UNIVERSITY OF MINNESOTA

GEOLOGICAL SURVEY

SIMPLE BOUGUER GRAVITY MAP OF MINNESOTA AND NORTHWESTERN WISCONSIN

Campbell Craddock, Harold M. Mooney, and
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A Discussion To Accompany
Miscellaneous Map Series
Map M-10

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P. K. Sims, Director

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INTRODUCTION

This map and report are the result of a geological and geophysical study of the Minnesota-Wisconsin segment of the Midcontinent Gravity High (fig. 1) begun in 1960 at the University of Minnesota. The geophysical program has included seismic refraction, magnetic, and gravity studies. The gravity program was started in 1961 and was soon expanded to integrate available gravity measurements from throughout the state of Minnesota. The purposes of this program have been to 1) obtain systematic gravity measurements in the area of the Midcontinent Gravity High, 2) establish a network of accessible gravity base stations in Minnesota, 3) compile gravity data available on the state of Minnesota and tie all surveys to a common master base, 4) construct a simple Bouguer anomaly map of Minnesota and northwestern Wisconsin, and 5) provide a geologic interpretation of the principal gravity anomalies.

Although scattered gravity pendulum measurements have been made in Minnesota since early in the century, modern surveys with gravimeters have been conducted only during the past twenty years. Beginning in 1948, Professor George P. Woollard and students from the University of Wisconsin established several gravity stations in the area, mainly at about 10-mile intervals along major highways. Later work by the Wisconsin group included a series of traverses across the northern part of the Minnesota-Wisconsin segment of the Midcontinent Gravity High by Thiel (1955; 1956) and a gravity survey of east-central Minnesota by Adams (1957). Later, Woollard and Rose (1963) published a Bouguer anomaly map of Minnesota having a contour interval of 20 milligals at a scale of about 1:4,000,000. The U.S. Geological Survey sponsored gravity surveys of the Cuyuna iron range by George Durfee in 1955 and of the Duluth area by Wayne Sonntag in 1959. From 1955 through 1959 the U.S. Coast and Geodetic Survey established a network of more than 2,400 stations throughout most of Minnesota at a spacing of about a station per township.

Gravity measurements by personnel of the University of Minnesota, from stations which exceed 12,000 in number, are also included on the gravity map. Fogelson (1956) made a detailed survey of Redwood County, and 30 of his base stations were used by us. In 1961, Barton Gross and Dennis Deischl (Craddock and others, 1963), extending the earlier work of Thiel (1956) southward to Iowa, ran ten traverses across the Midcontinent Gravity High using a station spacing of one-half mile. In 1962, K. Veith and B. Sharma (Veith, 1966) ran combined gravity and magnetic traverses across the same feature in the Minneapolis-St. Paul area. During 1963 and 1964, Bruce Hemingway and Sharma (Sharma, 1964) ran a series of traverses with a half-mile station spacing across the Douglas fault (fig. 2), mainly in Pine and Chisago Counties. Hemingway and James Frawley established sixteen new airport gravity base stations in Minnesota through a series of flights in 1964; and Hemingway and Craddock conducted a brief survey of southwestern Isle Royale, Michigan in the same year (see Appendix A). Later, Ikola (1967) made a detailed gravity survey in Carlton County. During 1964, Frawley and Robert Cairns ran a series of north-south lines with a half-mile station spacing in Douglas, Bayfield, and Ashland Counties, Wisconsin. The following summer, J. Carruthers and Stephen Johnson extended this work southward in Wisconsin by establishing a one-mile grid of gravity stations, and in 1966 Carruthers continued this survey southward to the Mississippi River.

At least three private companies are known to have made gravity surveys within the area of the map. The results of these studies had not been made available to the public in 1966, and hence are not included in the map.

All gravity measurements available in the fall of 1966 were punched on cards, and the simple Bouguer anomalies were incorporated in the map. All surveys were adjusted to a common datum by ties to a master base station in Pillsbury Hall, University of Minnesota, Minneapolis.

