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AEROMAGNETIC MAP OF PARTS OF MARQUETTE, DICKINSON, BARAGA, ALGER AND SCHOOLCRAFT COUNTIES, MICHIGAN AND ITS GEOLOGIC INTERPRETATION

By
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AEROMAGNETIC AND GEOLOGIC MAP OF PARTS OF MARQUETTE, DICKINSON, BARAGA, ALGER, AND SCHOOLCRAFT COUNTIES, MICHIGAN

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Introduction

The U. S. Geological Survey, in cooperation with the Geological Survey Division of the Michigan Department of Conservation, is conducting a comprehensive restudy of the iron-bearing districts of Michigan. The use of aeromagnetic data is one of the fastest and most reliable methods for outlining the areal distribution of magnetic iron-formation and thus is of material value in assessing the iron resources of the United States. As part of this program of restudy, aeromagnetic surveys of approximately 4,500 square miles of the Northern Peninsula have been made. The results of several of these surveys have been presented by Balsley and others (1949) and by Wier and others (1953). This report is about a survey made in 1950, over an area of about 1,400 square miles in Marquette County and adjoining strips in northern Dickinson and northeastern Baraga Counties, and a later survey flown in 1961, over about 500 square miles in parts of Marquette, Alger, and Schoolcraft Counties. The Marquette iron range extends in an east-west direction across approximately the west-central part of the area, and iron districts of lesser importance are located at Republic, in the southwestern part of the area, and near Gwinn, in the south-central part of the area.

Aeromagnetic surveys were flown along north-south lines spaced at intervals of one-quarter mile in the western part of the area and at intervals of from about 1 to 3 miles in the eastern part. Lines were flown at approximately 500 feet above the surface or at elevations of 1,100 to 2,400 feet above sea level. The flight path of the aircraft was recorded by a gyrostabilized continuous-strip camera, and elevation was continuously recorded by a radio altimeter. Magnetic measurements were made by an AN/ASQ-3A fluxgate magnetometer. Compilation of aeromagnetic data was by standard methods, described by Balsley (1952), under the supervision of John Kirby and Frank Petrafeso. The aeromagnetic contours are relative to an arbitrary datum.

Magnetic properties of rocks were measured by W. E. Huff.

At the time the earlier aeromagnetic survey was flown, the only base maps available were planimetric maps such as the Helena NW quadrangle and county road maps. Small errors, therefore, may exist in the location of flight lines and specific aeromagnetic anomalies.

The major magnetic anomalies and broad areas that have characteristic magnetic patterns are correlated herein with geology as determined from published reports and from mapping done since 1957 by the U. S. Geological Survey in the eastern part of the Marquette iron range. The geology north of the Marquette iron range and west of the line between R. 25 W. and R. 26 W. is based mainly on a compilation made by Robert Reed of the Geological Survey Division of the Michigan Department of Conservation from data in the files of the State Survey. In addition some aeromagnetic features have been checked by ground magnetometer in selected localities and correlated directly with the rock types. A few oriented samples have been collected for measurement of the magnetic properties of the major rock units, but many hundreds or thousands of samples would be required to obtain a full range of values of the magnetic susceptibility and remanent magnetization of the rocks over such a large area.

Although the geology of much of the area is still imperfectly known, the available aeromagnetic data together with the best obtainable geologic data are presented at this time, rather than awaiting the eventual extension or completion of the present mapping program, because the combined data provide much information on the extent and location of magnetic iron-formation and other major rock units where concealed beneath glacial, vegetative, and alluvial cover.

General geology

The geology of parts of the area included in this report has been described in early publications of the U. S. Geological Survey (Van Hise and Bayley, 1897; Van Hise and Leith, 1911, p. 251-288), and more recently by Leith and others (1935, p. 4-5). The Gwinn district, in the south-central part of the area, was also described by Allen (1915). Since the early work by the U. S. Geological Survey, studies of the central and western parts of the Marquette iron range have been made by Swanson (1930) and Zinn (1931). The most recent geologic map of the entire area was published by the State of Michigan in 1936 (Martin, 1936).

Rocks of early, middle (Animikie), and late (Keweenawan) Precambrian age (James, 1958) underlie most of the area, but generally they are not extensively exposed because of surficial Pleistocene deposits. Flat-lying Paleozoic rocks form a narrow fringe adjacent to much of the shoreline of Lake Superior and largely cover the Precambrian rocks eastward from about the eastern margin of the area shown on sheet 1.

Lower Precambrian rocks form the basement and consist of greenstones and other metavolcanic rocks, comprising the Mona and Kitchi Schists, and of tonalitic, granodioritic, and amphibolitic gneisses. One or more periods of metamorphism and deformation occurred before the end of early Precambrian time, and the basement rocks are separated from overlying metasedimentary rocks of middle Precambrian age by a major unconformity. Rocks of middle Precambrian age in Michigan have been placed with the Animikie Series (table 1) which is correlated with the Animikie Group of northeastern Minnesota and the Thunder Bay area, Ontario (James, 1958). The most notable of these units is the Negaunee Iron-Formation. It is the main source of iron ore in the area and locally causes magnetic anomalies in excess of 20,000 gammas.

Widespread deformation and regional metamorphism occurred at the close of middle Precambrian time. Prior to that time intrusive bodies of both early and middle Precambrian age were emplaced. The largest and most abundant of these were irregular and tabular masses of gabbro or diabase that were highly altered during the subsequent metamorphism. Several large bodies of ultramafic rock also were intruded during early Precambrian or late in middle Precambrian time. During late Precambrian (Keweenawan), diabase dikes having dominantly westward trends intruded the older rocks. Since then there has been little deformation, other than regional warping, and no regional metamorphism in the area.

