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D.L. SOUTHWICK, *Interim Director*

GRAVITY INVESTIGATION FOR POTENTIAL GROUND-WATER RESOURCES IN ROCK COUNTY, MINNESOTA

Val W. Chandler

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GRAVITY INVESTIGATION FOR POTENTIAL GROUND-WATER RESOURCES IN ROCK COUNTY, MINNESOTA

By

Val W. Chandler

ABSTRACT

The gravity method was used to investigate the thickness and potential ground-water resources of Cretaceous and Quaternary sediments in Rock County, Minnesota. This fill, which partially covers the Early Proterozoic Sioux Quartzite, is a major source of ground water for the county, but its deeper parts are very poorly known because of poor drill-hole control.

Local gravity signatures reflecting the low-density fill were isolated from a smooth, regional field reflecting deep, intrabasement sources by a graphical cross-profile procedure, which incorporated data from outcrops, drill holes, and seismic soundings, to define the regional field. At control points where fill thickness was known, the regional field value was determined by using a Bouguer slab approximation with a density contrast of 0.60 g/cm^3 to strip out the local effect of the fill. Additional control on the regional field was provided by iterative analysis of cross-profiles. Because it is assumed to be smooth, the regional field can be defined by relatively few control points, and subtraction of this field from the observed gravity data produces a residual map of the fill signatures. The residual field was transformed into estimates of fill thickness by using the same Bouguer slab approximation and density contrast of -0.60 g/cm^3, and the elevation of the Precambrian bedrock was estimated by subtracting the fill thickness from the surface elevation.

In southwestern, southeastern, and northeastern Rock County, the combined thickness of the Cretaceous and Quaternary deposits is interpreted to exceed 200 m (600 feet). The thick fill in southwestern Minnesota connects with a buried channel in South Dakota that contains several known aquifers. Potential ground-water resources may also be associated with several buried channels cut into the edges of a plateau of Sioux Quartzite in the northwestern and central parts of the county. Along the southern margin of this plateau, a buried and somewhat dissected escarpment is interpreted to be associated locally with at least 215 m (650 feet) of unconsolidated fill. Additional resources may lie within the fractured rock and thickened fill in a northwest-striking fracture zone in the Sioux Quartzite, which may extend in the subsurface across the county.

The results of this study indicate that the gravity method is an effective reconnaissance-scale tool for ground-water exploration in the Sioux Quartzite areas of southwestern Minnesota.

INTRODUCTION

Ground water is a critical natural resource for the domestic, agricultural, and municipal needs of southwestern Minnesota. Much of the ground water is produced from shallow outwash deposits in the Quaternary till, which are vulnerable both to pollution from the surface and to drought. New and more reliable resources may exist in the deeper parts of the Quaternary and Cretaceous deposits of southwestern Minnesota, but the distribution of these thick deposits is poorly known because of poor drill-hole control (Setterholm, 1990). Improved maps of the thickness of the Cretaceous and Quaternary deposits would be major assets to future ground-water exploration in southwestern Minnesota.

The Cretaceous and Quaternary deposits in southwestern Minnesota together form a poorly consolidated, low-density fill that overlies a basement of much denser Precambrian rocks. Because gravity is directly related to mass, changes in thickness of the fill produce subtle anomalies in the earth's gravity field. If these subtle anomalies can be properly isolated, they can be used to estimate fill thickness and bedrock topography. Along these lines, the gravity method has been used successfully to delineate part of a buried bedrock channel in southeastern South Dakota (Hansen, 1984).

In comparison to other geophysical methods, such as seismic profiling, the gravity method is much cheaper and faster to implement, thereby allowing a much larger region to be investigated per unit of field time. In southwestern Minnesota, a regional network of gravity stations spaced 1.6-3.2 km (1-2 miles) apart already exists, and by adding a minor amount of new gravity data, either as intercalated new stations or as strategically placed profiles, the data base can be upgraded for investigating the thickness of the Cretaceous and Quaternary fill. As with all geophysical methods, the gravity method can produce ambiguous results, but many ambiguities can be lessened by incorporating all available geologic control and rock-density information.

In this study we used the gravity method to investigate the thickness of the Quaternary and Cretaceous fill in Rock County, Minnesota (Fig. 1). Rock County is a suitable test case for the method, because the county has many of the geologic and ground-water problems that are typical of southwestern Minnesota, and because earlier geologic work has targeted two features that may be pertinent to ground-water resources.

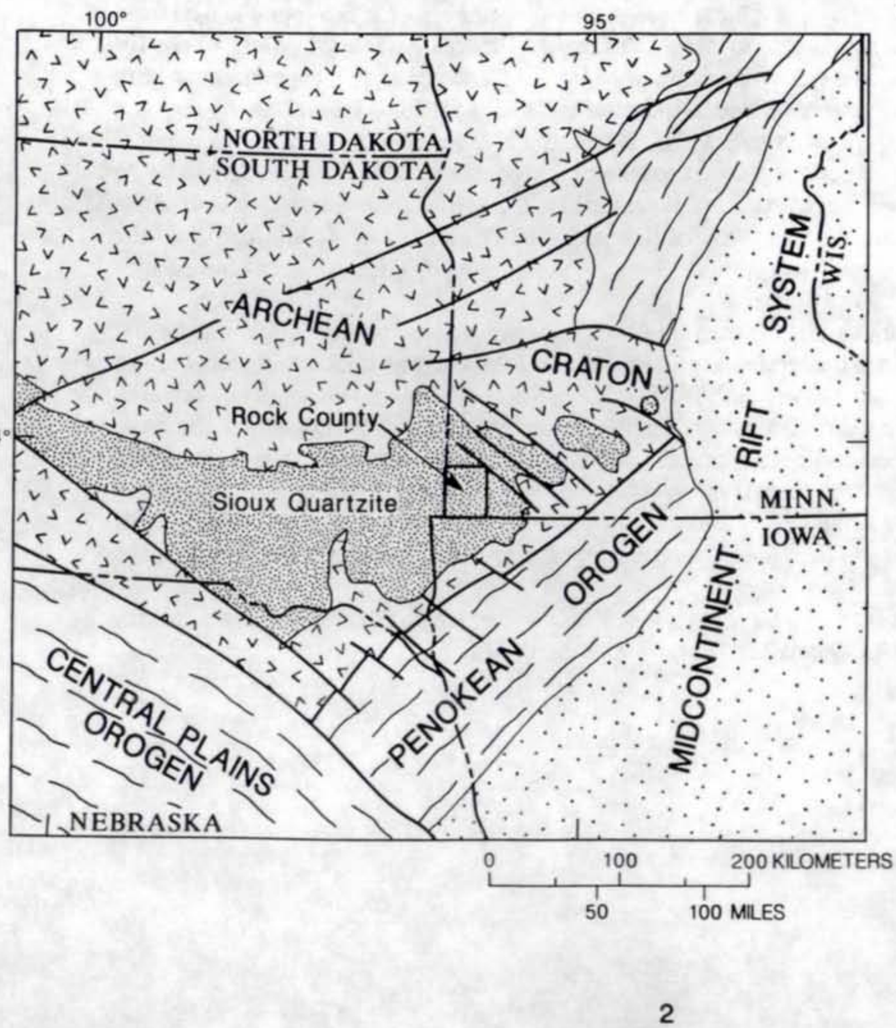

Figure 1. Location of Rock County and generalized Precambrian geologic map of the Sioux Quartzite area and surrounding regions (modified from Chandler and Morey, 1992).

GEOLOGY OF ROCK COUNTY

Most of Rock County is underlain by the Precambrian Sioux Quartzite, an Early Proterozoic quartz arenitic redbed sequence that crops out extensively in southwestern Minnesota and adjoining parts of South Dakota, Nebraska, and Iowa (Fig. 1). Besides quartzite, the formation also includes minor conglomerates and thin layers of argillite (Southwick and others, 1986). Gentle dips (generally less than 10 degrees) in the quartzite define a circular sub-basin in the quartzite outcrop area of northern Rock County (Fig. 2). In the outcrop areas the quartzite is typically well cemented by interstitial quartz, and forms resistant ridges that are glacially scoured and wind-polished. Although small bodies of gabbro and diabase are known to intrude the Sioux Quartzite in nearby South Dakota (Baldwin, 1951), no such rocks are known in Rock County, and none are indicated near the surface by high-resolution aeromagnetic data (Chandler, 1989). On the basis of stratigraphy and projected dips, Baldwin (1951) estimated a maximum thickness for the Sioux Quartzite in Rock County of 1.6-2.4 km (1.0-1.5 miles), within the range of magnetic-anomaly depths estimated at 1.3-1.7 km by Chandler using the general indices of Vacquier and others (1951) in central Rock County. Highly deformed gneissic and supracrustal rocks of Archean or Early Proterozoic age are believed to underlie the Sioux Quartzite, and some of these rocks may subcrop in the extreme northeastern corner of Rock County (Fig. 2).

The Precambrian rocks are partially overlain by the Late Cretaceous Split Rock Creek Formation, a near-shore marine facies associated with embayments in the Sioux Quartzite (Setterholm, 1990; not shown in Figure 2). It is believed to range in thickness from <1 to 120 m (<1 to 400 feet). Quartz arenites and gray claystones forming the lower part are overlain by a thinner upper unit consisting chiefly of spiculites (a rock unit composed almost wholly of sponge spicules). The Cretaceous rocks are flat lying and, with the exception of some spiculite layers, are essentially unconsolidated. The Split Rock Creek Formation laps onto the Sioux Quartzite ridges and is generally absent above elevations of 400 m (1,300 feet) (Dale Setterholm, oral commun.).

All of the Cretaceous rocks and much of the Sioux Quartzite in Rock County are covered by unconsolidated Quaternary till and outwash—the old gray drift of pre-Illinoian age (Hobbs and Goebel, 1982). The old gray drift, which may actually include several till sequences, has a well-dissected surface that is commonly covered by loess (Carrie Patterson, 1993 and oral commun.). In Rock County, the Quaternary deposits range in thickness from <1 to 120 m (<1 to 400 feet), with the thickest parts occurring in the southern and eastern parts of the county (Setterholm, 1990).

Geologic studies in the Rock County area have located two features that may be pertinent to ground-water resources. The first feature is a major channel in the Sioux Quartzite from near Valley Springs, South Dakota (Fig. 2). The Cretaceous and Quaternary channel fill is thicker than 150 m (500 feet) in South Dakota and includes several aquifers (Lindgren and Niehus (1992). Unfortunately, the course of this channel in southern Rock County is not well known, owing to a lack of drill-hole control (Dale Setterholm, oral commun.). The second feature is a northwest-striking fracture zone in the Sioux Quartzite, which is interpreted to lie along the southwestern margin of the major outcrop areas in Rock County. This fracture zone is inferred because of (1) a marked decrease in quartzite outcrops along and southwest of its proposed trace (Fig. 2) implying a thickened overburden over mechanically weakened quartzite; and (2) fracture patterns in the quartzite outcrops along or within the zone (David Southwick, oral commun.). Aquifers could occur in the fractured quartzite, as well as in the overlying thickness of Quaternary fill.

DENSITY DATA

The contrast in density—measured as grams per cubic centimeter (g/cm^3)—between the Sioux Quartzite and the poorly consolidated Cretaceous and Quaternary deposits is a critical parameter in applying the gravity method to estimate fill thickness. Table 1 summarizes the relevant density data. All densities for both Cretaceous and Quaternary deposits are fairly low; even a well-consolidated Cretaceous spiculite yields a low average density of 2.14 g/cm^3. The results in Table 1 indicate that the Cretaceous and Quaternary deposits are similar in density and probably have a combined average density around 2.00-2.10 g/cm^3.

