MINNESOTA GEOLOGICAL SURVEY
D.L. SOUTHWICK, *Director*

CONTRIBUTIONS TO THE QUATERNARY GEOLOGY OF SOUTHWESTERN MINNESOTA

Carrie J. Patterson, Editor

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ACKNOWLEDGMENTS

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NOTE ON MEASUREMENTS USED IN THIS REPORT

Although the metric system is preferred in scientific writing, certain measurements are still routinely made in U.S. customary units; for example, distances on land are measured in miles and depths in drill holes are measured in feet. Preference was given in this report to retaining the units that measurements were made in. To assist readers, conversion factors for some of the common units of measure are provided below.

Metric units to U.S. customary units:

To convert from	To	Multiply by
millimeter (mm)	inch (in)	0.03937
centimeter (cm)	inch (in)	0.3937
meter (m)	foot (ft)	3.281
kilometer (km)	mile (mi)	0.6214

U.S. customary units to metric units:

To convert from	To	Multiply by
inch (in)	millimeter (mm)	25.4
inch (in)	centimeter (cm)	2.540
foot (ft)	meter (m)	0.3048
mile (mi)	kilometer (km)	1.609

SURFICIAL GEOLOGY OF SOUTHWESTERN MINNESOTA

By

Carrie J. Patterson

INTRODUCTION

The Quaternary geologic component of the regional hydrogeologic assessment for southwestern Minnesota (Setterholm, 1995) consists of a map of the surficial geology at the scale 1:200,000 (Patterson, 1995) and an interpretation of the Quaternary stratigraphy (Patterson and others, 1995). More information was gained during this project than could be conveyed in the two plates of the published assessment. The purpose of this report is to provide this additional information and explain the interpretations for the origin of the glacial sediment.

REGIONAL SETTING

The study area for this report is that of the regional hydrogeologic assessment for southwestern Minnesota (Fig. 1). It extends from 44°30' north latitude southward to the Iowa border (43°30'), and from 95°15' west longitude westward to the South Dakota border (96°27'12"). The area encompasses 5100 square miles and includes all of Rock, Nobles, Pipestone, and Murray Counties and parts of Lincoln, Lyon, Redwood, Cottonwood, and Jackson Counties. The major population centers in the region are Marshall (12,000), Worthington (10,000), Pipestone (4,500), Luverne (4,400), Slayton (2,100), and Tracy (2,000). The area is primarily agricultural, with approximately 85 percent of the land under cultivation (Baker and others, 1979).

Topography

The elevation in the study area ranges from 1010 feet above sea level in the northeast corner (Redwood County) to more than 1950 feet along the Bemis moraine in Lincoln County (Fig. 2). Most of the elevation change (from 1100 to 1600 feet above sea level) occurs along the ten-mile-wide east-northeast-facing slope of the Coteau des Prairies, a flatiron-shaped upland that separates lowlands formerly occupied by the Des Moines and the James lobes (Fig. 3). The scarp of the Coteau is very pronounced in the northern part of the study area; southeastward it becomes increasingly subdued and finally unrecognizable. The scarp is even more pronounced in northeastern South Dakota and southeastern North Dakota, where it attains 860 feet of relief (Fig. 4).

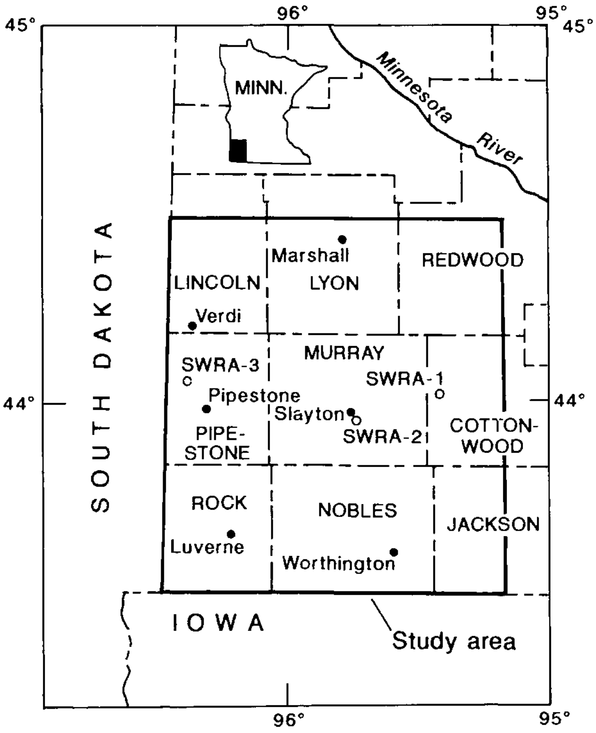


Figure 1. Map showing the location of the study area in southwestern Minnesota and the three Rotasonic test holes drilled for the project (SWRA-1, -2, -3).

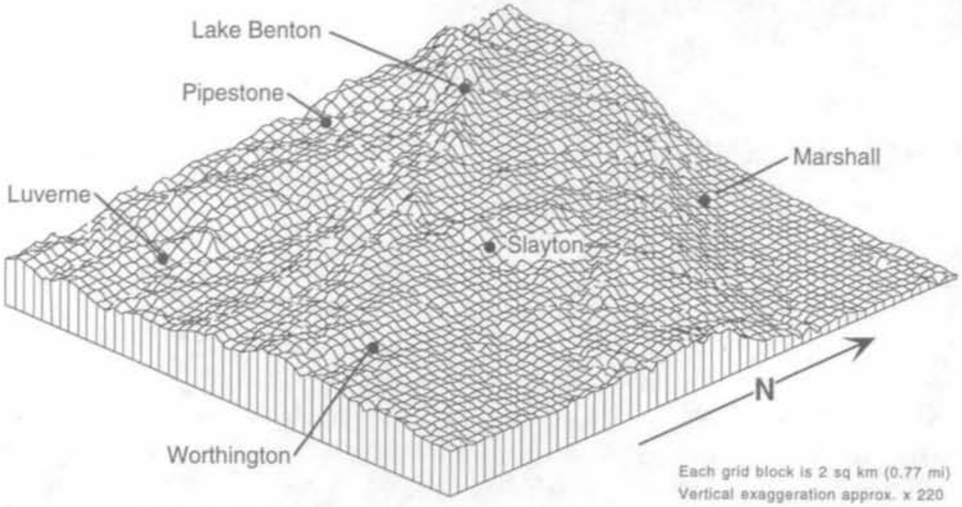


Figure 2. Model of the land-surface topography in southwestern Minnesota. The data used to create the model were provided by the U.S. Geological Survey 30-minute digital-elevation model. The sample spacing of these data is 1000 meters (about 3300 ft). The resulting model exhibits 973 feet of overall relief, with a maximum elevation of 1983 feet near Lake Benton (on the Bemis moraine) and a minimum of 1010 feet in the northeastern part of the study area. Model created by D.R. Setterholm.

Climate and Native Vegetation

The climate in the study area is continental; the average January temperature in the region is 11.8°F; average July temperature, 72.2°F (Baker and others, 1979). The average annual precipitation is 22–27 inches; 42–44 percent of this precipitation falls during the summer (Baker and others, 1967). Average annual evaporation from lakes is 35 inches. Soils are seldom fully recharged with water (Baker and others, 1979).

The climate originally supported a native-prairie vegetation in 90 percent of the study area. The remaining 10 percent included pockets of wet prairie along sloughs and local lows, river-bottom hardwood forests along the Rock River south of the confluence with Champepedan Creek and from Marshall to Burchard in the Redwood River valley, and isolated areas of oak openings and barrens (Marschner, 1974) (Fig. 5). Little of the original vegetation survives, however, owing to human settlement.

Surface Water

The divide of the Missouri River and Mississippi River watersheds trends northwest-southeast across the study area (Fig. 5). Part of this divide is formed by the prominent late-glacial Bemis moraine of the Des Moines lobe, which is locally known as Buffalo Ridge. The Mississippi River watershed lies northeast of the divide and includes the Redwood and Cottonwood Rivers, which flow northeast and southeast to the Minnesota River and the Des Moines River. The Des Moines River flows southeast into Iowa and eventually joins the Mississippi in southeastern Iowa. The Missouri River watershed lies southwest of the divide and includes the Rock, Flandreau, and Kanaranzi Rivers, which flow southwest to the Big Sioux River in South Dakota.

Natural lakes are restricted to the Mississippi River watershed northeast of the Bemis moraine (Fig. 5). Lakes Benton, Shaokatan, and Hendricks are impounded by the Bemis moraine and occupy long troughs that were created by subglacial streams. Lakes Okabena, Ocheda, Heron, Talcot, West and East Graham, Shetek, and Sarah had a similar origin but formed at retreatal positions of the ice lobe. Lakes Shetek and Sarah were significantly altered by ice-marginal streams. Many more small lakes and wetlands are within the glacial stagnation landscape of the Des Moines lobe. These lakes occupy shallow, closed depressions created by the disintegration of

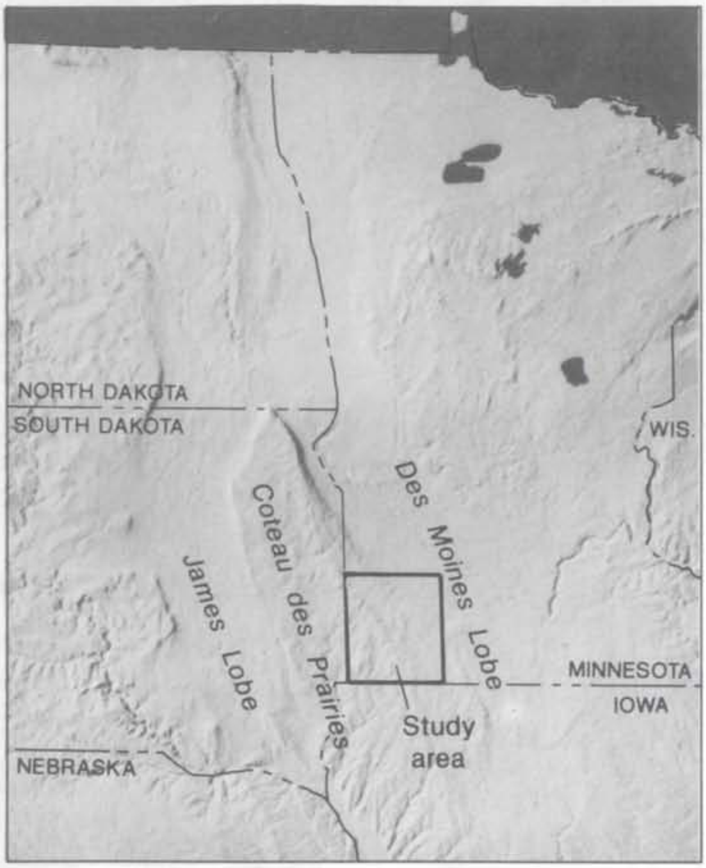


Figure 3. Shaded-relief map showing landforms of north-central United States. The lowlands are interpreted to have been shaped by erosion attributed to the Late Wisconsin advances of the Des Moines and James lobes. The Coteau des Prairies is an erosional remnant, and a thick sequence of older (pre–Late Wisconsin) glacial units is preserved beneath it. Modified from Thelin and Pike (1991).

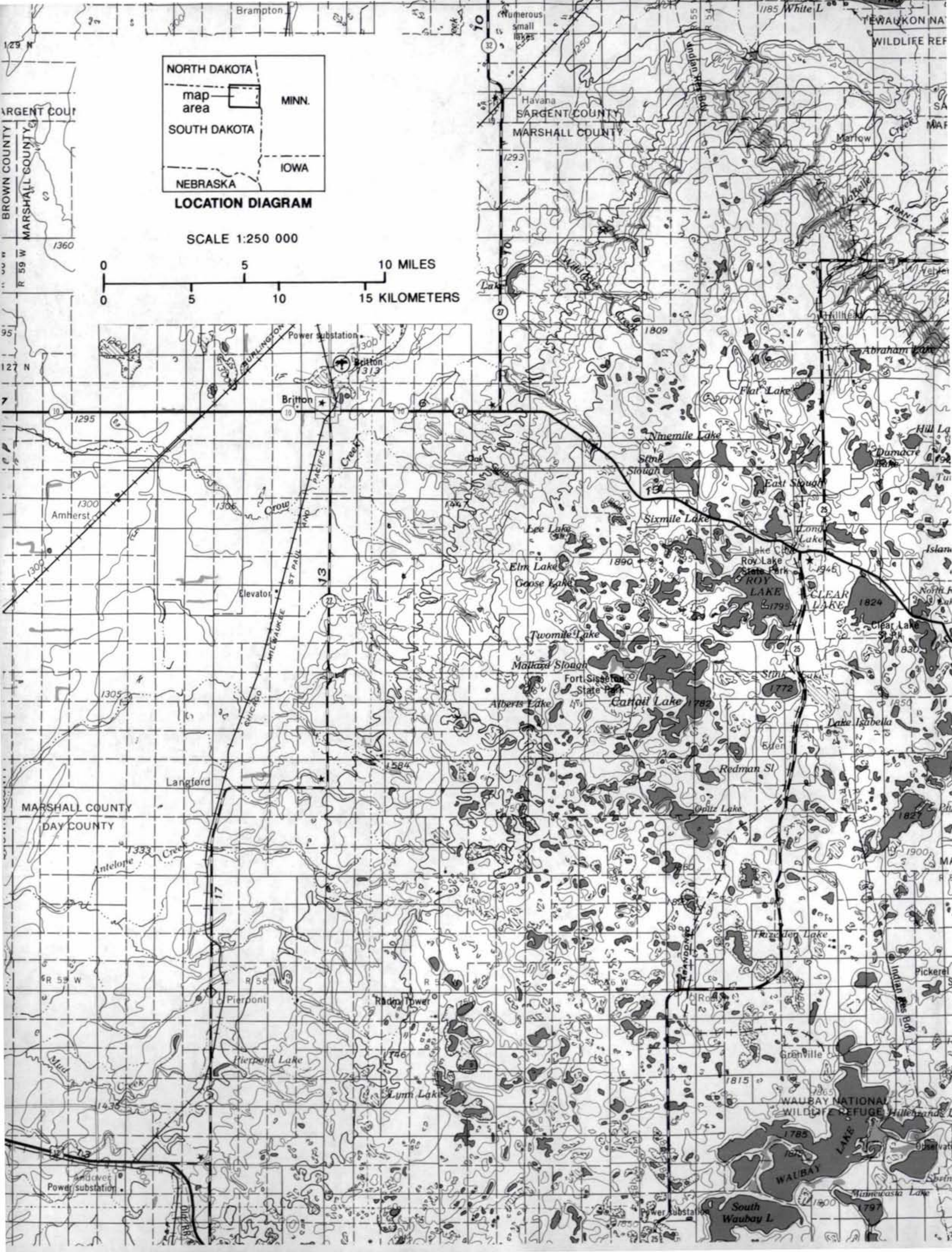
buried glacier ice. Many of the shallow lakes have been drained for agriculture, but their flat, generally circular plans are evident on topographic maps and aerial photographs.

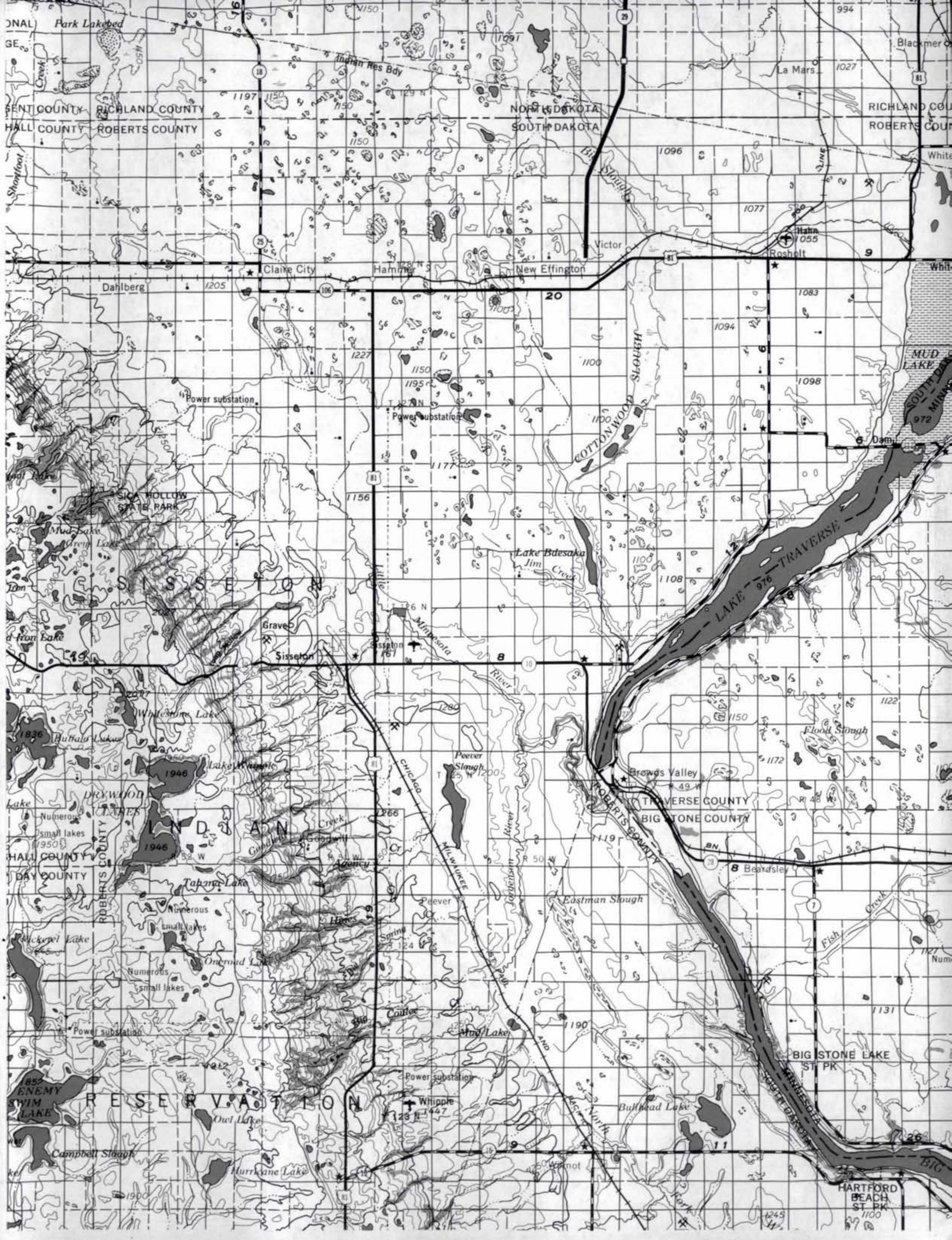
The landscape southwest of the Bemis moraine, although also predominantly glacial in origin, is older and lacks closed depressions owing to its well-developed drainage network. The only noticeable closed basin in this area is between the towns of Jasper and Hardwick, and it has been drained (Fig. 5). It may have been protected from stream development owing to its position in a small depression within a local high of Sioux Quartzite.

MAPPING METHODS

A geomorphological approach that relied on aerial-photograph interpretation was used to map the surface deposits in the study area. Interpretation for the southeastern part of the study area was difficult because the tones on the black-and-white photographs lacked the contrast needed to differentiate features of subdued topography. In the southwestern part of the study area deposits of loess locally obscure near-surface material. A preliminary surficial map was constructed using 1:80,000-scale high-resolution black-and-white stereo-pair aerial photographs. Interpretations from the photographs were drawn on 7.5-minute

Figure 4 (following two pages). Topographic map showing the "prow" of the Coteau des Prairies, North and South Dakota and Minnesota. The Minnesota River flows down the axis of the Des Moines lobe lowland. The James River flows down the axis of the James lobe lowland. Ice topped the Coteau during the Late Wisconsin and stagnated; the resulting landscape includes hummocky terrain and numerous lakes. The elevation of the lowland in Minnesota is approximately 1000 feet above sea level, and the general elevation of the upland is 1860 feet; the elevation of some stagnation landforms exceeds 2000 feet. U.S. Geological Survey Milbank sheet, 1 x 2–degree series, 1953, revised 1975; contour interval 50 feet.


LOCATION DIAGRAM
NORTH DAKOTA
map area
MINN.
SOUTH DAKOTA
IOWA
NEBRASKA
SCALE 1:250 000
0 5 10 MILES
0 5 10 15 KILOMETERS
Brampton
Numerous small lakes
White L
TEWAUKON NATIONAL WILDLIFE REFUGE
Havana
SARGENT COUNTY
MARSHALL COUNTY
BROWN COUNTY
DAY COUNTY
Marlow
Creek
LaBelle
Hillhead
Abraham Lake
Power substation
Britton
Amherst
Crow Creek
Elevator
Langford
Antelope Creek
Pierpont
Pierpont Lake
Mud Creek
Andover
Radio Tower
Lynn Lake
Ninemile Lake
Stink Slough
East Slough
Sixmile Lake
Lee Lake
Elm Lake
Goose Lake
Roy Lake State Park
ROY LAKE
Long Lake
Lake City
CLEAR LAKE
Clear Lake
Dumacre Lake
Hill Lake
Island Lake
Twomile Lake
Mallard Slough
Fort Sisseton State Park
Alberts Lake
Cattail Lake
Lake Isabella
Eden
Redman Sl
Opitz Lake
Hazeldon Lake
Grenville
Pickerel Lake
Indian Res Bdy
WAUBAY NATIONAL WILDLIFE REFUGE
WAUBAY LAKE
South Waubay L
Minnewasta Lake
Hillebrands L
Observation
Power substation
ABANDONED
R 59 W
R 58 W
R 57 W
R 56 W
R 55 W
129 N
127 N
1295
1300
1305
1306
1313
1333
1360
1435
1584
1746
1809
1815
1824
1827
1830
1850
1890
1900
1946
2000
2010
1772
1782
1785
1795
1797
1800
10
12
13
17
25
27
32


Park Lakebed
Creek
Shortfoot
RICHLAND COUNTY
ROBERTS COUNTY
Indian Res Bdy
129 N
NORTH DAKOTA
SOUTH DAKOTA
Big Slough
Blackmer
La Mars
RICHLAND COU
ROBERTS COUN
LINE
Victor
Hahn
1055
Rosholt
Claire City
Hammer
New Effington
Dahlberg
1205
1197
1150
1091
994
1027
1096
1077
1083
1094
1098
1100
20
9
MUD LAKE
SOUTH DAKOTA
MINN
972
Dam
COTTONWOOD SLOUGH
1227
1195
Power substation
T 127 N
Power substation
1177
1156
SICA HOLLOW STATE PARK
Mud Lake
Grey Lake
Iron Lake
S I S S E T O N
2027
Lake Bdesaka
Jim Creek
1108
LAKE TRAVERSE
976
12
18
Little Minnesota River
126 N
Grave
Sisseton
Sisseton
1161
8
10
2017
Whitestone Lake
1836
Buffalo Lakes
1280
1946
Lake Wamble
Peever Slough
T 125 N
1200
Browns Valley
R 49 W
R 48 W
1172
1150
1122
Flood Slough
DRYWOOD LAKES
TRAVERSE COUNTY
BIG STONE COUNTY
ROBERTS COUNTY
Numerous small lakes
1946
I N D I A N
Goodwill
Creek
1266
R 52 W
R 51 W
Agency
R 50 W
Jorgenson River
1119
BN
28
8 Beardsley
7
Tabbma Lake
Numerous small lakes
Peever
Eastman Slough
Pickerel Lake
Spring
Fish Creek
Oneroad Lake
Numerous small lakes
1950
CHICAGO MILWAUKEE ST PAUL AND PACIFIC
North Fork
1127
1131
Power substation
Coteau
Mud Lake
1190
BIG STONE LAKE ST PK
Power substation
1852
ENEMY SWIM LAKE
R E S E R V A T I O N
Whipple
1447
T 123 N
Owl Lake
Bullhead Lake
MINNESOTA
SOUTH DAKOTA
Campbell Slough
Hurricane Lake
9
11
26
Wilmot
1900
1245
HARTFORD BEACH ST PK
1100
BIG
81
29
18
25
106
15
ROBERTS COUNTY
DAY COUNTY
HALL COUNTY

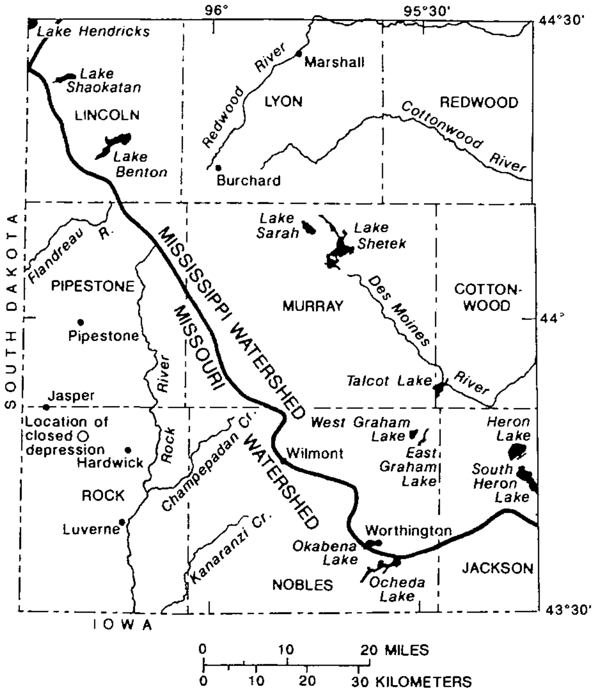


Figure 5. Significant surface-water features in southwestern Minnesota. Rivers northeast of the continental divide flow into the Minnesota River; those to the southwest flow into the Missouri River. Part of this divide, from the northwest corner of the study area to Wilmont, is formed by the Bemis moraine. The native vegetation of the study area was prairie except along some stream courses.

(1:24,000-scale) U.S. Geological Survey (USGS) topographic maps (10-foot contour interval). These preliminary maps were checked in the field during the summers of 1992 and 1993. The southwestern part of Minnesota is rural and has an extensive network of roads along section boundaries. At a minimum, field checking consisted of driving roads in search of outcrops. In addition, likely sites for natural exposures (e.g., river cuts) were visited, as were gravel pits and other sites of work involving excavations that were located with the help of county engineers and employees of local utility companies.

In addition to field checks of outcrops, shallow surface samples (maximum depth 30 feet) were collected using a truck-mounted soil auger in areas where data were sparse (Fig. 6). The samples are used to determine the texture, lithology, and color of the near-surface sediment, but they do not allow interpretation of sedimentary structures.

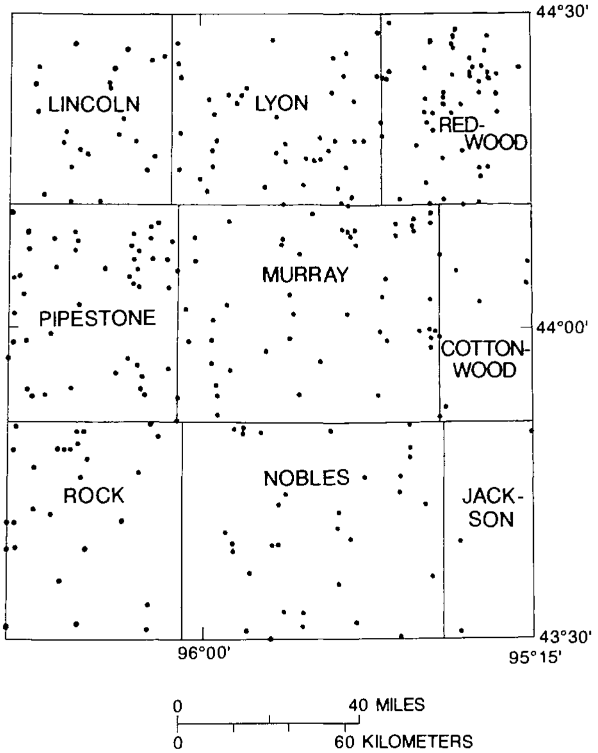


Figure 6. Surficial exposures and shallow auger holes in the study area. Reliability of mapping is greatest where these types of information are available.

Soil surveys (U.S. Department of Agriculture, Soil Conservation Service) at the scale 1:12,000 were available for all the counties in the study area. Soil units were grouped by inferred parent material and summary maps constructed for comparison with interpretations derived from aerial photographs and field observations.

Preliminary subsurface geologic information was extracted from water-well records maintained at the Minnesota Geological Survey (Fig. 7). Drilling records of domestic water wells generally include the approximate depth and thickness of major sand units. Additional information may be available, including color (which may signify the oxidized tops of older, buried glacial units), resistance to drilling, and type of bedrock (if encountered). However, many well logs do not differentiate the sediment within the glacial section and therefore are used only for establishing thickness of glacial sediment. Well locations were verified in the field to ensure accuracy and plotted on topographic maps. The verified locations and corresponding drillers' logs were then entered in the County Well Index (CWI) data base. These data are

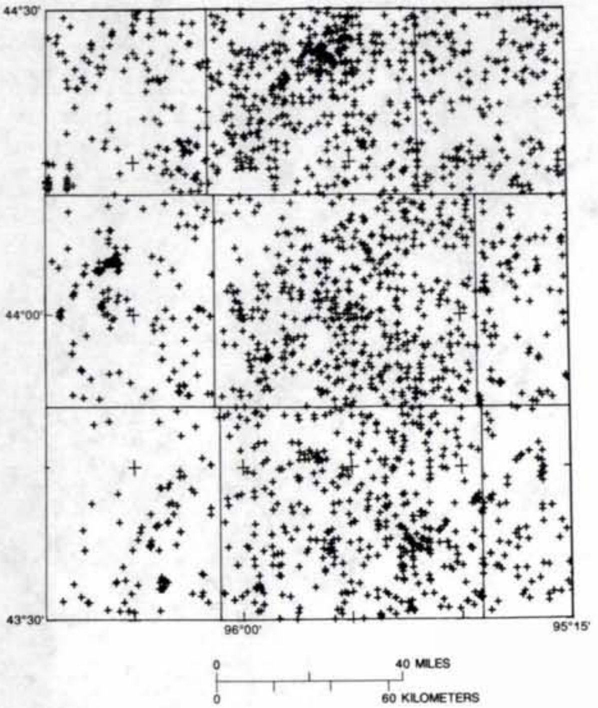


Figure 7. Distribution of well-hole data in the study area. Each symbol indicates the verified location of a well for which the Minnesota Geological Survey has some stratigraphic information.

available in different formats from the Minnesota Geological Survey.

To provide stratigraphic control, three scientific test holes were drilled using the Rotasonic method (Fig. 1). Rotasonic drilling provides a continuous, essentially undisturbed sediment core four inches in diameter. Descriptive logs of these holes are included in the appendix and summarized in Figure 9, where they are presented with the textural and lithologic data. The geochemical work is summarized in Patterson and others (1995); the complete report is available for inspection at the Minnesota Geological Survey. The cores are stored in Hibbing, Minnesota, at the Minnesota Department of Natural Resources, Division of Minerals Core Library.

Samples from rotary drill holes that were logged by a geologist are useful for making gross stratigraphic distinctions. Interpretations of rotary holes may be supplemented by gamma logs and information on drilling conditions. Information from five mud-rotary holes that were sampled and geophysically logged during a previous study (Southwick and others, 1993) were included in the data base.