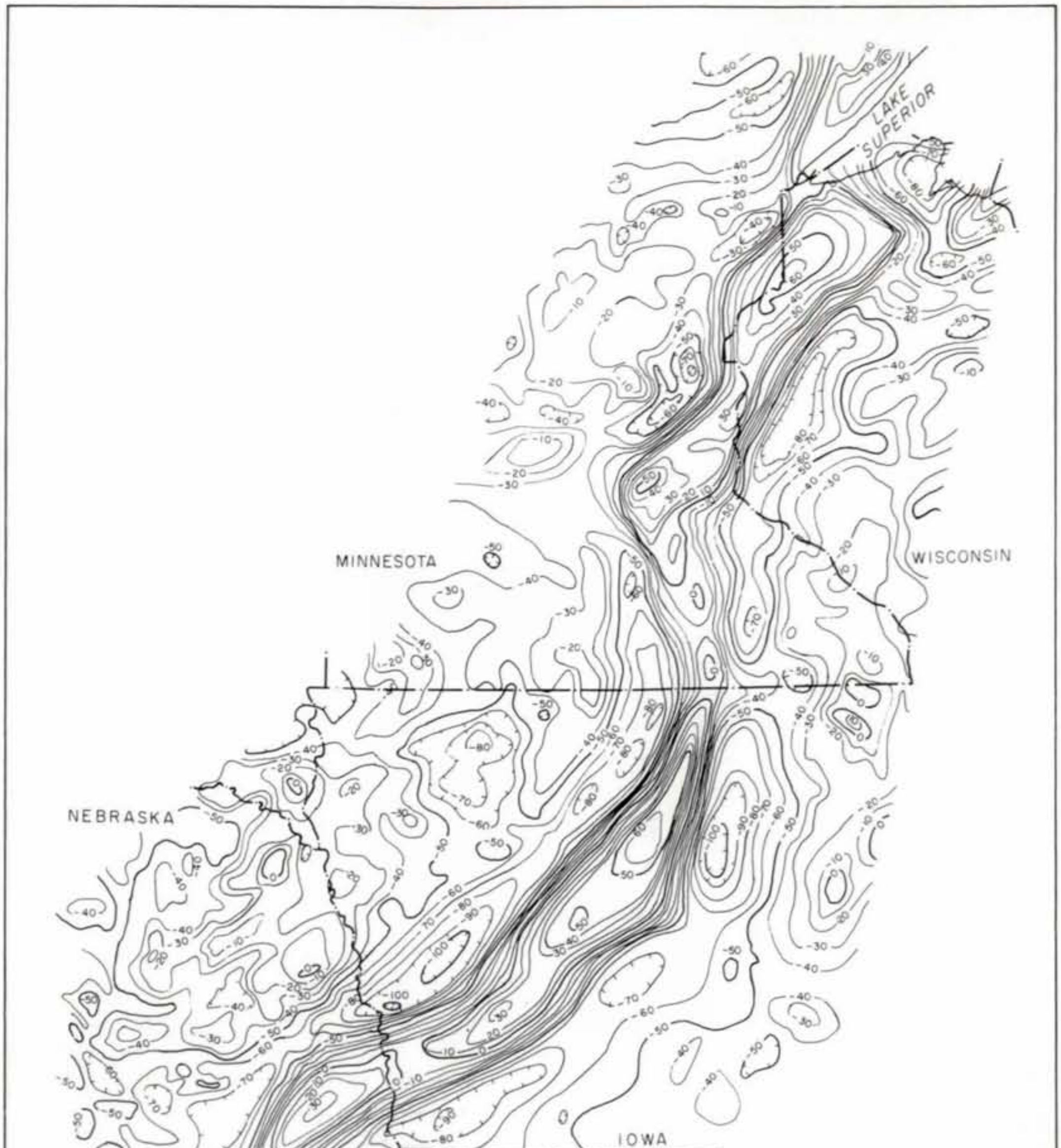

Figure 1 - Simple Bouguer anomaly Map of the Midcontinent Gravity High.

The financial support provided for this gravity program by the Graduate School of the University of Minnesota, the Minnesota Geological Survey, and the National Science Foundation is gratefully acknowledged. Appreciation is also expressed to the National Park Service for boat transportation during the work on Isle Royale.

THE UNIVERSITY OF MINNESOTA GRAVITY PROGRAM, 1961-1966

The purposes and scope of this program have been discussed above; the field and data reduction procedures are summarized here. Most gravity measurements were made with Worden gravimeters (Nos. 76 and 291), although a LaCoste-Romberg gravimeter was used by Veith. Gravity base stations were established in the field by multiple ties to the master base in Pillsbury Hall. Individual gravity stations were occupied in a looping pattern, and several stations were reoccupied daily to provide gravimeter drift control. The geographic position of each station was obtained from U.S. Geological Survey topographic quadrangle maps or from county highway maps using a variable scale ruler. Station elevations were based on U.S. Coast and Geodetic Survey level lines, bench marks, surveyed road intersections, or the average reading of two or more altimeters.

Data reduction began with the plotting of a drift curve for the gravimeter. The instruments used showed generally linear positive drift for the season, complicated by minor fluctuations during a typical day. The drift-adjusted Δg in scale units was converted to milligals using the appropriate scale constant, and all facts about each station were tabulated in a master ledger. The data for each station were keypunched into a standard 80-column machine punchcard according to the following system:

Columns	Information	Example
1-2	Last two digits of year of survey	66
3-4	Code for survey	QA
5-8	Station number in survey	0156
10-11	Code for geologic province of station	21
13-14	IBM code for state in which station is located	48 (Wisconsin)
16-18	IBM code for county in which station is located	109 (St. Croix)
20-21	Section of township in which station is located	27
23-26	Township of station	28N
27-30	Range of station	15W
32-38	Latitude of station	44 53.2
40-47	Longitude of station	92 11.7
49-53	Station elevation in feet	1170
55-57	Code for gravity base station on which this station depends	860 (Stillwater)
59-66	Absolute gravity at base station, in gals	980.5892
68-73	Difference in gravity (Δg) between base station and this station, in milligals	-112.8
75-80	Cumulative number of card in system	15369

The code for the surveys included in the punchcard system is as follows:

GA - Gross, ten traverse lines
GB - Gross, Minneapolis grid
HA - Hemingway, Pine and Chisago Counties
AA - Adams, east-central Minnesota
FA - Fogelson, Redwood County
SA - Sonntag, Duluth area
CA - U. S. Coast and Geodetic Survey, Minnesota grid
IA - Ikola, Carlton County
VA - Veith, Minneapolis area traverse lines
DA - Durfee, Cuyuna iron range
HB - Hemingway, airport base stations
QA - Frawley, Carruthers, northwestern Wisconsin

The code for the geologic province of the gravity station includes two digits. The first number describes the formations that overlie the Precambrian, whereas the second describes the underlying Precambrian rock. The code is as follows:

Column 10	Column 11
0 - Unknown	0 - Unknown
1 - Youngest bedrock is Precambrian	1 - Keweenawan•
2 - Paleozoic	2 - Pre-Keweenawan
3 - Paleozoic and Mesozoic	3 - Sioux or Barron Quartzite
4 - Paleozoic, Mesozoic and Cenozoic	4 - Pre-Sioux or Barron
5 - Paleozoic and Cenozoic	5 - Animikie
6 - Mesozoic	6 - Pre-Animikie
7 - Mesozoic and Cenozoic	
8 - Cenozoic	

A computer program was written to calculate gravity anomalies directly from the punchcards. Computer printout sheets include the following data: year, survey code, station number, latitude, longitude, gravity base station code, free air anomaly in milligals, and Bouguer anomaly in milligals. The reference datum for the Bouguer anomalies is sea level, and a density of 2.67 gm/cm^3 is assumed for the rock between the station and sea level. No terrain corrections were applied to the Bouguer anomalies; test calculations for stations in the narrow tributary valleys along the Mississippi River in southeastern Minnesota yielded corrections of less than one milligal.

Local variations in the thickness of low-density surficial deposits are the greatest obstacle to calculating exact Bouguer anomalies. In areas underlain by thick Cretaceous or Pleistocene deposits, errors in excess of 7 milligals are possible, but these errors will tend to be nearly uniform from station to station within that area. Estimated errors in the Bouguer anomalies, in milligals, are summarized below:

Source	Mean Error	Maximum Error
Gravimeter drift	0.2	1.0
Elevation	0.3	1.8
Terrain	0.2	1.0
Earth tides	0.1	0.2
Rock density	0.8	7.0
Latitude	0.04	0.08

For a typical station, if all errors had the same sign, an absolute error of about 1.6 milligals could be expected. Most stations yield Bouguer anomalies considered to be within one milligal of the true value.

The Bouguer anomalies, adjusted where necessary to the Pillsbury Hall master base station, were plotted on overlays to the U.S. Geological Survey 1:250,000 sheets of the area. Each overlay was contoured at a 10-milligal interval and reduced photographically to a 1:1,000,000 scale. These reductions were then compiled on a stable base into the present map.

GRAVITY BASE STATION NETWORK IN MINNESOTA

Pendulum stations established by the U.S. Coast and Geodetic Survey during the first half of this century represent the earliest network of gravity bases in Minnesota. Although these stations were few and scattered, they did disclose the existence of some large gravity anomalies in the area. However, recent evaluation of these pendulum stations with a gravimeter (Woollard and Rose, 1963) shows that they are accurate only to about ± 3 milligals and hence unsuitable as reference points for modern precision surveys.

Following the introduction of the Worden gravimeter in 1948, Professor George P. Woollard and students at the University of Wisconsin established a world-wide network of airport gravity base stations. Woollard and Rose (1963) provide descriptions of the bases in this network, including seven in southern Minnesota. These bases and seven other airport bases close to Minnesota in adjacent states are included in the present network (see Appendix B). The airport network is based upon a gravity value of 980.1188 gals for the national base in the basement of the Commerce Building in Washington, D.C., and a value of 980.3689 gals at the alternate base in the basement of Science Hall in Madison, Wisconsin (Woollard, 1958; Behrendt and Woollard, 1961).

When the University of Minnesota gravity program began, it was necessary to tie the new work to a reliable base in the national network. Woollard's base WA 118 at Wold-Chamberlain Airport, based on numerous airborne ties to the Madison base, was selected as most appropriate. However, at that time a new terminal building was under construction, and Woollard's original site soon became difficult of access. Accordingly, two new alternate bases were established, one in Pillsbury Hall at the University of Minnesota (Station No. 2 in Appendix B) and one in the new airport terminal building (Station No. 12). The Pillsbury Hall base has been used as the master gravity base in our work.

Woollard's gravity base network in southern Minnesota was extended northward with new bases tied to the Pillsbury Hall base. Airport bases were established using University of Minnesota aircraft from the Anoka County airport, and the others by automobile. The gravity base at the Windigo Ranger Station on Isle Royale was established by ship from Grand Portage. Selected bases in this network are plotted on the map, and the station locations are reported in Appendix B.

Since 1967, R. Ikola of the Minnesota Geological Survey has been establishing gravity base stations throughout the state with a pair of LaCoste-Romberg geodetic gravimeters. This program should result shortly in a more extensive and accurate gravity base network in Minnesota tied directly to the national gravity base in Washington, D.C.

