A GRAVITY STUDY OF THE GEOLOGY OF NORTHEASTERN WISCONSIN

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BARRY ALBIN CARLSON
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This is to certify that the

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A Gravity Study of the Geology
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ABSTRACT

A GRAVITY STUDY OF THE GEOLOGY
OF NORTHEASTERN WISCONSIN

By

Barry Albin Carlson

Results of a gravity survey conducted in northeastern Wisconsin were used to extend known Precambrian geology into a sparse outcrop area. During the survey, an area of 4500 square miles was covered by over 3500 gravity observations.

The Bouguer Gravity Anomaly Map with the aid of a Double Fourier Series Regional Gravity Map indicates prominent negative gravity anomalies underlying the granitic rocks of the Wolf River Batholith and the Northeastern Wisconsin Complex. The latter is much more extensive than suggested by outcrop studies, extending from the Pembine area across the entire study area to the western boundary of Forest County. The Dunbar Gneiss occupies the central portion of the Northeastern Wisconsin Complex anomaly in the Pembine area where units of the complex have been geologically defined.

The Argonne Gravity Trend is a strong positive gravity anomaly which separates the two major granitic areas and is associated with little known mafic and ultramafic rocks. The

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A THESIS

Submitted to
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in partial fulfillment of the requirement
for the degree of

DOCTOR OF PHILOSOPHY

Department of Geology

1974

Dedicated to my sons, Duncan and Eric.

ACKNOWLEDGEMENTS

An endeavor such as this cannot be accomplished without the aid of many people. Foremost among these is Dr. William J. Hinze, who provided direction and supportive encouragement throughout all phases of the study. The helpful suggestions of Drs. Harold S. Stonehouse, James W. Trow, Hugh F. Bennett, and Chilton E. Prouty are also greatly appreciated.

This study would not have been possible without the encouragement of Dr. Meredith E. Ostrom of the Wisconsin Geological and Natural History Survey, who was instrumental in providing financial assistance for the field work. I am indebted to Dr. Donald W. Merritt for his assistance in developing computer programs.

Gravity meters were provided by the U. S. Army Topographical Command.

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CHAPTER I

INTRODUCTION

Statement of the Problem

Precambrian igneous and metamorphic rocks, including gneisses, greenstones, and basic and acidic intrusives and extrusives, underlie the surface glacial deposits and Paleozoic sedimentary rocks of northeastern Wisconsin. The Precambrian geology south of the Menominee Iron Range has not received intensive study because of scattered outcrops and relative lack of economic interest until the last few years.

Geological studies of selected areas in northeastern Wisconsin by many investigators have shown that the Precambrian rocks are structurally and lithologically complex, with significant density contrasts present. A gravity study has therefore been made to aid in lithologic identification and determination of the regional geologic framework.

Objectives

The overall objective of this study is to determine the potential of the gravity method in establishing the regional geologic framework of a part of the Southern Province Precambrian complex where there are limited outcrops. If successful, this could assist in using gravity results to extrapolate geologic trends into areas of Paleozoic cover.

Primary specific objectives are:

1. to extrapolate known geology into geologically unknown areas
2. to determine the regional geologic framework by synthesizing geological and geophysical data
3. to define the subsurface configuration of critical lithologic units.

Auxiliary objectives are:

1. to ascertain effectiveness of Fourier techniques in regional-residual separation for this type of geology
2. to help in the location of areas favorable for mineral exploration.

Organization of the Survey

Figure 1 shows the area of investigation. This specific area was chosen to include the published local geologic studies, and was made large enough to include an extensive area of limited outcrops that could be used for testing the mapping. Gravity observations were made at one-mile (1.6 kilometer) intervals along all available roads. The density of roads is extremely variable, from section-line roads in agricultural areas of Marinette and Oconto Counties to widely scattered roads in the forested areas to the west and north. Over 3500 stations were established in the study area of approximately 4400 square miles (11,400 square kilometers). Elevation control was achieved by several different methods, dependend upon

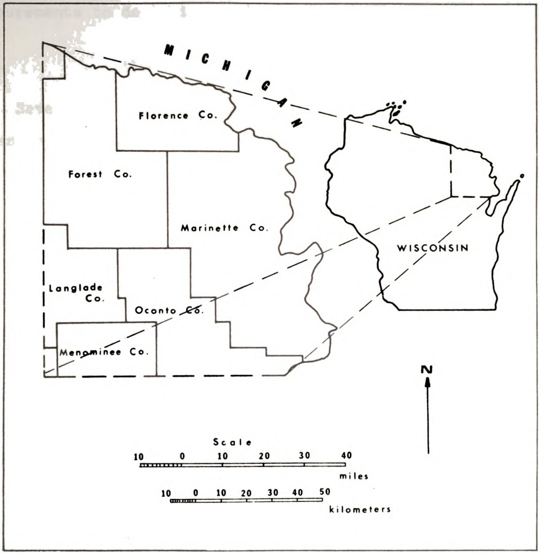


Fig. 1 INDEX MAP

the availability of elevation survey data. Rock samples were collected during the course of the gravity survey for later measurements to determine rock densities.

Previous Geophysical Studies

Several aeromagnetic maps have been published of local areas in the eastern and northern portions of the study area. Patenaude (1966) has compiled an aeromagnetic map of Wisconsin, but with a flight-line spacing too widely separated for detailed geologic analysis.

Mack (1957) made a gravity survey of Wisconsin based upon very widely spaced observations which was later incorporated in the compendium maps of northern Wisconsin by Dutton and Bradley (1970).

Crustal seismic studies have been made in the general area by Slichter (1951) and Steinhart, Mayer, and Woollard (1961). Changes in crustal thickness were inferred.

Crustal magnetotelluric studies in northern Wisconsin were begun by Dowling (1970) and have been continued by Bentley (1973).

No heat-flow measurements are known to have been made in northeastern Wisconsin. The closest known measurement is 50 miles to the northwest at White Pine, Michigan (Roy, 1963).

Many geophysical surveys of a local nature have been carried out by exploration companies, particularly in the last few years. Results have not been made public.

CHAPTER II

FIELD METHODS AND DATA REDUCTION

Gravity Survey and Instrumentation

LaCoste and Romberg Geodetic Gravimeters were used during the summers of 1967, 1968, and 1969 to take over 3500 gravity observations. Observations were made at one-mile (1.6 kilometer) intervals along all available roads.

Ten base stations were used for the purpose of determining instrumental drift by reoccupation of a base station before and after each day's field observations. More frequent reoccupations were made early in the survey, but it was discovered that the combinations of high instrumental stability and the application of earth tide corrections made any error introduced by drift almost negligible. For the 1967 data a comparison was made between the early morning and late afternoon reoccupations. For seventy-four available days, a mean reoccupation without respect to sign of 0.018 mgal was found, with a standard deviation of ± 0.023 mgal. Thirty-three changes were positive, thirty-two changes were negative, and on nine days no change was observed. Reoccupation measurements for other years showed comparable agreement.

A drift curve was constructed for each summer's data by fitting straight line segments to the daily base station

reoccupation means, after correction for tides. For the 1967 data, four line segments with negative drift account for the first nine weeks, reaching a cumulative drift of -0.57 mgal, or approximately 0.01 mgal per day. One line segment of positive drift represents the last three weeks, with a total drift value of +0.11 mgal. No reoccupation mean is more than 0.02 mgal from its line segment. A drift correction was applied for the drift represented by the straight line segments, but not for the deviations from the lines, as it was believed that this is a random error. Drift characteristics for other years had similar behavior patterns.

Base stations were tied to each other by triple-looping and by other ties made at convenient times during the survey (Figure 2). Base stations were tied to the international gravity network through University of Wisconsin base station GW3 (Behrendt and Woollard, 1961) by multiple ties. Gravity connections were also made with a previous survey in Michigan (Oray, 1971) and to a network of base stations in Wisconsin (Richard J. Wold, personal communication, 1969). Oray's and Wold's work had been tied to the international network, and all base station values for the present survey agree with their values within a tenth of a mgal after connections have been made.

Elevation Control

Approximately one-half of the gravity observations were made at points of known elevation, such as U. S. Geological Survey or U. S. Coast and Geodetic Survey bench marks, road

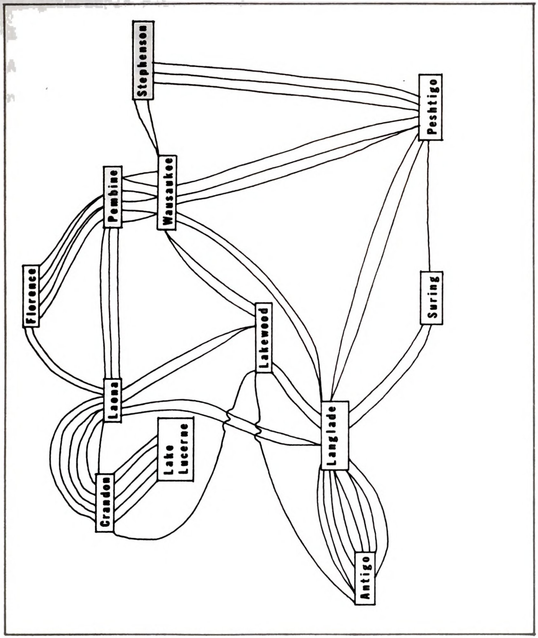


Fig. 2 BASE STATION TIES

intersections, section corners, lake elevations, or other specific elevations taken from U. S. Geological Survey topographic quadrangle maps. These stations have minimum accuracy of ± 1 foot (0.3 meter).

A total of 236 station elevations were determined by interpolation from U. S. Geological Survey maps which have a contour interval of either 5 or 10 feet. Stations were located where contour lines were at identifiable features, such as buildings or timber lines, so that they could be readily identified. Recent U. S. Geological Survey maps have an accuracy, at contour lines, of ± 10% of their contour interval according to a U. S. Geological Survey surveyor (Gerald Scroggins, personal communication, 1969). This error is increased by location uncertainty, so it is believed that these stations should have an accuracy of ± 2 feet (0.6 meter) or the same as those gravity stations located at known elevations. This assumes that station locations have been carefully placed with respect to contour lines.

An additional 91 station elevations were interpolated from U. S.Geological Survey maps having a contour interval of 20 feet. Applying the same reasoning as above, and allowing for the fact that these maps are somewhat older, these stations have an estimated accuracy of ± 5 feet (1.5 meters).

Elevations for four stations were interpolated from U. S. Geological Survey maps having a contour interval of 50 feet. This was necessary because of poor road conditions making stations inaccessible at the time of altimeter surveying. The

gravity values for these stations fit smoothly with contours drawn from nearby stations, so they were not discarded. Their estimated accuracy is ± 10 feet (3 meters).

Elevations for the remaining stations were determined by barometric altimeter surveying with Wallace and Tiernan Surveying Altimeters. During 1967 a recording barograph was not available, so two traveling instruments were used according to a triple-looping method where reoccupations were used to correct for changing conditions on days with relative atmospheric stability. Traverses were constructed of triple-looping sequences which connected points of known elevation, and then other station elevations were tied to these sequences. Operations were terminated whenever barometric conditions became unstable. This was possible be alternating gravimetric and barometric observations depending upon atmospheric conditions. Coleman, Athelstane, Dunbar, and Goodman quadrangles were completed during 1967 using these methods (Figure 3).

During 1968 and 1969 a recording barograph was used as a base station, with the two traveling altimeters employed on loop traverses with frequent reoccupations as field checks on accuracy. The same precautions as above were taken with respect to barometric conditions. The remaining planimetric quadrangles west of the 1967 area were covered in this way. Included here are Mountain, Langlade, White Lake, Lily, Wabeno, Thunder Mountain, Laona, Long Lake, and Alvin quadrangles, and the eastern portions of Antigo, Elcho, and Three Lakes quadrangles (Figure 3).

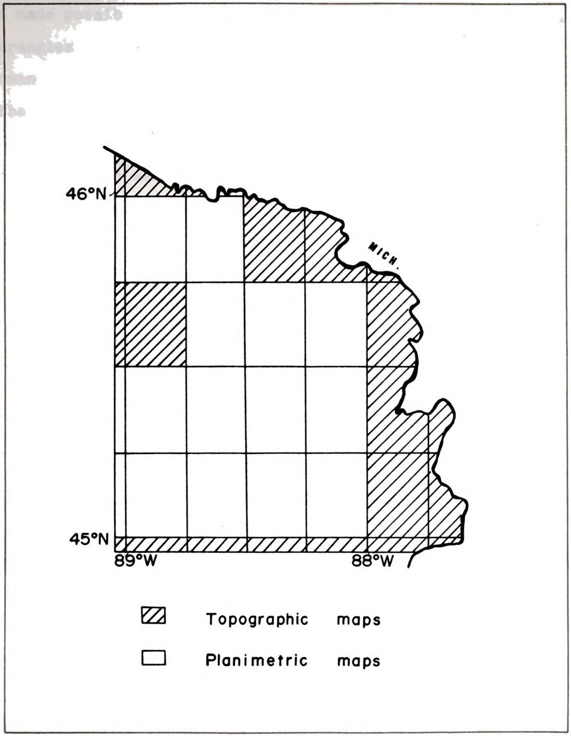
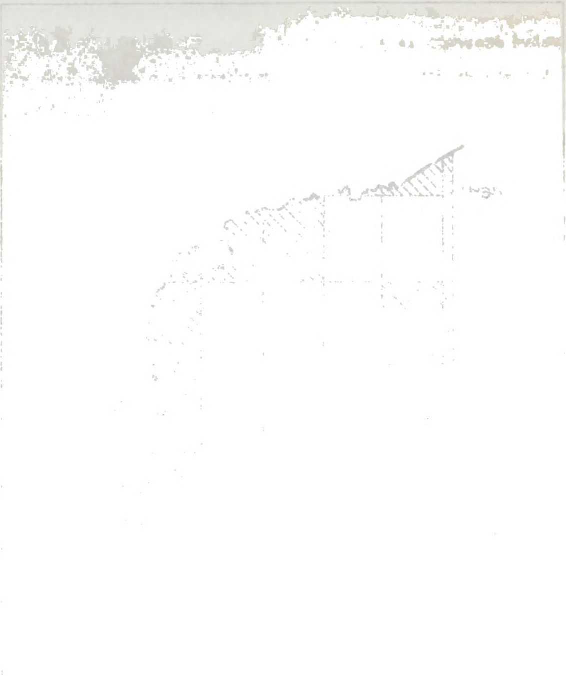


Fig. 3 DISTRIBUTION OF ELEVATION CONTROL



A check on the accuracy of the two altimeter methods has been made possible by the recent topographic mapping of certain quadrangles within the area. The preliminary maps for Dunbar, Goodman, and Laona quadrangles from the Rolla, Missouri office of the U. S. Geological Survey were searched for road corners and other known elevations that correspond to gravity stations whose elevations were determined by altimeter surveying. Locations were used for comparison only if it could be determined that the gravity station and the new elevation were made at essentially the same point. Results of the comparison are shown on Figure 4. The most significant result is that no discrepancies were greater than 6 feet (1.8 meters). There does not appear to be any essential difference in the accuracy of the two different altimeter methods, and accuracy does not seem to be dependent upon altimeter traverse distance.

From the above discussions, it can be seen that the survey area is divided into two areas of elevation accuracy, which are shown on Figure 3. The most reliable elevations have an accuracy of ± 2 feet (0.6 meter) and include the areas covered by topographic maps. Ninety-one elevations within this area were interpolated from 20-foot contour intervals and have a probable error of ± 5 feet (1.5 meters). These are scattered, and would not have a systematic effect. The area covered by planimetric maps has a maximum error of ± 6 feet (1.8 meters).

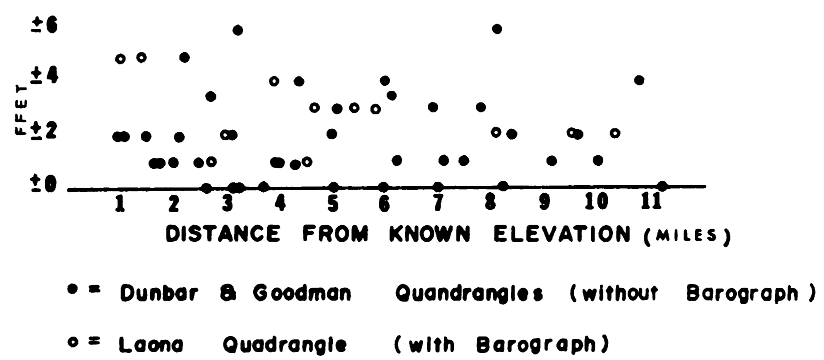


Fig. 4 ELEVATION ERRORS — ALTIMETER — CONTROLLED GRAVITY STATIONS

Accuracy of Horizontal Coordinates

Latitude and longitude coordinates were determined for each station from U. S. Geological Survey maps. The combined uncertainty of map error and station location error is estimated to reach a maximum on the planimetric maps of ± 0.05 minutes. Horizontal coordinates on all the maps were therefore determined to the nearest 0.05 minute.

Reduction of Data

Observed readings were first corrected for the earth tidal effect using the published tables of the European Association of Exploration Geophysicists. They were then corrected for observed instrumental drift as described previously in the first section of this chapter. The drift corrected readings were next converted to mgal using the manufacturer's calibration tables for the individual gravimeters, and then adjusted to the national gravity network (Behrendt and Woollard, 1961) using the gravity ties as previously discussed. This process has then produced the observed gravity values.

The simple Bouguer gravity anomalies were computed using standard techniques as described by Dobrin (1960). The theoretical gravity was determined for each station from the International Gravity Formula of 1930 and the Free-air correction was calculated using the vertical gradient of gravity of 0.09406 mgal per foot (0.3086 mgal per meter). The Geodetic Reference System of 1967 was not used so that the Bouguer gravity anomaly map would be consistent with published gravity maps from surrounding areas. The mass correction factor for

the material above sea level was computed using a density of 2.67 gm/cc, which gives a correction factor of 0.03407 mgal per foot (0.1117 mgal per meter). Terrain corrections were not made because gravity observations were made in areas without marked local topographic relief.

The observed gravity values were then adjusted for the above corrections to obtain the simple Bouguer gravity anomalies according to the following:

Simple Bouguer Anomaly = observed gravity
- sea level gravity (theoretical)
+ free-air correction
- mass correction

The Bouguer gravity anomaly map (Plate I), which shows the location of the observations sites, was machine contoured utilizing a computer program prepared by California Computer Products, Inc. A reduced version of this map is shown on Figure 5.

The gravity and elevation data are available at the Wisconsin Geological and Natural History Survey in Madison, Wisconsin.