The Minnesota Geological Survey uses a digital logger to collect gamma-ray, spontaneous potential,

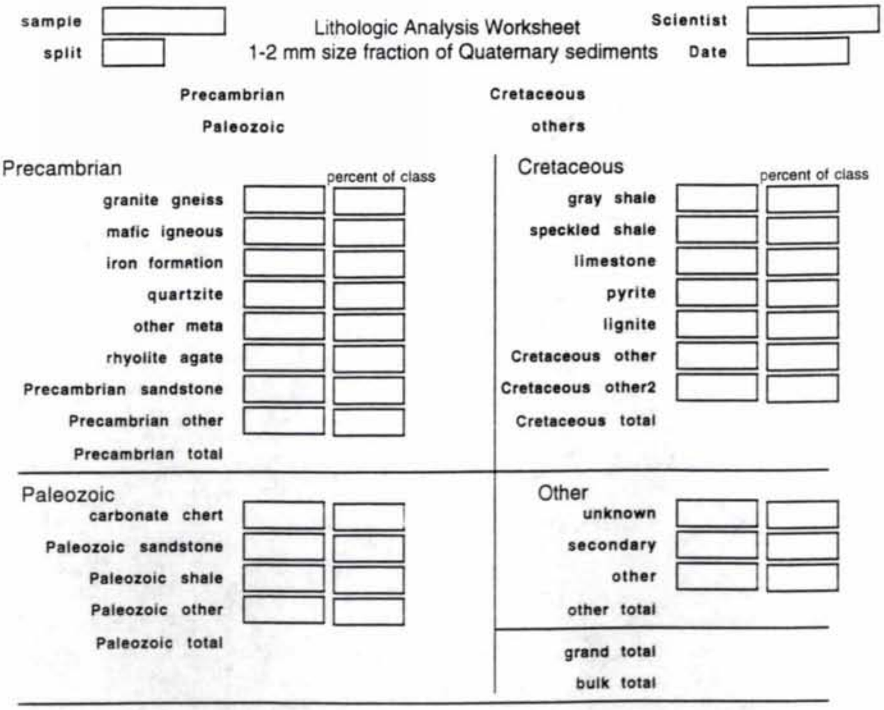


Figure 8. Example of the grain-count work sheet used by the Minnesota Geological Survey. Coarse sand grains (1–2 millimeters) are examined with a binocular microscope and divided into the categories listed. Spread-sheet tabulation of the data allows rapid calculations and exportation of data to other software programs.

sample ☐
split ☐

Lithologic Analysis Worksheet
1-2 mm size fraction of Quaternary sediments

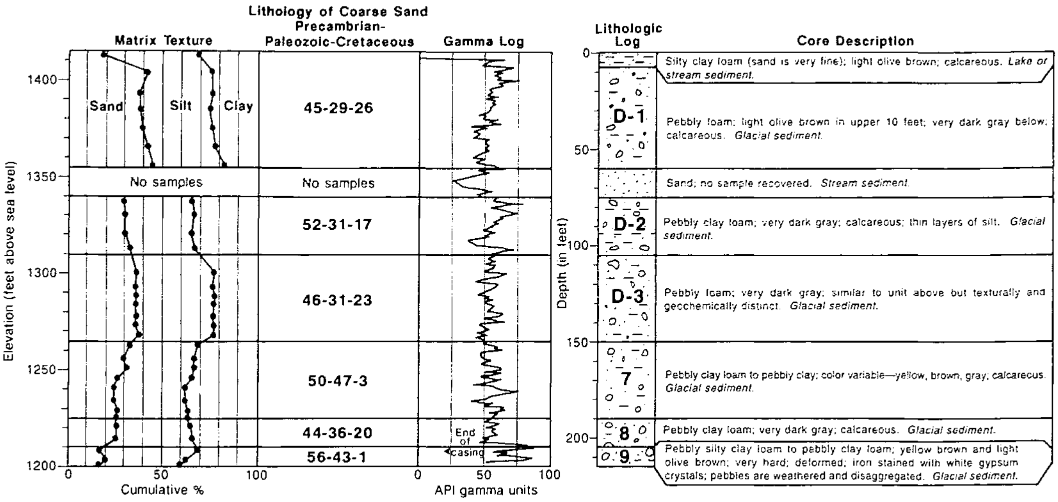
Scientist ☐
Date ☐

Precambrian **Cretaceous**
Paleozoic **others**

Precambrian		percent of class	Cretaceous		percent of class
granite gneiss	☐	☐	**gray shale**	☐	☐
mafic igneous	☐	☐	**speckled shale**	☐	☐
iron formation	☐	☐	**limestone**	☐	☐
quartzite	☐	☐	**pyrite**	☐	☐
other meta	☐	☐	**lignite**	☐	☐
rhyolite agate	☐	☐	**Cretaceous other**	☐	☐
Precambrian sandstone	☐	☐	**Cretaceous other2**	☐	☐
Precambrian other	☐	☐	**Cretaceous total**		
Precambrian total					

Paleozoic			Other		
carbonate chert	☐	☐	**unknown**	☐	☐
Paleozoic sandstone	☐	☐	**secondary**	☐	☐
Paleozoic shale	☐	☐	**other**	☐	☐
Paleozoic other	☐	☐	**other total**		
Paleozoic total			**grand total**		
			bulk total		

SWRA-1
Cottonwood County



Silty clay loam (sand is very fine); light olive brown; calcareous. *Lake or stream sediment.*

Pebbly loam; light olive brown in upper 10 feet; very dark gray below; calcareous. *Glacial sediment.*

Sand; no sample recovered. *Stream sediment.*

Pebbly clay loam; very dark gray; calcareous; thin layers of silt. *Glacial sediment.*

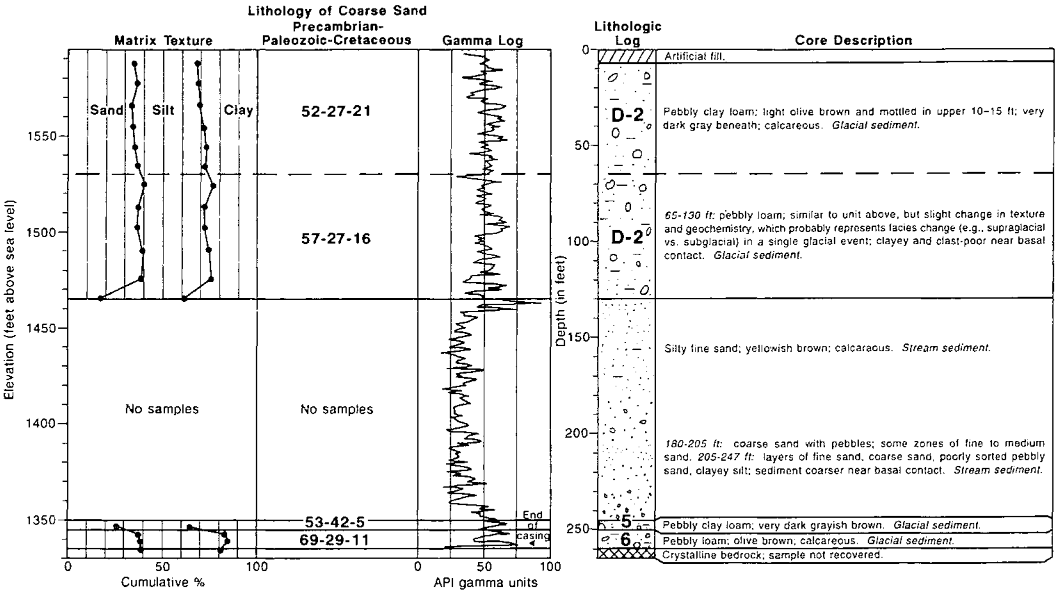
Pebbly loam; very dark gray; similar to unit above but texturally and geochemically distinct. *Glacial sediment.*

Pebbly clay loam to pebbly clay; color variable—yellow, brown, gray; calcareous. *Glacial sediment.*

Pebbly clay loam; very dark gray; calcareous. *Glacial sediment.*

Pebbly silty clay loam to pebbly clay loam; yellow brown and light olive brown; very hard; deformed; iron stained with white gypsum crystals; pebbles are weathered and disaggregated. *Glacial sediment.*

SWRA-2
Murray County



Artificial fill.

Pebbly clay loam; light olive brown and mottled in upper 10–15 ft; very dark gray beneath; calcareous. *Glacial sediment.*

65-130 ft: pebbly loam; similar to unit above, but slight change in texture and geochemistry, which probably represents facies change (e.g., supraglacial vs. subglacial) in a single glacial event; clayey and clast-poor near basal contact. *Glacial sediment.*

Silty fine sand; yellowish brown; calcaraous. *Stream sediment.*

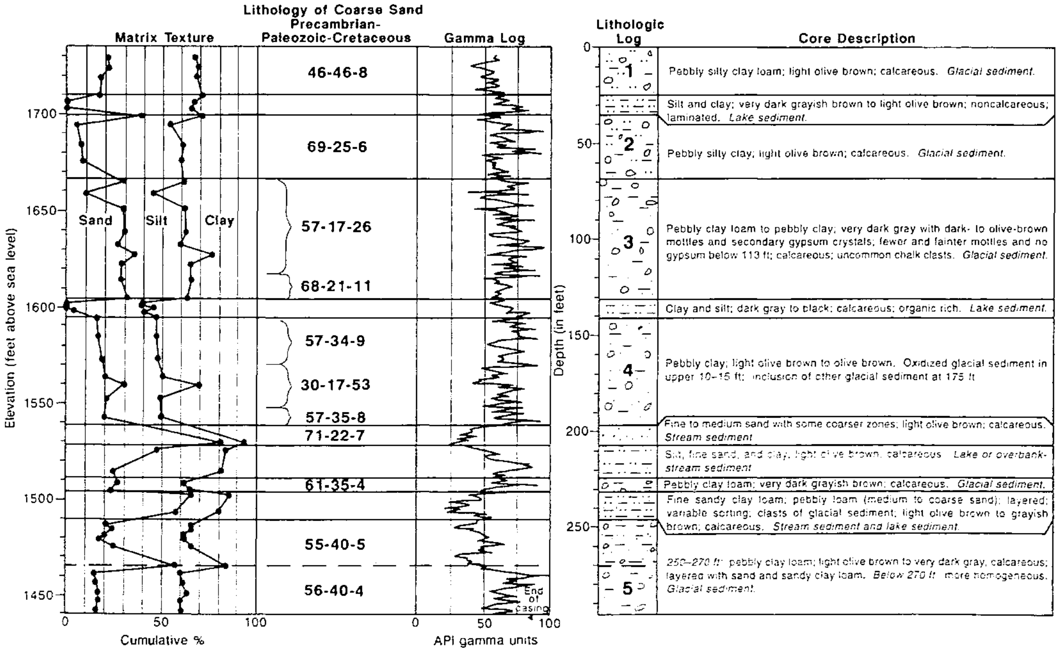
180-205 ft: coarse sand with pebbles; some zones of fine to medium sand. *205-247 ft:* layers of fine sand, coarse sand, poorly sorted pebbly sand, clayey silt; sediment coarser near basal contact. *Stream sediment.*

Pebbly clay loam; very dark grayish brown. *Glacial sediment.*

Pebbly loam; olive brown; calcareous. *Glacial sediment.*

Crystalline bedrock; sample not recovered.

SWRA-3
Pipestone County



Pebbly silty clay loam; light olive brown; calcareous. *Glacial sediment.*

Silt and clay; very dark grayish brown to light olive brown; noncalcareous; laminated. *Lake sediment.*

Pebbly silty clay; light olive brown; calcareous. *Glacial sediment.*

Pebbly clay loam to pebbly clay; very dark gray with dark- to olive-brown mottles and secondary gypsum crystals; fewer and fainter mottles and no gypsum below 113 ft; calcareous; uncommon chalk clasts. *Glacial sediment.*

Clay and silt; dark gray to black; calcareous; organic rich. *Lake sediment.*

Pebbly clay; light olive brown to olive brown. Oxidized glacial sediment in upper 10–15 ft; inclusion of other glacial sediment at 175 ft

Fine to medium sand with some coarser zones; light olive brown; calcareous. *Stream sediment*

Silt, fine sand, and clay; light olive brown; calcareous. *Lake or overbank-stream sediment*

Pebbly clay loam; very dark grayish brown; calcareous. *Glacial sediment.*

Fine sandy clay loam; pebbly loam (medium to coarse sand); layered; variable sorting; clasts of glacial sediment; light olive brown to grayish brown; calcareous. *Stream sediment and lake sediment.*

250–270 ft: pebbly clay loam; light olive brown to very dark gray, calcareous; layered with sand and sandy clay loam. *Below 270 ft:* more homogeneous. *Glacial sediment.*

and resistivity data. Gamma logs are particularly useful in distinguishing sandy layers from clay-rich tills and for identifying pre-Pleistocene rocks. Some private water wells, and all of the Survey test holes, were logged using geophysical techniques. In addition, some abandoned wells were logged before they were sealed.

Reflection-seismic profiling was conducted at four sites, and refraction-seismic profiling at eleven sites. A summary of results from this work is available for inspection at the Survey (for site locations, see Patterson, 1995).

The techniques commonly used in Minnesota to describe tills include determination of the matrix color and texture, and the lithology of the coarse-sand fraction. Textures are resolved into sand, silt, and clay percentages, and the one-to-two-millimeter sand grains are grouped by rock type (Fig. 8).

Recent work (Gowan, 1993; written commun., 1996) has shown that the geochemical signature of the fine fraction of a till is a promising attribute for till correlation in Minnesota. Accordingly, geochemical analyses helped define contacts between glacial units in the three Rotasonic cores, and the data may someday contribute to studies of ground-water geochemistry in the region. Results of the geochemical work are summarized in Patterson and others (1995); the complete report is available for inspection at the Minnesota Geological Survey.

GEOMORPHIC REGIONS

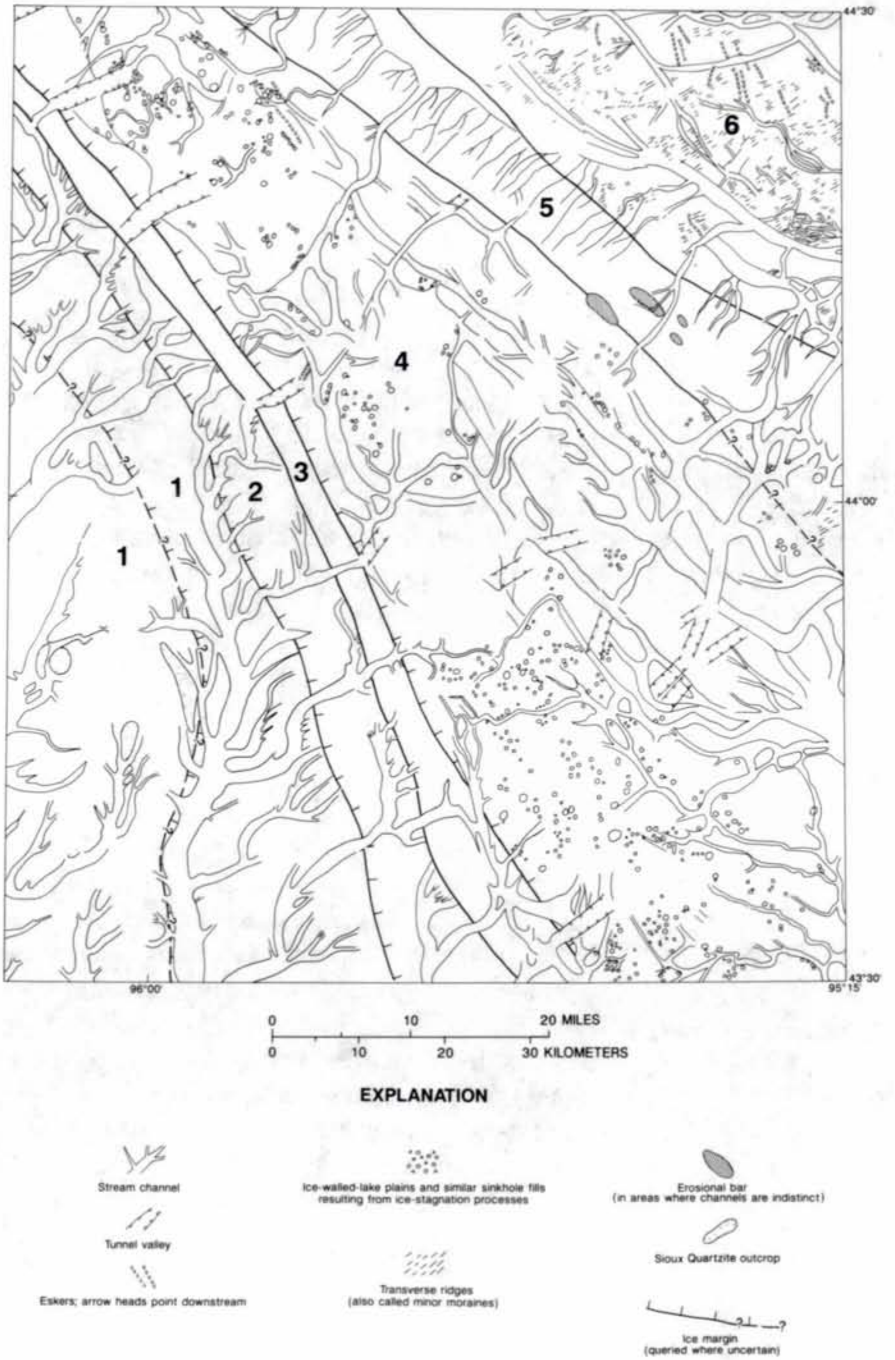
The topography of western Minnesota and the eastern Dakotas is dominated by a flatiron-shaped plateau (the Coteau des Prairies; also called the Prairie Coteau) that projects above the lowlands formerly occupied by the Des Moines and James lobes of the Late Wisconsin Laurentide Ice Sheet (Figs. 3, 4). The thickest Pleistocene section and the oldest tills are preserved beneath the surface of the plateau (Gilbertson, 1990; Lineburg, 1993).

The Coteau is a remnant of land that escaped glacial erosion during the last glacial period; as such, it is the glacial equivalent of an interfluve. The paths of the James and Des Moines lobes may have been directed by pre-existing topographic lows, but the presence of pre–Late Wisconsin units in the Coteau and the absence of many of these units from the lowlands, suggest that much of the erosion evident in the relief of the landform was a product of Late Wisconsin ice advances.

The commonly held assumption (e.g., Ojakangas and Matsch, 1982, p. 208) that the Coteau is cored with resistant bedrock is unfounded. Near Brookings, South Dakota (about 30 miles west of Lake Benton), over two-thirds of the relief of the Coteau is composed of glacigenic sediments. The first bedrock encountered beneath the glacial sediment is the soft Pierre Shale of Late Cretaceous age (Beissel and Gilbertson, 1987; Lineburg, 1993). The elevation of the Pierre Shale is generally between 1200 and 1300 feet above sea level near the northern part of the study area in South Dakota (Matsch and others, 1972; Beissel and Gilbertson, 1987). Precambrian chlorite schist was encountered in a drill hole north of Brookings at a depth of 1080 feet; the elevation of the top of the schist is 800 feet above sea level (Beissel and Gilbertson, 1987), well below the 1600-foot elevation of the top of the Coteau and the 1100-foot elevation of the base of the Coteau in this area. These findings are consistent with earlier interpretations (Matsch and others, 1972) and data from other holes that show crystalline rock generally below 750 feet above sea level.

Six geomorphic regions parallel the northwest-southeast trend of the Coteau des Prairies and the Late Wisconsin ice advances into southwestern Minnesota. Progressively younger regions are encountered from southwest to northeast (Fig. 10). Four of these regions are on the upland of the Coteau, one forms the northeast-facing slope, and one constitutes the lowland.

Figure 9 (left). Summary of pertinent lithologic and geophysical results from three scientific test holes in the study area. The holes were drilled as part of the Quaternary component of the southwestern Minnesota regional hydrogeologic assessment; they provided continuous, essentially undisturbed, four-inch-diameter core to depths of 214, 260, and 295 feet. The core is the most detailed and reliable source of information available on subsurface Quaternary deposits of southwestern Minnesota. The numbered units in columns headed Lithologic Log are discussed starting on page 20. See Figure 1 for the location of the holes and the appendix for detailed descriptive logs.



GEOMORPHIC REGIONS

1 **Trosky till plain**
Dissected pre-Wisconsin till plain overlain by windblown sediment in southwest corner. Loess border and heads of earlier drainages may delimit former ice margin(s).

2 **Verdi till plain**
Eroded till plain of Wisconsin Verdi ice position. No prominent end moraine. Recognized by heads of drainages.

3 **Buffalo Ridge**
Prominent Late Wisconsin Bemis moraine. Regional divide for Missouri and Mississippi Rivers. Becomes broader and less distinct southward.

4 **Hummocky highlands**
Ice-stagnation topography. Thick, heterogeneous supraglacial deposits.

5 **Coteau slope**
Northeast-facing slope of the Coteau des Prairies, a glacial erosional scarp. Less distinct to southeast.

6 **Marshall till plain**
Flay-lying till plain. Consists of thin subglacial till, locally overlain by thin, patchy supraglacial till.

Figure 10. Geomorphic regions and related glacial landforms of southwestern Minnesota. See text for discussion.

The ***Trosky till plain*** in the southwest corner of the study area is a pre-Wisconsin, stream-dissected, loess-covered area of till in which there are scattered outcrops of bedrock (Fig. 11). Remnants of a once-continuous cover of till and glacial stream sediment occupy the interfluves of nonglacial and glacial streams. Loess thicknesses as great as seven feet are common. This is the only geomorphic region with significant bedrock outcrop. Exposures of Sioux Quartzite were glacially striated and later polished and faceted by the wind.

The ***Verdi till plain*** is a loess-mantled, glacigenic landscape that lies immediately outside the most recent limit of glaciation. It is not as extensively dissected by alluvial streams as the Trosky till plain, but it was channeled by Late Wisconsin glacial streams (Fig. 12). The till is indistinguishable in the field from Late Wisconsin Bemis-phase deposits and is probably only slightly older. There are no obvious subglacial or ice-marginal landforms.

The prominent ***Buffalo Ridge*** borders the Verdi till plain on the northeast. It constitutes the Late Wisconsin Bemis moraine (Fig. 13), which along most of its length forms the divide between the Mississippi and Missouri drainage basins. The Bemis moraine was breached by discharge from glacial streams in several places, although modern streams do not transect it. Fields of wind turbines are being constructed on the moraine south of Lake Benton to take advantage of the high winds associated with this prominence.

The ***hummocky highlands*** form part of the upland of the Coteau des Prairies and lie within and parallel to the Bemis moraine (Fig. 14). Some of the hummocks are cylindrical plateaus that formed when holes in thin, stagnating ice filled with till, lake sediment, and stream sediment. These features are called ice-walled-lake plains when filled with lake sediment. Similar landforms on the Missouri Coteau have been described in detail by Clayton (1967). Other hummocks are simply irregular mounds of till.

In the southeast part of this region, the ice-walled-lake plains are lower and grade into a more continuous, thin lake deposit. This represents a gradual transition from ice-supported lakes to lakes that were "grounded."

Parallel meltwater streams trending northwest-southeast flowed along the ice margin as it progressively retreated during wasting. Branches of these streams trending southwest-northeast represent adjustments to the narrowing ice lobe.

Immediately northeast of the hummocky highlands geomorphic region is the northwest-southeast-trending ***Coteau slope.*** Remnants of ice-marginal drainage parallel this trend and are crosscut by more deeply incised streams that flowed down the flank of the Coteau des Prairies as the ice receded farther into the lowland (Fig. 15). These incised streams deposited alluvial fans at the base of the Coteau slope.

The ***Marshall till plain*** is a low, flat area of uniform dense till. Linear ridges composed of slightly coarser material appear to be draped over this uniform till. The ridges, which are easier to see on aerial photographs than in the field, are transverse to the general ice-flow direction and are generally less than 20 feet high (Fig. 16). Small eskers, perpendicular to the trends of the ridges, formed concurrently. Finally, marginal or submarginal streams created broad, sandy channels with some anastomosing tangles as they flowed across the landscape.

BEDROCK TOPOGRAPHY AND THICKNESS OF GLACIAL SEDIMENT

The bedrock topography of the study area is strongly influenced by the resistant Early Proterozoic Sioux Quartzite, which has occupied a topographic high in the region for most of the time since its deposition (Southwick and others, 1986). The buried, pre-Phanerozoic bedrock topography over the Sioux Quartzite is characterized by fairly level highs and abrupt drop-offs (Figs. 17a, 18). It is similar to the expression of the Sioux Quartzite as exposed at and near Blue Mounds State Park north of Luverne, Minnesota. The relief on the bedrock surface is as great as 1000 feet. Many of the steep box canyons in the Sioux are partially filled with Cretaceous deposits of shallow-water origin and include shale, sandstone, and spiculite (Setterholm, 1990) (Fig. 17b).

The sediment between the land surface and the bedrock surface is primarily of glacial origin. The thickness of this sediment is known only where drill holes penetrate the entire section of unconsolidated glacial sediment to bedrock. In the study area, such points of known sediment thickness are widely scattered and would provide only enough information to create a generalized depth-to-bedrock map.

To overcome this lack of adequate well control, a model of the bedrock surface was created by D.R. Setterholm (Patterson and others, 1995, Fig. 4). Bedrock topography is influenced by structural features

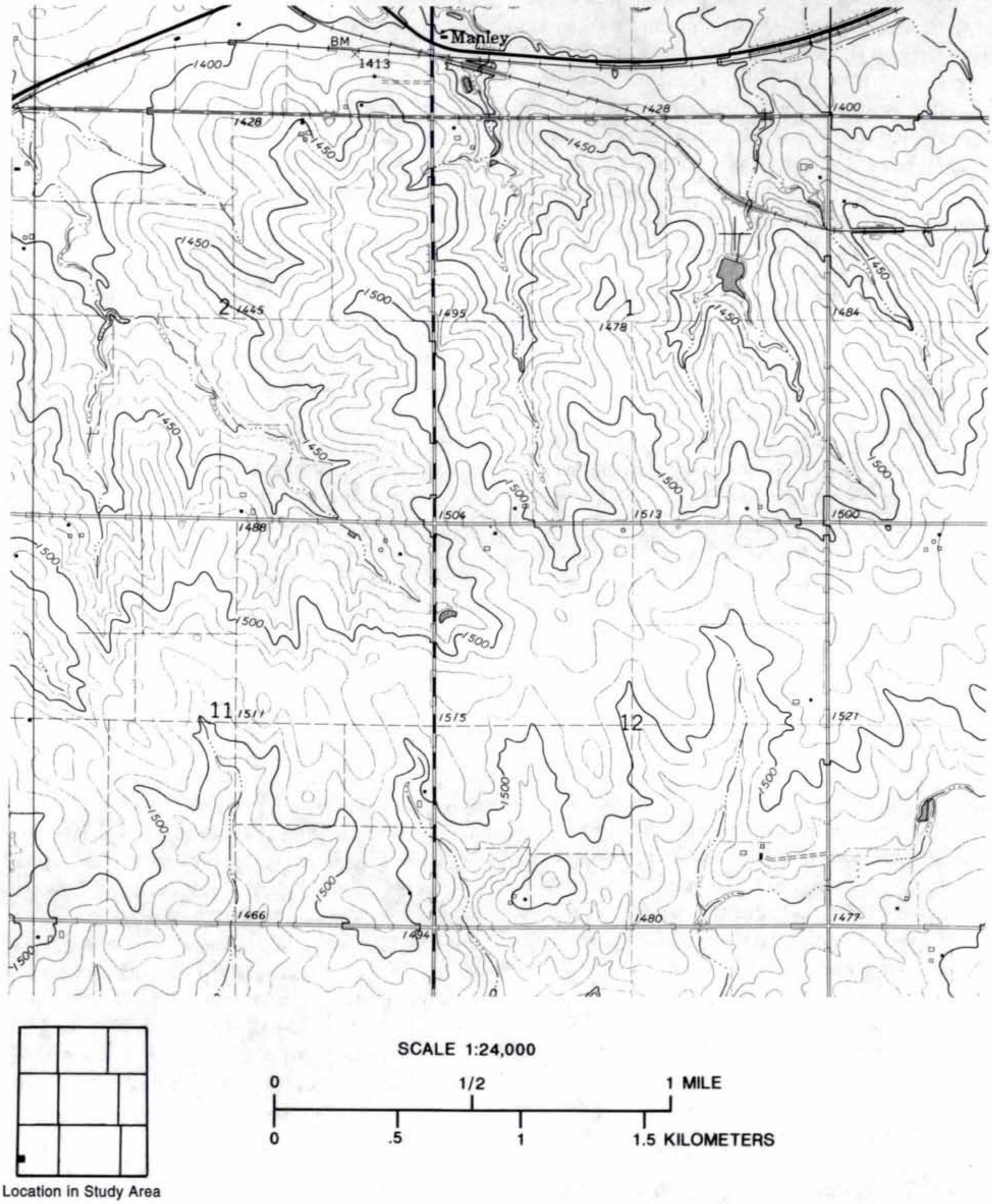


Figure 11. Representative area of the thick loess region of the Trosky till plain, Rock County. The loess overlies till in the uplands and is dissected by streams. The streams have a northwest-southeast orientation and are interpreted as having been aligned by the wind. Northwesterly winds, common during the last glacial period as well as today, influenced the stream courses through preferred erosion and deposition of wind-blown dust. Larger streams were not influenced as much (see Hallberg, 1979). From U.S. Geological Survey Valley Springs, Minn.–S. Dak.–Iowa, quadrangle, 7.5-minute series (topographic), 1967; contour interval 10 feet.

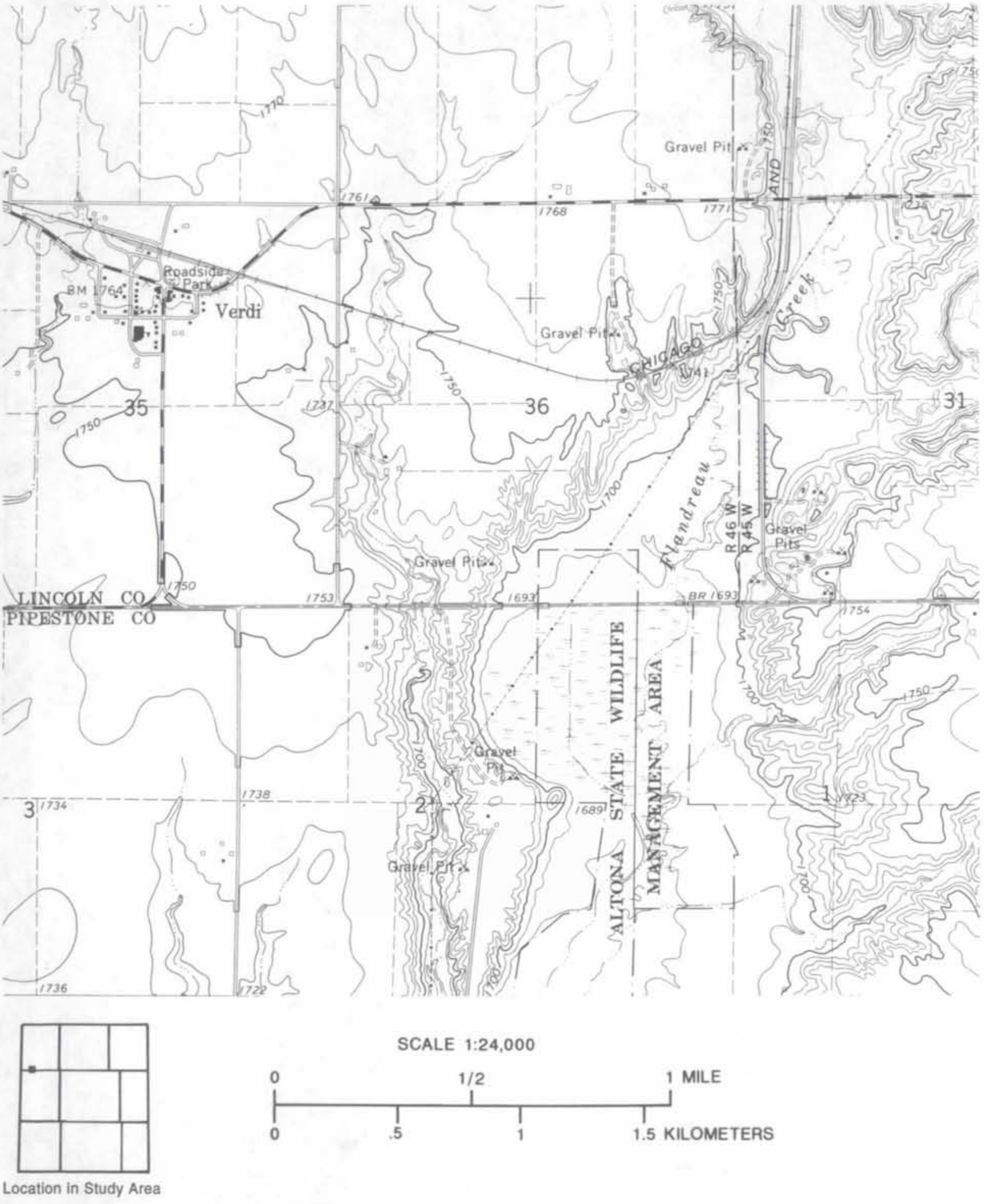


Figure 12. Representative area of the Verdi till plain in Lincoln and Pipestone Counties. This loess-mantled, glacigenic landscape is not extensively dissected by streams, but Late Wisconsin outwash stream channels, such as that through which Flandreau Creet flows, are prominent drainage features. From U.S. Geological Survey Verdi, Minn., quadrangle, 7.5-minute series (topographic), 1967; contour interval 10 feet.

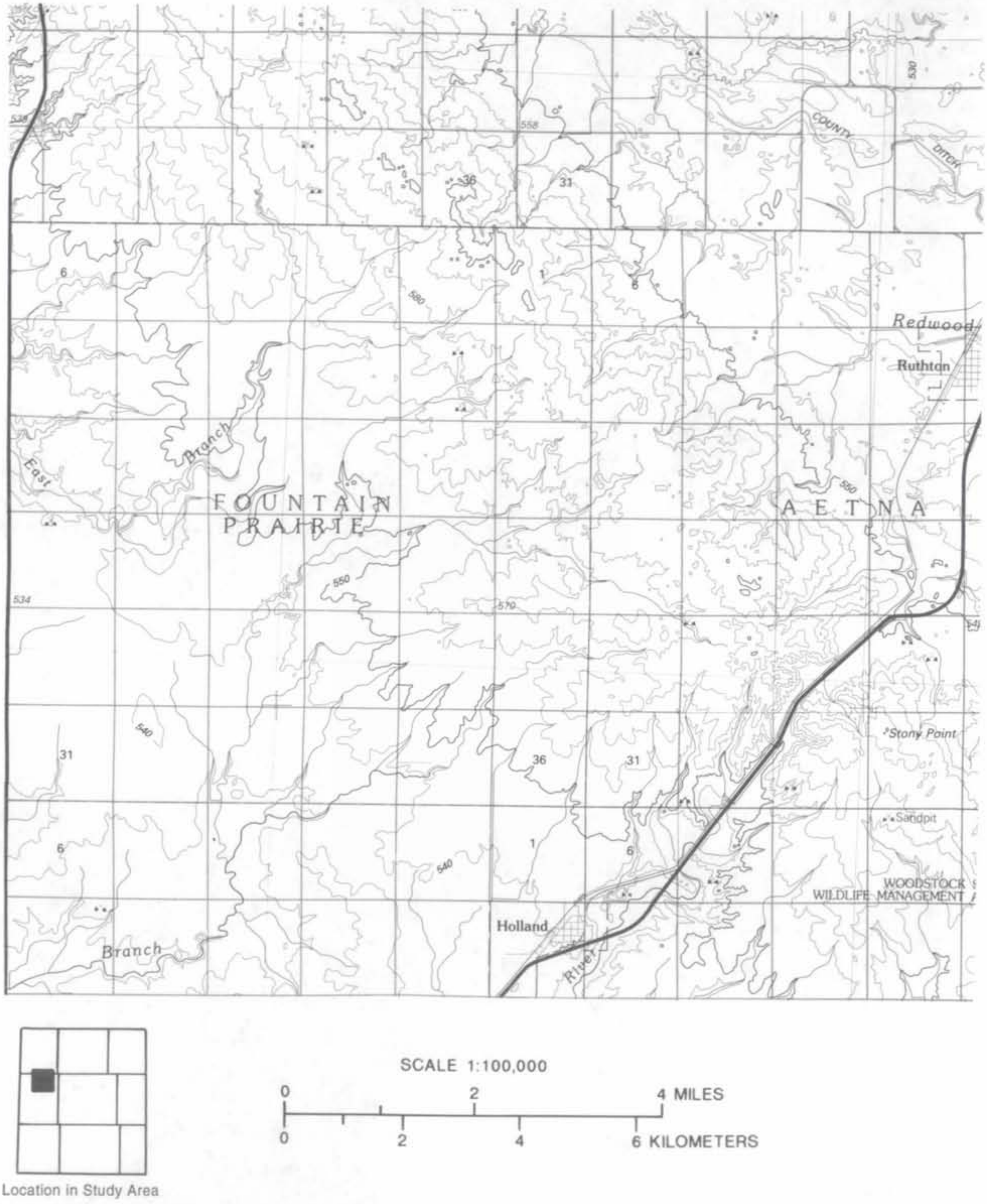


Figure 13. Representative area of the northwest-southeast-trending Bemis moraine, Lincoln and Pipestone Counties. The moraine is known locally as Buffalo Ridge. The northeastern slope of the moraine is relatively steep compared to its more gradual southwestern slope. Minnesota Highway 23 between Holland and Ruthton follows the path of a glacial stream channel that cut through the moraine. From U.S. Geological Survey 30 x 60–minute Brookings quadrangle (1:100,000-scale metric topographic map), 1985; contour interval 10 meters.

