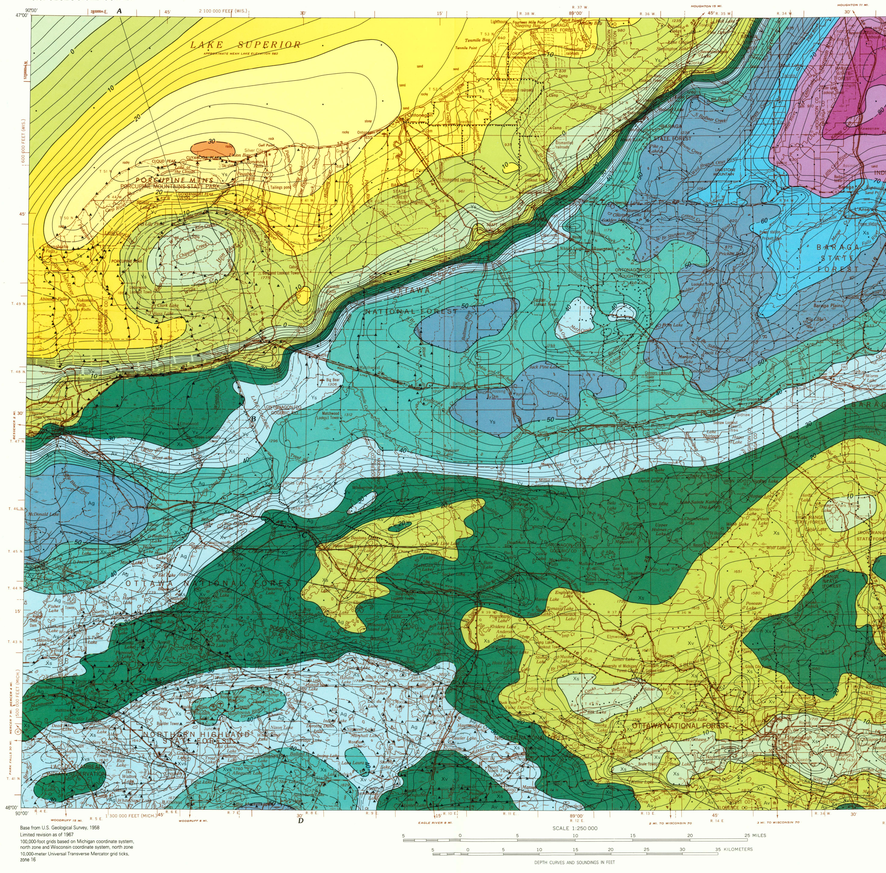

Base from U.S. Geological Survey, 1958
Limited revision as of 1967
100,000-foot grids based on Michigan coordinate system, north zone and Wisconsin coordinate system, north zone
10,000-meter Universal Transverse Mercator grid ticks, zone 16

EXPLANATION

BOUGUER GRAVITY CONTOURS

Contour interval 2 milligals (mGal). Dashed in areas of sparse data. Hachures indicate lower gravity. All gravity data were tied to the International Gravity Standardization Net 1971 (Morelli, 1974) and the Geodetic Reference System 1967 (International Association of Geodesy, 1971). Bouguer anomalies were calculated for a sea-level datum using 2.67 g/cm³ for the rock density and 1.00 g/cm³ for the water density.

MILLIGALS

-20 -10 0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210 220 230 240 250 260 270 280 290 300 310 320 330 340 350 360 370 380 390 400 410 420 430 440 450 460 470 480 490 500 510 520 530 540 550 560 570 580 590 600 610 620 630 640 650 660 670 680 690 700 710 720 730 740 750 760 770 780 790 800 810 820 830 840 850 860 870 880 890

ACKNOWLEDGMENTS

Digital filtering of the Iron River data was done according to a computer program written for the U.S. Geological Survey (USGS) by T. C. Hoskinson of the USGS. We thank him for the use of his program and for his suggestions concerning use of the filtered data.

The Defense Mapping Agency (DMA) supplied magnetic tapes of gravity data from the Iron River quadrangle. These data were edited and returned to the DMA with newly acquired gravity data.

We also thank B. Cowart, C. French, S. A. Jankowski, and W. A. O'Neill for their assistance in gathering new gravity data for this study.

THE GRAVITY DATA

The Bouguer gravity map was compiled from 5,226 stations which come from a variety of sources as shown in table 1. All the gravity data were tied to or adjusted to conform with the 1971 United International Gravimetric Net (Morelli, 1974). Digitized data were reduced to Bouguer gravity anomalies using standard procedures. The reduction formula for the experimental gravity field (International Association of Geodesy, 1971), and a density of 2.67 grams per cubic centimeter (g/cm³) for the rocks between the ground surface and datum.

A computer-generated isometric diagram (fig. 1) shows the Bouguer gravity anomaly surface as if it were viewed from the southeast at an elevation of 55° above horizontal.