Lower Precambrian basement rocks, particularly gneisses, occur in broad areas north and south of the Marquette iron range. Lower Precambrian greenstones and other metavolcanic rocks form a belt as much as several miles wide, immediately north of the eastern half of the iron range. The iron range is underlain by middle Precambrian rocks, is approximately 35 miles long and 2 to 5 miles wide, and is nearly coextensive with the Marquette synclinorium. The axis of the synclinorium passes from a little south of the line between T. 47 N. and T. 48 N. on the east to a little north of that line on the west. At the west edge of the mapped area the synclinorium opens into a broad basin underlain mainly by rocks of late Animikie age. The south limb of the Marquette synclinorium there bends southward and southeastward and is folded into the tight southeast-trending Republic trough. Gneissic basement rock bounds the trough and occupies the area between the trough and the Marquette synclinorium. Two broad poorly defined basins of metasedimentary rocks of unknown age but probably middle Precambrian are folded into the basement north of the Marquette synclinorium. They occur along the Dead River-Silver Lake low area and, north of there, in much of the upper drainage basins of the Yellow Dog, Salmon Trout, and Huron Rivers.

In the south-central part of the region a structural basin near Gwinn contains Negaunee Iron-Formation and other units of the Animikie Series.

Table 1.--Middle Precambrian formations of the Animikie Series on the Marquette iron range, Michigan

[Asterisk (*) indicates that future detailed mapping may show that the Clarksburg and Greenwood are separate formations beneath the Michigamme]

Upper Precambrian	Keweenawan Series		Mafic intrusive rocks	
Middle Precambrian	Animikie Series	Upper part	Michigamme Slate Upper slate member Bijiki Iron-Formation Member Lower slate member *Clarksburg Volcanics Member *Greenwood Iron-Formation Member Goodrich Quartzite	Metadiabase and metagabbro (some is younger than parts of the Michigamme and some may be as old as early Precambrian)
			—Unconformity—	
		Middle part	Negaunee Iron-Formation Siamo Slate Ajibik Quartzite	
			—Unconformity—	
		Lower part	Wewe Slate Kona Dolomite Mesnard Quartzite	
			—Unconformity—	?
Lower Precambrian			Syenite, gneiss, and greenstone	

In the eastern part of the area, one small exposure of pre-Animikie basement is known near Skandia, but over most of Alger, Schoolcraft, and eastern Marquette Counties, Precambrian rocks are concealed beneath Cambrian and Ordovician sedimentary rocks, along the northwestern side of the Michigan Basin.

General features of the aeromagnetic map

The aeromagnetic map is characterized by six distinct groups of anomalies or anomaly patterns:

1. In the central, western, and southwestern parts of the area iron-formation in the Animikie Series is shown by magnetic highs of large amplitude--up to 27,000 gammas. The pattern of magnetic highs over iron-formation generally outlines the west-trending synclinorium along the Marquette iron range, the Republic trough, and the belts of Animikie rocks south and west of the Republic trough.
2. Westward-trending reversely magnetized diabase dikes of Keweenawan age are shown by prominent elongate magnetic lows of moderate to high amplitude. The lows are most abundant in Tps. 48, 49, and 50 N.
3. Mafic intrusions into pre-Animikie basement rocks northwest of Ishpeming are the cause of a group of magnetic highs of large amplitude.
4. The basement gneiss is characterized by a pattern of discontinuous highs and lows of low to moderate amplitude.
5. Intrusive greenstone in the basement gneiss causes, in some places, isolated magnetic highs of moderate amplitude, but in other places it is apparently only weakly magnetic.
6. In the extreme eastern part of the area, where Precambrian rocks are covered by as much as 2,000 feet of lower Paleozoic sedimentary rocks, large magnetic highs and lows with relatively flat magnetic gradients predominate.

Another major feature of the mapped area is the regional northward increase in total magnetic intensity. This is in part related to the earth's magnetic field which increases northward by about 0.5 gammas per mile in this region.

The prominent lows associated with the diabase dikes tend to obscure the magnetic effects of the adjacent rocks; hence, ideally, the lows should be removed by graphical or analytical methods to permit interpretation of the magnetic effects of the adjacent country rock. Such techniques have not been attempted for this brief report.

Marquette synclinorium and iron range (sheet 1)

The Marquette iron range is underlain mainly by metasedimentary rocks of Animikie age, folded into a west-plunging synclinorium. Faults are common, generally dipping steeply, and are alined subparallel to the trend of the range. They occur both along the margins, separating Animikie from basement rocks in places, and within the synclinorium. The major known result of faulting is a large downdropped block of rocks of the middle and upper parts of the Animikie south of the main synclinorium in the Palmer district (formerly designated Cascade district), south and southeast of Negaunee.

Rocks of the lower part of the Animikie, comprised of the Mesnard Quartzite, Kona Dolomite, and Wewe Slate, occur between Marquette and the Negaunee-Palmer area. Magnetization of these rocks is generally weak. The magnetic susceptibility of 10 samples from 5 localities ranges from 0.010×10^{-3} to 1.00×10^{-3} cgs units (table 2). Measurements of 2 samples of Wewe Slate from 1 locality indicate that local magnetic zones are present: the magnetic susceptibility of the 2 samples is 0.920×10^{-3} and 1.000×10^{-3} cgs units and the remanent magnetization is 5.93×10^{-5} and 7.39×10^{-5} cgs units.

Rocks of the middle part of the Animikie--the Ajibik Quartzite, Siamo Slate, and Negaunee Iron-

TABLE 2:--*Some magnetic properties of Precambrian rocks from the Upper Peninsula of Michigan*

[Measurements by W. E. Huff]

Rock type or formation	Number of samples	Range of susceptibility, k (cgs/cc X 10^{-3})	Range of remanent magnetization, J * (cgs emu/cc)	Range of Q $Q = J/kH$ H = 0.6 oersted
Diabase of Keweenawan age	2	1.90 - 3.30	4.04×10^{-3}-7.16×10^{-3}	3.5 - 3.6
Bijiki(?) Iron-Formation Member	5	.167 - 86.00	4.74×10^{-2}-5.48×10^{-2}	.9 - 1.0
Clarksburg Volcanics Member	1	.060	Too weak to measure	
Goodrich Quartzite	1	.024	do	
Negaunee Iron-Formation	8	.92 - 385.00	1.34×10^{-4}-6.08×10^{-2}	.1 - 28.2
Siamo Slate	5	.01 - .157	Too weak to measure	
Ajibik Quartzite	5	0 - .01	do	
Wewe Slate	4	.017 - 1.000	5.93×10^{-5}-7.39×10^{-5}	.001 ca.
Kona Dolomite	3	.010 - .048	Too weak to measure	
Mesnard Quartzite	3	0 - .010	do	
Gneiss of early Precambrian age	16	.010 - .050	do	
Greenstone in Mona Schist	4	.400	1.00×10^{-4}	.42
Serpentine, serpentinized peridotite, and ultramafic rocks	10	.022 - 4.20	Weak to 7.93×10^{-3}	.7 - .8
Metadiabase, amphibolite, and layered greenstone of the pre-Animikie basement	10	.030 - .064	2.34×10^{-5}-1.98×10^{-3}	1.1 - 51.6

* Orientations of remanent magnetization are variable.

