MINNESOTA GEOLOGICAL SURVEY

Harvey Thorleifson, Director

GUIDEBOOK 22

LANDFORMS, STRATIGRAPHY, AND LITHOLOGIC CHARACTERISTICS OF GLACIAL DEPOSITS IN CENTRAL MINNESOTA

POWDER RIDGE SITE

Alan R. Knaeble, Coordinator

Prepared for the 50th Midwest Friends of the Pleistocene Field Conference

St. John's University, Minnesota

June 4-6, 2004

UNIVERSITY OF MINNESOTA

2006

Meetings of the Midwest Friends of the Pleistocene

1	1950	Eastern Wisconsin	
2	1951	Southeastern Minnesota	H.E. Wright, Jr. and R.V. Ruhe
3	1952	Western Illinois and eastern Iowa	P.R. Shaffer and W.H. Scholtes
4	1953	Northeastern Wisconsin	F.T. Thwaites
5	1954	Central Minnesota	H.E. Wright, Jr., and A.F. Schneider
6	1955	Southwestern Iowa	R.V. Ruhe
7	1956	Northwestern lower Michigan	J.H. Zumberge and W.N. Melhorn
8	1957	South-central Indiana	W.D. Thornbury and W.J. Wayne
9	1958	Eastern North Dakota	W.M. Laird and others
10	1959	Western Wisconsin	R.F. Black
11	1960	Eastern South Dakota	A.G. Agnew and others
12	1961	Eastern Alberta	C.P. Gravenor and others
13	1962	Eastern Ohio	R.P. Goldthwait
14	1963	Western Illinois	J.C. Frye and H.B. Willman
15	1964	Eastern Minnesota	H.E. Wright, Jr. and E.J. Cushing
16	1965	Northeastern Iowa	R.V. Ruhe and others
17	1966	Eastern Nebraska	E.C. Reed and others
18	1967	South-central North Dakota	Lee Clayton and T.F. Freers
19	1969	Cyprus Hills, Saskatchewan and Alberta	W.O. Kupsch
20	1971	Kansas and Missouri Border	C.K. Bayne and others
21	1972	East-central Illinois	W.H. Johnson and others
22	1973	West-central Michigan and east-central Wisconsin	E.B. Evenson and others
23	1975	Western Missouri	W.H. Allen and others
24	1976	Meade County, Kansas	C.K. Bayne and others
25	1978	Southwestern Indiana	R.V. Ruhe and C.G. Olson
26	1979	Central Illinois	L.R. Follmer and others
27	1980	Yarmouth, Iowa	G.R. Hallberg and others
28	1981	Northeastern lower Michigan	W.A. Burgis and D.F. Eschman
29	1982	Driftless Area, Wisconsin	J.C. Knox and others
30	1983	Wabash Valley, Indiana	N.K. Bleuer and others
31	1984	West-central Wisconsin	R.W. Baker
32	1985	North-central Illinois	R.C. Berg and others
33	1986	Northeastern Kansas	W.C. Johnson and others
34	1987	North-central Ohio	S.M. Totten and J.P. Szabo
35	1988	Southwestern Michigan	G.J. Larson and G.W. Monaghan
36	1989	Northeastern South Dakota	J.P. Gilbertson
37	1990	Southwestern Iowa	E.A. Bettis III and others
38	1991	Mississippi Valley, Missouri and Illinois	E.R. Hajic and others
39	1992	Northeastern Minnesota	J.D. Lehr and H.C. Hobbs
40	1993	Door Peninsula, Wisconsin	A.F. Schneider and others
41	1994	Eastern Ohio and western Indiana	T.V. Lowell and C.S. Brockman
42	1995	Southern Illinois and southeast Missouri	S.P. Esling and M.D. Blum
43	1996	Eastern North Dakota and northwestern Minnesota	K.I. Harris and others
44	1998	North-central Wisconsin	J.W. Attig and others
45	1999	North-central Indiana and south-central Michigan	S.E. Brown, T.G. Fisher, A.E. Kehew, and L.D. Taylor
46	2000	Southeastern NB and Northeastern KA	R.D. Mandel and E.A. Bettis III
47	2001	Northwestern ON and Northeastern MN	B.A.M. Phillips and others
48	2002	East-Central Upper Michigan	W.L. Loope and J.B. Anderton
49	2003	Southwest Michigan	B.D. Stone and K.A. Kincare and others
50	2004	Central Minnesota	A.R. Knaeble, G.N. Meyer and H.D. Mooers

* No meetings were held in 1968, 1970, 1974, 1977, and 1997.

The 1952 meeting that is commonly included in the list of Midwest FOP meetings as Southwestern Ohio was actually an Eastern FOP meeting in central Ohio, to which Midwest Friends were invited by Dick Goldthwait the previous week in Western Illinois.

UNIVERSITY OF MINNESOTA

MINNESOTA GEOLOGICAL SURVEY

LANDFORMS, STRATIGRAPHY, AND LITHOLOGIC CHARACTERISTICS OF GLACIAL DEPOSITS IN CENTRAL MINNESOTA

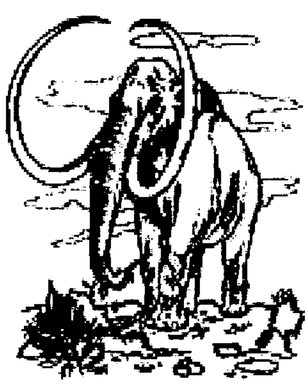
50th Midwest Friends of the Pleistocene Field Conference
Guidebook and Field Trip Road Log

June 4-6, 2004
Collegeville, Minnesota

Alan R. Knaeble, Minnesota Geological Survey, Coordinator
Gary N. Meyer, Minnesota Geological Survey, Contributor
Howard D. Mooers, University of Minnesota Duluth, Contributor

Convened by The Friends of the Pleistocene
and the Minnesota Geological Survey

Hosted by St. John's University/College of St. Benedict



MINNESOTA GEOLOGICAL SURVEY 1872

This publication is accessible from the home page of the Minnesota Geological Survey (http://www.geo.umn.edu/mgs) as a PDF file readable with Acrobat Reader 4.0.
Date of release: April, 2006

Recommended citation
Knaeble, A.R., coordinator, 2006, Landforms, stratigraphy, and lithologic characteristics of glacial deposits in central Minnesota: Minnesota Geological Survey Guidebook 22, 44 p.

On the cover: Borrow pit at the Powder Ridge ski hill near Kimball, Minnesota showing glacio-tectonic thrusting of Cretaceous bedrock and older pre-Wisconsinan sediments; photos by Alan R. Knaeble

Minnesota Geological Survey
2642 University Avenue West
Saint Paul, Minnesota 55114-1057

Telephone: 612-627-4780
Fax: 612-627-4778
E-mail address: mgs@tc.umn.edu
Web site: http://www.geo.umn.edu/mgs

ISSN 0192-6268

LANDFORMS, STRATIGRAPHY, AND LITHOLOGIC CHARACTERISTICS OF GLACIAL DEPOSITS IN CENTRAL MINNESOTA

50th Meeting of the Midwest Friends of the Pleistocene Field Conference

General Itinerary

Day 1; June 4, Friday

5:00-9:00 pm	registration and lodging check-in at Mary Hall; park in Mary Hall lot
6:00-11:00 pm	relaxation, libation, poster and map display, and discussion in Willie's Pub located in Sexton Commons—connected to Mary Hall

Day 2; June 5, Saturday

6:30-7:15 am	breakfast at campus dining hall—building with tower, S of Mary Hall
7:15-7:30 am	assemble in Mary Hall parking lot
7:30 am	depart
7:30-8:00 am	travel
8:00-9:00 am	**Stop 1**—Mayer's pit; SE of Melrose; Des Moines-lobe till/lacustrine sediments/Superior-lobe sand and gravel fan deposit
9:00-9:15 am	travel
9:15 am	**Stop 2**—St. Rosa esker drive-by; N of Freeport; Des Moines-lobe till/ Superior-lobe till/Superior-lobe sand and gravel esker deposits
9:15-9:30	travel
9:30-10:15 am	**Stop 3**—Wielenberg pit; W of Sylvia Lake; Wadena-lobe recessional moraine, till and sand and gravel deposits; **Refreshment break.**
10:15-10:45 am	travel
10:45-11:00 am	**Stop 4**—Superior-lobe till road cut; N of Big Swan Lake
11:00-11:15 am	travel
11:15-11:45 am	**Stop 5**—Gessel pit; W of Pillsbury; Superior-lobe till/Browerville till
11:45-12:00 pm	travel
12:00-12:30 pm	**Stop 6**—Loven's Swanville pit; Superior-lobe till/Browerville till/pre-Wisc. silty till/soil horizon/pre-Wisc. silty carbonate-rich till/silt
12:30-12:45 pm	travel
12:45-1:30 pm	**Lunch**—at Lake Charlotte park S of Long Prairie
1:30-1:45 pm	travel
1:45-2:30 pm	**Stop 7**—Johnson pit; in spillway E of Long Prairie; Superior-lobe sand and gravel/Browerville till
2:30-3:00 pm	travel
3:00-3:15 pm	**Stop 8**—Radio tower view of St. Croix moraine; SW of Browerville.
3:15-3:45 pm	travel
3:45-5:00 pm	**Stop 9**—Stewart pit; S of Staples; drumlin flank with Wadena-lobe till/ Browerville till/sand and gravel; **Refreshments!**
5:00-6:00 pm	travel back to St. John's
7:00-9:00 pm	**Banquet dinner** in the alumni lounge (above the breakfast dinning hall); followed by activities
9:00-11:00 pm	relaxation, libation, poster and map display, and discussion in lounge

Day 3; June 6, Sunday

6:30-7:30 am	breakfast at campus dining hall—building with tower, S of Mary Hall
7:30-7:45 am	assemble in Mary Hall parking lot
7:45 am	depart
7:45-8:00 am	travel
8:00-8:45 am	**Stop 10**—St. John's Arboretum; vegetation restoration project and walk
8:45-9:00 am	travel
9:00-10:00 am	**Stop 11**—Merden Lake esker; Superior-lobe till/incorporated pre-Wisconsinan till/Cretaceous marine sediment/esker core composed of Superior-lobe sand and gravel; **Refreshment break.**
10:00-10:30 am	travel
10:30-12:00 pm	**Stop 12**—Powder Ridge Ski Hill borrow pit; St. Croix terminal moraine formed by Superior-lobe glacio-tectonic thrusting of pre-Wisconsinan drift deposits and Cretaceous marine sediments
12:00-1:00 pm	**Lunch**—On top of Powder Ridge Ski Hill (weather permitting)
1:00-1:30 pm	travel to St. John's
1:30 pm	**Trip completed!**

INTRODUCTION

This guidebook was prepared for the 50th Midwest Friends of the Pleistocene Field Conference, sponsored by the Minnesota Geological Survey and held at St. John's University on June 4-6, 2004. The purpose of this guidebook is to provide conference participants with an up-to-date general summary of the glacial geology of central Minnesota and a comprehensive reference list of previous research completed in the area. There are a number of reasons why we were motivated to host the Friends of the Pleistocene in central Minnesota.

First, over the last 10 years the Minnesota Geological Survey has completed numerous mapping projects in the central Minnesota area (Stearns, Pope, and Crow Wing County atlases; the Otter Tail regional hydrogeological assessment; and the USGS Statemap St. Cloud, Baxter, Brainerd, and Gull Lake quadrangle maps), and is in the process of completing mapping projects in Todd, Traverse, and Grant Counties. The large volume of data (samples and descriptions from outcrops and drill holes) collected from these projects has allowed us to evaluate the work done by previous researchers and contribute new insights and interpretations.

Second, in 1954 Herb Wright, Al Schneider, and Harold Arneman led the 5th Midwest Friends of the Pleistocene field trip in central Minnesota. We will revisit the area, on this 50th anniversary of that trip, to examine how interpretations have changed and evolved. The guidebook will use a simple, direct approach to summarize the region's glacial geology, similar to that used in 1954. It is our intention to pay tribute to the accomplishments of Herb and Al during the field trip and banquet. We will also acknowledge other researchers who, over the last 50 years, have made contributions to the glacial geology of central Minnesota.

Third, we would like to discuss how mapping techniques and technology have changed in the last 50 years. We will examine which techniques have been most effective in understanding the complex stratigraphy of central Minnesota.

Finally, field exposures were selected to stimulate interest and discussion about the following glacial topics: erosion, transport, and deposition of source-area materials; processes involved in drumlin formation; the relationship between ice dynamics and glacial landforms; processes important in the formation of the St. Croix moraine; and the challenges of interpreting thick, complex drift stratigraphy. These stops highlight geomorphic features, stratigraphic relationships, and specific unit characteristics (lithology, color, etc.) in an attempt to provide an overview of the glacial geology of this region.

PREVIOUS RESEARCH

The early work of Winchell and Upham (Upham, 1881, 1896; Winchell and Upham, 1884, 1888; Winchell, 1889) initiated study of the regional aspects of the Pleistocene geology of the Laurentide Ice Sheet in central Minnesota. Leverett's research (1929, 1932), a reevaluation of the surficial geology of the area, led to two significant advances in understanding. He recognized deposits of multiple glacial advances and to each event attributed numerous recessional ice margins and landforms. Cooper (1935) provided detail by defining ice margins in his study of the origin of the Mississippi River (Mooers, 1988, p. 10-11).

From the late 1940s to the mid 1980s a comprehensive statewide understanding of Minnesota's glacial history was compiled under the leadership of Herb Wright (1972, 1973; Wright and Ruhe, 1965). A modern chronology, separating the Late Wisconsinan glacial period into four phases (Wadena, Rainy, Superior, and Des Moines lobes; Fig. 1) and correlating these phases with others throughout the Great Lakes region, was then developed (Wright, 1953, 1954, 1956,

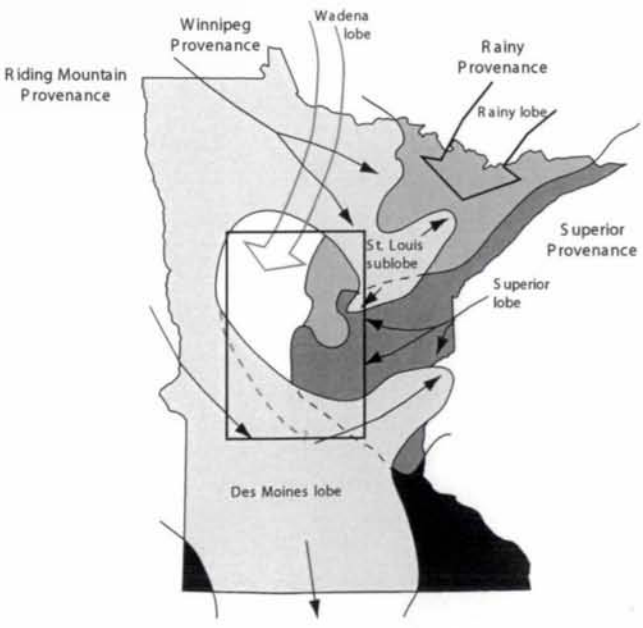


Figure 1. Ice-lobe phases with the approximate flow direction and ice-marginal extent of each lobe and the general locations of the source provenances (modified from Knaeble and Meyer, 2004). Box shows the central Minnesota FOP field conference area.

1962, 1964). In his mapping of the Randall region on the St. Croix moraine, Schneider (1956, 1961) used lithologic and geomorphic evidence to examine the possibility of whether the Wadena lobe, the Brainerd lobe, and the Pierz lobe (Fig. 2) were all contemporaneous (Mooers, 1988, p. 14-15). Anderson (1976) and Perkins (1977) researched the surficial geology in the northwestern portion of central Minnesota. Norton (1983) examined the glacial history in the area around the junction of the Itasca and St. Croix moraines (Fig. 3). Goldstein (1985, 1998) concluded that Wadena lobe ice approached central Minnesota from the northeast (Rainy provenance source area). This conclusion was contrary to Wright's hypothesis that ice advanced initially out of the northwest (Winnipeg provenance carbonate-rich source area), and was subsequently diverted

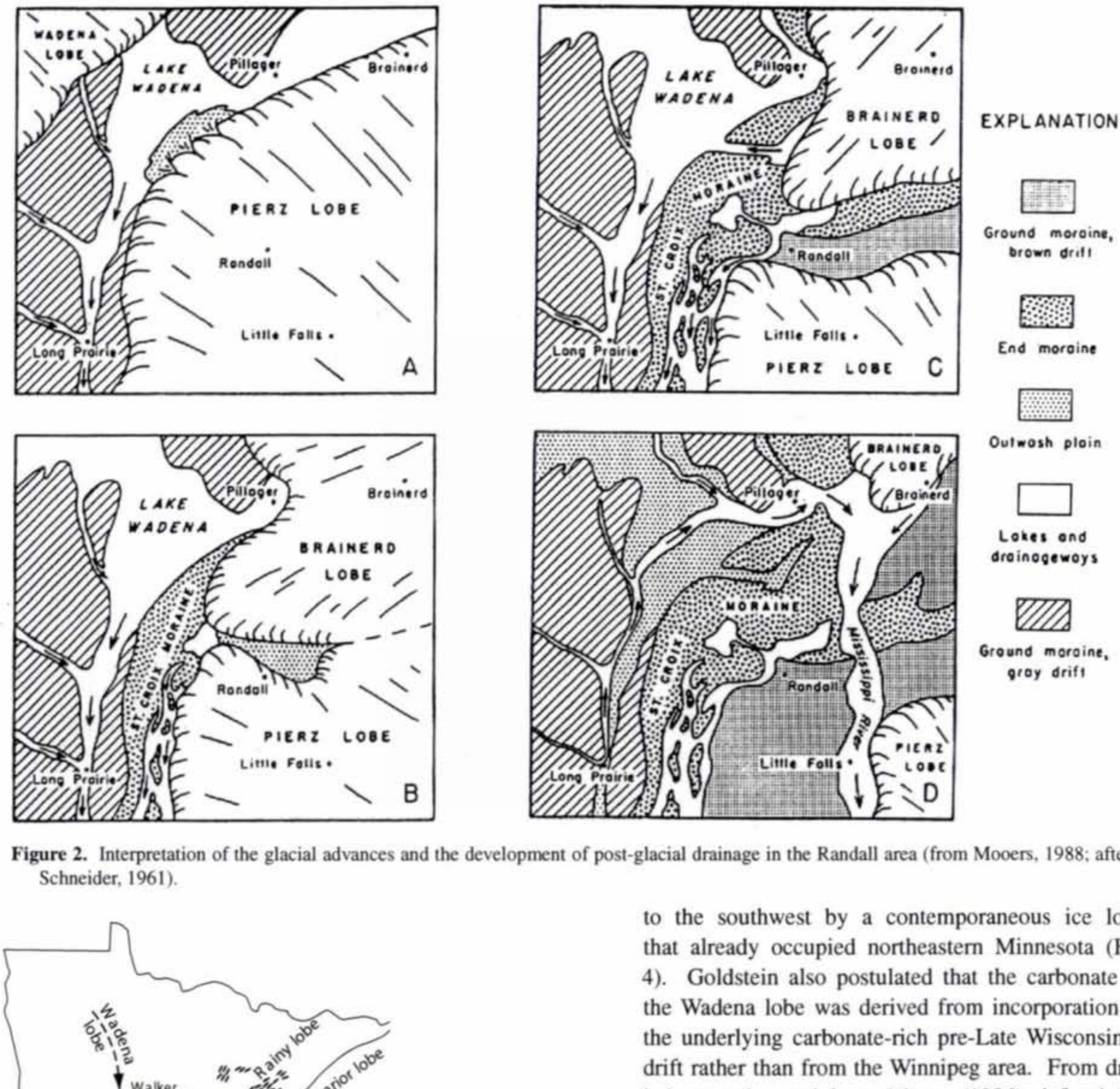


Figure 2. Interpretation of the glacial advances and the development of post-glacial drainage in the Randall area (from Mooers, 1988; after Schneider, 1961).