Error Analysis

The potential sources of error can be divided into those errors arising from the survey itself, and the more difficult to evaluate uncertainty due to choice of the mass correction factor. A mass correction factor based upon an assumed density may not be representative of the material between sea level and the gravity station. The magnitude of this error is a function of the amount of topographic relief, and is equal to 0.00128

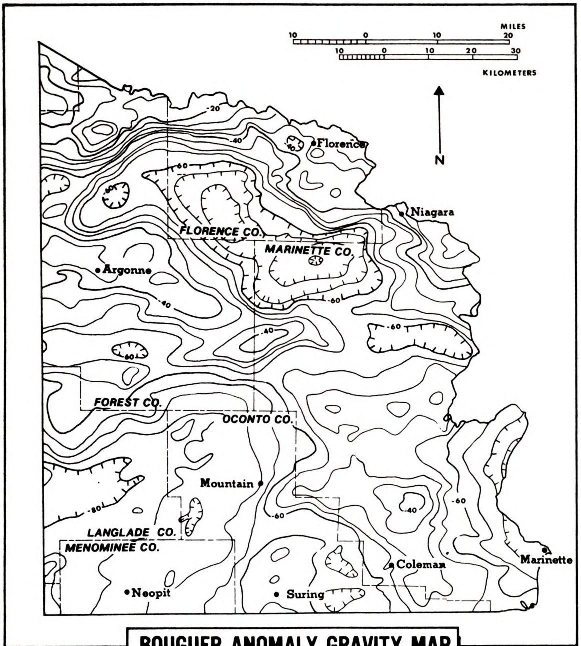


Fig 5

BOUGUER ANOMALY GRAVITY MAP OF NORTHEASTERN WISCONSIN

mgal per foot (0.0042 mgal per meter) for each 0.1 gm/cc density error. As an example, in an area having relief of 200 feet (61 meters) and underlain by greenstone having an average density of 2.95 gm/cc, the Bouguer anomaly values will be 0.7 mgal too high at the higher elevations. The range in elevations for gravity stations in the study area is from 582 feet (177 meters) above sea level along Lake Michigan to 1856 feet (566 meters above sea level in the northwest corner of the thesis area. Therefore, for the same greenstone rocks, the anomalies in the higher area could be in error by 4.6 mgal relative to the area along Lake Michigan. Glacial drift densities depart significantly from bedrock densities in the area, but drift thicknesses probably do not exceed a few hundred feet and would cause anomaly distortion only in local areas. The uncertainty arising from the mass correction factor, therefore, is of significant magnitude, but is inherent in any gravity survey and cannot be reduced by survey procedures. It can, however, be compensated for during interpretation.

The largest possible survey error is found for those stations whose elevations were determined using altimeters. The maximum elevation error for this method is 6 feet (1.8 meters). This would give a maximum error from the combined Free-air and mass correction factor of $\pm$ 0.36 mgal. In areas of topographic maps, an estimated uncertainty of 2 feet (0.6 meter) would give an error of $\pm$ 0.12 mgal. Figure 3 shows the distribution of these two areas of different types of elevation control.

Terrain corrections were not calculated, but it is

estimated that the maximum error from irregular topography would not exceed ± 0.25 mgal.

The accuracy of the determination of latitude controls the accuracy of the throretical gravity. The maximum estimated error of 0.05 minutes is equivalent to ± 0.07 mgal in the latitude range of this survey.

Normal reading scatter of the gravimeter after correction for drift, is estimated to contribute an error of ± 0.04 mgal. An estimated error of ± 0.01 mgal is possible from both the earth tide correction and the drift correction.

A net maximum error of ± 0.74 mgal is therefore possible for gravity stations whose elevations were determined by altimeters. A net maximum error of ± 0.50 mgal is possible for gravity stations with known elevations.

estimated that the maximum error from irregular topography would not exceed ± 0.25 mgal.

The accuracy of the [illegible]

CHAPTER III

SUPPLEMENTARY GEOPHYSICAL INFORMATION

Rock Densities

Bouguer gravity anomaly values are the summation of the gravimetric effect of horizontal density variations, both in the nearsurface and in the deeper crustal and upper mantle layers. In northeastern Wisconsin only minor gravity effects of the order of magnitude of 1 mgal or less are attributed to bedrock topography, to the presence of Lower Paleozoic sedimentary rocks in the southeastern corner of the area, and to lithologic variations within the glacial overburden. Lower crustal and upper mantle lithologic changes may cause broad gravity effects, but the majority of gravity anomalies in the study area are caused by variations in the composition of Precambrian rocks, and these changes are related to density variations.

Accessible rock samples were collected during the gravity survey in an attempt to gather information about significant density contrasts. Samples were collected as free from weathering effects as possible. In addition, published information (Woollard, 1962; Daly and other, 1966; Gibb, 1968; and others) concerning the densities of Precambrian rocks was utilized in

the gravity interpretation.

All rock densities were determined using the formula $D = w_1 / (w_1 - w_2)$, where D is the density, w_1 is the weight of the sample in air, and w_2 is the weight of the sample in water. Samples were soaked for thirty minutes and agitated to remove air bubbles. The density values measured fall between the dry and saturated densities, but porosity and permeability are low enough in igneous and metamorphic rocks that these values can be assumed to approximate closely the field densities.

Gravitational effects of the geology of the area are dominated by two assemblages of rocks with contrasting densities, reflecting different compositions. These are the greenstones and granitic rocks, including felsic gneiss. Their distribution is responsible for the major features of the Bouguer gravity anomaly map.

A summary of density information is given in Table 1. Samples from rock units defined in published geologic studies are listed together with samples from rock outcrops located in unstudied areas. From this information it can be seen that the most important density contrast in the area is that between the granitic rocks, including felsic gneiss, and the more dense greenstones. This contrast varies between 0.2 and 0.3 gm/cc.

TABLE 1

			N
Greenstones			
Quinnesec of Pembine area	2.97	±.08	15
Goodman Park area	3.00	.08	14
Allen Creek (5 miles east of Alvin)	2.89	.01	3
Brule Creek (2 miles northwest of Alvin)	2.94	.01	2
Waupee of Mountain area	3.06	.02	6
Nashville Quad (just west of thesis area)	2.97	.01	2
Badwater Greenstone	2.97		1
All greenstones	2.99		43
Other Volcanics			
"Siliceous rock" of Jenkins (Pembine area)	2.75	.08	2
Andesitic fragmental volcanics (Pembine area)	2.95		1
Hager Rhyolite (at Thunder Mountain)	2.78		1
Waupee water-laid ash (High Falls area)	2.75	.03	4
Waupee rhyolite porphyry (Mountain area)	2.63	.06	2
Rhyolite Porphyry (Nashville Quad)	2.65		1
Quinnesec felsic volcanics (west of 12 Ft. Falls)	2.77		1
Serpentinized basalt, (asbestos prospect, Pembine area)	2.80		1
Granitic and Intermediate-Composition Rocks			
Marinette Quartz Diorite	2.71	.02	5
Newingham Granodiorite	2.71	.01	4
" " (Cain,1964)	2.70	NA	53
Hoskin Lake Granite	2.67	.01	16
Twelvefoot Falls Quartz Diorite	2.90	.06	2

			N
Amberg Grey Quartz Monzonite	2.67	±.01	6
Athelstane Pink Quartz Monzonite (Amberg area)	2.64	.00	3
Athelstane Pink Quartz Monzonite (southern area)	2.74	.02	9
Granite north of Cauldron Falls (near sta. 740)	2.64	.03	2
Granite in Laona Quad (near sta. 1601)	2.69	.00	3
Granite 7 miles east of Mountain	2.69	.00	2
Peshtigo River Porphyry	2.72	.00	2
Otter Creek (Crandon, NE Quad)	2.78		1
Wolf River Batholith (not all samples from study area			
Hager Feldspar Porphyry	2.67		1
Belongia Granite	2.64	.00	2
Wolf River Quartz Monzonite	2.68	.02	3
Anorthosite	2.74		1
Red River Porphyritic Quartz Monzonite	2.66	.03	3
Wiborgite Porphyry	2.64	.01	3
Waupaca Quartz Monzonite	2.71		1
Monzonite-Trachyandesite	2.75		1
Metasediments			
Quartzite (at Thunder Mountain)	2.68	.00	3
Michigamme Slate (Leney, 1966)	2.99	NA	98
Michigamme Slate (Klasner and Cannon, 1974)	2.89	.17	6
Gneissic Rocks			
Dunbar Gneiss felsic phase	2.62	.01	4
" " intermediate phase	2.72	.04	4
on Dunbar Gneiss gravity trend (Armstrong Creek)	2.70		1
on Dunbar Gneiss gravity trend (Nelligan Pond)	2.64	.01	4
on Dunbar Gneiss gravity trend (Nelligan Pond)	2.98	.03	3
on Dunbar Gneiss gravity trend (Long Lake)	2.59	.00	2
on Dunbar Gneiss gravity trend (7 mi. west of Long Lake)	2.65	.00	3
on Dunbar Gneiss gravity trend (Monico Quad)	2.77	.05	3
Macauley Granite Gneiss	2.69		1

			N
Gneiss (Starks Quad, west of thesis area)	2.80	± .01	4
Gneiss (Starks Quad, west of thesis area) 50% or more of samples are mafic	2.90	.01	3
Hornblende Gneiss (Laona Junction)	2.79	.03	3
Gneiss (4 miles northeast of Argonne)	2.71	.00	2
Gneiss (4 miles northeast of Argonne) 80% of sample is mafic xenolith	2.85		1
Mafic Gneiss (north of Tipler)	2.88	.10	4

Miscellaneous Mafic Rocks

Metagabbro	2.93	.03	5
Gabbro (Peshtigo River Resort, below Cauldron Falls)	2.99		1
Gabbro (High Falls Reservoir, highly weathered)	2.77		1
Gabbro (7 miles east of Mountain)	3.01		1
Diorite (2 miles northeast of Peshtigo Resort)	2.91	.02	2
Diorite (7 miles east of Mountain)	2.90	.03	2
Diorite (southwest of Amberg)	2.75	.01	3
Mafic Dike (Goodman Park area)	2.93		1
Mafic Dike (Laona Quad, SE)	3.04	.07	3
Mafic Dike (Nashville Quad, west of thesis area)	2.83		1
Mafic xenolith in Athelstane Pink Quartz Monzonite	2.90		1
Mafic xenolith (Athelstane Quad, near sta. 741)	3.03	.01	2
Amphibolite (Wolf River Bridge, SE of Pearson)	2.99	.01	3

Residual Gravity Map - Double Fourier Series

Major geologic trends within the study area are readily apparent on the Bouguer gravity map. Examples would include the main outcrop area of the Quinnesec greenstone belt, the Dunbar Gneiss and its extensions, and the positive trend that extends across the study area through Wausaukee and Argonne. Anomalies which are less obvious were searched for by preparing a double Fourier series residual gravity map. The method of James (1966) for irregularly spaced data was used to calculate the regional and residual maps shown in Figures 6 and 7.

Reference axes were aligned east-west and north-south to accommodate the observed dominance of east-west directions on the Bouguer gravity map. Orientation of the reference axes can cause distortion of anomalies not parallel to the reference axes (Whitten and Beckman, 1969). However, in the example given by Whitten and Beckman (1969) to illustrate this problem, a reference axis shift of 40° produced structural axis trend shift of only 1.5°. An improvement in the total variability (sum of squares) from 94.37 to 95.44 percent was noted with the reference axis shift. It is concluded that distortion due to orientation of reference axes is not a serious problem for this study.

Most of the smaller anomalies on the Bouguer gravity map have a width of three to six miles (4.8 to 9.7 kilometers). The double Fourier series technique was therefore used to isolate anomalies of this width that might be obscured by

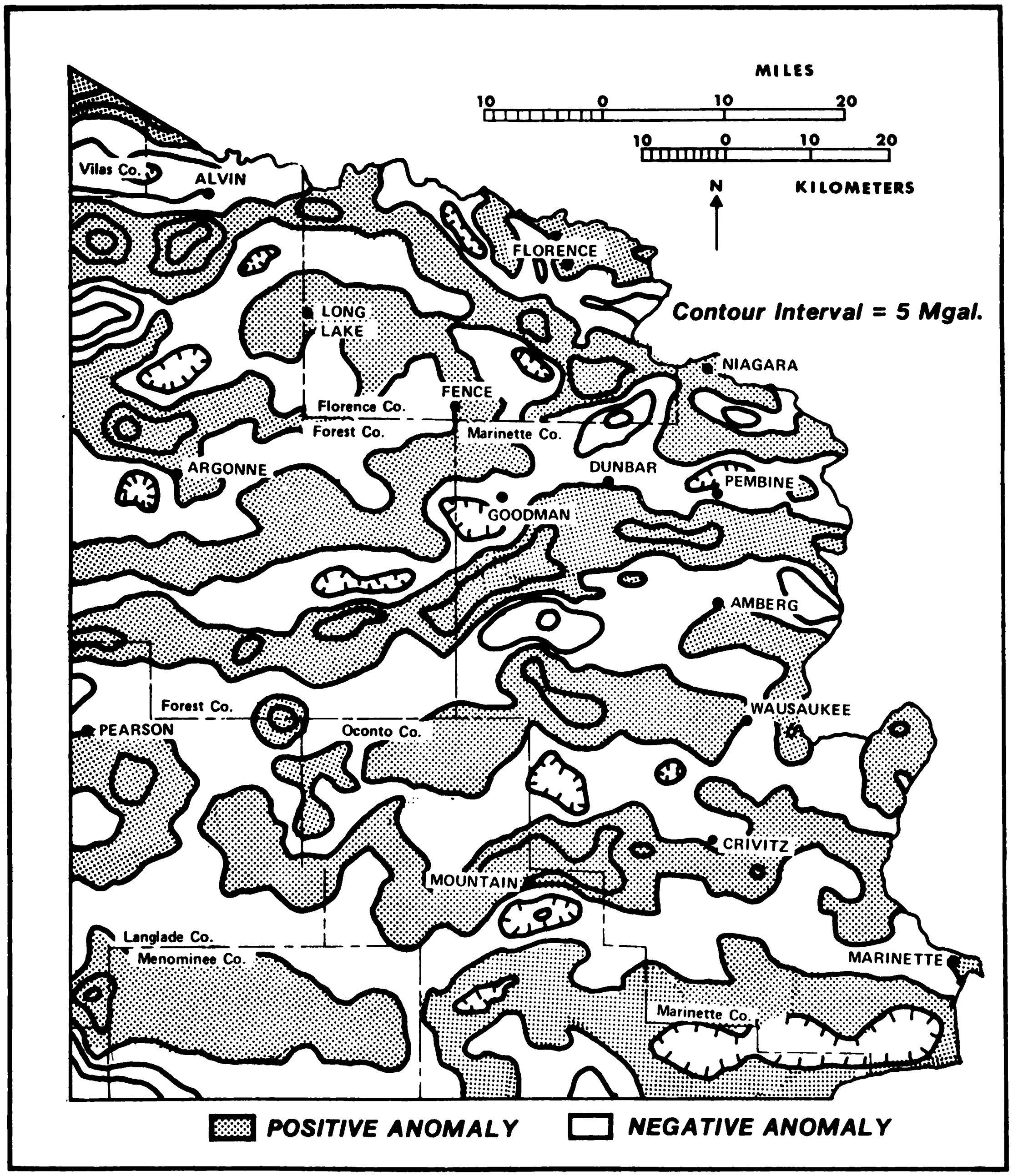


Fig 6 FOURIER RESIDUAL MAP OF NORTHEASTERN WISCONSIN

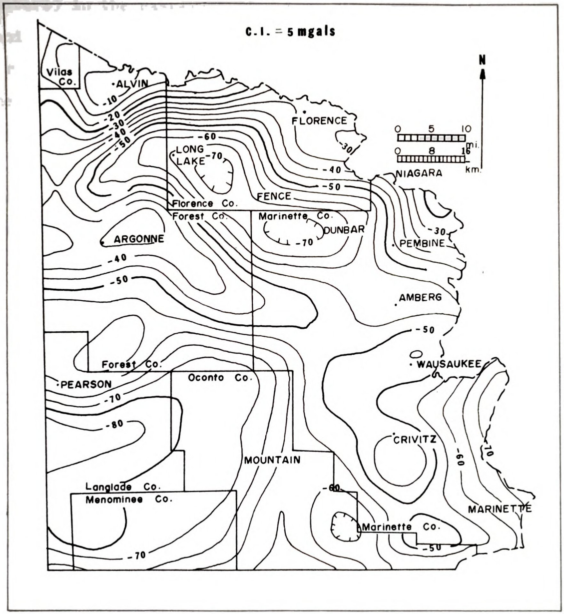


Fig. 7 FOURIER REGIONAL MAP

major features. Fundamental wavelengths of 85.35 miles (137.4 kilometers) in the north-south and 75.35 miles (121.3 kilometers) in the east-west direction were used. A fifth harmonic trend surface was calculated to map all anomalies larger than a wavelength of approximately eight miles (13 kilometers). This was removed from the Bouguer gravity map to give a residual gravity map delineating all anomalies having a width less than eight miles (13 kilometers).

Anomalies having a width less than twice that of the data spacing are not adequately defined due to the Nyquist frequency effect. Gravity stations were spaced one mile (1.6 kilometers) apart where roads made this possible. Therefore, the double Fourier series residual gravity map displays anomalies having a width of two to eight miles (3.2 to 13 kilometers), with less defination at the lower end of the range in areas of fewer roads.

An additional problem is spectral overlap between different anomalies (Odegard and Berg, 1965). Any anomaly contains a spectrum of wavelengths instead of just one. Distortion can therefore be caused by removing longer wavelengths components from shorter wavelength anomalies.