Formation--are found in the axial part of the synclinorium from about 6 miles east of Negaunee to Ishpeming, but along the limbs of the synclinorium these rocks extend to the west end of the range. Ajibik Quartzite and Siamo Slate generally are weakly magnetic, as indicated by 10 samples from 5 localities in which the magnetic susceptibility ranges from 0.01 X 10^{-3} to 0.157 X 10^{-3} cgs units. Aeromagnetic and ground magnetic anomalies over parts of the Siamo, however, indicate the presence of a thin magnetite-rich zone that persists for several miles in the Siamo, southeast of Negaunee.

The Negaunee Iron-Formation commonly consists of assemblages of quartz-specularite, quartz-siderite, quartz-specularite-magnetite, quartz-magnetite, quartz-magnetite-minnesotaite, or quartz-grunerite-magnetite. The generally strong positive magnetic anomaly caused by the Negaunee Iron-Formation clearly outlines the synclinal structure, although the trend of the anomaly where the iron-formation crosses the axis of the synclinorium between Negaunee and Ishpeming and south of there is partly obscured or modified by the magnetic effects of several interlayered sills of metadiabase and by variations in the amount of magnetite within the Negaunee.

Measurements of 8 samples of Negaunee Iron-Formation from 5 localities indicate that magnetic susceptibility ranges from 0.92 X 10^{-3} to 385.0 X 10^{-3} cgs units and that remanent magnetization ranges from 1.34 X 10^{-4} to 6.08 X 10^{-2} cgs units. Orientations of the remanent magnetization are variable. No corrections have been made for bedding attitudes, and the samples have not been demagnetized. These few measurements suggest that remanent magnetization constitutes an appreciable fraction of the total magnetization in the Negaunee Iron-Formation and should be considered in any quantitative computations based on magnetic data, as Q ranges from 0.1 to 28.2 (table 2). Q is the ratio of remanent magnetization to induced magnetization. The magnetic field of a body is the vector sum of the induced magnetization and remanent magnetization; thus when Q is large, a large proportion of the field is due to remanent magnetization. A full evaluation of the relative importance of induced and remanent magnetizations of these rocks would require many oriented samples, systematically collected, and should consider orientation of bedding. Bath (1962) made such a study of the iron-formation in the Mesabi area, Minnesota. He found that for relatively unmetamorphosed iron-formation of the main Mesabi district, the dominant magnetization is induced and is about 0.012 gauss; the dominant magnetization of the strongly metamorphosed iron-formation of the eastern Mesabi district is remanent and is about 0.100 gauss.

Rocks of the upper part of the Animikie occupy the axial part of the synclinorium westward from Ishpeming. They are the Goodrich Quartzite (table 1) and the Michigamme Slate. The Greenwood, Clarksburg (table 1), and Bijiki Members are at the base or in the lower part of the Michigamme. At the base of the upper part of the Animikie sequence is a widespread unconformity which cuts into, and possibly in places entirely through, the Negaunee Iron-Formation, and which might account for the local absence of Negaunee along the limbs of the synclinorium. Assemblages of grunerite and magnetite, or of grunerite, magnetite, and quartz, are common in the Greenwood and Bijiki Iron-Formation Members; parts of these units are grunerite schist which locally contains garnet. Early surveys failed to distinguish the Bijiki and Greenwood Iron-Formation Members from one another. According to detailed dip-needle and geologic surveys by Swanson (1930) and Zinn (1931), however, the magnetic belt formed by the Greenwood is a marker between the Goodrich Quartzite and the Clarksburg, whereas the Bijiki is stratigraphically higher in the Michigamme Slate. The Greenwood and Clarksburg evidently are lenticular and thus are not coextensive with the underlying Goodrich Quartzite. Magnetic belts within the Clarksburg in places have been interpreted by Zinn as the Greenwood brought to the bedrock surface by local folding.

The magnetic susceptibility of 1 sample of Goodrich conglomerate is 0.024 X 10^{-3} cgs unit, and the susceptibility of 1 sample of Clarksburg Volcanics Member is 0.060 X 10^{-3} cgs unit. Five samples of Bijiki(?) Iron-Formation Member were collected from 2 localities. The magnetic susceptibility of these samples ranges from 0.167 X 10^{-3} to 86.0 X 10^{-3} cgs units. Only 2 samples from 1 locality were oriented; their remanent magnetizations are 4.74 X 10^{-2} and 5.48 X 10^{-2} cgs units. Q values are 0.9 and 1.0.

In general, the positions of aeromagnetic highs and iron-formation shown on the map correlate somewhat more closely in the western part of the iron range than in the eastern part. The reason for this disparity may be that, because of relative scarcity of exposures in the western part, the mapped position of the iron-formations has been based largely on the results of early dip-needle surveys. Furthermore, geologic structure is evidently simpler in the western part of the range than in the eastern part; hence, correlation of the magnetic pattern with geology is better. Some of the apparent lack of correlation of aeromagnetic anomalies and iron-formation may be caused by a large divergence of the direction of strong remanent magnetization from that of the earth's present field.