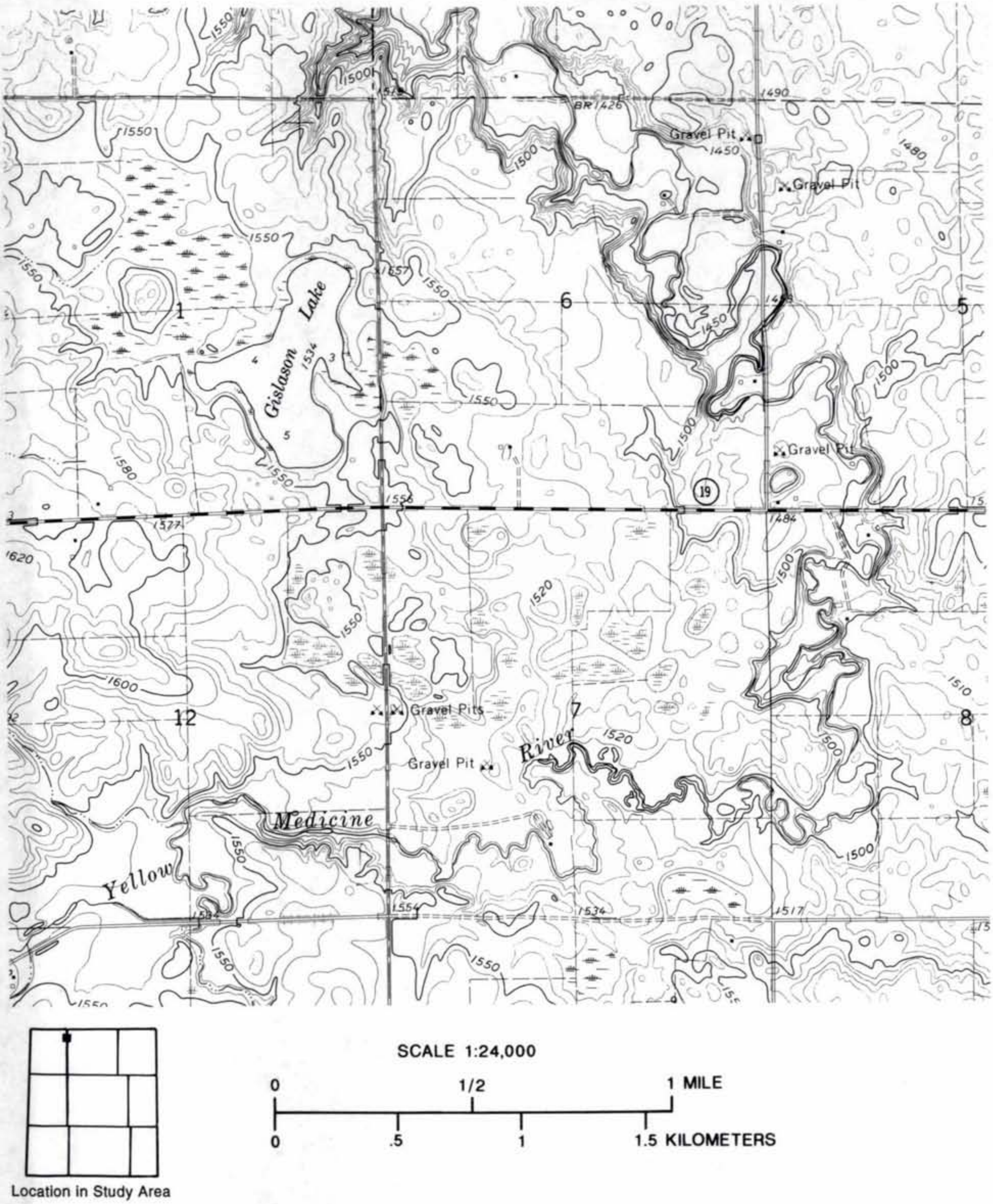


Figure 14. Representative area of the hummocky highlands, an area of ice-stagnation topography within the Bemis moraine in Lincoln and Lyon Counties. From U.S. Geological Survey Gislason Lake, Minn., quadrangle, 7.5-minute series (topographic), 1963; contour interval 10 feet.

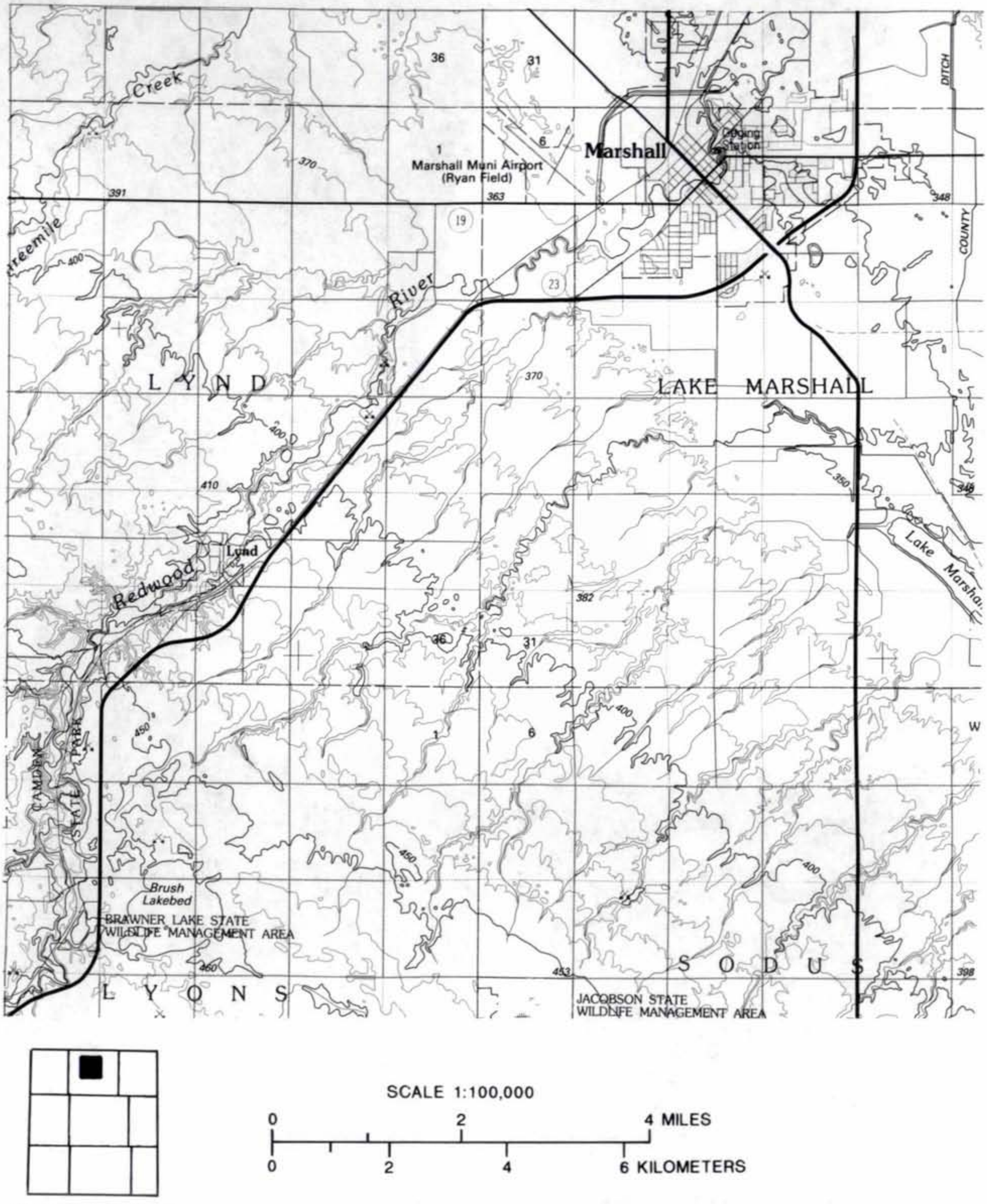


Figure 15. Northwest-southeast-trending flank of the Coteau des Prairies in Lyon County. Deeply incised drainages that flowed directly downslope formed as the ice retreated into the lowland; some streams built fans at the base of the slope like the one west of Marshall. U.S. Geological Survey 30 x 60–minute Tracy quadrangle (1:100,000-scale metric topographic map), 1986; contour interval 10 meters.

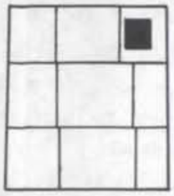


Figure 16. Representative area of the Marshall till plain in the northeastern corner of the study area, Redwood County. The ice flowed southeastward; therefore, the southwest-oriented ridges (lighter tone) are generally transverse to flow. The low relief of the ridges, generally less than 20 feet, makes them difficult to see on topographic maps. Marginal and submarginal outwash streams created broad sandy channels like that through which the Cottonwood River flows. Roads on section boundaries form a one-mile grid. From aerial photograph EKA 1276, strip 15, 4-9-77, by Mark Hurd Aerial Surveys, Minneapolis, Minn.

in the rocks, such as faults and joints. These structural features can be recognized in the pattern of drainages that develop on a bedrock surface. Information on structure was combined with depth-to-bedrock data to construct an inferred bedrock surface. This surface was then contoured and sampled at a 1000-meter spacing. The grid of bedrock elevations was subtracted from the U.S. Geological Survey 30-minute digital-elevation model for the land surface, which has the same 1000-meter sample spacing. The resulting grid of glacial sediment thicknesses was contoured for presentation (Fig. 19).

The thickest glacial sediment in the study area, 500 to more than 800 feet, is in the Bemis moraine, which itself has 200 feet of overall relief. Sediment thickness in the hummocky highlands northeast of the moraine is 200–600 feet. In both these areas thick Late Wisconsin glacial sediment was deposited (with little subglacial erosion) on older glacial sediment (Fig. 20). Thickness of glacial sediment decreases with decreasing elevation along the slope of the Coteau. Depth to bedrock is less than 100 feet, and generally less than 50 feet, in the Marshall till plain, an area of predominant subglacial erosion and minor deposition of till. The absence of units on the lowland that are present to the west suggests that an erosional unconformity lies beneath the Late Wisconsin till, implying significant late-glacial erosion (Fig. 20).

The preserved thickness of the glacial sediment varies as a function of the preglacial bedrock topography. The till is thinnest above bedrock highs and is variably thicker away from them. The flanks of the quartzite-cored Sioux Ridge locally exhibit abrupt paleo-relief of 300 feet or more in the subsurface, and the glacial deposits thicken substantially across the ridge flanks.

The greatest number of glacial units is preserved on the Coteau des Prairies within the Late Wisconsin margin or slightly outside it in the northwestern part of the study area. It is in this area that at least five pre–Late Wisconsin glacial units were identified in hole SWRA-3, and where a till with reversed magnetic polarity, implying an age of more than 788 ka B.P., was encountered at depth.

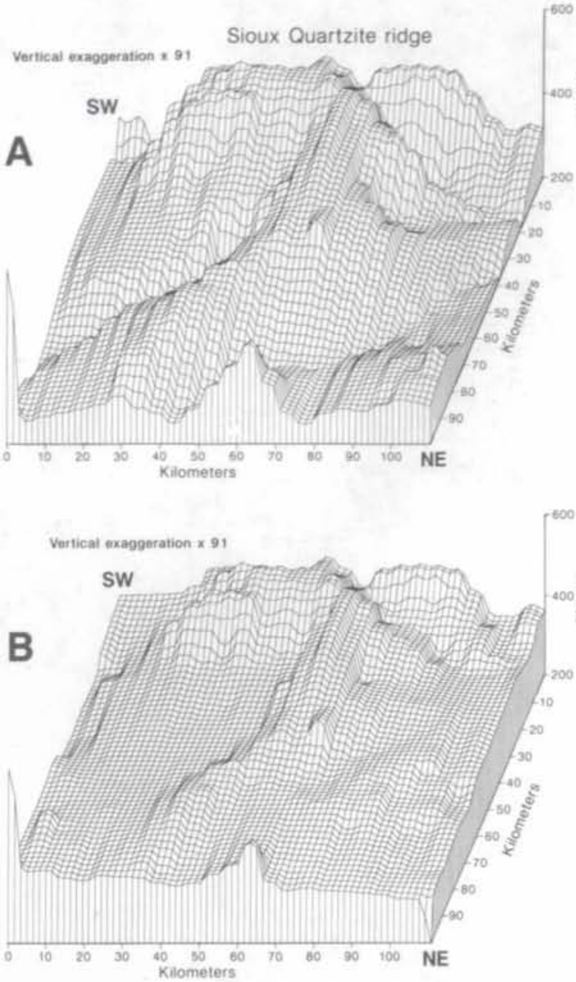
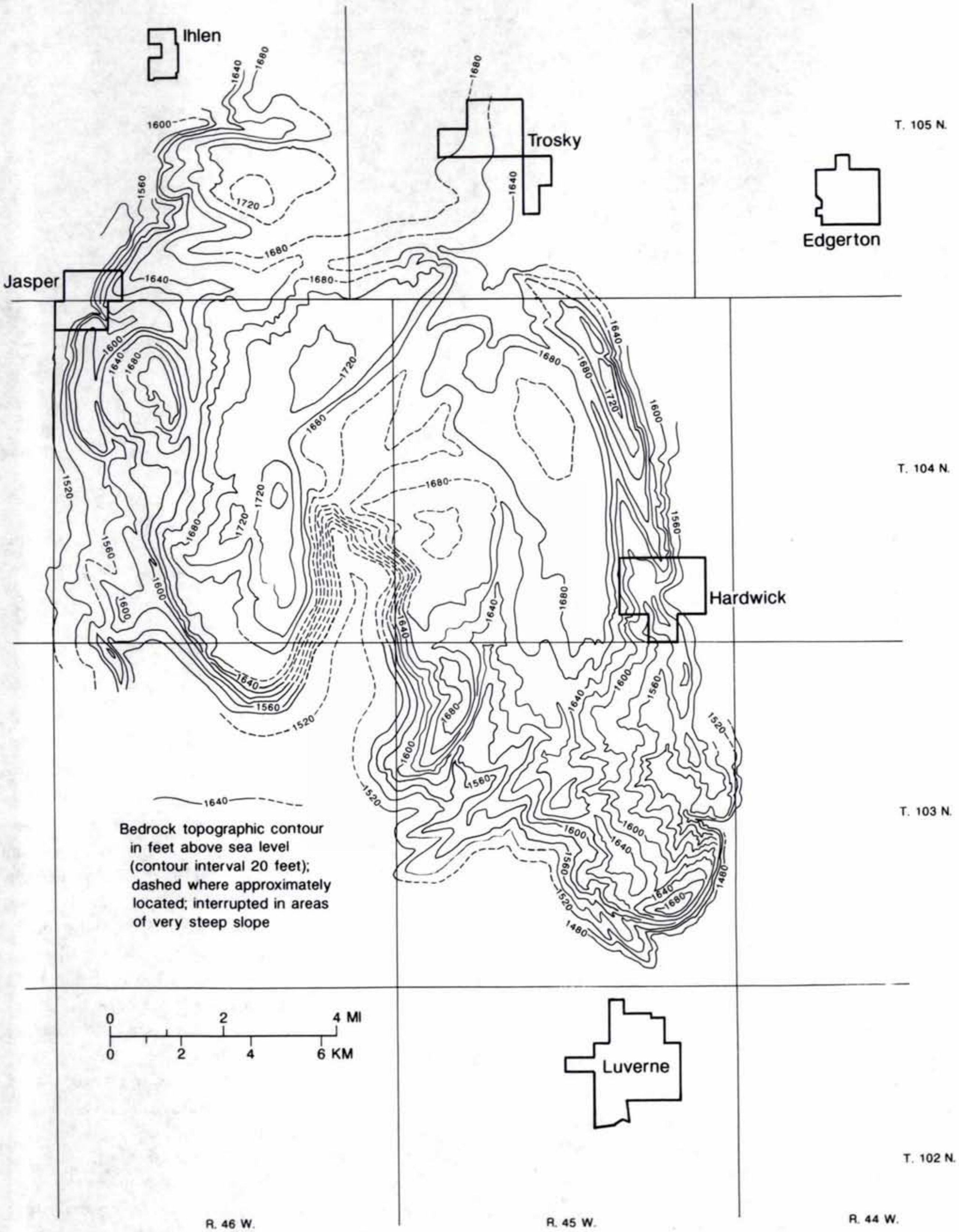


Figure 17. Topography of the pre-Phanerozoic (**A**) and Cretaceous (**B**) bedrock surfaces in southwestern Minnesota. Deep valleys in the Sioux Quartzite filled with shallow-water sediments during the Cretaceous when this region was at the eastern margin of the Western Interior Seaway. Models created by D.R. Setterholm.

EARLY GLACIAL DEPOSITS

The glacial record as preserved in southwestern Minnesota appears to be limited to the second half of the Pleistocene. Sediments of Late Pliocene ice advances, which are documented in western Iowa and northeastern Nebraska (Hallberg and Kemmis, 1986), may have been eroded from southwestern Minnesota. Numerous Middle Pleistocene ice advances are represented in the sedimentary record of Nebraska,

Figure 18 (right). Bedrock topography of the Sioux Quartzite north of Luverne. The quartzite is characterized by fairly flat, level highs with abrupt drop-offs and box canyons. Modified from unpublished mapping by D.L. Southwick, 1993.


Ihlen
Trosky
Edgerton
Jasper
Hardwick
Luverne
T. 105 N.
T. 104 N.
T. 103 N.
T. 102 N.
R. 46 W.
R. 45 W.
R. 44 W.
1480
1520
1560
1600
1640
1680
1720
1640
Bedrock topographic contour in feet above sea level (contour interval 20 feet); dashed where approximately located; interrupted in areas of very steep slope
0
2
4 MI
0
2
4
6 KM

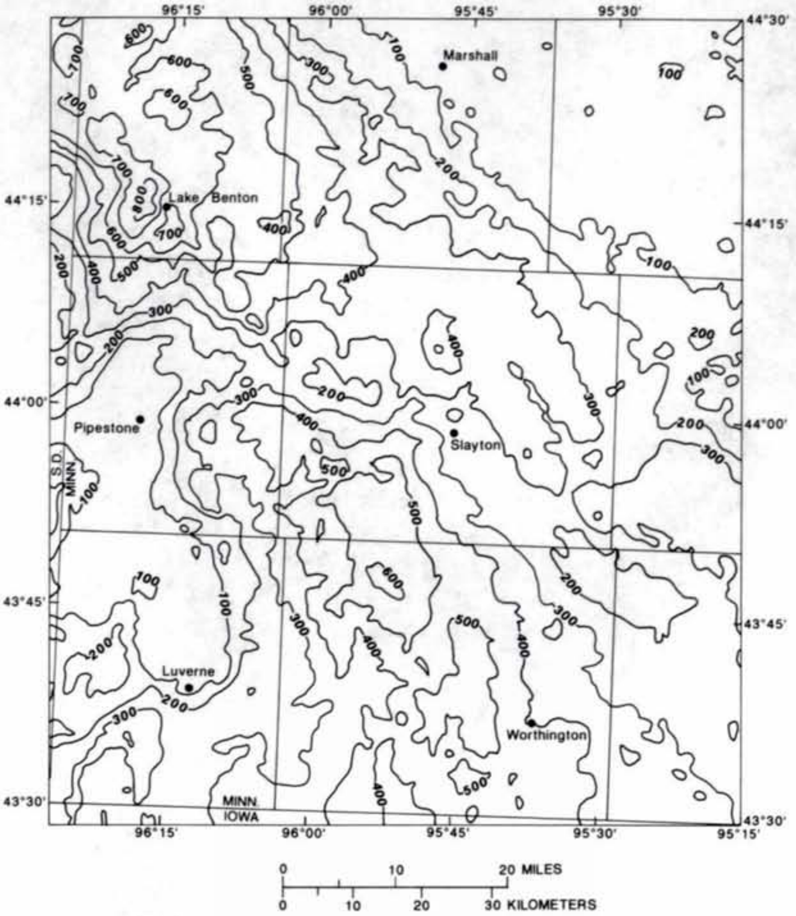


Figure 19. Thickness of glacial sediment in southwestern Minnesota amd contiguous areas of Iowa and South Dakota. Contour interval 100 feet.

western Iowa (Hallberg and Kemmis, 1986), northeastern Kansas (Aber, 1991), and eastern South Dakota (Gilbertson, 1990; Lineburg, 1993). The oldest glacial deposits mapped in southwestern Minnesota are inferred to date to the Middle Pleistocene on the basis of (1) correlation with dated ash units in South Dakota, (2) magnetic polarity of units in Minnesota, and (3) the timing of the largest global ice volumes as interpreted from isotopic evidence in ocean sediment cores.

Surficial Units

Two tills (units 1 and 2) attributable to glaciations older than the Wisconsin are exposed at the surface in southwestern Minnesota. Samples of the tills collected in the field are very similar, and they form a single map unit in the assessment (Patterson, 1995) and in Figure 21a. The area in which the tills are exposed has been dissected and altered by stream and wind erosion to the extent that no recognizable glacial landforms attributable to either of the advances remain. However, the geomorphology and geology of the area suggest a boundary between the till units based on (1) the coincidence of the upstream limit of outwash on the older till, (2) the border between thick, extensive loess and thinner discontinuous loess, (3) a high in the bedrock topography that may have deflected ice advancing into the area, and (4) an exposure near Ihlen of silty bouldery till, lake sediment with dropstones, and alluvial and colluvial deposits, suggesting an ice-marginal position (Fig. 21).

The two tills are dark gray and have a clay-loam matrix texture (average cumulative percentage of sand-silt-clay for unit 1 is 28-44-31; for unit 2,

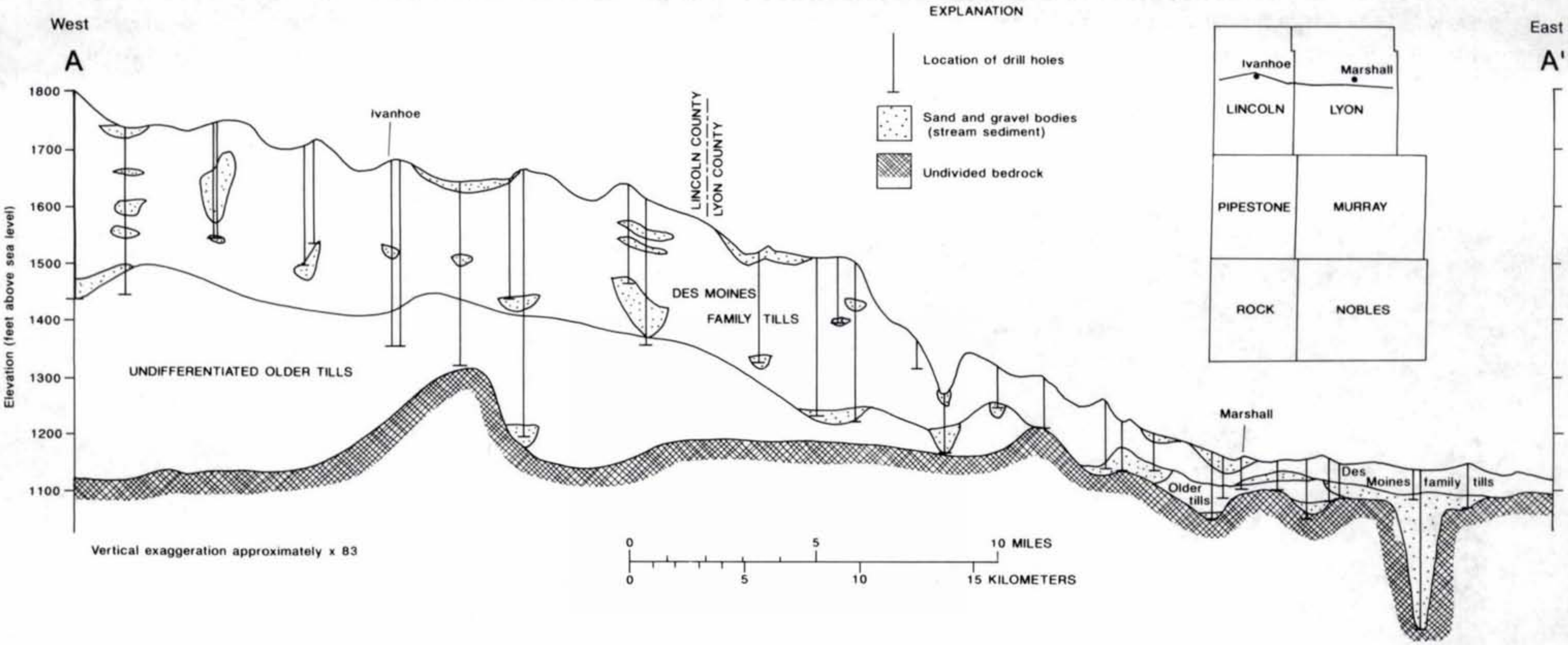


Figure 20. Stratigraphic cross section across central Lincoln and Lyon Counties. Des Moines–family and older tills are thickest in the morainic and hummocky stagnation region and thinnest in the subglacial area near Marshall, where there appears to be an erosional unconformity created by subglacial erosion of the Late Wisconsin ice advances. Drill holes are located within one mile of section line.

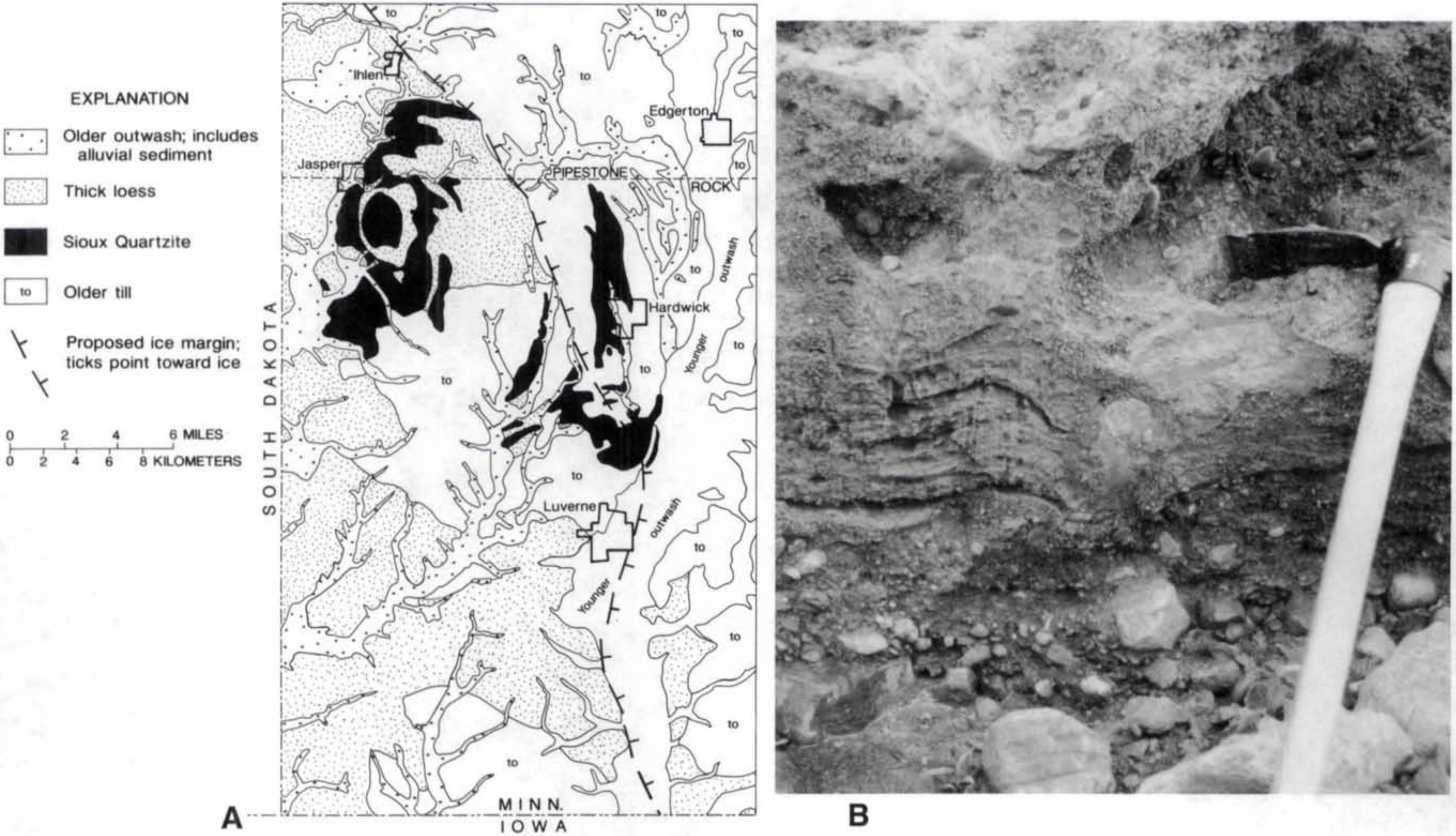


Figure 21. Coincidence of ice-marginal indicators within the Trosky till plain, Rock and Pipestone Counties.

A. Map showing exposed bedrock highs of Sioux Quartzite, the location of surface exposures of old glacial stream sediment, and the border of the thick loess region; taken together, these features suggest the position of an ice margin.

B. Outcrop with dropstone south of Ihlen in Pipestone County. The exposure was created by the bursting of the dam at Split Rock Creek State Park. It reveals sediments of a complex near-glacial environment that include bedded, silty lake sediment, which is deformed by at least one and maybe two dropstones (below blade of pickaxe), overlying coarse alluvial gravels. The dropstones were most likely emplaced by floating, debris-laden ice in a proglacial lake. The unit above the bedded silts is of unknown origin; it is a diamicton (massive, silty, clayey matrix with clasts) but may not be of direct glacial deposition—i.e., it could be a debris flow.

35-32-33). However, lithologic analysis of the coarse sand fraction (expressed as the average cumulative percentage of Precambrian-Paleozoic-Cretaceous rock types) indicates the differences, especially in the ratio of Precambrian crystalline grains to Cretaceous shale and Paleozoic limestone grains. The average grain ratio for unit 1 is 45-41-13; for unit 2, 73-21-4. Both tills are mapped as older till in Figure 21a; however, unit 2, which is located farther to the southwest, is the older till and typically has more than 70 percent crystalline rocks in the coarse-sand fraction. This preponderance of Precambrian grains may reflect flow from a more northerly or northeasterly direction (one that would pass over more crystalline rocks) or more complete weathering (due to the greater age of the till) of all but the resistant rock fragments. The presence of Lake Superior–type agates found at the surface near Jasper is consistent with flow from the northeast.

Shallow borings show that the lower till (unit 2) has a distinct olive cast. Soil development is indicated by a leaching depth of three feet, blocky structure, mottling and weak oxidation colors near the top, and secondary gypsum, calcium carbonate, and iron in the unoxidized or reduced part, mostly along joints in the till. Soil development is most likely during an interglacial or interstadial period.

Outcrops of Sioux Quartzite in this area commonly show striae and crescentic fractures. Two dominant sets of striae are about 40 degrees apart. One averages 168 degrees (ice flow from the north-northwest), the other, 207 degrees (ice flow from the north-northeast) (unpubl. data, D.L. Southwick, 1993). The two directions are consistent with the mineralogical differences in the two tills; however, no evidence relates the striae directly to those units rather than to older units present in the subsurface.

The glacial sediment comprising the two tills has been eroded, most likely by wind, as indicated by stone lag (probably created by deflation) and faceted, polished bedrock exposures. Wind erosion is a common phenomenon in the periglacial environment and could have occurred shortly after the initial deposition of the sediment. However, it is more likely to have occurred during the Wisconsin glaciation when this area was at the periphery of the ice. Windblown silt with clay and fine sand (loess) accumulated in downwind areas of lower wind strength. Loess thicknesses as great as seven feet are common in the southwest corner of the study area. The upper eight inches of the loess is leached; the underlying horizon contains calcium carbonate nodules. A northwest-southeast orientation of the drainages and interfluves in the area of thick loess is a result of the northwesterly wind direction that was predominant during the Wisconsin when the streams were developing (Fig. 11), as has been documented in adjacent areas of Iowa (Hallberg, 1979). Wind-polished and -faceted outcrops of Sioux Quartzite in this area also indicate a northwesterly paleowind direction (D.L. Southwick, written commun., 1996), but they were not systematically studied for this project.

Stream sediment found at or near the surface that appears to be unrelated to later ice advances is presumably related to these older tills. No lithologic studies were undertaken to make this connection with confidence, though, and nonglacial stream sediment is included in this map unit in both the assessment (Patterson, 1995) and Figure 21. This sediment is found not only in the topographic lows but also on interfluves. A large area of old stream sediment is mapped west of Ihlen (Fig. 22). East of Ihlen, loess buries a similar area of sand and gravel.

Incision of the landscape and the formation of a well-developed dendritic drainage system drained the closed depressions that may have formed in the area. Only one large closed depression remains (Fig. 23) three miles southeast of Jasper (Fig. 5). It is two miles in diameter and has 33 feet of overall relief. Lake sediment in the basin is as much as six feet thick and ranges in texture from clay to sand. The lake sediment is underlain by about 50 feet of glacial sediment, including two tills separated by a lacustrine sequence, that has no known counterparts in southwestern Minnesota and South Dakota. Sioux Quartzite was encountered at a depth of 53 feet in Minnesota Geological Survey hole PR-90-1, which was drilled within the basin. Exposures of the Sioux are immediately west and southwest of the basin and are shallowly buried elsewhere in this area of the Trosky till plain. Although some workers have suggested that this basin may be a meteorite crater,

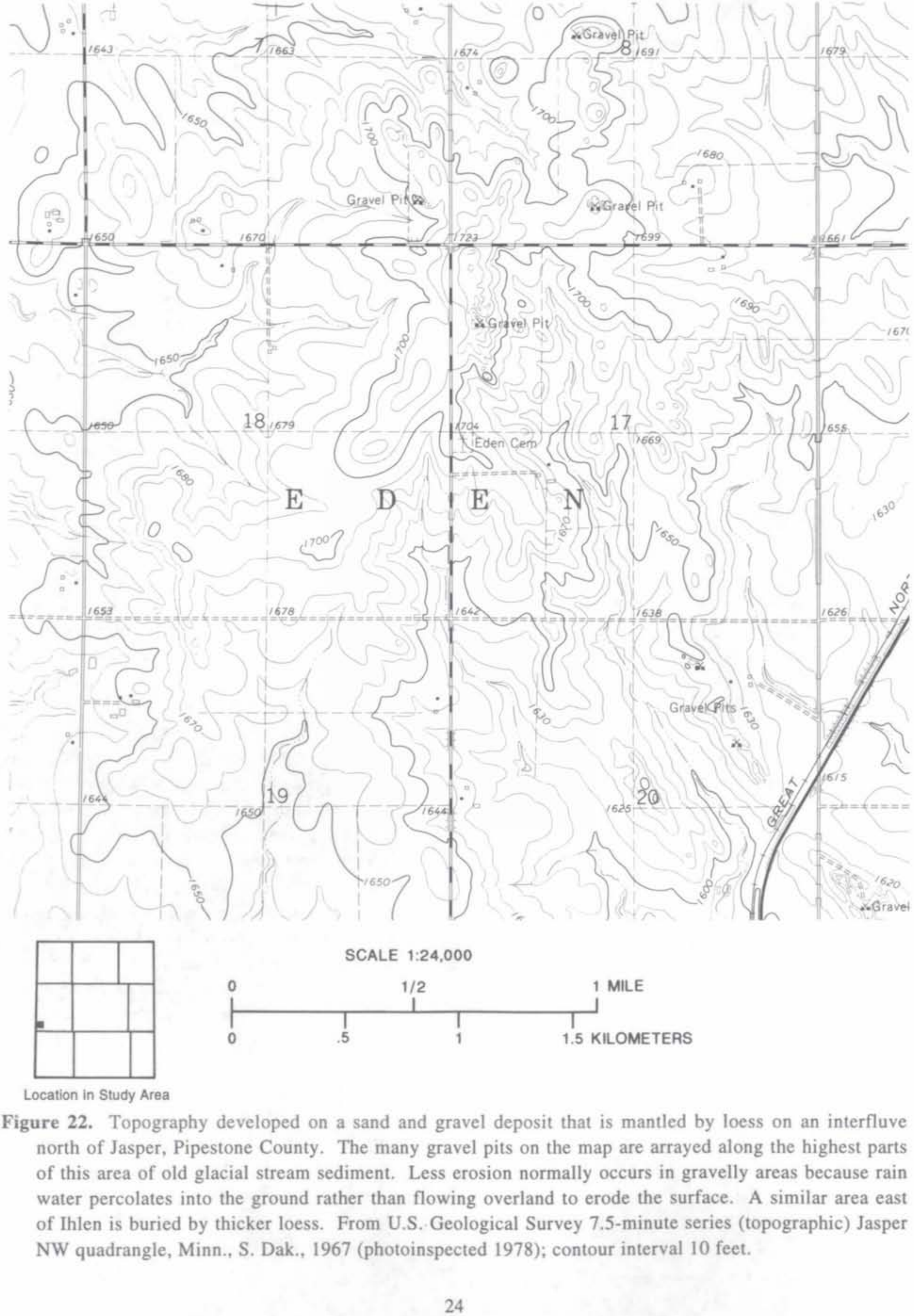


Figure 22. Topography developed on a sand and gravel deposit that is mantled by loess on an interfluve north of Jasper, Pipestone County. The many gravel pits on the map are arrayed along the highest parts of this area of old glacial stream sediment. Less erosion normally occurs in gravelly areas because rain water percolates into the ground rather than flowing overland to erode the surface. A similar area east of Ihlen is buried by thicker loess. From U.S. Geological Survey 7.5-minute series (topographic) Jasper NW quadrangle, Minn., S. Dak., 1967 (photoinspected 1978); contour interval 10 feet.

samples of Sioux Quartzite from hole PR-90-1 did *not* show high-velocity impact features such as shatter cones, veins of impact breccia, glassy melt or shock-dislocation lamellae (Southwick and others, 1993). The local high of Sioux Quartzite probably protected the area from headward erosion of streams, allowing the basin to remain a lake until it was drained for agriculture. Wind erosion may have deepened the basin during glacial periods when it was at the periphery of ice advances.