A comparison of Bouguer gravity anomaly profiles with derived double Fourier series regional and residual profiles can be seen in Figures 8, 9, and 10. Location of these profiles is shown in Figure 11. The regional and residual profiles when summed should be equivalent to the Bouguer profile. Discrepancies of 1 or 2 mgals can be noted which probably

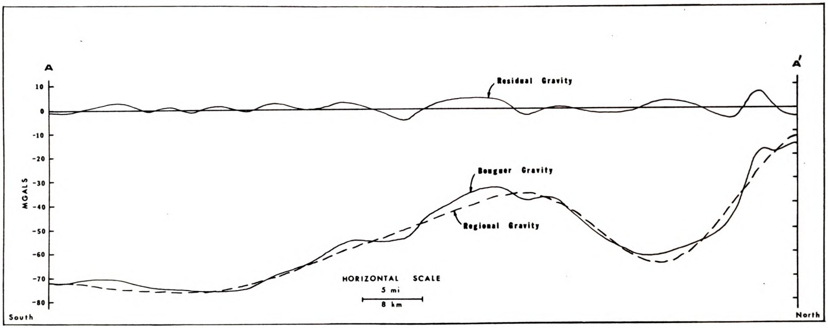


Fig. 8 PROFILE A — BOUGUER, REGIONAL, AND RESIDUAL GRAVITY CURVES

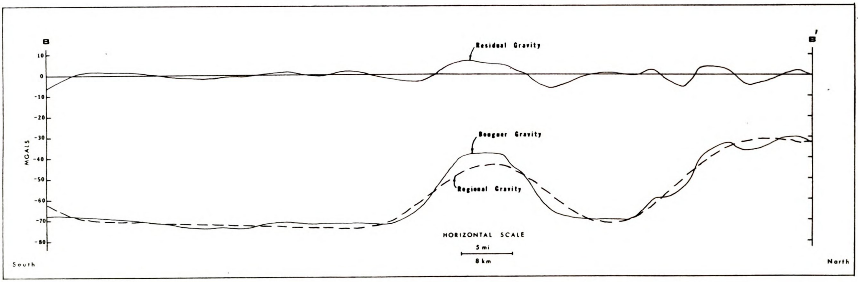


Fig. 9 PROFILE B — BOUGUER, REGIONAL, AND RESIDUAL GRAVITY CURVES

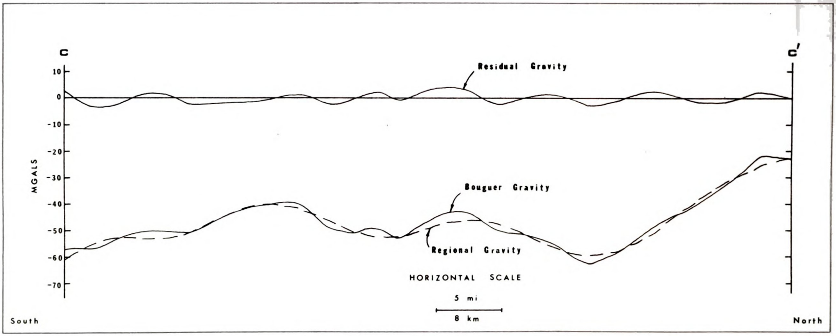


Fig. 10 PROFILE C — BOUGUER, REGIONAL, AND RESIDUAL GRAVITY CURVES

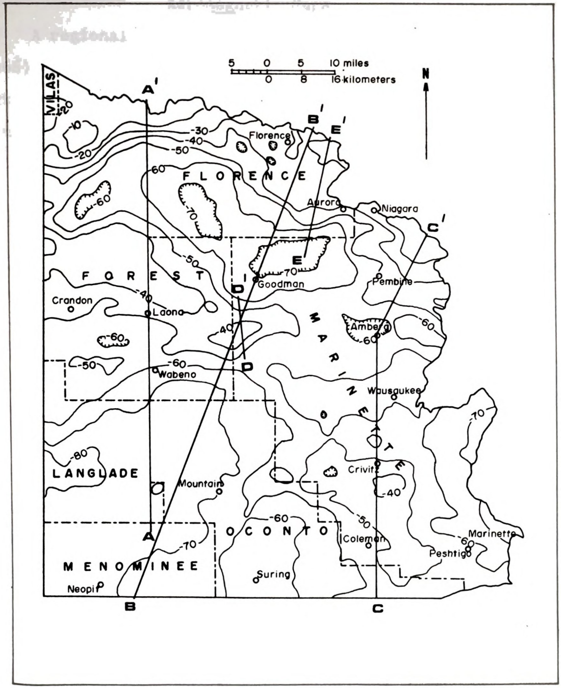


Fig. 11 INDEX MAP TO PROFILES

can be explained by the computer contouring program.

Aeromagnetic Maps

A regional aeromagnetic survey of Wisconsin (Patenaude, 1966) was made along range lines, with the exception of the extreme southwestern corner of the survey area where a flight line spacing of three miles was used. The survey was conducted at a barometric altitude of 3,000 feet (914 meters) above sea level. This constant altitude resulted in variation of flight elevation above the Precambrian surface of northeastern Wisconsin of between 3,000 feet (914 meters) near Lake Michigan and 1,100 feet (335 meters in the northwestern portion of the survey area. Patenaude published this map of Wisconsin with a contour interval of 400 gammas. Dutton and Bradley (1970) published Patenaude's data for northern Wisconsin, including all of the present study area, with a contour interval of 100 gammas.

A more detailed survey of portions of Florence, Forest, and Marinette Counties was flown with a flight line spacing of 1/4 mile (0.4 kilometer) (King, et. al, 1966). This area is underlain by portions of the Dunbar Gneiss and associated intrusives, by part of the Quinnesec Greenstone Belt, and by the Badwater Greenstone and metamorphosed sedimentary rocks of the Florence area. Dutton (1971a) republished the Florence area data at a more detailed scale. The survey was flown at an elevation of 500 feet above ground, and in this area Precambrian rocks are either at the surface or covered by thin glacial sediments.

Aeromagnetic maps with an approximate flight line spacing of 1/4 mile (0.4 kilometer) have been published of adjoining areas in Michigan between 87° 45' and 89° W longitude (U. S. Geological Survey, 1967). All of these aeromagnetic maps covering portions of Michigan, together with the map of King et. al. (1966), have been published as a colored regional map (Zietz and Kirby, 1971). These maps, together with the recently published Precambrian map of the Upper Peninsula of Michigan (Bodwell, 1972), were consulted for possible inferences that could be drawn from the geology of Michigan.

An aeromagnetic survey of the northern two-thirds of Wisconsin with a flight line spacing of 1/2 mile (0.8 kilometer) is planned (Ostrom, 1973).

CHAPTER IV

REGIONAL GEOLOGY

General Statement

Precambrian igneous and metamorphic rocks underlie all of northeastern Wisconsin, with surficial glacial deposits covering most areas and a thin wedge of Lower Paleozoic sedimentary rocks occurring in the southeastern corner of the study area. Previous geological investigators have shown that these Precambrian rocks are both structurally and lithologically complex, and that most of them are of Middle Precambrian age. Greenstones of the area have been assigned to the Lower Precambrian by some authors. The Upper Precambrian is apparently represented only by a few diabase dikes.

Two prominent greenstone belts of relatively high-density metamorphosed volcanic rocks have been intruded by lower-density granitic rocks. These granitic rocks occur widely, and belong to three different ages of acidic igneous activity. Felsic and intermediate gneissic rocks are common throughout the area. The Florence area is underlain by a thick sequence of metasedimentary rocks, and the McCaslin Range is made up of quartzite. Greenstones and granitic and gneissic rocks are the most common rock types in northeastern Wisconsin, but a variety of other

lithologies are found.

The following discussion summarized the geology of the previously studied areas within the survey region, incorporating geological observations made during the gravity investigation. Figure 12 is an index map to local maps showing geology and Bouguer anomaly contours. Certain critical isolated outcrops will not be discussed until the section on interpretation of gravity data. Table 2, adapted from Medaris and Anderson (1973), shows the sequence of Precambrian rocks in northeastern Wisconsin.

Geology of the Pembine Area

The most extensive outcrop area of northeastern Wisconsin is centered about Pembine. Figure 13 shows the mapped geologic units and Bouguer anomaly values in the Pembine area. As a result of these good exposures which include both greenstones and granitic intrusives, investigations have been carried out by several geologists (Cain, 1963, 1964a, 1964b; Wadsworth, 1963; Banks and Cain, 1969; Banks and Rebello, 1969; Hall, 1971; Jenkins, 1973).

The Quinnesec Formation has been considered by all workers to include the oldest rocks in the Pembine area, but its age has been variously interpreted as Lower Precambrian based on indirect evidence to the north (Bayley and others, 1966; Dutton, 1971a), or as late or post-Animikean (Middle Precambrian) based on a zircon age date of 1905 (+30 to -10) m.y. from porphyritic meta-rhyolite located 5 miles (8 kilometers) northwest of Amberg (Banks and Rebello, 1969). Recent work

A Pembine Area

B Menominee District

C Florence Area

D Northwestern Florence - Northern Forest Counties

E Goodman - Long Lake Area

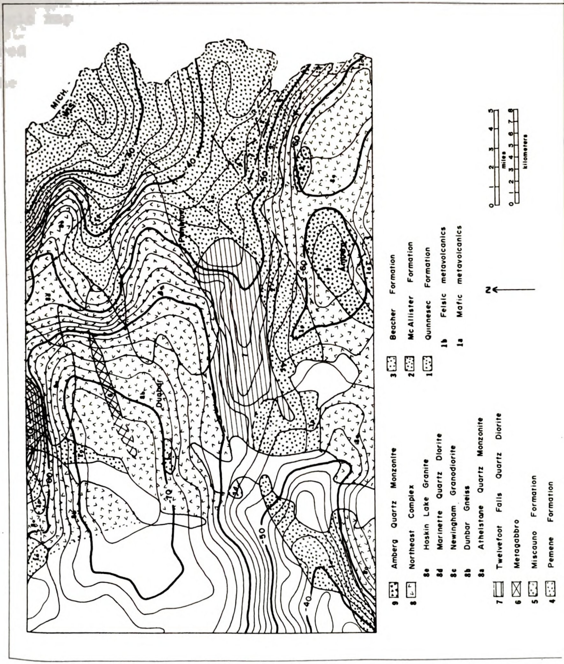
F Amberg - High Falls Area

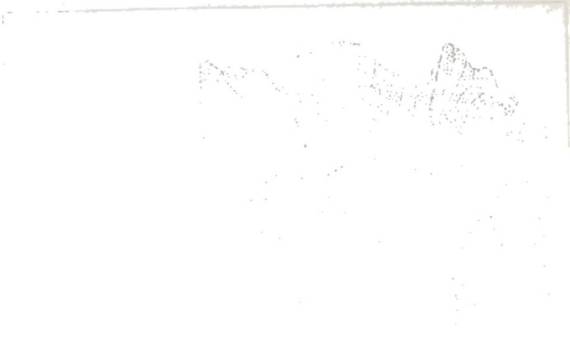
G McCaslin - High Falls - Mountain Area

Fig. 12 INDEX MAP TO GEOLOGIC STUDY AREAS

TABLE 2 - LIST OF GEOLOGIC NAMES

Ages Based on Isotopic Dates Age	Wolf River Batholith	Florence-Pembine-Amberg
1450-1500 m.y.	Belongia Granite Wolf River Hornblende Granite and Quartz Monzonite Hager Rhyolite Hager Feldspar Porphyry Hager Syenite	
Uncertain, possibly 1450-1500 m.y.	Hay Creek Quartz Monzonite Peshtigo Monzonite and Trachyandesite High Falls Granite	
Uncertain, possibly 1460-1670 m.y.		Amberg Grey Quartz Monzonite
1850-1910 m.y.		Athelstane Pink Quartz Monzonite Newingham Granodiorite Hoskin Lake Granite Marinette Quartz Diorite Dunbar Gneiss
Uncertain, possibly 1850-1910 m.y.		Twelve Foot Falls Quartz Diorite Metagabbro Pemene Felsic Volcanic Rocks McAllister Intermediate Volcanic Rocks
Uncertain, equal to or older than 1850-1910 m.y.		Beecher Felsic Volcanic Rocks Quinnesec Felsic Volcanic Rocks Quinnesec Mafic Volcanic Rocks
Middle Precambrian Possibly 1850-1910 m.y.	Mountain Area Baldwin Conglomerate McCaslin Quartzite Hines Quartz Diorite Macauley Gneiss Waupee Volcanic and Volcaniclastic Rocks	Paint River Group, undifferentiated Riverton Iron Formation Dunn Creek Slate Badwater Mafic Volcanic Rocks Michigamme Slate Saunders Formation


MICH.
WIS.
Pembine
Dunbar
Amberg
9 Amberg Quartz Monzonite
8 Northeast Complex
8e Hoskin Lake Granite
8d Marinette Quartz Diorite
8c Newingham Granodiorite
8b Dunbar Gneiss
8a Athelstane Quartz Monzonite
7 Twelvefoot Falls Quartz Diorite
6 Metagabbro
5 Miscauno Formation
4 Pemene Formation
3 Beecher Formation
2 McAllister Formation
1 Quinnesec Formation
1b Felsic metavolcanics
1a Mafic metavolcanics
N
miles
kilometers



by Jenkins (1973) suggests that this age date may be from a unit younger than the Quinnesec Formation. An even earlier interpretation assigned it to the Upper Precambrian (State Geologic map, 1949). Previous workers to Jenkins (1973) considered all metavolcanic rocks of the Pembine area to belong to the Quinnesec Formation.

Jenkins (1973) has reported on a more detailed study of part of the Pembine area in which he recognized three additional metavolcanic formations separated from each other and from the Quinnesec Formation by major faults. His relative age determinations are tentative due to structural complexity, but he still considers the Quinnesec Formation to be the oldest unit in the area. Younger units, in decreasing order of their suggested ages, are the McAllister, the Beecher, and the Pemene Formations.

Jenkins found the chemistry of each unit to be distinctive, suggesting several cycles of volcanism. A north-south gradation from tholeiitic basalt to calc-alkaline andesite in the Quinnesec Formation suggests association with an island arc environment. Two types of andesites are present, one pillowed and having a source to the west, and the other agglomeratic and having a source to the east. The McAllister Formation also includes tholeittic basalts, with agglomeratic textures important, but the Beecher Formation represents a change to typical calc-alkaline rhyolites and rhyodacites. The Pemene Formation is also made up of rhyolite and rhyodacite, but their chemistry is distinctive from the Beecher Formation, with higher Na_2O and lower K_2O suggesting almost continental affinities.

The Quinnesec and Beecher Formations are each over 10,000 feet (3050 meters) thick (Jenkins, 1973). The McAllister Formation ranges from 1,000 to 10,000 feet (305 to 3050 meters) thick, and the Pemene Formation is 7,000 feet (2130 meters) thick. All formations are regionally metamorphosed to greenschist facies and are strongly folded, with vertical dips predominating. In general, shearing has not been very strong.

Detailed work in the northeastern part of Marinette County, north of Jenkin's study area, shows the Quinnesec Formation to be predominately tholeiitic basalt, with chemical characteristics similar to Archean metavolcanics from the Superior Province in Canada (Mursky and Hall, 1973; Hall, 1971). Fragmental and pillowed basalts are most abundant, occurring in the northern two thirds of Hall's mapped area. He found massive basalt dominant in the southern third of his area, separated from the fragmental and pillowed basalts by a thin band of rhyolite. Small areas of myrmekitic and amygdaloidal basalts occur southeast of his massive basalts. Shearing is very important here (Hall, 1971), with distinct trends at N. 60° E. and S. 60° E. Regional metamorphism is of the greenschist facies, with higher subfacies near the Hoskin Lake Granite. A minor intrusion occurs 6 miles (9.7 kilometers) east-northeast of Pembine.

The Miscauno Formation of Trow (in Dutton and Bradley, 1970) consists primarily of iron-stained graywackes, tuffs, and cherts metamorphosed in varying degrees to sillimanite rank. It crops out southeast of Jenkin's mapped area and is placed within the Quinnesec Formation by Dutton and Bradley (1970).

This could be equivalent, however, to one of Jenkin's (1973) newly defined formations.

The oldest granitic unit in the Pembine area was at one time considered to be the Dunbar Gneiss because of its well-developed foliation and presence of xenoliths in other rocks (Cain, 1963), but zircon ages indicate that it is part of the granitic complex which formed over a few tens of millions of years between about 1,850 and 1,900 m.y. ago (Banks and Cain, 1969).

This has been referred to as the "Wisconsin Batholith" in the past, but Van Schmus (1973) has shown that this complex is just the oldest of three phases of granitic activity to affect Wisconsin, and he has given it the name "Northeastern Wisconsin Complex." Rocks of this age range are believed to represent the "Penokean Orogeny" (Van Schmus, 1972). The plutonic and gneissic units are younger than the Quinnesec Formation, but are truncated to the south by the Central Wisconsin Complex and the Wolf River Batholith. Westward extent of the Northeastern Wisconsin Complex is unknown, and it does not appear to be represented to the north in Michigan by anything other than minor intrusive bodies.

Three main rock types are present in the Dunbar Gneiss: medium to coarse-grained banded gneiss, migmatitic biotite gneiss, and coarse porphyroblastic granitic rock (Dutton and Bradley, 1970). The migmatitic phase occurs partly as xenoliths in the western portion of the banded phase. An original granitic texture is indicated by textural data (Cain, 1964a).

The Twelvefoot Falls Quartz Diorite contains xenoliths of the Quinnesec Formation, and petrographic studies have revealed the effects of regional metamorphism, hydrothermal activity, local metasomatism, and retrogressive metamorphism (Wadsworth, 1963). Weak foliation in the eastern part of the pluton grades westward into a typical gneissic texture (Cain, 1964a). Wadsworth's work was designed to test the hypothesis of Lyons (1953) that most plutonic rocks in the Pembine area owe their origin to metasomatic alteration of Quinnesec greenstones by intrusion of the Newingham Granodiorite. Coarseness-index trend surfaces indicate that a linear trend suggesting an external influence does not exist in the Twelvefoot Falls Quartz Diorite, and that a centrally located control of coarseness within this pluton is required (Wadsworth, 1963). On the basis of trend surface geometry and petrographic criteria, Wadsworth prefers a model of slower magma cooling within the quartz diorite pluton rather than appealing to metasomatism.

The Newingham Granodiorite is typically medium- to coarse-grained, with little foliation in its central area but with a pronounced gneissic texture around its margin (Cain, 1964a). Xenoliths of Dunbar Gneiss and Quinnesec Formation are found within the granodiorite, some of them one-half mile (0.8 kilometer) in length. Intrusions of Newingham Granodiorite into the Dunbar Gneiss, Marinette Quartz Diorite, and Hoskins Lake Granite have been identified at a distance of up to three miles (4.8 kilometers) from the main body. This is the only plutonic body in the Pembine area which has been

accepted by all workers as truly intrusive.

The Marinette Quartz Diorite is usually medium- or coarse-grained and massive, but is locally schistose (Cain, 1964a). It has sharp intrusive contacts with the Quinnesec Formation, and in turn has been intruded by the Hoskin Lake Granite to produce a contact zone of mixed rocks as much as 1,000 feet (305 meters) wide (Bayley and others, 1966). A zircon age date of 1,890 m.y. (Aldrich and others, 1965) is indistinguishable from that of the Hoskin Lake Granite (Banks and Cain, 1969). Lyons (1953) suggested that the Marinette Quartz Diorite represented a stage in the granitization of basalt. Field relations, however, clearly show that that the quartz diorite has intruded the Quinnesec metabasalts and is therefore an intrusive igneous body (Bayley and others, 1966). Mineralogical relations suggest that the original composition might have been hornblende diorite or even gabbro, and that the present quartz diorite could have been produced by metasomatism during intrusion of the Hoskin Lake Granite.