GEOLOGIC INTERPRETATION

Diverse Precambrian rocks, which represent the southern margin of the exposed Canadian Shield, comprise the bedrock throughout much of the map area (fig. 2). It is convenient to divide the Precambrian rocks into three major

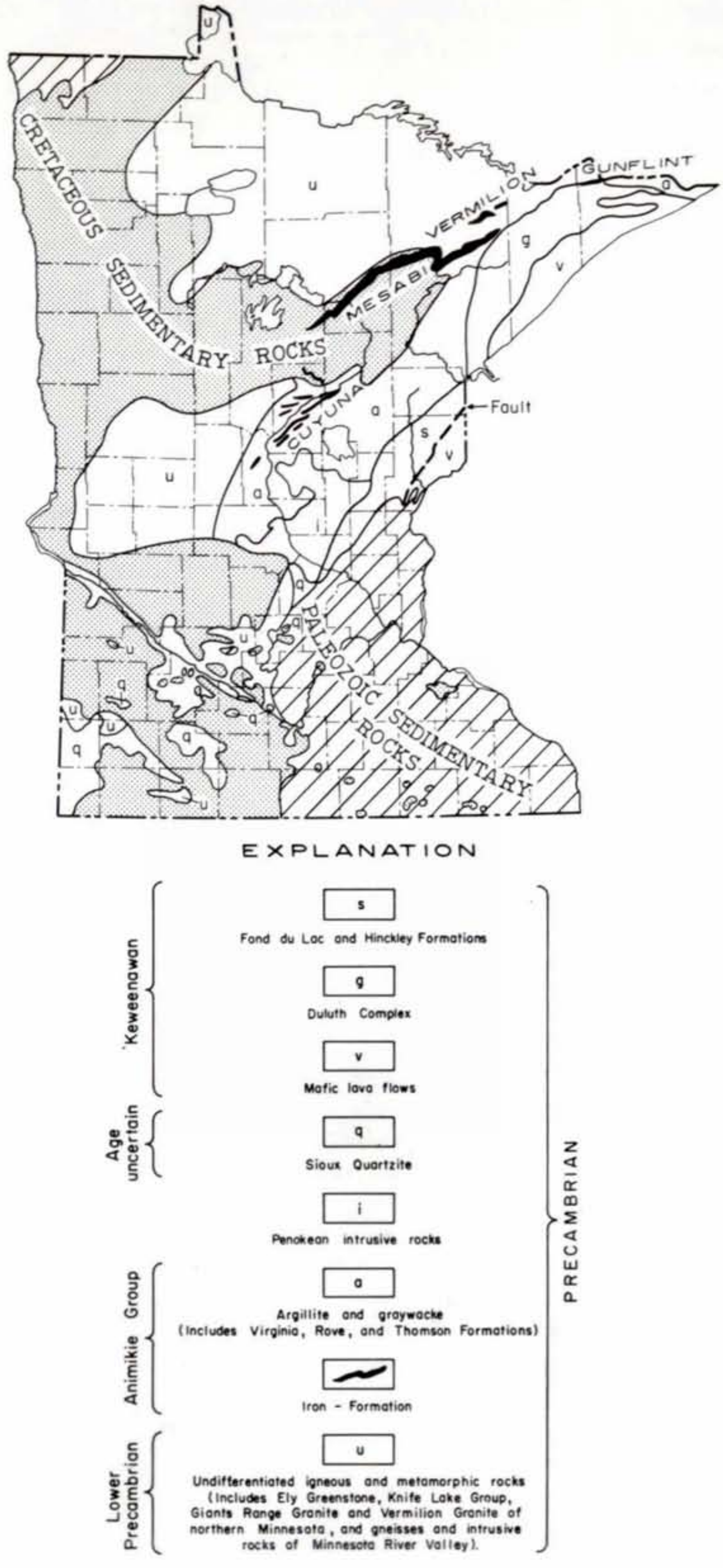

Figure 2 - Generalized geologic map of Minnesota.

units, as proposed by Goldich and others (1961). The Lower Precambrian includes all pre-Animikie rocks; strata of this age crop out north of the Mesabi iron range and in the Minnesota River Valley. The Middle Precambrian consists of the Animikie Group, together with igneous rocks that Goldich and others (1961) have designated as Penokean in age. Rocks of this age are found along the International boundary in northeastern Minnesota, on the Mesabi iron range and southward into east-central Minnesota, and in Ashland and Iron Counties in Wisconsin. The Upper Precambrian includes the Keweenawan rocks of northeastern and east-central Minnesota and most of northwestern Wisconsin, and possibly the Sioux Quartzite of southwestern Minnesota and the Barron Quartzite of Wisconsin. The Precambrian basement complex is overlain by lower Paleozoic strata in the northwestern and southeastern parts of the map area and by Mesozoic (Cretaceous) beds in the western part. These Paleozoic and Mesozoic strata attain a maximum thickness of about 1,500 feet. Pleistocene glacial deposits form a veneer throughout most of the area and are as much as 400 feet thick in some places in western Minnesota.