Accuracy of gravity data

Because the gravity data come from a variety of sources, the parameters used in obtaining it, such as station spacing and elevation control, are variable. Almost all stations on land were located along existing roads. Spacing along these roads varies from about 30 to 76 meters (100 to 250 feet). The largest gap in station coverage on the Bouguer gravity map is 6.5 kilometers (4 mi) in length. Elevations were obtained from U.S. Geological Survey topographic maps; some elevations were estimated from contours on USGS 1:62,500-scale topographic maps; and some elevations were determined by altimeter and checked against known elevations. Latitude and longitude were determined by map reading. The 1:62,500-scale topographic maps, Iron County, Michigan, and Florence County, Wisconsin, which are contour maps, were used to estimate elevations for most stations. Elevations were checked for accuracy by comparing them with those of other nearby stations. Accuracy of gravity data prepared for this publication is not easily seen and has not been previously mapped. The structural fabric expressed by the orientation of blocks of Archean gravity in the southeast corner of the map (fig. 3) is the same as that of the Archean basement rocks to the west (fig. 6), however, realistic low density, even less than Archean gneiss, as suggested by the average density of granite in Daly and others (1966).

Gravity data in Lake Superior were obtained from the Department of Commerce (Weild and Berkson, 1977) by using a Le Coste and Romberg underwater gravimeter. Vertical control was established by using pressure sensors. Because the gravity meter was suspended and oscillated by electronic triangulation. Lake-based data are also considered accurate to ±0.3 mGal.

Two data sets from the southwest part of the quadrangle in Wisconsin have, in a few cases, either high drift (as much as 2 mGal per base hour) or differ from older data sets in excess of 2 mGal. Because the newer data sets, which are from detailed gravity gravity surveys indicate that, in general, the older data are good, for these reasons, older data sets were used in contouring the gravity map, and newer and less accurate data sets were used where the older data were not available. Note the dashed contours in the southwest corner of the map.

The Florence County, Wisconsin, region of Michigan (northwest quadrant of the map), a few stations have duplicate observed gravity readings. Station locations are plotted, and is was not possible to determine which value was correct. For these measurements, the values were averaged, or the value that seemed to agree best with surrounding values was chosen. The contours in this part of the map are also dashed to indicate less reliable data.

In the Iron River quadrangle, 1,332 stations were added to the gravity data base to fill in these areas to indicate more reliable data. The relative accuracy of data from individual gravity stations is indicated by the locality symbols on the map.

Filtering of the gravity data

Potential-surface maps, such as Bouguer gravity anomaly maps, generally have a broad spectrum of wavelengths. Short wavelengths, or high-frequency components, generally reflect relatively small, near-surface geologic features and perhaps undesirable noise in the gravity data, whereas the long-wavelength, low-frequency components reflect broad variations in geology that occur within the deeper part of the crust. Thus it is often desirable to separate, or filter, the components of the gravity field to facilitate interpretation of the gravity data.

Two maps, figures 2 and 3, display the respective low- and high-frequency components of the observed gravity field. The maps were generated from a grid that had been first created an evenly spaced grid of discrete gravity values calculated from the unevenly spaced observed gravity data. The grid interval used for the Iron River quadrangle (Bouguer gravity, Iron River data is 2 km, about the same as the estimated 1.6-km average distance between observed gravity stations. The grid values were then filtered by a two-dimensional low-pass filter using techniques outlined in Dean (1958), Byerly (1965), Fuller (1967), and Naidu (1969) to create a trend-surface map (fig. 2). The low-pass filter retained frequencies in the gravity data that have wavelengths of 9 km or longer and 2/3 km or shorter. Features that retained shorter wavelengths were less regional, but these did not necessarily lead to the interpretation and are not shown here. The trend-surface map is considered to reflect broad-scale density variations within the crust and upper mantle beneath and other geologic features in the study area.

The residual map, figure 3, was obtained by subtracting the trend-surface map from the Bouguer (observed) gravity-anomaly map of the computer-generated grid points. It contains that part of the frequency spectrum that has wavelengths shorter than 20 km. Some of the anomalies shown on this map may be artifacts that were created by the grid generating process, especially in areas where gravity data were not available. Thus the map shows, in general, that part of the gravity field that is attributable to sources in the upper crust. Some of the gravity data in 2 km, about the same as the estimated 1.6-km average distance between observed gravity stations. The grid values were then filtered by a two-dimensional low-pass filter using techniques outlined in Dean (1958), Byerly (1965), Fuller (1967), and Naidu (1969) to create a trend-surface map (fig. 2). The low-pass filter retained frequencies in the gravity data that have wavelengths of 9 km or longer and 2/3 km or shorter. Features that retained shorter wavelengths were less regional, but these did not necessarily lead to the interpretation and are not shown here. The trend-surface map is considered to reflect broad-scale density variations within the crust and upper mantle beneath and other geologic features in the study area.

The residual map, figure 3, was obtained by subtracting the trend-surface map from the Bouguer (observed) gravity-anomaly map of the computer-generated grid points. It contains that part of the frequency spectrum that has wavelengths shorter than 20 km. Some of the anomalies shown on this map may be artifacts that were created by the grid generating process, especially in areas where gravity data were not available. Thus the map shows, in general, that part of the gravity field that is attributable to sources in the upper crust. Some of the gravity data in 2 km, about the same as the estimated 1.6-km average distance between observed gravity stations. The grid values were then filtered by a two-dimensional low-pass filter using techniques outlined in Dean (1958), Byerly (1965), Fuller (1967), and Naidu (1969) to create a trend-surface map (fig. 2). The low-pass filter retained frequencies in the gravity data that have wavelengths of 9 km or longer and 2/3 km or shorter. Features that retained shorter wavelengths were less regional, but these did not necessarily lead to the interpretation and are not shown here. The trend-surface map is considered to reflect broad-scale density variations within the crust and upper mantle beneath and other geologic features in the study area.