The complex anomaly pattern over Negaunee Iron-Formation on the nose of the synclinorium results from the overlap and merging of several magnetic features: some of the magnetic highs are related to magnetite-rich zones in Negaunee Iron-Formation and some to a magnetite-rich zone or iron-formation in Siamo Slate. These two magnetic units have been folded into subsidiary flexures on the nose of the synclinorium and have been cut by several faults. Moreover, the amount of magnetite in the Negaunee Iron-Formation--and hence the associated magnetic anomaly--varies erratically along strike. Metadiabase sills are abundant in this area, and some relatively small magnetic effects of these masses appear on the map.

Magnetic highs in secs. 19, 20, and 21, T. 47 N., R. 27 W., west of National Mine, coincide with Negaunee Iron-Formation on the southern limb of the synclinorium. East and northeast of sec. 21, the mapped width of the Negaunee and the accompanying magnetic highs become much broader, occupying much of the northeastern part of T. 47 N., R. 27 W., and the northwestern part of T. 47 N., R. 26 W. The lower part of the Negaunee is marked by prominent magnetic highs in secs. 23, 24, 25, and 26, T. 47 N., R. 27 W., and in secs. 7, 18, and 19, T. 47 N., R. 26 W., northwest of Palmer. The anomaly in the central part of sec. 19 is partly over the low-grade magnetite-rich ore body of the new Empire Mine. In contrast, iron-formation near Ishpeming and Negaunee has only moderate magnetic expression owing, in part, to a relatively low content of primary magnetite and, in part, to extensive oxidation of the iron-formation; mines near these cities are in soft hematitic ore. The pronounced magnetic low extending from sec. 4, T. 47 N., R. 27 W., to sec. 8, T. 47 N., R. 26 W., is in part a polarization low related to the magnetic highs south of the axis of the synclinorium, but some portion of this low may be due also to a reversed remanent magnetization of either iron-formation or the metadiabase sills.

A magnetite-rich bed of iron-formation in the Siamo Slate (Boyum, 1962, p. 3; Gair and Wier, 1963) extends through secs. 10, 15, 16, and 20, T. 47 N., R. 26 W., northeast of Palmer, as indicated by magnetic highs as much as 7,000 gammas in amplitude (anomaly A-A'). Folds of moderate breadth are indicated by the outcrop pattern of the metadiabase sill in this region, by bedding attitudes, and by the magnetic anomaly pattern.

East and south of Palmer, Negaunee Iron-Formation in a large downfaulted block is the source of prominent magnetic highs in secs. 27, 28, 31, and 32, T. 47 N., R. 26 W. A group of smaller magnetic highs (anomaly B-B') extending from sec. 31, T. 47 N., R. 27 W., to sec. 4, T. 46 N., R. 27 W., may be related to a similar downfaulted block of iron-formation, even though previous geologic mapping shows the area to be underlain by gneiss. If the Palmer fault or the Volunteer fault projects westward from secs. 26 or 36, T. 47 N., R. 27 W., either could cause downthrown iron-formation in the vicinity of secs. 31 and 32. This magnetic anomaly, although of only small amplitude (1,000 gammas), merits further exploration to test for iron ore.

To the west, in Rs. 28, 29, and 30 W., correlation between magnetic highs and iron-formation is more obvious. Iron-formation is overlain by a virtually continuous magnetic high from sec. 20, T. 47 N., R. 27 W., to sec. 36, T. 48 N., R. 30 W. Magnetic values are as great as 23,000 gammas in sec. 11, T. 47 N., R. 29 W., near the Humboldt Mine. Along the north limb of the synclinorium a nearly continuous line of magnetic highs related mainly, or entirely, to Negaunee Iron-Formation extends from sec. 36, T. 48 N., R. 29 W., to near the west edge of the mapped area, in sec. 19, T. 48 N., R. 30 W. The highs along the extreme south edge of the iron range are related predominantly to magnetic Negaunee Iron-Formation, but some are caused by the overlying Greenwood and Bijiki, as is discussed later.

Absence of magnetic highs in secs. 2, 3, and 4, T. 47 N., R. 28 W., an area of known iron-formation and bodies of soft hematitic ore, is attributed either to relatively low amounts of primary magnetite or to extensive oxidation of primary magnetite.

Magnetic highs in secs. 35 and 36, T. 48 N., R. 28 W., between Gold Mine Lake and Deer Lake, are related to ultramafic masses in the pre-Animikie basement. (See p. 8.)

Several groups of magnetic highs in the central part of the synclinorium are correlated with iron-formation that stratigraphically overlies Negaunee Iron-Formation. Some of these highs can be related directly to known layers of iron-formation: for example, the highs in secs. 1, 2, 3, and 4, T. 47 N., R. 29 W., and in secs. 6, 7, 8, 16, 17, 18, 19, and 20, T. 47 N., R. 28 W., coincide with Greenwood Iron-Formation Member, and outline a subsidiary syncline on the south limb of the synclinorium. West of sec. 16 magnetic effects of the Greenwood, however, apparently merge with those of the Negaunee. Between Lake Michigamme and sec. 28, T. 48 N., R. 29 W., some aeromagnetic anomalies are clearly related to the Bijiki, and some coincide with nearby exposures of Negaunee or Greenwood. The magnetic high in secs. 26 and 27, T. 48 N., R. 30 W. (anomaly C-C'), lies slightly north of the mapped position of the Bijiki. In secs. 28 and 29, T. 48 N., R. 29 W., a single aeromagnetic high, which overlies both the Bijiki and Greenwood, evidently represents a merging of magnetic effects at the level of observation, 500 feet above the ground surface.

Prominent magnetic highs occur locally in the synclinorium at some distance from reported iron-formation: for example, a magnetic high that is related to a magnetite-rich zone extends southeasterly in the Michigamme Slate from sec. 36, T. 48 N., R. 29 W., to sec. 10, T. 47 N., R. 28 W., along the axial part of the synclinorium (anomaly D-D').

The magnetic gradients on both limbs of the synclinorium tend to be somewhat steeper on the north sides of the anomalies than on the south sides. This magnetic asymmetry on both limbs might suggest that the south limb locally dips southward and that the axial plane of the synclinorium dips southward, but many sample measurements to determine the magnetization directions would be required for the model calculation necessary to check this possibility.