Figure 3. Location of glacial features in central Minnesota (modified from Johnson and Mooers, 1998; redrawn from Wright and others, 1973).

to the southwest by a contemporaneous ice lobe that already occupied northeastern Minnesota (Fig. 4). Goldstein also postulated that the carbonate in the Wadena lobe was derived from incorporation of the underlying carbonate-rich pre-Late Wisconsinan drift rather than from the Winnipeg area. From drill-hole samples and logs, Meyer (1986) defined the region's complex subsurface stratigraphy, a sequence composed of numerous northwest-source ice advances inter-layered with northeast-source ice advances, distinguished by color, texture, and lithology (Fig. 5). Mooers (1988, 1989a, b) contributed a detailed study of the geomorphology and glacial history of central Minnesota, particularly along the St. Croix moraine. He explored ice dynamics in relation to glacio-tectonic thrusting at the St. Croix moraine ice margin (Mooers,

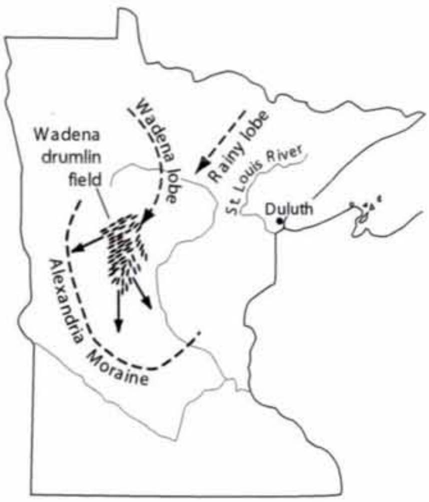


Figure 4. Advance of the Wadena lobe (modified from Johnson and Mooers, 1998; redrawn from Wright and others, 1973).

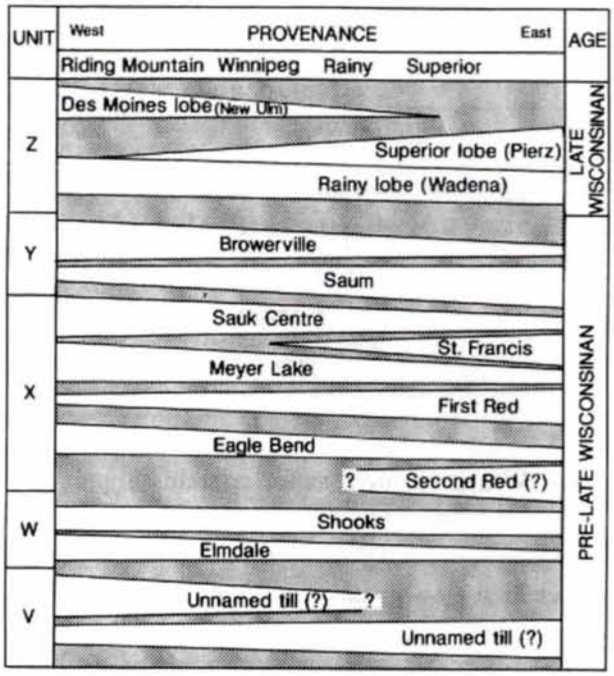


Figure 5. Diagram showing the provenance, and the relative timing, direction, and extent of ice advances that deposited till in central Minnesota (from Meyer and Knaeble, 1996).

1990b), drumlin formation (Mooers, 1988), and the use of statistical techniques in examining textural differences from tills of different lobes (Mooers, 1990a).

Geomorphic features and detailed surficial and stratigraphic relationships between the sediments of the various lobes have been recognized and defined during recently completed glacial mapping projects in Stearns County (Meyer and Knaeble, 1995, 1996; Meyer and others, 1995; Knaeble, 1996); the Otter Tail region (Harris and Knaeble, 1999; Harris and others, 1999); the Brainerd (Hobbs, 2001a), Gull Lake (Hobbs, 2001b), and Baxter (Knaeble, 2001) 7.5-minute quadrangles; the St. Cloud 30 x 60 minute quadrangle (Meyer and others, 2001); Pope County (Harris and Knaeble, 2003; Harris and others, 2003); Crow Wing County (Knaeble and Meyer, 2004; Knaeble and others, 2004) and during current mapping projects in the Traverse–Grant region (Harris and Knaeble, unpub. data) and Todd County (Knaeble and Meyer, unpub. data). Gowan (1998) employed statistical analysis in a study that concluded geochemical analysis testing could be used for differentiating Minnesota tills. A recent thesis by Whitehill (2002) studied the origin and extent of Des Moines-lobe moraines in the region east of Glenwood in west-central Minnesota. Prest and others (2001), Larson (unpub. data), and Larson and Mooers (2004) examined source-rock erosion and transport by Rainy-lobe ice and propose that the Hudson Bay basin may be the source for carbonate in the Wadena drumlin field, a hypothesis suggested earlier by Mooers and Lehr (1997).

SUMMARY OF CENTRAL MINNESOTA GLACIAL GEOLOGY

Central Minnesota was an unusually active stage upon which the glacial history of the Laurentide Ice Sheet played out. Sediment and landforms record multiple ice advances and retreats from the major source areas in northern Canada—the Keewatin ice center northwest of Minnesota, and the Labrador ice center northeast of Minnesota (Meyer and Knaeble, 1996; Fig. 6). Keewatin ice entered northwestern Minnesota along the present-day Winnipeg

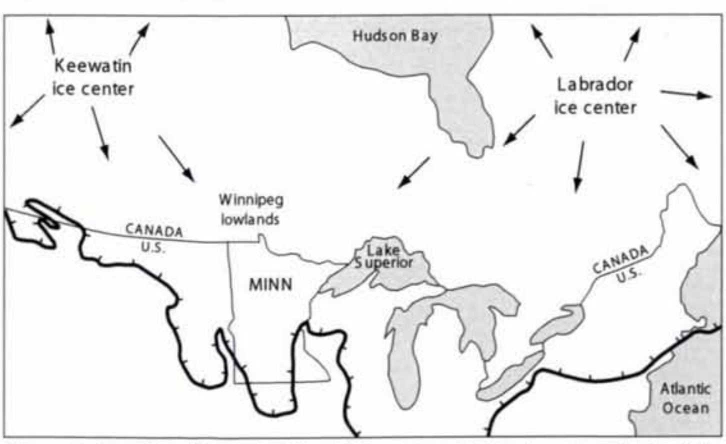


Figure 6. Location of Laurentide Ice Sheet accumulation centers. Includes ice-lobe flow directions and Late Wisconsinan ice margins (hachured line) at approximately 14,000 years ago (modified from Lusardi, 1998).

lowlands, and ice from the Labradorian center entered northeastern Minnesota through the Lake Superior basin (Wright, 1972). Ice occasionally entered the area from a northerly direction. The location of Central Minnesota, at the crossroads of Laurentide ice-lobe flow, resulted in the preservation of a complex sequence of glacial sediments containing a diverse suite of source-area materials that now forms a central highland. Four primary source areas, Riding Mountain, Winnipeg, Rainy, and Superior have been defined, based on distinctive rock types found in their respective ice deposits (Fig. 7). Another source of ice may have emanated from the southern part of Hudson Bay (Dyke and Prest, 1987). Surface deposits across the area were laid down during or after the last glaciation, the Late Wisconsinan, which lasted from about 35,000 to 10,000 years ago (Meyer and Knaeble, 1996). A few exposures of pre-Late Wisconsinan drift are found in both areas where erosion has occurred along river valley slopes and pit exposures along the flanks of drumlins. In places within and behind the St. Croix moraine (Fig. 3) only a veneer of Late Wisconsinan drift covers these older materials. This field conference will focus on glacial deposits in the southern portion of the central highland (Fig. 8).

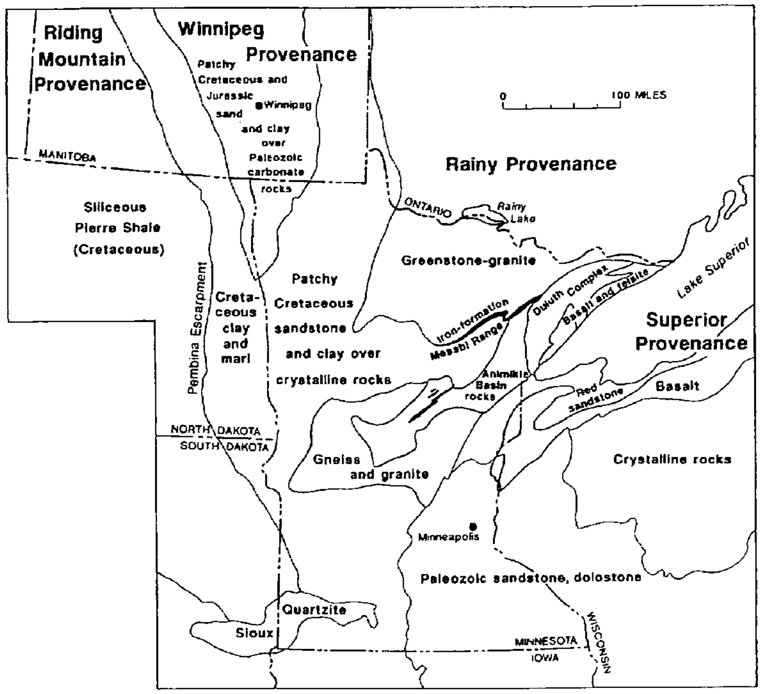


Figure 7. Provenance map showing the simplified bedrock geology over which glacial ice passed before entering Minnesota (from Meyer and Knaeble, 1996).

Pre-Wisconsinan Stratigraphy

Precambrian bedrock underlies the glacial drift of central Minnesota. In places where erosion has not stripped the upper weathered surface of the bedrock, a clayey saprolith remains. Remnant marine deposits of siltstone and shale related to the Cretaceous interior seaway are found in the southern portion of central Minnesota, particularly in Stearns County (Boerboom and others, 1995; Setterholm, 1995; Boerboom, 1996). They are also present in a few places in the central and northeastern parts of the region. This soft bedrock has been incorporated, often with pre-Late Wisconsinan deposits, into northeast-source Late Wisconsinan drift at numerous glacio-tectonic thrust sites in the St. Croix end moraine (Fig. 3) and in recessional moraine complexes of both the Superior and Rainy lobes (Mooers, 1990a, b; Knaeble, 1996). Thrusted Cretaceous sediment will be viewed at Stops 11 and 12 (Fig. 9).

Meyer (Meyer and Knaeble, 1996; Meyer, 1997) identified four distinct sequences of pre-Late Wisconsinan drift in central Minnesota. Each sequence is composed of sediments representing one or more depositional phases of both northwest- and northeast-source ice. These ice lobe pulses from both major source areas appear to be active during each major glaciation. Meyer and Knaeble (1996, p. 22-24) used the letters v, w, x, and y, to label the sequences from oldest to youngest (Fig. 5). Evidence of the oldest sequence (v) is sparse, and comes mostly from cuttings samples from a cluster of deep drill holes in southwestern Stearns County (Fig. 10). Winnipeg-provenance materials were identified in one phase of the sequence and Superior-provenance materials were identified in another phase.

Winnipeg and Rainy lobe sediments of the next youngest sequence (w) are most commonly observed in deep rotary-sonic drill-hole core, split-spoon samples, and in high-quality drill-hole cuttings. In a few places, they are found in surface exposures, typically at glacio-tectonic thrust sites (such as at Stop 12) or in outcrops in areas where Late Wisconsinan deposits are thin. Stop 11 may also include some older till of this age. Winnipeg-provenance till of the (w) sequence is generally characterized by a Paleozoic carbonate clast content of less than 15% and a Cretaceous clast (shale and dark limestone) content, ranging from 3% to 10%. The Rainy-provenance till is generally characterized by high sand content, less than 5% Paleozoic carbonate clast content, and only a trace amount of Cretaceous clasts (Meyer and Knaeble, 1996).

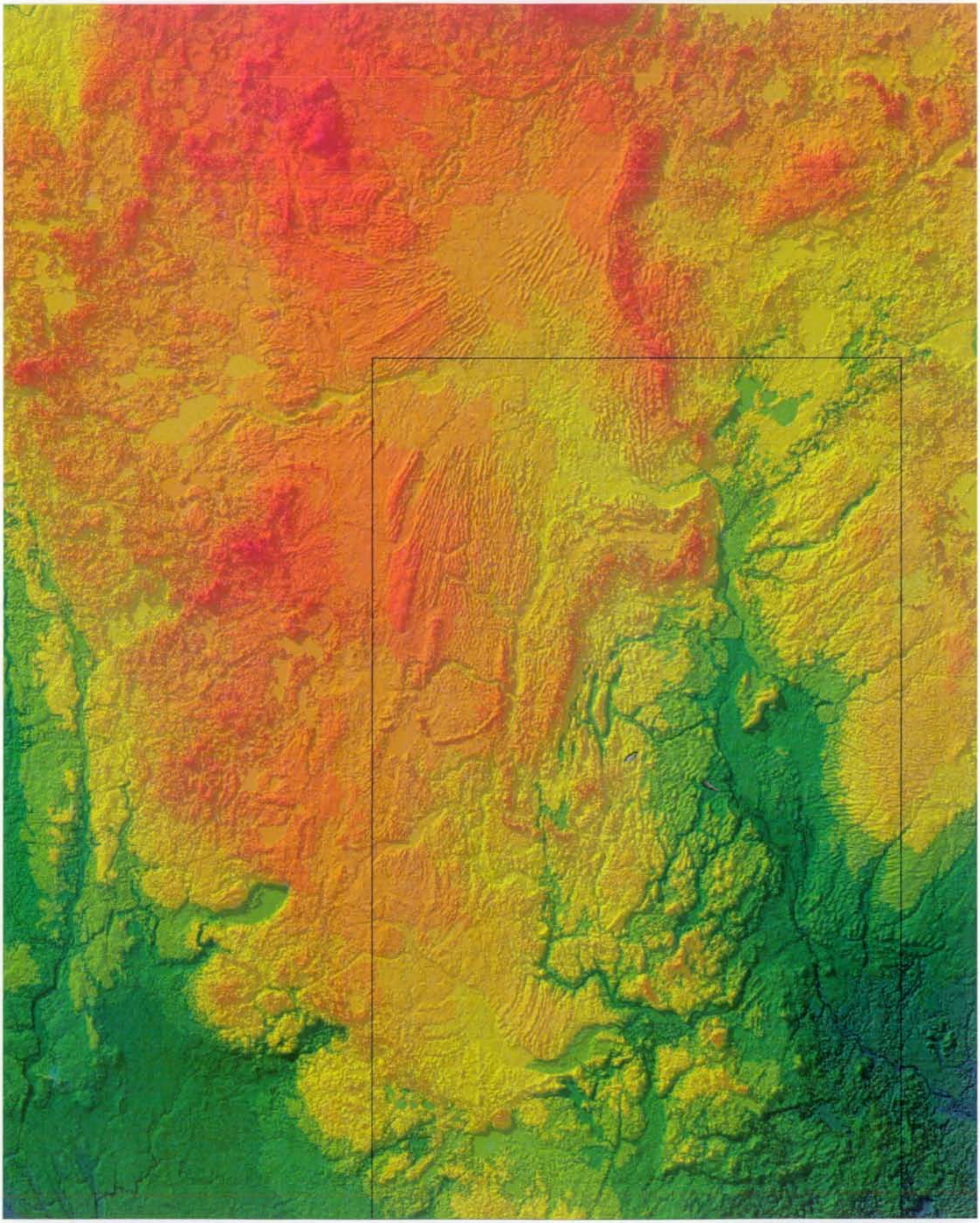


Figure 8. Hill-shade relief of the land surface for the central highlands of Minnesota. The outline indicates the general area of field trip stops. Approximate scale 1:2,000,000 (1 inch = 32 miles). Red = higher surface elevations, blue-green = lower elevations. Illumination is from the northwest (315°, with an azimuth of 30°. Elevation data were obtained from the 30 meter grid National Elevation Dataset (NED) available from the USGS.

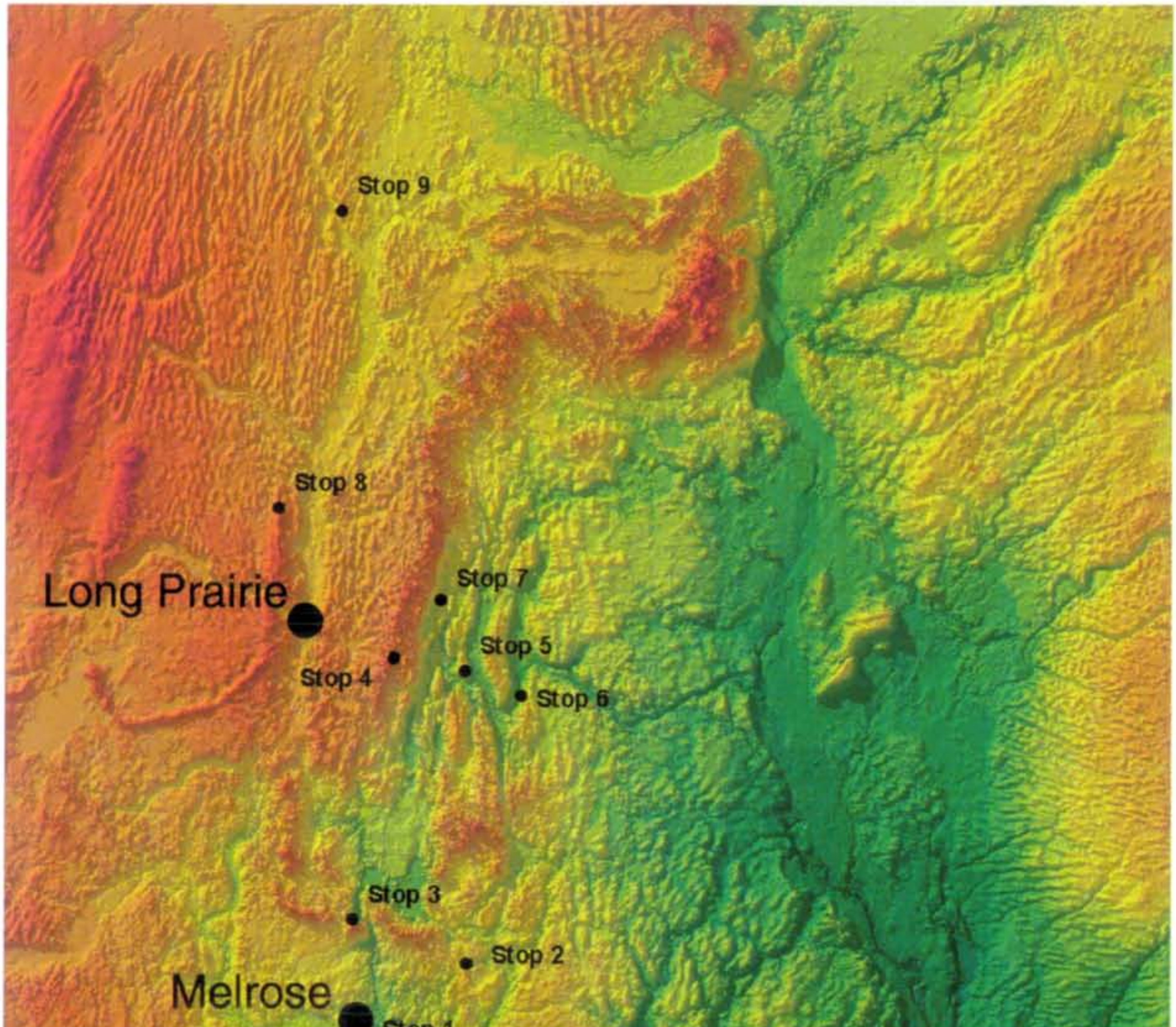


Figure 9. Hill-shade relief of the land surface for the southern portion of the central highland area of Minnesota, showing the locations of the field trip stops. Approximate scale 1:1,300,000 (1 inch = 20 miles). Red = higher surface elevations, blue-green = lower elevations. Illumination is from the northwest (315°, with an azimuth of 30°. Elevation data were obtained from the 30 meter grid National Elevation Dataset (NED) available from the USGS.