REGIONAL GEOLOGY AND TECTONIC HISTORY OF THE IRON RIVER QUADRANGLE

Geologic data and considerably in interpretation of the Bouguer gravity-anomaly map. Bedrock geologic features in the Iron River quadrangle have considerable influence on interpretation of the gravity data. In addition, well-established geologic ideas and models, such as White's (1972a) ideas concerning volcanic centers in the Lake Superior region, provide an important interpretive framework.

Regional geology

The Iron River quadrangle has undergone ongoing, regionally significant geological and geophysical features as shown in figure 4. The Great Lakes tectonic zone (Sims, 1980; Sims and others, 1980) and the Penokean foldbelt (Cannon, 1973) strike across the quadrangle. A geological belt, high that extends along the length of the Penokean foldbelt in northern Michigan and Wisconsin (Klasner and others, 1979; Klasner and Bonnke, 1977; 1978) in the Iron River 1° x 2° quadrangle, Michigan and Wisconsin. The Great Lakes tectonic zone anomalies. The southern half of the quadrangle contains sedimentary and volcanic rocks that are associated with the Keweenaw rift system (Green, 1978; White, 1972a), which is part of the 2,000-km-long Midcontinent rift.

Rocks of these major age are present in the study area (see fig. 5): Archean basement rocks, Proterozoic X Keweenawan volcanic and sedimentary rocks, Proterozoic X Keweenawan intrusive rocks, Proterozoic X metasedimentary and metavolcanic rocks, and Proterozoic X Keweenawan volcanic and sedimentary rocks unconformably overlain Archean and Proterozoic X rocks. Horizontal and vertical displacements of the Great Lakes tectonic zone also occur in the area. These structures, along with the bedrock geology, provide valuable information concerning the geologic and tectonic evolution of the area.

Several major regional geologic features (fig. 5) important to the interpretation of the gravity map are discussed in the following paragraphs. A more comprehensive report on the geology of the Iron River quadrangle is given by Cannon (1986).

Archean

Although thick Archean sequences of Proterozoic X and Y rocks mask underlying strata in most of the quadrangle, the geologic model (fig. 7, discussed later) constructed from gravity data suggests that the entire quadrangle is underlain by Archean basement, except where Proterozoic plutons or Keweenawan plugs and dikes exist.

Archean rocks are exposed in the southeast part of the quadrangle and either occur as isolated blocks relative to the younger rocks to the eastern part of the quadrangle as reported by Cannon (1973), or occur as manifest gneiss domes as reported by Sims (1980) and Sims and Peterman (1976) or occur as Archean intrusive bodies such as area I in figure 6 (Sims, 1976; Sims and others, 1977).

Table 2 shows that Archean rocks, which range in composition from granite and granite gneiss to mafic gneiss, have a wide range in densities. Generally, bulk density of Archean rocks increases with decreasing silica content. Archean rocks are subdivided into Archean Y basaltic rocks. Thus, relative to adjacent areas, gravity lows should exist above Archean terrane.

The Great Lakes tectonic zone (Sims, 1980) is a fundamental crustal feature of variable width along which both Archean and Proterozoic X rocks were affected. The southern boundary of the Great Lakes tectonic zone is a fault that is in part a zone of mylonite boundary between Archean granite-greenstone terrane on the north and gneiss terrane on the south (fig. 5). A gravity study by Klasner and Sims (1979) in the western part of the quadrangle shows that the tectonic line lies along the north edge of a broad, long-wavelength gravity high previously discussed by Klasner and Bonnke (1977; 1978) and Klasner and others (1979). Gravity models by Bacon (1966) and seismic data (Bacon, 1966) suggest that Keweenawan fault is rifted on the order of 3 km relative to low-density Archean basement rocks. Thus, the Great Lakes tectonic zone also occur in the area. These structures, along with the bedrock geology, provide valuable information concerning the geologic and tectonic evolution of the area.

Several major regional geologic features (fig. 5) important to the interpretation of the gravity map are discussed in the following paragraphs. A more comprehensive report on the geology of the Iron River quadrangle is given by Cannon (1986).

Proterozoic X

Proterozoic X rocks consist mostly of metagraywacke and slate, metavolcanic strata, and relatively rare occurrences of metaconglomerate and metacongloment. Economically important deposits of charty iron formation and ferruginous slate are associated with other Proterozoic X strata. The thickest sequences of metavolcanic strata, the Hemlock Formation and Badwater Greenstone, are found in the southeastern part of the quadrangle (Cannon, 1986). Volcanic rocks are also found in the western part of the quadrangle. Intrusive rocks of Proterozoic X age are the Michigamme Slate and equivalent rocks (Sims and others, 1978) and may extend into the southern part of the quadrangle.