The south limb of the synclinorium conforms with the basement arch southeast of Lake Michigamme in T. 47 N., R. 30 W., and passes into the Republic trough. Although iron-formation has not previously been reported around the nose of this arch, the nearly continuous magnetic high (anomaly E-E') indicates that one or more magnetic units of the Animikie Series are preserved and presumably are iron-formation.

Republic trough (sheet 1)

The Republic trough, a few miles south of the west end of the Marquette synclinorium, is a narrow northwest-plunging syncline in which rocks of the middle and upper parts of the Animikie are deeply folded into basement gneiss. Thin Ajibik Quartzite (table 1), at the base of the middle part of the Animikie in the trough, is overlain by Negaunee Iron-Formation. In the axial part of the trough the Negaunee is overlain unconformably by ferruginous conglomerate and quartzite of the Goodrich (table 1), which is succeeded by Michigamme Slate. Sills of amphibolitic metadiabase occur within the Negaunee Iron-Formation near the southeast end of the trough, where the iron-formation bends across the fold axis. Lenses of similar mafic rock occur in the iron-formation along the flanks of the trough to the northwest. The iron-formation is mainly laminated quartz-specularite rock with very small amounts of magnetite. Comparatively thin magnetite-rich beds in the lower part of the iron-formation, however, produce the strong magnetic anomaly that clearly defines the Republic trough on the aeromagnetic map. The aeromagnetic pattern suggests that the fold is nearly isoclinal, but the southwest limb may be slightly overturned, judged from asymmetry of the magnetic anomalies.

The iron-formation and its corresponding magnetic anomaly are missing on the southwest limb of the Republic trough, for about 2 miles northwestward from near the southeast end of the trough. The most likely explanation for this is (1) that the Negaunee Iron-Formation was eroded away at the beginning of Goodrich time, or (2) that the missing segment has been removed by faulting. The idea of removal by faulting is given some support by the magnetic anomaly, the magnetite-rich rock, and the quartz-grunerite rock in sec. 29, T. 46 N., R. 29 W., described in the following paragraph.

The positive anomaly in sec. 29, T. 46 N., R. 29 W., has not been fully investigated on the ground, but in the SE¼NW¼ sec. 29 large and variable magnetic highs and lows are associated with a metamorphosed mafic intrusive body. In that part of sec. 29 the intrusive rock seems to trend east-northeastward. The mafic rock contains abundant green amphibole and locally has much chlorite, epidote, garnet, and magnetite. Quartz-grunerite rock is exposed adjacent to the mafic intrusive rock. Vague layering and the composition of the rock are suggestive of a sedimentary origin although the quartz-grunerite rock is well within the area of gneiss that borders the Republic trough. The quartz-grunerite rock in the gneiss and the high magnetite content in parts of the metamorphosed mafic rock are anomalous. Magnetite is concentrated in the marginal parts of some mafic rocks intrusive into the Negaunee Iron-Formation in the Cliffs Shaft Mine at Ishpeming and probably represents assimilated iron-formation. The magnetite-rich mafic rock in sec. 29 may similarly be a result of assimilation of iron-formation by the intrusive rock. These features are nearly on trend with the southwest limb of the Republic trough, a position suggestive that owing to faulting they are related to the missing segment of iron-formation on the southwest flank of Republic trough.

Area south of the Republic trough (sheet 1)

Gneissic basement rocks border the Republic trough and extend southward from there to the limit of the surveyed area and beyond. The magnetic high over the iron-formation closely follows the contact between Animikie and basement rocks and forms a great arch in Tps. 45 and 46 N. that trends south and southeastward (anomaly F-F'). The anomaly in part represents Negaunee(?) Iron-Formation rimming the east side of an elongate oval of basement rock which lies mainly west of the mapped area. The elongate oval evidently is separated from the main area of basement gneiss south of Republic by a narrow northward-trending trough, which is partly defined by anomaly F-F'. The single magnetic high along the narrow trough overlies the eastern limb in some places and the western limb in others; evidently the limbs are so close locally that the magnetic effects of iron-formation on the limbs merge at the level of observation. At the western edge of the mapped area in secs. 8, 17, and 18, T. 45 N., R. 30 W., a magnetic high diverges westward from anomaly F-F' and presumably overlies iron-formation that borders the southeastern margin of the basement oval. Along the south part of magnetic high F-F' the contacts of the rock units shown on the map are based mainly on aeromagnetic data. Eastward bends of the magnetic anomaly in T. 45 N., Rs. 29 and 30 W., near the border between Marquette and Dickinson Counties (anomaly F-F') are suggestive of westward-plunging infolds of iron-formation and other Animikie rocks into the gneissic basement. Analysis of the magnetic data discloses a prominent digitation in the nose of the syncline in sec. 29, T. 45 N., R. 29 W. Anomaly F-F' extends at least to sec. 2, T. 44 N., R. 30 W., where it has a westerly trend.

The survey described in this report overlaps those described by Wier and others (1953) in Tps. 43 and 44 N. Anomaly A_1 of their report corresponds generally to anomaly G-G' of this report. Their discussion of anomaly A_1 strengthens the interpretation that both F-F' and G-G' are caused predominantly by magnetic Negaunee Iron-Formation, which is correlative with the Vulcan Iron-Formation cited here:

> Anomaly A_1 is well defined for a distance of about 5 miles, from sec. 12, R. 30 W., to sec. 32, R. 29 W., in a direction parallel to the contact between the Huronian [Animikie] metasediments and the crystalline gneiss complex to the northeast. Ground magnetometer profiles were made in secs. 19 and 29 [T. 44 N.], R. 29 W. The magnetic crest on these profiles is several hundred feet west of exposures of granite gneiss. In the SE 1/4 SW 1/4 sec. 29 [T. 44 N.], R. 29 W., conglomeratic quartzite of Huronian age... unconformably overlaps the granite gneiss and truncates its well-defined east-west foliation. Drilling in secs. 5 and 9, T. 45 N., R. 30 W., penetrated interbedded iron formation, quartzite, schist and greenstone. In the single drill hole that reached granite, the granite was separated from quartzite only by a thin bed of 'arkose'. Drilling in sec. 13 [T. 44 N.], R. 30 W., and sec. 19 [T. 44 N.], R. 29 W., penetrated thin beds of highly metamorphosed Vulcan iron-formation.
>
> It is reasonable to infer that the iron formation present above the quartzite in these areas is also present above the quartzite exposed in sec. 29, T. 44 N., R. 29 W., and causes the anomaly.