Subsurface Units

Three older glacial units (numbered three through five) were recognized directly beneath the two units that are exposed at the surface, and an additional four units (numbered six through nine) were recognized at depth in other parts of the study area (Fig. 24). SWRA-3, the Rotasonic drill hole that penetrated the five upper units (1–5; appendix), did not reach bedrock, so there may be more than five glacial units preserved at this location. In Rotasonic hole SWRA-2, two units (5 and 6) were recognized (see appendix). The correlation of unit 5 from SWRA-3 to SWRA-2 is tenuous, because it is based on identification of only one sample in SWRA-2 and general descriptions from well logs of intervening holes. Rotasonic hole SWRA-1 (appendix) penetrated three tills (units 7–9) beneath a group of three similar Late Wisconsin tills (units of Des Moines–family tills: D-1, D-2, D-3). Till units 7–9 are apparently stratigraphically below the

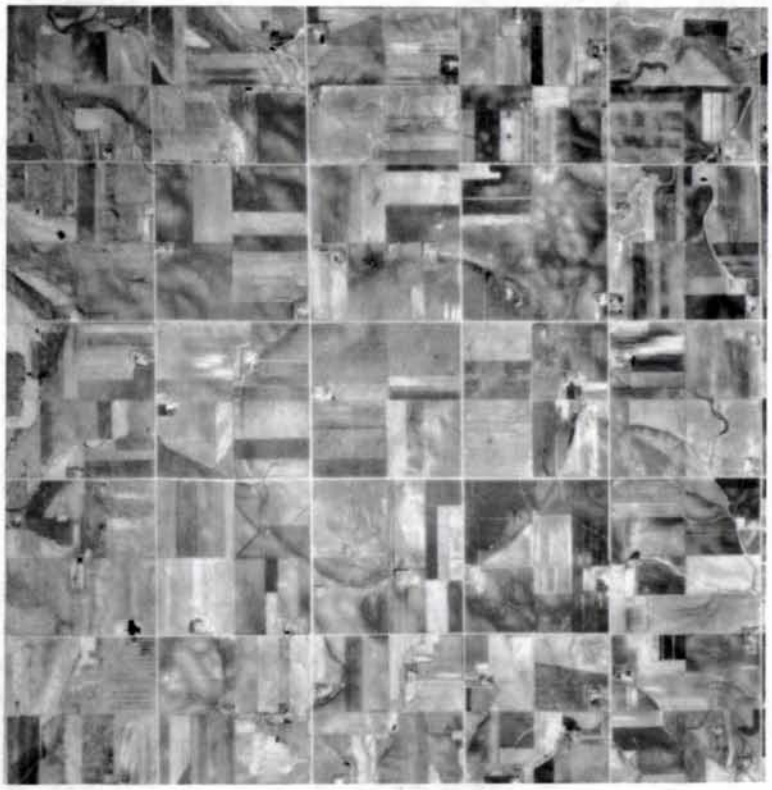


Figure 23. Aerial photograph of the nearly circular lake bed southeast of Jasper in Rock County. This is the only closed depression remaining in the region, and it has been artificially drained. It is most likely of glacial origin, and its preservation may be due to nearby bedrock highs that protected it from headward erosion. Core from a test hole (MGS-PR-90) drilled in the basin indicates that the Quaternary section includes two different tills and two layers of lake sediment. Sioux Quartzite at the bottom of the hole showed no indication of shock metamorphism. Scale is given by the gridwork of section-line roads spaced one mile apart.

other tills because they are at a much lower elevation and do not resemble any other sequence of three tills encountered; they are therefore presumed to be a distinct series.

It was impossible to date directly the older till units recovered in the three Rotasonic cores. They are too old for radiocarbon dating, and an ash layer used to date tills farther west in South Dakota by the potassium-argon method was not recognized in the study area (Hallberg, 1986). However, lithologic correlation of these subsurface tills with till units assigned relative ages in South Dakota permits some of the tills to be bracketed in time (Table 1, p. 29). Remanent magnetism measurements made on SWRA-3 core all showed normal polarity. Therefore, these glacial units are probably less than 788 ka B.P., the age of the last major magnetic reversal.

Sediments with reversed magnetism do occur within the study area, however. Fifteen miles north of hole SWRA-3, hole MGS-2873 encountered till between the elevations of 1184 and 1282 feet that conformably overlies lake sediment and gravelly stream sediment (see appendix). The cored interval is 158–344 feet below the bottom of hole SWRA-3 (elev. 1440 ft). Eleven of the twelve samples of till and lake sediment from this interval of MGS-2873 showed reversed magnetization. A somewhat shallow magnetic inclination (23–67 degrees) may be caused by compaction of the clay-rich sediments (V.W. Chandler, unpubl. data, 1995). Thus the till and lake sediment are probably older than 788 ka B.P.

Hole SWRA-1, 50 miles to the southeast of MGS-2873, extends to an elevation of 1200 feet above sea level. If the till sheets were flat-lying (a big assumption given the wide range in elevations of the Late Wisconsin tills found at the surface), the hole may have intersected these old, magnetically reversed units. The texture and grain lithology of till unit 8 (elev. 1210–1225 ft) resemble the till from hole MGS-2873 (elev. 1184–1272). However, the magnetic polarity of unit 8 from SWRA-1 is unresolved, because only three of the nine samples tested from it were reversed. The variation may be caused by magnetic pebbles in the till, which overwhelmed the magnetic signal, or the till may have been disturbed after deposition or during drilling. The sediment in hole MGS-2873 was better suited for magnetic work because it included lake sediment.

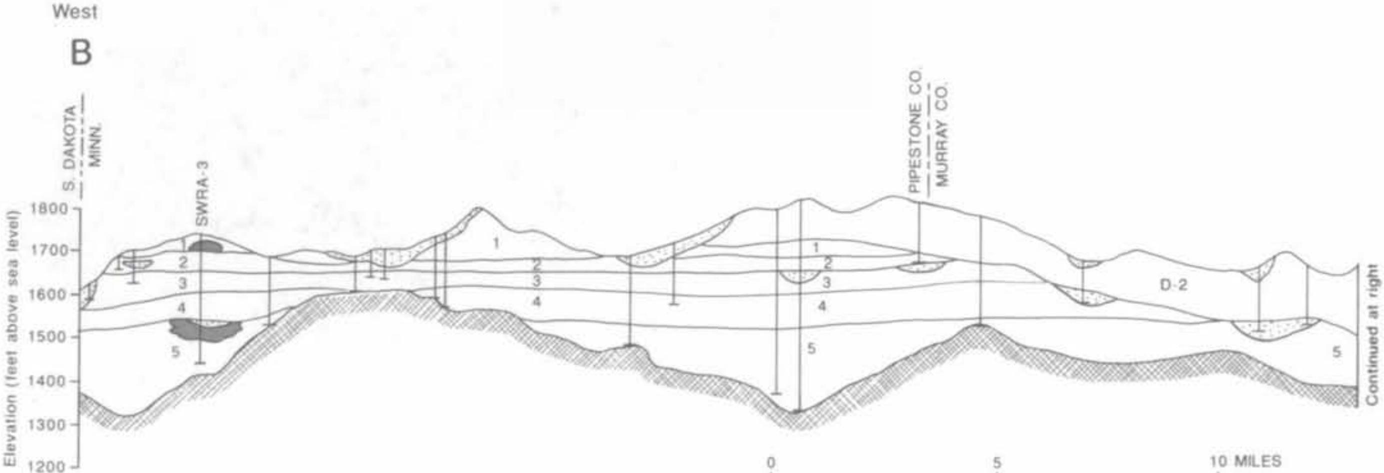


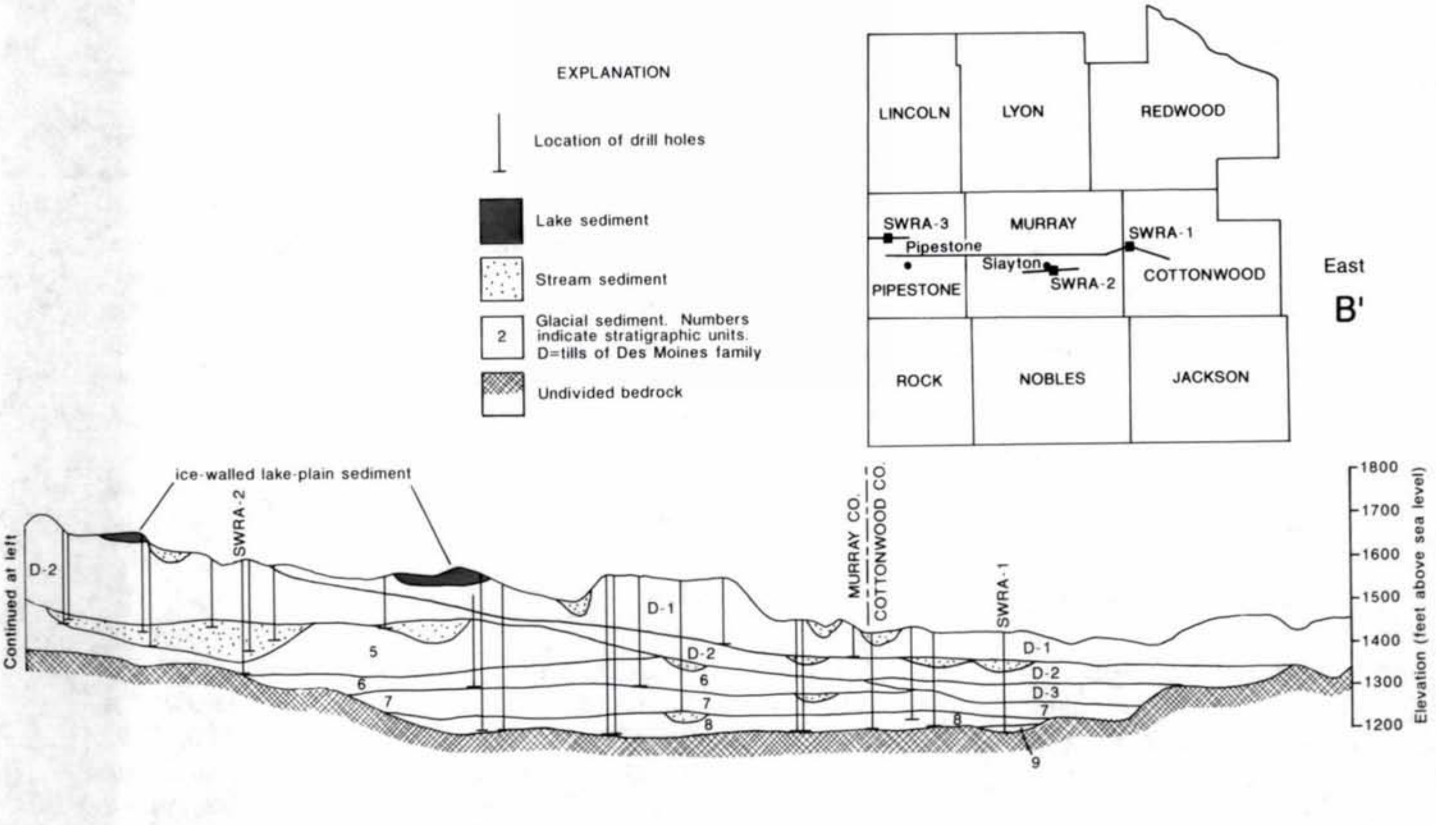
Figure 24. Generalized cross section through the central part of the study area. This section was created by combining information from three line segments indicated on the index map. All drill holes are located within one mile of the cross-section line. See the appendix for detailed information on the three test holes (SWRA-1, 2, 3).

Thus, although this till unit cannot be confidently correlated between holes MGS-2873 and SWRA-1 on the basis of magnetic signature, correlation is suggested by their similar grain-size distribution, lithology, and elevation.

Correlation of Early Glacial Deposits

By using till texture and lithology, tills in the study area can be correlated with tills that have been identified in eastern South Dakota (Table 1). The oldest known tills in the subsurface of South Dakota are similar to the oldest identified for this study in Minnesota. Unit 8 from this study (elev. 1184–1272 ft) resembles till C from drift complex 2 (Table 1; Qd2c, elev. 1245–1360 ft), identified in a core taken near Brookings, South Dakota (Gilbertson, 1990; Lineburg 1993; see Fig. 25b). This is a significant correlation because unit 8 appears to be magnetically reversed in Minnesota (it was not tested in South Dakota) and therefore is older than 788 ka B.P. Unit 9 is not well defined in Minnesota (only two available samples) and cannot be correlated with any tills in South Dakota.

The only till comparable to unit 7 is till D from drift complex 2 in South Dakota (Gilbertson, 1990; Lineburg, 1993). The South Dakota till is identified on the basis of two samples from an 11-foot core interval taken near Brookings and, in Minnesota, from four samples near the bottom of hole SWRA-1. The correlation appears weak but is stratigraphically logical if the stronger correlation of the underlying tills (unit 8 with till C) is considered. There is no obvious correlative of unit 6 in South Dakota.



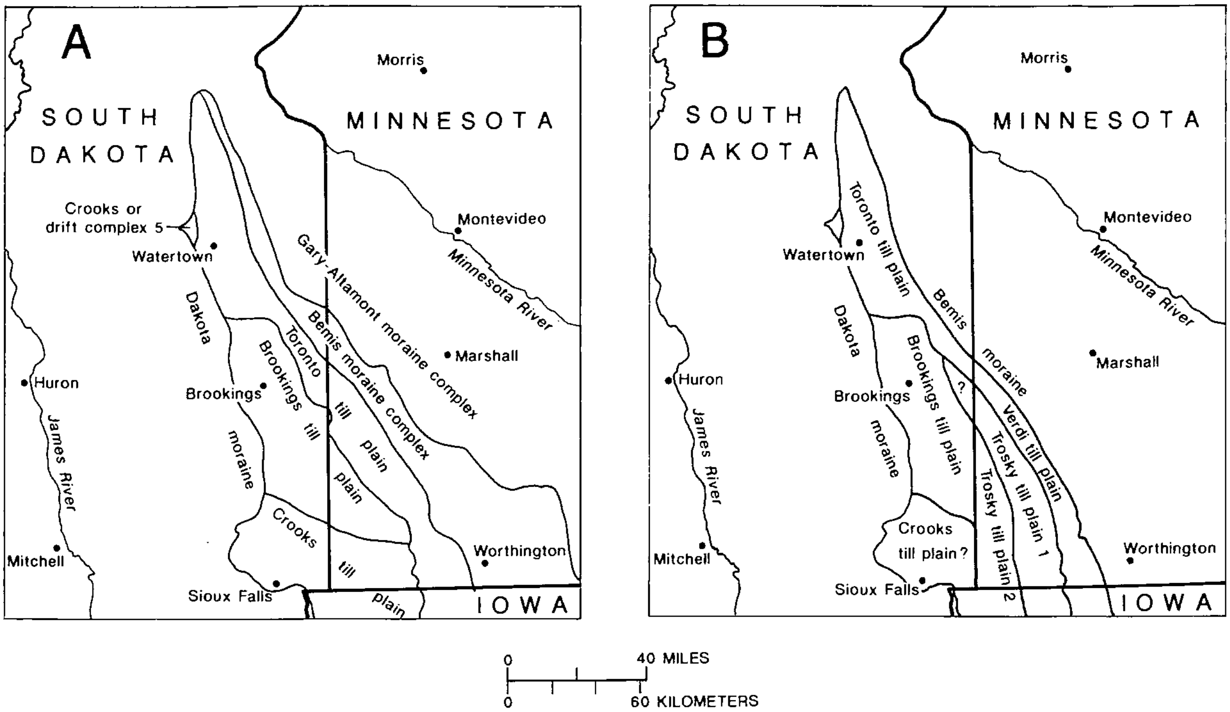


Figure 25. Revision of geomorphic regions of eastern South Dakota and southwestern Minnesota.

A. J.M. Lineburg's 1993 map is modified from Flint (1955), Steece and others (1960), and Gilbertson and Lehr (1989). It is inconsistent with recent mapping and stratigraphic work in Minnesota.

B. In the revision, the Toronto till plain is equivalent to the Verdi till plain, though the contacts are shifted in Minnesota. The area mapped by Lineburg as the Brookings till plain appears to be two tills in Minnesota. Both were included in the Trosky till plain because they are nearly indistinguishable in the field; the contact between them is approximate. The Crooks till plain is based on the recognition of morainic topography (Steece and others, 1960; Lineburg, 1993) that is here interpreted as a topographic high caused by selective preservation of coarse-grained sediments. It is unlikely that moraines of this age would be preserved. The unit in the study area closest to the Crooks till is unit 3, which is not exposed at the surface (Table 1). The eastern border for the Crooks till plain is therefore not in Minnesota.

Robust correlations can be made for units 2 through 5. Although unit 5 is encountered only in the subsurface in southwestern Minnesota (elev. 1465–1440 ft), it correlates closely with the Renner till, the oldest exposed unit in the Big Sioux drainage basin in South Dakota, where it is exposed at about 1460 feet above sea level. The Renner is not an extensive surficial unit but is visible in outcrops. Three exposures of the Renner described by Lineburg (1993) display 9–16 feet of dark gray till that is poor in Cretaceous fragments. Lineburg's fabric analysis of elongated clasts in the Renner shows predominantly northwest-southeast orientations. In all three exposures, the Renner is capped by a reddish clayey silt, which may be a paleosol; if so, it indicates deep weathering of the till.

Where exposed, the paleosol(?) developed in the Renner till is sharply overlain by 2–21 feet of Brandon till. The clayey Brandon, rich in Cretaceous fragments, correlates closely with unit 4 (this study). Gilbertson (1990) included the Brandon till in drift complex 3. Fabrics are strong in this till and indicate an ice advance from the north-northeast (Lineburg, 1993).

Table 1. Proposed correlation of glacial units in southwestern Minnesota with those in adjoining areas of South Dakota.

[Sample sources are surface, (s), and core, (c); NA, not applicable. Matrix texture is expressed as a cumulative percentage of sand-silt-clay. Lithology of the coarse (1–2-millimeter) sand fraction is expressed as a cumulative percentage of Precambrian-Paleozoic-Cretaceous rock types. See appendix for detailed logs of the three Rotasonic test holes (SWRA-1, 2, 3) and MGS-2873.]

SOUTH DAKOTA								SOUTHWESTERN MINNESOTA											
Lineburg (1993)				Gilbertson & Lehr (1989); Gilbertson (1990)[1]				SWRA-3 & nearby surface samples				SWRA-2				SWRA-1			
Till	No. of samples (sample source)	Matrix texture	Lithology	Till	No. of samples	Matrix texture	Lithology	Till	No. of samples (sample source)	Matrix texture	Lithology	Till	No. of samples (sample source)	Matrix texture	Lithology	Till	No. of samples (sample source)	Matrix texture	Lithology
New Ulm[2,3]	59 (s)	32-35-33;	38-38-31	**New Ulm**[2,3]	131	34-32-34;	50-22-28									**D-1**[2,3]	5 (c)	36-38-24;	47-32-30
												D-2a[2,3]	4 (c)	34-34-30;	53-27-19	**D-2**[2]	1 (c)	30-33-35;	53-30-17
												D-2b[2,3]	3 (c)	38-35-25;	57-27-15				
Toronto II[3]	18 (s)	22-42-35;	42-39-20	**Toronto**[3]	27	28-38-33;	55-28-17	**tv**[3,7]	13(s)	31-40-31;	42-35-22					**C-3**[2]	2 (c)	36-39-24;	46-31-23
Toronto I[3]	11 (s)	22-44-34;	42-37-21																
								1[3,8]	4 (c)	19-48-32	46-47-8								
								1[3,8]	7 (s)	28-44-31;	45-41-13								
Qd5[3,4]	28 (c)	33-28-31;	60-25-14	**Drift Complex 5**[4]	NA	NA	NA	**2**[3,4]	35 (s,c)	35-32-33;	73-21-4								
								2[3,4]	5 (c)	18-42-39;	61-30-9								
Crooks[3,4]	65 (s)	28-30-42;	64-21-16	**Drift Complex 4**[3,4,6]	NA	NA	NA	**3**[3]	5 (c)	25-33-41;	61-19-20								
Crooks[3,4]	7(c)	32-28-40;	67-19-14																
dated ash layer																			
Brandon[5]	10(s)	25-39-36;	49-27-34	**Drift Complex 3**	NA	NA	NA	**4**[3]	6 (c)	19-29-51;	43-26-31								
Brandon[5]	18 (c)	17-26-57;	49-31-20																
Renner[3,4]	18 (s)	32-37-31;	55-42-3	**Drift Complex 2**	NA	NA	NA	**5**[9]	5 (c)	29-37-32;	55-41-5								
Renner[3,4]	7 (c)	21-31-41;	57-41-2					**5**	5 (c)	16-43-39;	57-37-5	**5**	1 (c)	26-37-36;	53-42-5				
												6	3 (c)	37-43-18;	60-29-12				
Qd2d[3,4]	2 (c)	23-37-40;	56-41-3	**Drift Complex 2, Till D**	NA	NA	NA									**7**[3]	4 (c)	29-35-35;	50-47-3
Qd2d[3,4]	6 (c)	26-36-38;	51-37-13	**Drift Complex 2, Till C**	NA	NA	NA	**8**[10,11]	6 (c)	23-40-37;	49-29-20					**8**	4 (c)	24-41-34;	45-32-24
																9[3]	2 (c)	19-41-39;	56-42-1

[1] Gilbertson and Lehr (1989) and Gilbertson (1990) did not calculate average values for matrix texture and rock type for individual tills within drift complexes 2–5.

[2] Des Moines family of tills.

[3] Oxidation marks top.

[4] Paleosol.

[5] Beneath volcanic ash dated at 610–740 ka B.P.

[6] Also includes Big Sioux & Hartford tills.

[7] Surface sample east of hole.

[8] 10-Beryllium dating of striated bedrock at surface: ≥600 ka B.P. Striae assumed coeval with till 1, but this cannot be proved.

[9] Supraglacial sample.

[10] Magnetically reversed.

[11] Cored interval from MGS hole 2873.

A volcanic ash dated at 610 ka B.P. (Izett, 1981, as reported by Lineburg, 1993) is stratigraphically above the Brandon till. This is an important age constraint that requires the overlying units (1–3 in this study) to be younger than 610 ka B.P. Minnesota units 4 and 5 (correlative with the Brandon and Renner, respectively) and unit 7 have normal paleomagnetic signatures (as determined for this project), making them 610–788 ka B.P. (accepted age for the Brunhes-Matuyama reversal).

Two South Dakota tills (Hartford and Big Sioux) that overlie the ash in Lineburg's scheme (1993) have not been identified in southwestern Minnesota (Table 1).

The next younger correlatable unit is the Crooks till (Lineburg, 1993), part of drift complex 4 of Gilbertson (1990). This till is commonly exposed at the land surface in South Dakota at elevations of 1557–1570 feet (1520–1580 ft in a core from the Brookings area). The only comparable till in Minnesota—unit 3—is restricted to the subsurface (elev. 1605–1665 ft) (Table 1). In South Dakota, the upper contact of the unit is commonly a sharp deflation surface. A possible soil developed in the Crooks till may be Sangamon in age (Lineburg, 1993). Fabrics, which are weak to nonexistent in the till, suggest an advance from the north-northeast. This till supposedly underlies the "Crooks Till Plain," originally defined by Steece and others (1960) (Fig. 25a). The geomorphic designation may have merit in South Dakota, but if the proposed correlation of the Crooks till with unit 3 is correct, the till is not at the surface in Minnesota, and the soil is likely older than Sangamon.

Textures for the oldest till at the surface in Minnesota, unit 2, compare very closely with those of drift complex 5 in South Dakota (Gilbertson, 1990) (Table 1). Drift complex 5 (Qd5) was defined in South Dakota mainly from core taken near Brookings (elev. 1580–1650 ft) and Watertown (elev. 1655–1709 ft) (Fig. 25b). A very small area at the surface in central Codington County, northeastern South Dakota, has also been identified as till of drift complex 5 (Fig. 25a) (Gilbertson and Lehr, 1989; Gilbertson, 1990; Lineburg, 1993). As is the case with unit 2 in Minnesota, a paleosol, generally loess-covered, was found at the top of drift complex 5.

There is no counterpart for till unit 1 in the stratigraphic framework for South Dakota (Table 1). The orientation of the border of this till sheet in Minnesota (Trosky till plain border; Fig. 25b) makes the occurrence of this till in large areas of South Dakota unlikely.

Till of the Verdi phase of the Des Moines lobe as defined in Minnesota correlates closely with the Toronto till in South Dakota (Table 1). Textures, lithology, and, more importantly, geomorphology and continuity allow a robust correlation of these tills. However, it is difficult to distinguish the tills from the rest of the Des Moines family of tills using textural and lithologic data alone.

As proposed here, units 1, 2, and 3 are younger than the 610 ka B.P. ash found in South Dakota, and units 5, 6, and 7 are younger than the last magnetic reversal at 788 ka B.P. Only units 8 and 9 may be older than 788 ka B.P. These rough age assignments are consistent with current understanding, based on oxygen-isotope records in ocean sediments, of the history of Pleistocene glaciations. The largest ice volumes indicated during the Pleistocene glaciation were in the last 700 ka B.P. (isotopic stages 2, 6, 12, and 16; Broecker, 1995).

LATE GLACIAL DEPOSITS

The most recent glacial deposits in the study area are Wisconsin in age and represent the late-glacial fluctuations of the Des Moines lobe. Technically, the earliest advance of ice along the trajectory of the Des Moines lobe was not the advance that reached the 14 ka B.P. ice margin at Des Moines, Iowa. The early advance was less extensive but broader; it was mostly covered by till of the Bemis phase. In this report, this early advance is named the Verdi phase of the Des Moines lobe after a town near the margin in Lincoln County (Figs. 1, 26).

Verdi Phase of the Des Moines Lobe

There is clear geomorphic evidence for the Verdi phase of the Des Moines lobe. Deposits of this phase have been called Iowan, Tazewell, extramorainic shale-bearing drift, and Toronto till (Leverett and Sardeson, 1932; Ruhe, 1950; Matsch, 1972; Gilbertson, 1990, respectively). The till is very similar in texture and lithology to the Late Wisconsin suite of Des Moines tills and is most likely included in the New Ulm Formation of Matsch (1972). The Verdi phase is an earlier advance along the same general flow path as followed by the Des Moines lobe. Radiocarbon dates of 20–30 ka B.P. are reported for this till:

Clayton and Moran (1982)	20,670 ± 1,500–1,000 yr B.P.
Beissel and Gilbertson (1987)	26,150 ± 3,000–2,000 yr B.P. 22,900 ± 1,000 yr B.P.
Gilbertson (1990)	29,910 ± 1,100 yr B.P.

The southerly limit of the Verdi-phase ice may be just south of the Minnesota-Iowa border. At this approximate latitude a reentrant on both the west and east sides of the Bemis moraine reflects a constriction of the ice flow (Fig. 26). No topographic obstacle exists today to explain such a change in ice flow. An ice-cored moraine of the Verdi phase of the Des Moines lobe could have caused the constriction. The Verdi phase may correlate with the Moland margin (Fig. 26), which was identified in Rice County on the eastern side of the lobe (Patterson and Hobbs, 1995).

A significant retreat of the Verdi phase of the Des Moines lobe apparently occurred before the 14 ka B.P. advance to the Bemis moraine. In northern Iowa the stratigraphy clearly records a time of surface exposure of the Tazewell till (Verdi phase) (A. Bettis, Iowa Dept. of Nat. Resources, oral commun., 1995). Moreover, eolian deposits in southeastern Minnesota would have required a material source area and an upwind fetch in order to develop (Mason and others, 1994; E. Nater, Univ. of Minn., oral commun., 1994).

Verdi-phase outwash stream channels, which are clearly evident on topographic maps, were commonly reused by later Bemis-phase meltwater streams. The Verdi-phase sediment is generally more strongly iron stained than younger outwash, and carbonate pebbles are commonly coated with a thick rind of manganese and iron.

Bemis Phase of the Des Moines Lobe

Radiocarbon dates for the Bemis moraine in Iowa suggest that the maximum of the Bemis-phase ice was approximately 14 ka B.P. (Clayton and Moran, 1982; Hallberg and Kemmis, 1986). The margin of the Bemis phase of the Des Moines lobe is a prominent moraine in the northwest part of the map area (Fig. 13); it becomes broader and lower southward. The moraine contains a mixture of material deposited along the ice front, which may include supraglacial and proglacial sediments, as well as subglacial sediments pushed to this position. The principal sediment in the moraine is yellow-brown to gray diamicton with a clay-loam matrix texture. In places, especially on the distal side of the moraine, lenses of sand and gravel occur in amounts that are significant but unmappable owing to their unpredictable distribution. A broken linear ridge along parts of the moraine may represent the crests of thrust sheets, which are common in other well-formed push moraines.

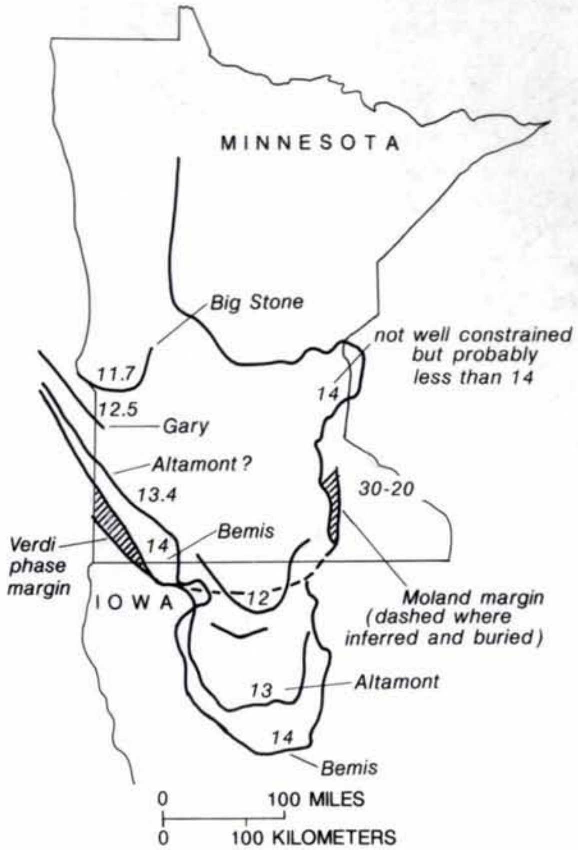


Figure 26. Late Wisconsin phases of the Des Moines lobe. Ages of ice margins are in thousands of radiocarbon years. Note the reentrant in the margin on the west side of the lobe in Iowa. Adapted from Kemmis (1991).

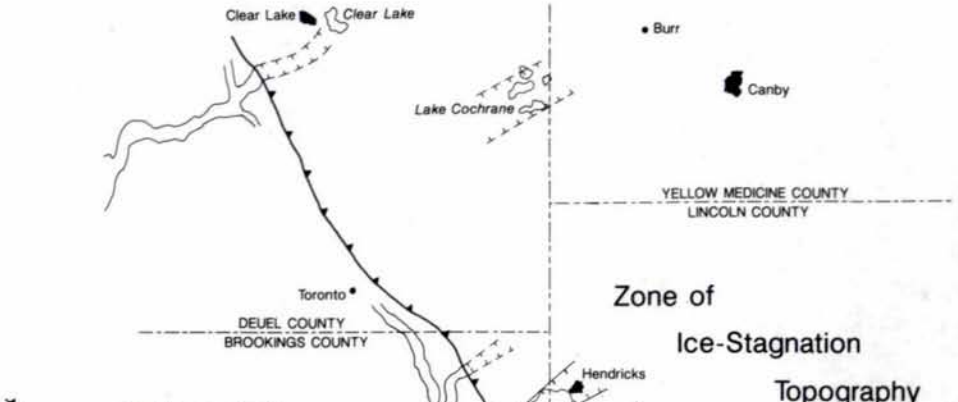


Figure 27. Tunnel valleys and major outwash streams along a segment of the Bemis moraine in Minnesota and South Dakota. Subglacial streams breached the Bemis moraine in several places. Lakes Hendricks, Shaokatan, and Benton occupy linear troughs that are interpreted as tunnel valleys. The major outwash streams began where the tunnel valleys discharged.

The Bemis moraine is interrupted in several places by glacial stream channels that are interpreted to be subglacial tunnel valleys (Fig. 27). The channels are as wide as one mile, extend on the up-ice side of the moraine for generally less than six miles, and have straight-sided flanks. Farther up-ice they disappear in the hummocky stagnation topography, perhaps because the channels were buried or because the drainage system became distributed and (or) englacial. The presence of eskers in some channels lends weight to the interpretation of their subglacial origin. Major outwash streams began where these streams discharged from the ice (Fig. 27).

As Bemis-phase ice retreated slightly from the moraine, meltwater flowed from northwest to southeast between the moraine and the ice. Channel scarps are clearly visible on aerial photographs, and minor concentrations of sand and gravel occur in this area of washed till. The dynamic environment between the retreating ice and the moraine could have led to local ponding of meltwater, but no thick or continuous lake sediment was mapped in this position.