The measured densities of the Sioux Quartzite vary somewhat from area to area (Fig. 2 and Table 1), but the three-area average of 2.68 g/cm^3 is a reasonable compromise. This average is, for all practical purposes, the same as the Bouguer reduction density of 2.67 g/cm^3 and makes it unnecessary to compensate for differential mass between the quartzite and Bouguer reduction density in the analysis that follows. Based on the average values in Table 1, an overall density contrast of 0.60 g/cm^3 was selected for the contact between the quartzite and fill. This contrast, for example, would distinguish between a quartzite with a density of 2.68 g/cm^3 and a fill with a density of 2.08 g/cm^3.

DESCRIPTION OF GRAVITY DATA

Field and Compilation Procedures

In July and October 1993, 190 new gravity stations along 11 profiles (Fig. 3) were acquired. Four east-west

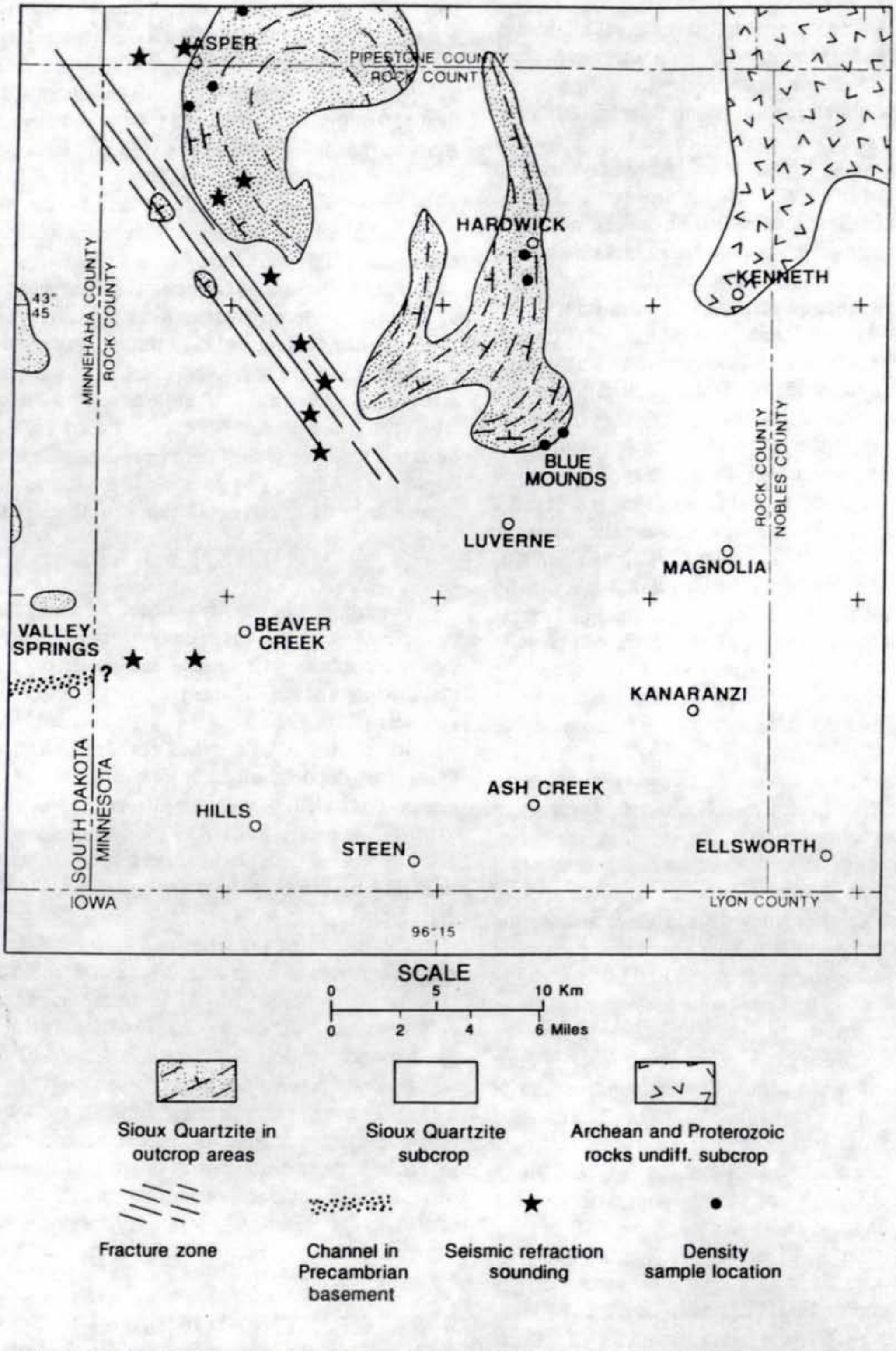

Figure 2. Geologic map of the Precambrian surface in Rock County and surrounding areas. Subcrop areas covered partially by Cretaceous deposits, and wholly by Quaternary deposits. Orientation of bedding in Sioux Quartzite outcrops shown by form lines and strike-and-dip symbols. Modified from Baldwin, 1951; and D.L. Southwick, oral commun.

Table 1. Summary of density data

Unit	Density (avg g/cm^3)	Number samples	Souce	Comment
Quaternary				
till	1.80	5	Fogelson (1956)	1
saturated deposits	1.99	8	This study	2
Cretaceous				
deposits	2.12	2	This study	2
clay	2.06	7	Fogelson (1956)	3
spiculite	2.14	4	This study	4
Sioux Quartzite				
Blue Mounds	2.72	9	This study	5
Jasper area	2.65	9	do	5
Hardwick area	2.67	5	do	5
Avg, 3 areas	2.68	3	do	6

(1) Determined by weighing and measuring the volume of bulk samples (1500 grams or larger) taken from freshly trenched surfaces in road cuts. A value of 2.0 g/cm^3 was assumed for till below the water table. Samples are from Redwood County, Minnesota, about 100 km (60 miles) northeast of Rock County.

(2) Density estimated from seismic velocity with averaged empirical curve of Gardner and others (1974). Number of samples is number of refraction lines where unit was recognized. Seismic refraction lines were acquired in western Rock County (Fig. 2) by the Minnesota Department of Natural Resources, Division of Waters.

(3) Determined by weighing in air and water of samples (about 300 grams in size) taken from walls of clay pits. Samples were coated with a thin layer of collodion to avoid desiccation prior to measurements. Samples are from Redwood County, Minnesota, about 100 km (60 miles) northeast of Rock County.

(4) Determined by weighing in air and water of chip samples (about 5 cm^3) taken from outcrop. Samples were soaked in water several hours before weighing. Samples from a site in South Dakota, about 9 km (5-1/2 miles) west of Beaver Creek, Minnesota (Fig. 2).

(5) Determined by weighing in air and water of 2.54-cm-diameter core samples ranging in length from 1 to 2.4 cm. Cores are essentially impervious and no soaking in water was done prior to measurements. See Figure 2 for sample locations.

(6) Determined by averaging the mean values for the Blue Mounds, Jasper, and Hardwick areas, as given above.

profiles and one north-south profile were across the northwest-striking shear zone (Figs. 2 and 3) and profiles D-D' and E-E' were extended to the east and south, respectively, to investigate the thickness of fill adjacent to the large quartzite ridge known locally as Blue Mound or Blue Mounds State Park. Five north-south profiles and one east-west profile were placed across the probable extension of the bedrock channel near Valley Springs, South Dakota (F-F' through K-K' in Fig. 3). General specifications for the 1993 surveying are given in Table 2. Spacing along profiles depended on estimated proximity to features of interest. Because the bench marks that were primary gravity bases at Pipestone and Beaver Creek had been removed, all new surveying was tied to the 1989 field base, which had been tied to the Pipestone base (see below). From this field base, two additional field bases for the present survey (SV1 and SV2 on Fig. 3) were established by two complete loops.

Two previous gravity data sets were incorporated into this study. One set was a detailed survey 10 km (6 miles) southeast of Jasper, Minnesota (Fig. 3), which consists of 69 stations acquired by the Minnesota Geological Survey in 1989, to investigate a shallow circular depression that is evident on topographic maps, soil maps, and air photos (see Southwick and others (1993) for description). General specifications for the 1989 surveying are given in Table 2.

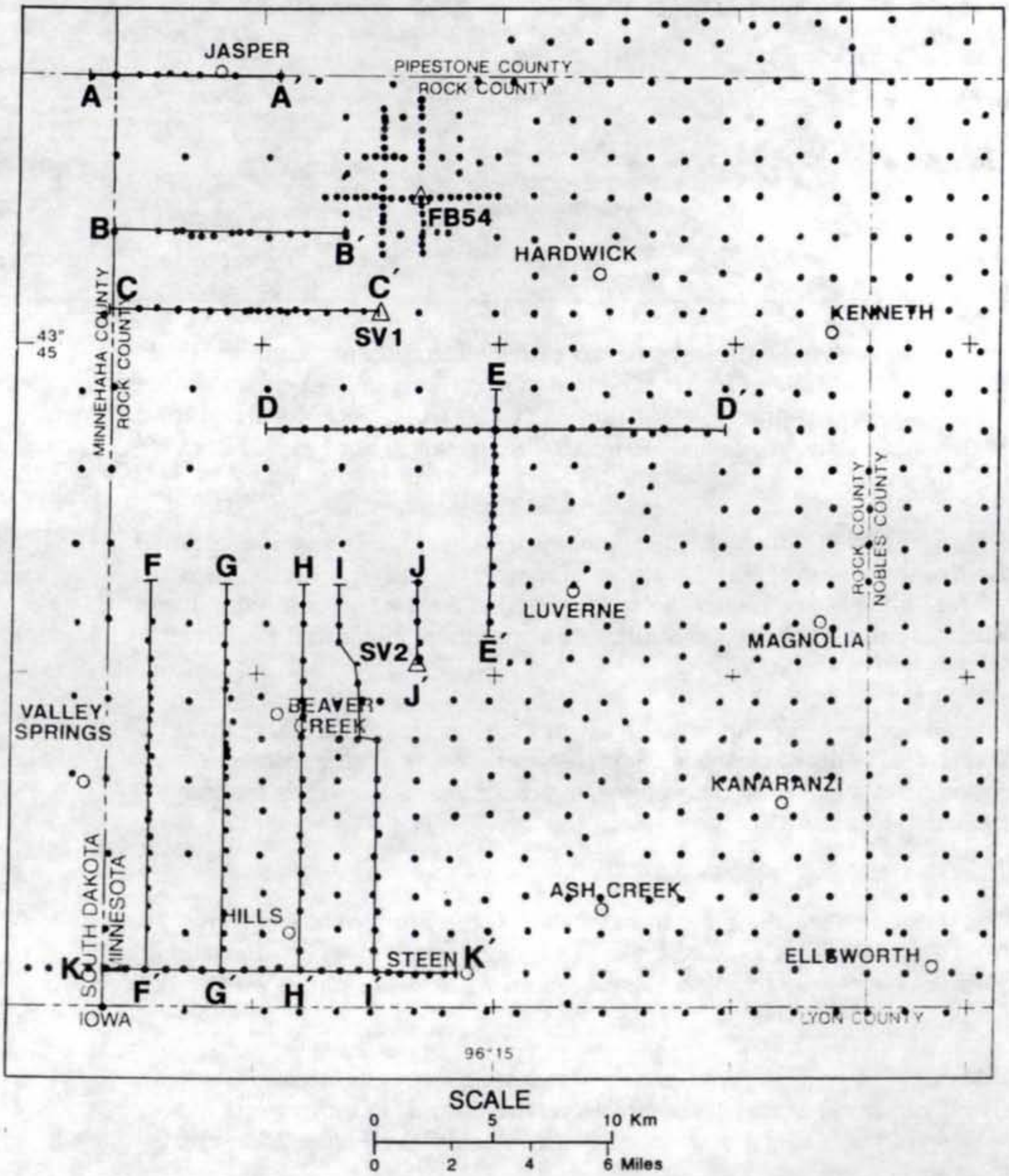

Figure 3. Map showing gravity station control in Rock County and surrounding areas. Dots, gravity stations; triangles, field base stations FB54, SV1, and SV2; profiles are stations acquired in 1993.