Table 2 shows that graywacke and slate, which form the bulk of the Proterozoic X section, have densities that are only close to those of the underlying Archean gneiss. But the presence of iron-formation and mafic volcanic rocks generally makes the bulk density of the Proterozoic X section greater than that of the underlying Archean gneiss. Because they are felsic, the Proterozoic X volcanic rocks are generally denser than Archean basement rocks. Although Proterozoic X granite plutons were not sampled for density, they probably have a relatively low density, even less than Archean gneiss, as suggested by the average density of granite in Daly and others (1966).

The Penokean orogeny, which included regional metamorphism and intrusion of plutonic bodies, all associated with Penokean orogeny, created several features that are reflected in the gravity data, as shown in table 3. Block faulting in early stages of the orogeny created prominent troughs, with infolded Proterozoic X strata between uplifted blocks of Archean crust (Cannon, 1973). The relatively high density of the iron-rich Proterozoic X sedimentary rocks, such as the iron-formation, causes gravity highs to occur over the troughs. This model across the Marquette trough (Klasner and Cannon, 1974) showed that in places it is as much as 2,500 m deep.

Regional metamorphic aureoles, perhaps including subjacent granitic plutons (James, 1955), generally have gravity lows over them (Klasner and others, 1979; Klasner and Bonnke, 1977). Similarly, granitic plutons have associated negative gravity anomalies.

Proterozoic Y

White (1972a) and Green (1978) have shown that thick sequences of basaltic Keweenawan lava and sedimentary rocks accumulated in a series of overlapping basins; the very emanated from volcanic centers in the Lake Superior region. The locations of the individual lava basins have been roughly outlined by Green (1978) and the numerous dikes that fed the lavas have been mapped in part by Green (1983) and Cannon (1986). Klasner and Sims's map shows that in the northern part of the Iron River quadrangle, thick sequences of Keweenawan basalt accumulated in three overlapping basins. For the most part, the basalt is covered by thick sequences of clastic sedimentary rocks. According to Hubbard (1975), the upper part of the Keweenawan sequence, specifically the unnamed formation of Bayfield Group, is as much as 3,000 m thick in the Iron River area and is much thicker than the lower flows. As discussed below, evidence for the source vent for these flows is seen in the gravity data.

Table 2 shows that the Keweenawan volcanic rocks are relatively dense and the overlying and interbedded conglomerate and sandstone of the Oronto Group and equivalent rocks are less dense than the lavas. Because the Keweenawan sedimentary rocks cover relatively thick basalt sequences, overlying sedimentary basins generally have associated negative anomalies, but positive anomalies may occur over sedimentary rocks that overlie thick sequences of basalt. Mafic dikes, such as the dikes of the Baraga Group dike swarm, if they are denser than the country rock, should have positive gravity anomalies. Felsic dikes, if they are less dense than the country rock, should have negative gravity anomalies. Felsic dikes will not be recognized. Volcanic stocks and plugs, if they are large enough and of different density than the country rock, should be recognizable in the gravity data.

Numerous faults formed during the Keweenaw rift event. The most prominent is the Great Lakes tectonic zone. Other major northeast-trending faults cut the Keweenawan fault, and we consider these to be tectonically significant features in that they may be expressions of larger, more pervasive northwest-trending faults that exist in the area as discussed later.

The general tectonic history of the Lake Superior region is summarized in table 3. The table shows the prominent structural features that can be recognized in the gravity data as shown in the table.

MAGNETIC DATA AND THE GRAVITY MAP

Aeromagnetic data for the Iron River quadrangle have been compiled into a map by King (1967). Many prominent magnetic anomalies on both King's map and a regional aeromagnetic map by Zietz and Kirby (1971) have an important bearing on interpretation of the gravity data. Comparison of gravity and magnetic anomalies in the Iron River quadrangle and therefore provide valuable information concerning the source rock. Generally in this area, coincident magnetic and gravity highs indicate the presence of iron-formation and (or) mafic volcanic rock.

Because of reversed magnetic polarity, Keweenawan diabase dikes of the Baraga Group dike swarm (Klasner and others, 1979) have negative magnetic anomalies. The dike swarm on the gravity maps at this scale, as previously mentioned, had their location may be significant in terms of interpretation of gravity gradients.

The relationship between gravity and magnetics is briefly discussed for some of the more prominent gravity features in the following section of this paper.

DISCUSSION OF THE GRAVITY MAPS

The most prominent feature on the Bouguer gravity-anomaly map is a strong northeast-trending ridge. This ridge reflects the regional northeast-trending gravity gradient. The ridge is bounded on the southeast and northwest by gravity lows that are generally parallel to the northeast-trending gravity gradient, labeled F and H. divide the gravity map into three distinct domains. The domain of highest amplitude gravity (A in figs. 1, 2, and 6) is over the Proterozoic Y Keweenawan basalt flows; a domain of relatively low-amplitude gravity (B in figs. 1, 2, and 6) is mostly over the Jacobsville Sandstone; and a domain of intermediate gravity (F-I, in fig. 6) are over the Proterozoic X and Archean terranes (see also fig. 5).