Abrupt differences in strike of anomaly F-F' in secs. 1 and 2 and anomaly G-G' in secs. 12 and 13, T. 44 N., R. 30 W., are suggestive that the iron-formation is faulted between the anomalies.

The magnetic high of about 1,000 gammas in T. 43 N., Rs. 28 and 29 W. (anomalies H-H' and I-I'), coincides in part with anomaly B_1 of Wier and others (1953), who attribute the anomaly to a fine-grained massive greenstone. Whether the arcuate high, J-J', is continuous with anomaly H-H' and thus outlines a fold in magnetic greenstone, or whether it is associated with metasedimentary rocks, is unknown. Anomaly J-J' is here tentatively shown as representing Animikie metasedimentary rocks downfolded into the gneiss.

Area of basement rocks south of Marquette iron range (sheet 1)

A wide area extending from the south edge of the Marquette synclinorium to the south edge of the mapped area is underlain by light-colored gneiss and amphibolite, cut by thin mafic dikes. Dikes intruded prior to the end of Animikie time have been metamorphosed to greenstone, and most of the known ones trend approximately north-south. Younger mafic dikes of Keweenawan (late Precambrian) age are virtually unmetamorphosed. They trend approximately east-west.

The magnetic pattern in most of the region south of the Marquette iron range is mainly one of small discontinuous highs and lows. These anomalies are typical of granitic or gneissic rocks containing minor and variable amounts of magnetite. In the southeastern part of the area shown on sheet 1 a magnetic high of several hundred gammas extends generally east-southeast from sec. 29, T. 45 N., R. 27 W., to sec. 2, T. 44 N., R. 25 W. This elongate high could be related to a dikelike mafic intrusion in the gneissic basement, or it may represent a hidden layer of iron-formation. In secs. 21, 22, 27, 34, and 35, T. 44 N., R. 25 W., a magnetic high of 200 gammas that strikes north-northwestward toward the east-southeast-trending high is probably related to a mafic mass in the basement.

Two small sharp magnetic highs near the boundary between Tps. 44 and 45 N., R. 29 W., are probably caused by shallow magnetic mafic intrusive bodies in the basement.

In T. 46 N., Rs. 26 and 27 W., a magnetic high of about 400 gammas (anomaly K-K') is apparently cut by a prominent east-northeast-trending magnetic low presumably caused by a diabase dike that is more than 30 miles long. The high may be caused by an elongate mafic mass in the basement or by downwarped, or downfaulted, iron-formation. Magnetic anomaly L-L' in T. 46 N., R. 28 W., may be caused by similarly buried rocks. A ground magnetic traverse made across anomaly K-K' with a total vertical intensity fluxgate magnetometer in secs. 13 and 14, T. 46 N., R. 27 W., found the ground anomaly to be only about 300 gammas along the traverse, and the magnetic gradients on the flanks of the anomaly to be relatively smooth and flat; therefore, the source of the anomaly is buried beneath as much as several hundred feet of cover.

Gwinn district (sheet 1)

The Gwinn district in the southeastern part of area mapped on sheet 1 has been a producer of soft hematitic ore. The iron ore evidently has been derived from sideritic Negaunee Iron-Formation, which with other rocks of Animikie age occupies a southeastward-plunging syncline bordered by pre-Animikie gneiss. There is no record of magnetite in the iron-formation or the ore; moreover, the aeromagnetic data indicate that the ore deposits of the district do not contain significant volumes of magnetite, as the anomalies are generally subdued and are tranverse to the known iron-formation.

A few miles north of Gwinn two magnetic highs of about 500 gammas each, in Tps. 45 and 46 N., R. 25 W., trend roughly northwestward. These anomalies presumably are related to moderately magnetic rocks of the basement, although their parallelism with the axis of the Gwinn trough suggests that the anomalies might represent another infold of Animikie metasedimentary rocks into basement gneiss.

A very prominent west-northwestward-trending magnetic anomaly of about 1,200 gammas occurs in the north-central part of T. 46 N., R. 25 W. This anomaly is crossed by a magnetic low caused by a diabase dike that extends through secs. 1, 2, 3, 7, and 8. These magnetic features have been noted previously by Alfons Buzas (1960, The interpretation of the aeromagnetics of southeastern Marquette County, Michigan: Michigan State Univ., unpub. M. S. thesis, 47 p.). Nothing is known about the bedrock source of the magnetic high because of a thick sand cover; but from the amplitude, steep gradient, and northwesterly elongation of the anomaly, the high is inferred to represent downwarped or downfaulted iron-formation that has moderate magnetite content. The anomaly conceivably could be related to an elongate mafic mass in the basement, but, because of its relatively great amplitude, it should be drilled to test for iron-formation. Ground magnetic profiles across the area indicate that the anomaly has a total vertical intensity ranging from 600 to 1,200 gammas.

Areas north of Marquette iron range (sheets 1 and 2)

The region north of the Marquette iron range consists largely of mafic metavolcanic and gneissic basement rocks of early Precambrian age and of metasedimentary rocks of younger Precambrian age, which occupy several basins downfolded in the gneiss. The metavolcanic rocks are the oldest known rocks in the area of this report. In the area east of the line between R. 25 W. and R. 26 W. the mafic rocks ostensibly in the basement are known actually to consist of metavolcanic rocks of early Precambrian age and intrusive greenstones; the placement of these rocks is uncertain; some of the greenstones are younger than the Animikie and some may be as old as early Precambrian. The gneissic basement rocks of that area are mainly tonalitic and granodioritic, locally with hornblende-rich varieties, and with widely distributed interlayered amphibolite. The metavolcanic and gneissic basement rocks are extensively cut by dikes and irregularly shaped bodies of metadiabase and metagabbro, and by upper Precambrian diabase dikes. Metadiabase and metagabbro intrusive into the basement are not shown on the maps accompanying this report, and diabase is shown only east of the line between R. 25 W. and R. 26 W. The gneiss east of that line is also intruded by a comparatively large body of serpentinized peridotite at Presque Isle, just north of Marquette.