Table 2. Error estimates and survey specifications

Data set	Tying error (mGal)	Elevation error (feet)	Elevation error (mGal)	Elevation error % of set	Latitude error (feet)	Latitude error (mGal)	Total error (mGal)	Comment
1993	± 0.07	± 5.0	± 0.30	15	± 330	± 0.08	± 0.45	1
		± 1.0	± 0.06	85			± 0.21	
1989	± 0.07	± 5.0	± 0.30	50	± 160	± 0.04	± 0.41	2
		± 1.0	± 0.06	50			± 0.17	
1967 1971 1974	± 0.30	± 1.0	± 0.06	100	± 330	± 0.08	± 0.44	3

(1) Readings taken with LaCoste-Romberg model 320 gravity meter, base ties every 2 to 3 hours, over which drift did not exceed 0.1 milligal. Field bases, over which drift did not exceed 0.02 milligal, were established using 1-hour loops. Elevations based on either spot elevations (± 1 foot) or on interpolation of contours between spot elevations (± 5 feet). Elevation error assumes a Bouguer density of 2.67 g/cm^3. Location by direct readout from Magellan GPS unit.

(2) Readings taken with LaCoste-Romberg model 320 gravity meter, base ties every 1-1/2 to 2 hours, over which drift did not exceed 0.1 milligal. Field base established using 1-hour loop, over which drift did not exceed 0.02 milligals and three single-ended loops of half-hour duration. Elevations based on either spot elevations (± 1.0 foot) or on interpolation of contours between spot elevations (± 5 feet). Elevation error assumes a Bouguer density of 2.67 g/cm^3. Location based on measuring-wheel distances from known points, which were subsequently scaled to 1:24,000 and digitized.

(3) Readings in 1967 taken with a Worden model 76 (about 12% of data); remaining readings with a LaCoste-Romberg model 320 gravity meter (about 88% of data). Base ties either every 2 to 3 hours (Worden) or every 3 to 5-1/2 hours (LaCoste-Romberg), over which drift did not exceed 0.3 milligal. Some field bases established using 3 hour loops. Elevations based on spot elevations (± 1 foot). Elevation error assumes a Bouguer density of 2.67 g/cm^3. Location by digitizing spot elevations.

Stations in the 1989 survey were acquired every 400-800 m (1/4 to 1/2 mile) along section-line roads (Fig. 3). A field base (station FB54 on Fig. 3) was established by one complete loop and three single-ended loops to the then primary gravity base at Pipestone, Minnesota.

The other existing gravity data set consisted of 485 stations that were acquired in 1967, 1971, and 1974. These older data are part of the state-wide data base that was used in producing the state gravity map (Chandler and Schaap, 1991), and they are spaced at intervals of 1.6-3.2 km (1-2 miles) along section-line roads (Fig. 3). General specifications for the 1967, 1971, and 1974 surveying are given on Table 2. Base stations for these earlier surveys consisted of either primary gravity bases or field bases that were tied to the primary bases. To ensure reliable gridding out to state boundaries, gravity data gridded at 6 km by 6 km from the Gravity Anomaly Map of North America (Committee for the Gravity Anomaly Map of North America, 1987) were used in adjacent parts of South Dakota and Iowa.

During the compilation of the Rock County gravity data, several significant errors were found and corrected in the state-wide data base. A 1.0-milligal tare was verified for a 5-1/2-hour loop acquired in 1974, which involved nearly all of the stations in the Hills 7.5-minute quadrangle. Overlapping stations from the 1967 and 1993 surveying provided sufficient control in locating the probable occurrence of the tare in the 1974 loop sequence (immediately after the fourth station) and allowed the creation of an artificial drift curve to compensate for the tare. In addition, a prominent, localized gravity low 2.5 km (1.5 miles) west of Jasper, Minnesota, was not verified by Line A-A' (Fig. 3), and was ultimately traced back to a single bad elevation used in the 1967 data. Finally, three stations roughly 9 km (5.5 miles) E-NE of Luverne, Minnesota were mislocated 0.8 km (half a mile) east of their true position according to the original field maps, and these stations were shifted.

The new and old data sets for Rock County were reduced to Bouguer anomaly values and combined. All gravity data were corrected for drift by assuming linear segments between base checks, and were reduced according to the 1967 Geodetic Reference System (International Association of Geodesy, 1971), assuming a sea-level datum, a Bouguer reduction density of 2.67 g/cm^3, and correction for earth curvature. Because most of the land is flat, no terrain corrections were made; terrain corrections estimated elsewhere in southwestern Minnesota are usually less than 0.1 milligal except near major river valleys (Fogelson, 1956; Beltrame and others, 1982). These data constitute the principal fact gravity data for the Rock County area. The Bouguer gravity data were gridded from the principal fact data at a 0.8-km (1/2-mile) interval using the minimum curvature program of Cordell and others (1992).

Sources of Error

No rigorous analysis of error was conducted on the combined gravity data, but consideration of survey and compilation procedures allows some general estimates (Table 2). For example, the 1989 and 1993 data used base ties every 1-1/2 to 3 hours and, in light of the generally stable drift characteristics of the LaCoste-Romberg type of meter, it seems unlikely that drift between ties departs from a linear approximation by more than half of the maximum observed drift (± 0.10 milligal), or more than ± 0.05 milligal. Additional error might be introduced by drift associated with the tying in of field bases, but observed drift during these ties indicates that the maximum error is probably around ± 0.02 milligal. Thus the maximum tying error for the 1989 and 1993 data is estimated to be ± 0.07 milligal (Table 2). In the case of the 1967, 1971, and 1974 data, however, the tying error could be considerably larger, in part because of the relatively more drift-prone Worden meter (1967 data) and the use of longer loops with the LaCoste-Romberg meter (1971 and 1974 data). Additional error for these older data may be introduced from long field base loops (Table 2) and residual error for the tare-corrected stations in the Hills Quadrangle. Therefore ± 0.3 milligal, equal to the maximum absolute drift observed between base reoccupations in these data, was selected as a reasonable estimate of maximum error for the older data (Table 2).

Other significant sources of error for the Bouguer anomaly values are introduced by errors in elevation and latitude. The greatest elevation-related error (± 0.3 milligal) is associated with some 1989 and 1993 stations, where values were inferred from 10-foot topographic contours on 7.5-minute quadrangles (Table 2). In general, elevations estimated from contours on U.S. Geological Survey maps are accurate to within half the contour interval for 90 percent of the time, which would equate to 1.5 m (5 feet) for the study area. Every effort was made to reduce this kind of error by locating stations precisely at recognizable points on the 7.5-minute quadrangles or where the topographic gradient was very low or approximately constant between spot elevations. Latitude error ranges from 0.04-0.08 milligal, depending on the precision of the digitized location (Table 2).

Based on the estimates on Table 2, the maximum error in the Bouguer anomaly probably does not exceed ± 0.5 milligal, and the error may be as small as 0.2-0.4 milligal for most stations. The latter range was generally consistent with Bouguer anomaly differences observed at several locations where stations of different surveys coincided. These errors will have some bearing on the estimates of overburden thickness and bedrock elevations, which are discussed further below.

Bouguer Anomaly Data

The Bouguer gravity anomaly map of the Rock County area (Fig. 4) has broad, regional anomalies with amplitudes on the order of 10-30 milligals superimposed on narrow, local anomalies with amplitudes of 1-5 milligals. Neither type of anomaly is likely to reflect sources within the Sioux Quartzite, because gravity anomalies arise from lateral contrasts in density, whereas the Sioux Quartzite in Rock County is interpreted to be gently deformed and laterally uniform (Baldwin, 1951; Southwick and others, 1986). An exception would be diabasic or gabbroic intrusions in the quartzite, but as mentioned above, no geologic or magnetic anomaly evidence exists for these rocks near the surface in Rock County. Therefore, basement sources below the Sioux Quartzite are the most likely cause of the regional anomalies, and the thickness variations of the Cretaceous and Quaternary fill on the quartzite surface are the most likely cause of the local anomalies.

In the western part of the county, the regional signature consists of a positive saddle that is about 10 milligal higher than the regional lows to the north and south (Fig. 4). At the east edge of the county, the regional signature has an eastward-increasing gradient, which is assumed to primarily reflect sources that are below the

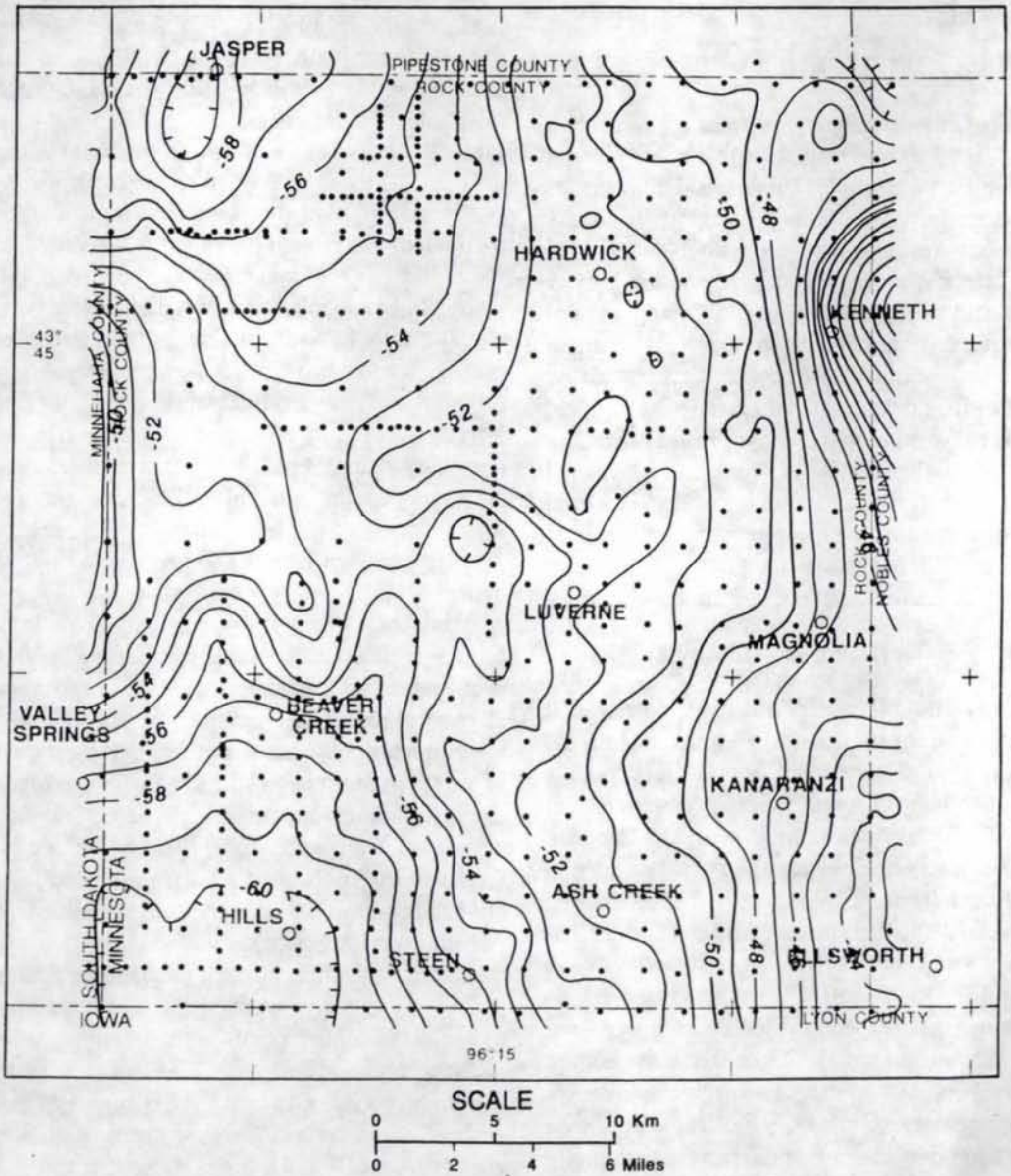

Figure 4. Contour Bouguer gravity anomaly map for Rock County and surrounding areas. Dots, gravity stations; values are milligals.