Because the Phanerozoic rocks and surficial deposits comprise a thin blanket that generally shows only gradual lateral changes in composition and thickness, the cause for major Bouguer gravity anomalies must be sought in the underlying Precambrian rocks. Abrupt local variations occur in the thickness of the low-density Pleistocene deposits, as in the buried pre-glacial bedrock valleys of the Minneapolis-St. Paul area (Payne, 1965), but such features do not produce anomalies greater than a few milligals. It is possible that some broad anomalies, several tens or hundreds of miles across, may be caused by variations in crustal thickness or density contrasts deep within the crust. However, in this stable region it is probable that most of the anomalies, especially those with large amplitude and steep gradients, are related to compositional changes in the Precambrian rocks within a few miles of the earth's surface. Accordingly, the Bouguer gravity map provides a basis for projecting the boundaries of Precambrian rock bodies from localities of surface outcrops or from drill holes into adjacent areas covered by Phanerozoic deposits.

It is well established that Bouguer gravity anomalies calculated for gravity stations tend to become more negative as station altitude increases. Woollard (1959) gives an empirical curve that relates the Bouguer anomaly to surface altitude; the curve is based on numerous gravity measurements in both the eastern and western hemispheres. If the local highlands in northeastern and southwestern Minnesota are excluded, the mean altitude for the map area is estimated at about 1,100 feet above sea level. Woollard's curve indicates that the mean Bouguer anomaly for such a region should be about -45 milligals. Colors for the contour intervals on the map were chosen to conform to the scheme commonly used on physiographic maps, with "sea level" at the -40 milligal contour, the approximate predicted or normal Bouguer anomaly for the region. In this way, significant departures from the expected Bouguer anomaly appear as distinctive highs and lows on the map. Such anomalies suggest the presence of relatively high- or low-density rock bodies in the underlying Precambrian complex.

The most conspicuous anomaly on the map is the positive feature that trends northward from the Iowa border through the Minneapolis-St. Paul area, comprising the northern part of the Midcontinent Gravity High, which extends southwestward across Iowa into Nebraska (fig. 1). Upper Precambrian Keweenawan rocks crop out just south of Lake Superior, and the gravity high at this locality is caused by an uplifted block of Middle Keweenawan mafic lava flows termed the St. Croix horst (Thiel, 1956; Craddock and others, 1963). The internal structure of the horst is synclinal, and Upper Keweenawan sedimentary rocks of the Oronto Group (Thwaites, 1912) occur along the axis of the syncline in northwestern Wisconsin (see geologic map of Wisconsin). These sedimentary rocks are lacking on the horst near the Minnesota-Wisconsin border, but similar rocks are preserved in small grabens and basins atop the horst (Sims and Zietz, 1967; Coons and others, 1967) to the southwest in Minnesota, Iowa, and Nebraska. The probable thickness of the Middle Keweenawan flow sequence is at least 20,000 feet in its outcrop area; scattered wells indicate that these volcanic rocks extend southward into Iowa and beyond along the gravity high.

Two significant bends in the anomaly over the Midcontinent Gravity High are apparent on the map. The larger one occurs just south of Minneapolis and St. Paul, and may be caused by a sinistral strike-slip fault having an apparent horizontal displacement of about 30 miles (Craddock and others, 1963). A northwest-trending fault that cuts Paleozoic strata near Belle Plaine along the Minnesota River may be the surface trace of the inferred fault in the underlying Keweenawan rocks (Sloan and Danes, 1962; Sloan and Austin, 1966). A smaller bend northeast of the Twin Cities near the Wisconsin border probably is related to a change in strike of the western edge of the horst. The axis of the gravity high, here as elsewhere, tends to bisect the horst. Moreover, the zone of steep gravity gradients along the southeastern edge of the high shows no indication of being offset by a transverse fault.

The St. Croix horst is bounded on the northwest and southeast by high-angle reverse faults which place basaltic flows against clastic sedimentary rocks, mainly sandstones. These faults are expressed on the map as narrow belts of steep gravity gradients; just northwest of Minneapolis, the Bouguer anomaly changes 17 milligals in one mile, and even higher gradients exist directly over the fault. In rare surface exposures these faults dip as low as 40°, but gravity profiles across them suggest steepening down the dip. Recent geophysical work (Craddock and others, 1963; Sharma, 1964; Veith, 1966; Barazangi, 1967; Farnham, 1967; Ikola, 1967; Volz, 1968) indicates that the throw on these major boundary faults is about 8,000-9,000 feet. The southeast boundary fault has been termed the Hastings fault near the Twin Cities by Sims and Zietz (1967); minor late movements have displaced the overlying Paleozoic strata slightly. To the northeast this fault bounds the southeast edge of the Hudson-Afton anticline, and it appears to extend into or near the Lake Owen fault, mapped in southern Bayfield County, Wisconsin by Aldrich (1929). The northwest boundary fault of the horst is the Douglas fault, which can be mapped at the surface from near Pine City, Minnesota northeastward across Douglas County, Wisconsin. The eastward disappearance of the sharp bend in the contours on the gravity map suggests that the Douglas fault dies out in Bayfield County, as also indicated by aeromagnetic profiles (Patenaude, 1966). Whether these boundary faults exist in Minnesota south of the Belle Plaine transverse fault is less certain, but the gravity high appears to have faulted margins in central Iowa.