The Hoskin Lake Granite is a coarse-grained poyphyritic granite with intrusive relations into both the Marinette Quartz Diorite and Quinnesec Formation (Bayley and others, 1966). Lyons (1953) has also suggested a granitization origin for the Hoskin Lake Granite, but this is contradicted by sharp-walled Quinnesec xenoliths which appear to be stoped blocks rather than relicts of granitization (Bayley and others, 1966). It is believed to be syntectonic, as evidenced by primary flow structures and deformational structures (Bayley and other, 1966).

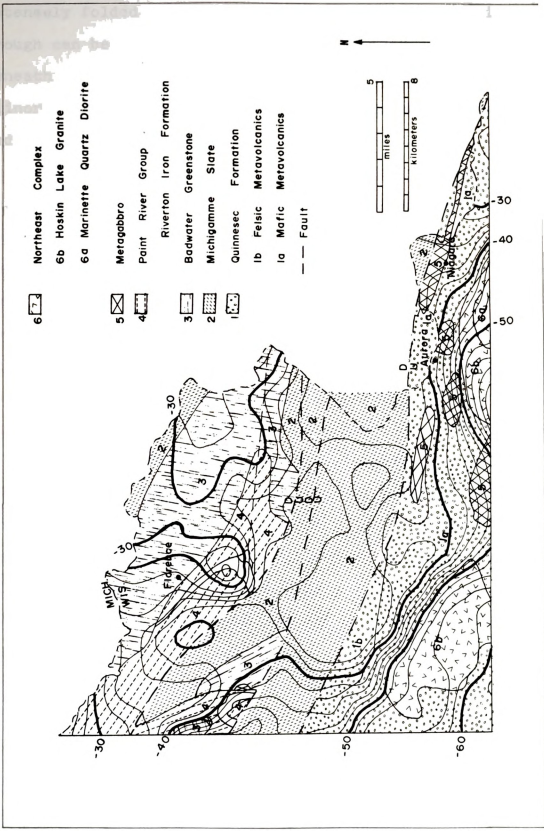
A Zircon age of 1,890 m.y. has been assigned (Banks and Cain, 1969).

A metagabbro sill several miles long extends through the Dunbar Gneiss and is similar to metamorphosed gabbros and diorites located to the north and northeast in the Menominee and Florence areas (Cain, 1964a). These bodies probably represent more than one episode of intrusion, because the metagabbro sills to the north are older than the Marinette Quartz Diorite and the Hoskin Lake Granite (Prinz, 1959), and yet the Dunbar Gneiss has been shown to be about the same age as these two bodies (Banks and Cain, 1969).

The Menominee Iron-Bearing District

Adjacent to the Pembine area on the north is the Menominee iron-bearing district, which is primarily in Michigan but partly in Wisconsin. It is one of a series of roughly east-west structural troughs in northern Michigan preserving middle Precambrian metavolcanic and metasedimentary rocks, including characteristic iron formation. These troughs are separated by masses of granitic rock and Lower Precambrian metamorphosed sedimentary and volcanic rocks (Bayley and others, 1966). Figure 14 shows the geology and Bouguer anomaly values for the Menominee district in Wisconsin and the Florence area. In the following discussion all information is after Bayley and others (1966) unless otherwise noted.

The broad structural framework of the Menominee district has been described as being composed of two anticlinal blocks separated by a trough which has been down-faulted. The trough is not symmetrical, but is a south-facing homocline which is


6 Northeast Complex
6b Hoskin Lake Granite
6a Marinette Quartz Diorite
5 Metagabbro
4 Paint River Group
Riverton Iron Formation
3 Badwater Greenstone
2 Michigamme Slate
1 Quinnesec Formation
Ib Felsic Metavolcanics
Ia Mafic Metavolcanics
Fault
miles
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N
MICH.
WIS.
Florence
Aurora
Niagara
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intensely folded and disrupted by faults. The Menominee trough can be traced for 40 miles (64 kilometers) to the east beneath Paleozoic rocks, and to the west broadens into a synclinorial structure which includes the Florence, Crystal Falls, and Iron River iron districts.

The Quinnesec Formation flanks the Menominee trough on the south. It has been intruded by the Hoskin Lake Granite on the south, and to the north is bounded by a major fault separating it from the Michigamme Slate. Greenstones and schist occur throughout its outcrop area, with pillow structures common in many of the mafic flows, and felsic metavolcanic rocks are abundant within a mile (1.6 kilometers) of the major fault on the north. Felsic metavolcanic rocks are unknown in the southern part of the Menominee area, although they are common farther south in the Pembine area. Metamorphic grade of the Quinnesec rocks increases southward toward the Hoskin Lake Granite, with an andesine amphibolite facies (medium grade) occurring near the granite and an oligoclase amphibolite facies (low grade) occurring away from the granite. Total thickness of the Quinnesec Formation is in excess of 10,000 feet (3050 meters).

The Michigamme Slate is the most widespread sedimentary formation in the Menominee district, but in the Wisconsin portion of the district underlies only a few areas along the Menominee River and is not exposed. The other rocks of the Animikie Series do not occur in the Wisconsin part of the Menominee district, and so all of these rocks will be discussed

in the section on the Florence area.

An important feature of the southern part of the Menominee district is the intrusion of long sill-like bodies of metamorphosed gabbro into the Quinnesec Formation. Exposed sills range in length up to 6.5 miles (10.5 kilometers) and in width up to 3,400 feet (1040 meters). Field evidence suggests that the tops of the sills face north, and that they were rotated from a horizontal position by the post-Animikie folding (Prinz, 1959). Not all of the sills were necessarily horizontal; the so-called Western sill is actually a dike as evidenced by rotation of rhythmical layering and schist inclusions, also according to discordance with Quinnesec strata. Mineralogy of the various sills fits into the metamorphic pattern of the area, suggesting that they are related to the post-Animikie orogeny and regional metamorphism.

Serpentinite and pyroxenite are found in several locations in association with the Sturgeon Falls sill, where metagabbro is intrusive into the ultramafic rocks and has chilled borders. These rocks have been explained as either early fractionation of the gabbroic magma (Prinz, 1959), or as unrelated early Precambrian ultramafics (Bayley and others, 1911). The Sturgeon Falls sill has been mapped to the southeast, and ultramafic rocks occur here in a similar relationship (Robert Reed, personal communication, 1972).

Diabasic dikes which are undeformed and unmetamorphosed are found in a few places and are believed to be of Keweenawan age.

In the section on the Florence area.

An important feature of the southern part of the Menominee district is the intrusion of long sill-like bodies of metamorphosed gabbro into the

Of major interest to the present study is the so-called "South fault" which separates the Menominee trough from the uplifted Quinnesec complex to the south. The attitude of this fault is vertical, and displacement is estimated as "considerably more" than 8,000 feet (2440 meters), which is the estimated maximum displacement along the south iron range fault to the north. Throughout both the Menominee trough and Florence areas to the South fault places Michigamme Slate opposite Quinnesec Formation with metagabbro sills in the Quinnesec strata close to the fault. This fault continues to the west beyond the Florence area and is one of the major structural features of northeastern Wisconsin.

The facies patterns of post-Animikie regional metamorphism have been displaced, but Upper Cambrian rocks to the east are not disturbed. The fault is therefore orogenic, but probably Precambrian. Bayley and others (1966) state that the Marinette Quartz Diorite and Hoskin Lake Granite are small with respect to the size of the metamorphosed area; these intrusions are believed to be pinnacles or cupolas that are part of much larger igneous masses at depth that caused the regional metamorphism.

The Florence Area

The Florence Area is on the same structural trend as the Menominee trough, only more geologic units are involved on the Wisconsin side of the state border because of the irregular course of the Menominee River (Figure 14). The following discussion is after Dutton (1971a), unless otherwise noted.

Three faults, including the previously discussed South fault, enter the Florence area from the Menominee trough and strike west-northwest. Dutton and Bradley (1970) have applied the name "Niagara Fault" to the extension of the South Fault in Wisconsin, and this name will be used here. These faults are inferred, as the actual fault traces are not seen in outcrops. The following names, from north to south, have been given to the structural blocks which are defined by the faults: Brule River, Keyes Lake, Pine River, and Popple River blocks.

The Brule River block is dominated by the Commonwealth syncline, a northwest-plunging fold which includes the once-productive iron formation of the Florence and Commonwealth areas and is one apex of a triangular basin whose other apices are at the Iron River and Crystal Falls iron districts.

The Keyes Lake and Pine River blocks are vertical to steeply dipping homoclines, and the Popple River block, which actually is part of a large area in northeastern Wisconsin which is continuous with the Pembine area, shows north dip according to pillow basalts.

The Quinnesec Formation is made up of metavolcanic rocks with minor metasedimentary rocks. The felsic volcanic rocks are younger than the mafic volcanic rocks based on a few pillow structures, and the felsic outcrop belt appears to be part of a twenty-mile (32 kilometer) long trend which extends from near Niagara along the Niagara Fault. Maximum thickness indicated by outcrops is 40,000 feet (12,200 meters), although there could be duplication by folding and faulting.

The Baraga Group of the Animikie Series is represented in the Wisconsin part of the Florence area by the Michigamme Slate and the Badwater Greenstone. The Michigamme Slate is made up of metasedimentary rocks, primarily interbedded metamorphosed slate and graywacke, with minor amounts of iron formation and greenstone agglomerate. Quartzite and quartzitic conglomerate, however, are the most commonly exposed rocks. Its outcrop area includes all of the Pine River block, much of the Keyes Lake block, and the northern part of the Brule River block. In its main southern area of outcrop the estimated maximum thickness of the Michigamme Slate is 20,000 feet (6,100 meters).

Conformable with the Michigamme Slate and overlying it is the Badwater Greenstone, 5,000 to 15,000 feet (1520 to 4570 meters) of metamorphosed basalt with some inter-bedded metasedimentary rocks that are locally tuffaceous and also some thin iron-rich beds. No felsic volcanic rocks are present. The main outcrop area is in the Brule River block in association with the Commonwealth syncline. Smaller outcrop areas of the greenstone are located in the Keyes Lake block in the vicinity of Keyes Lake and to the northwest extending off Dutton's mapped area.

The Paint River Group of the Animikie Series occurs here only in the Commonwealth syncline and in a smaller syncline in the Keyes Lake block. It is made up of metamorphosed sedimentary rocks, primarily slate and graywacke, and is approximately 3,000 feet (910 meters thick. The Riverton Iron-Formation,

part of this group, is 600 feet (180 meters) thick and consists of chert, siderite and their altered iron-formation products. Iron ore shipped had a range of 48-51% metallic iron as mined.

Two large metagabbro masses in the southeast part of the Florence area have sill-like relations to the Quinnesec Formation and are an extension of similar occurrences in the Menominee trough area. Smaller metagabbro outcrops are found within the Quinnesec Formation and are numerous within all three outcrop areas of the Badwater Greenstone.

Scattered outcrops of Hoskin Lake Granite, though less porphyritic than at the type locality, have been identified over an area of several square miles in the southwest part of the Florence area. Location of the boundary on Dutton's map is inferred from aeromagnetic data. Dutton (1971a) believes that other granite outcrops just west of the Florence area are part of, or closely related to, the Hoskin Lake Granite.

In contrast to the Menominee trough area, no unmetamorphosed basic dikes have been found here.

Area West of Florence Area

The geology and Bouguer anomaly values of northwestern Florence and northern Florence counties is shown on Figure 15. Magnetic anomalies (King and others, 1966) and outcrop information (Dutton and Bradley, 1970) both demonstrate that the geologic trends of the Florence area continue in a northwesterly direction. Mafic metavolcanic rocks associated with positive linear magnetic anomalies are located north of scattered

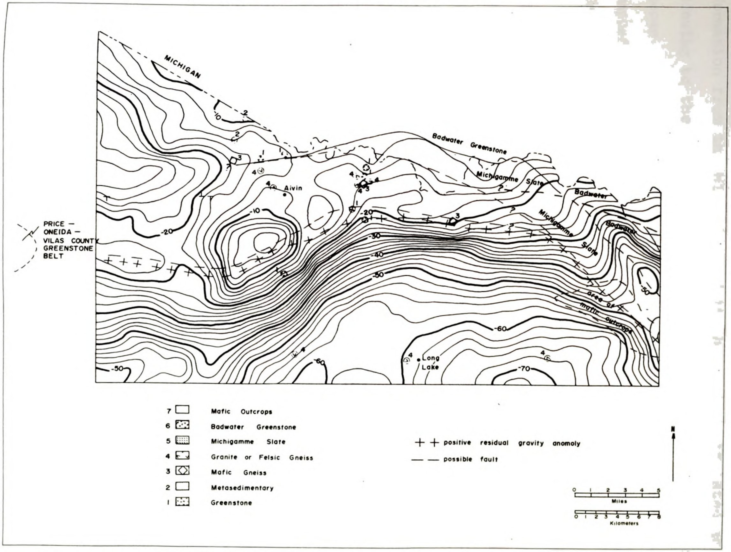

Fig. 15 GEOLOGY OF NORTHWESTERN FLORENCE AND NORTHERN FOREST COUNTIES

granitic outcrops and the major fault separating the Quinnesec Formation from the Michigamme Salte has been postulated as continuing to the west by Dutton and Bradley (1970). Granites occur farther north when proceeding westward and have been mapped almost to the Michigan border near Alvin (Dutton and Bradley, 1970).

The Conover district of northern Wisconsin enters the northwest corner of the survey area in T41N, R12E. Geology of this district is known only from diamond drilling of dip-needle anomalies, and the following discussion is after Allen and Barrett (1915).

A series of east-west magnetic lineations are caused by steeply dipping slate beds with ferruginous chert and siderite. These slates are "exactly similar" to beds associated with the Vulcan iron formation in the Crystal Falls and Iron River districts. In the western part of the Conover district, out of the survey area, a granitic intrusion has metamorphosed the slates to mica schists and gneisses, which have been cut by dikes of white biotite granite. In the eastern part of the Conover district, within the survey area, such effects are not present. The metamorphosed area to the west is part of the Watersmeet node of regional metamorphism (James, 1955).

The slates of the Conover district are believed to be continuous eastward with the slate-iron formation series of the Iron River district. This is suggested by the presence of slate in several drill hotes in Michigan and in one drill hole in Wisconsin in section 9, T41N, R13E. Granite was penetrated

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The slates of the Conover district are believed to be continuous eastward with the slate-iron formation series of the Iron River district. This is suggested by the presence of slate in several drill hotes in Michigan and in one drill hole in Wisconsin in section 9, T41N, R13E. Granite was penetrated granitic outcrops and the major fault separating the Quinnesec Formation from the Michigamme Slate [illegible] clining to the west [illegible] in another drill hole approximately one and one-quarter miles (2.0 kilometers) southwest of the section 9 drill hole in the NE1/4 of section 17.

Goodman-Long Lake Area

Figure 16 summarizes information on known outcrops in this area, and also shows Bouguer anomaly contours. Scattered outcrops of gneiss occur in this area. Rocks similar to the Dunbar Gneiss are exposed at Nelligan Pond, and just west of Long Lake. The latter outcrop is shown by Dutton and Bradley (1970) to be a mafic gneiss, though samples were not examined by Dutton. Density samples collected by the writer at this outcrop are gneissic and are of granitic composition. Granitic rocks are shown by Dutton and Bradley (1970) as outcropping both north and south of the gneissic complex in a manner similar to the western part of the Pembine area, where the Dunbar Gneiss is flanked by felsic intrusives.

Amberg-High Falls-Mountain-McCaslin Area

Figures 17 and 18 show the geology and Bouguer anomaly contours for this area. The Amberg Granite (Figure 17) originally named by Cain (1963), has been divided into pink and grey varieties, with the grey variety finer-grained and somewhat more mafic (Cain and Beckman, 1964). Both varieties show foliation and recrystallization textures. Banks and Cain (1969) have delineated a granodiorite variety, which corresponds to part of the grey Amberg Granite of Cain and Bechman. The granitic mass is generally unaltered and undeformed, although the grey variety is commonly gneissic at the margins of the

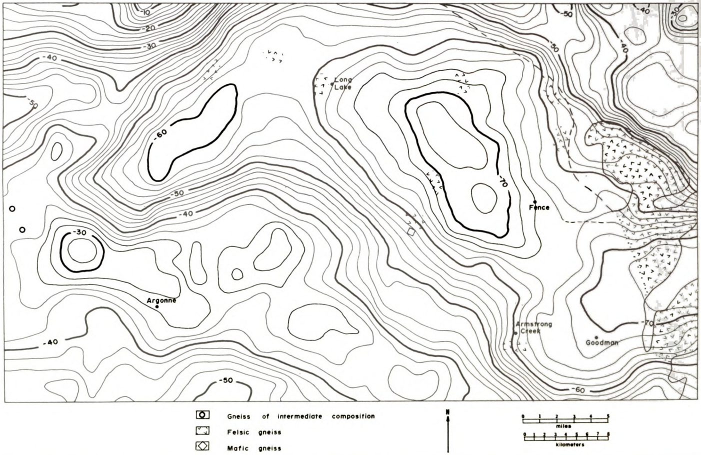

Fig. 16 KNOWN OUTCROPS OF THE GRANITIC GNEISS COMPLEX IN GOODMAN – LONG LAKE AREA

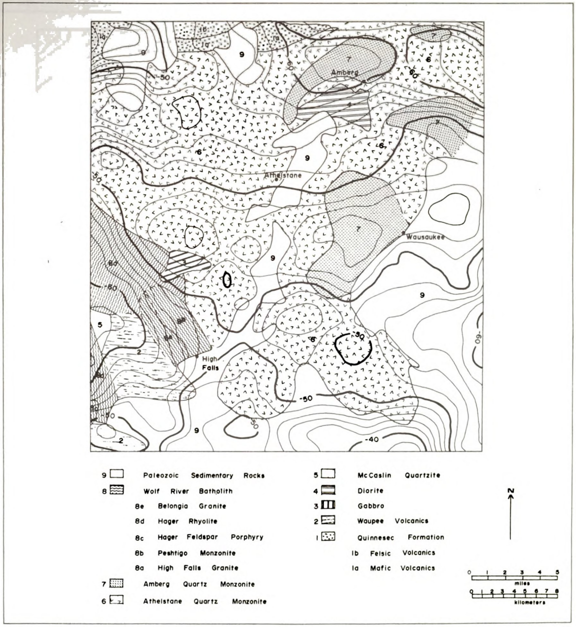

Fig. 17 GEOLGY OF AMBERG — HIGH FALLS AREA

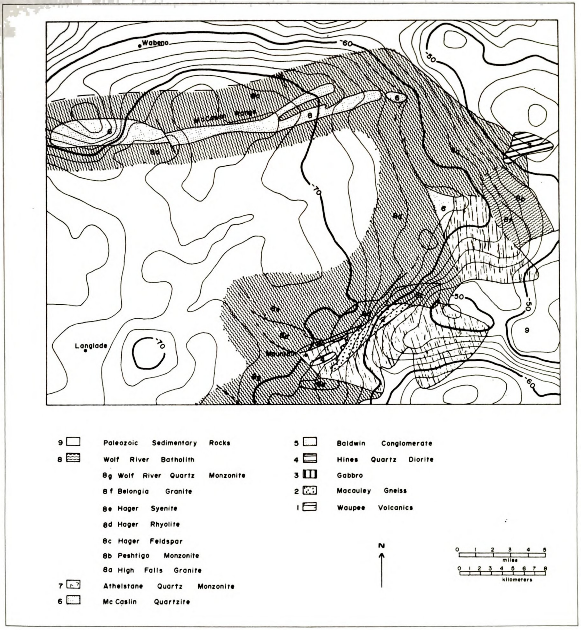

Fig. 18 GEOLOGY OF McCASLIN — HIGH FALLS – MOUNTAIN AREA

granite body, and until radiometric dates were available was considered younger than granitic bodies to the north. Zircon ages (Banks and Cain, 1969) yield synchronous dates for the pink Amberg Granite and the Newingham Granodiorite of 1860 ± 15 m.y. A Rubidium-Strontium whole rock isochron for both the pink Amberg Granite and the Hoskin Lake Granite of 1810 ± 50 m.y. is in good agreement (Van Schmus, 1973).