quartzite, although it could in part reflect the gradual eastward thinning of the quartzite over a denser basement. A prominent high of about 15 milligals amplitude near the east edge of the county is related to a large, east-west belt of mafic igneous rocks, which predates the Sioux Quartzite and subcrops at the Precambrian surface to the east in adjoining Nobles County (Southwick and others, 1993).

Local anomalies with amplitudes of 1-5 milligals, presumably reflect contrasts between the Sioux Quartzite ridges and the flanking, thick fill of low-density Cretaceous and Quaternary deposits. These local anomalies are most evident immediately south and east of the Sioux outcrop areas (Figs. 2 and 4), but they are obscured by the regional signature. Further investigation of the local anomaly signatures requires that they be isolated from the regional anomaly component.

ANALYSIS OF THE GRAVITY DATA

Isolating local anomaly signatures from the effect of a strong regional field is a classical problem for gravity interpretation, and a variety of regional-residual schemes have been developed over the years (Hinze, 1990). Many quantitative regional-residual schemes, such as polynomial surface fitting, are not generally satisfactory for gravity studies of fill-and-basement topography; they cannot incorporate geologic control, and the resulting residual anomalies are mathematical abstractions that cannot be directly related to fill thickness. In this study the regional field was removed by a graphical cross-profile procedure that incorporated geologic control from outcrops, drill holes, and seismic refraction soundings. The resulting residual anomalies are assumed to represent the effect of low-density fill, and can be readily converted into estimates of fill thickness and basement surface elevation.

Separation of Regional and Residual Anomalies

In this study the regional field was determined graphically along a series of cross-profiles taken from the Bouguer anomaly map. The regional isolation procedure is schematically shown by a hypothetical cross-profile in Figure 5. If the Sioux Quartzite is a thick, laterally uniform unit, the observed Bouguer anomaly data consist of both the effects from near-surface fill (the desired residual field) and deep basement sources (the desired regional field). The regional field is assumed to be a smoothly varying function relative to the residual field, as is consistent with their respective depths of burial (see geologic cross section in Fig. 5). Note that a thickening of fill, either in a bedrock channel or a surface hill, causes a local negative anomaly. For hills, the effect is produced by a Bouguer correction in the Bouguer gravity anomaly data that assumed a density of 2.67 g/cm^3 (see above discussion on reduction of gravity data), which overcompensates for the effect of the low-density hill.

Along a given cross-profile, the graphical selection of the regional field curve may be constrained by geologic control (Fig. 5). Over outcrop areas of Sioux Quartzite, with little or no fill, the observed Bouguer gravity should approximate the regional field. At control points, such as drill holes or seismic refraction soundings, where the thickness of fill is known (see DH1 and DH3 in Fig. 5), the negative anomaly effect of the low-density fill can be compensated approximately to the regional field (Fig. 5) using the following Bouguer slab approximation:

$$\Delta g = (0.01276) \times (\Delta p) \times (h)$$

Where Δg is the gravity effect (in milligals) of a horizontally infinite slab of thickness h (in feet) and density contrast Δp (in g/cm^3), which in this study is assumed to be 0.60 g/cm^3. By the same procedure, deep drill holes that do not penetrate the fill, at least provide a minimum possible value for the regional curve (see DH2 on Fig. 5). This application of the Bouguer slab equation is a modification of the gravity-geologic method described by Ibrahim and Hinze (1972) and Adams and Hinze (1990).

After the regional field has been defined at control points, the remainder of the regional curve on each profile is graphically inferred. These inferred curves on all cross-profiles are then readjusted through several iterations until regional curves for intersecting profiles are equal at intersection points (Hinze, 1990). Several iterations are necessary before a set of regional profiles is derived that honors both the control points and the cross-profile intersections. Selected values from these final regional profiles can then be used to produce a regional anomaly grid.

In Rock County, 14 north-south and 14 east-west profiles were taken from the Bouguer gravity data for cross-profile analysis. In most cases these cross-profiles were aligned along actual gravity stations. Regional curves were first proposed along profiles that passed within a mile of at least two control points, which included outcrop areas, drill holes, and seismic refraction soundings (Fig. 6), and these were used to constrain the regional curves. Regional curves were then inferred along the less well constrained profiles, incorporating available control points. All proposed regional curves along all 28 profiles were then iteratively adjusted until they agreed at all intersecting points. During the iterative process every effort was made to honor the control points, although minor allowance was given when a control point was not located precisely on the cross-profile. Observed and regional values are shown with geologic control for four north-south and two east-west cross-profiles in Figures 7 and 8, respectively.

Gravity anomaly curves

a. Relationship between gravity anomalies

b. Residual gravity anomaly C where C = B - A

Geologic cross section

a. Near-surface geology responsible for residual gravity anomaly C.

b. Anomaly source beneath the Sioux Quartzite responsible for anomaly B.

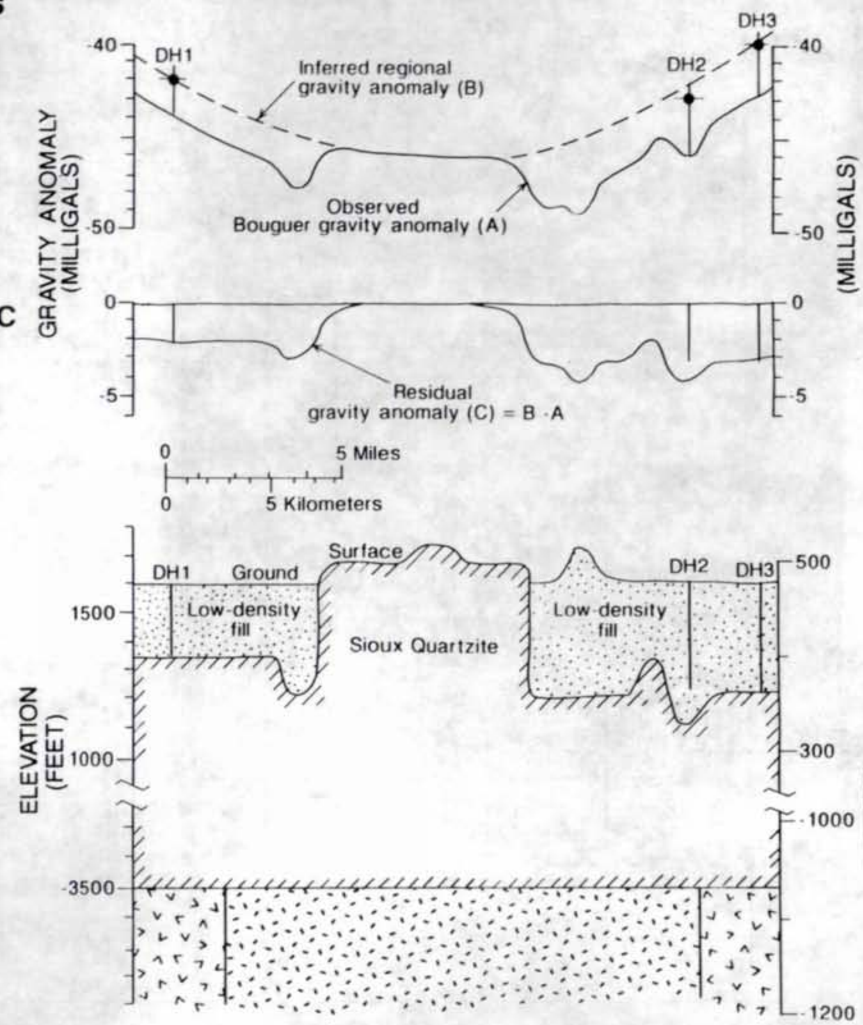

Figure 5. Schematic sketch of gravity cross-profile showing the regional-residual separation procedure used in this study. If the Sioux Quartzite is a laterally uniform unit, the observed Bouguer anomaly data (A) are the effect of both the near-surface fill and deep basement sources (see geologic cross section). At drill holes (DH) where thickness of fill is known, the Bouguer slab approximation and an assumed density contrast can be used to correct for the negative effect of fill. Thus corrected, the control-point values, as well as observed Bouguer gravity over quartzite outcrop areas (no fill), consist essentially of the regional field. Additional points on the regional field can be determined by analysis of intersecting cross-profiles (see text). If the regional field can be assumed to be a smoothly varying function (reasonable for deep origin), it can be determined from relatively few points. Subtraction of the regional field (B) from the observed Bouguer gravity (A) yields the residual anomaly (C), which is only the effects of the fill.

