GEOPHYSICS, VOL. 56, NO. 1 (JANUARY 1991); P. 123–132, 9 FIGS.

Moving-window Poisson analysis of gravity and magnetic data from the Penokean orogen, east-central Minnesota

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ABSTRACT

Analytical correlation of gravity and magnetic data through moving-window application of Poisson's theorem is useful in studying the complex Precambrian geology of central Minnesota. Linear regression between the two data sets at each window position yields correlation, intercept, and slope parameters that quantitatively describe the relationship between the gravity and magnetic data and, in the case of the slope parameter, are often accurate estimates of magnetization-to-density ratios (MDR) of anomalous sources. In this study, gridded gravity and magnetic data from a 217.6 x 217.6 km area in central Minnesota were analyzed using a 8.5 x 8.5 km window. The study area includes part of the Early Proterozoic Penokean orogen and an Archean greenstone-granite terrane of the Superior Province.

The parameters derived by the moving-window analysis show striking relationships to many geologic features, and many of the MDR estimates agree with rock property data. Inversely related gravity and magnetic anomalies are a characteristic trait of the Superior Province, but moving-window analysis reveals that direct relationships occur locally. In the Penokean fold-and-thrust belt, gravity and magnetic highs over the Cuyuna range produce a prominent belt of large MDR estimates, which reflect highly deformed troughs of iron-formation and other supracrustal rocks. This belt can be traced northeastward to sources that are buried by 3–5 km of Early Proterozoic strata in the Animikie basin. This configuration, in conjunction with recent geologic studies, indicates that the Animikie strata, which may represent foreland basin deposits associated with the Penokean orogen, unconformably overlie parts of the fold-and-thrust belt, and that earlier stratigraphic correlations between Cuyuna and Animikie strata are wrong. The results of this study indicate that moving-window Poisson analysis is useful in the study of Precambrian terranes.

INTRODUCTION

Poisson's theorem, which established a linear relationship between gravity and magnetic potential, can be applied to gravity and magnetic data to determine magnetization-to-density ratios (Garland, 1951; Kanasewich and Agarwal, 1970; Hildenbrand, 1985) and direction of magnetic polarization (Ross and Lavin, 1966; Cordell and Taylor, 1971). However, the underlying assumptions of a common gravity and magnetic anomaly source that is uniform and completely isolated from the effects of other sources have usually restricted use of Poisson's theorem to fairly simple, well-isolated anomalies. Chandler et al. (1981) extended use of Poisson's theorem to data sets containing complex, interfering anomalies by applying it piecemeal within a moving data window. Within a small segment of data, a dominant source will adhere closely to the linear relation, whereas contributions from surrounding sources usually vary much less within the segment and contribute more to a base level shift. Thus within a small window Poisson's theorem can be approximated by

$$Tz = A + 1/G(\Delta J/\Delta\rho)\ (\delta g/\delta z), \tag{1}$$

where Tz = total magnetic intensity anomaly reduced to vertical polarization (reduced-to-pole),
$\delta g/\delta z$ = the first vertical derivative of the gravity anomaly,
A = an intercept parameter that reflects changes in apparent base levels due to anomaly interference,
G = universal gravitational constant,
ΔJ = magnetization contrast of dominant source, and
$\Delta\rho$ = density contrast of the dominant source.

At each window position a least-squares linear regression (York, 1969) performed on the points within the window yields three parameters—slope, correlation coefficient, and intercept—which describe the internally varying relationships between the gravity and magnetic anomalies in an area. The correlation coefficient indicates the sense of the correlation (direct or inverse), with values approaching ± 1.0 signaling a high-quality linear fit. The intercept parameter reflects apparent changes in base level caused by anomaly interference. The slope, corrected