Correlation of regional tectonic and other geologic features (fig. 5) with the general configuration of the Bouguer gravity-anomaly map shows that the gravity highs, as shown on the trend-surface map, (fig. 2), is readily apparent. The steep south-dipping gravity gradient I, for example, over the Keweenawan basalt flows and high-density Keweenawan basalt is not by low-density Jacobsville Sandstone causing gravity variations exceeding 150 mGal. Gradient **H** overlies the Great Lakes tectonic zone and separates Proterozoic X Keweenawan volcanic rocks.

Although the trends of the Midcontinent rift, Jacobsville trough, and Penokean foldbelt are all northeast, the axes of the Jacobsville trough and the Penokean foldbelt in northern Michigan-Lake Superior region (Klasner and others, 1979) shows that east and west of the Iron River quadrangle, gravity anomalies over the Midcontinent rift cut across the Jacobsville trough and Penokean foldbelt.

Numerous gravity anomalies, gradients, and lineations are apparent on the Bouguer gravity map. Some of these are discussed in the preceding paragraphs. Gravity highs, such as F, and some of the same symbols are used for some corresponding features on the isometric diagram of the gravity surface (fig. 1), the trend-surface map (fig. 2), the residual gravity map (fig. 3), and the gravity profile (fig. 7). The symbols are also correlated with the stratigraphic column in the explanation of figure 5.

Accumulate over Proterozoic Y terrane

A (northeast)—This sequences of relatively dense Keweenawan basalt cause the large positive gravity anomaly at **A**. A gravity high at **A1** (east-central, fig. 3 and 6) marks the position of lower Keweenawan basalt that lies in contact with Proterozoic X rocks (Hubbard, 1975). **A1**, along with anomaly **E**, is a compound anomaly, caused in part by these volcanic rocks and other rocks as discussed later.

B (northeast)—The gravity low at **B** is over the Porcupine Mountains syncline. An unpublished map by W. S. White shows that the Nonesuch Shale and Copper Harbor Conglomerate, which fill the syncline, are only a few hundred feet thick. The modelled gravity profile (fig. 7) shows that the low-density shale and conglomerate cannot cause the observed gravity low. The gravity low must be caused by a deeper, more extensive syncline. The Porcupine Mountains syncline may be a collapsed caldera and the gravity low may be caused by a low-density felsic volcanic pipe beneath the "syncline;" the gravity model shown in figure 7 supports this concept. This small mark one of the volcanic centers in the Lake Superior region as proposed by White (1972a). A prominent horseshoe-shaped magnetic high (Zietz and Kirby, 1971; King, 1967) encircles **B** on the south side. This magnetic anomaly probably indicates the presence of thick layers of near-surface basalt as shown by the gravity model.

C (north-central)—The two positive gravity anomalies at **C** is within the Baraga Plateau. The gravity gradient between **C** and **B** is very steep and may be interpreted to mark the position of a ridge of Keweenawan basalt that lies beneath Jacobsville Sandstone. It appears on the residual gravity map (fig. 3) as a northeast-trending high. Regional (1978) has shown that at **C1** (figs. 2 and 6), the widest part of the anomaly, the top of the basalt lies about 150 m below ground surface.

D (north-central-northeast)—A pronounced gravity low at **D** is caused in part by a trough of low-density Jacobsville Sandstone. Bacon (1966) has suggested from gravity and magnetic data that the trough has up to 3 km of Jacobsville Sandstone overlying Keweenawan basalt.

Anomalies over Proterozoic X terrane

E (west-central)—The gravity high at **E** is especially apparent on the residual gravity map (fig. 3). The high is a compound anomaly caused, in part, by Keweenawan volcanic rocks (**A1**) and, in part, by Proterozoic X sedimentary rocks that mark the eastward extent of the Gogebic Iron Range. A prominent magnetic high associated with anomaly **E** is shown on the aeromagnetic map by Zietz and Kirby (1971) and King (1967).

F (south-central—east-central)—A series of positive and negative gravity anomalies that lie on top of the broad regional east-west-trending gravity anomaly associated with the Penokean foldbelt are designated **F1-F7**. The positive anomalies are caused by Proterozoic X sedimentary rocks that are generally denser than underlying Archean basement rocks.

F1 (east-central)—The gravity high at **F1** is coincident with a prominent positive magnetic anomaly. It is similar to **F3**, suggesting that it is caused by dense iron-formation at depth. To the best of our knowledge, the deposits have not been confirmed by drilling.

F3 (east-central)—The gravity high at **F3** over the Iron River basin (fig. 3) is also caused by deposits of dense iron-formation. Although the trend-surface map (fig. 2) suggests that the anomaly is part of a broad, east-west-trending gravity high, the residual gravity map (fig. 3) shows that the Iron River basin extends east-west 4.5 km to gradient **I/F** on the gravity index map (fig. 6) and does not connect with **F4**.

F4 (south-central)—The gravity high at **F4** may be caused by mafic volcanic rocks. It has a narrow east-west-trending positive magnetic anomaly beneath it, and two drill holes have encountered dense iron-formation.

F5 (south-central)—The gravity high at **F5**, as shown on the gravity model (fig. 7), is in part caused by accumulations of iron-rich sedimentary and mafic volcanic rocks.