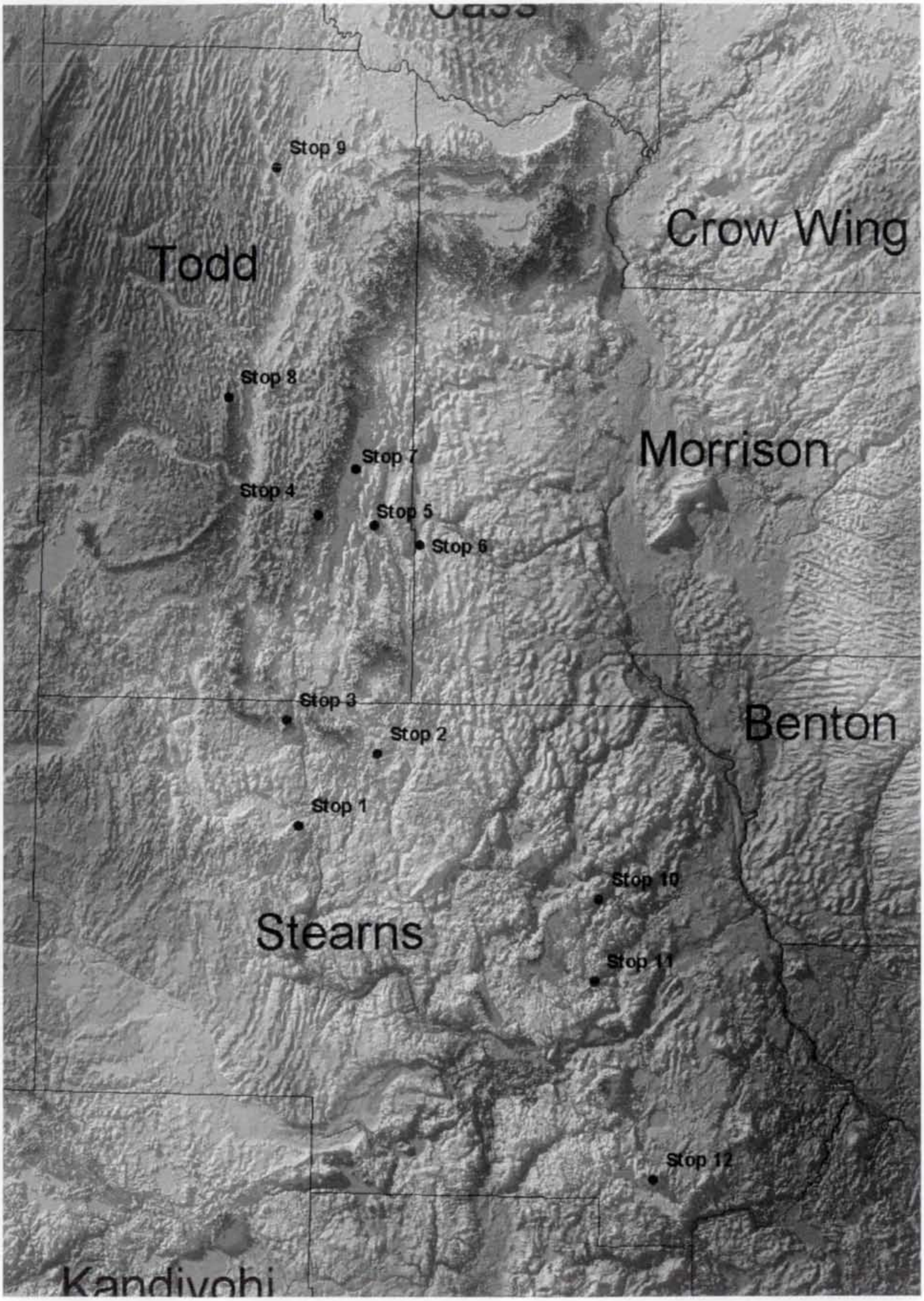


Figure 10. Hill-shade relief of the land surface for southern portion of the central highland area of Minnesota, showing the locations of the field trip stops and county boundaries. See Figure 9 caption for details.

During the next glacial period, materials of Superior provenance and Winnipeg provenance (x) sequence were deposited and include three distinct northeast-source ice advances and at least three distinct northwest-source ice advances. Surface exposures of these units are rare, but can be found at glacio-tectonic thrust sites along the St. Croix moraine. Subsurface core and cutting samples show evidence of a relatively thick, widespread package of Winnipeg-source (x)-sequence deposits. These sediments may also occur at the surface or near the surface in areas where late Wisconsinan till is thin, such as in the eroded meltwater spillways behind the St. Croix moraine (Fig. 11d), and along drumlin flanks. Distinguishing characteristics of the Winnipeg-provenance materials are high (>35%) silt content and high (30-60%) Paleozoic carbonate clast content. Red color from the presence of red volcanic and sandstone clasts and low to moderate (10-20%) Paleozoic carbonate clast content distinguishes the northeast-source deposits from northwest-source tills (Meyer and Knaeble, 1996). We will preview (x)-sequence till exposures in Stops 6 and 12 (Fig. 9).

The youngest pre-Late Wisconsinan till sequence (y) may be Illinoian Stage in age (Meyer, 2000). It is comprised of Rainy-lobe northeast-source sediments and of Winnipeg-lobe northwest-source Browerville formation sediments. The sandy Rainy-lobe deposits are chiefly identified in drill-hole samples in northern Stearns and southern Todd Counties (Meyer, 1986; Meyer and Knaeble, 1996; Fig. 10). Northwest-source Browerville sediment is commonly found beneath Wisconsinan drift in much of Todd County and surrounding areas. It was correlated with a surface till in Mower County in southern Minnesota by Meyer (2000). Goldstein (1985) also correlated the Browerville till to the Kandiyohi till in Kandiyohi County. However, recent fieldwork in the area and in adjacent Pope County (Harris and Knaeble, 2003) suggested that the Kandiyohi till is a Des Moines-lobe deposit and Late Wisconsinan in age. The Browerville till forms a distinct pre-Wisconsinan drift high in northwestern Todd County where the overlying Wadena drumlin field till may be thin. Some drumlins in the Wadena drumlin field appear to be composed of partially eroded Browerville till (and sometimes other older tills) that has been streamlined by Wadena-lobe ice and then capped with Wadena-lobe sediment, usually till. Exposures on drumlin flanks in places reveal Browerville sediments at the surface (Knaeble, unpub. data). Distinguishing lithologic characteristics of the Browerville till include the presence of tabular, dark, Cretaceous limestone clasts (2-10%) along with small amounts of gray Cretaceous shale, and a moderate (~30%) Paleozoic carbonate clast content (Meyer, 1986; Meyer and Knaeble, 1995; Meyer and others, 2001). The till texture is commonly finer than the overlying Wadena drumlin field till yet not as silty as the underlying (x) sequence tills. These characteristics along with the Browerville's stratigraphic position make it one of the most identifiable pre-late Wisconsinan ice deposits. We will see Browerville till at Stops 5, 6, 7, and 9 (Fig. 9).

Late Wisconsinan Glacial Deposits and Features

Wadena lobe

Controversy concerning ice-lobe flow direction, as it relates to source-area provenances, surrounds the oldest Late Wisconsinan ice deposits, those of the Wadena lobe. Wright (Wright and Ruhe, 1965; Wright, 1972) suggested its deposits could vary in age from 20,000 to greater than 40,000 years ago. Mooers and Lehr (1997) interpreted an age of about 26,000 to 21,000 years ago. These sediments are at the surface over a large area of central Minnesota (Fig. 1), most of which is readily distinguishable by its drumlinized landscape (Fig. 11a). Wright (1954, 1957, 1962) characterized the Wadena lobe's material properties and geomorphology. Drumlin orientation favored a northeast-source ice flow direction (Fig. 4), yet Wright postulated that the ice lobe source area was the Winnipeg provenance to the northwest, thereby accounting for the source of low to moderate (10-25%) amounts of Paleozoic carbonate clasts commonly found in unleached samples. He hypothesized that a contemporaneous ice lobe in northeastern Minnesota deflected the Wadena lobe to the southwest, resulting in the flow direction shown by the drumlins (Fig. 4). Subsequent work by Goldstein (1985) and Meyer (Meyer, 1986; Meyer and Knaeble, 1996) suggested that the ice actually had a Rainy-lobe source to the northeast. These researchers attributed the Paleozoic carbonate clast content to the incorporation of carbonate-rich, pre-late Wisconsinan deposits that underlay much of central Minnesota. Gowan (1998) suggested a northeast source for the Wadena lobe based on her comparison of Minnesota tills using geochemical analysis. Mooers and Lehr (1997) and Larson (unpub. data) also supported a northeast source for the Wadena lobe, but they attributed the Paleozoic carbonate clast content to the erosion of bedrock deposits in the Hudson Bay lowland region (Fig. 6). Thus, if research in the last ten years proves to be correct, the Wadena lobe should perhaps be more appropriately renamed as an early phase of the Rainy lobe or as a sublobe of the Rainy lobe (the ice that passed north of the Mesabi Iron Range; Fig.7).

In contrast to the controversy that surrounds the Wadena lobe's flow direction, the till itself is uniform and easily recognizable over a large area of central Minnesota. The Wadena-lobe till is characteristically a yellow-brown, sandy loam having an average matrix texture of sand, silt, and clay percentages of 60-28-12, respectively, for 23 samples (Mooers,

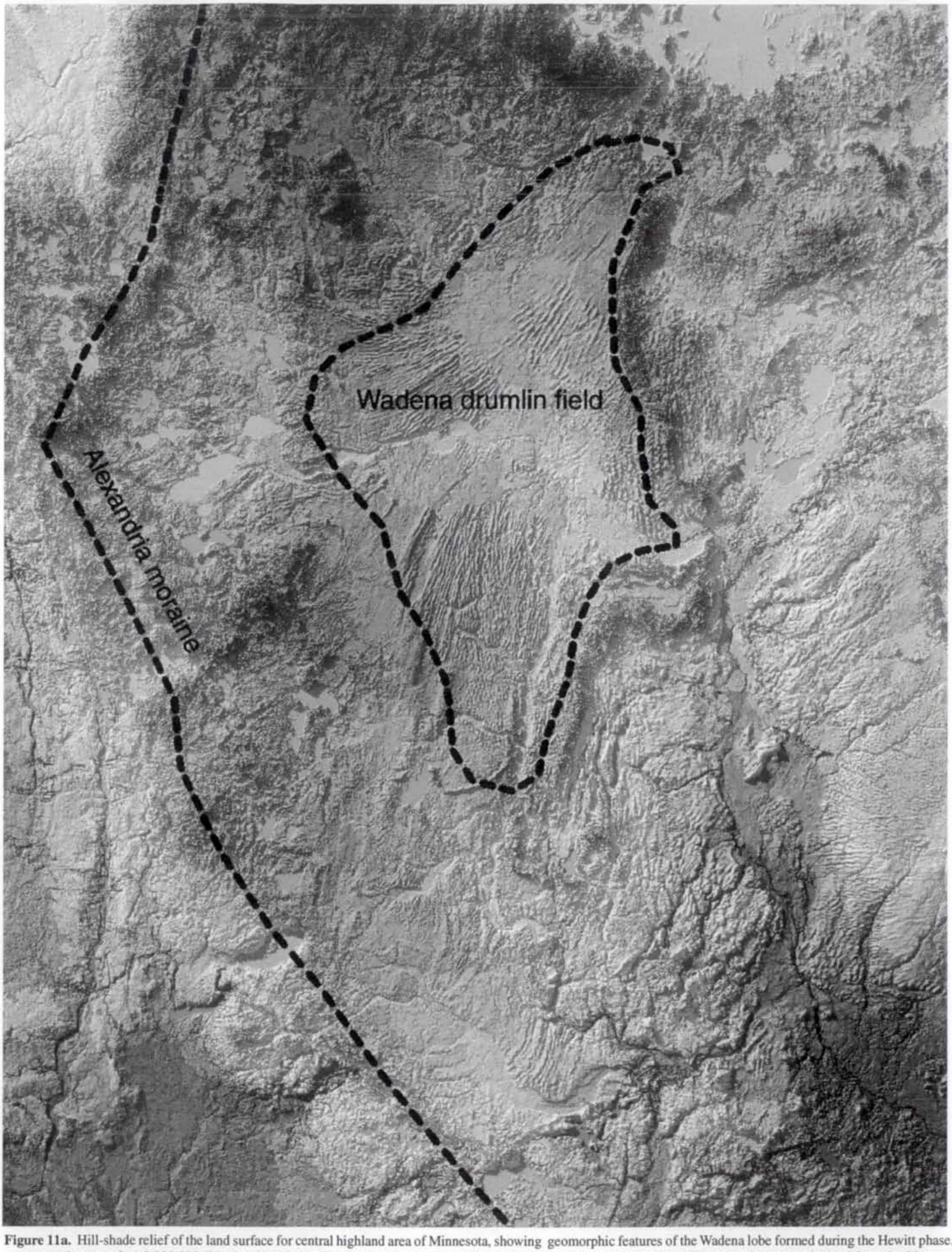


Figure 11a. Hill-shade relief of the land surface for central highland area of Minnesota, showing geomorphic features of the Wadena lobe formed during the Hewitt phase. Approximate scale 1:2,000,000 (1 inch = 32 miles). Illumination is from the northwest (315°), with an azimuth of 30°. Elevation data were obtained from the 30 meter grid National Elevation Dataset (NED) available from the USGS.

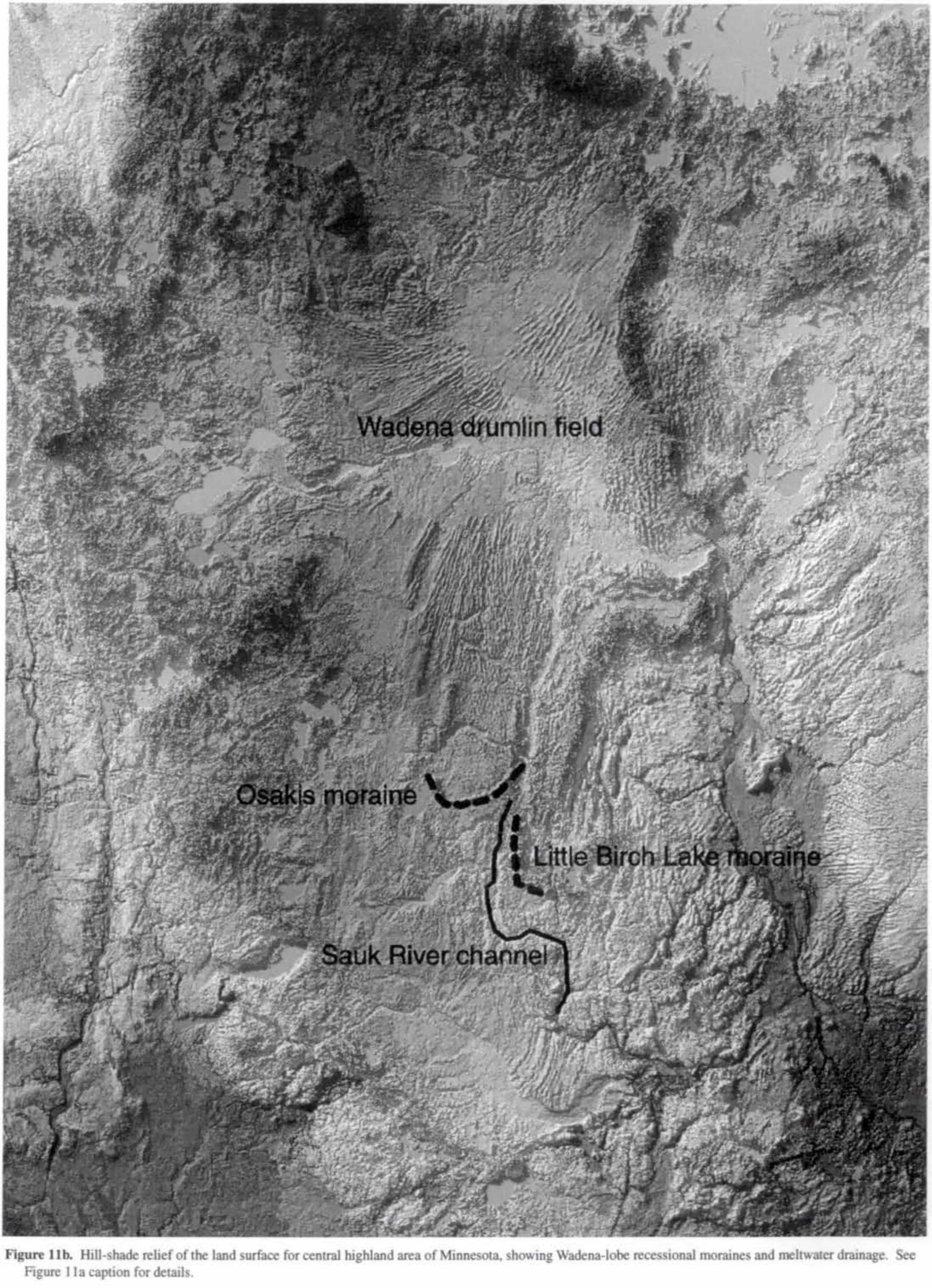


Figure 11b. Hill-shade relief of the land surface for central highland area of Minnesota, showing Wadena-lobe recessional moraines and meltwater drainage. See Figure 11a caption for details.