The gravity high bifurcates in northwestern Wisconsin, where it gives way to a nearly circular gravity low centered on the Bayfield peninsula. The southern branch follows an outcrop belt of Middle Keweenawan mafic igneous rocks, including both lava flows and gabbroic intrusive rocks, to the east into Michigan. The northern branch extends northward across the Douglas fault into northeastern Minnesota, where it overlies Middle Keweenawan rocks of the North Shore Volcanic Group and the Duluth Complex. The gravity low on Bayfield peninsula coincides with a thick clastic sedimentary sequence of the Oronto Group (Upper Keweenawan) and the Bayfield Group (Upper Keweenawan or younger), which may reach a total thickness of 25,000 feet (Thwaites, 1912).

Along most of its extent south of Lake Superior the Midcontinent Gravity High is flanked by linear gravity lows that define significant sedimentary basins. The basin east of the Hastings fault underlies the River Falls syncline, a gentle flexure developed in the Paleozoic strata that crop out in this area. The gravity low disappears to the northeast, south of the first outcrops of rocks older than Upper Cambrian; hence the sedimentary rocks causing the gravity low cannot be seen at the suface. Wells into bedrock over the gravity low in Wisconsin are shallow, and only a few have penetrated sedimentary rocks possibly older than Upper Cambrian. Such older rocks, known locally as the Red Clastic Series, have been encountered in deep wells in Minnesota; they are at least 340 feet thick at Hastings and 2,033 feet thick at Rochester. Both gravity profiles (Craddock and others, 1963) and seismic refraction lines (Farnham, 1967; Volz, 1968) indicate that these strata attain a thickness of more than 10,000 feet in the eastern basin. The precise age and correlation of these sedimentary rocks are unknown, but they may be equivalent to the Jacobsville Formation, which lies southeast of the mechanically similar Keweenawan fault northeast of Lake Gogebic in upper Michigan. The Jacobsville Formation may be as old as Keweenawan or as young as Cambrian (Hamblin, 1958).

West of the Midcontinent Gravity High in Minnesota, rocks assigned to the Fond du Lac and Hinckley Formations form a comparable sedimentary basin. These strata are less than 2,500 feet thick west of Minneapolis (Sims and Zietz, 1967), thicken northeastward to about 10,000 feet (Welch, 1941; Craddock and others, 1963), thin to a few thousand feet in Douglas County, Wisconsin (Farnham, 1967), and thicken again to perhaps 25,000 feet in Bayfield County (Thwaites, 1912). The sedimentary rocks in this basin are older than Upper Cambrian and in Minnesota are assigned by the Minnesota Geological Survey to the Upper Keweenawan.

In southwestern Minnesota, rock outcrops are sparsely scattered south of the Minnesota River Valley. Much of this area is underlain by Precambrian Sioux Quartzite, which is at least 3,800 feet thick at Wagner, South Dakota (Baldwin, 1951) but possibly thinner in Minnesota. The Sioux Quartzite forms two main basins in Minnesota, one centered in Cottonwood County and the other in Rock and Pipestone Counties. Interpretation of the gravity anomalies in this area is uncertain. Somewhat higher gravity values occur in Cottonwood County, and relatively low values are found in Rock and Pipestone Counties. These small gravity variations may be caused by density contrasts between the Sioux Quartzite and unknown adjacent rock bodies or may be related to contrasts within the underlying, older Precambrian rocks.

The Precambrian strata that crop out in the Minnesota River Valley between Ortonville and New Ulm are mainly plutonic igneous and metamorphic rocks (Lund, 1956; Goldich and others, 1961) of Early Precambrian age (Sims, P.K., oral comm.; 1969). Density data on these rocks are lacking, but the gravity anomaly patterns show interesting relationships to the exposed rocks. The lower part of the valley between New Ulm and Sacred Heart is underlain by the Morton quartz monzonite gneiss of Lund (1956) and associated granitic intrusive rocks. These rocks trend eastward, and appear to be responsible for the prominent east-trending gravity low that crosses the valley near Redwood Falls. To the northwest, in the valley near Granite Falls and Montevideo, outcrops consist mainly of mafic gneisses and a granitic gneiss (Himmelberg, 1968). These rocks also trend eastward and appear to be responsible for the distinct gravity high of the same trend that crosses the valley between Granite Falls and Montevideo. The minor gravity low north of Ortonville is possibly related to the Precambrian granitic rocks that crop out in that part of the valley.

Central Minnesota is marked by a belt of high gravity values about 100 miles wide that trends west-southwestward from the edge of the Keweenawan province. This belt extends south to the linear gravity high near Granite Falls, discussed above, and its northern margin is defined by a roughly parallel gravity low. Outcrops within this area consist of igneous and metamorphic plutonic rocks and lower rank metasedimentary rocks; radiometric ages on these rocks are mainly in the 1.6 to 1.8 billion year range. This belt of high gravity anomalies appears to define the approximate extent of the Penokean orogen in Minnesota (Goldich and others, 1961). The northward decrease in Bouguer anomaly values toward the edge of the belt, as from Carlton County into St. Louis County, possibly reflects the northward reduction of metamorphic grade and deformational intensity. A minor linear gravity high appears to be related to gently-dipping strata of the Animikie Group that are exposed on the Mesabi range.