West of the line between R. 25 W. and R. 26 W. the basement rocks are in general only broadly distinguished as gneiss or greenstone of early Precambrian age and as metasedimentary rocks assigned to the Animikie Series. A northeastward-trending belt of serpentinized peridotite, about 6 miles in length, is known in T. 48 N., Rs. 27 and 28 W., just north of the iron range. A magnetic high of as much as 7,000 gammas is caused by this ultramafic mass. The magnetic susceptibilities of two samples of the peridotite are 3.820 X 10^{-3} and 4.200 X 10^{-3} cgs units and remanent magnetization ranges from 1.88 X 10^{-3} to 2.20 X 10^{-3} cgs units. Q values range from 0.7 to 0.8. A smaller high of about 800 gammas in secs. 17 and 20, T. 48 N., R. 27 W., indicates that a lobe of serpentinized peridotite extends northward from the main mass, beneath the metasedimentary rocks of the southwestern part of the Dead River drainage basin.

Over the greenstone area north of the Marquette range, the magnetic pattern is variable. In T. 48 N., R. 25 W., southwest of Marquette, a prominent magnetic high of about 500 gammas extends westward from Lake Superior. This high is just north of the contact between basement greenstone and the Animikie Series. Much of the area of greenstone, however, is one of nondescript discontinuous magnetic anomalies of low to moderate amplitude.

The main basins of metasedimentary rocks are located (1) along the Dead River storage basin and the Silver Lake Basin (sheets 1 and 2), (2) along Clark and Deer Creeks, a short distance north of the Dead River storage basin (sheets 1 and 2), and (3) along the upper part of the Yellow Dog River, principally in the Yellow Dog Plains (sheet 2). Slates, graywacke, and a thin iron-formation are known to occur in these basins of metasedimentary rock, which have not yet been mapped in detail. Metasedimentary rocks of the Dead River storage basin are, in general, weakly magnetized, as indicated by gentle magnetic gradients and low amplitudes of the anomalies. The northeastern edge of the basin is approximately located by the magnetic high extending northwest from T. 48 N., R. 26 W., to T. 49 N., R. 28 W. This high overlies magnetic greenstone of the basement.

A curved belt of syenite has been recognized near the east end of the Dead River storage basin. It is overlain by a magnetic high of about 500 gammas along its southern limb. This magnetic high extends into secs. 13 and 14, T. 48 N., R. 27 W., and may represent an extension of the syenite beneath glacial cover.

Metasedimentary rocks underlying most of the Yellow Dog Plains are virtually nonmagnetic. However, an elongate magnetic high near the southern margin of the plains may be related to a nearly continuous layer of magnetic metasedimentary rock containing a moderate amount of magnetite (anomalies M-M' and N-N'). This high is complicated by the magnetic low, related to a diabase dike, which splits the high into two parts.

Areas of gneiss north of the Marquette iron range show only a small variation in magnetic values. Anomalies associated with the rocks in this area are of low amplitude and are largely obscured by magnetic lows associated with a swarm of diabase dikes.

Cambrian sedimentary rocks form a fringe several miles wide adjacent to most of the shore of Lake Superior in the area. These rocks are weakly magnetic, as far as is known, and most of the magnetic anomalies over the sedimentary rocks are related to the underlying crystalline rocks. Much of the near-shore area northwest of Marquette is underlain at depth by gneissic basement, as inferred from the small irregular magnetic anomalies. In T. 49 N., R. 26 W., some magnetic highs may be related to greenstone beneath the Cambrian beds. Reversely magnetized diabase dikes beneath the Cambrian cover are indicated by westward-trending elongate magnetic lows that extend over such diabase dikes in the Precambrian basement rocks from the areas of Cambrian outcrops.

North and east of Silver Lake Basin the greenstone shows a diverse magnetic pattern, but much of it is of low to moderate magnetization as inferred from the small amplitude of associated anomalies. A local high mainly over greenstone extends from sec. 27, T. 50 N., R. 28 W., to sec. 33, T. 50 N., R. 27 W., northeast of Silver Lake. Another extends from sec. 6, T. 49 N., R. 28 W., to sec. 13, T. 49 N., R. 28 W.; this continuous high crosses an area of Animikie metasedimentary rocks in secs. 9 and 10, T. 49 N., R. 28 W., indicating continuity of the greenstone at depth beneath the Animikie. A third high is in secs. 9, 10, 16, and 17, T. 49 N., R. 27 W., and it also extends over adjacent greenstone from Animikie rocks, indicating that the greenstone persists below the Animikie. A conspicuous polarization low in secs. 9 and 10, T. 49 N., R. 27 W., is associated with the magnetic high. In secs. 18 and 19, T. 49 N., R. 27 W., a high of about 1,800 gammas seems to overlie Animikie beds, but it is near the contact with greenstone and is probably caused by magnetic greenstone rather than by magnetic metasedimentary rock.

Anomalies related to diabase dikes (sheets 1 and 2)

In the northern part of the surveyed area the most prominent magnetic feature is a swarm of magnetic lows corresponing to reversely magnetize diabase dikes of Keweenawan age. Judged from the pattern of aeromagnetic lows, dikes are much less abundant in Tps. 51 and 52 N., north of the Yellow Dog Plains, and in Tps. 43 through 47 N., south of the Marquette synclinorium, than in the intervening area. Most of the dikes trend east-west, but variations in trend to N. 60°-70° E. can be observed on the magnetic map. In the region near Marquette where the dikes have been mapped by Gair and Thaden, the correlation between the mapped positions of the dikes and the plotted aeromagnetic lows ranges from good to poor. Lack of positional agreement may be due to low magnetite content of some dikes, to small errors in plotting the aeromagnetic anomalies, or to offsets of aeromagnetic anomalies as a result of strong directional remanent magnetization.