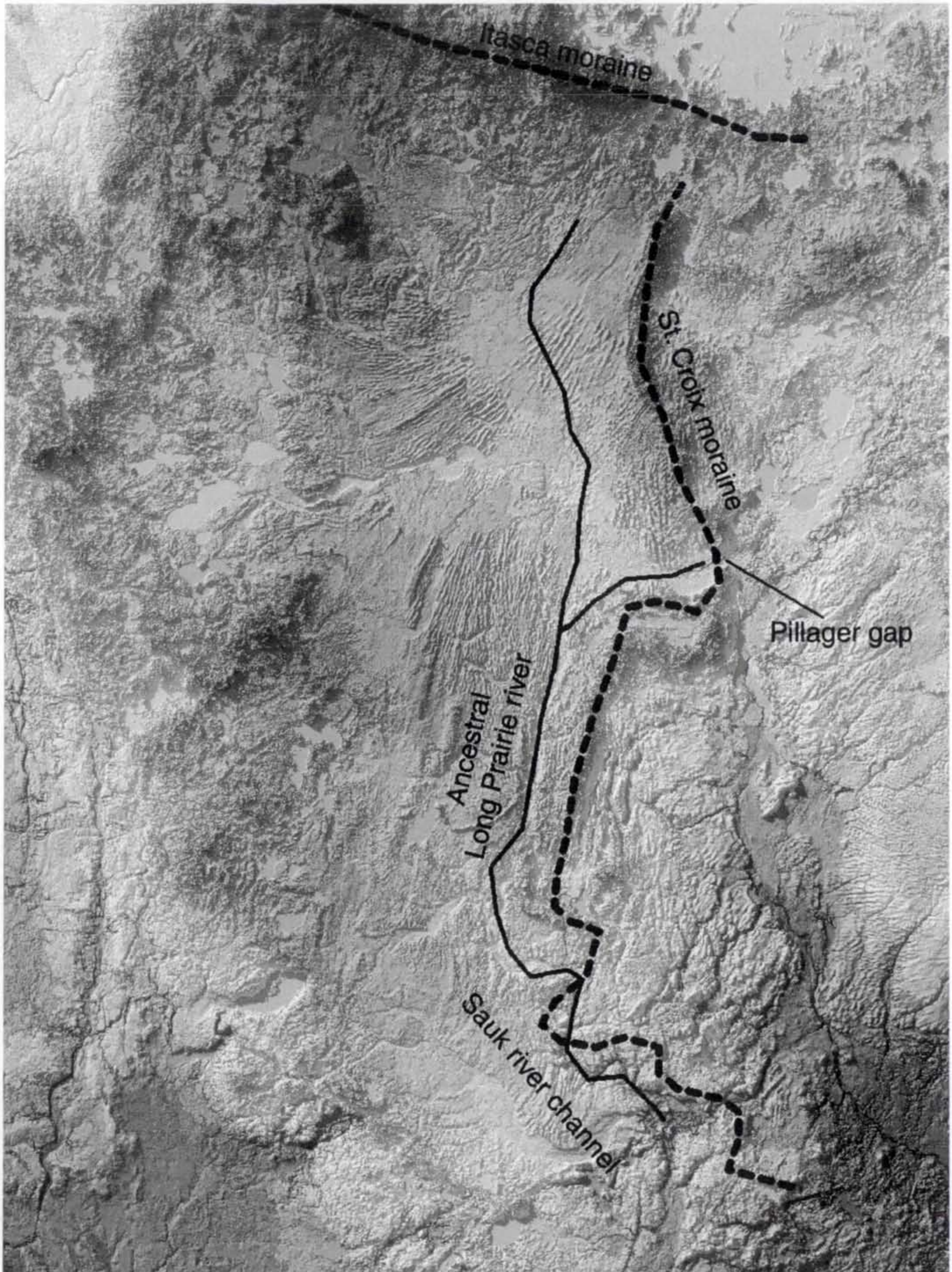


Figure 11c. Hill-shade relief of the land surface for central highland area of Minnesota showing Wadena-, Rainy- and Superior-lobe moraines and ice-marginal meltwater drainage. See Figure 11a caption for details.

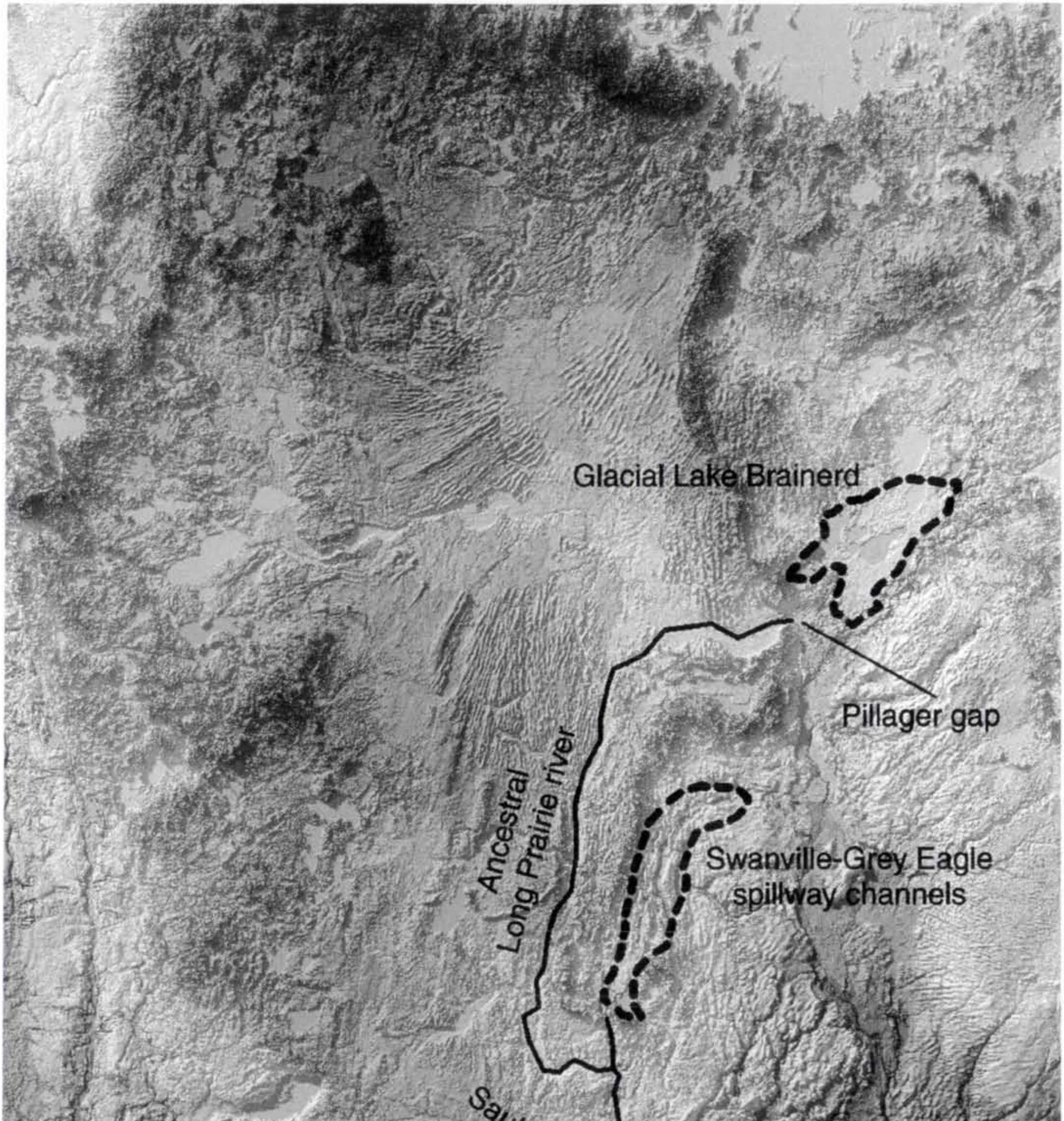


Figure 11d. Hill-shade relief of the land surface for central highland area of Minnesota, showing Rainy- and Superior-lobe recessional meltwater drainage. See Figure 11a caption for details.

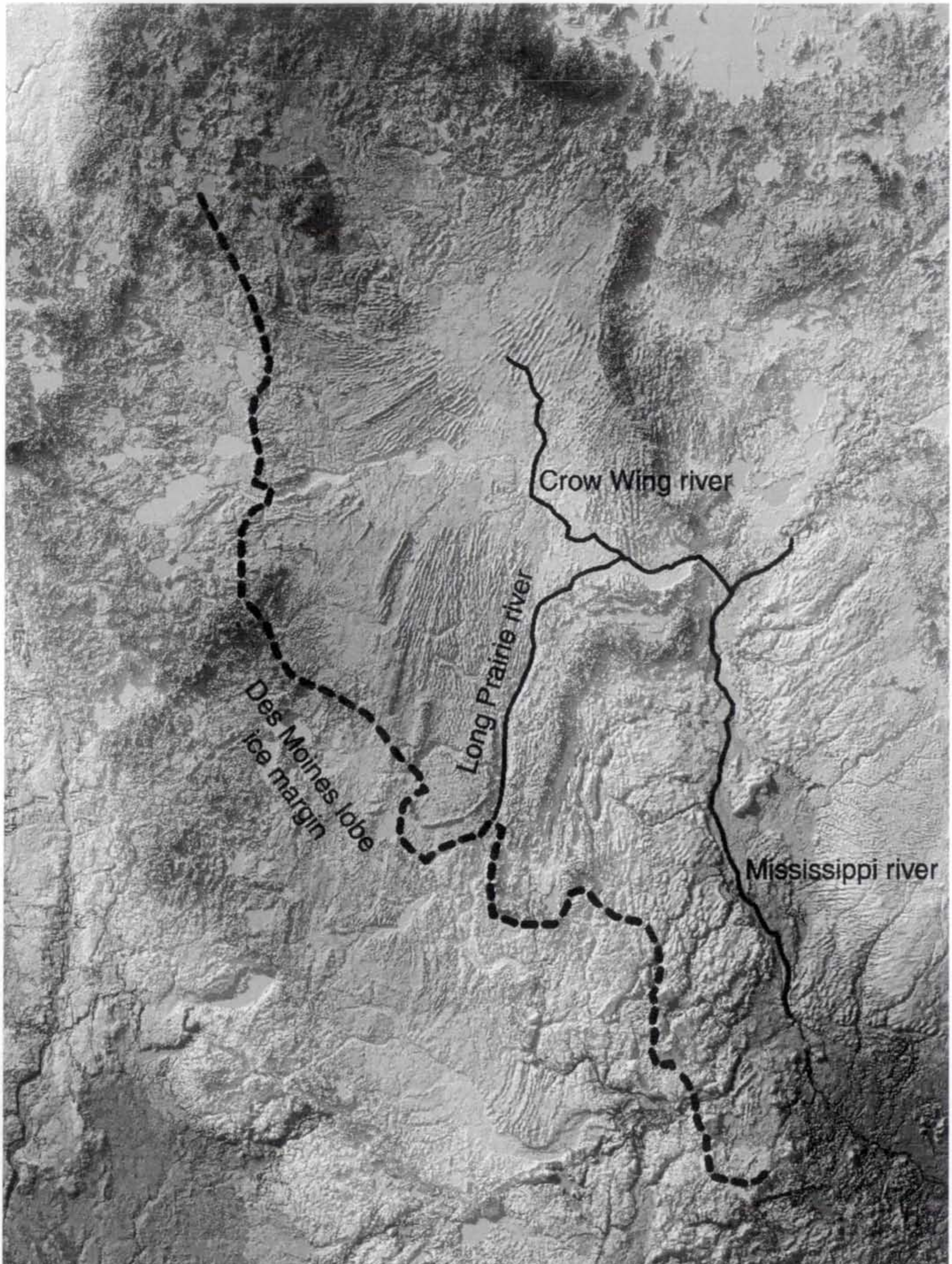


Figure 11e. Hill-shade relief of the land surface for central highland area of Minnesota, showing Des Moines-lobe maximum ice margin and meltwater drainage. See Figure 11a caption for details.

1988, p. 64-65); 56-32-12, for 46 samples (Meyer and Knaeble, 1996); 59-28-13, for 118 samples (Meyer and others, 2001, unpub. data); and 60-27-13, for 140 samples (Harris and others, 1999; note that in this publication the Crow Wing River Group member RRV-16 is the equivalent of Wadena-lobe till). Other distinguishing characteristics are the virtual absence of Cretaceous shale and dark limestone (an exception is in places where the Wadena till has incorporated these materials at its basal contact as it overrode Browerville formation materials) and a Paleozoic carbonate clast content ranging from 10-25%. Three recent studies that analyzed the very coarse-grained (1-2 millimeters) sand fraction show an average of 17% carbonate for 28 samples (Meyer and Knaeble, 1996), 14% carbonate for 118 samples (Meyer and others, 2001; unpub. data), and 18% carbonate for 140 samples (Harris and others, 1999). The till has been observed to be sandier and more deeply leached in the northeast region of the drumlin field (Wright, 1962; Goldstein, 1985; Mooers, 1988). Stops 3 and 9 have Wadena till exposures (Fig. 9).

Wright (1972) divided Wadena-lobe events into the Hewitt phase, the time period during which the drumlins formed and the core of Alexandria moraine (Figs. 4, 11a) was deposited, and the younger Itasca phase, the time period when the Itasca moraine was formed (Figs. 3, 11c). Goldstein (1985) separated Wadena lobe events into four phases: Granite Falls, Alexandria Moraine, Hewitt, and St. Croix. A recent detailed study in the Minnesota River Basin (Patterson and others, 1999) failed to find significant evidence that the Granite Falls till of Matsch (1971, 1972) correlates with the Wadena drumlin field till—the basis of Goldstein's Granite Falls phase. In that study, the Granite Falls materials of Matsch were interpreted to be comprised of carbonate-rich (x) sequence pre-Wisconsinan deposits and deposits of the oldest phases of the Des Moines lobe. Gowan (1998) also concluded that the Granite Falls till and the Des Moines-lobe till were geochemically similar. Recent mapping (Harris and Knaeble, 1999, 2003; Harris and others, 1999, 2003) has confirmed that the Alexandria moraine is cored with Wadena-lobe deposits. Two recessional moraine deposits of the Wadena lobe in southern Todd County form arcuate features concave to the north with a common junction at the ancestral Long Prairie-Sauk River valley—the original interlobate south-flowing drainage valley (Fig. 11b). The westernmost moraine was informally named the Osakis moraine by Goldstein (1985), who hypothesized that Des Moines-lobe ice was responsible for its formation. However, recent mapping (Meyer and others, 2001) has shown that this moraine is composed of Wadena-lobe sediments and is a recessional moraine of the Wadena lobe. The easternmost moraine, informally named the Little Birch Lake moraine (Meyer and others, 2001), was attributed by Hobbs and Goebel (1982) to be a portion of the St. Croix moraine but recent mapping (Meyer and Knaeble, 2001) confirmed that this moraine is composed of sediments of the Wadena lobe and represents a recessional ice margin. Ice of the Itasca phase deposited the Itasca moraine, which is interpreted to have formed at the same time as the St. Croix moraine (Wright, 1972; Norton, 1983; Goldstein, 1985; Mooers, 1988; Fig. 11c). Wright (1972) noted the difficulty in determining the eastern extent of Wadena-lobe sediments. He proposed that these deposits were either deeply buried under younger Superior- and Rainy-lobe materials or else Rainy-lobe ice blocked any advance to the east. Meyer and Knaeble (1996) suggested that the Hewitt phase of the Wadena lobe was in places confluent with the Superior lobe. When Wadena-lobe ice retreated first, Superior-lobe ice then advanced westward depositing its sediments on top of Wadena-lobe drift. Recently completed mapping in Crow Wing County (Knaeble and Meyer, 2004) found no evidence for Wadena-lobe sediments east of the Mississippi River.

Superior and Rainy lobes

Following retreat of the Hewitt phase of the Wadena lobe, ice of the Rainy and Superior lobes readvanced into central Minnesota between about 20,000 and 16,000 years ago (Wright, 1972; Clayton and Moran, 1982; Mooers and Lehr, 1997). At their maximum extent they formed the St. Croix moraine. The Superior lobe formed the portion south of the Pillager gap and the Rainy lobe formed the portion north of the gap (Fig. 11c). Schneider (1956, 1961) concluded from geomorphic evidence (the existence of two separate drumlin fields with distinct drumlin orientations) that two lithologically similar lobes (Brainerd and Pierz), occupied the region east and south of Pillager gap (Fig. 3). Wright (1964) later referred to the Brainerd and Pierz lobes as sublobes of the Rainy lobe based on the similar brown color of their tills. Mooers (1988) confirmed that the Brainerd sublobe was associated with the Rainy lobe but attributed the Pierz sublobe origin to the Superior lobe. Portions of the St. Croix moraine and also recessional moraines of the Superior and Rainy lobes have been identified as having been formed by thrusting of subglacial drift and bedrock (Mooers, 1990c; Knaeble, 1996). The thickness of the St. Croix moraine has generally been assumed to be the height of its topographic relief above the surrounding land surface, although Mooers (1988) questioned this assumption. Recent mapping extending from southern Todd County to north of the Swanville spillway area (Fig. 11d) has found that Superior-lobe sediments in this portion of the moraine, at least in places, are commonly less than 25 feet (8 meters) thick over Wadena lobe and pre-Late Wisconsinan drift (Meyer and others, 2001). This suggests that a pre-existing topographic ridge composed of older drift may core the moraine in this area.

Both the Superior- and Rainy-lobe deposits have a sandy loam matrix texture comparable to Wadena-lobe till (Mooers, 1988). Two recently completed mapping studies found a matrix texture of sand-silt-clay percentages of 61-27-12, respectively, for 47 samples (Meyer and others, 2001, unpub. data) for till deposits of the Pierz sublobe (Superior lobe), and 67-22-11, respectively, for 194 samples (Knaeble and Meyer, 2004) for till deposits of the Brainerd sublobe (Rainy lobe) in Crow Wing County. Materials of both lobes are commonly leached of Paleozoic carbonate to a depth of 10 feet (3.1 meters) or more. Thus, analyses of the very coarse-grained (1-2 millimeters) sand fraction of these samples showed only trace amounts of carbonate. Deep unleached samples of Brainerd till contained 3-4% carbonate (Knaeble and Meyer, 2004). Sand grain analyses for the same matrix texture samples referred to above, found 9% and 7% of the Precambrian 1-2 millimeter grains were red volcanics or sandstones, for the Superior (Pierz sublobe) and Rainy (Brainerd sublobe) lobes, respectively. Exposures of Superior-lobe (Pierz sublobe) drift are visible at Stops 2, 4, 5, 6, 7, 11, and 12 (Fig. 9).

While the Superior and Rainy lobes were at the St. Croix moraine, drainage along the western ice margin flowed south in the same valleys that the present day Long Prairie and Sauk Rivers now occupy (Fig. 11c). As the Superior lobe ice margin retreated east, meltwater eroded a series of deep spillway channels behind the moraine from approximately the midpoint of Todd County southward along its eastern border (Schneider, 1961; Wright, 1972; Goldstein, 1985; Mooers, 1988; Meyer and others, 2001; Fig. 11d). To the north, Rainy-lobe ice was also retreating, forming a series of recessional moraines. Meltwater of the Rainy lobe ponded behind the terminal St. Croix moraine northeast of Pillager gap forming glacial Lake Brainerd (Goldstein, 1985; Mooers, 1988; Fig. 11d). Recent mapping in Crow Wing County indicated that the lake was in existence for at least 100 years, had stagnant ice buried beneath its sediments, and that its maximum extent was approximately 150 square miles (384 square kilometers; Knaeble and Meyer, 2004; Knaeble and others, 2004). The lake may have drained to the west through the Pillager gap or possibly south down the Mississippi River drainage way, if it had opened up by this time (Mooers, 1988).