Younger Phases of the Des Moines Lobe

Inside the Bemis moraine of the Des Moines lobe are younger supraglacial and subglacial deposits created by a fluctuating ice lobe. The abundance of hummocky supraglacial deposits suggests that the lobe repeatedly advanced into stagnant ice, emplacing debris on the surface of the old ice. Ice-marginal bands of hummocky topography in the area have been called moraines; the Altamont moraine, Gary moraine, and Big Stone moraine are examples. However, these broad belts of hummocky stagnation topography represent the contact between active ice and stagnant ice and are not typical end moraines. In consideration of this ambiguity, they will herein be referred to as "moraines."

In the central part of the lobe, these stagnation complexes are distinct, but along the flanks of the lobe they merge. The Altamont "moraine" is dated at about 13.4 ka B.P.; by approximately 12.5 ka B.P. the ice was at the Gary "moraine;" at 11.7 ka B.P. it was at the Big Stone "moraine." Thereafter, Glacial Lake Agassiz formed in the northwestern part of the basin of the Des Moines lobe and existed from 11.7 to 9.5 ka B.P. (Gilbertson, 1990).

Several more stagnant ice–active ice positions were mapped by Leverett and Sardeson (1932) (Fig. 28) between the Altamont and the Gary margins than have been identified on recent maps (e.g., Hobbs and Goebel, 1982). The stagnation topography has low relief, which may explain in part the lack of consistent mapping. In some places the position is only represented by ice-marginal stream channels. The

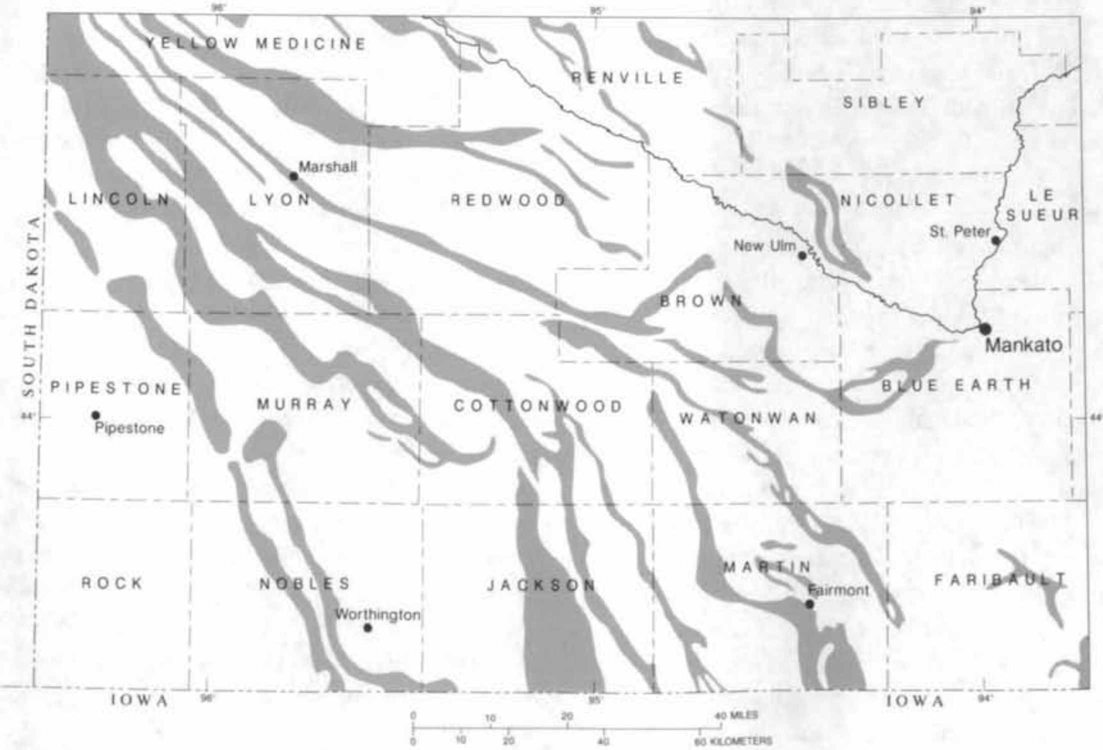


Figure 28. Terminal moraines of Keewatin ice in southwestern and south-central Minnesota as mapped by Leverett and Sardeson in 1932. Their surficial geologic map shows more margins of the retreating Des Moines lobe in southern Minnesota than are typically reported. In particular, the margins near the Minnesota River Valley are marked by low-relief stagnation deposits and ice-marginal streams. Adapted from Leverett and Sardeson (1932).

ideal place to identify these ice positions is near the former center of the lobe, but this study area is located along the west flank, where the lateral stagnation margins converge. Interpretation from aerial photographs of the area near the center of the lobe should help to delineate these margins.

At least two stagnation margins on the Coteau coalesce in the north but diverge to the south near Heron Lake (Fig. 5). A glacial lake impounded here was probably restricted by stagnant ice to the west and southwest and by active ice to the east and northeast. It was fed by ice-marginal streams flowing southeast along the flank of the lobe (Patterson, 1995).

Throughout the region of stagnation topography on the Coteau there is a general pattern of drainage to the southeast, parallel to the former ice margin, and to the northeast, down the regional slope. The stream sediment is uncollapsed where water cut through the stagnant ice to the bed. In many areas, however, the stream sediment is collapsed. Some streams show a complex chain of uncollapsed stream sediment or stream-eroded till (grounded stream), collapsed stream sediment (flowing on the ice), and collapsed till (stream flowing under the ice and stream sediment obscured by hummocky till), indicating the tortuous path through the changing stagnant-ice landscape.

The hummocky supraglacial deposits are mainly till-like, although textures vary significantly, presumably owing to sorting in the supraglacial environment. Saturated debris on stagnant ice may be remobilized a number of times as the ice thins differentially. Water that is ponded on the stagnant ice, or that reflects a water table in the ice, offers an environment in which sorted lake sediment can accumulate in a supraglacial or ice-walled environment. Flat-topped circular hills with no recognizable lake sediment at the surface resemble ice-walled-lake plains in form. These landforms probably had a similar origin in holes in stagnant ice, the only difference being the depth of water in the ice-walled depression.

The flat-topped circular hills seem to line up along a northwest-southeast trend. For example, a string of circular flat-topped hills follows the trend of collapsed till along an ice margin near Dovray (Fig. 29). This line of hills may overlie the path of a subglacial stream that later collapsed, forming circular depressions in the ice. Such holes can fill with a variety of sediment depending on what is on the ice surface and how much water is available for sorting. At least one of these plains is predominantly sand. Sinkholes in a karst landscape are preferentially located near bluffs (Thornbury, 1958, p. 318), where potential gradients for ground water are steepest. Similarly, there may be a limit to how far beyond the stagnant ice front the subglacial drainage system is effective. Such a limit could lead to a higher density of well-developed ice-walled-lake plains near the ice margin. Whatever the mechanism, the concentration of well-developed ice-walled-lake plains along the ice margin is real.

The final stages of ice disintegration produced shallow lake basins that resemble thaw lakes in a permafrost environment. Some ice-disintegration basins contain lake sediment, and some would contain lakes today had they not been drained. The shallow (generally less than 10 feet deep) lakes are rounded depressions having the same or smaller diameter as ice-walled-lake plains, among which they are found. Because the origin of these shallow lake basins appears to be related to the final stage in the disintegration of the stagnant ice, they are unrelated to true permafrost-thaw lakes, which originate in unglaciated permafrost areas. The similarity in form is noted, however, because an erroneous interpretation of climate could be made by assuming that the presence of the shallow lake basins required permafrost conditions, reflecting the ambient subfreezing climate, rather than debris-covered stagnant ice, which need not be in equilibrium with the ambient climate.

The slope of the Coteau is probably an erosional feature that developed in the subglacial environment during repeated advances of the Des Moines lobe. The transition from supraglacial to subglacial environments is along this slope. The till at the surface is texturally and mineralogically very similar to the subglacial till, and also to the *average* supraglacial till in the hummocky highlands. The large, streamlined features oriented northwest-southeast resemble bars and some channel scarps; they may have been created by water flowing beneath the margin of the ice lobe or at the edge of the ice (Fig. 10). However, the main features mapped on this slope are channels of streams that flowed to the northeast, directly downslope, after the area was deglaciated (Fig. 15). The streams west of Marshall created fans at the base of the Coteau slope. Lake sediment found there reflects a short-lived ponding of water between the Coteau and the ice.

Figure 29. The Dovray hills in Murray County are part of a string of generally circular, flat-topped hills oriented northwest-southeast. The hills are on both sides of the town of Dovray, although only the northwest segment is shown. The ice margin at the time of the hills' formation was likely less than two miles to the southwest. Drilling records and seismic work on one of the hills west of Buffalo Lake suggest that it is predominantly sand. From U.S. Geological Survey 7.5-minute series (topographic), Dovray quadrangle, Minn., 1967; contour interval 10 feet.

Leverett and Sardeson (1932) mapped a moraine at Marshall (Fig. 28). Although there is no clear geomorphic evidence for a moraine here, modern and glacial stream channels parallel what may have been a margin. The glacial streams were probably located in a topographic low between the base of the Coteau and the wasting ice. The abrupt beginnings of these glacial channels probably represent positions from which supra- and subglacial water issued. The streams can be traced into Glacial Lake Minnesota and thus outline a phase of the Des Moines lobe that terminated near Mankato (Fig. 30). Areas of stagnation topography north and south of New Ulm may represent the terminus of this phase of the lobe.

In the northeast corner of the study area (the Marshall till plain), subglacial till of the Des Moines lobe is at the surface or thinly buried (Fig. 10). The area is flat except for low linear ridges parallel and are transverse to former ice flow (Fig. 16). Ridges parallel to ice flow—and therefore to the ice-surface slope—are predominantly composed of sorted sediment, an indication that they represent deposits of streams that flowed on, in, or under the ice. Some channels terminate in small fans or begin in small kames. Others merge with larger streams that were initially supraglacial but eroded through the stagnant ice and into the substrate. This left ridges of collapsed stream sediment that join incised channels filled with uncollapsed stream sediment (Fig. 31).

The transverse ridges are composed of sediment ranging from diamicton to sand and gravel. Most of the sampled transverse ridges were only slightly coarser and more sorted than the underlying and surrounding till. The ridges are interpreted to be a result of deposition localized in crevasses (Fig. 32). The crevasses may have carried streams for part of their length but were mainly not water filled.

Both the transverse and flow-parallel ridges are common in the central part of the lobe and have been interpreted in a variety of ways (Beaudry and Prichonnet, 1991; Fisher and Shaw, 1992; see Kemmis and others, 1981, for a summary of theories). That the ones in the study area have a supraglacial component is supported by the gradual change in landform from linear transverse ridges in the center of the lobe to strings of transversely elongated, ice-stagnation doughnuts, and, finally, to unelongated doughnuts, which are definitely a supraglacial landforms.

The total thickness of glacial sediment in the Marshall till plain is generally less than 50 feet, compared to over 400 feet in the area of ice stagnation (hummocky highlands). In addition, the stratigraphy

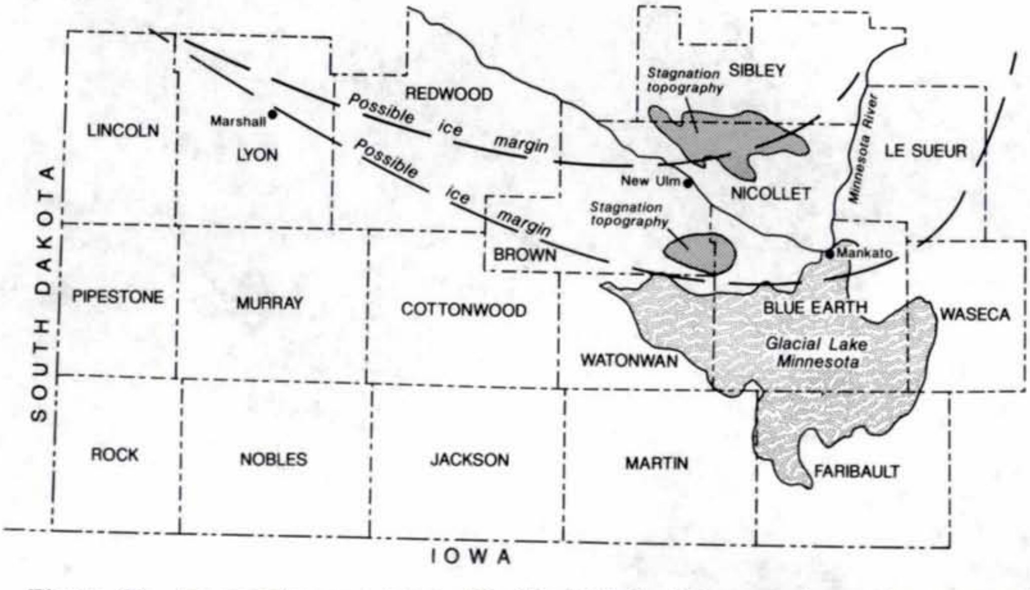


Figure 30. Ice margins associated with Glacial Lake Minnesota in southwestern and south-central Minnesota. Ice-marginal streams that begin near Marshall outline a phase of the Des Moines lobe that terminated near Mankato and likely fed Glacial Lake Minnesota. Modified from Patterson and Hobbs (1995).

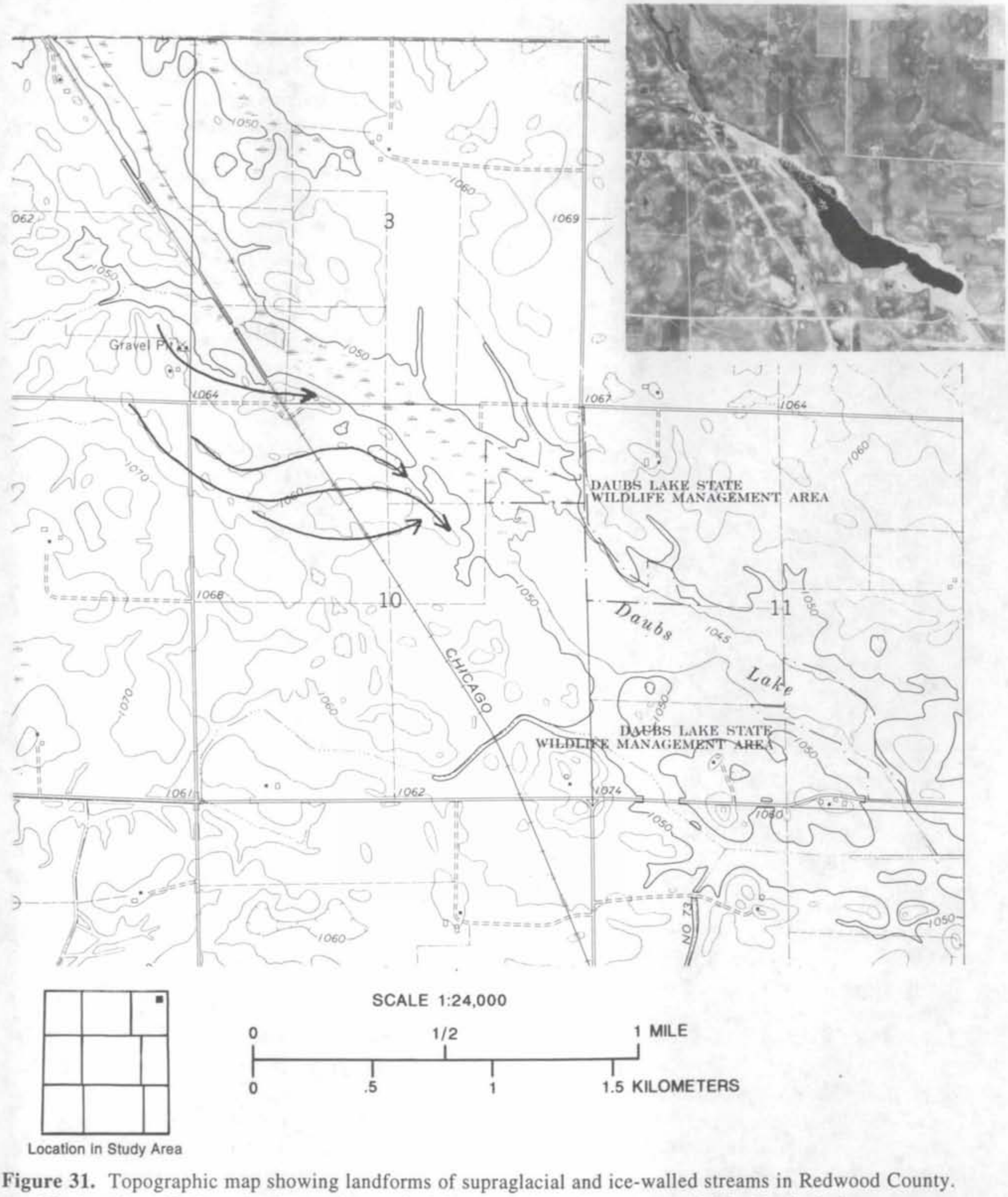


Figure 31. Topographic map showing landforms of supraglacial and ice-walled streams in Redwood County. The location of tributaries (arrows) to a glacial stream channel, now occupied by Daubs Lake, are represented by ridges of collapsed stream sediment. The ridges—which are not obvious on the topographic map—show as curved lighter toned lines on the inset aerial photograph of approximately the same area. Apparently the streams represented by the collapsed sediment flowed on the surface of the ice, whereas the stream in the Daubs Lake channel melted through the ice and eroded a channel in the substrate. From U.S. Geological Survey 7.5-minute series (topographic) Wabasso quadrangle, Minn., 1967; contour interval 10 feet. Aerial photograph (BIK-667, strip 9, 4-30-68) by Mark Hurd, Aerial Surveys, Minneapolis, Minn.

Figure 32. Heavily crevassed, post-surge ice surface of the Bering Glacier, Alaska. Photograph reproduced with the permission of B. Molnia.

in the Marshall area indicates that far fewer till units are preserved there. This, combined with the general trough shape of the lowland, leads to the interpretation that the lowland was created by glacial erosion associated with the multiple advances of the Des Moines lobe. Much of the material that was eroded may have moved only a short distance—perhaps to a supraglacial position along the margins of the lobe. The subglacial erosion was progressively less effective down-ice; the stratigraphy is better preserved and the total thickness of glacial sediment is greater to the south.

INTERPRETATION OF GLACIAL DYNAMICS

The exemplar of a valley glacier has an accumulation area, ablation area, and an equilibrium line and advances in response to a net increase in accumulation. Neither the Des Moines lobe nor any of the other lobate projections of ice along the southern Laurentide Ice Sheet appears to fit this model. The Des Moines lobe repeatedly advanced and stagnated; therefore, the concept of steady advance in response to accumulation seems irrelevant.

The Des Moines lobe was most active during a very warm period of general ice wastage in the Laurentide Ice Sheet. Oxygen-isotope records indicate that at this time the ice sheet had already lost 50 percent of its volume (Dyke and others, 1989). The lobe advanced not in response to an increase in accumulation but despite decreasing ice volume. Ruddiman and McIntyre (1981) suggest that because there was relatively little recession of the ice margin from 15 to 13 ka B.P., the period of the halving of Laurentide ice volume, deglaciation probably began with drawdown of the Laurentide Ice Sheet, mainly by drainage through Hudson Strait. Unstable advances of southern Laurentide ice lobes (including the Des Moines and James lobes) would be consistent with the general deglaciation picture, i.e., that the entire ice sheet was collapsing and a marine terminus was not necessary for drawdown.

Each successive advance of the Des Moines lobe after the Bemis phase was less extensive than the preceding one, suggesting that the area of the ice sheet that the lobe was draining was being drawn down. The ice may never have actively retreated from any of these advance positions, but stagnated and downwasted. The stagnant ice was then reactivated and possibly overridden by a reinvigorated lobe. This mechanism is hypothesized to have emplaced the great thickness of sediment on the ice necessary to create ice-walled-lake plains and stagnation hummocks over 50 feet high. It is also consistent with the stagnation zones being located within, but not at, the Bemis moraine.

Previous hypotheses for the emplacement of thick supraglacial debris relied on compressive forces to create shear planes within active ice as it advanced against a topographic obstacle, e.g., the James lobe advancing against the Missouri Coteau (Clayton, 1967). This emplacement mechanism is untenable for areas like the eastern margin of the Des Moines lobe that had no such relief. Furthermore, the frequently suggested existence of thrust planes in active ice in these hypothetical zones of compressive flow may be based on misinterpreted field evidence. The debris bands (usually referred to as thrust planes) that shear debris to the surface of the ice may be merely foliation planes (possibly resulting from basal freezing-on of debris) that have been rotated in response to the cumulative strain in the ice. Near the surface at the margin this can cause a steep dip up-glacier (Hooke and Hudleston, 1978; Hudleston, 1992). However, the dip decreases rapidly with depth (Hooke, 1973). Though the differential movement apparently can occur along these foliation surfaces at temperatures close to the melting point (Brugmann, 1988), the amount of debris delivered to the glacier surface in this way is likely to be small, particularly in areas approximately more than a half mile from the margin. Proposed thrusting of material in active ice along debris bands is therefore not a viable mechanism for emplacing debris on the surface of the Des Moines lobe.

Glacial Surges

Many features of the Des Moines lobe resemble those created by surging glaciers (Wright, 1980; Clayton and others, 1985), and the dynamics may be similar. An issue of the *Canadian Journal of Earth Sciences* (Ambrose, 1969) contains papers from two scientific meetings that were held during a period of intense research on glacier surges. In the discussion that follows some of the papers are cited, but the general observations are common to many. The phenomena associated with surging glaciers are described to present a picture of the possibilities for the Des Moines lobe.

A glacier surge involves a transfer of ice from a reservoir to a receiving area; both of these regions may lie within what is conventionally defined as the ablation area (Hattersley-Smith, 1969; Meier and Post, 1969; Muller, 1969). The ice in the reservoir may develop a prominent bulge before a surge (Meier and Post, 1969). The transfer of ice is abrupt, with velocities of as much as one kilometer (0.62 mi) per year. Particular ice-surface features can be tracked during the propagation of a surge. In the Steele Glacier surge (1966–67) in the Yukon Territory of Canada, tracking of surface structures on the surging ice indicated little transverse or vertical displacement, suggesting that the ice was moving as a unit (Stanley, 1969). The displacement of the terminus associated with the transfer of ice is not equivalent to a glacier retreat and readvance. There is no net change in ice volume; the ice simply is relocated, though to an area where ablation rates may be higher (Thorarinsson, 1969). Usually little or no net advance occurs in surging glaciers because a similar volume of ice is required to trigger the instability that results in each successive surge (Robin, 1969). Ice in the surge behaves brittlely and is heavily crevassed with intricate patterns of intersecting crevasses (Meier and Post, 1969) (Fig. 32). The advance is erosive (Rutter, 1969) and surging glaciers may leave a spoon-shaped depression in the substrate (Thorarinsson, 1969). Subglacial water is a likely agent in the initial propagation of a surge, and the frictional heat of rapid ice flow can melt more ice, thus possibly sustaining the surge (Weertman, 1969). The end of a surge may be accompanied by large discharges of subglacial water that can issue from the ice front in jets (Weertman, 1969; Molnia and others, 1994a; Paterson, 1994).

After the surge, the ice in the receiving area stagnates. Well-engraved surface drainages develop on the stagnant ice (Hattersley-Smith, 1969; Thorarinsson, 1969). Subsequent surges into a stagnant terminus result in buckling and fracture of the stagnant ice (Stanley, 1969; Raymond and others, 1987). Active ice may override the stagnant terminus and emplace subglacial debris on the stagnant ice. Ice-marginal sediment is also commonly sheared in imbricate thrust planes (Thorarinsson, 1969). In rare instances, lobes may surge over other lobes (Nielsen, 1969) or be redirected by the presence of stagnant ice (Field, 1969).

Ice Streams

Fast-moving outlet glaciers or ice streams may be more aptly compared to the Des Moines lobe because they are of a similar scale and because the duration of the fast flow in an ice stream is hundreds of years rather than a couple of years, as in a surge. Ice streams and some outlet glaciers have been hypothesized to move using the same mechanism as surging glaciers, the only difference being the length of time that the fast flow is sustained (Weertman, 1969). The issue is still debated, though. The West Antarctic ice streams flow rapidly (0.3–2.3 meters [11.8–90.6

in] per day) *within* the slower moving ice of the West Antarctic Ice Sheet (Engelhardt and others, 1990). The streams, which are 300–500 kilometers (186–311 mi) long and 30–80 kilometers (19–50 mi) wide, drain an "ice shed" about one third the size of the West Antarctic Ice Sheet (Paterson, 1994, p. 308). Most flow is along lows in the ice surface and bed (Shabtaie and others, 1987), and the ice eventually discharges into the Ross Sea to create the Ross Ice Shelf. The troughs that these and other ice streams occupy can be well below sea level (Paterson, 1994).

The West Antarctic ice streams apparently switch on and off (Paterson, 1994). This is difficult to document, however, because of the long period of activity. The mechanism for switching off an ice stream may be the capture of its drainage area by another ice stream (Rose, 1979).

Discharge of Ice Streams on Land

Ice streams similar to those in West Antarctica formed within the Laurentide Ice Sheet in an area where they discharged onto land rather than into the sea, thus creating the ice lobes along the southern margin of the Laurentide. In this hypothesis, the high water pressures that allowed the ice to stream within the Laurentide also allowed the outlet glacier to flow at a similar rate, but only for as long as the subglacial water pressures could be maintained. The initial advance of such an ice-stream-fed lobe would result in "normal" end moraines. After a period of ice-stream inactivity, subsequent periods of ice-stream activity could result in ice-stagnation topography if ice from the previous surge remained in the landscape. Thus, each stagnation complex of the Des Moines lobe may represent the decay from a period of ice-stream activity spanning hundreds of years, followed by a period, several hundred years long, of ice-stream inactivity. Successive advances would be shorter because the ice sheet was being drawn down. No active retreat of ice is required in this model.

If the conditions for fast glacier flow develop at the base of thick ice and involve (1) decreased viscosity of basal ice, (2) pressure melting, which enhances sliding, and (3) bed deformation, as previously hypothesized (Paterson, 1994), then the flow of ice should be sustained regardless of the disposition of the discharged ice. The question is how much back pressure is exerted on an ice stream by the discharged ice? If the back pressure is not enough to shut down the ice stream, then ice streams can develop as easily in continental positions as in tidewater locations. The continued movement of the lobate projection of ice issuing from the ice stream depends on the maintenance of the subglacial conditions required for fast glacier flow—most likely, high water pressures.

Pervasively deforming, saturated subglacial sediments that have porewater pressures very close to the ice overburden pressure are said to result in fast glacier flow (Alley, 1991; Clark, 1992). Alternatively, high-water-pressure events are said to decouple the glacier from the bed, thus allowing rapid flow (Iverson and others, 1995). In either case, high subglacial water pressures are key. In both models rapid movement is sustained only for as long as the water pressures are maintained. If a channel system developed that could effectively drain the subglacial system, then rapid movement would cease.

Tidewater ice streams have been proposed as the major drainages for the Laurentide Ice Sheet in Hudson Strait (Laymon, 1992), St. Lawrence Strait (Ocheitti, 1989), and Prince of Wales Island (Dyke and Morris, 1988). However, as noted above, ice streams need not be restricted to these areas, because the conditions required for them to form develop within the ice sheet, not at the margin. The floating margin simply allows for quicker removal of the discharged ice. In a land-based part of the Laurentide Ice Sheet, such as in Ontario east of Lake Nipigon, a plume of exotic, thick, fluted till within a region of thin, local tills has been interpreted to be a deposit of such an ice stream (Thorleifson and Kristjansson, 1993). Several plumes of fine-grained carbonate till that extend beyond the Paleozoic outcrop region surrounding Hudson Bay into the area underlain by crystalline bedrock to the west and south are also interpreted to have "formed beneath ice streams near the margin of the Laurentide Ice Sheet under conditions of rapid ice flow and enhanced debris transport" (Hicock and others, 1989).

The dynamics of the southern Laurentide lobes is similar to that of ice streams—they started and stopped on a time scale of hundreds to thousands of years. Some lobes, such as the Des Moines and James, maintained for a longer time the requisite conditions for fast flow, probably because of their clay-loam substrate (Clayton and others, 1985; Clark, 1992), and they advanced for hundreds of miles beyond the ice-sheet margin. But when the basal water left the system, perhaps fairly abruptly by way of the tunnel valleys that are recognized at all of the Des Moines lobe margins in Minnesota, the drained marginal ice stagnated.

To further test this hypothesis one must look for evidence of an ice stream up-ice from the Des Moines lobe. The Winnipeg lowland, a topographic low in the bedrock and in the reconstructed ice surface (Fisher and others, 1985), is directly up-ice from the Des Moines lobe in a likely position for an ice stream (Fig. 33). The region is midway between the Keewatin and Hudson ice centers and could have been the location of a major ice drainageway. Most of the erosion of the Lake Winnipeg basin was late-glacial, which is consistent with an ice stream being located here (L.H. Thorleifson, oral commun., 1995). The herein-named Winnipeg ice stream appears to have been active in this ice shed until the separation of the ice centers, as inferred by the pattern of ice retreat (Dredge and Cowan, 1989) (Fig. 33). Further evidence for fast glacier flow along this trajectory is a large surge that is inferred to have occurred during deglaciation along the Lake Winnipeg lowland (Dredge and Cowan, 1989).

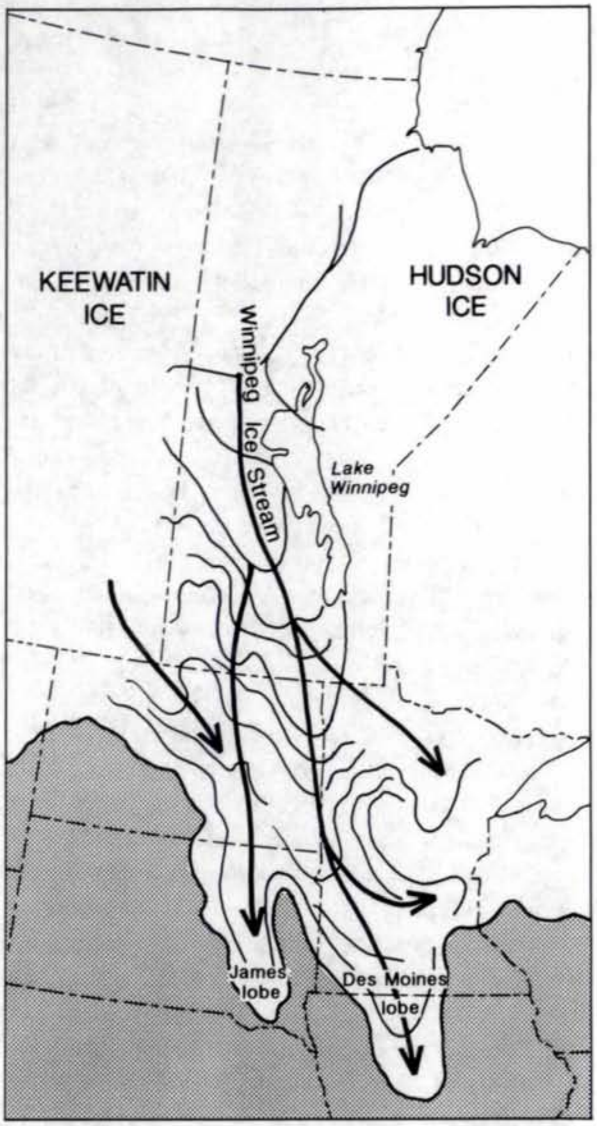


Figure 33. Ice-retreat pattern in the central Laurentide Ice Sheet and the hypothesized location of the Winnipeg Ice Stream. The ice stream is proposed to have flowed along the Lake Winnipeg lowland. The lobate nature of the ice margin persisted during the retreat of the lobe. The ice stream would have occupied one side of what has been modeled as a northwest-southeast-trending saddle in the ice surface in the vicinity of Hudson Bay. Adapted from Dredge and Cowan (1989).

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

By

Val W. Chandler

ABSTRACT

New gravity data were used to map in greater detail buried bedrock channels in northwestern Rock County. The channels are cut in the Precambrian Sioux Quartzite and filled with poorly consolidated Cretaceous and Quaternary deposits. Components of this fill have significant potential as ground-water resources. The new gravity stations were taken along roads at intervals measuring one-half to one mile; they augment previous gravity compilations that largely used two-mile spacing of data sources. The low-density fill of the channels has a negative gravity signature that can be isolated from the regional effect of deep, unrelated sources by employing a variation of the gravity–geologic method in combination with graphical separation utilizing cross-profiles. The residual gravity effect of the channels can be converted using a Bouguer slab approximation to estimates of the thickness of the channel fill, which in turn can be combined with land-surface elevation to compute elevations of the quartzite surface.

The gravity data indicate that five major channels and attendant tributary channels partially dissect a plateau of Sioux Quartzite that underlies northwestern Rock County. Three of the channels are west, north, and east of the village of Beaver Creek. These channels are interpreted to be associated with more than 500 feet of fill locally; they appear to coalesce to form a large, filled embayment lying south and southeast of Beaver Creek. The two other channels, west and southwest of the village of Jasper, are associated locally with more than 300 feet of fill; they appear to follow the underlying structure of the Sioux Quartzite.

All the Cretaceous and Quaternary channel fill may be enriched locally in sand and gravel deposits, which have potential as sources of ground water. The most favorable targets are areas where the paleogradient in the channels changes abruptly, such as near the headward parts of the bedrock channels, and where a main channel is joined by steep tributary channels.

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

INTRODUCTION

A previous reconnaissance gravity study in Rock County, which was undertaken to identify potential ground-water resources, detected several channels cut into the Precambrian Sioux Quartzite and filled with poorly consolidated Quaternary and Cretaceous deposits (Chandler, 1994). These buried channels have locally steep paleogradients that may have favored deposition of sand and gravel in parts of the Cretaceous and Quaternary fill. Test drilling of three holes by the U.S. Geological Survey in western Rock County (Fig. 1) verified the presence of two channels and indicated that minor sand bodies in the Cretaceous section may locally be thick enough to serve as aquifers (Rick Lindgren, oral commun., 1995). Unfortunately, the existing gravity grid for northwestern Rock County had station spacing as wide as two miles, which prevented detailed mapping of some prominent channels. For this study the coverage was augmented by additional gravity stations at one-half and one mile intervals. The improved coverage should prove a much more reliable guide for ground-water exploration.