Magnetic properties of such dikes in the region just west of the area mapped have been studied by Graham (1953), who postulated that the reverse magnetization of these dikes could have been produced with the earth's magnetic field in its present orientation. In contrast, however, DuBois (1962, p. 59) has correlated the dikes studied by Graham with the Logan sills of Ontario; he computed the pole position as lat 45° N., long 99.5° W.

From a regional study of magnetic properties of many groups of diabase dikes from the Canadian Shield, Strangway (1961) discovered that the stable component of remanent magnetization tends to parallel the strike of the dike. He postulated that the reversed magnetization is probably not parallel to the direction of the earth's field at the time of dike emplacement but rather is related to the geometry of the dike and to its cooling history.

The dikes extend westward at least to R. 35 W. (Graham, 1953; Balsley and others, 1949) and are apparently concentrated most heavily in Tps. 48 and 49 N. Thus the total length of the dike swarm is at least 65 miles. The dikes were emplaced along a major zone of fractures, approximately of Keweenawan age, trending parallel to the Marquette synclinorium and subparallel to the axis of the Lake Superior syncline. They extend along the arch which separates the late Keweenawan Lake Superior syncline from the Michigan Basin. It is, therefore, likely that the dikes were emplaced in longitudinal tension fractures of Keweenawan age.

Anomalies related to the dikes evidently die out eastward in R. 24 W. (sheet 3). Whether this reflects termination of the dike swarm or loss of observable magnetic effects due to increasing depth of the Precambrian surface is unknown.

Area east and southeast of the city of Marquette (sheet 3)

The magnetic anomalies east and southeast of Marquette are generally broader and somewhat more subdued than those shown on sheets 1 and 2 because the depth to the Precambrian surface increases beneath the Paleozoic cover and beneath Lake Superior. The Precambrian surface is about 600 feet above sea level near Marquette and is at sea level southeast of Munising, according to Cohee's (1948, p. 1440) structure-contour map. Lake Superior is as much as 600 feet deep northwest of Grand Island; thus the rock surface there is about 1,100 feet below the level of observation.

A major magnetic anomaly occurs over Lake Superior in the northwestern part of the area shown on sheet 3. A broadly arcuate magnetic high (anomaly O-O') extends from near Presque Isle (sheet 1) eastward to the region northward of Laughing Fish Point (sheet 3), then southward to Laughing Fish Point, and then westward to near Marquette (sheet 1). Whether this high has a composite source or results from a single magnetic and geologic source is unknown. As the anomaly is generally on the same trend as the belt of lower Precambrian greenstone on shore, the most likely interpretation is that it is related to an arcuate belt of magnetic greenstone. A magnetic high in excess of 1,000 gammas, superimposed on anomaly O-O', 7 miles offshore in Lake Superior, northwest of Shot Point, may have a different source, however, because comparable magnetic highs are rare in the exposed greenstone to the west. The local magnetic high northwest of Shot Point may be caused by a mass of serpentinized peridotite, comparable to that underlying Presque Isle and intrusive into magnetic greenstone. Less likely than this interpretation is that all or part of anomaly O-O' is caused by moderately magnetic iron-formation, folded or faulted to a position north of the eastward projection of the Marquette iron range. If this lobate anomaly (O-O') represents a syncline in magnetic greenstone, infolded rocks of the Animikie Series might be expected along the axial part, analogous to relations around the nose of the Dead River drainage basin to the west. Moreover, the bulging or widening of the nose of the postulated syncline is analogous to the structure east of the middle of the main Marquette synclinorium.

An elongate westward-trending magnetic high extends across the southern part of T. 46 N., Rs. 21 through 23 W. This high is approximately on strike with the prominent high in the northern part of T. 46 N., R. 25 W. (sheet 1), and also may represent a belt of weakly magnetic iron-formation.

The broadest magnetic anomaly in the surveyed area is the huge triangular high that centers on Grand Island. This high presumably is caused by a large deep-seated mass of moderate magnetization. Relative flatness of magnetic gradients on the flanks of the anomaly is suggestive that the source lies at considerable depth, perhaps as much as 5,000 feet or more.

Major conclusions

Areas of known and inferred iron-formation are clearly outlined by the magnetic anomaly pattern over the Marquette iron range, along the Republic trough, and in regions south and west of the Republic trough. Appraisal of the aeromagnetic data can eliminate vast areas as potential sites for prospecting for magnetic iron-formation. However, iron deposits of commercial grade in some districts, such as the Gwinn district, may not be sufficiently magnetic to cause a detectable aeromagnetic anomaly.

Magnetic anomalies, not located over known iron deposits, that should receive further attention include the following:

- Anomaly B-B', sec. 31, T. 47 N., R. 27 W., to sec. 4, T. 46 N., R. 27 W. (sheet 1);
- Anomaly D-D', sec. 35, T. 48 N., R. 29 W., to sec. 10, T. 47 N., R. 28 W. (sheet 1);
- Anomaly, sec. 29, T. 46 N., R. 29 W. (sheet 1);
- Anomaly, T. 46 N., R. 25 W., south of Sands (sheet 1); and
- Anomalies M-M' and N-N', T. 50 N., Rs. 28 through 30 W., and T. 51 N., R. 30 W. (sheet 2).

These anomalies seem to offer the greatest possibilities for economic deposits of iron-formation.

Reversely magnetized diabase dikes of Keweenawan age are concentrated in Tps. 48, 49, and 50 N. The swarm extends at least 65 miles, from R. 35 W., west of the surveyed area, to R. 24 W., beneath the Paleozoic cover.

The arcuate magnetic high over Lake Superior is inferred to overlie a continuous belt of magnetic greenstone which possibly outlines a synclinal fold and which may be intruded by serpentinized peridotite. Rocks of the Animikie Series may occupy the axial part of the inferred fold.

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