F6 (southeast)—An elongate gravity high at **F6** has an associated positive magnetic anomaly that is attributed to deposits of iron-formation.

F7 (east-central)—The gravity high at **F7** is not known. If Zietz and Kirby's map shows that the northern part of the Iron River quadrangle, thick sequences of Keweenawan basalt accumulated in three overlapping basins. For the most part, the basalt is covered by thick sequences of clastic sedimentary rocks. According to Hubbard (1975), the upper part of the Keweenawan sequence, specifically the unnamed formation of Bayfield Group, is as much as 3,000 m thick in the Iron River area and is much thicker than the lower flows. As discussed below, evidence for the source vent for these flows is seen in the gravity data.

Table 2 shows that the Keweenawan volcanic rocks are relatively dense and the overlying and interbedded conglomerate and sandstone of the Oronto Group and equivalent rocks are less dense than the lavas. Because the Keweenawan sedimentary rocks cover relatively thick basalt sequences, overlying sedimentary basins generally have associated negative anomalies, but positive anomalies may occur over sedimentary rocks that overlie thick sequences of basalt. Mafic dikes, such as the dikes of the Baraga Group dike swarm, if they are denser than the country rock, should have positive gravity anomalies. Felsic dikes, if they are less dense than the country rock, should have negative gravity anomalies. Felsic dikes will not be recognized. Volcanic stocks and plugs, if they are large enough and of different density than the country rock, should be recognizable in the gravity data.

Numerous faults formed during the Keweenaw rift event. The most prominent is the Great Lakes tectonic zone. Other major northeast-trending faults cut the Keweenawan fault, and we consider these to be tectonically significant features in that they may be expressions of larger, more pervasive northwest-trending faults that exist in the area as discussed later.

The general tectonic history of the Lake Superior region is summarized in table 3. The table shows the prominent structural features that can be recognized in the gravity data as shown in the table.

MAGNETIC DATA AND THE GRAVITY MAP

Aeromagnetic data for the Iron River quadrangle have been compiled into a map by King (1967). Many prominent magnetic anomalies on both King's map and a regional aeromagnetic map by Zietz and Kirby (1971) have an important bearing on interpretation of the gravity data. Comparison of gravity and magnetic anomalies in the Iron River quadrangle and therefore provide valuable information concerning the source rock. Generally in this area, coincident magnetic and gravity highs indicate the presence of iron-formation and (or) mafic volcanic rock.

Because of reversed magnetic polarity, Keweenawan diabase dikes of the Baraga Group dike swarm (Klasner and others, 1979) have negative magnetic anomalies. The dike swarm on the gravity maps at this scale, as previously mentioned, had their location may be significant in terms of interpretation of gravity gradients.

The relationship between gravity and magnetics is briefly discussed for some of the more prominent gravity features in the following section of this paper.

DISCUSSION OF THE GRAVITY MAPS

The most prominent feature on the Bouguer gravity-anomaly map is a strong northeast-trending ridge. This ridge reflects the regional northeast-trending gravity gradient. The ridge is bounded on the southeast and northwest by gravity lows that are generally parallel to the northeast-trending gravity gradient, labeled F and H. divide the gravity map into three distinct domains. The domain of highest amplitude gravity (A in figs. 1, 2, and 6) is over the Proterozoic Y Keweenawan basalt flows; a domain of relatively low-amplitude gravity (B in figs. 1, 2, and 6) is mostly over the Jacobsville Sandstone; and a domain of intermediate gravity (F-I, in fig. 6) are over the Proterozoic X and Archean terranes (see also fig. 5).

Correlation of regional tectonic and other geologic features (fig. 5) with the general configuration of the Bouguer gravity-anomaly map shows that the gravity highs, as shown on the trend-surface map, (fig. 2), is readily apparent. The steep south-dipping gravity gradient I, for example, over the Keweenawan basalt flows and high-density Keweenawan basalt is not by low-density Jacobsville Sandstone causing gravity variations exceeding 150 mGal. Gradient **H** overlies the Great Lakes tectonic zone and separates Proterozoic X Keweenawan volcanic rocks.

Although the trends of the Midcontinent rift, Jacobsville trough, and Penokean foldbelt are all northeast, the axes of the Jacobsville trough and the Penokean foldbelt in northern Michigan-Lake Superior region (Klasner and others, 1979) shows that east and west of the Iron River quadrangle, gravity anomalies over the Midcontinent rift cut across the Jacobsville trough and Penokean foldbelt.

Numerous gravity anomalies, gradients, and lineations are apparent on the Bouguer gravity map. Some of these are discussed in the preceding paragraphs. A more comprehensive report on the geology of the Iron River quadrangle is given by Cannon (1986).

Accumulate over Proterozoic Y terrane

A (northeast)—This sequences of relatively dense Keweenawan basalt cause the large positive gravity anomaly at **A**. A gravity high at **A1** (east-central, fig. 3 and 6) marks the position of lower Keweenawan basalt that lies in contact with Proterozoic X rocks (Hubbard, 1975). **A1**, along with anomaly **E**, is a compound anomaly, caused in part by these volcanic rocks and other rocks as discussed later.