GEOLOGY OF NORTHWESTERN ROCK COUNTY

The northwestern part of Rock County is underlain by the Precambrian Sioux Quartzite, a sequence of shallow-dipping quartz arenitic red-beds having minor conglomerate and thin beds of argillite (Southwick and others, 1986). The shallow dips in the quartzite define

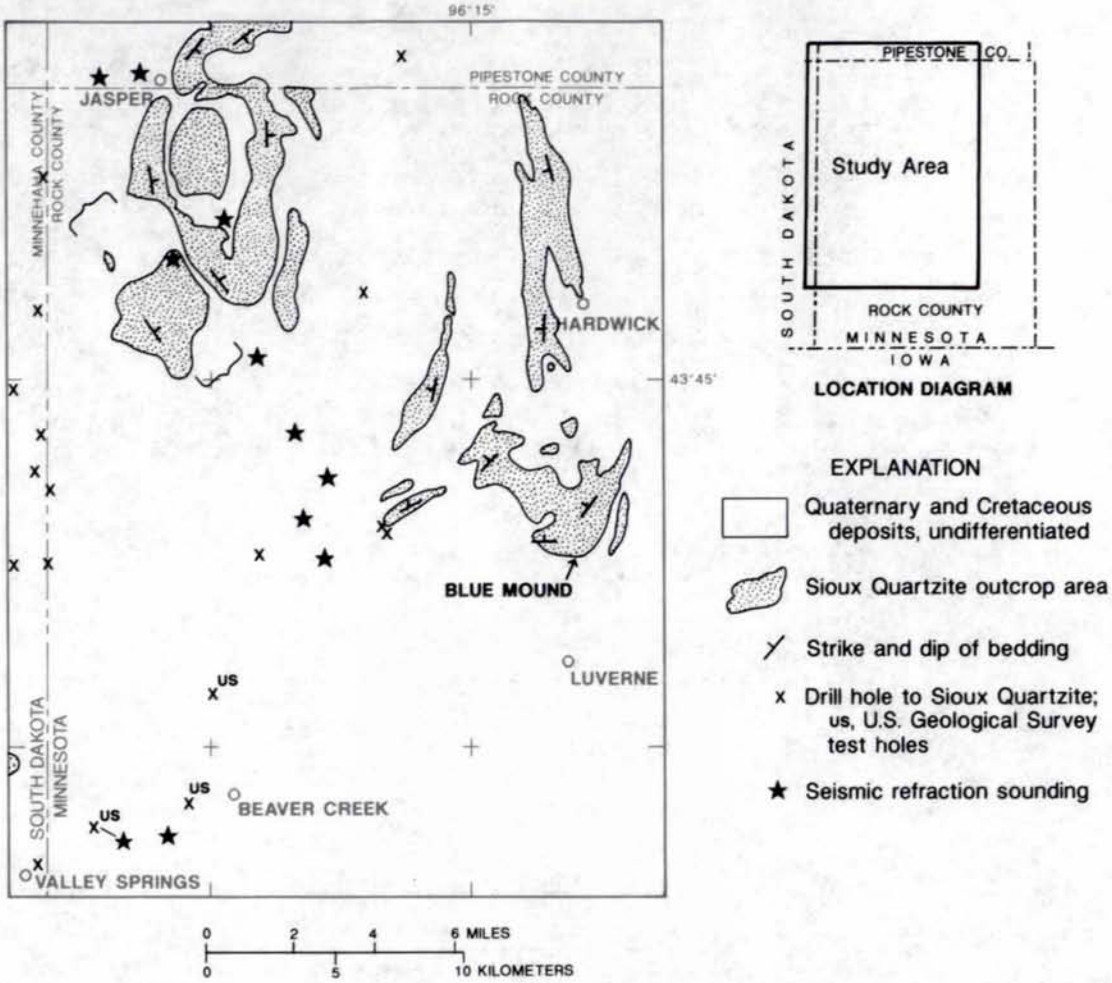

Figure 1. Surficial geologic map of northwestern Rock County and adjacent areas of Minnehaha County, South Dakota and Pipestone County, Minnesota. Brackets delineate a northwest-striking fracture zone in the Sioux Quartzite. Compiled from Baldwin (1951), D.L. Southwick, unpubl. mapping (1993), and Patterson (1995).

a sub-circular basin (Fig. 1). In outcrop, the Sioux forms highly resistant ridges that are glacially scoured and polished by the wind. The Sioux Quartzite is partially overlain by the Upper Cretaceous Split Rock Creek Formation, which consists chiefly of poorly consolidated claystone and sandstone overlain by a unit of spiculite (Setterholm, 1990). The Cretaceous sequence and much of the Sioux Quartzite are covered by pre-Wisconsin glacial deposits that have a well-dissected surface, which in turn is commonly covered by 6–14 feet of Late Wisconsin loess (Patterson, 1993, 1995).

Most ground water in Rock County is drawn from shallow Quaternary outwash. Many of these shallow aquifers offer limited yields and are vulnerable to drought and surface pollution. New and more dependable sources of ground water may exist in the deeper parts of the Quaternary section and underlying Cretaceous sequence, but relatively little is known of these deposits in Rock County because of inadequate drill-hole control (Setterholm, 1990).

DESCRIPTION OF GRAVITY DATA

The gravity analysis presented in this paper relies on the use of a representative density contrast between the Sioux Quartzite and the overlying Cretaceous and Quaternary deposits. Density data compiled from southwestern Minnesota (Chandler, 1994) indicate that the Cretaceous and Quaternary deposits differ little in density (range of 1.99–2.14 gm/cm^3 [grams per cubic

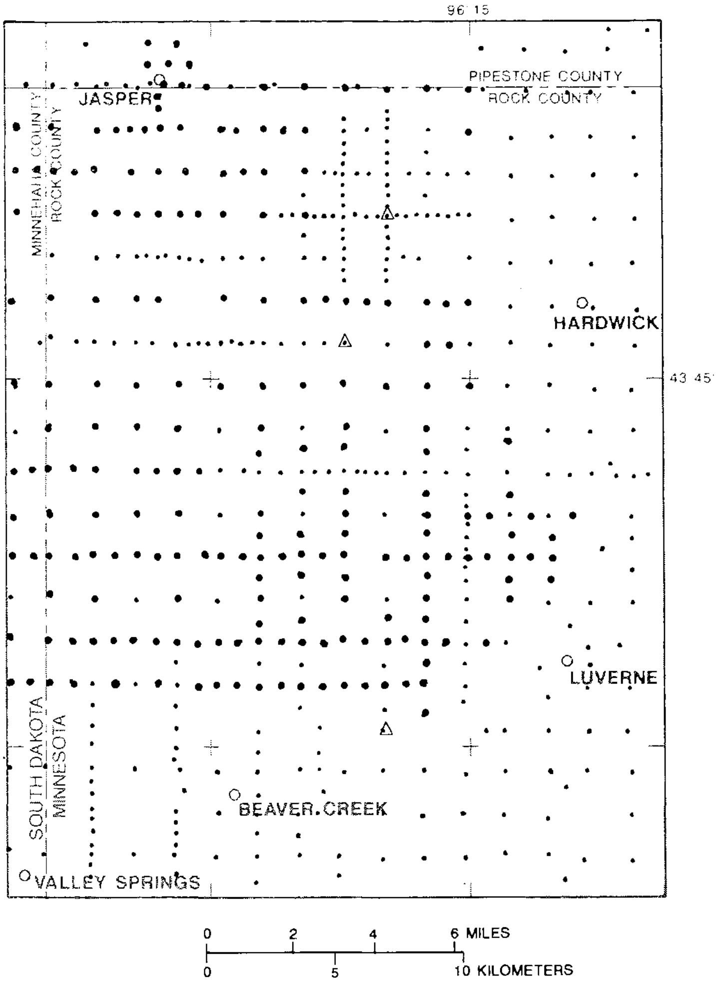

Figure 2. Map showing gravity stations and geologic control in the study area. Small dots designate gravity stations acquired prior to 1994; triangles designate field base stations; large dots designate gravity stations acquired in 1994. Some 1994 stations taken west of the study area in South Dakota are not shown.

centimeter]); their probable average contrast with the underlying quartzite is about 0.60 gm/cm^3 (range of 2.65–2.72 gm/cm^3). This contrast is assumed in the following discussion.

Field and Compilation Procedures

Gravity surveying was conducted in October 1994 in northwestern Rock County and neighboring areas of Minnehaha County, South Dakota, and Pipestone County, Minnesota. Readings were taken at 216 new stations at spot elevations along roads using intervals of one-half to one mile (Fig. 2). Previous gravity surveys in Rock County acquired data in 1967 and 1974 having spacing of two miles and one mile, respectively, and, in 1989 and 1993, acquired data having spacing of 0.25–0.5 mile (Fig. 2).

The positions of most gravity stations in northwestern Rock County were digitized to an accuracy of 164 feet or less, but stations in the northeastern part (north and east of 43°45'N–96°15'W) and extreme southeastern part (south and east of 43°37'30"N–96°15'W) of the study area (Fig. 2) were accurate to 0.1 minute (about 605 feet north-south, 445 feet east-west). All gravity data were corrected for drift by assuming linear segments between base checks (commonly two to three hours apart) and were reduced

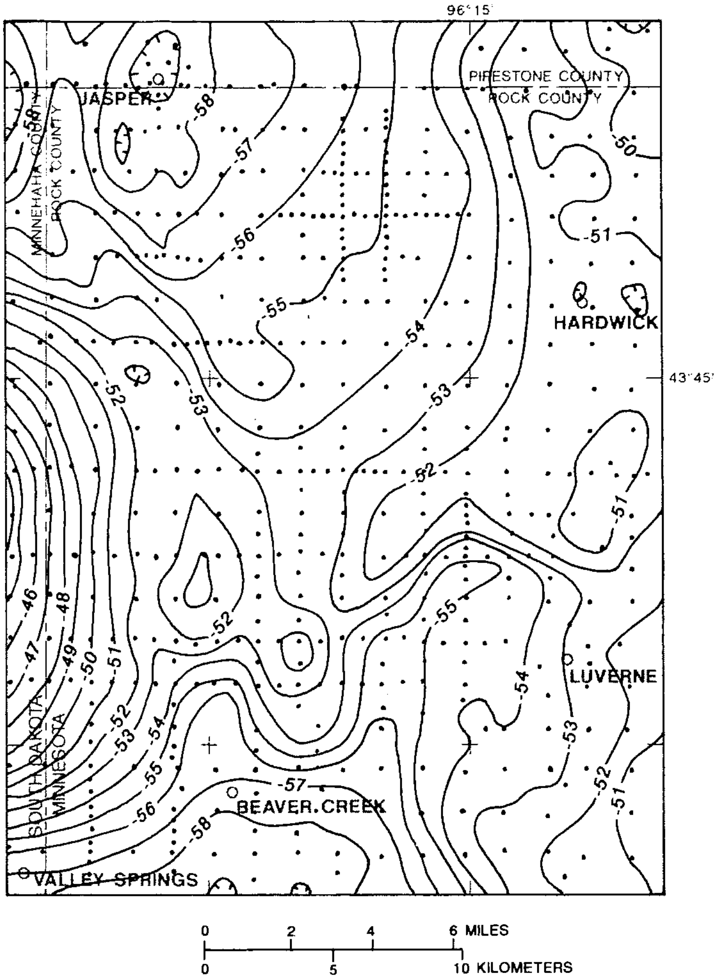

Figure 3. Contour Bouguer gravity anomaly map for northwestern Rock County and adjacent areas. Dots, all gravity stations; values are milligals; contours with tick marks enclose areas of lower milligal values.

according to the 1967 Geodetic Reference System (Inter. Assoc. of Geodesy, 1971), assuming a sea-level datum, a Bouguer reduction density of 2.67 gm/cm^3, and correction for Earth curvature. Owing to the generally low relief of the region, no terrain corrections were needed. Considering all reasonable uncertainties (summarized in Chandler, 1994), the Bouguer values for all the 1994 data and most of the pre-1994 data are precise to about +/-0.2 milligals, although some of the older data could be off by as much as +/-0.45 milligals. The Bouguer gravity data were gridded at a 0.8-kilometer (about 0.5-mi) interval using MINC, a minimum-curvature program that was developed by the U.S. Geological Survey (Cordell and others, 1992).

Bouguer Anomaly Data

The revised Bouguer gravity anomaly map of northwestern Rock County and adjacent areas shows a 10–15 milligal positive anomaly along the western margin of the study area and a broad positive saddle of about 5 milligals amplitude extending east-northeast across the study area (Fig. 3). These broad signatures are assumed to represent a deep source buried beneath the Sioux Quartzite. Superimposed on the broad anomalies are local variations of 1–5 milligals amplitude that are assumed to reflect the buried topography on the quartzite surface and its contrast with the overlying fill of low-density Cretaceous and Quaternary deposits.

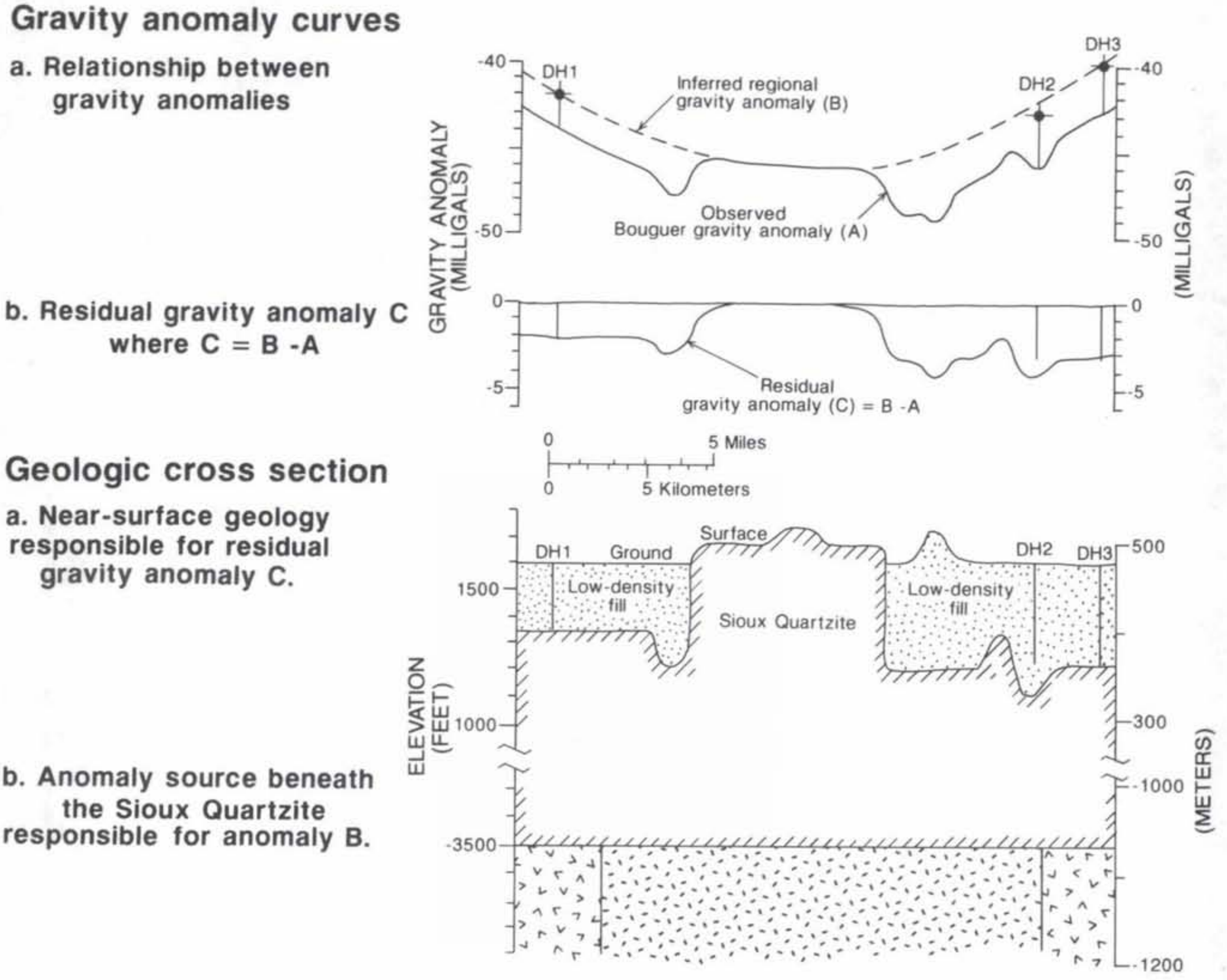

Figure 4. Schematic sketch of gravity cross-profile showing the regional residual separation procedure used in this study. Assuming that the Sioux Quartzite is a laterally uniform unit, the observed Bouguer anomaly data (A) consists of effects of near-surface fill and deep intra-basement sources (see split geologic cross section at bottom of figure). At control points where the thickness of fill is known (drill holes designated by DH on upper part of the geologic cross section) the Bouguer slab approximation and an assumed density contrast can be used to backfill the negative effect of fill. Thus corrected, control-point values (designated by DH on curves A and B), as well as observed Bouguer gravity over quartzite outcrop areas (no fill), consist essentially of the regional field from deep intra-basement sources (B). Additional points on the regional field can be determined by analysis of intersecting cross-profiles (see Chandler, 1994). If the regional field can be assumed to be a smoothly varying function (consistent with deep source origin), it can be determined by relatively few points. Subtracting the regional field (B) from the observed Bouguer gravity (A) yields the residual anomaly (C), which is only the effects of fill.

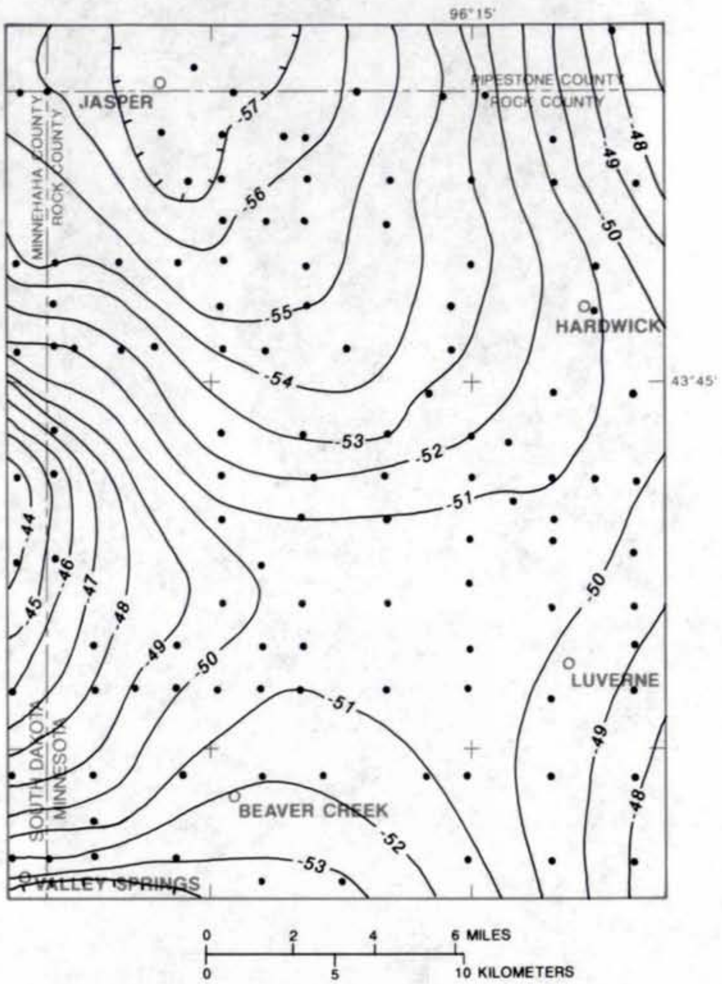

Figure 5. Contour map (in milligals) of the regional gravity field for northwestern Rock County and adjacent areas. Revised from the regional field of Chandler (1994) to agree with new control points. Control points (shown as dots) were drawn from cross-profile analysis and selected gravity stations at outcrops and drill holes. Contours with tick marks enclose areas of lower milligal values.

ANALYSIS OF THE GRAVITY DATA

To use gravity data for estimating fill thickness, the effect of fill and bedrock topography must first be isolated from the regional field reflecting deep sources. In the previous Rock County study, Chandler (1994) removed the regional field using a variation of the gravity–geologic method (Ibrahim and Hinze, 1972; Adams and Hinze, 1990). Because there is little fill in the large outcrop areas of Sioux Quartzite (Setterholm, 1990), the Bouguer values observed in these areas should closely approximate the regional field (refer to the central part of Figure 4). For drill holes or seismic-refraction soundings that provide reliable measures of fill thickness (see DH1 and DH3 in Figure 4), the negative anomaly effect of the low-density fill can be approximately compensated back to the regional curve (Fig. 4) using the Bouguer slab approximation

$$dg=(0.01276)X(dp)X(h)$$

where dg is the gravity effect (in milligals) of a horizontally infinite slab of thickness h (in feet) and density contrast dp (in gm/cm^3), which in this study is assumed to be 0.6 gm/cm^3. By the same procedure,

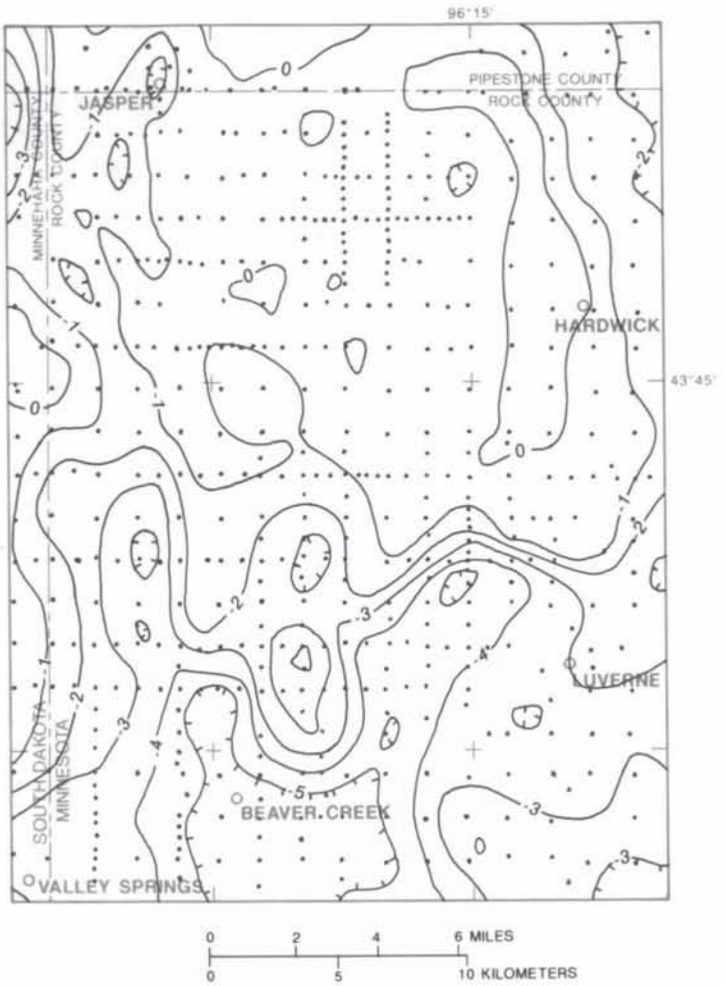

Figure 6. Contour map of residual gravity values (in milligals) for northwestern Rock County and adjacent areas. Calculated by subtracting the regional field (Fig. 5) from the Bouguer anomaly field (Fig. 3). Dots, all gravity stations; contours with tick marks enclose areas of lower milligal values.

deep drill holes that do not penetrate the fill provide at least a minimum possible value for the regional curve (see DH2 on Figure 4). Assuming that the regional curve is a smooth function, it can be inferred along a profile on the basis of relatively few control points.

The procedure described above was applied to 28 intersecting profiles in the previous gravity study of Rock County (Chandler, 1994). The inferred regional curves on all cross profiles were then readjusted through several iterations until regional curves for intersecting profiles were equal at intersection points (Hinze, 1990). Selected values from these final regional profiles were used to produce a regional anomaly grid using the minimum-curvature program MINC (Cordell and others, 1992). For the present study, the regional field used by Chandler (1994) was slightly readjusted in several areas to agree with new regional-field control points produced by the three test holes drilled by the U.S. Geological Survey (Fig. 1) and by new stations that were located either on or very near outcrops of quartzite (observed Bouguer value approximates regional value).

The revised regional grid (Fig. 5) was subtracted from the new grid of the Bouguer gravity anomaly data (Fig. 3) to produce a residual gravity map (Fig. 6) that is assumed to reflect low-density fill. The residual gravity values were converted into thickness

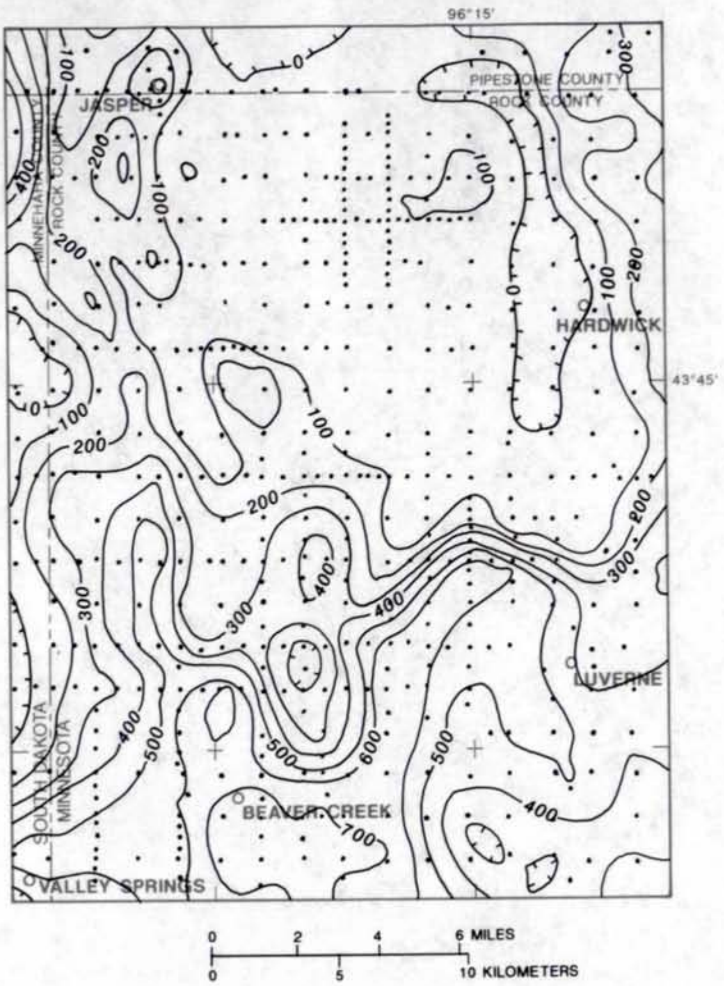

Figure 7. Contour map (in feet) of estimated thickness of combined Quaternary and Cretaceous fill for northwestern Rock County and adjacent areas. Calculated from residual gravity values (Fig. 6) using Bouguer slab approximation and density contrast of -0.60 gm/cm^3. Dots, all gravity stations; contours with tick marks enclose areas of lesser thickness.

estimates of the combined Cretaceous and Quaternary fill (depth to Precambrian basement) by applying the Bouguer slab approximation with a density contrast of -0.6 gm/cm^3 (Fig. 7). Using program MINC (Cordell and others, 1992), elevation data from the principal-fact gravity file were used to produce a generalized grid of surface elevation (Fig. 8), from which the thickness grid of Cretaceous and Quaternary fill (Fig. 7) was subtracted to produce a elevation grid of the Sioux Quartzite surface (Fig. 9).

LIMITATIONS OF THE RESULTS

Various uncertainties must be considered when using the interpretive maps of the thickness of channel fill (Fig. 7) and the elevation of the Precambrian surface (Fig. 9). An uncertainty of +/-0.2 milligals in the Bouguer gravity data equates to an uncertainty of +/-26 feet in the thickness of the fill or elevation of the Precambrian bedrock surface. Local variations in the density contrast can feasibly depart 10 percent or more from the assumed value of 0.60 gm/cm^3; this equates to a roughly proportionate uncertainty in fill thickness and Precambrian surface elevation (Adams

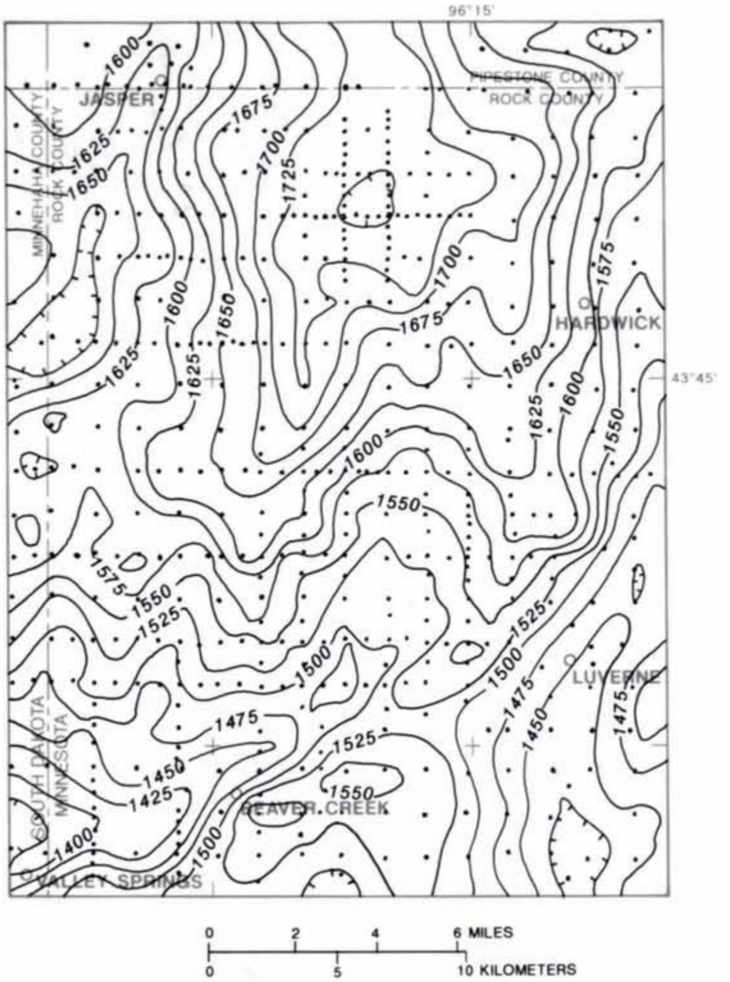

Figure 8. Contour map of land-surface elevations for northwestern Rock County and adjacent areas. Based on elevations in feet above mean sea level of gravity stations (shown as dots); contours with tick marks enclose areas of lower elevation.

and Hinze, 1990). Use of the (infinite) Bouguer slab in data analysis tends to subdue the actual variations in fill thickness and bedrock elevation, but this effect is minimal if a channel is several times wider than it is deep (Adams and Hinze, 1990). Unlike a true isopach of the fill, which would incorporate the land-surface topography in detail, the estimates of the fill thickness in Figure 9 take into account only topography that is apparent from elevations at gravity stations. A final source of uncertainty exists in the inference of a regional anomaly curve in areas of poor depth-to-bedrock control, such as south of Luverne (Fig. 2), where an error of one milligal in the regional field would equate to about a 130-foot error in fill thickness.

Therefore, the margin of error for any point on the fill-thickness or bedrock-elevation maps in Figures 7 and 9 is thirty or more feet. Nonetheless, the maps are adequate for recognizing major channels and other large-scale variations of these features.

DISCUSSION

The revised maps of estimated channel-fill thickness (Fig. 7) and Precambrian surface elevation (Fig. 9) show considerably more detail for the buried channels than previous gravity mapping (compare with Figures 11 and 13 in Chandler, 1994). The new data clearly delineate three major buried channels lying west, northwest, and northeast of the village of Beaver Creek

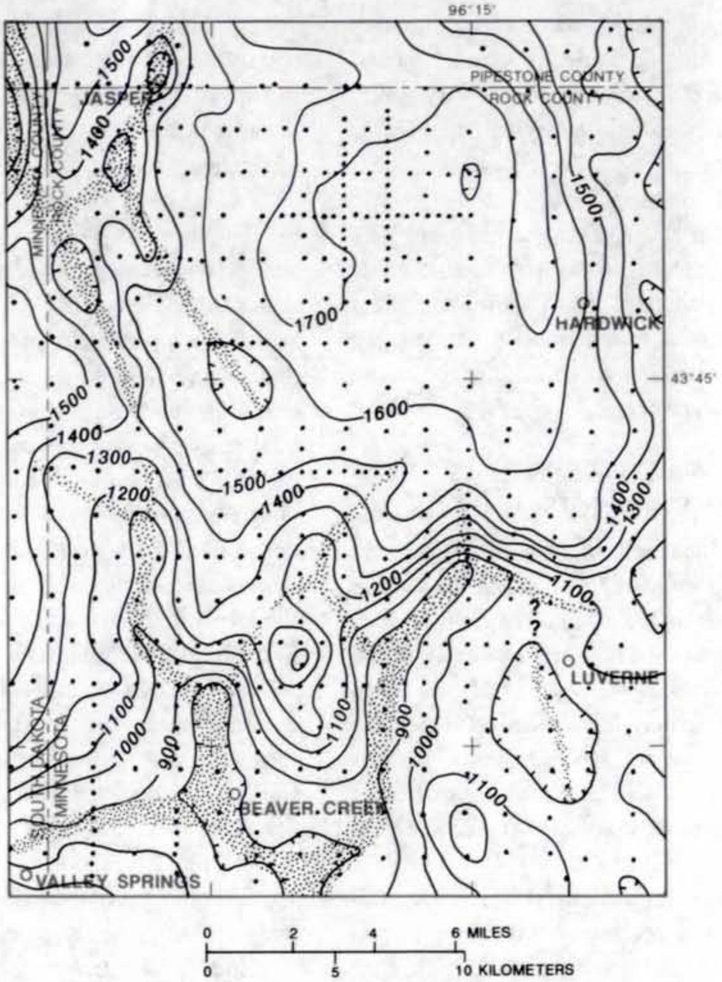

Figure 9. Contour map of estimated elevation (in feet above sea level) of the Sioux Quartzite surface for northwestern Rock County and adjacent areas. Calculated from the difference between the land-surface elevation (Fig. 8) and the estimated thickness of Quaternary and Cretaceous fill (Fig. 7). Contours with tick marks enclose areas of lower elevation; dots, all gravity stations; stipple indicates major and tributary channels.

(Fig. 9). The confluence of the three channels is south and southeast of Beaver Creek, where the combined thickness of Cretaceous and Quaternary fill is interpreted to exceed 700 feet. The western channel, as described by Chandler (1994), extends into South Dakota just north of the village of Valley Springs (Fig. 9). The northwestern channel extends about eight miles north and northwest from the village of Beaver Creek and appears to include some well-developed tributary channels (Fig. 7). The eastern channel, which also appears to have some well-developed tributary channels, extends for at least nine miles north and northeast along the base of a prominent quartzite escarpment northwest of Luverne (Figs. 7 and 9). The three major channels are interpreted to be associated with more than 500 feet of fill along much of their length. Northeast of Beaver Creek the deep fill of the northwestern and eastern channels is separated by a buried ridge of quartzite (Fig. 9) that may in one place be covered by less than 200 feet of fill (Fig. 7).