Field mapping by Medaris, Van Schmus (1973) and others has found four distinct plutons of the grey variety in the Amberg area whose individual size ranges from one by two miles (1.6 to 3.2 kilometers) to a width of 8 miles (12.9 kilometers). The pink variety is widely distributed both in the Amberg area and to the west and southwest through the Athelstane area all the way to the High Falls area. They have therefore proposed that the grey variety be called the Amberg Grey Quartz Monzonite and the pink variety be called the Athelstane Pink Quartz Monzonite.

Preliminary isotopic data for the Amberg Grey Quartz Monzonite reported by Medaris, Van Schmus and others (1973) suggests a younger age in the range of 1640 to 1670 m.y. Field relations confirm the above relative age dates of these two units, with dikes of Amberg Grey Quartz Monzonite intruding Athelstane Pink Quartz Monzonite. This absolute age places the Amberg Grey Quartz Monzonite in the Central Wisconsin Complex of Van Schmus (1973), which according to him comprises the bulk of the Precambrian basement of Wisconsin and is part of a major structural belt extending from Arizona to Wisconsin.

The Amberg Grey Quartz Monzonite is, however, the only definitely dated representative of the complex within the study area.

Mafic and felsic metavolcanic rocks occur in several places and have been identified as Quinnesec Formation. It is uncertain how these rocks would correlate with Jenkin's expanded classification of his restricted Quinnesec Formation and three other formations. Cain and Beckman (1964) identified metabasalt and metarhyolite outcrops north and northwest of Amberg as being an east-west extension of Quinnesec outcrops in the Pembine area. Distribution of these units is after the compilation map of Medaris and Anderson (1973). An age date for the metarhyolite was discussed in the section on the Pembine area.

Quinnesec-type outcrops have been mapped southwest of Amberg, and at an abandoned molybdenum mine 5 miles (8 kilometers) southwest of Wausaukee (Cain and Beckman, 1964). Southwest of Amberg the outcrops are primarily metabasalt with amphibolite schist at the eastern margin (Cain and Beckman, 1964). At the old molybdenum mine schistose greenstone is found (Cain and Beckman, 1964), although the molybdenite occurs in quartz veins in the surrounding granite (Kirkemo and others, 1965). Kirkemo and others (1965) have interpreted the greenstone as a basalt dike.

Two drill holes near Crivitz have penetrated greenstone (Dutton and Bradley, 1970).

The most recent study of the Waupee greenstone belt (Figure 18)

is by Lahr (1972), and the following discussion is after him. The Waupee Volcanics in the type area east of Mountain include metamorphosed volcanic flows, tuffs, agglomerates, and sedimentary rocks. Basalt is the dominant type of flow, with some andesite present. The Waupee rocks dip steeply to the northwest, and strike N. 45° E. Regional metamorphism is to the amphibolite facies. The basal Waupee member consists of massive flows, volcaniclastic sedimentary rocks and minor agglomerates. This is overlain by a middle sandstone member with subordinate flows and an upper thin-bedded tuff member. An island arc setting is suggested by the calcalkaline nature of the volcanic rocks. The Macauley Gneiss (granodiorite to quartz monzonite) then cut the Waupee rocks, and this was followed by deformation and regional metamorphism to the amphibolite facies. The Hines Quartz Diorite was then intruded, with accompanying contact metamorphism (Medaris, Van Schmus, and Lahr, 1973). The Baldwin Conglomerate was deposited next, and according to Lahr, the Hager Granite was then intruded. This unit was originally named the Hager Rhyolite by Mancuso (1957) on the basis of field relations, although he pointed out that the coarse grain size and great thickness suggested a granite. Read and Weis (1962) suggested that the Hager might actually be intrusive. Contact metamorphism described by Lahr (1972) supports the intrusive origin of the Hager. Medaris, Anderson, and Myles (1973) on the basis of further mapping, have defined three separate bodies: the Hager Rhyolite, the Hager Syenite, and the Hager Feldspar Porphyry. Intrusion of

the Belongia Granite then took place southwest of the main Waupee mass at approximately the same time as the High Falls Granite was intruding to the northeast. The High Falls Granite is clearly intrusive into Hager rocks (Mancuso, 1960).

The Hager, Belongia, and High Falls bodies have been included by Medaris, Anderson, and Myles (1973) within their Wolf River Batholith, a rapakivi massif that was defined as the result of their field work and the age dating of Van Schmus (1973). The High Falls Granite is a questionable member of the batholith, and isotopic dating will be necessary to resolve its age. Shear zones occur extensively within the High Falls Granite, but are not found in other units of the Wolf River Batholith, except for the Eau Claire mylonite zone, a major shear zone mapped by LaBerge (1973) along the western margin of the batholith. It extends for thirty miles (48 kilometers) along a strike of N30°E to near Antigo, at a point nine miles (14.5 kilometers) west of the western boundary of the study area. Medaris, Anderson and Myles (1973) have assigned the High Falls Granite to the Wolf River Batholith on the basis of its spatial relation to the other bodies of the batholith and because it intrudes the McCaslin Quartzite.

Also included in the Wolf River Batholith, and occurring within the study area, are the Peshtigo Monzonite and Trachyandesite, the Hay Creek Quartz Monzonite, and the Wolf River Granite and Quartz Monzonite. The Peshtigo Monzonite and Trachyandesite are more mafic than other units within the batholith, and the trachyandesite is a porphyritic equivalent of the monzonite.

The Hay Creek Quartz Monzonite is a small body between the High Falls Granite and the Hager Rhyolite. The Wolf River Granite and Quartz Monzonite occurs southwest of the Belongia Granite and extending beyond the southern boundary of the study area. Quartz monzonite predominates within this unit, with granite occurring close to the Belongia Granite.

A total of twelve intrusive bodies belonging to the batholith have been distinguished over an area of 3600 square miles (9300 square kilometers), extending southwest from the area of High Falls Reservoir and out of the study area. Of the exposed area, 87% is made up of quartz monzonite. Also present are granite, syenite, monzonite, rhyolite, and trachyandesite. Anorthosite occurs within the batholith and has been intruded by granite (Weis, 1973), and it is believed to underlie part of the southwestern corner of the study area. Van Schmus (1973) has determined an age range of 1450-1500 m.y. for the Wolf River Batholith, so it is the youngest of three major phases of acidic plutonic activity in northeastern Wisconsin.

Two structural features are readily noticed within the batholith without further detailed studies. These are an ENE trend within the quartz monzonites south of the study area, and the possibility of a ring complex at the northeastern end of the batholith. The Belongia Granite, Hager Rhyolite, Hager Feldspar Porphyry, and the Peshtigo Monzonite would be included in the postulated ring complex. This is suggested by their arcuate pattern, porphyritic textures, high-level characteristics, and the structural attitude of metasedimentary rocks occurring within the igneous rocks.

The McCaslin district was studied by Mancuso (1960), and the following discussion is after him. The McCaslin Range (Figure 18) is formed of the resistant McCaslin Quartzite, which reaches a maximum thickness of 5,000 feet (1520 meters) and extends twenty miles (32 kilometers) in an east-west direction. This quartzite also forms Thunder Mountain, a shorter north-south ridge located roughly half-way between the east end of the McCaslin Range and the east end of the main Waupee outcrop area near Mountain. The quartzite is unconformable upon rocks that have been correlated with the Waupee volcanics. These rocks outcrop at several places north of the McCaslin Range, and also just east of Thunder Mountain. Over half of the pebbles in the basal conglomerate of the McCaslin Quartzite are quartzite. Other rock types present have been identified as Waupee volcanics, banded hematite iron formation, and red jasper. The quartzite pebbles are well rounded indicating a distant source; the non-quartzite pebbles are angular to subrounded. This relationship, together with current directions inferred from cross-bedding observations, suggests a source in Waupee or Waupee-like rocks north and west of the McCaslin Range.

The McCaslin Quartzite dips to the south, and the quartzite beds at Thunder Mountain dip to the west. Mancuso correlated the Baldwin Conglomerate with the quartzite to set up the framework for a postulated broad syncline plunging westward. Only the eastern portion of the syncline remains, however, as granitic intrusives have cut off both the Baldwin Conglomerate and the McCaslin Quartzite to the west. A fault cuts the McCaslin Range

in section 4, T33N, R15E with a trend of N. 30° W. The east side has been displaced southward by a distance of 1/4 to 1/2 mile (0.4 to 0.8 kilometer). There is some evidence for a similar fault near the east end of the range in section 28, T34N, R17E.

A few mafic outcrops occur in the area of the High Falls Reservoir, which is east and northeast of Thunder Mountain. Most important of these is an extensive area of gabbro south of the Peshtigo River between Caldron Falls Reservoir and High Falls Reservoir (Myles, personal communication, 1972). Another gabbro outcrops three miles (4.8 kilometers) to the south at the bridge across High Falls Reservoir in association with the informally-named Peshtigo River Porphyry (Read and Weis, 1962). A diorite outcrop occurs in section 31, T34N, R19E, two miles (3.2 kilometers) to the northeast of the main gabbro area (Myles, personal communication, 1972).

CHAPTER V

INTERPRETATION

Introduction

Interpretation of gravity and geology patterns has been carried out using all available types of data, including the Bouguer anomaly map, published geological information, rock densities, the Fourier residual anomaly map, and various magnetic maps. Refraction seismologic data has been utilized together with broad gravity variations to investigate the lower crust and upper mantle.

The two major greenstone belts and the three ages of granitic activity will be discussed first because they cause the dominant gravity anomalies in northeastern Wisconsin. Other rocks will then be treated, followed by interpretation of possible causes of gravity variations from below the upper part of the crust.

Extrapolation and interpolation of mapped geology has been based upon continuity of anomalies in terms of their critical characteristics. Quantitative calculations of two-dimensional model profiles were made in certain critical areas in an effort to better define geological relationships of the area. An attempt was also made to point out situations where gravity is not useful.

Bouguer anomaly values range from -2 mgal just south of Alvin to -84 mgal approximately 9 miles (15 kilometers) south of Pearson (Plate I). In the southwest and southcentral portions of the map the gravity field is dominated by a regional low. A strong negative gravity anomaly also extends across the northern part of the map from Pembine and Dunbar to near the western boundary of Forest County. These two gravity low areas are separated by a belt of strong positive gravity anomalies extending across the entire study area from near Wuasaukee through Argonne. Other positive anomalies are prominent, especially along the entire northernmost portions of northeastern Wisconsin, in the Pembine area, and in the Mountain-Crivitz areas.

Directional trends on the Bouguer map are strongly east-west, with important northeast-southwest and northwest-southeast lineations. A few anomalies are circular.

Greenstone Belts

The existence of the Quinnesec and Waupee greenstone belts as separate bodies is supported by the Bouguer gravity map. They are separated by about 15 miles (24 kilometers) of quartz monzonite, and the gravity map does not show any connections between the two positive belts. Individual greenstone belts are shown in Figures 13 and 18, and the intervening area is shown in Figure 17. The Quinnesec belt has extensive outcrop areas, but the Waupee exposures in the Mountain area may be the exposed western portion of a much larger greenstone belt. The term Quinnesec belt will be used to include the Beecher, McAllister, and

Bouguer anomaly values range from -9 mgal just south of Alvin to -84 mgal approximately 9 miles [illegible] of Pearson (Plate I). [illegible] tions of the map [illegible] [illegible]

Pemene Formations in that a typical greenstone belt of the Superior province in Canada includes differentiated intermediate and felsic volcanic rocks (Wilson and others, 1965).

The surface configuration of both greenstone belts as derived from gravity is similar in character to the areas of preserved early Precambrian lavas in the Superior province of Canada and in South Africa (Anhaeusser and others, 1969). The characteristic pattern of long and relatively narrow arcuate synformal structures with many shorter arcuate tongues extending out into the surrounding granitic terrain is developed in both the Quinnesec and Waupee greenstone belts.

The eastern end of the Quinnesec belt under the Paleozoic overlap is undefinable at the present time due to lack of sufficiently close gravity control in Michigan, but Oray's (1971) gravity mapping with a station spacing of approximately 5 miles (8 kilometers) does allow for an eastward extension of the Quinnesec greenstones under the Paleozoic sediments of Michigan. More detailed mapping would be necessary to identify the characteristic outline of this greenstone belt in Michigan. It is also possible that the Waupee greenstone belt could extend east under Lake Michigan from a point several miles south of Marinette. Details of these two greenstone belts will be discussed in following paragraphs, the Quinnesec first because of its more extensive outcrops.

The greenstone outcrops of the Goodman Park area (Figure 13) are part of an elongated arcuate tongue extending west-south-west from the main mass of the Quinnesec belt. Density

sampling of these outcrops yields density values very close to those of the main Quinnesec outcrop area (Table 1). The positive anomaly associated with the Goodman Park area outcrops lies astride the Marinette-Forest County line, and is the only break in the otherwise continuous positive anomaly extending from the Michigan border east of Wausaukee to the western boundary of the study area. Beyond the Goodman Park area a positive trend can be followed continuously to the southwest corner of Forest County, where it bifurcates into a narrow anomaly continuing westward to the margin of the map, and a southwestern extension which rapidly widens to become almost circular near Pearson (Plate I). Density samples collected at the Wolf River bridge 1.5 miles (2.5 kilometers) southeast of Pearson appear to be from an amphibolite. The circular nature of this anomaly suggests an original gabbro or diorite intrusive body.

The Twelvefoot Falls Quartz Diorite (Figure 13) appears to be part of the positive anomaly associated with the Quinnesec Formation, and there are field indications that it may be altered Quinnesec rocks (R. Jenkins, personal communication, 1973). This unit is highly variable, and density sampling was inadequate to give a valid estimate of its average density. It is possible, however, to conclude from density sampling and gravity mapping that the Twelvefoot Falls Quartz Diorite is probably not a low density diapiric intrusive such as postulated for the Marinette Quartz Diorite to the north.

The Fourier residual map (Figure 7 and Plate II) shows a sampling of these outcrops yields density values very close to those of the main Quinnesec outcrop area (Table 1). The posi- tive anomaly associated with the Goodman Hill area outcrops lies astride the Marinette-[illegible] in the [illegible] continuous anomaly extending from the southeastern portion of the Pembine area westward all the way to the western boundary of the study area, including the Twelvefoot Falls Quartz Diorite, the Goodman Park area, and the above-mentioned extensions. The Bouguer and Fourier residual maps, together with outcrop information, indicate a long, narrow extension of the Quinnesec greenstone belt that stretches across the entire width of the study area.

Density samples from the Quinnesec outcrop area southwest of Amberg (Figure 17) yield an average density of 2.75 gm/cc and appear to be from a metamorphosed diorite. Dutton and Bradley (1970) show no greenstone outcrops in this area, and so this is not interpreted as a tongue of the Quinnesec greenstone belt. This area has no apparent expression on the Bouguer map, although surrounded by the slightly lower density Amberg Grey Quartz Monzonite. The Fourier residual map shows that these outcrops occur just west of a west-northwest trending positive anomaly which could be a northern extension of the Wausaukee positive trend. The lack of close association with the gravity anomaly suggests that these outcrops represent either large xenoliths or an intrusive body which has been deeply eroded.

An arcuate tongue of Quinnesec greenstone has been mapped geologically extending westward 8 miles (12.9 kilometers) from the main outcrop mass of the Pembine area, and is clearly shown by gravity (Figure 13). It separates the Hoskin Lake Granite on the north from the Newingham Granodiorite on the south, and is a good example of how the arcuate shape of a tongue of

greenstone is caused by granitic intrusives (Anhaeusser and others, 1969).

Within the main Pembine outcrop area (Figure 13) a southward decrease of gravity values reflects both a broad regional trend across the entire study area and a southward transition from mafic to intermediate and felsic volcanic rocks. The metagabbro sills intrusive into the northern portions of the Quinnesec greenstones have the same densities as the metabasalts, and so are not defined as separate anomalies.

The southward decrease in gravity values through the Pembine area is interrupted by a flattening and a 2 mgal positive anomaly in the area of Pemene felsic volcanics. This is not defined on the Fourier residual map (Plate II) because of map edge effects and also because it is weak and narrow compared to nearby features. A negative gravity anomaly would normally be expected under an area of felsic volcanics surrounded by more dense mafic and intermediate volcanics. The faults defined by Jenkins (Medaris and others, 1973) may explain this relationship if the Pemene felsic volcanics have been preserved here because of their location in a down-faulted basin. A great thickness of mafic volcanics could have escaped erosion under the felsic volcanics, thereby causing the positive anomaly. Jenkins (1973) has described the structure of this area as an east-trending asymmetric doubly plunging syncline, with vertical dips on the south limb and dips of 55° to the south on the north limb. An east-west trend is shown by the Bouguer gravity anomaly.

continuous anomaly extending from the southeastern [illegible] the Pembine area westward [illegible] of the study area, including [illegible]

[illegible] the Goodman [illegible]

[illegible]

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Maximum Bouguer values in the Pembine area are reached in the northeastern part of the area. Shape and orientation of the maximum-value contours show a relationship to the previously discussed Quinnesec tongue extending between the Hoskin Lake Granite and the Newingham Granodiorite. The Fourier residual map (Plate II) shows this continuity by an east-west positive anomaly, suggesting structural preservation of a greater thickness of greenstone along this trend.