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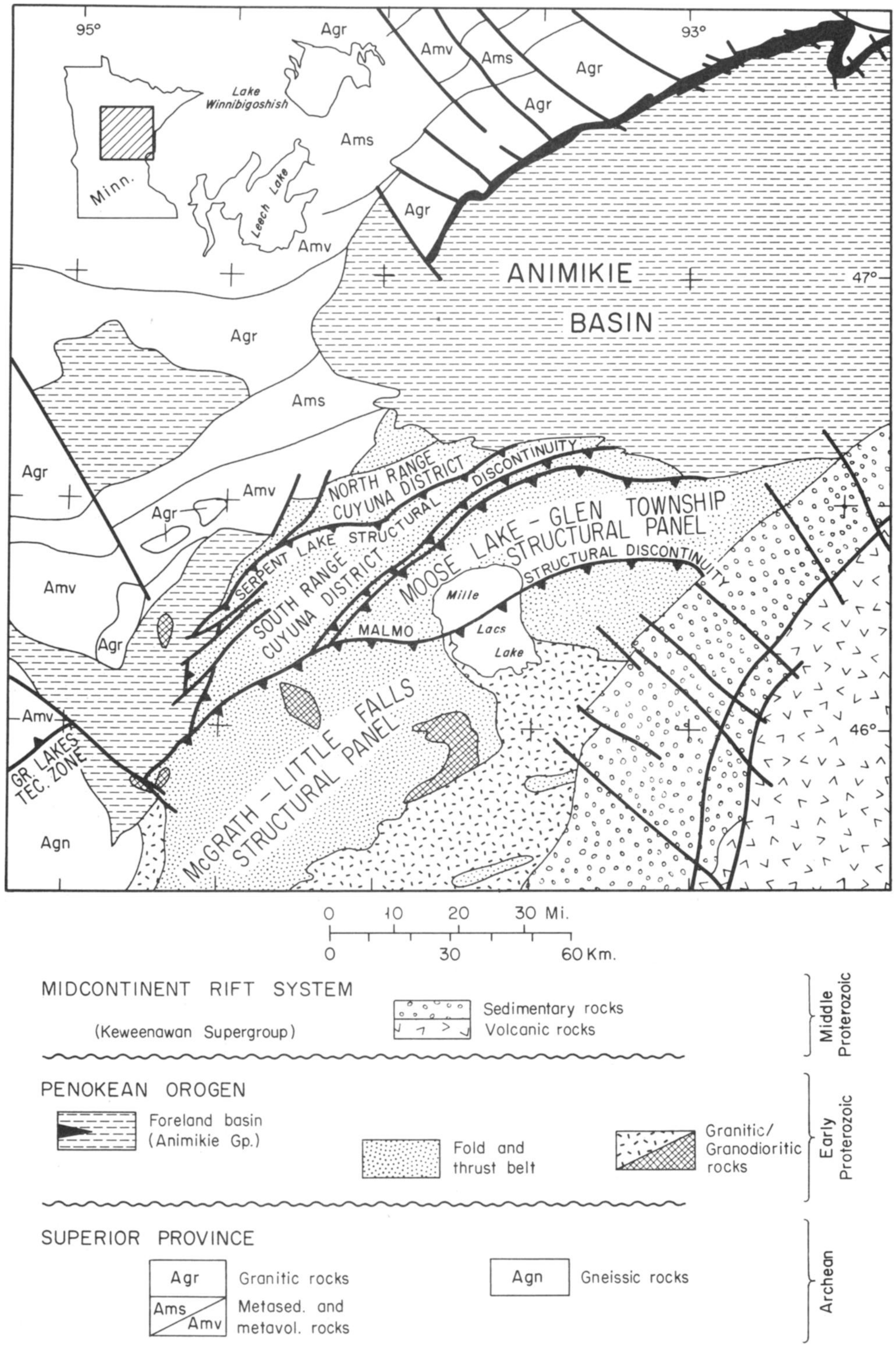

FIG. 1. Map of Precambrian geology of east-central Minnesota, after Morey et al. (1981) and Southwick et al. (1988). Location is the same as Figures 2–9.

for 1/G, provides an estimate of MDR for the anomaly source [equation (1)]. Model studies by Chandler et al. (1981) indicate that accurate estimates of MDR are possible with the moving-window approach, even in some cases of extreme anomaly interference and source heterogeneity. They found that accurate MDR estimates are associated with plateaus of constant MDR and intercept values, correlation coefficients approaching $\pm$ 1.0, and gravity and magnetic anomalies that can be visually recognized.

Moving-window Poisson analysis has been extensively tested by model studies (Chandler et al., 1981; Carlson, 1985), but its use on natural anomalies has been mostly limited to studies of gross crustal structure using data upward continued to 50 km or more (Chandler et al., 1981, 1982). Carlson (1985) used the moving-window method on high-resolution aeromagnetic data to investigate Precambrian geology and shallow crustal structure in central Minnesota, and it is an updated version of this study that we present in this paper. We demonstrate the utility of the method in geologic studies and describe its role in a recent reinterpretation of the Precambrian geology of the area (Southwick et al., 1988).

GEOLOGY OF EAST-CENTRAL MINNESOTA

The northern and western parts of the study area are underlain by a 2600–2750 Ma greenstone-granite terrane of the Superior Province (Figure 1), which consists of east- to northeast-trending belts of tightly folded, steeply inclined greenschist-facies metavolcanic and metasedimentary rocks, that are interspersed with belts of granitic rocks (Morey and Van Schmus, 1988). The southwestern corner of the area is underlain by gneissic rocks that may be equivalent to the Archean gneiss exposed in the Minnesota River valley (Goldich et al., 1980). The gneissic rocks and the greenstone-granite terrane are joined along the Great Lakes tectonic zone (Sims et al., 1980), a major crustal boundary that is most likely a shear zone of late Archean age (Morey and Sims, 1976; Southwick et al, 1988). Except for the southwestern corner of the area, the Great Lakes tectonic zone probably has been obliterated by structures associated with the Penokean orogen.