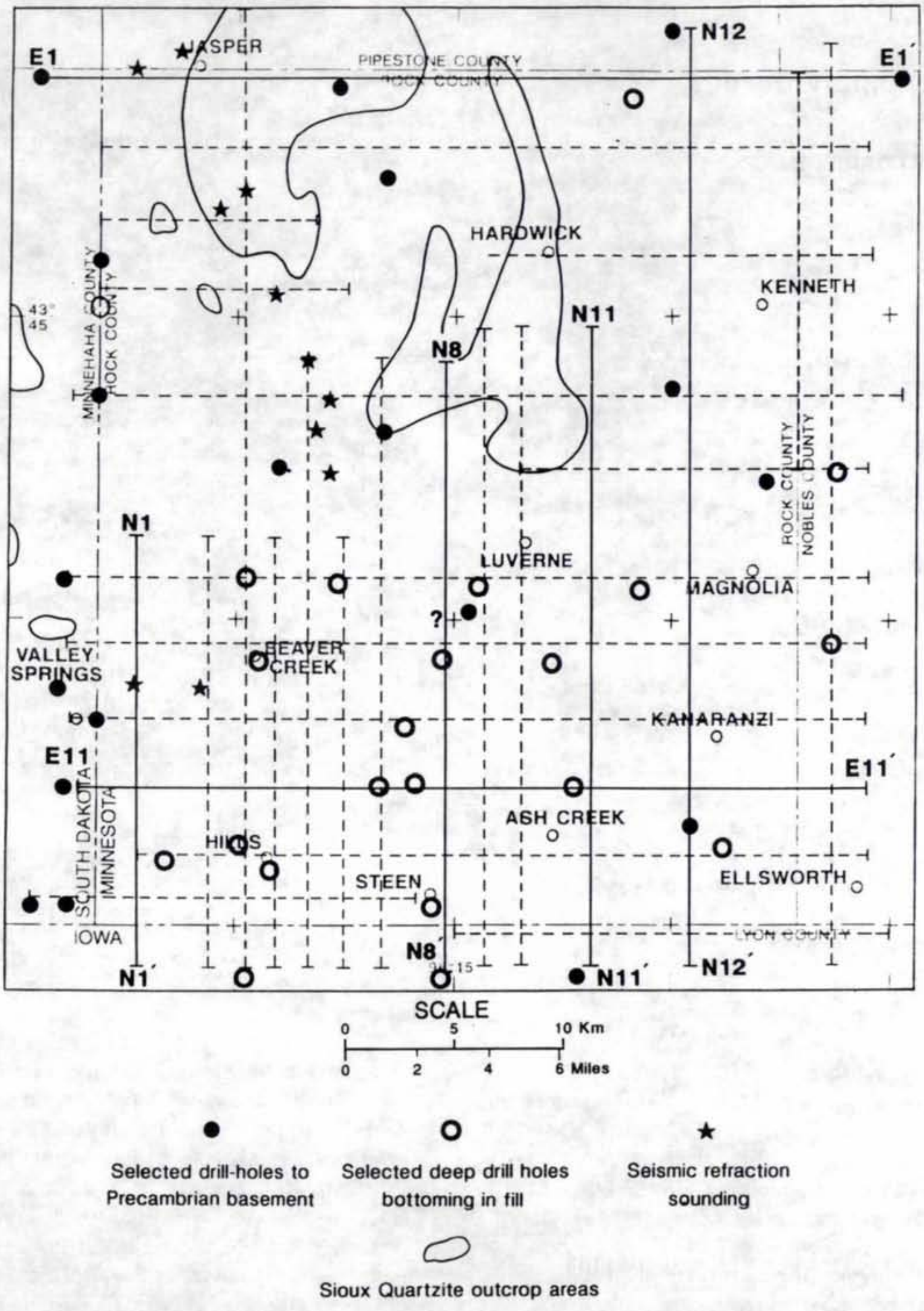

Figure 6. Map of Rock County and surrounding areas showing location of cross-profiles (Figs. 7 and 8), outcrop areas, selected drill holes, and seismic refraction soundings. The drill holes (mostly water wells) were compiled by Dale Setterholm of the Minnesota Geological Survey, with additional control in Iowa from Munter and others (1983). Seismic refraction soundings were acquired by the Minnesota Department of Natural Resources, Division of Waters.

Ultimately, one control point was rejected. This point is a drill hole near the middle of cross-profile N8-N8' (noted with a question mark in Figs. 6 and 7), which had been interpreted to have reached bedrock at a depth of 65 m (213 feet). Inclusion of this control point put a peculiar cleft in the otherwise smooth regional curves that were fit to the cross-profiles in this area. In cross-profile N8-N8' (Fig. 7), the cleft (shown by a dotted line) is accentuated by a deep drill hole about a mile to the south, which did not reach bedrock, and by a southward-increasing gradient over an outcrop area to the north. If the drill hole was in error, having reached a boulder instead of quartzite subcrop, the preferred regional curve would imply that the quartzite in this area is some 60-70 m (195-230 feet) deeper than indicated by the drill hole.

Selected points along the regional profiles were converted to vector data and were transformed into a regional field gridded at 0.8 km using a minimum curvature program (Cordell and others, 1992). Some additional points, consisting chiefly of single-station gravity values near or on outcrops of quartzite, were also incorporated into the regional grid. The resulting regional field and selected points that were used in gridding are shown in Figure 9.

Residual Gravity Data and Derived Maps

As schematically shown in profile form in Figure 5, subtraction of the regional field from the observed Bouguer data yields a residual field that is assumed to have only the negative effects of the low-density fill. In this study the regional gravity grid (Fig. 9) was subtracted from the observed Bouguer gravity grid (Fig. 4) to produce a residual gravity grid (Fig. 10). The residual gravity values were converted into estimates of the combined thickness of Cretaceous and Quaternary fill (depth to Precambrian basement) by applying the Bouguer slab approximation with a density contrast of -0.60 g/cm^3 (Fig. 11). Elevations from the principal fact gravity data were used to produce a generalized map of surface elevation (Fig. 12) from which the thickness map of Cretaceous and Quaternary fill (Fig. 11) was subtracted, producing an elevation map of the Precambrian basement surface (Fig. 13).

Limitations and Errors of the Results

The fill thickness (Fig. 11) and the Precambrian surface elevation (Fig. 13) maps are interpretations that are only as good as the data and assumptions used to create them. The maximum error in the Bouguer gravity data of $\pm$ 0.5 milligal equates to an error of $\pm$ 20 m (65 feet) with the Bouguer slab approximation and density contrast of 0.60 g/cm^3. Similarly, an error range of 0.2-0.4 milligal, which may be more representative of the gravity data, equates to an error of 8-15 m (26-52 feet). Variations in the density contrast will introduce additional error—a 10-percent error in density contrast would equate to approximately a 10-percent error in fill thickness and Precambrian surface elevation (Adams and Hinze, 1990).

The estimated variations of fill thickness and basement elevation are certain to be somewhat more subdued than their actual configurations. Most of this effect can be attributed to use of an infinite Bouguer slab to approximate finite features on the bedrock surface, although this error is less than 10 percent over features that are several times wider than they are deep (Adams and Hinze, 1990). Unlike a true fill isopach, which would have to incorporate the surface topography in detail, the fill thickness estimates in Figure 11 take into account only topography that is apparent from elevations at gravity stations.

Another significant source of error is the subjectiveness of inferring a regional curve in areas where control is poor for the Precambrian surface. This problem is particularly noticeable in parts of the deeply filled areas of southern and northeastern Rock County, where preliminary analysis of cross-profiles yielded plausible regional surfaces that differed locally by as much as 2.0 milligals. With the Bouguer slab approximation and density contrast of 0.60 g/cm^3, this difference equates to 79 m (260 feet) in fill thickness. Furthermore, some caution is warranted with the initial assumption that the regional field from basement sources is distinctly smoother than signatures of near-surface fill. This assumption is reasonable over much of Rock County, where thick, laterally uniform Sioux Quartzite separates the two types of sources, but in the easternmost part of the county, where the quartzite is believed to be pinching out, the difference between basement and fill signatures should be less, and some of the residual anomalies could be contaminated by basement sources.

DISCUSSION

In spite of the errors and limitations described above, the maps of estimated fill thickness (Fig. 11) and Precambrian surface elevation (Fig. 13) are useful geologic tools; they provide geologically reasonable and testable interpretations in areas where little or no inference was previously possible, and the maps in Figures 10 and 12 provide a suitable starting point from which further investigations, using detailed geophysical studies and test drilling, can be targeted. Some of the more prominent features on the buried Precambrian surface (Fig. 13) are summarized on an interpretative map (Fig. 14).

The thickness map in Figure 11 implies that the combined Cretaceous and Quaternary fill in Rock County ranges from absent to at least 240 m (800 feet) in

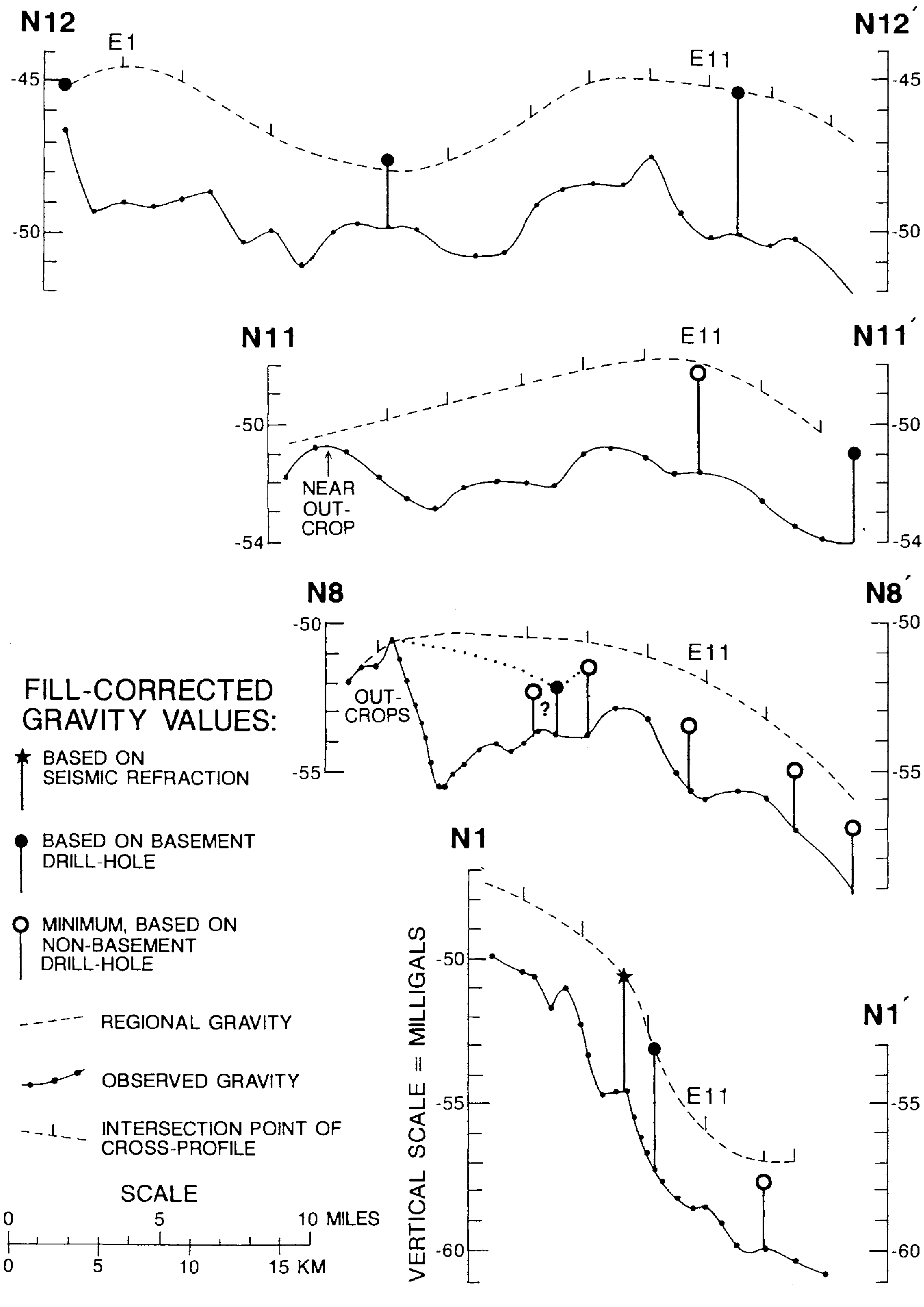

Figure 7. Four north-south cross-profiles showing observed gravity, inferred regional gravity, and control points corrected for fill thickness. See text for discussion of rejected regional field shown by dotted line on profile N8-N8'. Dots along observed profiles represent actual gravity stations.