A positive trend along the Michigan border north of the Hoskin Lake Granite is shown on both the Bouguer and Fourier residual maps. It has been produced primarily because of the density contrast between the Hoskin Lake Granite and the Quinnesec greenstones with its intruded metagabbro sills. This positive trend is continuous along a west-northwest trend through the Florence area (Figure 14 and Plate II) following the known outcrop pattern of the Quinnesec greenstones. This trend continues on both Bouguer and Fourier residual maps to the vicinity of the Michigan border, where the trend becomes east-west through Alvin (Figure 15) and then curves slightly to the west-southwest before continuing westward to the margin of the study area. Greenstone was sampled at Allen Creek, 5 miles (8 kilometers) east of Alvin, and at Brule Creek 2 1/2 miles (4 kilometers) northwest of Alvin (Figure 15). These outcrops are located on negative Fourier residual anomalies, and are close to granite outcrops (Dutton and Bradley, 1970). They are north of the positive trend interpreted here as an extension of the Quinnesec greenstones, and probably represent intruded

Maximum Bouguer values in the Pembine area are reached in the northeastern part of the area. Shape and [illegible] of the maximum-value contours show a relationship to [illegible] discussed Quinnesec [illegible] granite and the [illegible] map (Plate [illegible]) [illegible] remnants of a formerly wider greenstone belt. Greenstone also outcrops on the southeast side of the gravity maximum southeast of Alvin (Dutton and Bradley, 1970). Bouguer gravity values reach a maximum for the study area of -0.1 mgal at Gravity Station 3408, 3 miles (5 kilometers) southwest of Alvin. A magnetic high is located over the southeast portion of the gravity anomaly (Patenaude, 1966).

Dutton inferred a greenstone belt west of the study area underlying parts of Price, Oneida and Vilas Counties based on a few scattered outcrops and linear magnetic anomalies suggested by the work of Hotchkiss (1915), Hotchkiss and Bean (1929), and Patenaude (1966). The map outline of his inferred greenstone belt ends 3.5 miles (5.6 kilometers) west of the Forest County line (Figure 15), and the trend of its axis is aligned with the positive Fourier residual anomaly extending westward from the Alvin area.

The continuous nature of the Fourier residual anomaly along this entire trend from north of Pembine through Alvin to the margin of the map is similar to the gravity pattern of the postulated westward extension of the Quinnesec greenstones through the Goodman Park area and beyond to the western edge of the study area. The extent of the Quinnesec greenstone belt is therefore similar to greenstone belts in the Superior Province of the Canadian Shield, with long, narrow extensions and arcuate tongues extending into surrounding granitic rocks. Mursky (1973) has noted the chemical similarities of the Wisconsin greenstones to the Archean volcanic assemblages of the Superior Province.

remnants of a formerly wider greenstone belt. Greenstone also outcrops on the southeast side of the area [illegible] of Alvin (Dutton and [illegible] reach a maximum [illegible]

A Fourier positive residual anomaly extends southwestward from the Alvin positive anomaly towards the Argonne positive trend. Density samples were collected from intermediate to mafic gneisses on this anomaly at the edge of the map. It is common for non-felsic gneisses to occur around the margins of the Dunbar Gneiss and its extensions, and the location of the anomaly suggests that it is caused by these denser gneisses. No greenstone outcrops are known in the immediate area of this anomaly.

The Waupee volcanic rocks of the Mountain area (Figure 18) are associated with a well-defined positive anomaly on both the Bouguer and Fourier maps. Gravitational delineation of the heavier Waupee rocks is due to proximity to the surrounding Wolf River Batholith and Northeastern Wisconsin Complex. Paleozoic sedimentary rocks have concealed Precambrian relationships to the southeast and east of the Waupee outcrop area, but anomaly patterns show that the Wolf River Batholith bounds the Waupee rocks all along their southern margin, and suggests that the Waupee greenstones may continue eastward under the Paleozoic cover. Two drill-holes have penetrated greenstones in the Crivitz area (Dutton and Bradley, 1970). Granite was found in two adjacent drill-holes, suggesting intimate greenstone-granite relationships similar to those found in the Quinnesec greenstone belt. An alternate hypothesis will be suggested in the following section.

This postulated eastward continuation is shown by both the Bouguer and Fourier maps, with an east-west axis passing south

A Fourier positive residual anomaly extends southwestward from the Alvin positive anomaly towards the A[illegible] trend. Density samples were collected from intermediate to mafic gneisses on this [illegible] common for non-[illegible] the Dunbar [illegible] of Crivitz. This is especially well shown by the Fourier map due to its designed removal of features larger than eight miles (12.9 kilometers). For this reason the broader overall shape of the postulated Waupee greenstone belt south of Crivitz is not apparent on the Fourier residual map, but can readily be seen on the Bouguer map. The characteristic pattern of a greenstone belt, as discussed previously, is evident with its elongate extensions of greenstone and embayments of granitic intrusives.

An eastward extension under Lake Michigan of postulated Waupee greenstones is suggested by a steep Bouguer gravity gradient south of Marinette and an east-west positive gravity trend through Peshtigo (Plate I). This is also supported by the Fourier map, although use of this map may be ambiguous close to its edges.

The two stronger positive gravity trends within this positive anomaly, one south of Crivitz and the other through Peshtigo, suggest that these may be synclinal structural zones that have preserved thicker sections of mafic rocks. These trends, as in the Quinnesec greenstone belt, are east-west.

The Crivitz trend is also a magnetic positive anomaly (Dutton and Bradley, 1970), but is aligned in an east-southeast direction. This disagreement in direction may be the result of the six-mile aeromagnetic flight line spacing.

The positive anomaly south of Porterfield (Plate I) appears to represent a short eastward extension of greenstone from the postulated greenstone belt, separated from greenstone to the of Crlyits. This is especially well shown by the Fourier map due to its designed removal of features larger than eight miles (12.9 kilometers). For this reason the broader [illegible] of the postulated wedges [illegible] not apparent [illegible] on the [illegible] south by a narrow granitic intrusive embayment. It is on trend with the Crivitz magnetic anomaly.

The southeastern boundary of the Waupee greenstone belt is not clearly defined and could extend southeastward under Lake Michigan. Gravity gradients are of considerably less magnitude than in the Crivitz area, however, suggesting a thinner section of greenstone combined with increasing depth of burial beneath Paleozoic rocks.

A positive gravity anomaly in the Breed and Suring areas is separated from the Waupee greenstone belt by a negative anomaly varying in width from 3 to 6 miles (5 to 8 kilometers). This negative anomaly almost disappears between Mountain and Breed, however, indicating a possible connection between the Waupee greenstone belt and the Breed-Suring positive anomaly. The positive anomaly is almost rectangular, slightly longer in the north-south direction, and its southern portion is beyond the limit of the survey. There are two gravity maxima within this anomaly, one located east of Breed with a northeast-trending axis, and the other south of Suring and cut off by the map boundary. Both of these coincide with magnetic positive anomalies, with the Suring magnetic anomaly circular in shape (Dutton and Bradley, 1970).

The close proximity of the Waupee volcanic rocks and the magnetic positive anomalies are suggestive of greenstones, but the overall shape of the anomaly and lack of gravity evidence for granitic embayments discourage this hypothesis. No outcrops or drill-holes are known on this anomaly, either within

the survey area or to the south. An alternative hypothesis will be suggested later relating this anomaly to the Wolf River Batholith.

The Badwater Greenstone of the Florence area represents a small portion of a third greenstone belt, with most of it occurring in Michigan. The Wisconsin portion has not undergone widespread granitic intrusion like the Quinnesec and Waupee greenstone belts, and so it cannot be analyzed in a similar manner. It will be discussed later in the section dealing with the Florence area.

Argonne Gravity Trend

This gravity survey has defined a strong positive anomaly extending through Argonne (Plate I) which is associated with poorly known mafic and ultra-mafic rocks. Maximum values on this anomaly are reached near the western boundary of the study area, suggesting that it extends to the west beyond its length of 30 miles (48 kilometers) as defined by this survey. The anomaly is too wide to appear on the Fourier residual map, but is very obvious on both the Bouguer anomaly map and the Fourier regional map.

A peridotite dike has been identified by drilling 4 miles (6.4 kilometers) north of Argonne on the crest of the anomaly. Recent exploration by several companies for sulfide mineralization has taken place in the Armstrong Creek area, which is on the east flank of this anomaly.

Continuity of this trend is broken to the southeast by the Goodman Park extension of the Quinnesec greenstone belt.

A two-dimensional analysis was carried out along profile D (Figure 19) to investigate the subsurface configuration at this junction. The location of this profile is shown on Figure 11. Known outcrops have been used to constrain the interpretation. A first attempt at modeling assumed that the major feature is a basin-shaped greenstone belt, but it was not possible to approximate the anomaly shape while adhering to the distribution of rocks at the surface. Other shapes were tried, and the model in Figure 19 came closest to the observed Bouguer profile. Body 1 is a mafic body with greenstone outcrops, but may include units of the Argonne gravity trend. Body 2 consists of known felsic volcanic rocks. An intrusive mixture of felsic and mafic rocks is interpreted as Body 3. Body 4 is not represented by outcrops, but is modeled as an intermediate-composition gneiss body such as is known to occur marginal to the Northeastern Wisconsin Complex in other areas. Body 5 represents the Northeastern Wisconsin Complex of granitic rocks, and the Wolf River Batholith is present as Body 6.

A positive anomaly of diminished amplitude extends eastward through Wausaukee from this junction with the Quinnesec greenstone belt, and is a possible continuation of the Argonne Gravity Trend. Gabbro outcrops occur on this anomaly along the Peshtigo River 7 miles (11.3 kilometers) southwest of Athelstane (Figure 17). Other outcrops have been mapped as granitic rocks similar to those to the north and south, suggesting that a possible mafic source of this anomaly is below the surface. The gabbro outcrop area, however, does not produce a local anomaly

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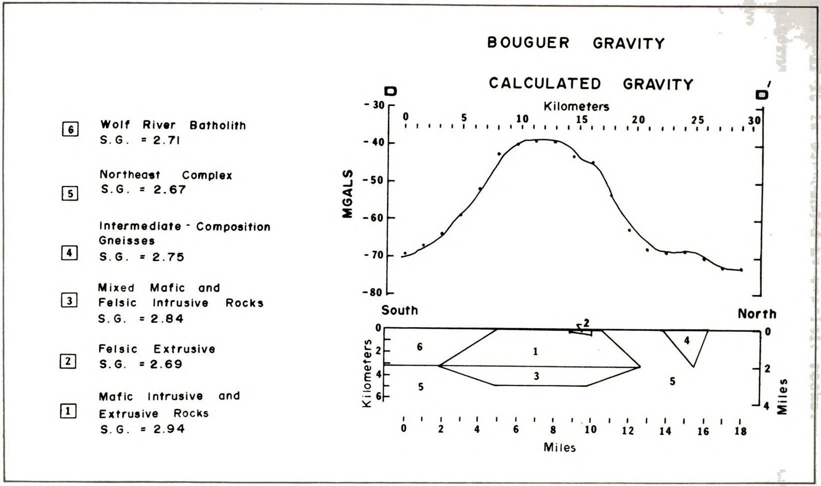

Fig. 19 GEOLOGICAL MODEL AND OBSERVED AND COMPUTED GRAVITY ANOMALY PROFILE ALONG D – D'

as it should if it is surrounded by granitic rocks.

An alternate explanation for the anomaly through Wausaukee would involve granitic rocks of a somewhat higher density. Density data (Table I) for the Athelstane Pink Quartz Monzonite can be divided into two areas, with significantly higher densities in a southern area located over the Wausaukee positive anomaly. The lower density contrast involved in this hypothesis correlates with the observed lower anomaly amplitude. Reconnaissance geologic field work by the students of Medaris at the University of Wisconsin (Medaris, personal communication, 1973) has not delineated this more dense facies of the Athelstane Pink Quartz Monzonite. Further detailed petrologic work should be done.

Inspection of the Fourier regional map (Figure 6) suggests that the Argonne Gravity Trend has a continuation to the south through the Crivitz area. It has been previously suggested in this study that the positive anomaly in the Crivitz area represents an extension of the Waupee greenstone belt. An alternate hypothesis would extend the mafic and ultra-mafic rocks of the Argonne Gravity Trend through the Crivitz area and imply that the Waupee greenstone belt is not much larger than its outcrop area.

This gravity survey is not sufficient by itself to choose between the two different interpretations of the Crivitz positive anomaly. It will be necessary to have aeromagnetic data to decide between a greenstone belt and a mafic intrusive.

Granitic Rocks

Of the three ages of granitic activity in northeastern Wisconsin (Van Schmus, 1973), the youngest and oldest are represented by igneous complexes of batholithic proportions, while only scattered plutons belong to the intermediate-age phase of intrusive activity.

The Northeastern Wisconsin Complex, the oldest of the granitic rocks, is well-defined both by geological mapping and by gravity in the Pembine area (Figure 13) where all but one of its various units have been differentiated. These units occur as the eastern portion of a major gravity minimum extending westward through Dunbar, Goodman, Fence, and Long Lake (Plate I) almost to the boundary of the study area. The Athelstane Pink Quartz Monzonite to the south is of the same approximate age according to radiometric dating, but is not as well defined gravimetrically and is separated from the main part of the Northeastern Wisconsin Complex by the Goodman Park extension of the Quinnesec Greenstone Belt and its Bouguer positive anomaly. The major negative gravity anomaly extending west through Dunbar and then into Forest County can be subdivided into three connected closures. The entire anomaly will be referred to as the Dunbar Gneiss Gravity Trend, as this unit coincides with the dominant portion of the anomaly in the Pembine-Dunbar area. The separate closures along this trend will be termed the Dunbar-Goodman, Fence-Long Lake, and Forest County closures. It is uncertain whether the Dunbar Gneiss underlies the entire Dunbar-Goodman closure, as only a few granitic

outcrops are known in its western half (Dutton and Bradley, 1970). More extensive glacial drift cover in this area and lack of geologic investigations are probably both responsible for the lack of outcrop information. Continuity of the Dunbar-Goodman closure with a constant magnitude suggests continuation of the Dunbar Gneiss throughout the area of the closure.

The Bouguer gravity pattern suggests that the Hoskin Lake Granite and Marinette Quartz Diorite together form a satellite body to the Dunbar Gneiss, extending northeast and east from the northeast corner of the Dunbar Gneiss. Both of these eastward extensions are isolated by the Fourier residual map.

A similar granitic extension from the Dunbar Gneiss into surrounding greenstones to the south and southwest is suggested by the Bouguer anomaly pattern near Goodman. The Fourier residual map shows a negative anomaly here, and a granitic outcrop occurs 3 miles (4.8 kilometers) south of Goodman (Dutton and Bradley, 1970). No other outcrops are known in the immediate area.

An analogous northern extension into Quinnesec greenstones of the Florence area has been mapped by Dutton (1971a) using scattered granitic outcrops and aeromagnetic data (King, et. al., 1966). Dutton assumed that the granite was underlain by low magnetic values, and the contact with the Quinnesec greenstones shown on the geology map is based on the magnetic pattern. He correlates this granite with the Hoskin Lake Granite, although it isn't as porphyritic as the Hoskin Lake Granite in its type

area. Regardless of whether this granite is part of the Hoskin Lake Granite, the gravity pattern demonstrates that it is found in a similar tectonic setting as a satellite body to the Dunbar Gneiss.

The four granitic extensions from the Dunbar Gneiss correlate with negative Fourier residual anomalies having similar sizes and magnitudes. The four anomalies have a magnitude of six to eight mgal.

The negative anomaly associated with the Dunbar Gneiss is remarkably flat within the last closing contour line, considering the variable amounts of mafic constituents present in different phases of the gneiss. Four samples of the felsic coarse, porphyroblastic phase have a mean density of $2.62\pm.01$gm/cc whereas four samples of the intermediate migmatitic phase from northwest of Dunbar have a mean density of $2.72\pm.04$gm/cc. The migmatitic phase is known primarily from the area northwest of Dunbar, which is at the west end of the known outcrop extent of the Dunbar Gneiss. Smoothness of the central part of the Dunbar-Goodman closure suggests either thorough mixing of the two phases to avoid producing local anomalies, or that the migmatitic phase is insignificant in terms of its total mass.

Two areas of greenstone have been mapped on the Dunbar-Goodman gravity closure, but they have no gravity expressions, suggesting they are thin erosional remnants. A half-mile (0.8 kilometer) wide metagabbro sill has been mapped extending east-northeast for over 6 miles (10 kilometers) through the eastern portion of the Dunbar-Goodman closure. Detailed outcrop

area. Regardless of whether this granite [illegible]
Hoskin Lake Granite, the gravity pattern [illegible]
it is found in a similar [illegible]
to the Dunbar [illegible]

The "our gr[illegible]
[illegible]

information is not available, although Dutton and Bradley's (1970) outcrop map shows four outcrop locations. This body also has no gravity expression, which is surprising considering that several gravity stations are well located to identify any local anomaly. The age problem of this mafic intrusive body was mentioned previously, resulting from the demonstrated intrusion of the Hoskin Lake Granite and Marinette Quartz Diorite into the metagabbro sills to the north and the approximate age equivalence of the Dunbar Gneiss with the Hoskin Lake Granite and Marinette Quartz Diorite. Lack of gravity expression by this body suggests either that it is very thin, unlike the metagabbro bodies to the north, or that mapped outcrops are actually metagabbro xenoliths of the same age as the sills to the north.

The Fence-Long Lake closure (Figure 16) is the same size and magnitude as the Dunbar-Goodman closure, but much less geologic information is available. Two granitic outcrops are reported in the southeastern portion of the closure and two outcrops of gneissic rocks are known in the Long Lake area (Dutton and Bradley, 1970). As mentioned previously, these gneissic rocks have been termed mafic, although samples collected from the outcrop just west of Long Lake have densities in the felsic range (Table 1). The samples are similar to the coarse porphyroblastic phase of the Dunbar Gneiss. An additional outcrop of felsic gneiss located 7 miles (11.3 kilometers) east of Long Lake was discovered during the gravity survey. Northwest of this outcrop a granitic outcrop occurs on a northeast

nosing of the anomaly (Dutton and Bradley, 1970).