The Early Proterozoic Penokean orogen consists of the Animikie basin and associated outliers, along with the Penokean fold-and-thrust belt (Figure 1). Southwick et al. (1988) proposed that the fold-and-thrust belt formed at a convergent plate margin, with the Animikie basin representing a tectonic foredeep or foreland basin, which formed in response to tectonic loading at the fold-and-thrust belt. On the basis of test drilling and visual interpretation of gravity and magnetic maps, they divided the fold-and-thrust belt into four structural panels bounded by major structural discontinuities (Figure 1) that consistently indicate northward vergence and may include nappes (Holst, 1984). In general the amount of plutonic and volcanic rocks increases southward into the fold-and-thrust belt, as do the tectonic depth and deformational complexity. The moving-window Poisson analysis provided an important supplement to their interpretation.

Post-Penokean rocks are a minor component of the Precambrian geology in the study area. Keweenawan sedimentary and volcanic rocks of the Midcontinent rift system underlie the southeastern corner of the area (Figure 1). A few thin, isolated patches of Cambrian and Cretaceous rocks occur locally (not shown on Figure 1), and Quaternary till and outwash form a nearly continuous veneer which locally exceeds 33 m in thickness. Thus geologic studies in the area must rely on a combination of outcrop studies, test drilling, and geophysical studies (Morey et al, 1981; Southwick et al., 1988).

PREPARATION OF THE GRAVITY AND MAGNETIC DATA

The gravity and aeromagnetic data used in this study were compiled from numerous sources (summarized in Carlson, 1985) and are available through the Minnesota Geological Survey. The gravity data consist of about 15 000 stations, most of which are spaced at intervals of 1.6–4.0 km (Figure 2). The aeromagnetic data were acquired on north-south flight lines flown 400 m apart and 150 m above ground, and were reduced using a regional geomagnetic field model by Peddie and Fabiano (1976). A preliminary gravity grid at a spacing of 1.707 km was created using the nearest neighbor method (Sampson, 1975), whereas a preliminary magnetic grid at a spacing of 0.427 km was based on minimum curvature (Briggs, 1974).

The gravity and magnetic grids were prepared for moving-window Poisson analysis by differentiation and upward continuation using fast Fourier transform software designed by Reed (1980). Polarization along the Earth's magnetic field (average declination/inclination = 4°30′E/74°30′N) was assumed, and the magnetic data were transformed to the equivalent field at vertical polarization, or "reduced-to-pole" (Baranov, 1957; Bhattacharyya, 1965, 1972). Rock magnetism data from the region indicate that most Archean and Early Proterozoic rocks are indeed polarized approximately along the Earth's field (Symons, 1966; Hall, 1968; Sims, 1972; and Hall et al., 1979). To give the magnetic data wavelength characteristics similar to the less sampled gravity data, both data sets were upward continued to a common elevation of 3 km above surface. Following upward continuation, the data grids were resampled and registered at an interval of 0.853 km. Finally, because of strong regional anomalies in the gravity data, the signature of near-surface geology was enhanced by differentiating the input data so that Poisson's theorem has the form

$$\delta Tz/\delta z = A + 1G(\Delta J/\Delta\rho)\ \delta^2 g/\delta^2 z. \qquad (2)$$

DISCUSSION OF THE GRAVITY AND MAGNETIC ANOMALIES

Figures 3 and 4 show unfiltered gravity and magnetic data, respectively, and Figures 5 and 6 show the upward-continued and derivative gravity and magnetic data, respectively. The gravity and magnetic data are not significantly affected by the glacial materials or the Phanerozoic sedimentary rocks; rather, they primarily reflect physical property contrasts in the Precambrian bedrock. Density and magnetic properties of rock units in the area are summarized in Table 1.

In the gravity and magnetic data (Figures 3 and 4) many anomalies in the greenstone-granite terrane (Figure 1) appear to be inversely related, as is typical of Superior Province greenstone-granite terranes (Hall, 1968; McLaren and Charbonneau, 1968; Goodwin, 1972). Gravity and magnetic anomaly relief is 20–50 mGals and 100–500 nT, respectively (Figures 3 and 4), with the granitic belts corresponding to gravity lows and magnetic highs, and the metavolcanic belts corresponding to