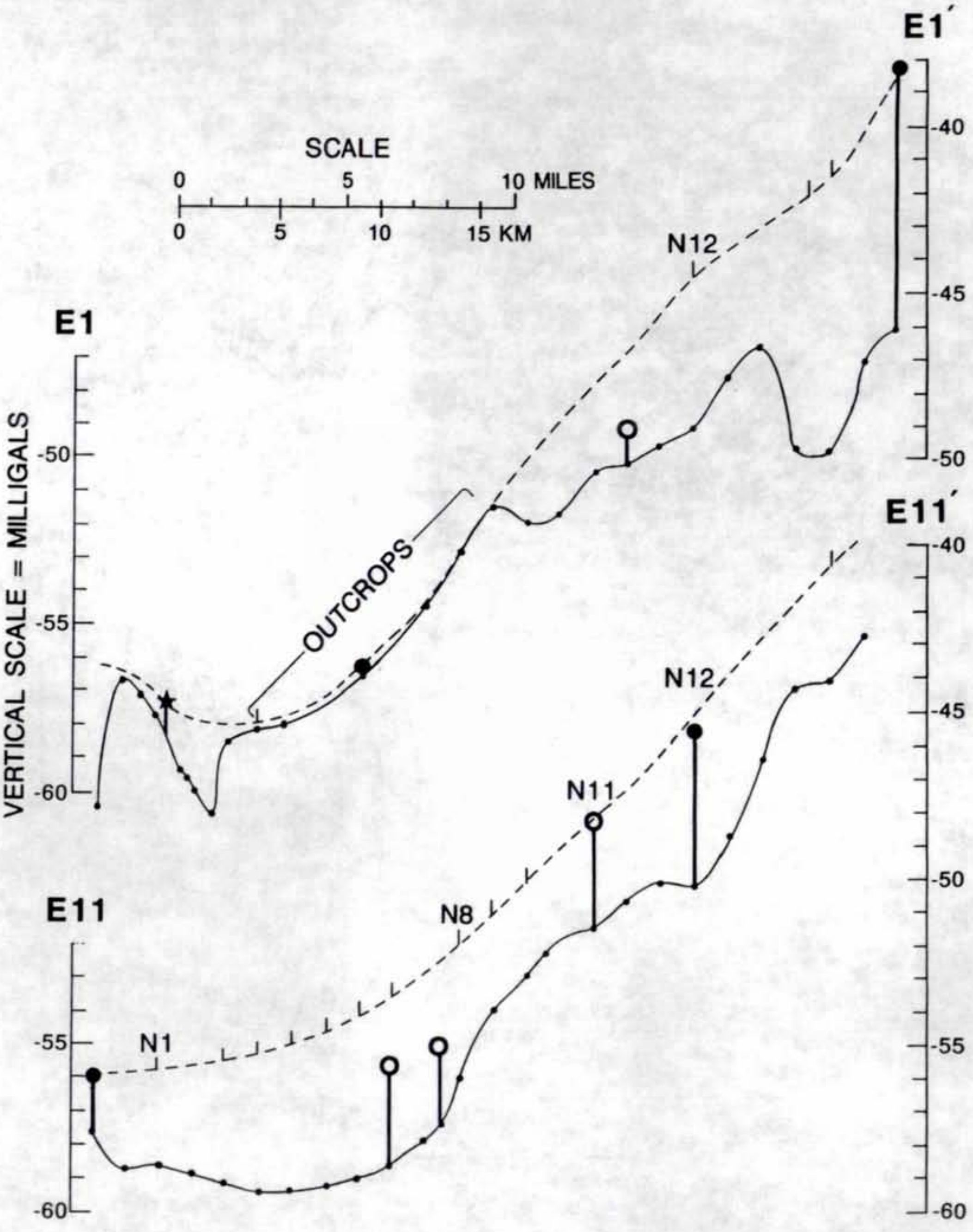

Figure 8. Two east-west cross-profiles showing observed gravity, inferred regional gravity, and control points corrected for fill thickness. Dots along observed profiles represent actual gravity stations; other symbols as in Figure 7.

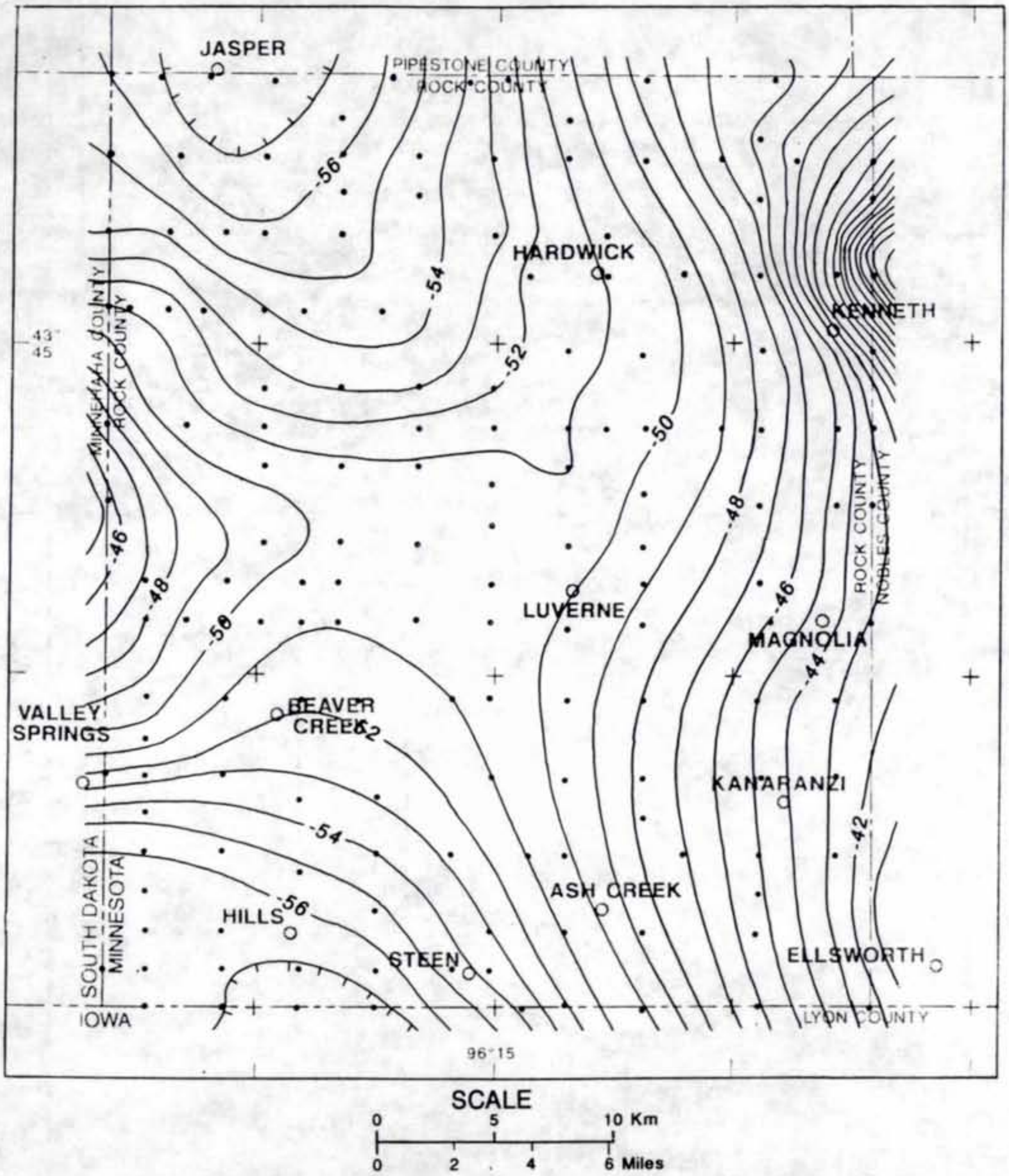

Figure 9. Contour map (in milligals) of regional gravity field for Rock County. Control points inferred from cross-profile analysis, together with selected gravity stations at outcrops, are shown as dots.

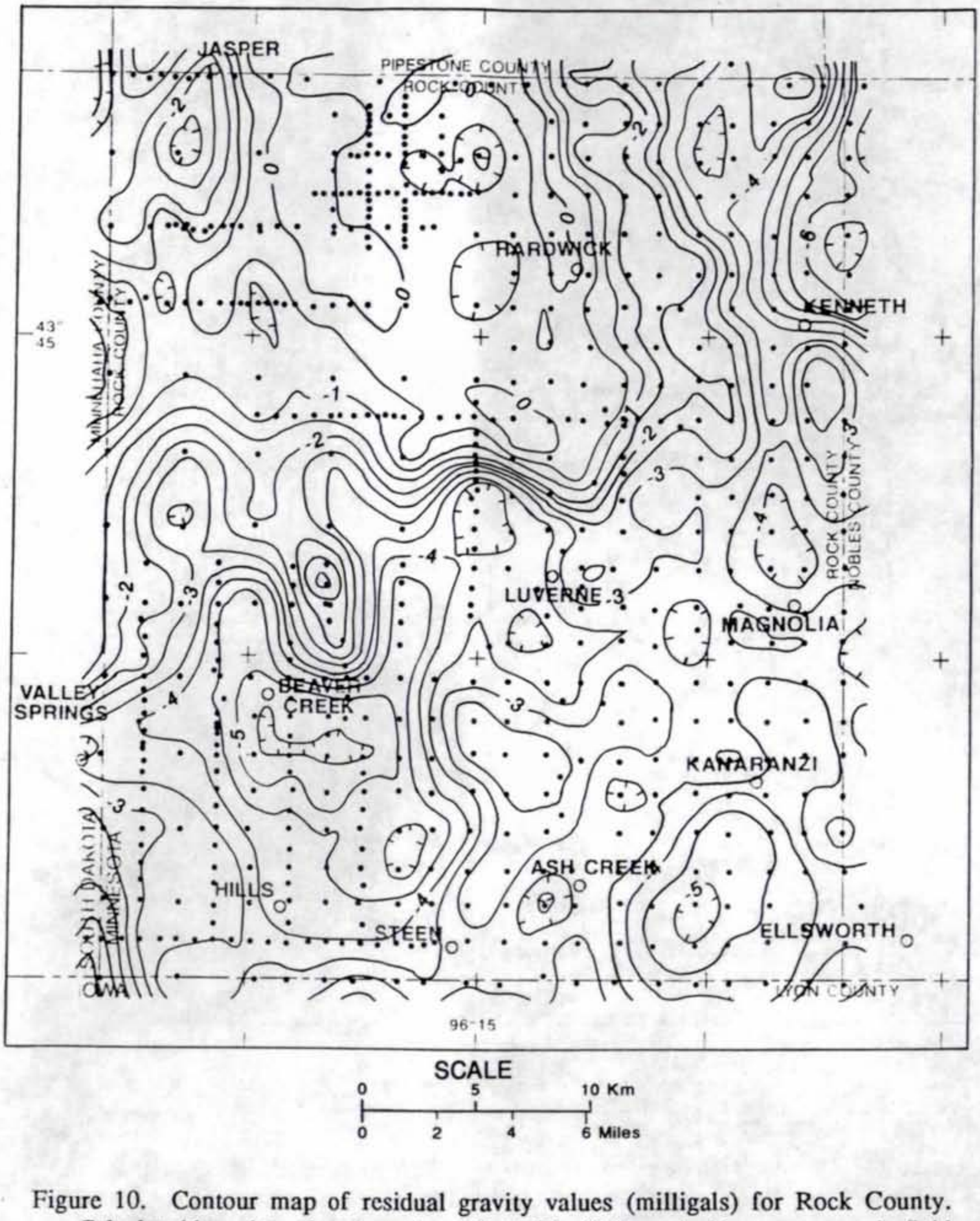

Figure 10. Contour map of residual gravity values (milligals) for Rock County. Calculated by subtracting the regional field (Fig. 9) from the Bouguer anomaly field (Fig. 4). Dots, gravity stations (Fig. 4).