North of the Mesabi range and west of the Keweenawan basin lies a complex terrane of Lower Precambrian rocks. These rocks are fairly well exposed in Cook, Lake, and St. Louis Counties, but are covered by glacial deposits in northwestern Minnesota and knowledge there is based on widely spaced drill holes and sparse exposures. In reconnaissance mapping of such terranes the bedrock may be divided into two main categories, as in southwestern Ontario (Geological Map of the Province of Ontario, 1958). One category consists of strongly deformed and somewhat metamorphosed volcanic and clastic sedimentary rocks, predominantly chloritized mafic flows and graywackes; these rocks form linear belts commonly termed "greenstone belts." The other major category includes granitic intrusives and associated gneisses, which are mainly felsic in composition. On the basis of extensive measurements on rocks from the southern Canadian Shield, Innes (1960) has shown that the greenstone belts have an average density 0.1 to 0.3 gm/cm^3 greater than that of the granitic rocks.

The most prominent Bouguer anomaly low in Minnesota lies immediately north of and parallel to the Mesabi range. This low overlies the outcrop belt of the Giants Range Granite and must be related to it. An irregular gravity high just to the north appears to be related to the mafic volcanic rocks that extend west-southwestward from the Vermilion district (Sims and others, 1968). The gravity low in northern St. Louis County coincides with the general outcrop area of the Vermilion Granite.

The gravity anomaly patterns in northwestern Minnesota are difficult to interpret because so little is known about the bedrock geology. The Bouguer anomalies define linear highs and lows that have a general east-northeastward trend, conforming to the expected structural grain projected from the nearest exposed Precambrian rocks to the northeast. In southwestern Ontario along the International boundary between Lake of the Woods and Rainy Lake, Innes (1960) demonstrated good correlations between gravity highs and greenstone belts and between gravity lows and granitic rocks. On the basis of his results and the anomalies associated with the Giants Range Granite, the Ely Greenstone, and the Vermilion Granite, it is probable that the linear gravity highs in northwestern Minnesota define greenstone belts and the gravity lows indicate areas of granitic rocks. The prominent gravity high south of Lake of the Woods appears to mark the continuation of a greenstone belt across the Rainy River in Ontario.

Appendix A - Bouguer anomaly map of Isle Royale

Gravity measurements were made on Isle Royale by Thiel (1955) and by Hemingway and Craddock during August, 1964. Simple Bouguer anomalies have been calculated for the stations, using sea level as datum and 2.67 gm/cm^3 for the density of the rocks between the station and sea level (fig. 3).

The 1964 survey, done in a period of four days, is based on an established gravity value of 980.8671 gals at Windigo Ranger Station on Washington Harbor. On the first day, three stations were established along the Greenstone Ridge Trail on a round trip from Windigo. On the second day, a base was established at Siskiwit Bay Campground after a flight from Windigo, and two other measurements were made along the Island Mine Trail. On the third day, five shore stations were established by boat on a trip from Siskiwit Bay Campground to Windigo. The reading at Huginnin Cove on the northwest shore was obtained on foot from Windigo the last day.

Three stations believed common to both surveys show anomaly differences at Windigo, Washington Island, and Fisherman's Home Cove of 1.3, 1.0, and 10.3 milligals respectively. Thiel's values at all three stations are lower than those obtained by us in 1964. One of the two derived anomalies at Fisherman's Home Cove is significantly in error, probably through a mistake in gravimeter reading or calculation.

The Bouguer anomalies tend to become more positive toward the southeast, across Isle Royale, probably reflecting an increase in thickness of the southeast-dipping Middle Keweenawan mafic igneous rocks that crop out over most of the island. The lower anomalies at the two stations southeast of Siskiwit Bay probably are related to the low-density Upper Keweenawan clastic sedimentary rocks present there.

Appendix B - Gravity base stations

Gravity base stations in Minnesota and bordering areas have been assigned numbers according to the following system.

Nos. 1-10 - modern pendulum stations
11-50 - airport gravimeter stations in and bordering Minnesota
51-920 - other Minnesota gravimeter stations, alphabetically by county
921-960 - other Wisconsin gravimeter stations
961-999 - other gravimeter stations in Iowa, South Dakota, North Dakota, Canada, and Isle Royale

The locations of the gravity bases shown on the map are as follows:

No. 2 - Room 8, Pillsbury Hall, University of Minnesota, Minneapolis (master base, assigned gravity value 980.5979 gals)
12 - Gate 9, new terminal building, Wold-Chamberlain Airport, Minneapolis
13 - Fort Pembina Airport, Pembina, North Dakota