Distribution of the few known outcrops on the Fence-Long Lake closure can be summarized as felsic gneiss outcrops located on an east-west axis and granitic outcrops associated with extensions from that axis. The Dunbar Gneiss also has an east-west axis.

Central portions of both the Dunbar-Goodman and Fence-Long Lake gravity closures have little magnetic relief, but the saddle area between the two closures is characterized by an 8 mile (13 kilometers) wide area of many ovoid positive magnetic anomalies (King, et. al., 1966). No outcrops are known in this area. Magnetic character is similar to the Quinnesec Formation to the north, but the broad shape and low magnitude of the positive gravity saddle argue against the area being underlain by greenstone. An extensive outcrop area at Nelligan Pond on the southwest flank of the Fence-Long Lake closure was discovered during the gravity survey and offers a possible clue to the cause of the positive saddle. Felsic gneiss outcrops similar to the coarse porphyroblastic phase of the Dunbar Gneiss are found together with mafic gneiss outcrops. Locally felsic intrusions into the mafic gneiss are found, and in places mafic xenoliths occur. The aeromagnetic map of King et. al. (1966) does not include this area, but it is suggested that local concentrations of mafic gneiss could cause positive magnetic anomalies and decrease the amplitude of the Dunbar Gneiss Gravity Trend between the Dunbar-Goodman and Fence-Long Lake closures.

A gravity saddle similar in size and magnitude to the above area also separates the Fence-Long Lake and Forest County closures. Detailed magnetic maps are lacking for this area, however. The only exposures reported on the saddle are three granitic outcrops (Dutton and Bradley, 1970).

The Forest County closure (Figure 16) is smaller than the other two closures on the Dunbar Gneiss Gravity Trend, and has not been as well defined due to lack of roads. Anomaly shape, amplitude, and orientation all suggest, however, a geologic continuation of felsic gneiss and associated granite. The only known bedrock on this closure is an outcrop area of gneiss 7 miles (11.3 kilometers) west of Long Lake. These rocks were sampled for density values (Table 1).

Several previously unreported outcrops of gneiss occur along the western boundary of Forest County (Figure 16) at the intersection of the Forest County negative gravity closure and the positive Argonne Trend. These rocks are of intermediate composition. The location of this intersection of gravity trends along the margin of the study area makes it impossible to predict whether the Dunbar Gneiss Gravity Trend continues to the west.

The Wolf River Batholith, youngest of the three phases of granitic activity, does not show the close correlations between geology and gravity that the Northeastern Wisconsin Complex does, possibly due to the less detailed geologic mapping that is has received to date, partial cover by the Paleozoic overlap,

and lack of outcrops west of the Mountain-McCaslin area. There are certain correlations, however, which suggest that gravity could aid in further study of this rapakivi massif. Medaris, Anderson, and Myles (1973) have compiled a geologic map of the known extent of the Wolf River Batholith. Distribution of outcrops strongly suggests that the southwestern portion of the study area, which is lacking in known outcrops, is underlain by units of the Wolf River Batholith. This coincides with a broad gravity minimum having the lowest Bouguer gravity values of the study area.

The Eau Claire River shear zone (LaBerge, 1973) is at or near the western margin of the Wolf River Batholith to the south. Gravity coverage of the exposed Eau Claire River shear zone is not available. It strikes N30°E, and has been extended into the study area using topographic lineaments (LaBerge, 1972), passing just south of Pearson. This would be too far north for the gravity-indicated edge of the Wolf River Batholith, but a parallel topographic lineament extends along the steep gravity gradient north of Lily (LaBerge, 1972). The Wolf River Batholith anomaly does not continue to the north with the lineament but has a generally east-west boundary in the area east of Lily.

The positive anomaly in the Breed-Suring area, along the southern margin of the study area (Plate I) has been discussed as a possible greenstone area. An alternate hypothesis would relate it to known anorthosite bodies in the Wolf River Batholith south of the study area. A sample of one of these outcrops has yielded a density of 2.74 gm/cc. It is therefore suggested

that the Breed-Suring positive anomaly could indicate the presence of anorthosite.

A sharp local positive anomaly occurs in the extreme southwestern corner of the study area. Patenaude (1966) found a ring-shaped magnetic anomaly in this area, with a strong negative central zone and an annular positive outer zone. The positive gravity anomaly of this study coincides with the northeastern portion of the positive magnetic zone. The gravity anomaly trends north-south whereas the lineation of the magnetic anomaly here is northwest-southeast. This disagreement may be partly explained by the 3 mile (4.8 kilometer) flight-line spacing of the magnetic survey. The magnetic anomaly becomes irregular south of the gravity study area, with small, sporadic anomalies in an area of anorthosite outcrops. Weis (Read and Weis, 1962) describes the anorthosite as locally containing magnetite.

Patenaude has suggested three possibilities to explain the magnetic anomaly: a ring-dike, preservation of iron formation, and a carbonatite deposit. The existence of a mafic intrusive in the area near the margins of the broader magnetic anomaly suggests a local denser phase of the intrusive complex. The well-defined gravity anomaly at the margins of the study area suggests that gravity mapping of the entire magnetic anomaly area to the west and south would be useful, particularly if combined with a more detailed magnetic survey.

Units of the Wolf River Batholith do not occur on the east-west positive gravity anomaly passing through Wausaukee, that the Breed-Surfing positive anomaly could indicate the presence of anorthosite.

A sharp local positive [illegible] southwestern corner [illegible] a ring-shaped [illegible] negative [illegible] although granitic rocks of the other two age groups have been found. The High Falls Granite has not been dated radiometrically, but Medaris et. al. (1973) have assigned it to the Wolf River Batholith based on lithology. The Bouguer gravity map supports this interpretation.

Menominee Trough - Florence Area

The Florence area and the Menominee Trough in Wisconsin (Figure 14), discussed together here because of their geologic continuity, are part of a larger province which includes adjoining portions of Michigan. Because of this, an attempt at interpretation must consider available information from Michigan. It must also be kept in mind that the Fourier residual and regional maps become less reliable near their margins.

The geology of much of this area contrasts greatly with previously discussed areas. The Niagara Fault appears to be a major structural feature separating crustal blocks of differing composition. This is supported by the regional contrast of Bouguer anomaly values which change from strongly negative south of the fault to relatively more positive values to the north. The only exception to this is in the Pembine area where the dense greenstones of Quinnesec Formation extend to the south, causing relatively positive values to also extend southward.

Rocks which are not found in Wisconsin north of the Niagara Fault include granitic intrusives, felsic gneisses, and the Quinnesec Formation greenstones. Felsic gneisses and granites are found in Michigan, however, north of the Menominee Trough.

although granitic rocks of the other two age groups have been found. The High Falls Granite has not been dated radiometrically, but Medaris et al. (1973) [illegible] Wolf River Batholith [illegible] map supports [illegible]

Rocks which occur north of the Niagara Fault but not to the south include the iron formation and characteristic associated metasedimentary rocks of the Middle Precambrian. Major metagabbro bodies are located south of the fault, but only minor occurrences outcrop to the north.

A two-dimensional modeling analysis was carried out along Profile E (Figure 20) to investigate the subsurface configuration. This profile extends from the Michigan border on the north to the negative anomaly of the Dunbar Gneiss, and its location is shown on Figure 11. It crosses the faulted Florence area, underlain by metavolcanic and metasedimentary rocks, and is located to include the effect of the metagabbro intrusions. The interpretation has been constrained by known geology.

Fault blocks were named by Dutton (1971a) and will be discussed from south to north. He has not estimated the amounts of movement on the faults, but Bayley and others (1966) have estimated displacements immediately to the east based on diamond drilling and field mapping. Fault offsets shown in Figure 20 are based on the work of Bayley. All three faults are upthrown to the south. The two northern faults are assumed to be near-vertical based upon geologic control to the east, and this study suggests that the southern fault dips steeply to the north.

The Dunbar Gneiss has been used as the standard of comparison for all densities. A mean density for the Dunbar Gneiss of 2.67 gm/cc was determined. Granitic gneiss is believed to underlie the rocks filling the Menominee Trough, as is characteristic of similar troughs in northern Michigan. Klasner and Cannon

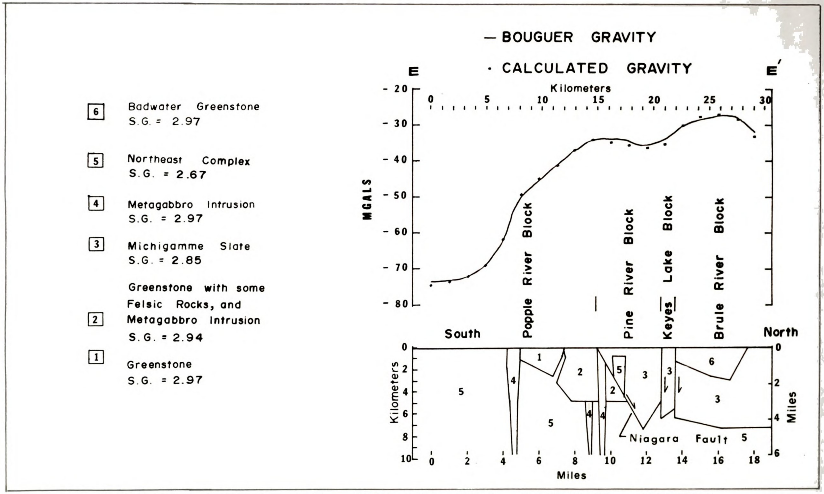

Fig. 20 GEOLOGICAL MODEL AND OBSERVED AND COMPUTED GRAVITY ANOMALY PROFILE ALONG E – E'

(1974) report that the basement rocks in the Republic Trough and Marquette Trough consist of about 90 percent granitic rocks and about 10 percent mafic rocks. Bayley and others (1966) believe that the granitic intrusions south of the Niagara Fault enlarge downward and join much larger igneous masses that caused the regional metamorphism.

This suggests a different history for this area compared to the troughs to the north, where the Middle Precambrian rocks fill troughs in Lower Precambrian rocks. In the Menominee Trough and Florence area Lower Precambrian granitic rocks are unknown, with the exception of the Carney Lake Gneiss north of the Menominee Trough. Similarity of structural style, however, suggests that the Hoskin Lake Granite and associated granitic rocks have merely remobilized a pre-exisitng granitic basement. In either case, the gravitational effects should be equivalent.

Popple River Block

Body 1 represents the Quinnesec Formation where it is entirely basaltic and similar to the Quinnesec rocks of the Pembine area. A stratigraphic thickness of 40,000 feet (12,200 meters) for the entire Quinnesec sequence is indicated by outcrops (Dutton, 1971a). Because dips are steeply to the north it is not necessary to have a vertical dimension of 40,000 feet (12,200 meters) in the model. Also, some duplication by faulting may be included in this thickness (Dutton, 1971a).

The separation between bodies 1 and 2 is based on an inferred minor granitic intrusion suggested by aeromagnetic data - a quiet zone which appears to be on strike with the

(1974) report that the basement rocks in the Republic Trough and Marquette Trough consist of about [illegible] and about 10 percent mafic rocks. [illegible] believe that the granitic [illegible] enlarge downward [illegible] caused the [illegible]

Hoskin Lake Granite area to the west. No granite outcrops are known in this area, so densities are assumed to be equal to densities of the Hoskin Lake Granite.

Body 2 represents the Quinnesec Formation adjacent to the Niagara Fault. Felsic metavolcanic rocks occur within a mile (1.6 kilometers) of the Niagara Fault a few miles to the west. Outcrops are lacking in the immediate area of the cross-section area. A minor metagabbro intrusion is present, however, which will tend to offset the effect of the felsic rocks. It is believed that the net effect has been a slight reduction of density.

The Niagara Fault follows the axis of its associated positive Fourier residual anomaly, suggesting that at depth the excess of mass associated with Quinnesec beds continues to the north of the surface trace of the fault. Of the three faults studied by Bayley and others (1966) to the east, only the two faults to the north are clearly of near-vertical attitude. The Niagara Fault is south of the old mining area and, since definitive data are lacking it was assumed to also be vertical. Following the suggestion of the residual gravity map, a north-dipping fault plane was incorporated in the model. Klasner and Cannon (1974) have found using gravity methods, a dip of 60° associated with bounding faults for the Marquette Trough near Michigan.

An alternate model can be suggested utilizing a vertical dip for the Niagara Fault. In this case a larger metagabbro intrusion is necessary to replace the excess mass of the

Quinnesec greenstones lost by rotating the fault. This interpretation is considered less reasonable because the observed anomaly configuration continues for several miles to the west, and it is unlikely that a metagabbro intrusion would retain its continuity. On the other hand, the Niagara Fault maintains its relationship to the positive residual anomaly, and it seems reasonable to postulate a dipping fault which will allow excess mass to be found north of the surface fault trace at depth.

Bodies numbered 4 are feeders to the outcropping metagabbro sills. It has been assumed that they gradually taper downwards. Assigned densities are slightly higher than observed densities because collected density samples were all somewhat weathered.

Pine River Block

The Michigamme Slate has a highly variable lithology, and since outcrops are sparse in the study area, no density samples were collected. These outcrops are a westward extension from southern Dickinson County, Michigan, where the dominant rock is slate, with large quantities of graywacke, quartzite, conglomerate, dolomite, and iron-formation (Bayley and others, 1966). Of the few outcrops in the Pine River block, the most common lithology is quartzitic conglomerate (Dutton, 1971a). Other known rock types include quartz slate, greenstone agglomerate, tremolite schist, graywacke, and gruneritic iron-formation. An average density of 2.99 has been reported (Leney, 1966) for 98 samples of the Michigamme Slate from the East Menominee Range and central Dickinson County. This density is probably too high

for the amount of quartzite and quartzitic slate that is present in the Pine River Block. Bayley and others point out that the sediments indicate a change from shelf types - quartzite, dolomite, and slate - to geosynclinal types - graywacke slate - when proceeding from the Menominee district to the northwest. Klasner and Cannon (1974) determined a density of 2.89 gm/cc for 8 samples from the western Marquette district in Michigan. A density of 2.85 gm/cc has been assigned on the basis that shelf sediments should have lower density values. A thickness of 20,000 feet (6,100 meters) has been reported in the Pine River Block, with steep dips to the south.

A few scattered outcrops of metagabbro are found in the southern portion of the Pine River block. A deeper metagabbro body (Body 5) has been inferred on the basis that this downthrown block has not been eroded as deeply as the upthrown Popple River block to the south. The main metagabbro body has therefore not been exposed.

The Pine River block has been modeled as tilted by its two boundary faults, although the structure is undoubtedly more complex. Support for a northward change of thickness is provided by Dutton's observation that the Brule River block, the northernmost of the faulted blocks, has a Michigamme thickness of 5,000 feet (1,500 meters).

Keyes Lake Block

This block is very narrow where cut by the cross-section, and is made up entirely of Michigamme Slate.

Brule River Block

The Commonwealth Syncline has preserved up to 15,000 feet (4,500 meters) of the Badwater Greenstone, with 5,000 feet (1,500 meters) of Michigamme strata outcropping to the north. Dutton has tentatively identified amphibolite occurring in Michigan, 3.5 miles (5.6 kilometers) north of Florence, as belonging to the Hemlock Formation, a greenstone sequence whose main outcrop area is farther to the north. It could also be a lens of metavolcanic material within the Michigamme Slate, since agglomerate is found within Michigamme rocks elsewhere. Also, an extensive area of metagabbro occurs along the state border northeast of Florence, and similar bodies could extend to the line of the cross-section. This is also suggested by three small metagabbro outcrops close to the line of cross-section. Aside from the questionable Hemlock rocks, information on pre-Michigamme strata are lacking. For the above reasons, interpretation of the Brule River block is more uncertain than blocks to the south. The modeling procedure carried out here demonstrates that neither of these two possibilities is needed to model the observed gravity profile. Since rocks of varying density are present in Michigan north of the profile, and the Michigamme Slate has an intermediate density, the body representing the Michigamme Slate in the Commonwealth Syncline has been extended to the north with a constant depth.

Two positive Fourier residual anomalies are associated with the Menominee Trough in the area of Profile E and are parallel to structural trends. The northern one is caused by

the high-density Badwater Greenstone of the Commonwealth Syncline, and the southern positive anomaly closely follows the Niagara Fault. This anomaly is south of the closed positive Bouguer anomaly of the Pine River block and is located over the steep gravity gradient associated with the thick Quinnesec greenstones and metagabbro bodies of the northern portion of the Popple River block. In this area the regional anomaly change is caused by the density contrast between the Northeastern Complex to the south and the higher density rocks of the Menominee Trough. Location of the positive residual anomaly is related to the maximum concentration of high-density rocks associated with the Niagara Fault. The closed Bouguer positive anomaly over the Pine River block can then be regarded as the resultant of the local and regional effects.

The southern limb of the Commonwealth Syncline has been truncated by erosion, and it is represented on both the Bouguer and the residual gravity maps as a nosing from the main positive anomaly. This anomaly, following the Badwater Greenstone outcrop belt on the northeast limb of the syncline, continues west-northwestward towards Florence and then enters Michigan.

A strong local positive anomaly is located south of Florence, and appears on both the Bouguer and residual maps as a southward extension from the Badwater Greenstone anomaly. This local anomaly is coincident with a prominent circular magnetic anomaly, however, which contrasts with the low magnetic values for the Badwater Greenstone in the northeast limb of the Commonwealth Syncline. Dutton (1971a) has identified the magnetic source as the high-density Badwater Greenstone of the Commonwealth Syncline, and the southern positive anomaly [illegible] follows the Niagara Fault. [illegible] tive Bouguer anomaly [illegible] over the steep [illegible] post-Riverton slates which are probably equivalent to the Stambaugh Slate. This magnetic anomaly is on trend with a well-defined linear anomaly extending northwest to Stambaugh outcrops in Iron County, Michigan. Dutton (1971a) has presumed that the circular magnetic anomaly has been built up by a steep northwestward plunge and extreme plication. He does not consider the Riverton Iron Formation to be a possible source of the anomaly because magnetometer traverses across outcrops of these beds have not detected anomalous values.

The gravity anomaly is believed to be caused by the Riverton Iron Formation, which is about 600 feet (180 meters) thick and separated from the above-mentioned slates by less than 100 feet (30 meters) of graywacke. The density of the iron formation is impossible to estimate because of its extremely variable composition, which includes hematite, limonite, siderite, and chert as the most common constituents. Dutton (1971a) has stated that data are too limited to determine the proportions of various facies that are present. Location of the anomaly coincides with the apex of the syncline, suggesting that the anomaly has been built up by a steep plunge and a strong degree of plication as with the magnetic anomaly.