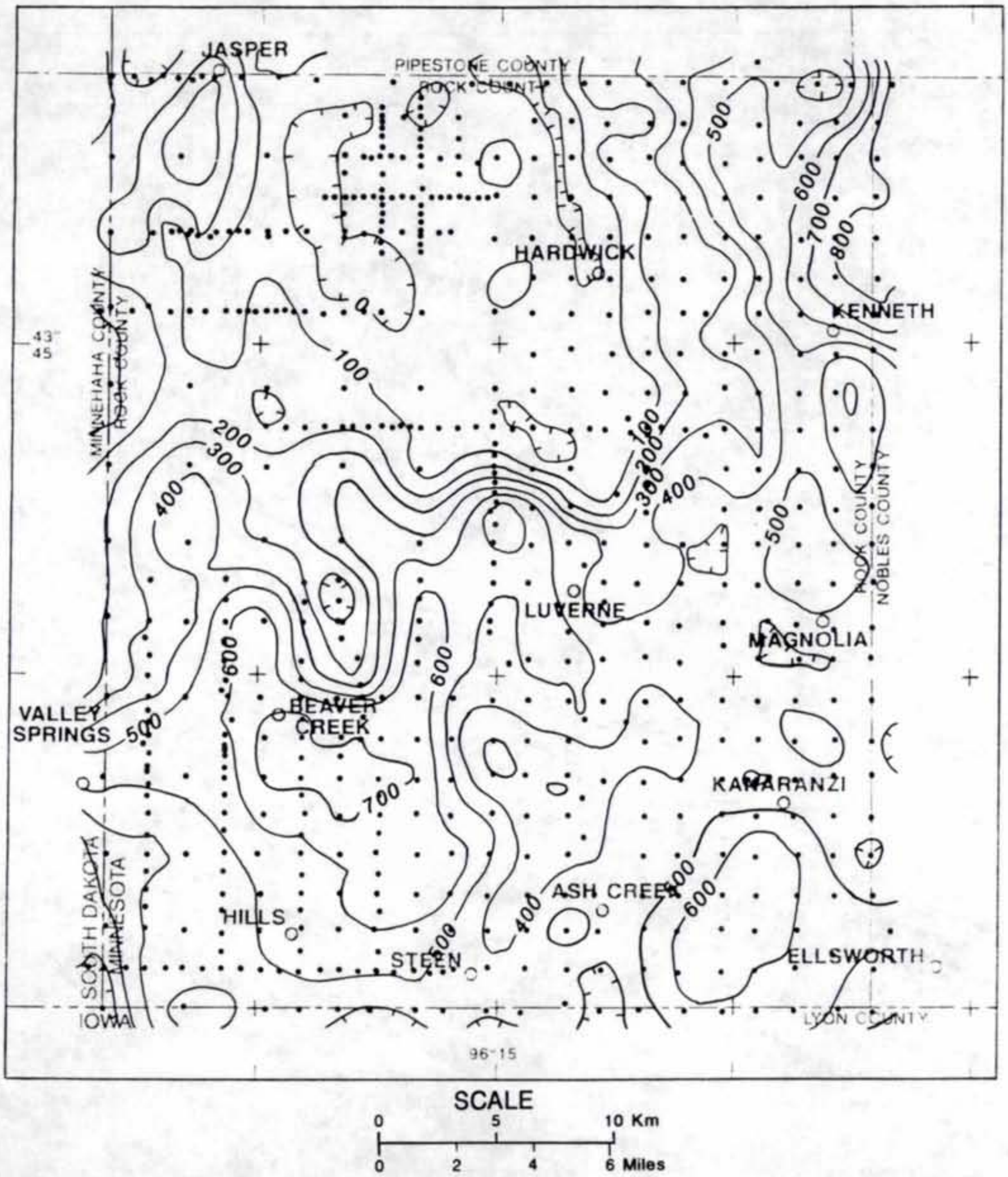

Figure 11. Contour map of estimated thickness (in feet) of combined Quaternary and Cretaceous fill for Rock County. Calculated from residual gravity values (Fig. 10) using Bouguer slab approximation and density contrast of -0.60 g/cm^3. Dots, gravity stations (Fig. 4).

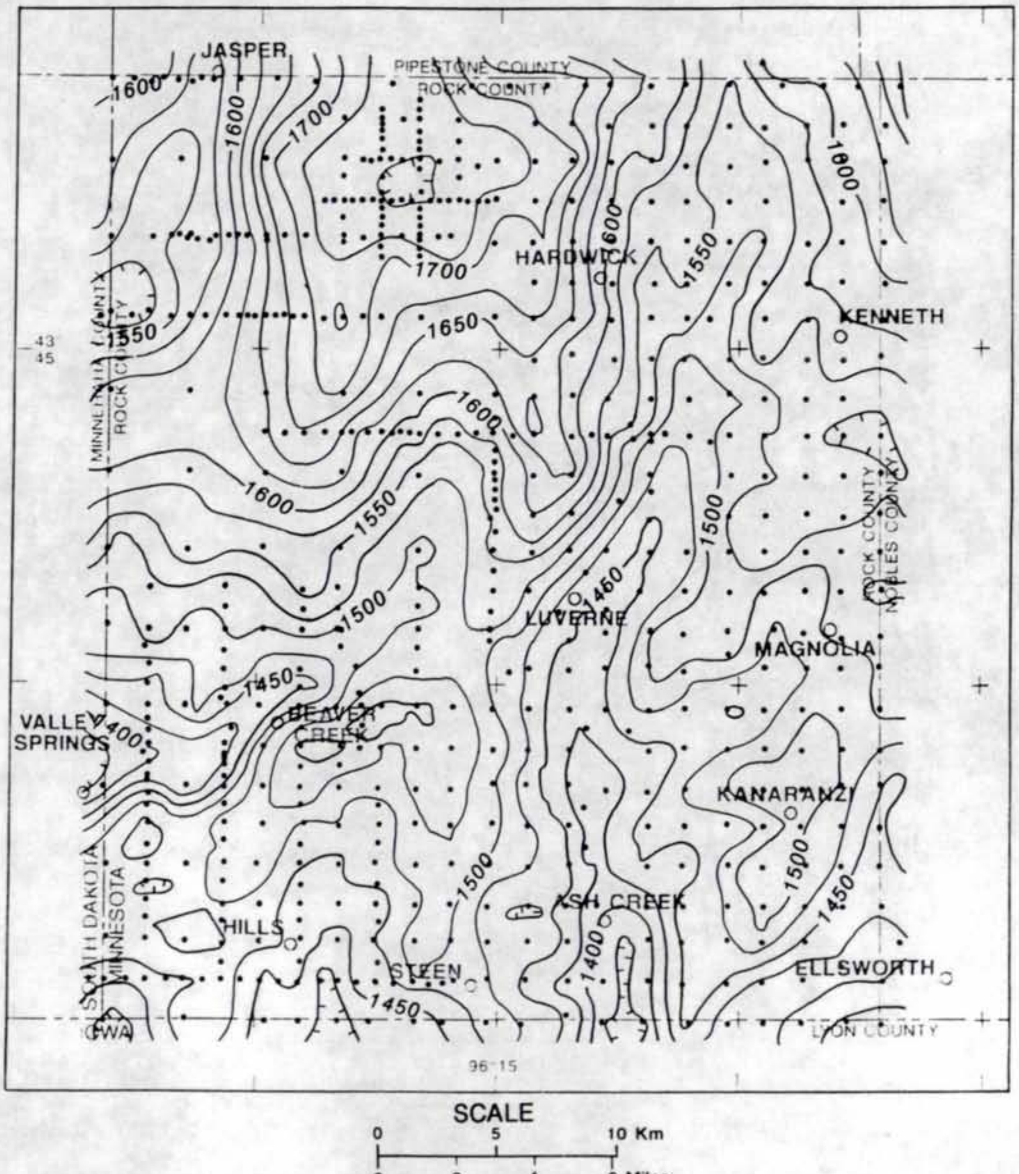

Figure 12. Land surface elevations in Rock County. Contoured from known elevations of gravity stations (Fig. 4) shown as dots.

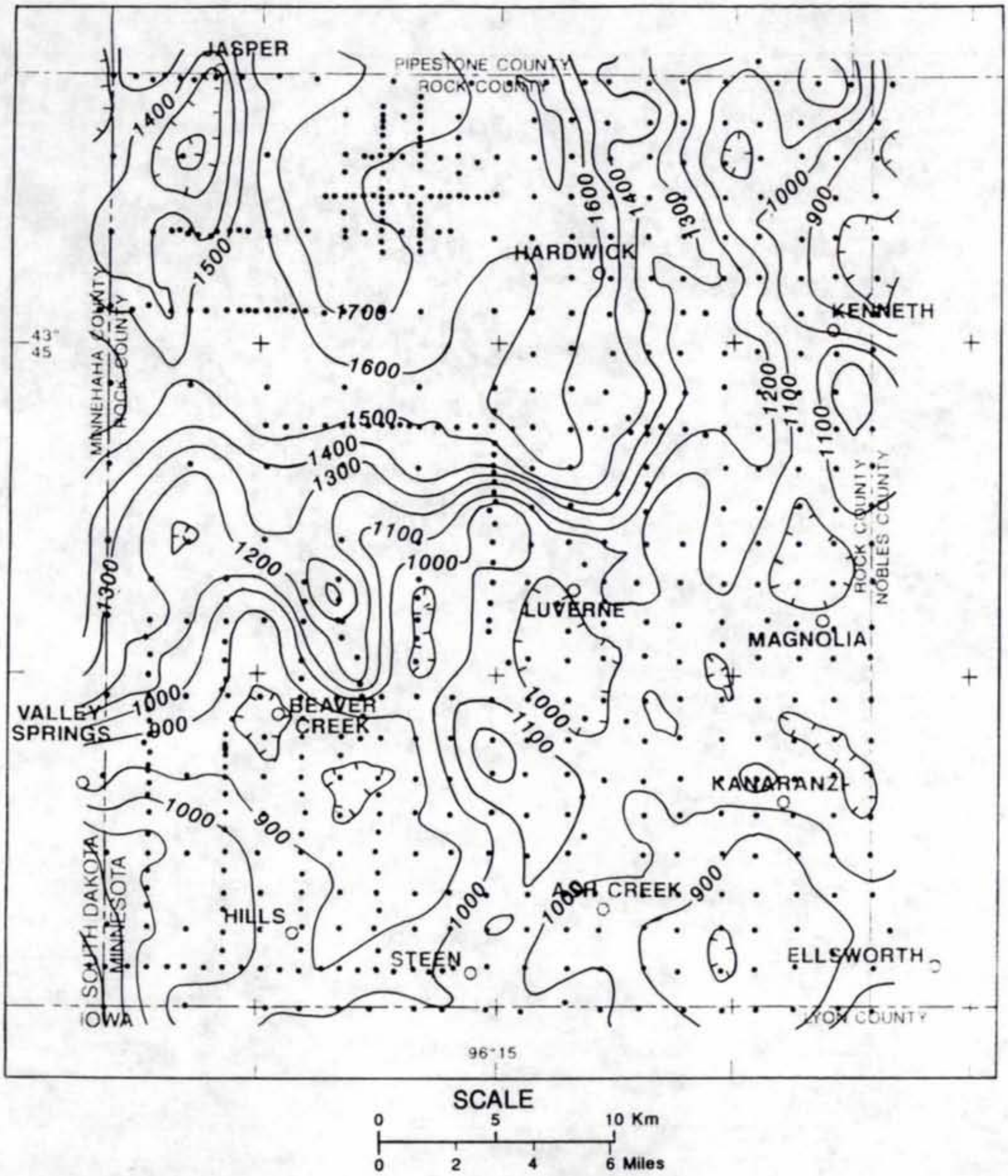

Figure 13. Contour map of estimated elevation (in feet) of Precambrian bedrock in Rock County. Calculated from the difference between the surface elevation (Fig. 12) and the estimated thickness of Quaternary and Cretaceous fill (Fig. 11). Dots, gravity stations (Figs. 4, 10-12).