Des Moines lobe

Between 16,000 and 12,000 years ago, Des Moines-lobe ice entered the central Minnesota region from the northwest and west by overriding the Alexandria moraine (Wright, 1972; Goldstein, 1985; Mooers, 1988; Whitehill, 2002; Fig. 11e). Its sediments blanket the moraine except for a few topographic highs where Wadena lobe drift, which cores the moraine, is exposed (Harris and Knaeble, 1999, 2003). As the ice advanced southeastward, it eventually damned the south-flowing ancestral Long Prairie-Sauk River drainages, reversing the flow direction northward, creating the Long Prairie River. The Long Prairie River drains into the Crow Wing River, which flows east through Pillager gap into the Mississippi River (Wright, 1972; Goldstein, 1985; Mooers, 1988). An esker, with an associated fan deposit just north of Little Sauk, marks the maximum extent of Des Moines-lobe ice and also the location where the damming originated (Meyer and others, 2001).

Des Moines-lobe till is commonly yellow-brown (oxidized) with a loam to clay loam texture. It is characterized by the presence of varying quantities (ranging from 5% to 60%) of gray siliceous Pierre Shale. Stop 1 is at an exposure of Des Moines-lobe till (Fig. 9).

TECHNOLOGY USED FOR RECENT MAPPING

The methods and technology used in research and mapping of glacial geology over the last century have evolved as the need for detailed understanding of the sediments and landforms has increased. Today, as was true in the 1880s or in the 1950s, there is no substitute for accurate observation, detailed, concise field notes and diagrams, systematic sampling procedures, and routine measurement and testing at outcrops. Drill cuttings, split-spoon samples, and rotary-sonic core have become increasingly important in subsurface interpretation. Geophysical logging and testing, magnetic susceptibility and orientation measurements, geochemical analysis, x-ray diffraction for clay mineralogy, computer-assisted statistical analysis (Harris, 1998), age dating, texture analysis testing, and lithologic grain counting (Hobbs, 1998; an evolved derivative of the older pebble and stone count method) have emerged as effective tools in differentiating glacial sediments. The recent development of computer generated digital elevation model and three-dimensional maps provides an enhanced geomorphic perspective when compared to topographic maps.

Recent Minnesota Geological Survey mapping projects in central Minnesota have gravitated toward the use of methods that are effective in differentiating glacial sediments derived from different source areas. Material from outcrops, rotary-sonic core, and shallow (10 to 50 feet deep) Giddings probe auger borings (approximately 5-8 boring per 7.5-minute quadrangle) is described and sampled. Matrix texture analysis and lithologic grain counts of the very coarse-grained (1-2 millimeters) sand fraction are completed on almost all samples. Aerial photography, correlation with soil map units, water-well drillers' logs, analysis of cutting samples, and bridge boring logs are also used in interpretation and compilation. The most important factors in differentiating sediments of the various lobes and different ages are stratigraphic position and lithology. Therefore, our emphasis has focused on first describing and sampling exposures and drill sites with stratigraphic contacts in order to determine stratigraphic sequences, and then completing texture analyses and lithologic grain counts of all samples so that stratigraphic units can be correlated by using distinctive source-area bedrock indicators. Because central Minnesota's location was at the crossroads of continental ice flow, the sediments deposited by these ice lobes usually have a distinct lithologic signature, which can be determined for each sample by microscope analysis of the 1-2 millimeter coarse-grained sand fraction. This procedure is a low-cost, labor-intensive approach that has proven very effective in a tight-budget environment.

CONCLUSION

The 50th Friends of the Pleistocene field conference will examine research and mapping conducted in central Minnesota over the last 50 years in order to better understand: the region's complex glacial stratigraphy, the evolution of ideas in comprehending the glacial history, and the development of techniques and technology used to make these advances possible.

ACKNOWLEDGMENTS

Sincere appreciation is extended to the following people for their assistance in making the 50th Midwest Friends of the Pleistocene Field Conference possible:

Ginger Delles (St. John's University/College of St. Benedict)—events coordinator.
Larry Davis (St. John's University/College of St. Benedict)—geologist, source of inspiration for St. John's hosting this year's FOP; planning and contact support.
Lori Day (Minnesota Geological Survey)—design and accounting support.
Lisa Dosch (Minnesota Geological Survey)—logistical support.
Lyle and Jane Gessel—Pillsbury pit owners.
Aaron Hirsch (St. John's University/College of St. Benedict)—student; poster.
Howard Hobbs (Minnesota Geological Survey)—chair of the entertainment committee.
Anna Knaeble—text editing.
Phil Larson (Minnesota State University)—poster and speaker at stop.
Rich Lively (Minnesota Geological Survey)—map, figures, and guidebook design.
Jim Loven—Swanville pit owner.
Barb Lusardi (Minnesota Geological Survey)—technical review, editing and figure design.
Mayer Excavating—Melrose pit.
Paul Morin (University of Minnesota Geology Department)—provided 3D imaging maps
Lorne and Paullet Johnson—pit owners west of Long Prairie.
Wade Reynolds (Minnesota Geological Survey)—logistical support.
Lori Robinson (Minnesota Geological Survey)—text editing.
Bill Scherer—Merden esker pit.
William Stewart—pit owner south of Staples.
Jerry Whalen—owner Powder Ridge Ski Hill pit.
Joe and Marie Wielenberg—pit owners.

ROAD LOG AND STOP DESCRIPTIONS

Day 1
Saturday, June 5, 2004

Miles (T=total miles, I=interval mileage)

T	I	
0.0	0.0	Leave St. John's from south end of Mary Hall parking lot.
0.1	0.1	From east Mary Hall parking lot exit, turn left (north) onto a campus road.
0.2	0.1	Stop sign continue north on County Road (CR) 159. Lake and wetland on right (east) side of road is northeast-flowing postglacial drainage for surrounding Superior-lobe stagnation topography.
0.9	0.7	St. John's Arboretum on right (east)—Stop 10 on Sunday.
1.5	0.6	Turn left (west) on I-94.
2.2	0.7	On right (north) old stone house, architecture typical of early building in area.
3.5	1.3	Starting here and for approximately the next 5 miles (8 kilometers), large hills on both sides of I-94 near the town of Avon contain Cretaceous sediments and pre-Late Wisconsinan drift and are interpreted to have been produced by Superior-lobe glacio-tectonic thrusting. Some hills have lakes lying up-ice to the northeast and they may be associated hill-hole pairs (Bluemle and Clayton, 1984).
9.2	5.7	Cross the Des Moines-lobe ice margin. The Des Moines lobe advanced from the southwest. Near-surface stratigraphy in this area is Des Moines-lobe till over Superior-lobe drift (Meyer and Knaeble, 1995).
22.6	13.4	Exit I-94 at Melrose; turn left (south) on County Highway (CH) 13.
22.8	0.2	Turn left (east) on CR 173.
23.8	1.0	Turn left (east) on River View Rd.
24.2	0.4	Turn right into pit entrance. **Stop 1—Mayer pit** (Fig. 12). At this site there is a surface layer of yellow-brown, calcareous Des Moines-lobe till, which contains gray Cretaceous shale, and varies from about 15 feet (5 meters) thick on the west side of the pit to less than 6 feet (2 meters) thick on the east side of the pit. The basal 5 feet (1.7 meters) or less of this till appears to be more reddish in color. Beneath the till in the southwest corner of the pit there lies 30 feet (10 meters) of interbedded very fine, fine, and medium sand and silt. These lacustrine layers are horizontally bedded and in places show loading deformation and faulting. The bottom unit is about 15 feet (5 meters) thick (it thickens to the east) and is mostly slumped sand and gravel deposits of the Superior lobe. The upper till unit dips down into a low on the south end of the pit, where lake sediment is no longer present, and overlies sand and gravel. An exposure near the base of the pit, 150 feet (50 meters) north of the low south-wall area, shows the base of the till is dark gray and unoxidized, contains buried wood, and displays what appear to be debris flows dipping south towards the topographic low. This will be the only stop where we see Des Moines-lobe till. It is characterized by its oxidized yellow-brown (2.5Y5/4—Muncell) color, loam to clay loam texture, gray siliceous Cretaceous shale content of between 5% and 60%, and approximately 20% to 30% carbonate content.

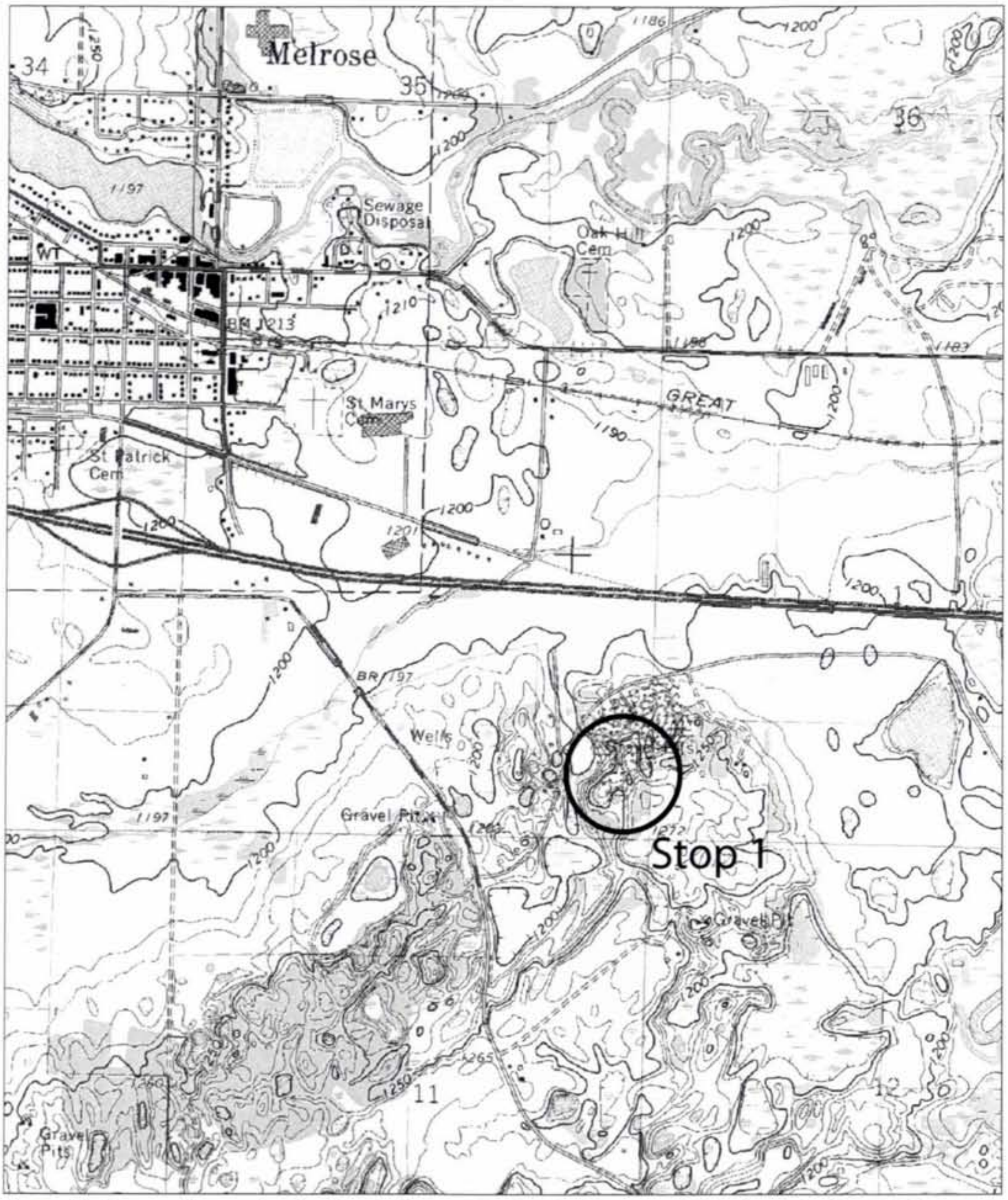


Figure 12. Topographic map showing Stop 1—Mayer pit in Superior-lobe outwash fan deposit 2 miles (3.2 kilometers) southeast of Melrose (NE1/4SE1/4SE1/4, sec. 2, T. 125 N., R. 33 W.; U.S.G.S. Melrose quadrangle, 7.5-minute series, 1979).

The basal sand and gravel at this site has been interpreted to be a recessional fan deposit of the Superior lobe, whose ice-marginal source lies about 2 miles (3.2 kilometers) to the northeast. The St. Rosa esker, which will be viewed at Stop 2, is related to the fan as the subglacial component of this depositional system. After Superior-lobe ice left the area, Des Moines-lobe ice advanced from the west. Meltwater from this advancing lobe formed a local pro-glacial lake, which deposited lacustrine sediments. Eventually the Des Moines-lobe ice overrode the esker deposits and lake sediments depositing a till cap. The slightly redder lower portion of the Des Moines-lobe till is probably a result of underlying Superior-lobe sediment being incorporated and mixed into the overriding Des Moines-lobe basal ice (Meyer and Knaeble, 1995).

24.2 0.0 Leave pit; go right onto River View Rd.

25.7 1.5 Cross the Sauk River bridge. The Sauk River valley channeled meltwater away from the Wadena, Superior, and Des Moines lobes. Therefore, the channel sediments have a complex history of deposition and erosion.

26.5 0.8 Turn left (north) on State Hwy 337.

27.5 1.0 Cross over I-94.

28.0 0.5 Turn right (east) on CR 157.

28.9 0.9 Turn left (north) on Long Lake Rd.

33.5 4.6 Turn left (north) on CH 11.

34.4 0.9 Cross the St. Rosa esker (most visible on the east side).

34.9 0.5 Turn right (east) on CH 17.

35.3 0.4 Pull off on shoulder of road. View the St. Rosa esker on right (south) side of bus.

Stop 2—St. Rosa esker (Fig. 13).

An exposure in the esker that can be seen from the road shows the following sequence (from top to bottom): 3 feet (1 meter) of Des Moines-lobe till capping the esker, 3 feet (1 meter) of sand and gravel with interbedded red till streaks, 3 feet (1 meter) of red Superior-lobe till, and sand and gravel forming the esker core. Site access was unavailable for this field trip. Documentation of the materials in this esker was completed by Wright (1965) at a time when an excellent fresh pit exposure was available (that pit is now mostly overgrown). His description of the deposits showed the esker to be more complicated than those viewed in the modern exposure. He described isoclinal folds with interbedded Superior-lobe and Wadena-lobe till (Fig. 14). Recent interpretation suggests that the esker was formed at a recessional ice margin of the Superior lobe, possibly overridden by a readvance of Superior-lobe ice, and finally overridden and deformed by ice of the Des Moines lobe (Meyer and Knaeble, 1995, 1996; Meyer and others, 2001).

35.3 0.0 Continue east on CH 17.

35.9 0.6 Turn around at intersection with 269th Street.

37.9 2.0 Turn right (north) at stop sign in downtown St. Rosa and continue on CH 17.

38.9 1.0 Turn left (west) and continue on CH 17.

42.1 3.2 Descend into Adley Creek valley, a drainage way for Superior-lobe meltwater. Later, as Des Moines-lobe ice advanced from the west it dammed the Sauk River valley drainage, channeling flow south through the Adley Creek valley (Fig. 11e). The advancing Des Moines lobe filled the valley with ice and then reused the valley drainage for its meltwater as ice wasted.

43.1 1.0 Turn right (north) on CH 13 and ascend the Little Birch lake recessional moraine of the Wadena lobe.

43.5 0.4 Crest of recessional moraine.

43.9 0.4 Turn right (east) into pit.

Stop 3—Wielenberg pit (Fig. 15).

At this site till is interbedded with sand and gravel, all of which are Wadena-lobe deposits. Samples of the till that were analyzed show characteristics typical of Wadena-lobe materials: sandy loam texture, carbonate content of about 15%, and the absence of Cretaceous shale.

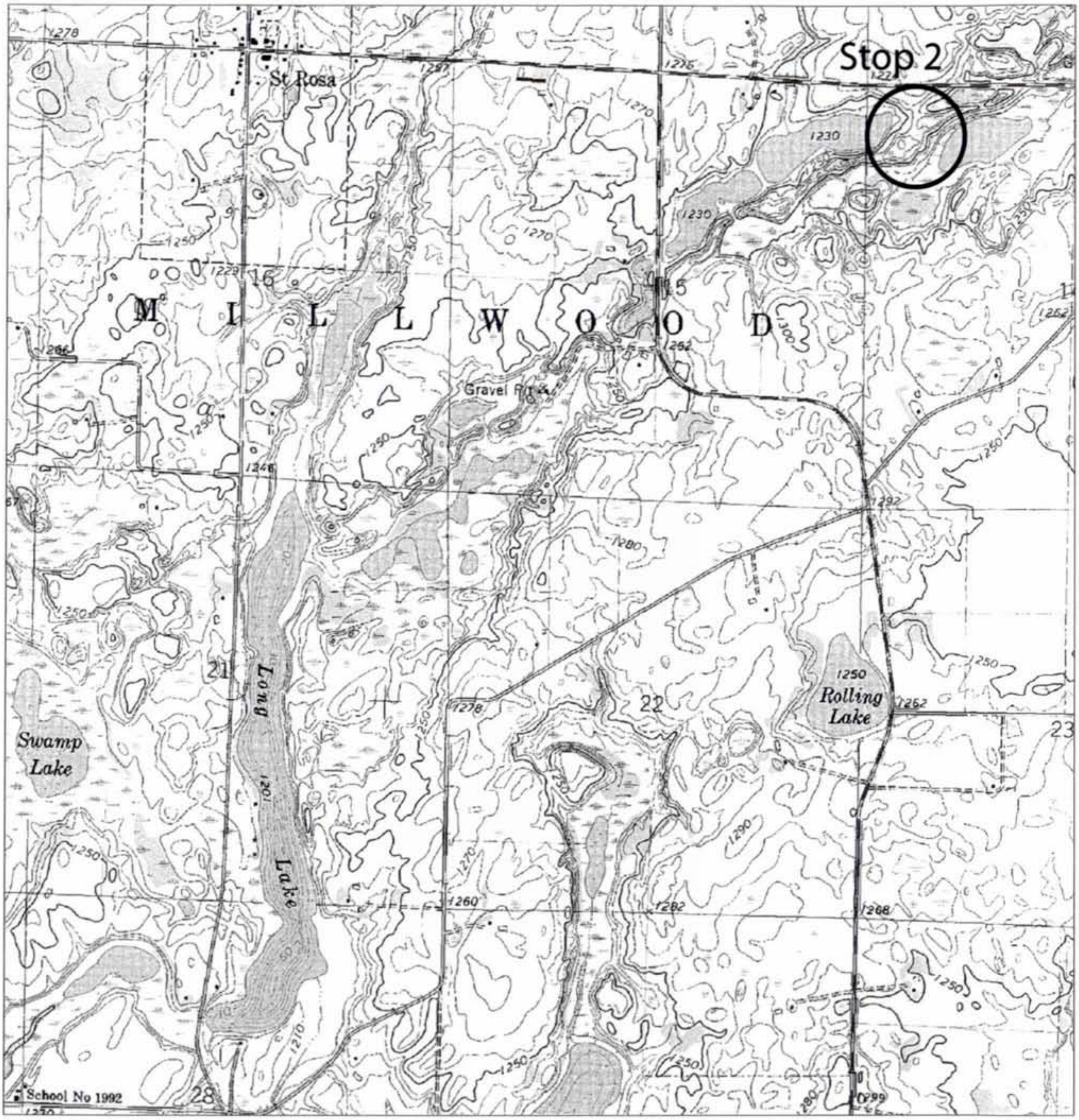


Figure 13. Topographic map showing Stop 2—St. Rosa esker located 3 miles (5 kilometers) east of St. Rosa (NW1/4NW1/4NW1/4, sec. 14, T. 126 N., R. 32 W.; U.S.G.S. Freeport quadrangle, 7.5-minute series, 1979).