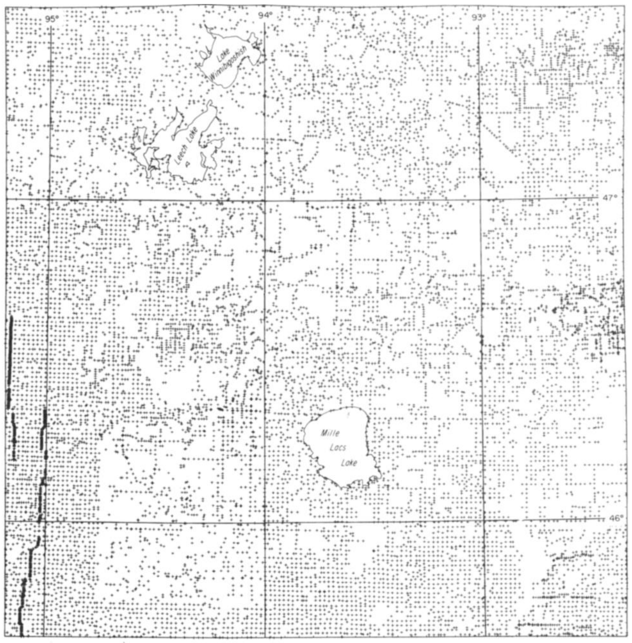

FIG. 2. Map showing control for gravity data in east-central Minnesota. Note the lack of gravity data over the large lakes.

gravity highs and magnetic lows. Metasedimentary belts are typically associated with intermediate to low gravity expression and a subdued magnetic signature. High magnetic iron formations in the greenstones locally produce curvilinear magnetic highs with intensities greater than 1000 nT. Northwest-striking linear anomalies transecting the greenstone-granite terrane on Figure 4 reflect a swarm of 2120 Ma diabase dikes (Southwick and Day, 1983; Southwick and Halls, 1987). In the southwestern corner of the area, rocks of the Archean gneiss terrane correspond to a complex magnetic high, whose sharp northern truncation traces the Great Lakes tectonic zone (Figure 1).

The iron formation along parts of the northern rim of the Animikie basin (Biwabik Iron Formation) is strongly magnetic (Table 1) and produces a sinuous magnetic high with amplitudes commonly over 1000 nT (compare Figures 1, 4, and 6). Most of the Animikie basin, however, corresponds to a very subdued magnetic signature, reflecting a deep fill of nonmagnetic slate and graywacke (Table 1), which, according to magnetic depth estimates, could be as thick as 3–6 km (Chandler, 1982; Ferderer, 1988). Within the fold-and-thrust belt the magnetic anomalies in Figures 4 and 6 are produced by strongly magnetic iron formations and granodioritic rocks (Table 1). A regional gravity high completely obscures the signature of sources in the fold-and-thrust belt (Figure 3), but the second vertical derivative data isolate highs along structural troughs and over some of the granodioritic intrusions (Figures 1 and 5).

MOVING-WINDOW POISSON ANALYSIS

Moving-window Poisson analysis was conducted between the second vertical derivative of gravity data in Figure 5 and the reduced-to-pole magnetic data in Figure 6. The choice of a window size is a compromise between including enough points to attain a statistically significant linear regression and keeping the spatial size small enough to window single anomalies (Chandler et al, 1981). A window size of 11x11 grid units (8.5 x 8.5 km) was selected as a reasonable compromise (Carlson, 1985), and the resulting correlation, slope, and intercept parameters are shown in Figures 7, 8 and 9, respectively.

Many regions of consistent slope values in Figure 8 are assumed to contain accurate MDR estimates, because they correspond to plateaus in intercept values (Figure 9), correlation coefficient values approaching +1.0 (Figure 7), and visually recognizable gravity and magnetic anomalies (Figures 5 and 6, respectively); these regions are emphasized below. However, even the less reliable MDR estimates are useful in the overall interpretation, in that they portray the continually varying relationships between gravity and magnetic anomalies within the area and commonly form patterns of geologic significance.

Superior Province

In the Superior Province the correlation coefficient and slope (MDR) parameters (Figures 7 and 8) indicate that, besides the characteristically inverse relationships, direct relationships between gravity and magnetic anomalies are locally prevalent. Belts of inverse correlation are associated with MDR values generally ranging from −0.001 to −0.010, which are consistent with values expected for granitic rocks in contact with denser and less magnetic mafic metavolcanic rocks (Table 1). Areas of direct correlation with large MDR estimates ranging from 0.014 to >0.100 occur in the northwestern part of the study area (Figures 7 and 8); on the basis of their strong magnetic signature, they are interpreted to reflect iron formations within the greenstone belts. Averaged values for Archean iron formations and contrasting metasedimentary and metavolcanic rocks in Table 1 yield comparable MDR values of 0.022 and 0.5800, respectively. Direct correlations over some of the granitic belts (Figure 1) may reflect contrasts between felsic and more intermediate phases (Table 1). West of 94° along the southeastern margin of Superior Province rocks, a broad region of positive correlation and exceptionally stable slope (MDR) and intercept parameters (Figures 7–9) corresponds to what Southwick et al. (1988) interpret to be a metasedimentary belt that contains dense and magnetic plugs of dioritic and tonalitic rocks.