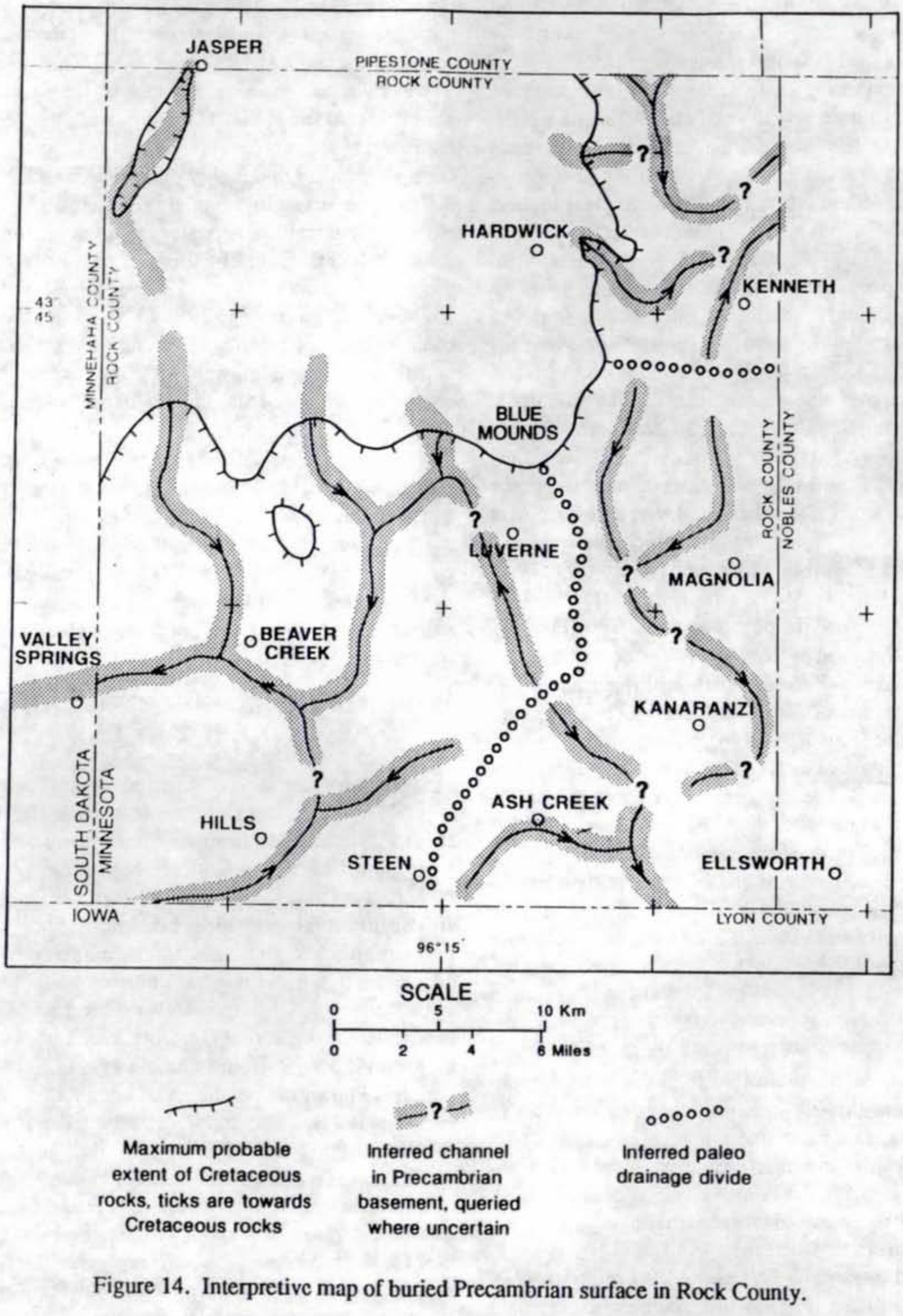

Figure 14. Interpretive map of buried Precambrian surface in Rock County.

thickness. The fill is interpreted to locally exceed 183 m (600 feet) in thickness in the southwestern part of the county, near the southeastern corner of the county, and near the northeastern corner of the county (Figs. 11 and 14). In the northeastern corner of the county, the fill is interpreted to be as much as 240 m (800 feet) thick, which is consistent with a drill hole just northeast of Rock County, which penetrated more than 305 m (1,000 feet) of Quaternary and Cretaceous fill (east end of Profile E1-E1' on Figs. 6 and 8). The Precambrian surface elevation map (Fig. 13) portrays the surface upon which the Cretaceous and Quaternary sediments were deposited. The highest elevation for the Cretaceous rock in this area appears to be around 396 m (1,300 feet; Dale Setterholm, oral commun.); therefore, the 1,300-foot contour on Figure 13 should approximately mark the maximum limit of Cretaceous subcrop in Rock County (Figs. 13 and 14).

The outcrop areas in northwestern and north-central Rock County are part of a broad plateau of Sioux Quartzite (Figs. 2 and 13). The Quaternary fill across the eastern lobe of this plateau is uniformly thin, generally less than 31 m (100 feet, Fig. 11). The eastern margin of the quartzite plateau is possibly associated with an escarpment of 31-61 m (100-200 feet), beyond which the quartzite surface descends toward the deep embayment on the east edge of Rock County (Fig. 13); minor irregularities probably reflect minor channels in the quartzite (Fig. 14). South of 43°45' and about 6.5 km (4 miles) east of the quartzite plateau, a buried, north-striking channel is interpreted to lie about 60 m (200 feet) below adjacent ridges of quartzite (Figs. 13 and 14).

A bedrock channel along the northwestern margin of the quartzite plateau, near Jasper, Minnesota (Fig. 14), is interpreted to contain more than 90 m (300 feet) of fill (Figs. 11 and 13). The detailed gravity data (acquired along line A-A', Fig. 3) at the west end of cross-profile E1-E1' imply that the channel wall is quite steep (Fig. 8), and the thickness estimates here, which are based on a Bouguer slab approximation, may be too small. This channel appears to extend to the south, but its position is uncertain because gravity control is poor (Fig. 3).

The proposed, northwest-striking shear zone (Fig. 2) cuts across the quartzite plateau in the vicinity of 43°45'-96°22'30", where the fill locally thickens to about 45 m (150 feet; Fig. 11). The southern margin of the quartzite plateau is somewhat irregular in map view, and includes several apparent escarpments in the buried quartzite (Fig. 13). The detailed gravity data (acquired along line E-E', Fig. 3) at the north end of cross-profile N8-N8' (Fig. 7) imply a buried escarpment of about 200 m (650 feet). West of Blue Mound (Fig. 2) this southern escarpment appears to be offset or dissected in several places. These interruptions in the escarpment, together with a series of buried, northwest-striking features in central and southeastern Rock County (Fig. 13), align with the southeast projection of the northwest-striking shear zone along the outcrop area (Fig. 2). The overall configuration of the Precambrian surface implies that the proposed shear may extend from the northwestern to the southeastern corner of the county.

Because of errors introduced by subsurface density variations and regional field removal, the longitudinal gradients along the interpreted channels in the basement (Fig. 14) have an undulatory character (Fig. 13), making it difficult to determine the direction of paleodrainage. However, the regional topography of the basement surface (Fig. 13) and the overall pattern of the buried channels in the Sioux Quartzite (Figs. 13 and 14) allow some very tentative inferences. The channels in the northeastern part of the county appear to have drained toward the northeast, and these channels may be separated from those in the southeastern part of the county by an inferred drainage divide south of 43°45' (Fig. 14). Another paleodrainage divide may separate the channels in the southeastern part of the county from those in the southwestern part (Fig. 14). In the southwestern part of the county, the overall patterns of the interpreted channels (Fig. 14) and the inferred basement topography (Fig, 13) imply that paleodrainage may have been toward the west, but considerable caution is warranted in light of the uncertainties and errors in the interpretation.

IMPLICATIONS FOR GROUND-WATER RESOURCES

The thickness map of Cretaceous and Quaternary fill (Fig. 11) and the map of Precambrian surface elevation (Fig. 13), as derived from residual gravity anomaly data, have significant implications regarding ground-water resources in Rock County. The Cretaceous and Quaternary fills in the southwestern, southeastern, and northeastern parts of Rock county are thick and largely unknown sequences that could contain undiscovered aquifers. The thickened sequence in the southwestern part of the county is in an embayment that connects with a bedrock channel at Valley Springs, South Dakota (Figs. 2, 11, and 13), which is known to contain several aquifers (Lindgren and Niehus, 1992). The thick fill along the irregular and locally abrupt southern margin of the quartzite plateau provides a favorable environment for aquifers; channels that cut the quartzite here probably provided drainage for the quartzite highlands to the north, during both Cretaceous and Quaternary time. Therefore parts of these channels may contain significant deposits of sand and gravel. By the same reasoning, the relatively minor channels cut into the eastern and western margins of the quartzite plateau (Fig. 13) may also contain sand and gravel. The northwest-striking shear zone also provides favorable targets for ground-water exploration, in that it appears to correlate locally with a thickening of fill above the quartzite, and the fractured quartzite itself may locally be an aquifer.

Further gravity surveying in Rock County would be helpful in several places. Intercalating additional stations or profiles in the northwestern and west-central part of the county, where most of the data are spaced 3.2 km (2 miles) apart, would considerably improve the detail on several crucial features. The course of the buried channel at Jasper, Minnesota, could be mapped more reliably, and the southern escarpment of the quartzite plateau could be investigated in greater detail, especially with regard to any downcut channels.

This study, as well as an earlier study by Hansen (1984), illustrates the use of the gravity method for investigating ground-water resources in the Sioux Quartzite regions of southwestern Minnesota, southeastern South Dakota, and northwestern Iowa. Buried channels of low-density Cretaceous and Quaternary fill produce anomalies that can be adequately isolated from regional effects of unrelated sources. Some ambiguity exists in the selection of a density contrast, and in the removal of regional gravity components in areas of poor control on the Precambrian surface. Furthermore, the gravity method cannot discriminate between a fill sequence that contains sand and gravel aquifers and one that is entirely clay. In spite of these limitations, however, the gravity method provides a basis for siting detailed geophysical studies and test drilling. In Minnesota, all of the Sioux Quartzite areas (Fig. 1) already are covered by a regional network of gravity stations spaced 1.6-3.2 km (1-2 miles) apart, and relatively minor acquisition of new data should allow successful application of the gravity method in ground-water resource problems.

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