B (northeast)—The gravity low at **B** is over the Porcupine Mountains syncline. An unpublished map by W. S. White shows that the Nonesuch Shale and Copper Harbor Conglomerate, which fill the syncline, are only a few hundred feet thick. The modelled gravity profile (fig. 7) shows that the low-density shale and conglomerate cannot cause the observed gravity low. The gravity low must be caused by a deeper, more extensive syncline. The Porcupine Mountains syncline may be a collapsed caldera and the gravity low may be caused by a low-density felsic volcanic pipe beneath the "syncline;" the gravity model shown in figure 7 supports this concept. This small mark one of the volcanic centers in the Lake Superior region as proposed by White (1972a). A prominent horseshoe-shaped magnetic high (Zietz and Kirby, 1971; King, 1967) encircles **B** on the south side. This magnetic anomaly probably indicates the presence of thick layers of near-surface basalt as shown by the gravity model.

C (north-central)—The two positive gravity anomalies at **C** is within the Baraga Plateau. The gravity gradient between **C** and **B** is very steep and may be interpreted to mark the position of a ridge of Keweenawan basalt that lies beneath Jacobsville Sandstone. It appears on the residual gravity map (fig. 3) as a northeast-trending high. Regional (1978) has shown that at **C1** (figs. 2 and 6), the widest part of the anomaly, the top of the basalt lies about 150 m below ground surface.

D (north-central-northeast)—A pronounced gravity low at **D** is caused in part by a trough of low-density Jacobsville Sandstone. Bacon (1966) has suggested from gravity and magnetic data that the trough has up to 3 km of Jacobsville Sandstone overlying Keweenawan basalt.

Anomalies over Proterozoic X terrane

E (west-central)—The gravity high at **E** is especially apparent on the residual gravity map (fig. 3). The high is a compound anomaly caused, in part, by Keweenawan volcanic rocks (**A1**) and, in part, by Proterozoic X sedimentary rocks that mark the eastward extent of the Gogebic Iron Range. A prominent magnetic high associated with anomaly **E** is shown on the aeromagnetic map by Zietz and Kirby (1971) and King (1967).

F (south-central—east-central)—A series of positive and negative gravity anomalies that lie on top of the broad regional east-west-trending gravity anomaly associated with the Penokean foldbelt are designated **F1-F7**. The positive anomalies are caused by Proterozoic X sedimentary rocks that are generally denser than underlying Archean basement rocks.

F1 (east-central)—The gravity high at **F1** is coincident with a prominent positive magnetic anomaly. It is similar to **F3**, suggesting that it is caused by dense iron-formation at depth. To the best of our knowledge, the deposits have not been confirmed by drilling.

F3 (east-central)—The gravity high at **F3** over the Iron River basin (fig. 3) is also caused by deposits of dense iron-formation. Although the trend-surface map (fig. 2) suggests that the anomaly is part of a broad, east-west-trending gravity high, the residual gravity map (fig. 3) shows that the Iron River basin extends east-west 4.5 km to gradient **I/F** on the gravity index map (fig. 6) and does not connect with **F4**.

F4 (south-central)—The gravity high at **F4** may be caused by mafic volcanic rocks. It has a narrow east-west-trending positive magnetic anomaly beneath it, and two drill holes have encountered dense iron-formation.

F5 (south-central)—The gravity high at **F5**, as shown on the gravity model (fig. 7), is in part caused by accumulations of iron-rich sedimentary and mafic volcanic rocks.

F6 (southeast)—An elongate gravity high at **F6** has an associated positive magnetic anomaly that is attributed to deposits of iron-formation.

F7 (east-central)—The gravity high at **F7** is not known. If Zietz and Kirby's map shows that the northern part of the Iron River quadrangle, thick sequences of Keweenawan basalt accumulated in three overlapping basins. For the most part, the basalt is covered by thick sequences of clastic sedimentary rocks. According to Hubbard (1975), the upper part of the Keweenawan sequence, specifically the unnamed formation of Bayfield Group, is as much as 3,000 m thick in the Iron River area and is much thicker than the lower flows. As discussed below, evidence for the source vent for these flows is seen in the gravity data.

Table 2 shows that the Keweenawan volcanic rocks are relatively dense and the overlying and interbedded conglomerate and sandstone of the Oronto Group and equivalent rocks are less dense than the lavas. Because the Keweenawan sedimentary rocks cover relatively thick basalt sequences, overlying sedimentary basins generally have associated negative anomalies, but positive anomalies may occur over sedimentary rocks that overlie thick sequences of basalt. Mafic dikes, such as the dikes of the Baraga Group dike swarm, if they are denser than the country rock, should have positive gravity anomalies. Felsic dikes, if they are less dense than the country rock, should have negative gravity anomalies. Felsic dikes will not be recognized. Volcanic stocks and plugs, if they are large enough and of different density than the country rock, should be recognizable in the gravity data.

Numerous faults formed during the Keweenaw rift event. The most prominent is the Great Lakes tectonic zone. Other major northeast-trending faults cut the Keweenawan fault, and we consider these to be tectonically significant features in that they may be expressions of larger, more pervasive northwest-trending faults that exist in the area as discussed later.

