michigan State University, East Lansing.

Shaw, Richard M., 1971, Mobile ground magnetometer survey of a portion of the Southern Peninsula of Michigan: Unpublished M. S. thesis, Geol. Dept., Michigan State University, East Lansing.

Stevenson, J. C., 1964, A vertical magnetic intensity study of the Grand Rapids anomaly: Unpublished M. S. thesis, Geol. Dept., Michigan State University, East Lansing.

Thiruvathukal, J. V., 1963, A regional gravity study of basement and crustal structures in the Southern Peninsula of Michigan: Unpublished M. S. thesis, Geol. Dept., Michigan State University, East Lansing.

Woollard, G. P., (Chairman), and Joesting, H. R., 1964, Bouguer gravity anomaly map of the United States: U. S. Geol. Survey Spec. Map.

PUBLICATIONS ON GEOPHYSICS AND SUBSURFACE GEOLOGY AVAILABLE FROM THE GEOLOGICAL SURVEY

Report of Investigation 2 MICHIGAN'S SILURIAN OIL AND GAS POOLS, by Garland D. Ells, 1967, 49 pages, 22 illustrations, 1 chart, and 2 tables.

Report of Investigation 3 GEOLOGY FOR LAND AND GROUND-WATER DEVELOPMENT IN WAYNE COUNTY, MICHIGAN, by Andrew J. Mozola, 1969, 25 pages, 9 figures, 4 folded plates, 1 folded chart, and 1 folded map in pocket.

Report of Investigation 4 GEOLOGY AND MAGNETIC DATA FOR NORTHERN IRON RIVER AREA, MICHIGAN, by H. L. James, C. E. Dutton, and K. L. Wier, 1967, 46 pages, 9 illustrations, table, and 2 folded plates in pocket.

Report of Investigation 5 GEOLOGY AND MAGNETIC DATA FOR CENTRAL IRON RIVER AREA, MICHIGAN, by C. E. Dutton, 1969, 17 pages, 2 illustrations, table, and 2 folded plates in pocket.

Report of Investigation 6 GEOLOGY AND MAGNETIC DATA FOR SOUTHEASTERN IRON RIVER AREA, MICHIGAN, by H. L. James and K. L. Wier, 1969, 30 pages, 9 illustrations, and 3 folded plates in pocket.

Report of Investigation 7 GEOLOGY AND MAGNETIC DATA BETWEEN IRON RIVER AND CRYSTAL FALLS, MICHIGAN, by H. L. James, F. J. Pettijohn, and L. D. Clark, 1970, 17 pages, 6 illustrations, table, and 4 folded plates in pocket.

Report of Investigation 8 GEOLOGY AND MAGNETIC DATA FOR THE NORTHERN CRYSTAL FALLS AREA, MICHIGAN, by F. J. Pettijohn, 1970, 23 pages, 6 illustrations, 2 tables, and 3 folded plates in pocket.

Report of Investigation 9 GEOLOGY AND MAGNETIC DATA FOR SOUTHERN CRYSTAL FALLS AREA, MICHIGAN, by F. J. Pettijohn, 1972, 33 pages, 8 illustrations, 2 tables, and 3 folded plates in pocket.

Report of Investigation 10 GEOLOGY AND MAGNETIC DATA FOR ALPHA-BRULE RIVER AND PANOLA PLAINS AREAS, MICHIGAN, by F. J. Pettijohn, J. E. Gair, K. L. Wier, and W. C. Prinz, 1969, 12 pages, illustration, 2 tables, and 3 folded plates in pocket.

Report of Investigation 11 GEOLOGY AND MAGNETIC DATA FOR NORTHEASTERN CRYSTAL FALLS AREA, MICHIGAN, by K. L. Wier, 1971, 14 pages, illustration, table, and 2 folded plates in pocket.

Report of Investigation 12 GEOLOGIC INTERPRETATION OF AEROMAGNETIC DATA IN WESTERN UPPER PENINSULA OF MICHIGAN, by Wafik M. Meshref and William J. Hinze, 1970, 25 pages, 7 figures, 4 tables and 3 folded plates in pocket.

Report of Investigation 13 GEOLOGY FOR ENVIRONMENTAL PLANNING IN MONROE COUNTY, MICHIGAN, by Andrew J. Mozola, 1970, 34 pages, 18 figures, 2 tables, 6 folded maps, 1 folded chart, and 1 folded map in pocket.

Annual Statistical Summary 15 MINERAL INDUSTRY OF MICHIGAN, 1970, (1972) (Preprints from the Bureau of Mines MINERALS YEARBOOK), by Grace N. Broderick, 18 pages, 16 tables. (Some previously published numbers in this odd numbered series may still be available from the Geological Survey).

Annual Statistical Summary 16 MICHIGAN'S OIL AND GAS FIELDS, 1971 (1972), Compiled by Garland D. Ells, Beverly L. Champion and Robert A. Dunn, 44 pages, 15 tables, and 1 chart. (Some previously published numbers in this evenly numbered series may still be available from the Geological Survey).

Request latest Geological Survey Publications Price List from DNR Publications Room, 102 Commerce Center, 300 S. Capitol Ave., Lansing, Michigan 48933, for availability and prices of publications.

STATE OF MICHIGAN
William G. Milliken, *Governor*

DEPARTMENT OF NATURAL RESOURCES
A. Gene Gazlay, *Director*

GEOLOGICAL SURVEY DIVISION
Arthur E. Slaughter, *State Geologist and Chief*
NATURAL RESOURCES COMMISSION

E. M. Laitala, *Chairman*, Hancock, 1961-74
Carl T. Johnson, Cadillac, 1963-75
Hilary F. Snell, Grand Rapids, 1971-76
Harry Whiteley, Rogers City, 1961-73
Charles G. Younglove, Trenton, 1972-74
Charles J. Guenther, *Executive Assistant*

Published by authority of State of Michigan CL ‘48 s.321.6
Printed by Speaker-Hines and Thomas, Lansing, Michigan

Available from the Publications Room, Department of Natural Resources, 102 Commerce Center, 300 S. Capitol Avenue, Lansing, Michigan 48933

On deposit in public libraries