Two buried channels in the extreme northwestern part of the study area are evident on the maps of channel-fill thickness (Fig. 7) and Precambrian bedrock elevation (Fig. 9). A 300-foot-deep buried bedrock channel beneath the west edge of Jasper (Fig. 7) was very poorly defined by the previous gravity surveying (see Figures 11 and 13 in Chandler, 1994). The new data show it extending south and southeast along a curving trace. Parallel ridges of quartzite and another channel with more than 300 feet of fill lie west of this channel (Figs. 7 and 9). The channels and intervening ridges follow the geologic strike of the area and, in part, the trend of a northwest-striking shear zone proposed by D.L. Southwick (oral commun., 1995) (Figs. 1 and 9).

IMPLICATIONS FOR GROUND-WATER RESOURCES

Several buried channels in the Sioux Quartzite that were mapped in greater detail during this study warrant further investigation as sources of ground water. During the Cretaceous and Quaternary Periods the quartzite highlands flanking these channels had high drainage gradients that may have locally favored the deposition of sand and gravel. Three bedrock channels lying west, northwest, and east of the village of Beaver Creek are interpreted to be associated with more than 500 feet of fill. Test drilling in 1994 of the west channel by the U.S. Geological Survey (Figs. 1 and 9) encountered some sand bodies, 30–40 feet thick, in the Cretaceous strata (Rick Lindgren, oral commun., 1995). West of Beaver Creek, a test hole near the confluence of the northwestern and western channels encountered a clay-rich fill sequence having little sand, but another hole about three miles upstream along the northwestern channel (Figs. 1 and 9) encountered sand units about 10–20 feet thick in the upper part of the Cretaceous sequence (Rick Lindgren, oral commun., 1995). More extensive sand deposits may exist in other parts of the northwestern and eastern channels. Favorable targets for locating sand and gravel deposits include areas having paleodrainage gradients that change abruptly, such as the headward parts of the main channel and where a main channel is joined by steep tributary channels.

Buried bedrock channels in the Jasper area have fairly steep flanks and are interpreted to contain more than 300 feet of fill, giving them significant potential as a source for ground water.

The results of this study can be used to guide further ground-water exploration in northwestern Rock County. Prior to drilling, however, some additional geophysical investigation, such as seismic surveying and acquisition of detailed gravity profiles (spacing of a quarter mile or less) may profitably be used to pinpoint and evaluate targets.

CONCLUSIONS

New gravity data for northwestern Rock County were used to delineate buried channels that were only partially mapped by an previous gravity survey. The channels are cut into the Precambrian Sioux Quartzite and filled with poorly consolidated Cretaceous and Quaternary deposits. A variation of the gravity–geologic method, used in conjunction with graphical analysis along cross profiles, is effective in isolating the negative signature of the poorly consolidated fill, which in turn can be used to produce maps showing the estimated thickness of the fill and the surface elevation of the underlying Sioux Quartzite. Three bedrock channels, each associated with more than 500 feet of Cretaceous and Quaternary fill, are interpreted to extend west, northwest, and northeast from their confluence in the vicinity of Beaver Creek, Minnesota. Two buried channels near the village of Jasper are interpreted to contain more than 300 feet of Cretaceous and Quaternary fill. These channels may be structurally controlled along a possible shear zone and less resistant units in the gently folded quartzite.

The buried channels identified in this study warrant further investigation as potential ground-water resources. Owing to the steep paleogradients along parts of these channels, both the Cretaceous and Quaternary fill may host significant sand and gravel deposits. Preliminary test drilling by the U.S. Geological Survey has verified the presence of sand in the channels west and northwest of Beaver Creek, and more extensive sand and gravel deposits may exist elsewhere along these and the other channels delineated by this study. Particularly favorable prospects include areas where the paleodrainage gradients abruptly change, which may be present near the headward parts of a main channel and where steep tributary channels join a main channel.

The results of this study demonstrate that the gravity method is an effective tool for ground-water exploration in areas underlain by the Sioux Quartzite in southwestern Minnesota and surrounding regions.

ACKNOWLEDGMENTS

Minnesota Geological Survey staff who assisted in this study include Alan Knaeble and Dale Setterholm, who provided assistance in the field, and Robert Tipping, who digitized station positions. I thank Carrie Patterson, Dale Setterholm, and D.L. Southwick of the Minnesota Geological Survey for many useful discussions on the geology of southwestern Minnesota. Rick Lindgren of the U.S. Geological Survey Division of Waters office in Mounds View, Minnesota, shared preliminary results of their test drilling program. Seismic-refraction work was conducted by the Minnesota Department of Natural Resources, Division of Waters, under the supervision of Todd Peterson.

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TERRESTRIAL GAMMA RADIATION IN SOUTHWESTERN MINNESOTA AND AN ASSESSMENT OF ITS UTILITY IN SURFICIAL GEOLOGIC MAPPING

By

R.S. Lively

INTRODUCTION

The southwestern Minnesota regional hydrogeologic assessment (Quaternary geologic component) was designed to map and interpret the surface geology and Quaternary stratigraphy in the region (Fig. 1). As part of the assessment, a map of the surface geology was prepared at the scale of 1:200,000 (Patterson, 1995). The availability of a new, detailed map of the surficial geology for the study area coincided with the acquisition and analysis by the Minnesota Geological Survey of spectral gamma radiation data for the entire state. The availability of these two sources of information on surface sediment within the study area provided the impetus to assess the relation of measured gamma radiation at the ground surface to the units and boundaries on the surficial geologic map.

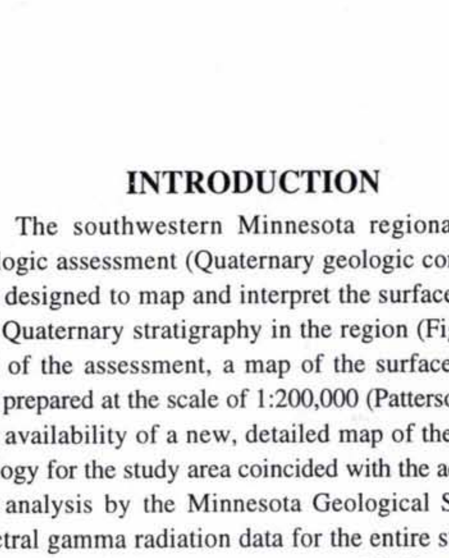


Figure 1. The area of the southwestern Minnesota regional hydrogeologic assessment.

Additional information within the study area was obtained by analyzing radioisotope activities in soil samples and measuring the ground-level total gamma activity at each of 50 soil-sample locations. The samples were collected during field work for the assessment.

The radiometric data were evaluated to determine (1) how closely the spectral radioactivity measurements corresponded with measurements made at ground level (ground truth), (2) if the gamma radiation data were capable of distinguishing surficial geologic units and contacts, and (3) if the gamma data, particularly the airborne spectral measurements, provided information that could aid surficial geologic mapping in glaciated terrains.

DESCRIPTION OF DATA

Airborne Survey

From 1977 to 1981, the National Uranium Resource Evaluation program (NURE) of the U.S. Department of Energy conducted high-sensitivity airborne radiometric surveys over each 1 x 2–degree U.S. Geological Survey topographic quadrangle in Minnesota and adjacent states. Gamma radioactivity was measured using large-volume detectors (57,000 cm^3 [cubic centimeters]) composed of sodium iodide crystals that were flown in fixed-wing aircraft at an average elevation of 390 feet above the land surface. The detector system was configured and shielded to simultaneously measure radiation emanating from the ground surface (49,000 cm^3) and from the sky (8,400 cm^3). Parts of four 1 x

2–degree quadrangles—Watertown, New Ulm, Sioux Falls, and Fairmont (Fig. 2a)—form the coverage for the study area; each quadrangle was surveyed separately. For all quadrangles except New Ulm, east-west flight lines were established at a spacing of 6 miles; north-south flight lines were spaced 24 miles apart. The New Ulm quadrangle had east-west flight lines spaced 3 miles apart, and north-south flight lines were spaced 12 miles apart (Fig. 2a).

Accumulated counts of gamma radioactivity were recorded digitally at one-second intervals. About 60 percent of the gamma radioactivity at the detector was derived from a cone with a diameter at the ground of 240 feet centered on and perpendicular to the flight line. This was considered the size of the area on either side of the flight path where the system was sensitive enough to distinguish different radioactive targets. Data acquired along flight lines oriented perpendicular to the long axis of geologic boundaries, particularly if the line spacings are wide, are most useful for identifying geologic trends. In Minnesota, the east-west flight lines are nearly perpendicular to most geologic trends in the Quaternary sediments.

Terrestrial gamma radiation detectable by aerial surveys is produced by nuclear transformation of radioactive elements within approximately the upper foot of soil or rock. In the NURE project, separate energy windows were established for the diagnostic photopeaks of ^{238}U (bismuth-214 at 1.76 MeV [million electron volts]), ^{232}Th (thallium-208 at 2.61 MeV), and K (^{40}K at 1.46 MeV). Radioactive equilibrium within the decay series of uranium and thorium was assumed, and concentrations were reported as eU (equivalent uranium), and eTh (equivalent thorium) in ppm (parts per million). Potassium-40 (with a content of 0.0118 percent natural potassium) was reported as the fraction of natural potassium in the sample. Although not a consideration for ^{40}K, and of minor importance for the ^{232}Th series, lack of equilibrium within the ^{238}U decay series is possible, and eU values based on ^{214}Bi activity may not accurately reflect the uranium content or distribution. See Saunders and Potts (1977) and GeoMetrics (1978) for further information on the apparatus, methodology, calibration, corrections for background interference (aircraft, cosmic ray), altitude, radon in the atmosphere, and preliminary analysis of the data.

Raw data for potassium, thorium, and uranium were processed for consistency by the U.S. Geological Survey (Duval and others, 1989, 1990), and the flight-line data were made available to the Minnesota Geological Survey by J.S. Duval. Lively gridded the data separately for each 1 x 2–degree quadrangle and combined the results to produce isopleth maps at the 1:1,00,000 scale showing relative concentrations of the radioactive elements within the study area.

Ground Survey

Soil samples were collected for radiometric analysis in 1992 by the Minnesota Geological Survey at fifty sites within the study area (Fig. 2b). The samples (each about one kilogram of sediment) were collected using a bucket auger from the upper foot of soil. The samples were weighed after drying and sealed in one-liter Marinelli beakers for quantitative analysis by gamma-ray spectroscopy of eU, eTh, K, and ^{137}Cs concentrations (Steck, 1989). Chemical concentrations of the radionuclides in the sediment samples were not determined as part of this study; the lack of these data prevented analysis of the relative equilibrium within the decay series in the sediments.

In addition to collection of soil samples at each site, total gamma radiation (not differentiated by isotope) was measured at ground level using a Ludlum gamma scintillometer (one-inch diameter) and a battery-operated Ludlum Model 2000 ratemeter/scaler. The scintillometer (unshielded) was also used to measure soil radioactivity at depths of one and three feet in the auger holes. Performance was monitored with a gamma check-source and through background readings made each morning at a base site. However, the field measurement system was not calibrated, and the activities were not converted to radionuclide concentrations. The soil analyses and total gamma counts were plotted as isopleth maps at the same 1:1,000,000 scale as the aerial data.

The Surficial Geologic Map

The surficial geologic map of southwestern Minnesota emphasizes interpretive rather than descriptive attributes of the sediments (Patterson, 1995). The map units are defined on the basis of sediment genesis, age, and lithology. In contrast, the radioactivity maps relate to the lithology or mineralogy of the upper foot of material, and a correspondence with all features and units of the surficial geologic map is not expected. See Patterson (1995 and this volume) for descriptions of surficial sediments and interpretation of Quaternary stratigraphy and glacial mechanics in the study area.

Table 1. Summary of radionuclide activities measured by airborne and ground surveys compared to average radionuclide activities in world soils.

[Values are Bq kg^{-1} (Becquerels per kilogram).]

Radionuclide†	Airborne	Ground	Avg. world soils*
^{238}U	18.7 ± 4	29.9 ± 8	24.6
^{232}Th	27 ± 4	29.4 ± 6	24
^{40}K	349 ± 46	437 ± 46	388

†For comparison, ^{238}U in a standard farm-store fertilizer was 574 ± 67 Bq kg^{-1} and ^{40}K was 3800 ± 150 Bq kg^{-1} (D. Steck, St. John's University, Collegeville, Minn., oral commun., 1992).

*National Council on Radiation Protection and Measurements (1976), p. 17.

RESULTS AND DISCUSSION

Interpretation of the relative levels of radioactivity reported in this paper apply only within the study area of the southwestern Minnesota regional hydrogeologic assessment (Fig. 1).

The average radionuclide activities determined from the aerial radiometric data generally agree with the gamma spectroscopy results obtained from the upper foot of soil (Table 1). The range of both data sets is comparable to the average radionuclide content of world soil activities (National Council on Radiation Protection and Measurements, 1977) and shows no significant enrichment or depletion that would suggest source areas with elevated radionuclide content or secondary geochemical mobilization. Measurements for eU and K from the aerial radiometric data are on average lower than the same measurements made in the soil samples, although the one-sigma errors overlap. The values for eTh from the aerial data are nearly identical to those for eTh from the soil samples. The soil spectroscopic data for eU and eTh have slightly higher standard deviations than the aerial radiometric data, suggesting more variability in that data. Differences in both activity concentration and variability are relatively small and may be attributable to scale, i.e., individual soil samples having element distributions that may not be homogeneous versus averaged flight-line data. Lower eU values in the aerial radiometric data could result from loss of radon into the atmosphere, whereas the sediments in the laboratory were sealed to allow radon to reach equilibrium with the parent and progeny radionuclides before measurement. The loss of radon from the surface may lower the measured activity of ^{214}Bi in the upper foot of soil and reduce the calculated eU values

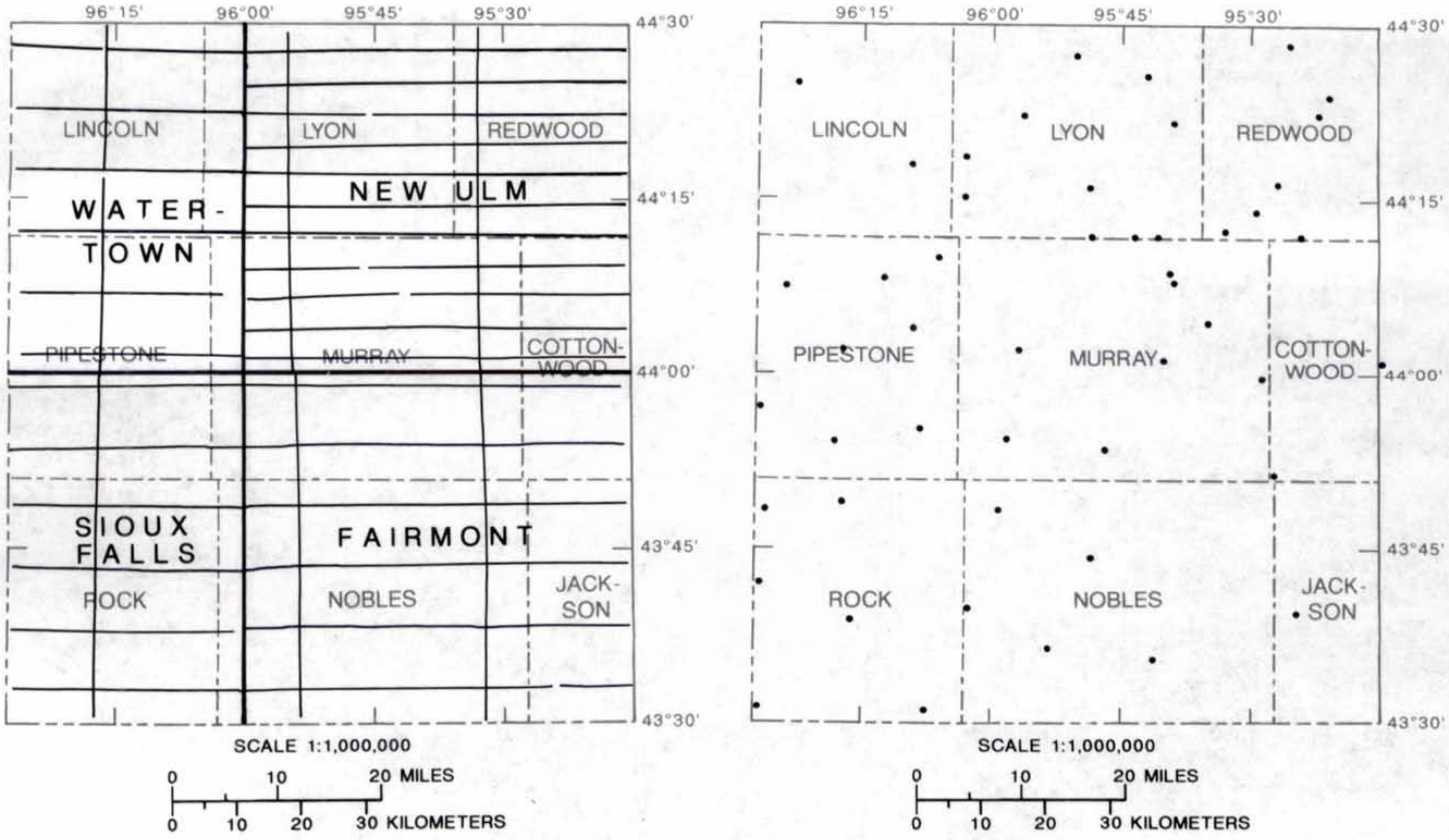
Radioactive equilibrium is maintained in the thorium decay series because thorium is immobile under surface geochemical conditions, and because ^{220}Rn, with a short half-life—55 seconds, does not migrate far from either the parent or daughter nuclides. Although these characteristics could explain the similar aerial and soil measurements of eTh, the data may also indicate that thorium is evenly distributed within the surface sediments.

Potassium is abundant in the Earth's crust but not part of a decay series. Variations at the land surface are probably related to distributions of illitic clays and feldspars present as detrital grains and, possibly, potassium-rich fertilizers. Minor variations in K distribution in the sediments might produce higher ^{40}K values locally relative to the more regionally averaged aerial radiometric results.

Regional Distribution of Radioactivity

The regional distribution patterns of eU, eTh, and K from the aeroradioactivity data are broadly similar (Figs. 3a–5a). The three isotope activity maps show northwest-southeast axial trends, or boundaries, which are also reflected in the regional geomorphology (Fig. 6) and surface topography (Fig. 7). The trend is most apparent on the isopleth map of eTh and least apparent on the isopleth map of eU. The highest levels of radioactivity in the study area are in the western and southwestern margins of the study area; the activity decreases gradually northeastward. The northeast corner of the study area consistently shows the lowest activity on each of the three maps. Several circular areas of low radioactivity are also apparent in the north-central and southeast parts of the study area.

The reconnaissance soil survey (Fig. 2b) provided samples from 50 sites across the study area, but the



EXPLANATION

Flight lines for the surveys of the National Uranium Resource Evaluation program of the U.S. Department of Energy. The boundaries and names of the four survey blocks are also shown.

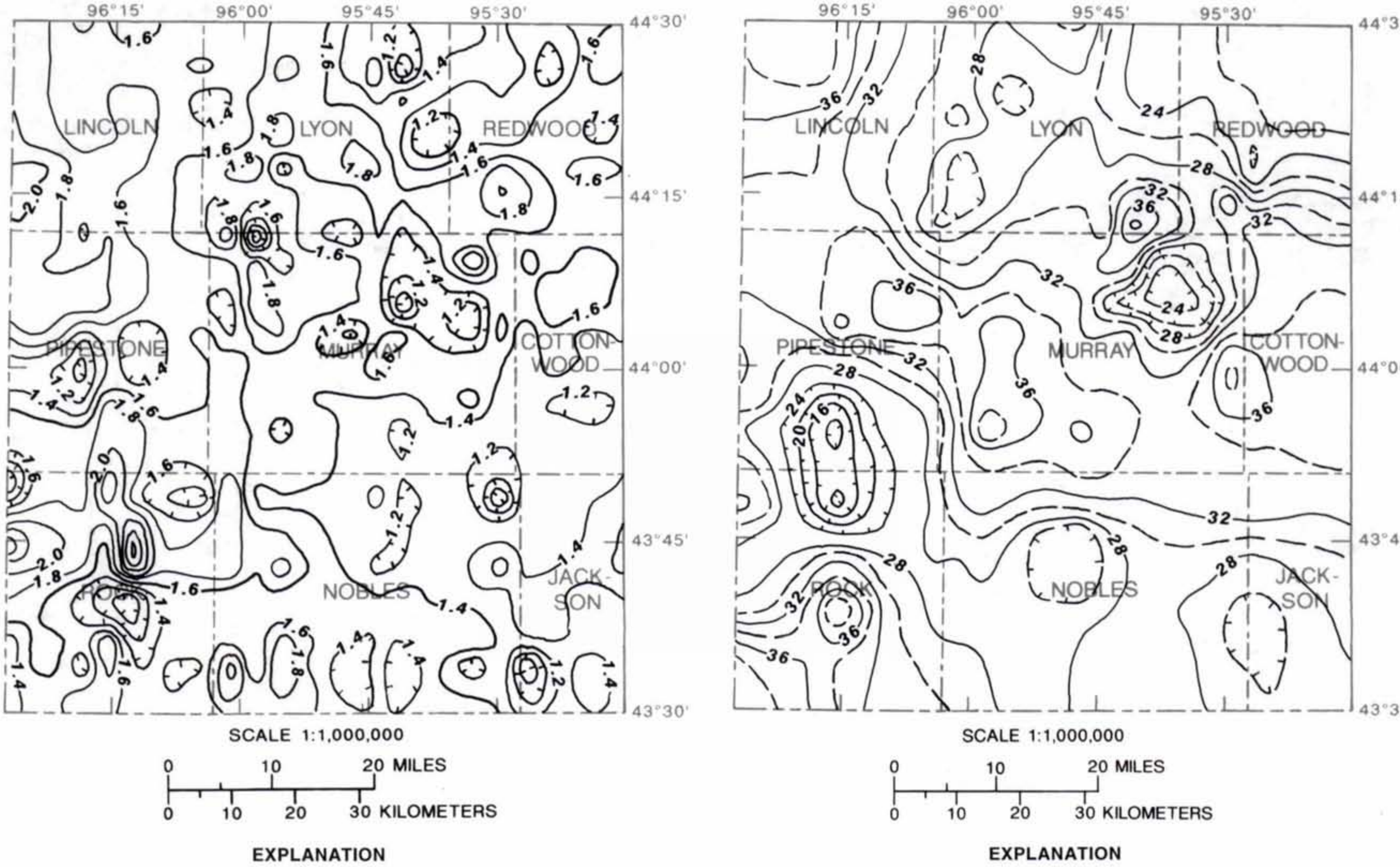
A. Data Sources—Airborne Survey

EXPLANATION

● Soil-sample site.

B. Data Sources—Ground Survey

Figure 2. Locations of airborne and ground radiometric surveys in the area of the southwestern Minnesota hydrogeologic assessment.



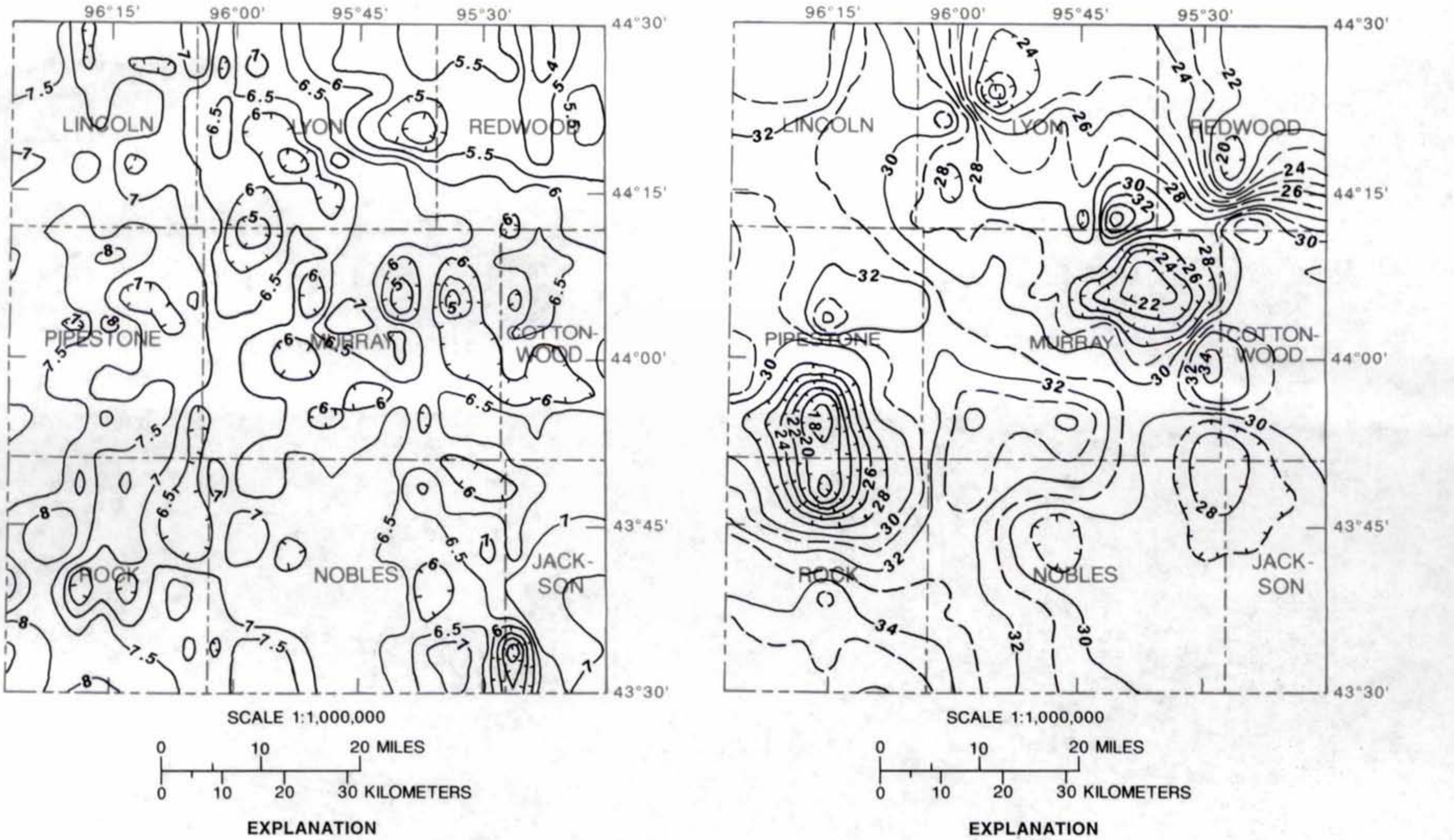
Isopleth interval 0.2 ppm eU;
hachures enclose areas of lower values.

A. Uranium—Airborne Survey

Isopleth interval (top foot of soil) 4 Bq kg^{-1}; supplementary isopleths (dashed) at 2 Bq kg^{-1} intervals; hachures enclose areas of lower values.

B. Uranium—Ground Survey

Figure 3. Uranium levels determined from airborne and ground surveys in the area of the southwestern Minnesota hydrogeologic assessment.



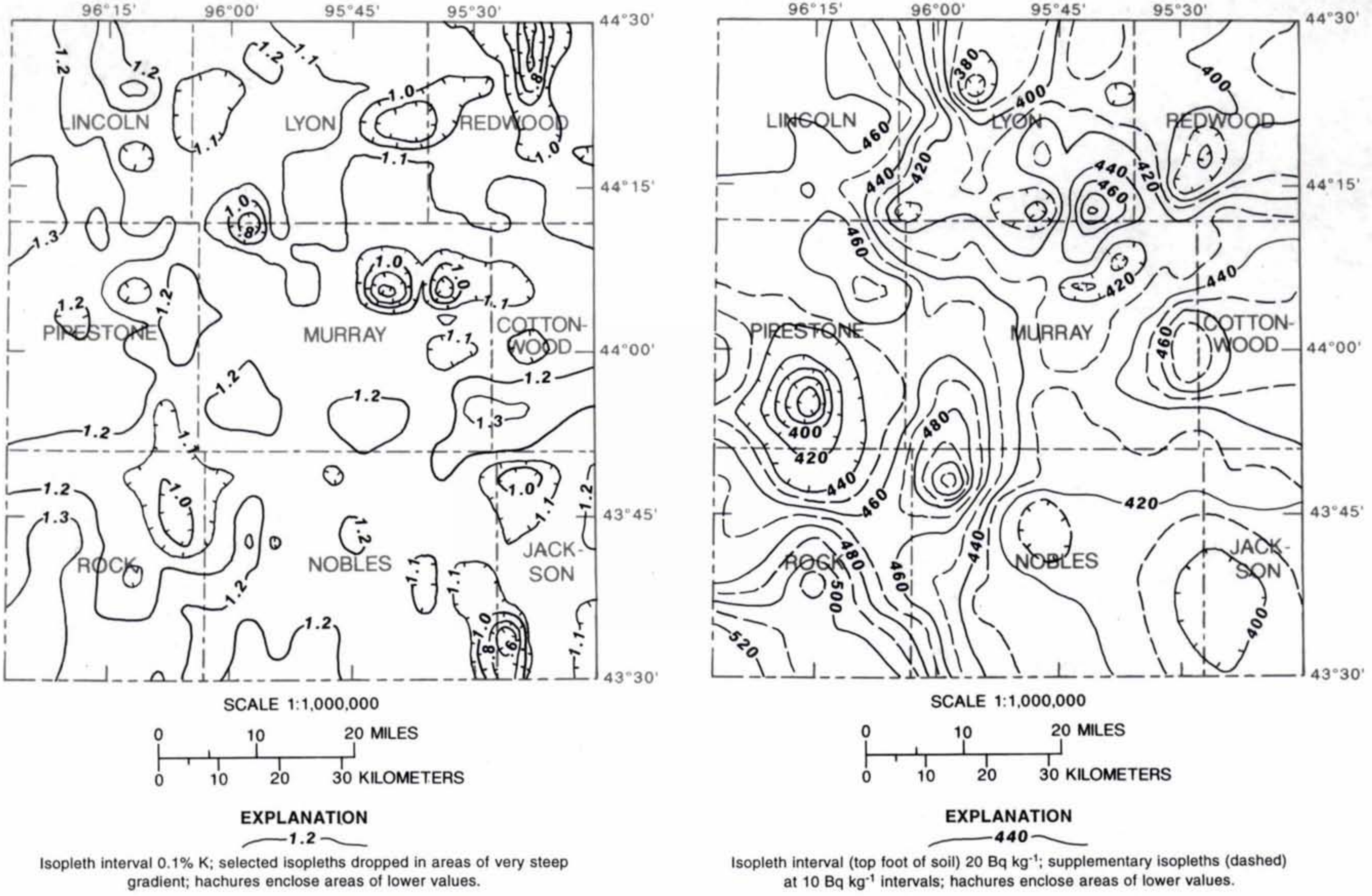
Isopleth interval 0.5 ppm eTh; selected isopleths dropped in areas of very steep gradient; hachures enclose areas of lower values.

A. Thorium—Airborne Survey

Isopleth interval (top foot of soil) 2 Bq kg^{-1}; supplementary isopleths (dashed) at 1 Bq kg^{-1} intervals; hachures enclose areas of lower values.

B. Thorium—Ground Survey

Figure 4. Thorium levels determined from airborne and ground surveys in the area of the southwestern Minnesota hydrogeologic assessment.



Isopleth interval 0.1% K; selected isopleths dropped in areas of very steep gradient; hachures enclose areas of lower values.

A. Potassium—Airborne Survey

Isopleth interval (top foot of soil) 20 Bq kg^{-1}; supplementary isopleths (dashed) at 10 Bq kg^{-1} intervals; hachures enclose areas of lower values.

B. Potassium—Ground Survey

Figure 5. Potassium levels determined from airborne and ground surveys in the area of the southwestern Minnesota hydrogeologic assessment.

sampling did not approach the density of the flightline data (Fig. 2a). Nevertheless, the soil radiometric data (Figs. 3b–5b) show regional distribution patterns that are similar to the aerial radiometric data: the highest activities of eU, eTh, and K in soil samples are in the southwestern and western parts of the study area, and activities gradually decline toward the northeast. Field descriptions indicate that most of the sediment samples were moist, silty to clayey topsoil, although a small number of samples were sandy. Sediments collected in the southwest contained less carbonate than those collected in the east and northeast. Other textural and lithologic analyses were not carried out for this study.

The total surface-gamma radiation (Fig. 8) shows patterns that are comparable to the regional patterns of the individual soil radioactivity maps and approximates the eTh aerial radiometric data. Localized areas of either high or low levels of radioactivity, such as the area of low radioactivity on either side of the boundary of Rock and Pipestone Counties, are most evident on the soil radioactivity maps. The contouring of the sparse soils data probably produces more adjacent highs and lows than do the aerial radiometric data. Localized trends are also more apparent on the soils radioactivity maps. For instance, higher concentrations trending east across the center of the study area show on all three soils radioactivity maps but are visible as a weak trend of elevated values only on the aerial radiometric K map.