The general tectonic history of the Lake Superior region is summarized in table 3. The table shows the prominent structural features that can be recognized in the gravity data as shown in the table.

MAGNETIC DATA AND THE GRAVITY MAP

Aeromagnetic data for the Iron River quadrangle have been compiled into a map by King (1967). Many prominent magnetic anomalies on both King's map and a regional aeromagnetic map by Zietz and Kirby (1971) have an important bearing on interpretation of the gravity data. Comparison of gravity and magnetic anomalies in the Iron River quadrangle and therefore provide valuable information concerning the source rock. Generally in this area, coincident magnetic and gravity highs indicate the presence of iron-formation and (or) mafic volcanic rock.

Because of reversed magnetic polarity, Keweenawan diabase dikes of the Baraga Group dike swarm (Klasner and others, 1979) have negative magnetic anomalies. The dike swarm on the gravity maps at this scale, as previously mentioned, had their location may be significant in terms of interpretation of gravity gradients.

The relationship between gravity and magnetics is briefly discussed for some of the more prominent gravity features in the following section of this paper.

DISCUSSION OF THE GRAVITY MAPS

The most prominent feature on the Bouguer gravity-anomaly map is a strong northeast-trending ridge. This ridge reflects the regional northeast-trending gravity gradient. The ridge is bounded on the southeast and northwest by gravity lows that are generally parallel to the northeast-trending gravity gradient, labeled F and H. divide the gravity map into three distinct domains. The domain of highest amplitude gravity (A in figs. 1, 2, and 6) is over the Proterozoic Y Keweenawan basalt flows; a domain of relatively low-amplitude gravity (B in figs. 1, 2, and 6) is mostly over the Jacobsville Sandstone; and a domain of intermediate gravity (F-I, in fig. 6) are over the Proterozoic X and Archean terranes (see also fig. 5).

Correlation of regional tectonic and other geologic features (fig. 5) with the general configuration of the Bouguer gravity-anomaly map shows that the gravity highs, as shown on the trend-surface map, (fig. 2), is readily apparent. The steep south-dipping gravity gradient I, for example, over the Keweenawan basalt flows and high-density Keweenawan basalt is not by low-density Jacobsville Sandstone causing gravity variations exceeding 150 mGal. Gradient **H** overlies the Great Lakes tectonic zone and separates Proterozoic X Keweenawan volcanic rocks.

Although the trends of the Midcontinent rift, Jacobsville trough, and Penokean foldbelt are all northeast, the axes of the Jacobsville trough and the Penokean foldbelt in northern Michigan-Lake Superior region (Klasner and others, 1979) shows that east and west of the Iron River quadrangle, gravity anomalies over the Midcontinent rift cut across the Jacobsville trough and Penokean foldbelt.

Numerous gravity anomalies, gradients, and lineations are apparent on the Bouguer gravity map. Some of these are discussed in the preceding paragraphs. A more comprehensive report on the geology of the Iron River quadrangle is given by Cannon (1986).

Accumulate over Proterozoic Y terrane

A (northeast)—This sequences of relatively dense Keweenawan basalt cause the large positive gravity anomaly at **A**. A gravity high at **A1** (east-central, fig. 3 and 6) marks the position of lower Keweenawan basalt that lies in contact with Proterozoic X rocks (Hubbard, 1975). **A1**, along with anomaly **E**, is a compound anomaly, caused in part by these volcanic rocks and other rocks as discussed later.

B (northeast)—The gravity low at **B** is over the Porcupine Mountains syncline. An unpublished map by W. S. White shows that the Nonesuch Shale and Copper Harbor Conglomerate, which fill the syncline, are only a few hundred feet thick. The modelled gravity profile (fig. 7) shows that the low-density shale and conglomerate cannot cause the observed gravity low. The gravity low must be caused by a deeper, more extensive syncline. The Porcupine Mountains syncline may be a collapsed caldera and the gravity low may be caused by a low-density felsic volcanic pipe beneath the "syncline;" the gravity model shown in figure 7 supports this concept. This small mark one of the volcanic centers in the Lake Superior region as proposed by White (1972a). A prominent horseshoe-shaped magnetic high (Zietz and Kirby, 1971; King, 1967) encircles **B** on the south side. This magnetic anomaly probably indicates the presence of thick layers of near-surface basalt as shown by the gravity model.

C (north-central)—The two positive gravity anomalies at **C** is within the Baraga Plateau. The gravity gradient between **C** and **B** is very steep and may be interpreted to mark the position of a ridge of Keweenawan basalt that lies beneath Jacobsville Sandstone. It appears on the residual gravity map (fig. 3) as a northeast-trending high. Regional (1978) has shown that at **C1** (figs. 2 and 6), the widest part of the anomaly, the top of the basalt lies about 150 m below ground surface.

D (north-central-northeast)—A pronounced gravity low at **D** is caused in part by a trough of low-density Jacobsville Sandstone. Bacon (1966) has suggested from gravity and magnetic data that the trough has up to 3 km of Jacobsville Sandstone overlying Keweenawan basalt.

Anomalies over Proterozoic X terrane

E (west-central)—The gravity high at **E** is especially apparent on the residual gravity map (fig. 3).