Penokean fold-and-thrust belt

Southwick et al. (1988) divided the Penokean fold-and-thrust belt into panels based primarily on new drill-hole data and qualitative interpretation of gravity and aeromagnetic maps, and the moving-window analysis generally supports their interpretation. The structural panels (Figure 1) correspond to prominent, internally consistent patterns in the correlation and slope (MDR) parameters (Figures 7 and 8), supporting the idea that each accretionary panel may be lithologically and stratigraphically distinct from adjacent panels. For example, the Moose Lake-Glen Township panel, consisting of a diverse suite of highly deformed Early Proterozoic supracrustal rocks, is dominated by inverse correlation and MDR values ranging from 0.000 to −0.022, whereas the McGrath-Little Falls panel, consisting of supracrustal outliers and dioritic plugs of Early Proterozoic age on a basement of gneissic and migmatitic rocks, is dominated by direct correlation and MDR estimates ranging from 0.000 to 0.038 (Figures 7 and 8). Magnetization and density values for supracrustal (Denham formation) and dioritic (Freedhem Granodiorite) rocks and gneissic basement (McGrath Gneiss)

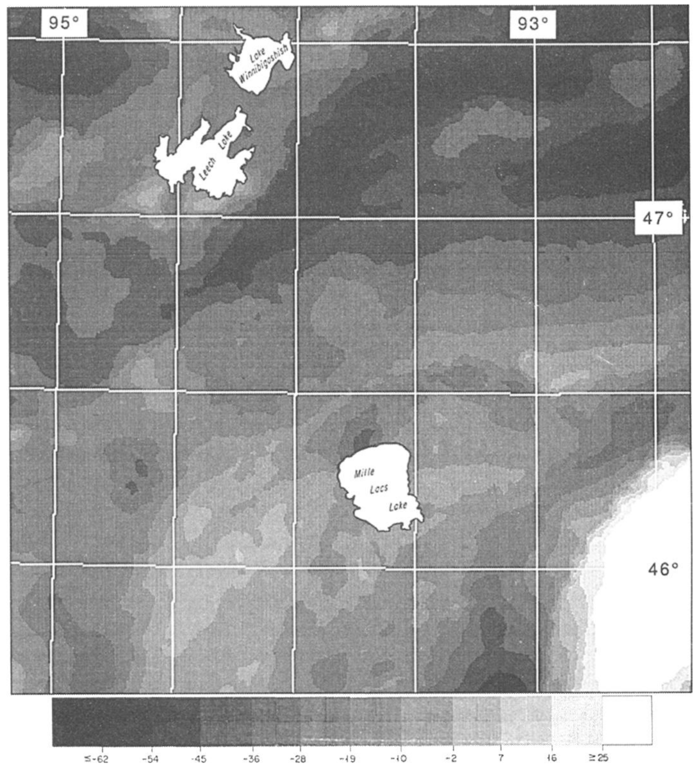

FIG. 3. Bouguer gravity anomaly data from east-central Minnesota. Units are milligals.

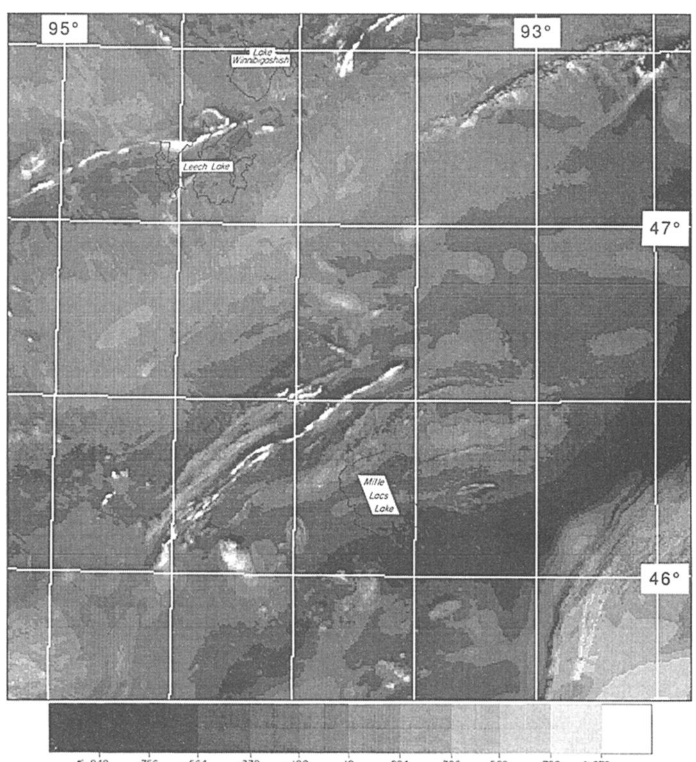

FIG. 4. Total-field aeromagnetic anomaly map of east-central Minnesota. Units are nanoTeslas (nT).