West of Florence (Figure 14) the gravity configuration becomes less clearly related to the mapped geology. A negative anomaly 2 miles (3.2 kilometers) west of Florence and a positive anomaly 5 miles (8.0 kilometers) west of Florence both have a predominantly north-south direction and cut across faults in the area. The negative anomaly just west of Florence is probably post-Riverton slates which are probably equivalent to the Stambaugh Slate. This magnetic anomaly is on trend with a well-defined linear anomaly [illegible] outcrops in Iron County [illegible] that the circular magnetic [illegible] northeastward [illegible] produced both a contrast of the post-Riverton slates with the iron-formation south of Florence, and also by the lighter quartzites in the Michigamme Slate of the Keyes Lake block. The positive anomaly is aligned with an anticlinal area of Badwater Greenstone in the southwestern portion of the Keyes Lake block. Outcrops are not available to define the structure under the positive anomaly. In this absence it is suggested that the Badwater Greenstone has a thick development in the subsurface north of its known outcrop area.

West of the above positive anomaly is a strong negative anomaly which trends northwestward parallel to the positive anomaly associated with the Niagara Fault. An anticlinal exposure of the Badwater Greenstone extends over much of this area, making this the only negative gravity anomaly in northeastern Wisconsin associated with greenstone. A northeast nosing from the Fence-Long Lake closure of the Northeastern Complex is apparent on the Bouguer map. Although granite and felsic gneiss are not known north of the Niagara Fault, the nosing from the Northeastern Complex suggests that a granitic body may have been intruded thereby causing the anticlinal upwarping of the Badwater Greenstone and allowing erosion to reduce thickness of the greenstones and therefore diminish their gravity effect. The downthrown nature of the block north of the Niagara Fault could have prevented the inferred granitic rock from being exposed.

produced both a contrast of the post-Eiver[illegible]

the iron-formation south of [illegible]

quartzites in the Michigamme [illegible]

The positive anomaly [illegible]

Badwater Greenstone [illegible]

[illegible] block. [illegible]

[illegible]der [illegible]

Western Florence and Northern Forest Counties

Only scattered outcrops are found west of the Florence area. This information combined with the gravity mapping, however, is enough to infer the geologic framework of the area (Figure 15).

Relatively positive Bouguer values are found between the Fence-Long Lake and Forest County negative closures and the Michigan border. The Fourier residual map defines a positive anomaly extending across this area all the way to the western boundary of the study area. It can be traced continuously from the positive anomaly associated with the Niagara Fault. This major regional fault has therefore been mapped as following this anomaly, in contrast to the geologic interpretation of Dutton and Bradley (1970) based on very limited information which placed the fault as following the Michigan border and then passing north of Alvin.

Support for the gravity interpretation comes from the Price-Oneida-Vilas County greenstone belt inferred by Dutton (1971b) on the basis of drill-hole and magnetic evidence to the west of the study area. This linear belt is outlined by Dutton as extending to within 3.5 miles (5.6 kilometers) of the study area, and it lines up with the residual positive anomaly. It is therefore postulated that the greenstone belt to the west and the Quinnesec greenstone belt are connected and that the Niagara Fault follows the trend established in the Florence area of delineating the northern edge of the Quinnesec outcrop area.

Dutton and Bradley's (1970) lithology compilation map shows

frequent mafic outcrops along the positive anomaly for about 5 miles (kilometers) west of the Florence area. Beyond this there are only six known outcrops in the general area of the positive anomaly, and five of these are mafic. The lithology evidence therefore corroborates this interpretation, with a definite need for more thorough geologic study.

Aeromagnetic information is available (King and others, 1966) for this belt as far west as the Florence-Forest County line. The magnetic trends are east-west for several miles east of the county line, as would be the case if the rock units follow the pattern suggested by the positive Fourier residual anomaly.

South of Alvin the positive anomaly is 15 mgal greater than normal values on the positive trend. The Bouguer value of -1 mgal reached on this anomaly is the highest observed gravity value in the study area. Only one outcrop is known (Dutton and Bradley, 1970) on this anomaly. It is greenstone and is located on the southeast flank of the anomaly. The circular shape of this anomaly, however, suggests a mafic intrusive. Aeromagnetic mapping would be useful here, but is not available.

Several granite outcrops are found north of the positive anomaly and coincide with a negative Fourier residual anomaly. If the Niagara Fault follows the positive anomaly to the south, these granite outcrops do not agree with the distribution of rocks in the Menominee Trough and Florence area. This area is southwest of the Menominee Range, however and may be in a

different tectonic setting.

This negative anomaly is also on trend with the Conover District. Although Allen and Barrett (1915) have connected the metasedimentary areas of the Conover and Iron River districts across the extreme northwest corner of the study area, gravity suggests that an eastward extension of the Conover district may lie north of the greenstone belt in an analagous position to the Michigamme Slate of the Menominee Trough and Florence area, where the Michigamme Slate is marked by a negative residual anomaly. Granitic intrusions are known in the Conover district.

Gravity values become more positive towards the Michigan border. This reflects the regional increase in gravity towards the positive anomaly of the Menominee Range. A few greenstone outcrops near the border have been assigned to the Badwater Greenstone. Faulting has undoubtedly occurred in this area, as it has in the studied areas to the east. The faults north of the Niagara Fault do not display a consistent relationship to gravity as does the Niagara Fault, and therefore it has not been possible to extend these faults into the area. These faults should be related to gravity contours because significant density contrasts are present. Dutton (1971a) has noted the difficulty of interpreting faults based on the scattered outcrops of the area and stated that faults have never been seen in outcrop.

ROLE OF DOUBLE FOURIER SERIES METHOD IN REGIONAL - RESIDUAL SEPARATION

The double Fourier method has been effective in separating regional and residual components of the Bouguer gravity field which have the approximate anomaly dimensions specified in the separation procedure. Inspection of three profiles (Figures 8-10) displaying Bouguer, regional, and residual gravity demonstrates how this method has isolated residual components. Other methods could have been used, but this method is particularly advantageous because approximate wavelengths can be specified.

This method has been particularly effective in identifying possible extensions of the Quinnesec greenstone belt and in outlining granitic bodies related to the Northeastern Wisconsin Complex. Most of these bodies are of an optimum size to be defined by the double Fourier residual filter used in this study.

The double Fourier regional map has been useful in studying broader features of the map, particularly in considering different hypotheses for the strong positive anomalies extending into the areas of Wausaukee and Crivitz from the Argonne Gravity Trend. The broad features of the Northeastern Wisconsin Complex and the Wolf River Batholith are also readily apparent.

This method loses effectiveness for anomalies which have strong components of the Bouguer gravity anomaly field within them at the cut-off wavelength. These components may go into

either the residual or regional map. This could be rectified by performing another regional-residual separation with a different cut-off wavelength. Another problem consists of edge effects near the map boundaries, but this problem is also found with other separation techniques.

ADDENDUM

Deeper Anomaly Sources

Although the study area is of somewhat limited extent for investigation of deep crustal structure, an attempt has been made to synthesize previously published information with gravity data. Because of its less direct application, this section has been placed in the addendum.

Seismic refraction measurements have been made in northern Wisconsin and adjoining Michigan by Schlichter (1951) and Steinhart, Meyer, and Woollard (in Steinhart and Meyer, 1961). Steinhart et. al. analyzed both sets of data and inferred an increase in crustal thickness from approximately 36 km in the southwestern portion of the present study area to 40 km along the eastern margin.

The Wisconsin uplift, whose axis extends roughly north-south through central Wisconsin, is characterized by a negative Bouguer anomaly (Woollard, 1972). Woollard has discussed the relation of this anomaly to inferred subnormal crustal and upper mantle velocities and subnormal crustal thickness for the surface elevation. He concluded that this fits the general ideas of isostatic compensation.

The suggestion has been made that the subnormal velocities of the thinner crust are related to the "Wisconsin Batholith",

which at one time was believed to cover much of north-central Wisconsin. Subsequent mapping has shown that the geology is much more complicated, with many other lithologies present. Van Schmus (1973) has established three different ages of granitic activity, but no pervasive granitic intrusions are present.

Therefore, the subnormal velocities and densities considered by Woollard to account for the gravity anomalies must be found deeper than the shallow crust. The change in crustal thickness across the area is undoubtedly accompanied by density changes, because of the systematic relationship between seismic velocity and density for crystalline rocks. The regional gravity map does not show, however, a systematic effect which would be correlated with the observed change in crustal thickness. This can be explained by the dominant effect of near surface geology, and it would be necessary to prepare a very long wavelength regional map to see a correlation. Woollard (1972) has prepared a 1° by 1° Bouguer anomaly map of the United States which indicated an increase in gravity from west to east across northeastern Wisconsin. This correlates with the crustal thickness changes as observed by seismic refraction measurements.

In summary, a broad gravity effect related to changing crustal thickness can be demonstrated, but specific configurations cannot be established due to the overriding effect of near surface geology.

Relationship of Gravity Anomaly Trends and Elevation

An inverse relationship between Bouguer gravity anomalies and basement elevations has been noted by many authors, including Woollard (1962, 1966), Henderson and Zietz (1958), Hinze (1963), and McGinnis (1966). Verma (1971) has shown that for the midcontinent of the United States this is not a simple relationship, but is complex and variable from area to area. In the eastern midcontinent area this relationship holds only for basin areas where basement elevations are below sea level. Basement elevations in northeastern Wisconsin, however, are near sea level in southeastern Marinette County and increase steadily to the northwest.

Calculation of mean anomalies and elevations was carried out to determine how northeastern Wisconsin agrees with predicted anomalies based on elevation. The mean Bouguer anomaly for each township was estimated by inspection of the contour map. Two or three gravity stations which were close to this value were then selected from the quadrangle maps. Elevations and free-air anomalies for those stations were used to calculate mean values for each township.

Mean Bouguer, elevation, and free-air values were determined for each township tier (Table 3), and mean values for the entire study area were then calculated. Township tiers were used as the basis of calculation because of the dominant east-west direction of anomalies. All values were weighted according to area.

TABLE 3

Township	Area (Sq.Miles)	Mean Bouguer Anom.	Mean Elev.	Mean Free-air Anom.
29N	334	-62.2	875	-32.0
30N	427	-63.2	908	-32.3
31N	398	-64.2	996	-30.2
32N	393	-64.9	1099	-27.8
33N	415	-63.0	1115	-29.4
34N	363	-55.6	1260	-12.8
35N	367	-53.3	1300	- 9.2
36N	372	-48.3	1332	- 3.0
37N	372	-48.3	1341	- 2.7
38N	345	-51.0	1429	- 2.4
39N	284	-49.0	1474	+ 1.3
40N	255	-28.2	1551	+24.6
41 & 42N	117	-17.6	1625	+37.6
Summary				
29N-33N	1967	-63.5	1002	-29.4
34N-39N	2104	-51.0	1350	- 5.0
40N-42N	372	-25.0	1572	+28.7
Entire Area	4443	-54.4	1215	-13.0

Mean Bouguer anomaly values become more positive to the north, with a significant increase between T33 and 36N, and a very sudden increase between T39 and 40N (Figure 21). There are two dominant Bouguer anomaly levels, with weighted means of -63.5 mgal, -51.0 mgal, and a suggested third level to the north with more positive values. These levels correspond to known geology, with the more negative values to the south influenced by the Wolf River Batholith and the more positive values to the north caused by the greenstones and other dense rocks that become common near the Michigan border.

Woollard (1972) considers that isostatic equilibrium can be achieved with $3^{o} \times 3^{o}$ areas. The study area of approximately $1^{o} \times 1^{o}$ is therefore not large enough to consider by itself. A Bouguer anomaly of -41 mgal would be expected for isostatic equilibrium of an area having the observed mean elevation of 1,215 feet. Predicted values can be obtained from a plot of Bouguer values against elevation for $2^{o} \times 2^{o}$ rectangles of the U.S. midcontinent (Verma, 1971) or from the formula for the slab correction. The two methods yielded results within 1 mgal of each other for the study area. An actual weighted mean Bouguer value of -54 mgal was observed. The observed discrepancy with predicted Bouguer values can be most easily explained as an effect of local geology, with the granitic rocks of the Wolf River Batholith and the Northeastern Wisconsin Complex contributing to a depressed mean Bouguer anomaly. The Bouguer map of the Iron-River-Crystall Falls district of

Mean Bouguer anomaly values become [illegible]

north, with a significant increase [illegible]

very sudden increase [illegible]

are two dominant [illegible]

of -63.5 mgal, [illegible]

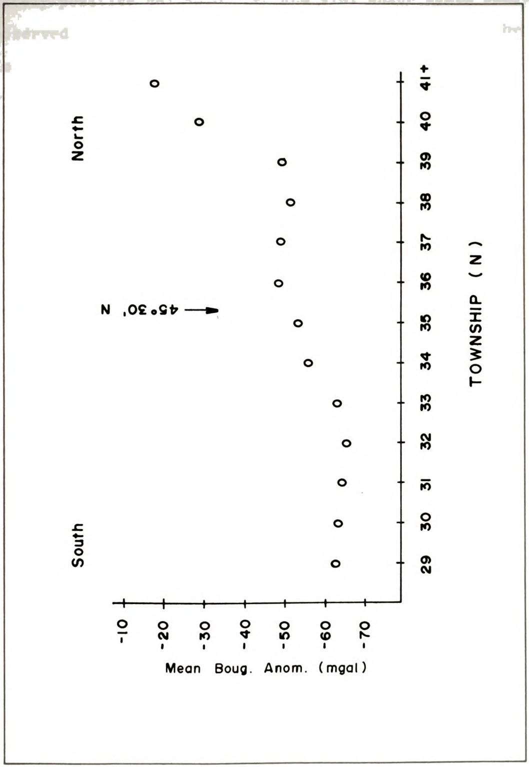

Fig. 21 MEAN BOUGUER ANOMALIES OF TOWNSHIP TIERS

Michigan (Bacon and Wyble, 1952) shows a continuation of the relatively positive values of T40 and 41N, which would cause the observed mean Bouguer values to closely approximate the predicted anomaly if part of Michigan were included in the study area.

The mean free-air anomaly of -13 mgal for the study area corroborates the results of the Bouguer analysis, showing a net deficiency of mass in the study area.

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The mean [illegible]

[illegible]

[illegible]

CHAPTER VI

Conclusions

A one-mile (1.6 kilometer) station spacing is necessary in defining major rock units and in measuring their gradients, but is not sufficient for determining all units. In some areas of this study a one-mile (1.6 kilometer) spacing was not possible because of lack of roads.

The double Fourier series technique is very useful in the separation of regional and residual components of the observed gravity anomaly field if sufficient information is available to aid in the selection of a cut-off wavelength and if a density contrast is present. For example, the observed gravity anomaly field over the low density gneissic and granitic rocks of the Northeastern Wisconsin Complex has been separated into a regional component which extends from the Dunbar Gneiss outcrop area across the entire study area and a residual component which defines satellite granitic bodies.

Extrapolation and interpolation with gravity of geologic trends from areas of known geology has been effective for both greenstone belts and granitic-gneiss complexes.

Greenstone belts are more extensive than defined by outcrop studies. Fourier series residual anomalies suggest that narrow tongues of greenstone may extend to the western margin of the

study area from the main outcrop area of the Quinnesec Formation and be related to greenstone belts to the west. This distribution pattern is similar to Archean greenstone belts in Canada. An extension of the Waupee Greenstone to the east is suggested by gravity, but aeromagnetic evidence will be necessary to decide between this and other hypotheses.

The Northeastern Wisconsin Complex is well defined by gravity, with the Dunbar Gneiss occupying the central portion of the anomaly in its outcrop area. Gravity and scattered outcrops suggest that this granitic complex extends to the western margin of the study area. Granitic bodies occupying a satellite position to the major anomaly are well defined by Fourier series residual anomalies.

The Wolf River Batholith is represented by a broad gravity minimum, but separate bodies within the batholith that have been established by geologic mapping are not defined by gravity. Anorthosite bodies may be present within the batholith near the southern boundary of the study area.

Major bodies have not been found representing the Central Wisconsin Complex. Intrusive bodies known to belong to this age of activity are not defined gravimetrically because of lack of density contrast with surrounding rocks.

The Argonne Gravity Trend is a strong positive anomaly associated with little known mafic and ultramafic rocks. Gravity has established that this is a significant feature of considerable extent which should be further studied.

The Niagara Fault is probably steeply dipping to the north, as suggested by two-dimensional model studies and by location of the fault trace relative to a positive Fourier series residual anomaly. An alternate hypothesis to published geologic interpretations is advanced for extension of the Niagara Fault to the west.

Two-dimensional modeling has aided in the interpretation of selected areas, but the geology is of such complexity that considerable ambiguity is attached to modeling results.

Figure 22 summarizes the major geologic features of northeastern Wisconsin based upon previously published studies and the interpretations of this investigation.

The two major granitic complexes of the area, the Wolf River Batholith and the Northeastern Wisconsin Complex, are separated by the Argonne Gravity Trend. The Quinnesec greenstone belt is interpreted to have a greater extent than previously reported.

The Niagara Fault is probably steeply dipping to the north, as suggested by two-dimensional model studies and by location of the fault trace relative to a positive [illegible] series residual anomaly. An alternate hypothesis [illegible] geologic interpretation [illegible] Niagara Fault [illegible]

Two-dimensional [illegible]

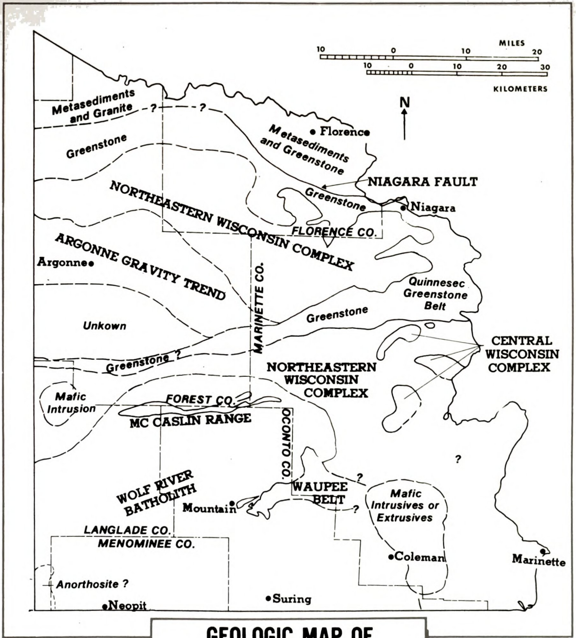

Fig 22

GEOLOGIC MAP OF NORTHEASTERN WISCONSIN

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