Correlating Activity and Surficial Units

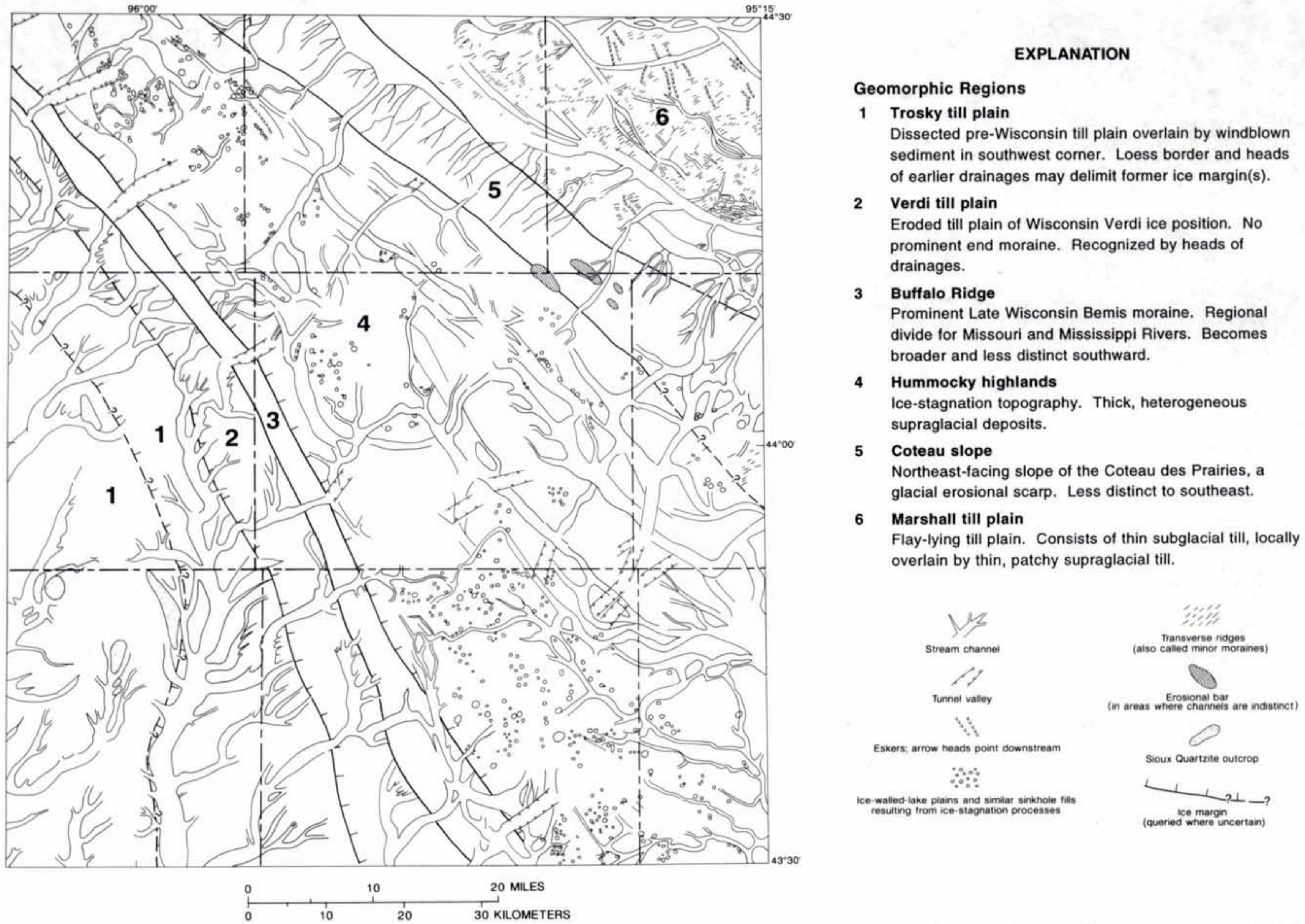
Activities of eU, eTh, and K are higher over surficial pre-Wisconsin glacial deposits. However, most of these deposits are in turn overlain by windblown sediment, or loess (Trosky till plain; Fig. 6). The contoured highs in the southwest extend north into Lincoln County, crossing areas of eroded Wisconsin-age till (Verdi till plain; Fig. 6), which is also overlain by thin, discontinuous loess. For the most part, this pattern of relatively high radioactivity was consistent in both the aerial and soil radioactivity data. Moderately elevated levels of radioactivity also were present within and over Late Wisconsin lake sediment in western Jackson County. Of the three aerial radioactivity maps, thorium provided the most definitive regional patterns correlative with the surficial geologic map (Patterson, 1995). Correspondence of the uranium flight data and surficial units was spotty, with the highest activity recorded over outcrops of Sioux Quartzite. Potassium showed the most uniform distribution, although the highest K activity corresponded with higher eTh activities in the southwestern and western parts of the study area.

Small areas of low radioactivity, particularly those of a bulls-eye nature (e.g., north-central Murray and southern Lyon Counties), may be associated with marshes, lakes, and sandy surficial material. There is a regional radioactive low in the northeast corner of the map area, which is evident on all the aerial radiometric maps. The predominantly subglacial till of this region (Marshall till plain; Fig. 6) is similar in texture and lithology to till of the Bemis moraine (Buffalo Ridge; Fig. 6). Another area of low radioactivity, in northeastern Rock County, may be associated with sand and gravel deposits of pre-Wisconsin ice positions.

Loess was usually too thin (2 m or less) and discontinuous to map at the intermediate scale of the surficial map (Patterson, 1995), although its presence could appreciably affect the radioactivity measured at the land surface. This lack of detail on loess distribution makes it difficult to interpret a radioactivity signature for a mapped surface glacial unit; a unit may well be below the 12-inch depth from which gamma radiation is emitted. The large drainage channels on the western edge of the Verdi till plain (Fig. 6) are not well defined in the radioactivity maps, even though they are composed predominantly of sand and gravel and would be expected to show as linear features of low activity. The sand and gravel deposits may have radioactive-element concentrations similar to the surrounding tills, or, more likely, the surface has a radioactive signature (possibly reflecting a thin or discontinuous cover of loess) that does not represent the sands and gravels on the surficial geologic map (Patterson, 1995).

A Surface Mapping Tool?

Sediment and surface radioactivity were measured for this study to verify and augment the aerial radiometric data and to assess the relative usefulness of the two data sets in surficial geologic mapping. Despite significant differences in the density and distribution of sample points, at a regional scale the two data sets agree fairly well. Within the study area, the aerial radiometric data were used to identify variations in radionuclide activities in surface sediments. In fact, the aerial radiometric data were more useful



EXPLANATION

Geomorphic Regions

1 Trosky till plain
Dissected pre-Wisconsin till plain overlain by windblown sediment in southwest corner. Loess border and heads of earlier drainages may delimit former ice margin(s).

2 Verdi till plain
Eroded till plain of Wisconsin Verdi ice position. No prominent end moraine. Recognized by heads of drainages.

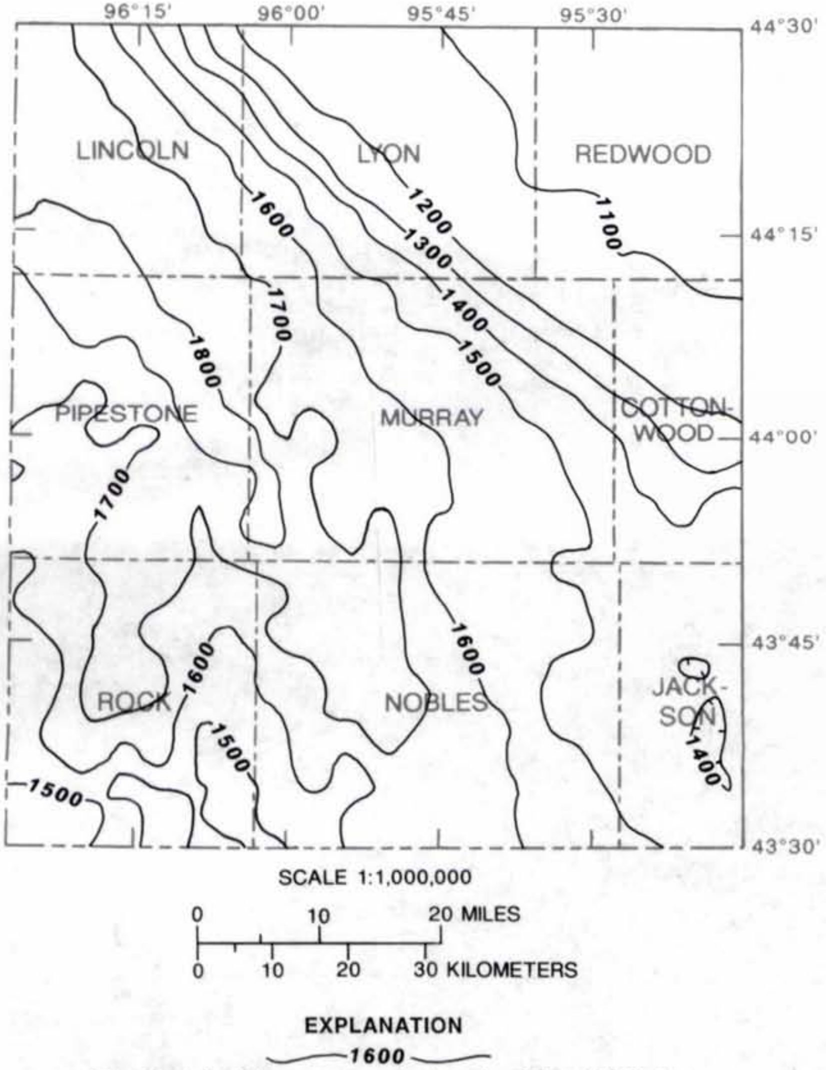
3 Buffalo Ridge
Prominent Late Wisconsin Bemis moraine. Regional divide for Missouri and Mississippi Rivers. Becomes broader and less distinct southward.

4 Hummocky highlands
Ice-stagnation topography. Thick, heterogeneous supraglacial deposits.

5 Coteau slope
Northeast-facing slope of the Coteau des Prairies, a glacial erosional scarp. Less distinct to southeast.

6 Marshall till plain
Flay-lying till plain. Consists of thin subglacial till, locally overlain by thin, patchy supraglacial till.

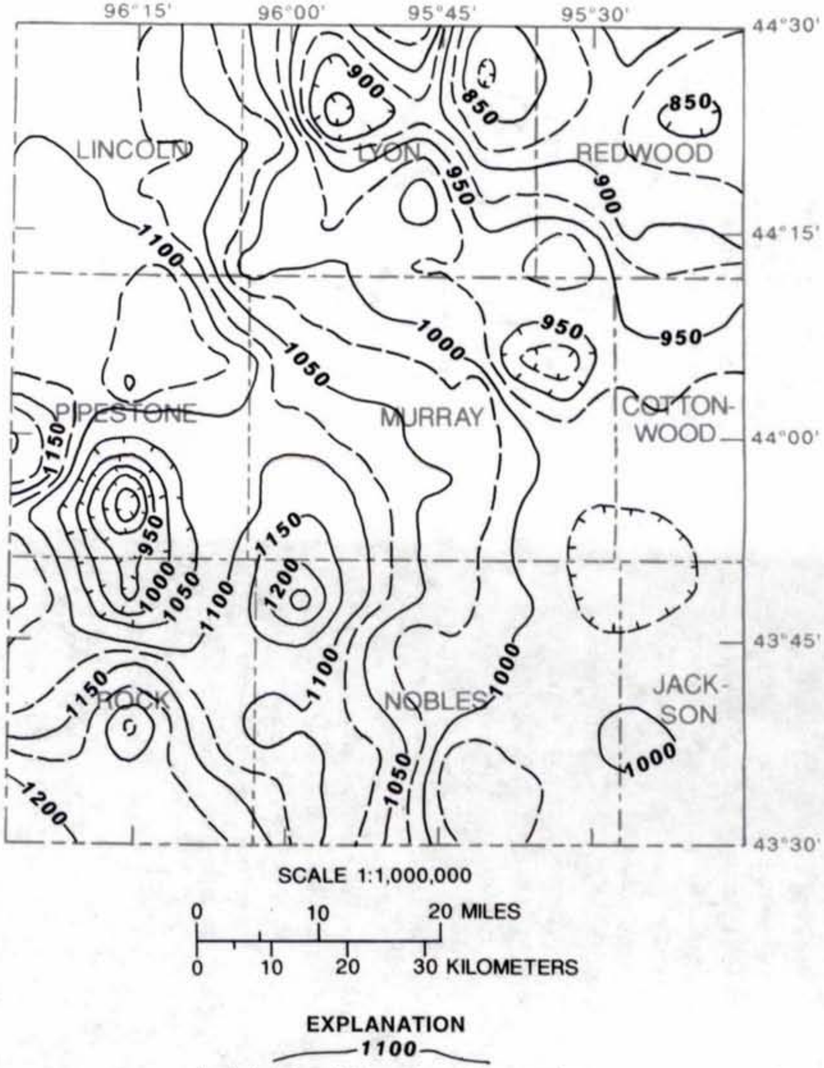
Figure 6. Geomorphic regions and glacial landforms of southwestern Minnesota.



EXPLANATION

Elevation in feet above mean sea level; contour interval 100 feet; hachures enclose areas of lower elevation

Figure 7. Surface topography in the area of the southwestern Minnesota hydrogeologic assessment.



EXPLANATION

Isopleth interval 50 counts per 30 seconds;
supplementary isopleths (dashed) at intervals of 25 counts per 30 seconds;
hachures enclose areas of lower values

Figure 8. Total gamma activity at the ground surface in the area of the southwestern Minnesota hydrogeologic assessment.

than analyses of scattered soil samples for identifying regional trends and distinguishing surficial geologic units. However, the aerial radiometric data were less likely to differentiate small, local anomalies that were identified through analyses of individual ground samples.

Although the contoured aerial radiometric data can be used to distinguish relatively small differences in radionuclide activity of surface sediments, assigning a radioactive signature to individual surficial units is difficult. A surface sediment may be too thin to be mapped, yet thick enough to be the principle source of airborne radiation. For example, high eTh values in the western part of the study area trend northwest from till of pre-Wisconsin age across the younger Des Moines lobe till of the Verdi till plain and Bemis moraine (Fig. 6). These younger units, to the east, have radioactive signatures different from the pre-Wisconsin units in the southwest. Though clearly differentiated on the surficial geologic map (Patterson, 1995), The pre-Wisconsin and Des Moines units along the western margin of the study area have very similar levels of radioactivity. It is probable but not conclusive that the radioactive similarity is due to thin, unmapped loess that covers the sediments. If the entire study area is considered, however, the loess, if present, does not obscure the regional geologic trends or the boundaries between the major surficial geologic units. It is notable that the eroded subglacial till of the Des Moines lobe in the northeast part of the study area—a region consistently lower in radioactivity—has no mapped loess.

Moisture content in surface sediments also influences aerial radioactivity measurements. Water-saturated soils attenuate gamma radiation more effectively than dry soils. When measured with remote detection systems, soils having equal quantities of radionuclides may show different levels of gamma radioactivity according to their degree of water saturation. The degree of moisture retention, combined with the mineralogy and lithology of surface sediment, may in part explain why the northeastern corner of the study area is consistently low in radioactivity relative to the rest of the study area. However, without measurements of the concentration of radioactivity in soil samples and more complete characterization of the surface materials, it is impossible to determine the cause of the lower radiation activities. Regardless, radioactivity does correspond with changes in mapped glacial materials, so a lack of detailed source description does not significantly detract from the observed correlations.

CONCLUSIONS

Low-resolution, aerial-gamma-radiation surveys can broadly differentiate surficial geologic units on the basis of radioactivity emanating from the land surface. The aerial radiation data are consistent with activity measurements and regional distribution patterns in surface sediments. Low-resolution ground-based radioactivity measurements are more variable and do a poorer job of distinguishing surficial geologic units. This finding is not unexpected, as the aerial radiometric results averaged data over much larger sampling areas. Determining a quantitative relationship between aerial radiation data and measurements in surface sediments was not possible because of the differences in sampling density and because absolute radionuclide concentrations and moisture contents in the sediments were not measured. These deficiencies did not prevent correlation of variations in radioactivity with mapped surficial geologic units. However, more complete data on the location of radionuclides in the sediments (i.e., association with fine- or coarse-grained material, a particular rock type or mineral suite) and the influence of moisture (and by association topographic differences and soil type) would enhance the interpretation of gamma radiation data from surficial geologic materials.

The exercise described in this paper shows that aerial gamma radiation is in fact a useful reconnaissance tool in surficial geologic mapping. It distinguishes broad differences within and between geologic units based on measurable radioactivity from naturally occurring radioactive elements. For the study area, the radioactivity maps showed some regional differences from the surface geologic maps, further indicating their usefulness. By indicating that surficial materials contain more variability than shown on a surficial geologic map, the radioactivity data can provide a regional-scale screening tool to identify where the surface materials may be are different from those mapped or where more detailed surficial mapping could be carried out.

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Appendix

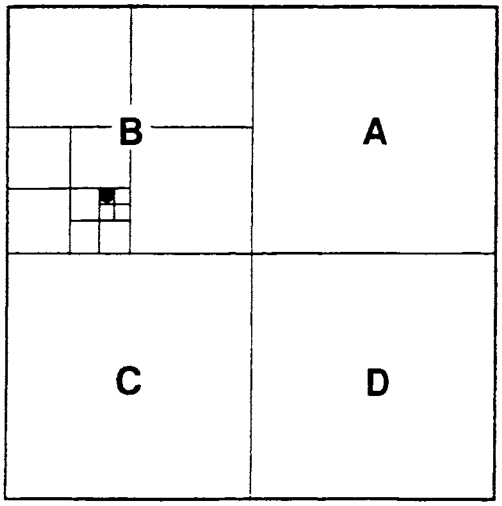
Descriptive Logs of Selected Boreholes

EXPLANATION

T-R-S subsection—See diagram below.

Color—Color descriptors from:

Munsell Color, 1994, Munsell soil color charts (1994 rev. ed.): New Windsor, N.Y., Macbeth Division of Kollmorgen Instruments Corp., 1 vol. (loose-leaf).



The location of drill holes is described by township number (T), range number (R), section number (S), and subdivisions of sections by quarters. The abbreviated T-R-S system used here reflects the fact that all townships in southwestern Minnesota are north of a zero standard parallel, and west of a zero principal meridian, thus N and W are implied. The system used by the Minnesota Geological Survey to subdivide a section (one square mile) assigns letters to the quarters of a section where A is the NE1/4, B is the NW1/4, C is the SW1/4, and D is the SE1/4. Each quarter is then subdivided into four more quarters using the letter system. In listing quarters the largest subdivision is given first and each quarter of a quarter is given in succession. In the example above, the subdivisions of the section would read BCDAB.

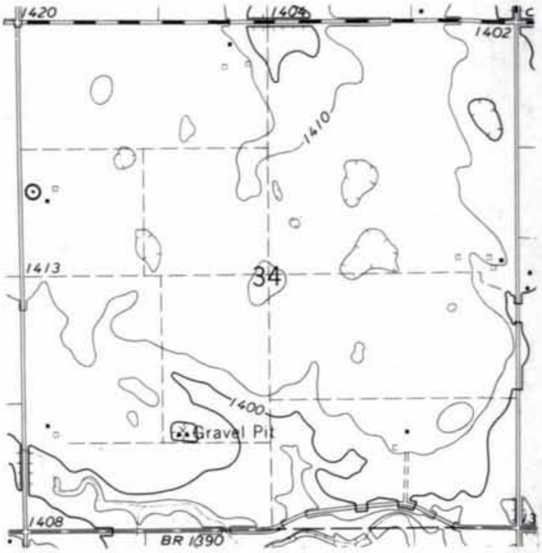
Diagram to illustrate the process of locating a drill hole (bullet) within a section by means of the abbreviated T-R-S system.

Field number: **SWRA-1**
MGS unique number: 249609
Date finished: 1-14-93

LOCATION
Cottonwood County
T. 107 N., R. 38 W., sec. 34 BCBCB
Westbrook 7.5-minute quadrangle

HOLE PARAMETERS
Surface elevation: 1415 +/- 5 ft
Total depth: 214 ft
Core interval: 0-214 ft

Described by C. Patterson, B. Lusardi and A. Knaeble



LITHOLOGIC LOG (intervals recorded are depths in feet)

INTERVAL	DESCRIPTION
0–.5	Black topsoil.
.5–7	Silt, light olive brown (2.5 Y 5/4), oxidized, calcareous; trace of very fine sand that increases in amount and size with depth; few pebbles. *Lacustrine or alluvial sediment.*
7–13.5	Loam till, light olive brown (2.5 Y 5/4), oxidized, calcareous, pebbly; pebbles are carbonate, granitic, mafic, and shale; a few fine sand lenses. *Oxidized Des Moines till.*
13.5–16.5	Loam till, light olive brown (2.5 Y 5/4) and dark gray (2.5 Y 3/0), partially oxidized, interbedded; pebbly; pebbles same as in above interval plus gypsum crystals. *Partially oxidized Des Moines till.*
16.5–60	Loam till, dark gray (2.5 Y 3/0), calcareous, pebbly; pebbles are carbonate, granitic, mafic, and shale; some chert pebbles; some lignite at 50 ft. *Unoxidized Des Moines till.*
60–76	Sand; no recovery; sample lost.
76–150	Loam till, dark gray (2.5 Y 3/0), calcareous, pebbly; pebbles are carbonate, granitic, mafic, and shale; some sand and gravel beds at 77–79, 85–88, 102–104; 122–123.5, 149–150 ft; thin gray beds and lenses of silt at 76–102 ft; more clay and cobbles at 125–150 ft. *Unoxidized Des Moines till.*
150–190	Loam till; composed of light yellowish brown (2.5 Y 6/4) and very dark grayish brown (2.5 Y 3/2) zones; partially oxidized, calcareous, pebbly; pebbles are carbonate, granitic, and mafic; some chert and a few rhyolite pebbles, no shale pebbles; lignite and gypsum crystals below 185 ft. *Partially oxidized older till.*
190–200	Loam till, dark gray (2.5 Y 3/0), calcareous, clayey, pebbly; pebbles are carbonate, granitic, mafic, and gypsum; no shale pebbles; some wood fragments; thin oxidation zone at 197.5 ft; abundant carbonate flakes. *Unoxidized older till.*
200–214	Loam till, olive brown (2.5 Y 4/4), gray (10 YR 6/1), and yellowish brown (10 YR 5/4), very hard, deformed, clayey; oxidation varies; pebbly; pebbles are carbonate, chert, dark mafic, and gypsum; brownish yellow (10 YR 6/8) sand grades downward into gray silt at 205–208 ft. This till has distinct features: very dense, distorted, locally swirled, stained; it has a rotten, weathered appearance. White gypsum crystals. Abrupt change at 200 ft noted by drillers and in gamma log. *Deformed second old till.*

Field number: **SWRA-2**
MGS unique number: 249610
Date finished: 1-14-93

LOCATION
Murray County
T. 106 N., R. 41 W., sec. 23 BAAAC
Avoca 7.5-minute quadrangle

HOLE PARAMETERS
Surface elevation: 1595 +/- 5 ft
Total depth: 265 ft
Core interval: 0–265 ft

Described by C. Patterson, B. Lusardi and A. Knaeble

LITHOLOGIC LOG (intervals recorded are depths in feet)

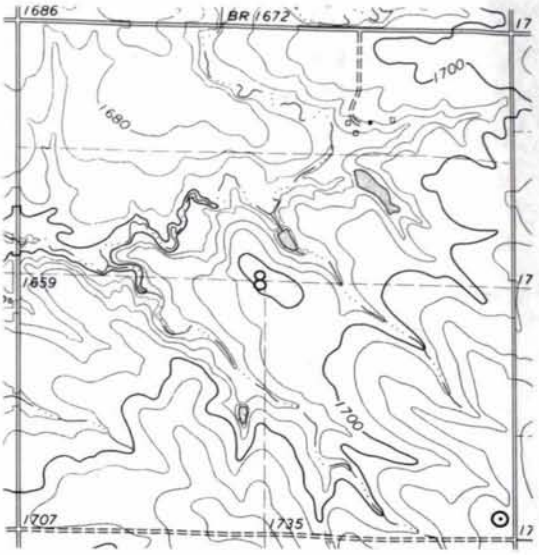
INTERVAL	DESCRIPTION
0–6	Fill (gravel and oxidized till); six-inch layer of black soil at base.
6–22	Loam till, brownish yellow (10 YR 6/6); gray mottling; oxidized, calcareous, pebbly; below depth of 10 ft, oxidation diminishes as very dark gray (2.5 Y 3/1), slightly oxidized to unoxidized till predominates; pebbles are carbonate, granitic, mafic, and shale. *Partially oxidized Des Moines till.*
22–130	Loam till, very dark grayish brown (2.5 Y 3/2) and dark gray (2.5 Y 3/0), calcareous, pebbly; pebbles are carbonate, granitic, mafic, and shale; some chert, pyrite, and lignite pebbles; a few rhyolite pebbles; deformation at lower contact shows silt mixed with till. *Unoxidized Des Moines till.*
130–247.5	Sand, light yellowish brown (2.5 Y 6/3), calcareous, feldspathic. Where present, pebbles are granitic, mafic, carbonate, shale, and red volcanic rock fragments. 130–180 Silty fine sand with some thin silt beds; lignite and twigs at 160 ft. 180–205 Coarse sand with some pebbles; a few beds of fine to medium sand. 205–247 Interbedded fine sand, silty clay, clayey silt, and coarse sand with pebbles.
247.5–260	Loam till, very dark grayish brown (2.5 Y 3/2) and olive brown (2.5 Y 4/3), slightly oxidized, calcareous, pebbly; few shale pebbles; thin bed of fine to medium sand at 251 ft. *Slightly oxidized old till.*
260–265	Very hard; changed bit and cored; dropped and lost sample. *Presumed bedrock.*

Field number: **SWRA-3**
MGS unique number: 249611
Date finished: 1-23-93

LOCATION
Pipestone County
T. 107 N., R. 46 W., sec. 8 DDDD
Elkton SW 7.5-minute quadrangle

HOLE PARAMETERS
Surface elevation: 1735 +/- 5 ft
Total depth: 295 ft
Core interval: 0-295 ft

Described by C. Patterson



LITHOLOGIC LOG (intervals recorded are depths in feet)

INTERVAL	DESCRIPTION
0–2.5	Black topsoil, one-ft thick, over olive brown (2.5 Y 4/3), noncalcareous, very fine sandy silt. *Loess.*
2.5–25	Loam till, light olive brown (2.5 Y 5/6–5/3); oxidized to partially oxidized, mottled, calcareous, pebbly; pebbles are carbonate, granitic, mafic, and shale. *Oxidized and partially oxidized old till.*
25–36	Clay, very dark grayish brown (2.5 Y 3/2), unoxidized, noncalcareous, silty. Overlain and interbedded with yellow brown (2.5 Y 5/4), oxidized, slightly calcareous (increasing to calcareous with depth), silty clay; faint laminations; secondary carbonate concretions, silt, sand, and deformation at 34.5–36 ft. *Lacustrine sediment.*
36–71	Clay loam till, light olive brown (2.5 Y 5/4), calcareous, oxidized, pebbly; pebbles are carbonate, shale, mafic, granitic, siltstone, and rhyolite; some gypsum crystals below 68 ft; secondary carbonate pebbles and thin marl beds at top of unit; secondary manganese coating on pebbles. *Oxidized second old till.*
71–132	Clay loam till, very dark gray (2.5 Y 3/1–3/0), unoxidized, calcareous, pebbly; pebbles are carbonate, granitic, mafic, Greenhorn Formation limestone, red rhyolite, iron-formation, gypsum, and sandstone; gray chalk clasts (possibly from the Niobrara Formation); trace amounts of pyrite and wood; some mottling; rounded and polished pebbles and cobbles at 132 ft. *Unoxidized second old till.*
132–136	Silt and clay, dark gray (5 Y 4/1), calcareous, organic-rich. *Lacustrine sediment.*
136–195	Clay loam till, light olive brown to olive brown (2.5 Y 5/4–4/3), oxidized, calcareous, pebbly; pebbles are carbonate, dark-gray waxy shale, Greenhorn Formation limestone, granitic, mafic, gypsum; trace amounts of chert and quartzite pebbles; bentonite clasts(?); possible wave-washed till at 136–138 ft. *Oxidized third old till.*
195–208	Fine to medium sand, light olive brown (2.5 Y 5/6), calcareous; coarse sand at 207 ft. *Fluvial sediment.*
208–226	Silt, light olive brown (2.5 Y 5/6–5/4), gray-mottled, calcareous, clayey; a few pebbles. *Lacustrine sediment.*

226–231	Loam till, very dark grayish brown (2.5 Y 3/2), calcareous, pebbly; pebbles are carbonate, granitic, mafic; trace of shale pebbles. *Faintly oxidized fourth old till.*
231–249	Silt, yellow brown (2.5 Y 5/4), oxidized, calcareous, clayey; thin beds and zones of sand, sand and gravel, and till balls; chalk pebbles and a large limestone cobble at lower contact. *Fluvial and lacustrine sediment.*
249–269	Clay, variably gray brown, laminated, silty; interbedded with pebbly till and yellow-brown gravel and sand layers; many of the interbeds are thin; pebbles are carbonate, granitic, mafic, and shale. *Ice-contact sediment.*
269–295	Loam till, dark gray (2.5 Y 3/0), unoxidized, calcareous, dense, clayey; many thin sand and gravel beds; pebbles are carbonate, granitic, mafic, soft shale, and Sioux Quartzite. *Fifth old till.*

Field number: **MGS 2873 (KNF 188)**
MGS unique number: 249611

LOCATION
Lincoln County
T. 110 N., R. 45 W., sec. 31 CDDC
Lake Benton 7.5-minute quadrangle

HOLE PARAMETERS
Surface elevation: 1920 +/- 5 ft
Total depth: 824 ft
Core interval: 638-824 ft

Described by A Knaeble

LITHOLOGIC LOG (intervals recorded are depths in feet)

INTERVAL	DESCRIPTION
0–5	Sand, light olive brown (2.5 Y 5/4), calcareous, shaly, gravelly, clayey, silty. *Oxidized sandy till.*
5–25	Similar to 0–5 ft; less oxidation; samples collected every five feet within this interval.
25–30	Sand, moderately sorted, medium-coarse; trace of gravel. *Outwash.*
30–40	Similar to 25–30 ft.
40–45	Sand, light olive brown (2.5 Y 5/4); calcareous and shaly gravel; silty. *Slightly oxidized till.*
45–80	Similar to 40–45 ft.
80–240	Similar to 40–45 ft; unoxidized.
240–245	Sand, light yellowish brown (2.5 Y 6/3), calcareous, shaly, gravelly, silty. *Oxidized old till.*
245–270	Similar to 240–245 ft.
270–305	Similar to 240–245 ft; less oxidation.
305–310	Sand, gray (2.5 Y 5/1), calcareous, shaly, gravelly, silty. *Unoxidized old till.*
310–628	Similar to 305–310 ft.

628–638 ....No sample.

638–647 ....Till, gray (2.5 Y 5/1), hard, calcareous; aligned pebbles (10 degrees from horizontal) and fabric; clayey silty sand. Gravel is oriented, striated, and polished; 2–4-cm fraction mostly limestone, dark and light igneous rock fragments, shale, and a trace of pyrite. *Unoxidized till.*

647–656 ....Similar to 638–647 ft; piece of charcoal (1–2 cm) at 650 ft.

656–665 ....Similar to 638–647 ft; no charcoal or pyrite; trace of conchoidal and polished chert.

665–675 ....Similar to 638–647 ft; no chert.

675–684 ....Similar to 638–647 ft; more and larger fragments of gravel (2–6 cm) and sand; slightly less consolidated.

684–694 ....Similar to 638–647 ft; very hard and brittle (more clay?); some disc-shaped pyrite.

694–703 ....Similar to 638–647 ft.

703–712 ....Similar to 638–647 ft; some chert pebbles.

712–721 ....Similar to 638–647 ft; slight decrease in gravel; slight increase in silt.

721–731 ....Similar to 638–647 ft but more silt, fewer pebbles; granite cobbles (10–15 cm) at 730 ft; charcoal or wood (5–25 mm) at 724 ft; slight oxidation (2.5 Y 5/2) from about 723 ft to 729 ft; stronger oxidation at 726 ft extending about 5 cm (10 YR 5/4) and at 728 ft, about 3 cm (2.5 Y 6/6).

731–736 ....Till; grayish brown (2.5 Y 5/2) when dry, dark gray (2.5 Y 4/1) when wet; moderately hard; aligned pebbles and fabric; less clay than 721–731 ft, more fine sand and silt, fewer pebbles (limestone, chert, shale, igneous); 5–20-mm piece of wood at 737 ft. *Slightly oxidized silty till.*

736–738 ....Sand, grayish brown (2.5 Y 5/2) when dry; very dark grayish brown (2.5 Y 3/2) when wet; silty, very fine to medium; trace amount of gravel. *Lacustrine sediment.*

738–739 ....Sand and silt, gray (2.5 Y 6/1) when dry, dark gray (2.5 Y 4/1) when wet; some clay(?) lamination along bedding. *Lacustrine sediment.*

739–742 ....Sand, gray (colors similar to 738–739 ft), very fine to fine, silty; trace amount of gravel; bedding and cross-bedding. *Lacustrine sediment.*

742–751 ....Sand, gray (colors similar to 738–739 ft), silty, very fine to fine; cross-bedding; slightly coarser than 739-742 ft. *Lacustrine sediment.*

751–793 ....Gravel, poorly sorted, very coarse (dark and light igneous rock fragments, limestone, shale, and chert). *Outwash.*

793–824 ....Similar to 751-793 ft; fine to coarse, subrounded to angular sand. *Outwash.*

Field number: **MGS 444** (U.S. Geological Survey Coteau #2 Deep)
MGS unique number: 235582

LOCATION
Lincoln County
T. 110 N., R. 44 W., sec. 33 DCAC
Tyler 7.5-minute quadrangle

HOLE PARAMETERS
Surface elevation: 1738 +/- 5 ft
Total depth: 971 ft
Core interval: 455-971 ft

Described by A. Knaeble

LITHOLOGIC LOG (intervals recorded are depths in feet)

INTERVAL	DESCRIPTION
0–10	Sand, pale yellow (2.5 Y 7/3), clayey, silty. *Oxidized till.*
10–20	Sand, pale yellow (2.5 Y 7/3), clayey, silty, calcareous, shaly, gravelly. *Oxidized till.*
20–30	Similar to 10–20 ft.
30–40	Similar to 10–20 ft.
40–50	Sand, gray (2.5 Y 6/1), clayey, silty, calcareous, shaly, gravelly. *Unoxidized till.*
50–60	Similar to 40–50 ft..
60–130	Similar to 40–50 ft.
130–140	Sand, moderately sorted, fine to coarse. *Ice contact or outwash.*
140–150	Sand, gray (2.5 Y 6/1), clayey, calcareous, shaly, gravelly, silty. *Unoxidized till (possibly a second till).*
150–200	Similar to 140–150 ft.
200–210	Gravel, poorly sorted, calcareous, shaly, sandy. *Outwash.*
210–220	Similar to 200–210 ft.
220–230	Similar to 200–210 ft.
230–240	Sand, gray (2.5 Y 6/1), calcareous, shaly, gravelly, clayey, silty. *Older till.*
240–250	Similar to 230–240 ft.
250–260	Gravel, gray (2.5 Y 6/1), sandy, clayey, silty, shaly, slightly calcareous. *Older till.*
260–290	Similar to 250–260 ft.
290–300	Similar to 250–260 ft; slightly darker; trace of lignite.
300–380	Similar to 250–260 ft.
380–390	Some of 250–260 ft and pale yellow (2.5 Y 7/3), clayey, calcareous, shaly, gravelly, sandy silt. *Oxidized old till.*
390–400	Silt, pale yellow (2.5 Y 7/3), clayey, calcareous, shaly, gravelly, sandy. *Older till..*
400–445	Similar to 390–400 ft.
445–455	No sample.
455–465	Sand, streaked and mottled light yellowish brown to gray (2.5 Y 6/4–6/1); calcareous, gravelly, silty, clayey; trace of shale. *Partially oxidized, hard, calcareous, old till.*

465–475........Similar to 455–465 ft.
475–493........Similar to 455–465 ft; yellow gray to gray (2.5 Y 6/2–6/1).
493–504........Similar to 455–465 ft; more oxidized sand lenses. *Sandy till.*
504–515........Sand, light gray (2.5 Y 7/2), silty, fine, well-sorted. *Lacustrine sediment.*
515–517........*Till.*
517–531........Sand.
531–535........Sand, light yellowish brown to light brownish gray (2.5 Y 6/3–6/2), calcareous, gravelly, clayey, silty; trace amount of shale. *Sandy old till.*
535–553........Gray old till similar to 531–535 ft with layers of shale at 536–540 ft; red brown colors at lower contact. *Mixed till.*
553........Cretaceous sandstone, siltstone, and shale beds.

Hole drilled to 971 ft; remainder not described for this project.