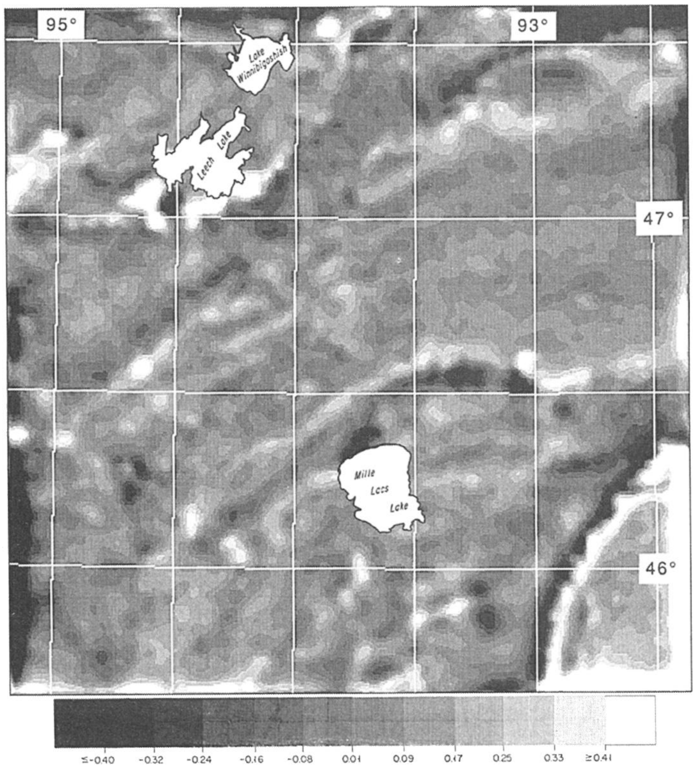

FIG. 5. Second vertical derivative of the Bouguer gravity anomaly data from east-central Minnesota. Upward continued to 3 km above surface. Units are mGals/km^2.

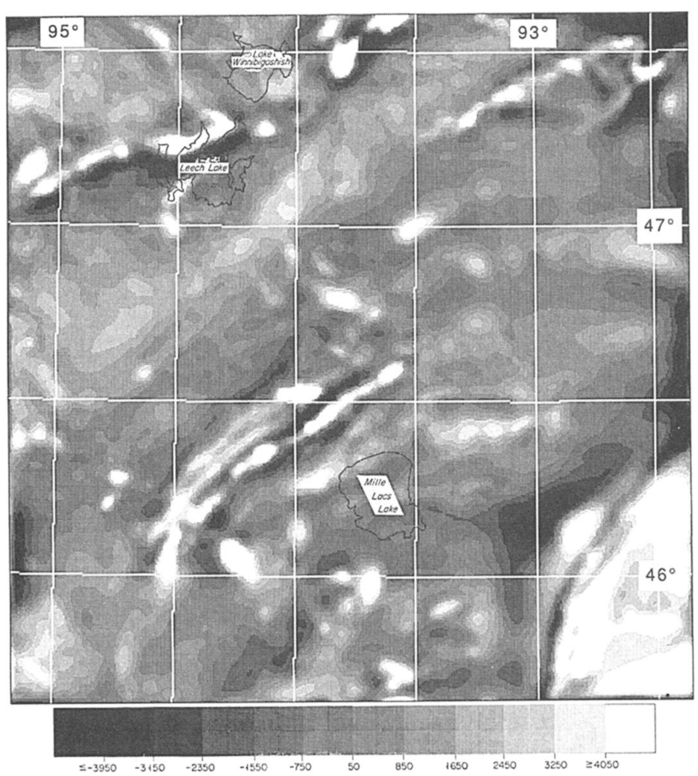

FIG. 6. First vertical derivative of the total-field aeromagnetic anomaly data from east-central Minnesota. Reduced to the pole and upward continued to 3 km above surface. Units are nT/km.

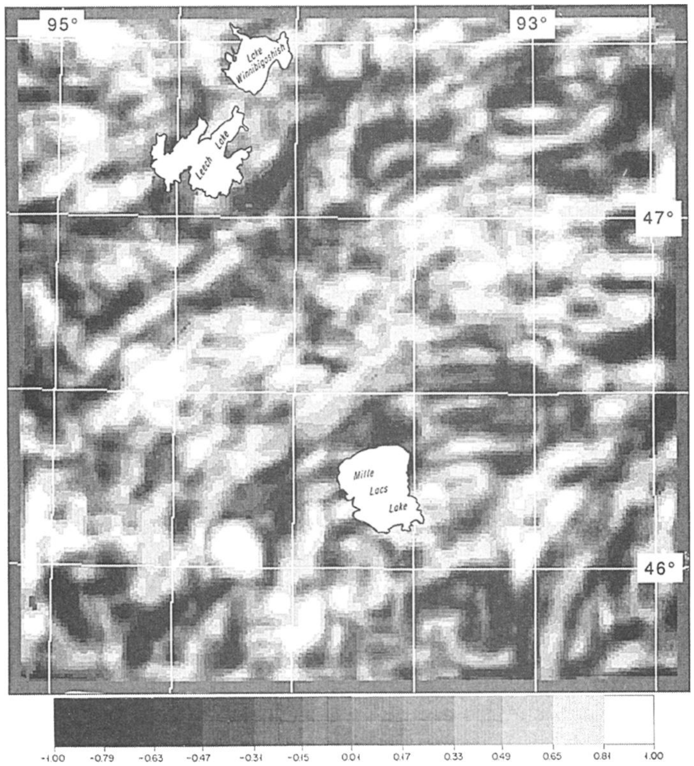

FIG. 7. Moving-window Poisson analysis of the east-central Minnesota data—correlation coefficient.