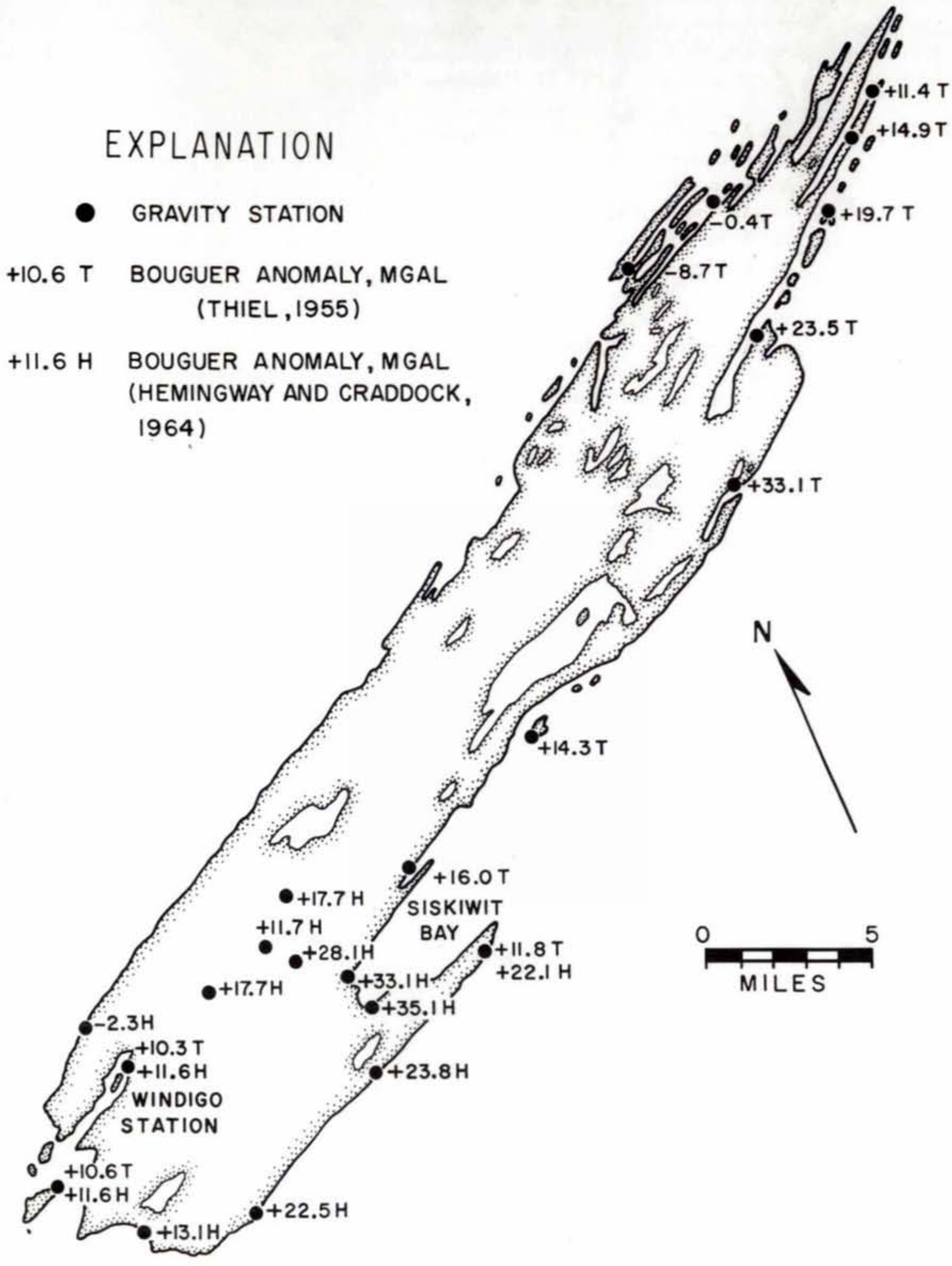

Figure 3 - Simple Bouguer anomaly map of Isle Royale.

14 - Hector Airport, Fargo, North Dakota
18 - Airport, La Crosse, Wisconsin
20 - Airport, International Falls, Minnesota
21 - Airport, Thief River Falls, Minnesota
22 - Airport, Bemidji, Minnesota
23 - Airport, Hibbing-Chisholm, Minnesota
24 - Airport, Duluth, Minnesota
25 - Airport, Brainerd-Crow Wing, Minnesota
26 - Airport, Alexandria, Minnesota
27 - Airport, St. Cloud, Minnesota
28 - Airport, Marshall, Minnesota
29 - Airport, Mankato, Minnesota
30 - Airport, Rochester, Minnesota
31 - Airport, Winona, Minnesota
32 - Airport, Blooming Prairie, Minnesota
33 - Airport, Austin, Minnesota
34 - Airport, Fairmont, Minnesota
35 - Airport, Jackson, Minnesota
36 - Airport, Moose Lake, Minnesota
37 - Airport, Big Fork, Minnesota
38 - Airport, Erskine, Minnesota
39 - Airport, Glencoe, Minnesota
40 - Airport, Redwood Falls, Minnesota
130 - County courthouse, Carlton, Minnesota
201 - Poplar Grove Cemetery, Grand Marais, Minnesota
202 - Stockade lodge building, Grand Portage, Minnesota
620 - Bench mark, Hinckley, Minnesota
622 - Railway station, Kerrick, Minnesota
680 - Highway intersection, Sanborn, Minnesota
730 - County courthouse, Duluth, Minnesota
992 - Windigo ranger station, Isle Royale, Michigan

Information on the exact location and assigned value of gravity for these and for additional newer base stations has been placed in open files and can be obtained upon request from the Minnesota Geological Survey.

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