This large pit is interpreted to be a recessional moraine, informally named the Little Birch Lake moraine, of the Wadena lobe (Meyer and others, 2001; Fig. 11b). This moraine had previously been mapped as part of the St. Croix moraine by Hobbs and Goebel (1982) but lithologic evidence shows that the moraine is composed of Wadena-lobe deposits (Meyer and others, 2001). Another arcuate ridge lies about 3 miles (5 kilometers) east of the Little Birch Lake moraine (it can be seen to the right, in the east, while driving to the next Stop). This ridge is the St. Croix moraine, which is covered by materials typical of the Superior lobe. The next Stop is an exposure on the St. Croix moraine in Superior-lobe till, where a comparison of the different materials seen at Stops 2 and 3 can be made.

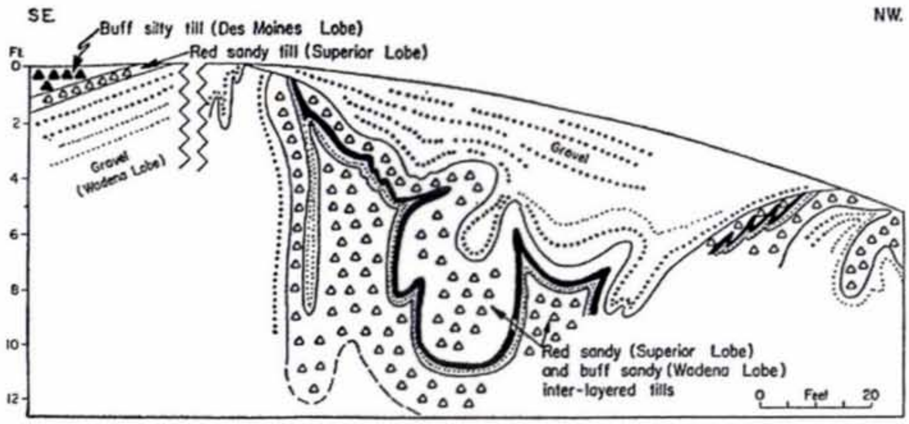


Figure 14. Diagram of St. Rosa esker exposure showing materials and isoclinal folds (from Wright, 1965, Fig. 5-11, p. 42).

Beverage break!

43.9 0.0 Turn right (north) out of pit and continue on CH 13.

45.5 1.6 Descend into Gray Eagle basin.

46.5 1.0 Turn right (east) on State Hwy 28.

48.3 1.8 View of the St. Croix moraine to the east and Wadena lobe recessional moraine to the west.

49.8 1.5 Turn left (north) on Cartway Rd. S. as you enter Gray Eagle.

49.9 0.1 Turn left (west) on State St. W. (State Hwy 287).

53.5 3.6 Big Swan Lake lies in a spillway channel on the right (east). Spillway channels will be crossed and driven along while traveling from Stop 4 through Stop 7. They were eroded by ice-marginal meltwater of the Superior lobe as ice retreated to the east (Fig. 11d). A detailed explanation of the spillways will be provided later.

56.8 3.3 Turn right (north) on CH 39.

58.7 1.9 Turn left (west) on 218th Street.

59.2 0.5 Pull over onto shoulder of road at outcrop.

Stop 4—Superior-lobe till road cut (Fig. 16).

This exposure of Superior-lobe (Pierz sublobe) till is located on the St. Croix moraine less than a mile east of the Superior-lobe ice margin. West of this margin extensive older Wadena drumlin field deposits lie at the surface. A tested sample from this site recorded typical Superior-lobe till characteristics: red-brown (7.5YR5/4 Munsell) color, noncalcareous (deeply leached of carbonate), sandy loam texture (61-28-11; sand-silt-clay percentages, respectively), and a significant percentage of dark mafic igneous and metasediment (31% of the Precambrian fraction) and red volcanic (14% of the Precambrian fraction) clasts. All these clasts are Superior basin source-area indicators. Evidence from auger holes and outcrops (Meyer and others, 2001) suggests that Superior lobe drift is thin in this area (southern half of Todd County; Fig. 10) and that the core of the St. Croix moraine is composed of Wadena lobe and Browerville drift and other pre-Wisconsinan sediments.

59.2 0.0 Turn around and go east on 218th Street.

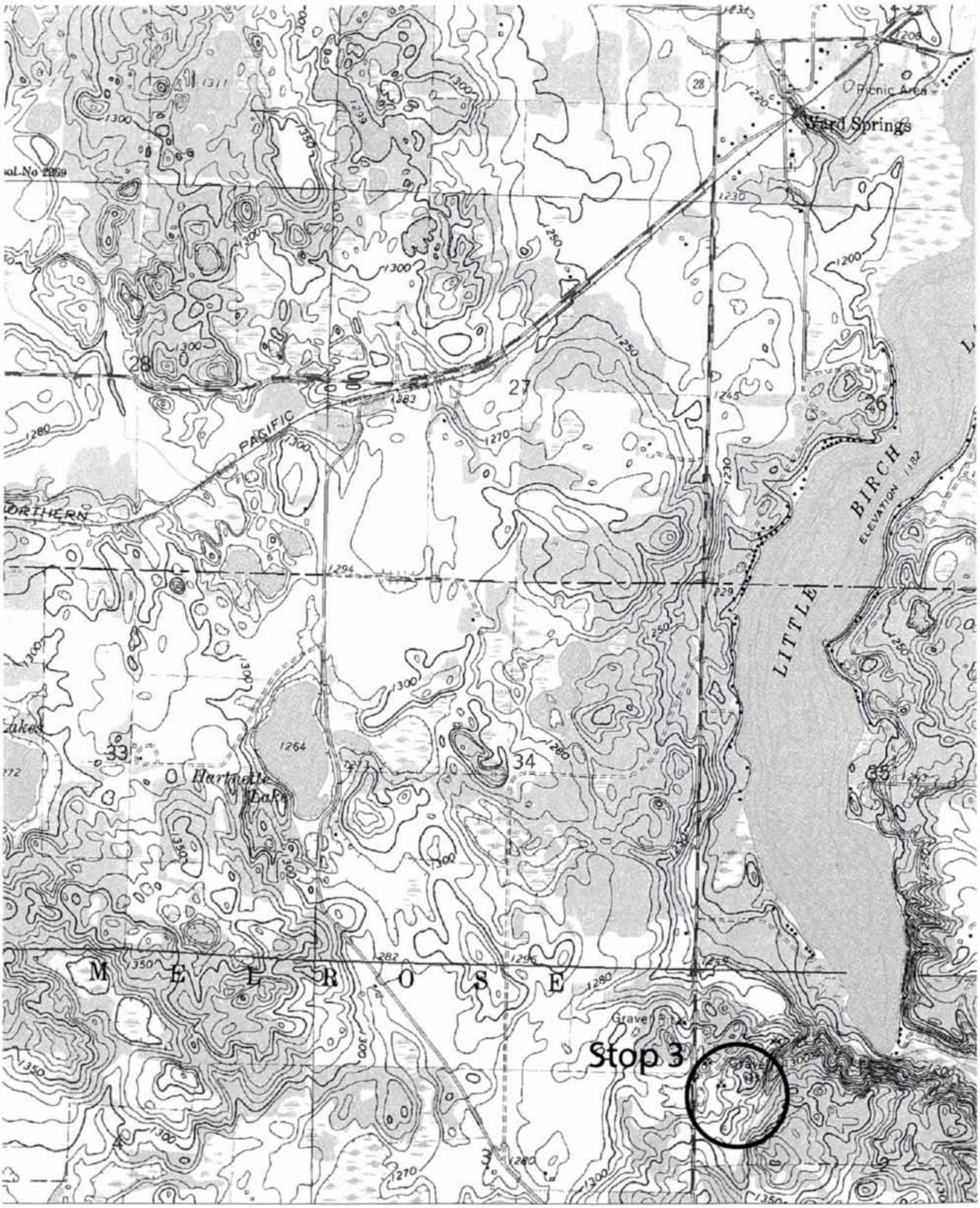


Figure 15. Topographic map showing Stop 3—Wielenberg pit on top of the Little Birch Lake moraine, a recessional moraine of the Wadena lobe (NW1/4SW1/4NW1/4, sec. 2, T. 126 N., R. 33 W.; U.S.G.S. Ward Springs quadrangle, 7.5-minute series, 1977).

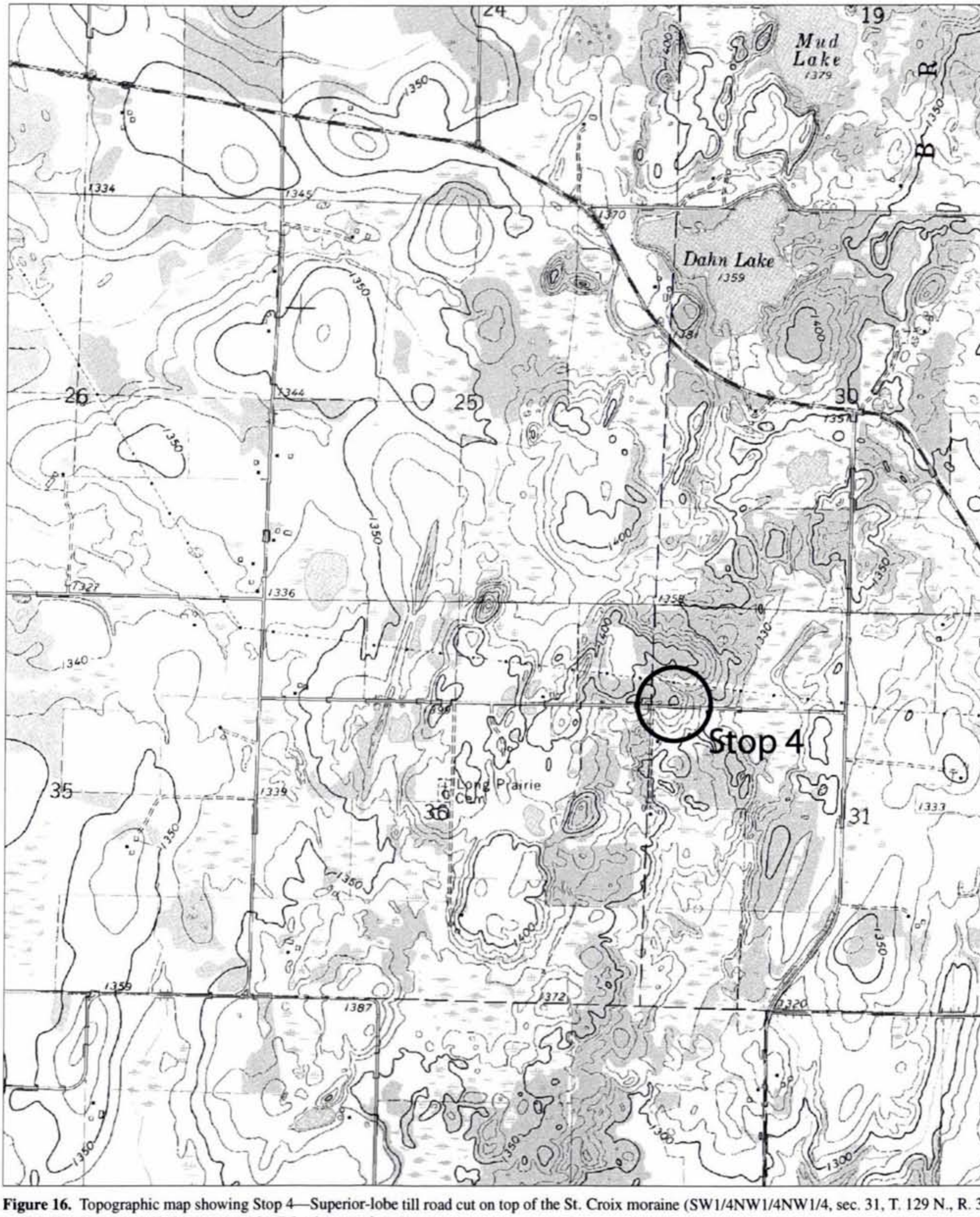


Figure 16. Topographic map showing Stop 4—Superior-lobe till road cut on top of the St. Croix moraine (SW1/4NW1/4NW1/4, sec. 31, T. 129 N., R. 32 W.; U.S.G.S. Long Prairie quadrangle, 7.5-minute series, 1977).

59.7	0.5	Turn left (north) on CH 39.
60.4	0.7	Turn right (east) on CH 12.
62.0	1.6	Enter the first of a series of spillway channels.
64.4	2.4	Turn left (north) into pit.

Stop 5—Gessel pit (Fig. 17).

Two units are exposed in this pit, Superior-lobe till overlying Browerville till. The contact between the tills is sharp. In the southeast corner of the pit there appears to be a channel eroded into the Browerville till, which is filled with Superior-lobe sand and gravel (Fig. 18). The upper red-brown till is similar in texture and lithology to that seen at the last stop. The lower till is oxidized to a yellow-brown (2.5Y5/4 Muncell) color, has a loam texture, and shows a lithology characteristic of the Browerville till. The very coarse-grained (1-2 millimeters) sand fraction contains about 30% carbonate, 7% dark Cretaceous limestone, trace amounts of gray siliceous Cretaceous shale, and only a trace of red Superior-basin volcanic and sandstone clasts (Meyer and Knaeble, 1996; Knaeble and Meyer, unpub. data). The Browerville formation materials are derived from the Winnipeg source area and are estimated to be Illinoian Stage or older in age (Meyer, 1997). In central Minnesota it is the most common pre-Wisconsinan drift found beneath Late Wisconsinan deposits. It is also the most easily recognizable because of its significant dark Cretaceous limestone content.

64.4	0.0	Turn left (east) to exit pit, continuing on CH 12.
67.2	2.8	Descend into Swanville area spillway channel (eastern-most spillway channel).
67.6	0.4	Turn right (south) on Morrison Line Rd. (State Hwy 28). In 100 feet (33 meters) turn left (east) and enter Swanville on 1st Avenue.
67.9	0.3	Turn left (north) on Springbrook Drive.
68.2	0.3	Park on shoulder at exposure.

Stop 6—Loven pit (Fig. 19).

There are four till units, a soil horizon, and a lacustrine silt layer exposed at this site. An auger boring completed at the base of exposure near the road encountered a fifth till. The upper exposure has a stratigraphy similar to that seen at the last Stop. It has 7 feet (3.1 meters) of red-brown Superior-lobe till overlying yellow-brown Browerville till. Beneath these deposits there is an extensive area of slump and reworked material. Another exposure beneath the disturbed materials contains two yellow-brown, carbonate-rich, silty tills, separated by a 1 foot-thick (0.3 meter) organic horizon. Based on texture and lithology both these tills represent pre-Wisconsinan deposits of the (x) sequence age (Fig. 5). Near the base of the slope underlying these tills is yellow-brown lacustrine silt. Red till (5YR5/6 Muncell) was found in an auger drill hole at the base of the exposure. This red till was interpreted as belonging to a pre-Wisconsinan, northeast-source, (x) sequence deposit (Meyer and others, 2001).

Channel erosion at this site uncovered tills interpreted as having ages that span three major glaciations. They were exposed as south-flowing meltwater from the retreating Superior-lobe ice margin, either incised a series of north-south trending spillway valleys into older deposits or eroded, to a greater extent, sediments in existing pre-Wisconsinan drainage valleys. These spillway channels are located along the lower half of eastern Todd County (Fig. 11d) and this site is located on east side of the eastern most spillway channel.

68.2	0.0	Turn around and go south on Springbrook Drive.

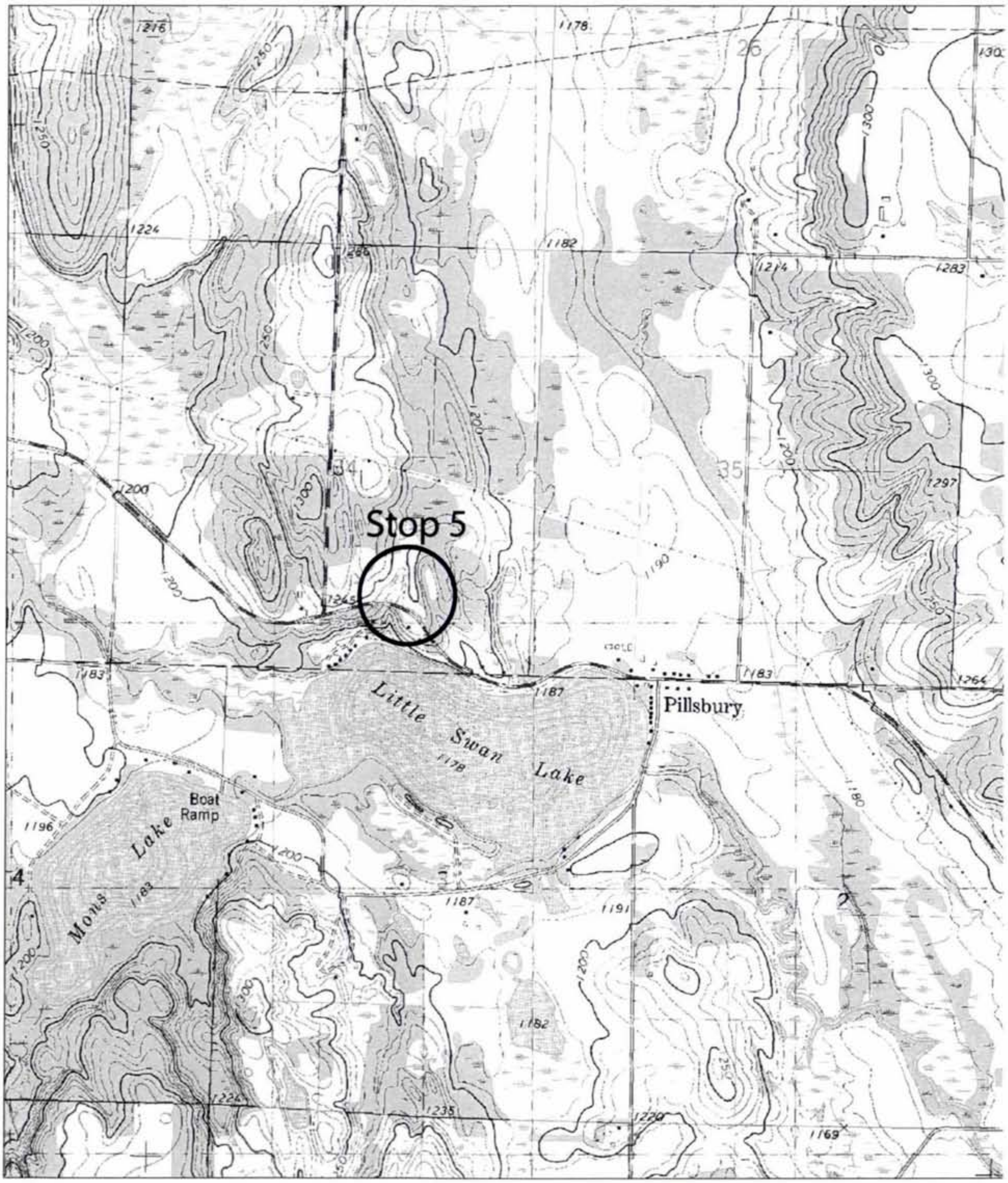


Figure 17. Topographic map showing Stop 5—Gessel pit located north of Little Swan Lake (NE1/4SW1/4SE1/4, sec. 34, T. 129 N., R. 32 W.; U.S.G.S. Swanville quadrangle, 7.5-minute series, 1978).