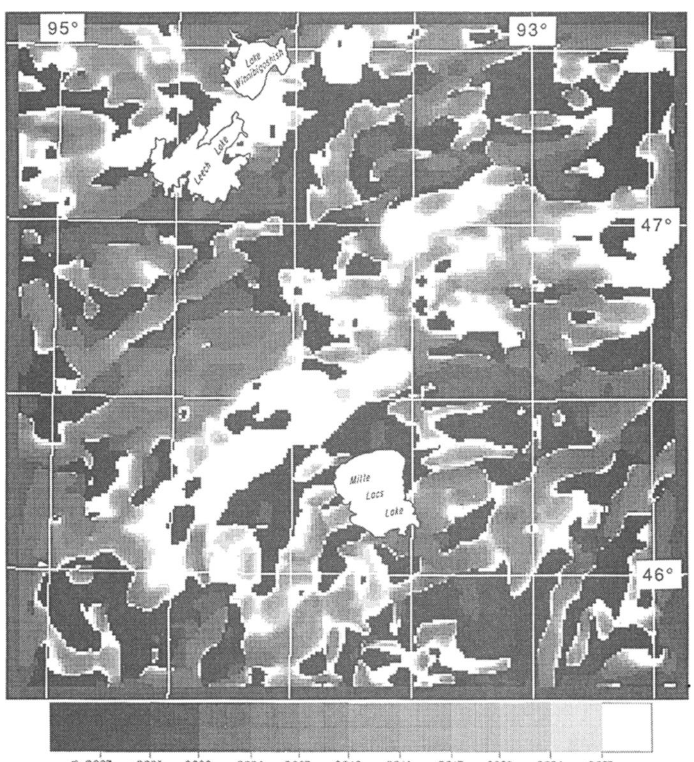

FIG. 8. Moving-window Poisson analysis of the east-central Minnesota data—slope (MDR). Units are SI.

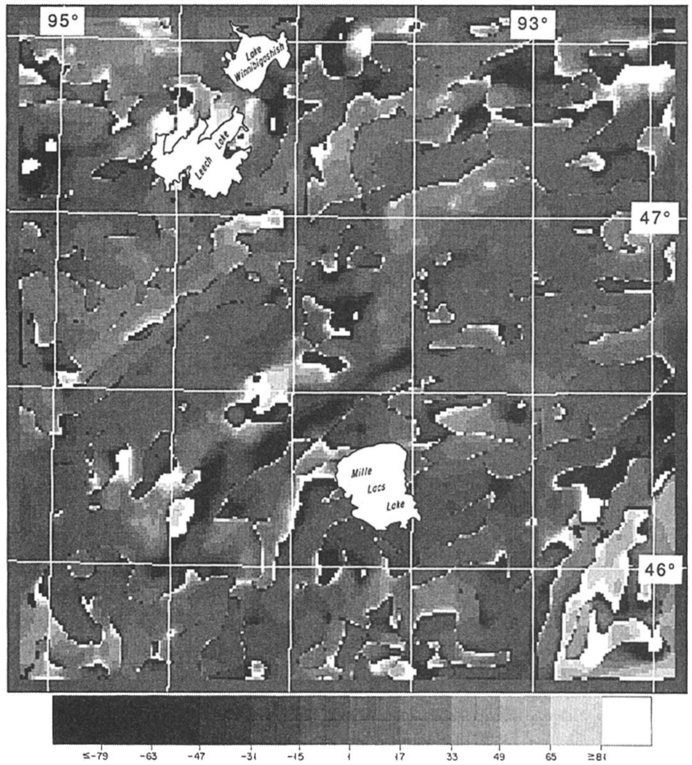

FIG. 9. Moving-window Poisson analysis of the east-central Minnesota data—intercept. Units are nT/km.

Table 1. Densities and magnetic susceptibilities of representative rock units. Asterisks denote average value based on five or fewer samples. Induced magnetizations based on geomagnetic field intensity of 59 500 nT.