68.5	0.3	Turn right (west) on 1st Avenue.
68.7	0.2	Turn right (north) on State Hwy 28.
68.8	0.1	Turn left (north) on CR 219. Travel along west side of Irish Creek spillway channel.

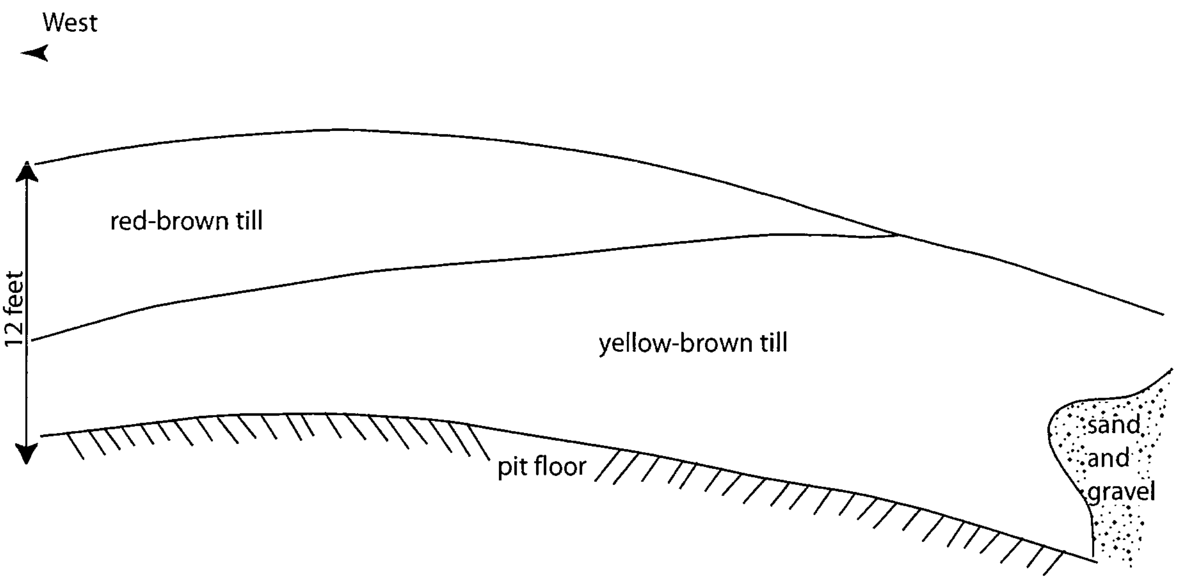


Figure 18. Diagram of Gessel pit exposure showing Superior-lobe till overlying Browerville formation till.

71.0	2.2	View of the Swan River drainage as it flows east out of Irish Creek spillway.
72.9	1.9	Turn left (west) on State Hwy 27. Ascend ridge and leave spillway channel.
73.5	0.6	View from crest of ridge looking west at series of spillways and the St. Croix moraine in the distance.
76.4	2.9	Pit located on southwest corner of intersection has Superior-lobe till/Superior-lobe sand and gravel.
77.0	0.6	Ascend the St.Croix moraine.
78.5	1.5	Crest of the St.Croix moraine. View of Wadena drumlin field to the west.
82.7	4.2	Turn left (south) on 6th Street NE upon entering Long Prairie.
82.9	0.2	Slight jog left in 6th Street NE; continue on 6th Street NE.
83.1	0.2	Continue straight on 6th Street NE at CH 12 stop sign.
83.8	0.7	Turn right (west) on Lake Charlotte Drive.
83.9	0.1	Turn left into Lake Charlotte park parking lot.

Lunch Stop.

83.9	0.0	Turn right (east) on Lake Charlotte Drive out of parking lot.
84.0	0.1	Turn left (north) on 6th Street NE.
84.7	0.7	Continue straight on 6th Street NE at CH 12 stop sign.
84.9	0.2	Jog left and continue on 6th Street NE.

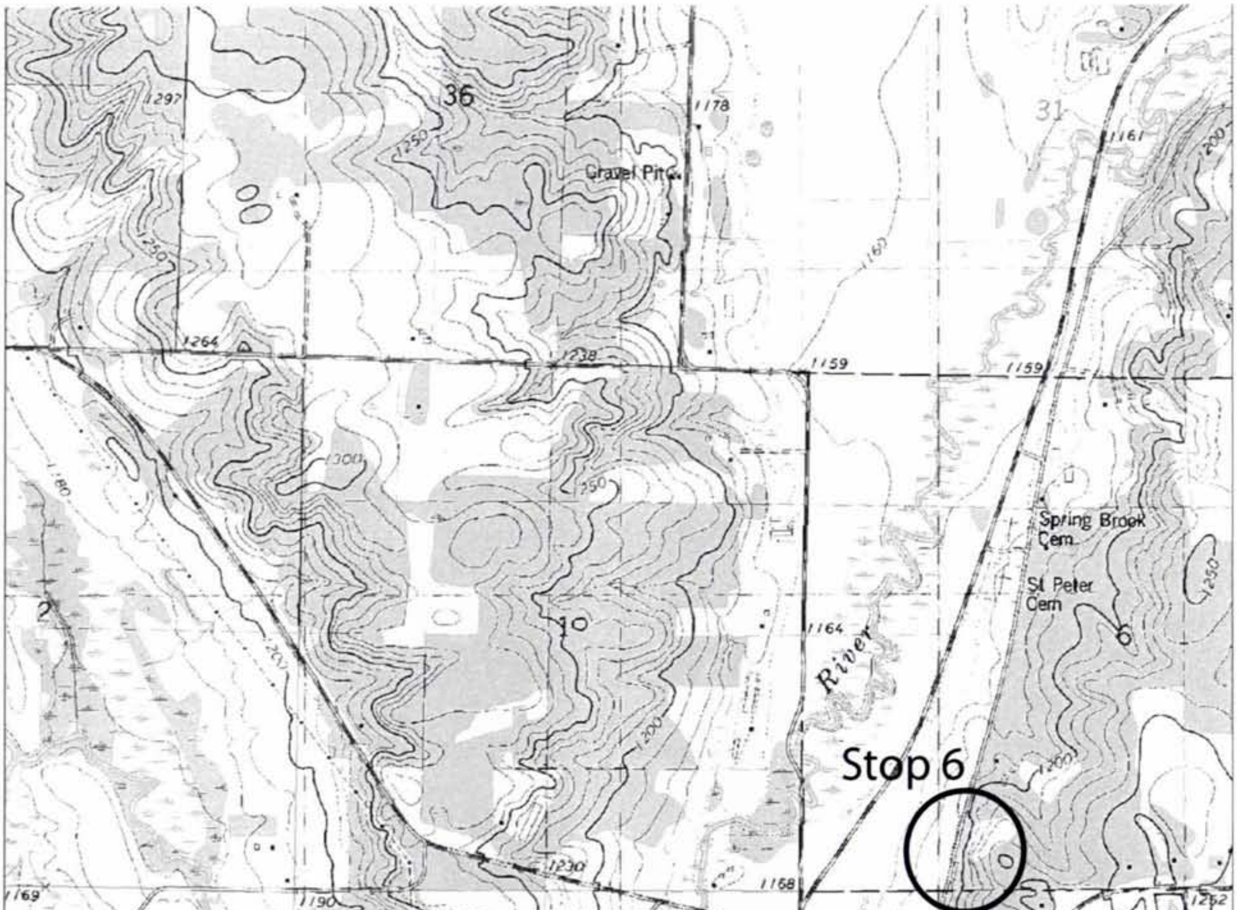


Figure 19. Topographic map showing Stop 6—Loven pit on east wall of spillway channel located north of Swanville (SW1/4SE1/4SW1/4, sec. 6, T. 128 N., R. 31 W.; U.S.G.S. Swanville quadrangle, 7.5-minute series, 1978).

85.2	0.3	Turn right (east) on State Hwy 27.
89.0	3.8	Ascend the St.Croix moraine.
91.3	2.3	Turn left (north) on 309th Avenue.
92.0	0.7	Park along road at second pit entrance.

Stop 7—Johnson pit (Fig. 20).

There are two pits at this site. The north pit displays Superior-lobe sand and gravels, which overlie oxidized yellow-brown Browerville till. At the base of the exposure on the east side the Browerville till is an unoxidized dark gray color (Fig. 21). Dark Cretaceous limestone clasts, diagnostic of the Browerville till, are visible in both the oxidized and unoxidized till. Near the top of the exposure on the west side a channel is incised into the till. Superior-lobe sand and gravel deposits, most of which have been scraped off the top of the exposure down to the till, fill the channel. A chunk of red till lies in the middle of the sand and gravel channel deposit. On the west side of the knob a second pit exposure also has Superior-lobe stream deposits overlying both oxidized and unoxidized Browerville till.

This pit site lies on the north side of a knob that sticks up above the floor of a spillway channel. The incised channel at the top of the pit filled with Superior-lobe sand and gravel, and containing a Superior-lobe till ball (Fig. 21) suggests that: south-flowing Superior-lobe meltwater eroded the top and probably the sides of the knob, any overlying Superior-lobe till was eroded along with some of the Browerville till deposits, and sediments from these streams later left a veneer of sand and gravel partially covering the knob.

92.0	0.0	Continue north on 309th Avenue.
92.2	0.2	Follow curve left (west) onto 250th Street.
92.5	0.3	Ascend the St. Croix moraine.
92.6	0.1	Ditch exposures on the left (south) side of the road contain two pre-Late Wisconsinan tills, the first cut has Browerville till and the second cut has an (x)-sequence till.
93.5	0.9	Turn left (south) on 295th Avenue.
94.5	1.0	Turn right (west) on State Hwy 27.
99.8	5.3	Turn right (north) in Long Prairie on U.S. Hwy 71. Drive north along Long Prairie River channel.
105.7	5.9	Turn left (west) on 300th Street.
106.0	0.3	Climb out of Long Prairie River channel.
106.5	0.5	Ascend Wadena lobe fluted highland or recessional moraine.
107.0	0.5	Turn left (south) on 225th Avenue.
107.9	0.9	Park on left road shoulder across from first radio tower.

Stop 8—Radio tower view (Fig. 22).

The radio tower is located on a ridge interpreted to be either a fluted highland or a recessional moraine associated with the Wadena lobe (Fig. 11b). To the west is a view of the Wadena drumlin field. On the horizon to the east lies the rugged topography of the St. Croix moraine, which was the terminal ice margin of the Superior lobe as its ice advanced into central Minnesota from the

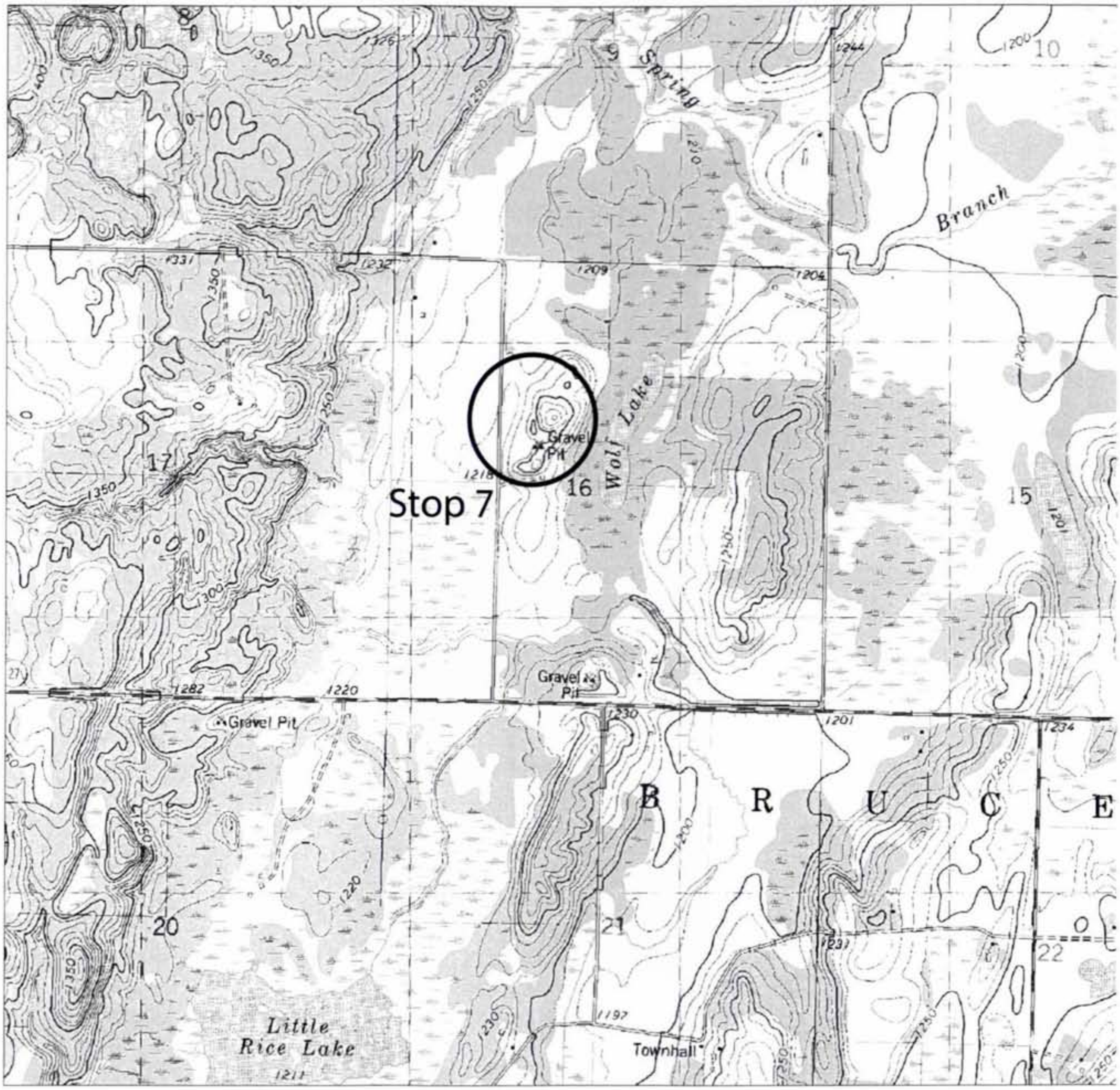


Figure 20. Topographic map showing Stop 7—Johnson pit located on knob in spillway channel (SE1/4NE1/4NW1/4, sec. 16, T. 129 N., R. 32 W.; U.S.G.S. Swanville quadrangle, 7.5-minute series, 1978).

east (Fig. 11c). In the low area between the St. Croix moraine and the radio tower can be seen the eastern-most surface exposure of the Wadena-lobe deposits, where they form vague drumlin shapes. Wadena-lobe deposits extend east of the St. Croix moraine but there they are buried by Superior-lobe drift. In the lowest area immediately to the east of the radio tower ridge, the Long Prairie River valley dissects the Wadena-lobe sediments. The present-day Long Prairie River flows north into the Crow Wing River, which passes through Pillager Gap and enters the Mississippi east of the St. Croix moraine (Fig. 11e). At an earlier, time when the Superior-lobe ice was at the St. Croix moraine and when Wadena-lobe ice had retreated north and was forming the Itasca moraine, meltwater drainage from both lobes flowed to the south through this valley (Fig. 11c). Later when Des Moines-lobe ice blocked drainage about 15 miles (24 kilometers) to the south, flow in the valley was reversed, assuming its present-day northward flow direction (Wright, 1972; Goldstein, 1985; Mooers, 1988).

107.9 0.0 Continue south on 225th Avenue.

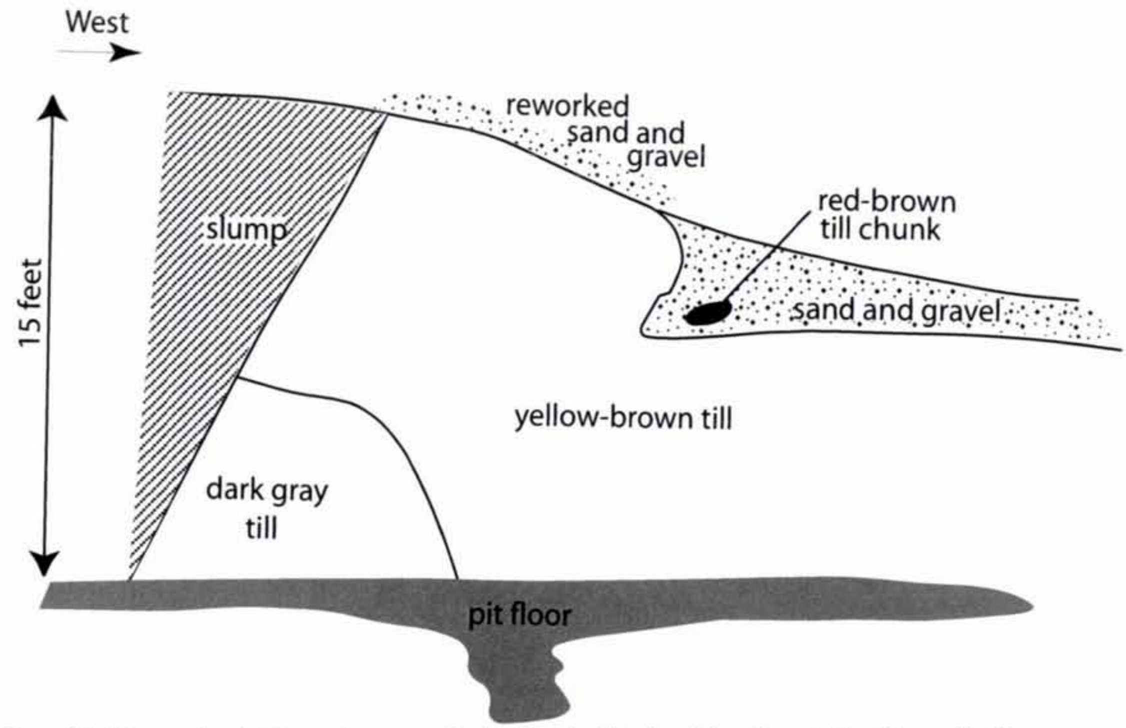


Figure 21. Diagram of north Johnson pit exposure showing Superior-lobe channel deposits eroded into Browerville till.