	Density (x1000 kg/m^3)	Density range	Induced magnetization (SI)	Induced magnetization range
Early Proterozoic				
Stearns Granitic Complex	2.64	2.60–2.74	0.305	0.119–1.607
Freedhem Granodiorite				
Magnetic	2.86*	2.82–2.93	2.060*	0.855–3.727
Nonmagnetic	2.85*	no data	0.060*	0.055–0.067
Cuyuna Iron Formation	3.34	3.10–3.90	19.790	5.229–47.420
Biwabik Iron Formation	3.45	3.04–3.92	35.050	2.203–78.480
Denham Formation				
Schist	2.91	2.69–3.12	0.532	0.005–2.114
Quartzite	2.69	2.60–2.87	0.021	0.004–0.058
Phyllite	2.74*	2.70–2.79	0.017	0.006–0.030
McGrath gneiss	2.68	2.62–3.27	0.465	0.019–2.050
Archean				
Giants Range Granite	2.69	2.59–2.86	0.389	0.019– 3.768
Soudan Iron Formation	2.95*	2.62–3.27	5.900	0.015–31.790
Metavolcanic rocks	2.94	2.65–3.14	0.058	0.024– 0.226
Metasedimentary rocks	2.68*	2.62–2.73	0.049	0.020– 0.118
Minnesota River Valley gneiss	2.64	2.54–2.88	0.251	0– 1.651

from the McGrath-Little Falls panel (Table 1) yield some MDR values consistent with the estimates in Figure 8.

The Cuyuna North and South ranges are characterized by a 30 km wide belt of positive correlation coefficient values and large MDR estimates ranging generally from 0.025 to 0.100 (Figures 7 and 8). These parameters reflect structural troughs of Early Proterozoic supracrustal rocks that contain a significant portion of dense and magnetic iron-formation (Table 1). This distinctive belt extends eastward into the Animikie basin along 47° N (Figures 7 and 8), where smooth magnetic anomalies (Figure 4) have been interpreted to reflect sources lying beneath 2–5 km of Animikie strata (Chandler, 1982; Ferderer, 1988). Test drilling along this extension revealed that the deformation of Animikie strata is significantly less than that observed in the Cuyuna ranges (Southwick et al., 1988); thus, if the highly deformed troughs of the Cuyuna ranges extend into the Animikie basin, they must be unconformable with the overlying Animikie strata. This observation, supported by drill-hole data, led Southwick et al. (1988) to conclude that a pronounced angular unconformity exists between the Cuyuna and Animikie strata and that earlier stratigraphic correlations between the sequences were wrong. This line of reasoning is an integral part of the plate-tectonic model of the Penokean orogen where the Animikie strata represent foreland basin deposits that may be younger than the parts of the fold-and-thrust belt formed earlier.

Other geologic features

Early Proterozoic granitic rocks with minor supracrustal inliers along the south-central margin of the study area (Figure 1) correspond to a triangular zone of inverse correlation (Figure 7) with MDR values ranging from 0.000 to 0.013. These parameters contrast sharply with those in the rest of the McGrath-Little Falls panel and may delineate an additional panel in the fold-and-thrust belt. The Archean gneissic rocks in the southwestern corner of the study area (Figure 1) correspond to generally poor but inverse correlation of anomalies (Figures 7 and 8). The area of positive correlation in the southeastern corner of the study area doubtless reflects mafic igneous rocks of the Midcontinent rift system (Figure 1), but a strong remanent magnetization in these rocks (Sims, 1972) was not accounted for in the reduction to pole, and the MDR estimates in Figure 8 should therefore not be trusted.

CONCLUSIONS

Moving-window Poisson analysis of gravity and aeromagnetic data correlates and amplifies the geologic interpretation of poorly exposed Precambrian terranes in east-central Minnesota, and therefore appears to be an interpretive technique of value to geologic mapping in other Precambrian areas. The study area includes part of the Archean Superior Province and the Early Proterozoic Penokean orogen, with the latter consisting of an imbriccated fold-and-thrust belt and associated flexural foredeep.

Inversely and directly related gravity and magnetic anomalies, and MDR estimates that are consistent with rock property data, are associated with the Superior Province rocks. In the Cuyuna districts of the Penokean fold-and-thrust belt, troughs of supracrustal rocks with a significant portion of iron formations are associated with a distinct belt of positive correlation and large MDR estimates (0.025–0.100). This belt of positive correlation extends northeastward into the Animikie basin, where the anomaly sources appear to be deeply buried. This pattern has been used recently in conjunction with new drill-hole data to argue that the Animikie strata unconformably overlie highly deformed rocks of the fold-and-thrust belt.

Moving-window Poisson parameters show regionally coherent patterns over other panels within the fold-and-thrust belt, including inverse correlations associated with the intensely deformed Early Proterozoic supracrustal rocks of the Moose Lake-Glen Township panel and direct correlations associated with granodioritic intrusions and supracrustal inliers within gneissic and migmatitic rocks of the McGrath-Little Falls panel. A zone of inverse correlation along the southern margin of the study area between 93°30′ and 94°15′ W may delineate a previously unrecognized panel of the Penokean fold-and-thrust belt. belt.

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