108.0	0.1	Turn left (east) on 290th Street.
109.3	1.3	Turn left (north) on U.S. Hwy 71.
111.8	2.5	Turn right (east) on CH 14 at north end of Browerville.
112.2	0.4	Turn left (north) on CH 21. Over the next 10 miles notice the north-south trending Wadena lobe drumlins on each side of the highway.
122.1	9.9	Drive over Wadena-lobe drumlin crest.
125.2	3.1	Turn left (west) on CR 74.
126.3	1.1	Turn right (north) at pit entrance.
126.9	0.6	Stay right at fork in pit road; park on north side of storage piles.

Stop 9—Stewart pit (Fig. 23).

This extensive pit forms a ravine for about 0.75 mile (1.2 kilometers). Most sediment on the left (west) side of the pit is channel sand and gravels that have a mixed lithology. They are composed of Des Moines- and Wadena-lobe materials and also some Browerville formation sediments. The right (east) side of the pit has many exposures and is more complex. It commonly displays a cap of oxidized yellow-brown sandy Wadena-lobe till overlying sand and gravel. These stream sediments are probably associated with the Wadena lobe or else the Browerville formation, or both. The sand and gravel is very oxidized and in places is cemented. In one exposure this underlying sand and gravel has been deformed by overriding Wadena-lobe ice, to the extent that the intact bedding is almost vertical. In a cul-de-sac exposure towards the north end of the pit a layer of Browerville till lies between the Wadena-lobe till and lower sand and gravel deposits. Texture and lithology analyses of both the oxidized and the unoxidized layers in this till confirm that it is correlative to

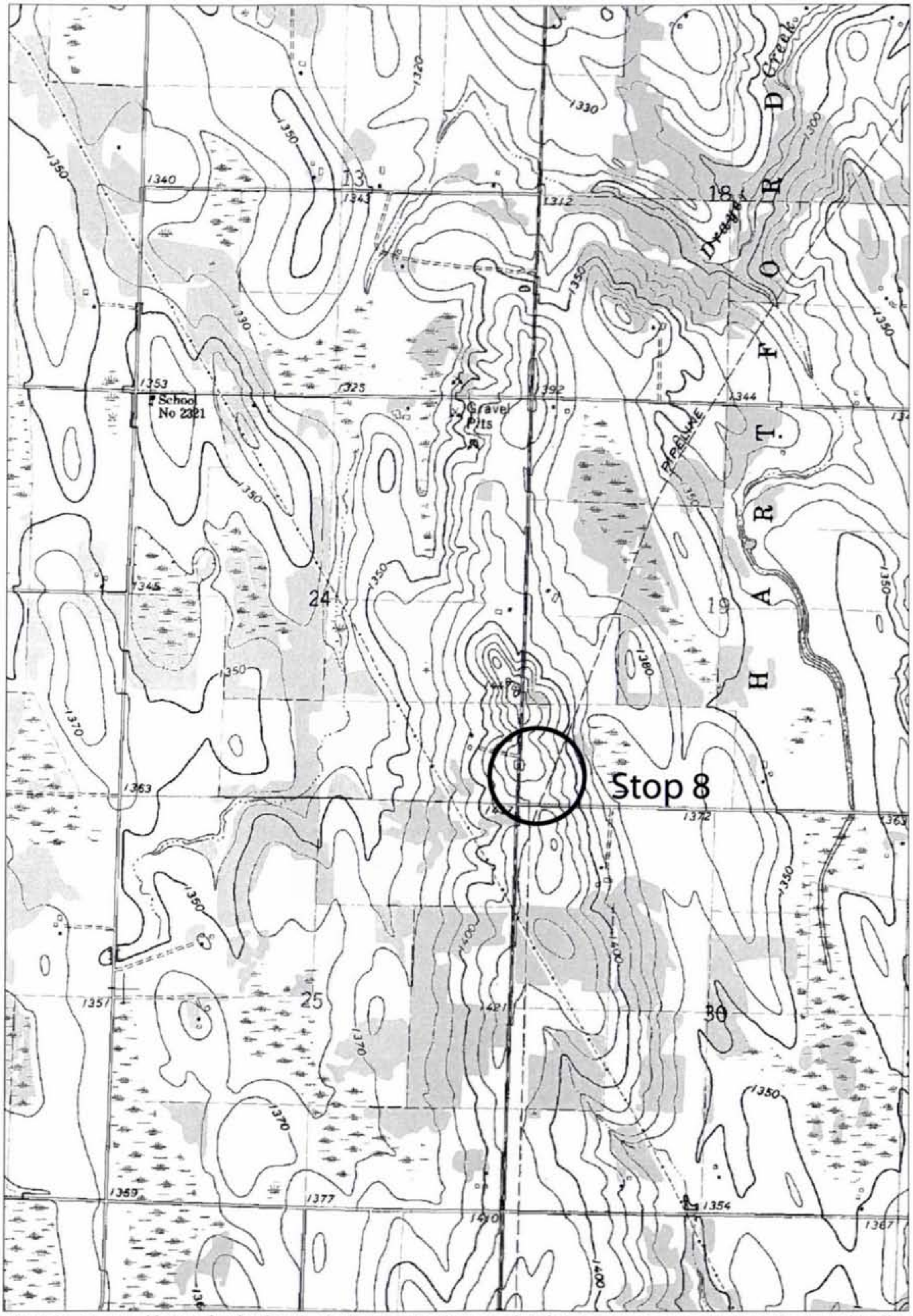


Figure 22. Topographic map showing Stop 8—Radio tower view from top of Wadena-lobe flute or recessional moraine, located 3 miles (5 kilometers) southwest of Browerville (SW1/4SW1/4SW1/4, sec. 19, T. 130 N., R. 33 W.; U.S.G.S. Browerville SW quadrangle, 7.5-minute series, 1966).

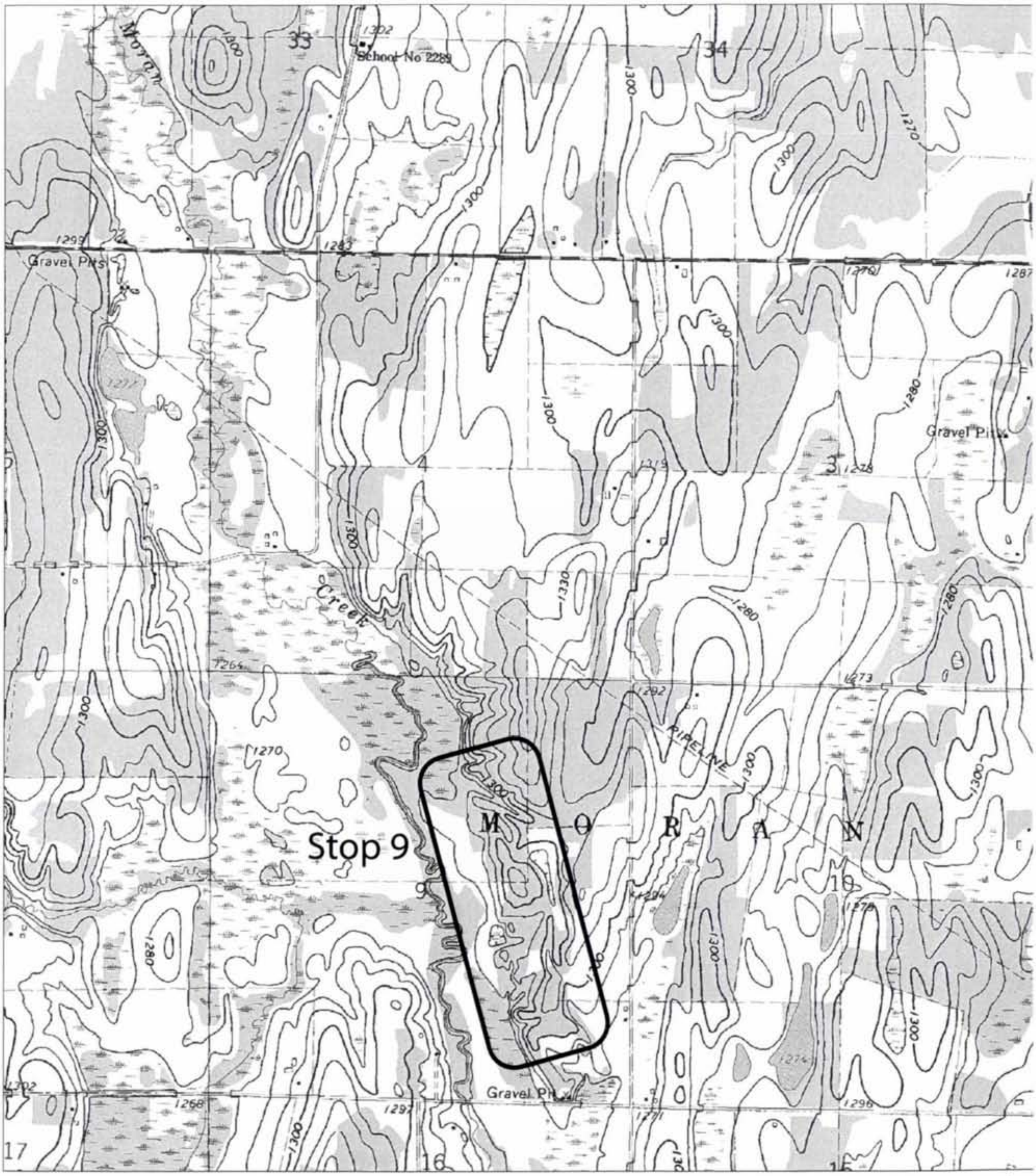


Figure 23. Topographic map showing Stop 9—Stewart pit in drumlinized landscape with stream erosion, located 7 miles (11.2 kilometers) southwest of Staples (NE1/4, sec. 9, T. 132 N., R. 33 W.; U.S.G.S. Staples quadrangle, 7.5-minute series, 1966).

the Browerville formation. Note that dark, tabular, Cretaceous limestone clasts are present in this till and also in the underlying sand and gravel.

This pit is located on the western edge of an area of drumlinized topography, where a stream appears to have been eroding into the landscape. The exposures on the east side of the pit suggest that Wadena-lobe ice scoured and molded the drumlin shape predominantly from pre-existing subglacial drift. Later, the Wadena lobe deposited a cap of till, covering the older sediments.

Most sediment on the left (west) side of the pit is channel sand and gravels, which may have been deposited by Des Moines lobe meltwater as it was draining off a portion of the Alexandria moraine that lay to the west (Figs. 11a, e). Meltwater may have flowed south through this valley eventually entering the Long Prairie valley drainage system, which still flowed south at this time (Des Moines-lobe ice had not yet advanced far enough east to block this drainage). The sand and gravels exposed on the west side of the pit may derive their mixed lithology from eroded Wadena-lobe and Browerville-formation sediments that lay upstream to the northwest.

Refreshment!

127.5	0.6	Turn around in the pit and turn right (west) onto CR 74.
127.8	0.3	Turn left (south) on Quarry Rd.
129.7	1.9	Continue on Quarry Rd. to left.
130.4	0.7	Turn right (south) on CH 21.
131.7	1.3	View of a drumlin on left (east) with a farmhouse on it.
139.5	7.8	Turn left (south) on U.S. Hwy 71. Drive south along Long Prairie River channel valley.
153.5	14.0	The next 2 miles (3.2 kilometers) contain outwash fan deposits emanating from the Des Moines-lobe ice margin. This ice blocked the southward flow of the ancestral Long Prairie-Sauk River valley drainage.
163.0	9.5	Sauk Lake on left (east) in Sauk River valley.
166.2	3.2	Turn left (east) on I-94 at south end of Sauk Center.
168.5	2.3	The approximate location of a buried portion of the St. Croix moraine. It marks the maximum extent of Superior-lobe deposits. Des Moines-lobe drift covers the Superior-lobe materials.
176.1	7.6	Cross over the Sauk River.
185.0	8.9	View of glacio-tectonic thrust hills (around Avon), ahead in the east.
188.3	3.3	Thrust hill on north side of I-94.
190.0	1.7	Thrust hills to east and southeast.
194.5	4.5	Exit I-94 and turn right (south) on CH 159.
195.9	1.4	Stop sign, continue straight on campus road.
196.0	0.1	Turn right into Mary Hall parking lot.
196.1	0.1	Turn left to enter parking area.
196.1	0.0	End of first day field trip.

ROAD LOG AND STOP DESCRIPTIONS

Day 2
Sunday, June 6, 2004

Miles (T=total miles, I=interval mileage)

T	I	
0.0	0.0	Leave St. John's from the south end of Mary Hall parking lot.
0.1	0.1	From the east Mary Hall parking lot exit, turn left (north) onto a campus road.
0.2	0.1	Stop sign continue north on County Road (CR) 159. Lake and wetland on right (east) side of road is northeast-flowing postglacial drainage for surrounding Superior-lobe stagnation topography.
0.9	0.7	Turn right (east) into St. John's Arboretum parking area. **Stop 10—St. John's Arboretum** (Fig. 24) At this stop an arboretum employee will provide information about St. John's University's program to preserve and restore natural habitat. This landscape was formed by stagnating ice of the Superior lobe. The Des Moines-lobe ice did not cover this area but meltwater from its ice margin, approximately 6 miles (9.6 kilometers) to the west, established eastward drainage along the North Fork of the Watab River. Drainage from this wetland flows north into the North Fork of the Watab River and then east into Mississippi River (Fig. 11e).
0.9	0.0	Turn left (south) out of parking lot and go back towards campus on CR 159.
1.6	0.7	Turn right (west) at stop sign and continue on CR 159.
2.0	0.4	On the left is St. John's pottery studio, directed by master potter Richard Bresnahan, and on the right is the pottery kiln. Bresnahan's philosophy is to use all indigenous materials. The clays used for most of his pottery were extracted from a road cut south of Avon, about 5 miles (8 kilometers) west of St. John's campus. They are Cretaceous marine sediments, which make up a portion of one of the many incorporated thrust slabs that form the large hills in that area.
3.1	1.1	Turn left (east) on CH 51.
3.7	0.6	Turn right (south) on Island Lake Rd.
6.3	2.6	Drive up onto the Merden Lake esker sand and gravel fan deposit.
6.6	0.3	Turn left (east) on CR 160.
7.2	0.6	Turn left into pit entrance. **Stop 11—Merden esker pit** (Fig. 25). Typical esker deposits are exposed along the east wall of the pit. Here, less than a 6 foot-thick (2 meters) layer of sandy, Superior-lobe till overlies about 25 feet (8.3 meters) of Superior-lobe sand and gravel (Fig. 26). A large exposure on the west end of the pit contains about 15 feet (5 meters) of Superior-lobe till. Incorporated into the lower portion of the Superior-lobe till there are at least two older tills and a thin layer of Cretaceous marine sediments (at the base of the unit). Beneath the till lies 25 feet (8.3 meters) of Superior-lobe sand and gravel, which forms the core of the esker (Fig. 26; Knaeble, 1998).

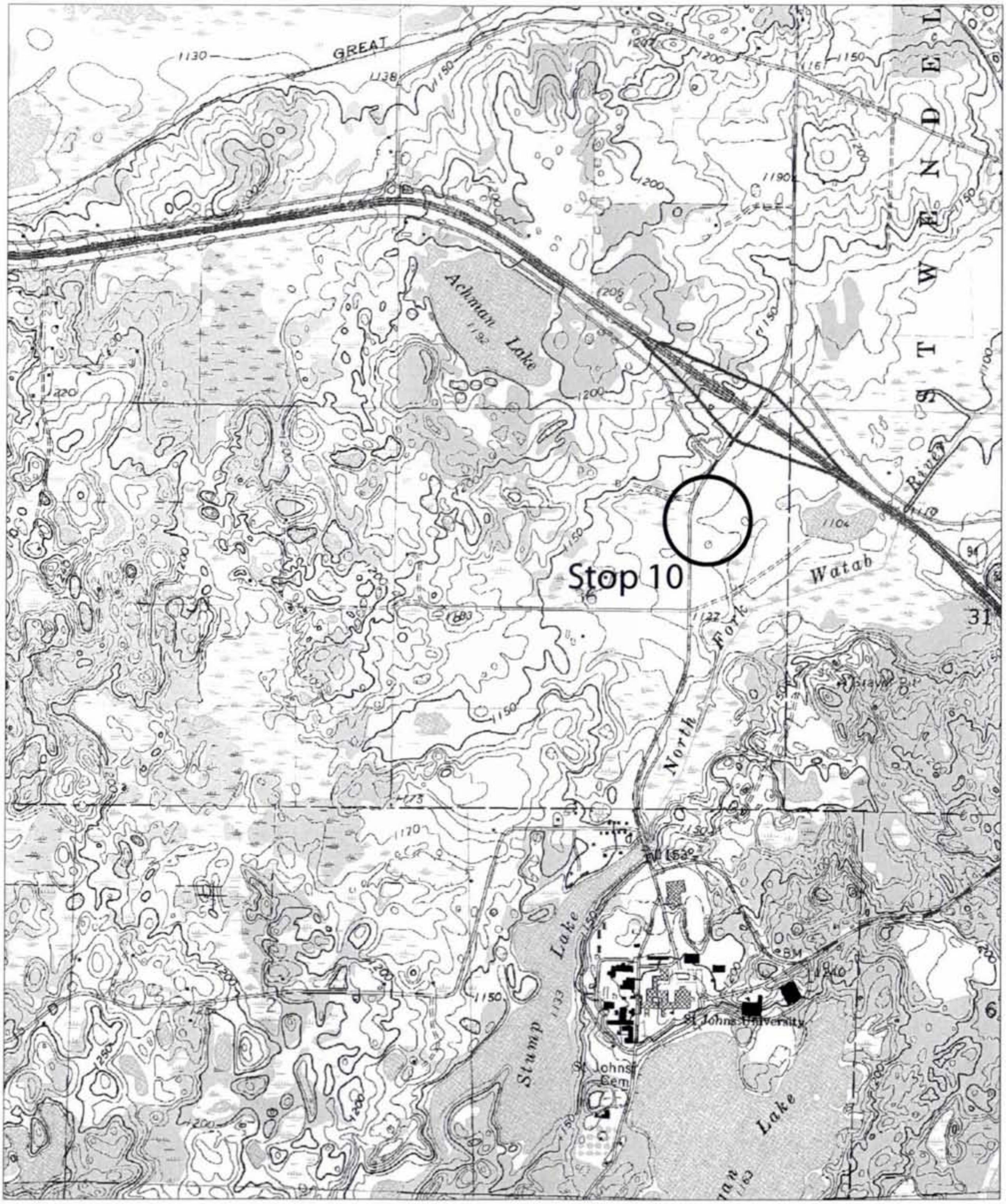


Figure 24. Topographic map showing Stop 10—St. John's arboretum located 1 mile (1.6 kilometers) north of campus (NW1/4SE1/4NE1/4, sec. 36, T. 124 N., R. 30 W.; U.S.G.S. Avon quadrangle, 7.5-minute series, 1979).

This esker is interpreted to have formed beneath retreating Superior-lobe ice. At the western terminus of the esker there is an elevated flat area (fan deposit) composed of sand and gravel, which was deposited by meltwater as it exited from beneath the ice. The sand and gravels of the esker core contain Superior-lobe source clasts. They also have a considerable pisolite clast

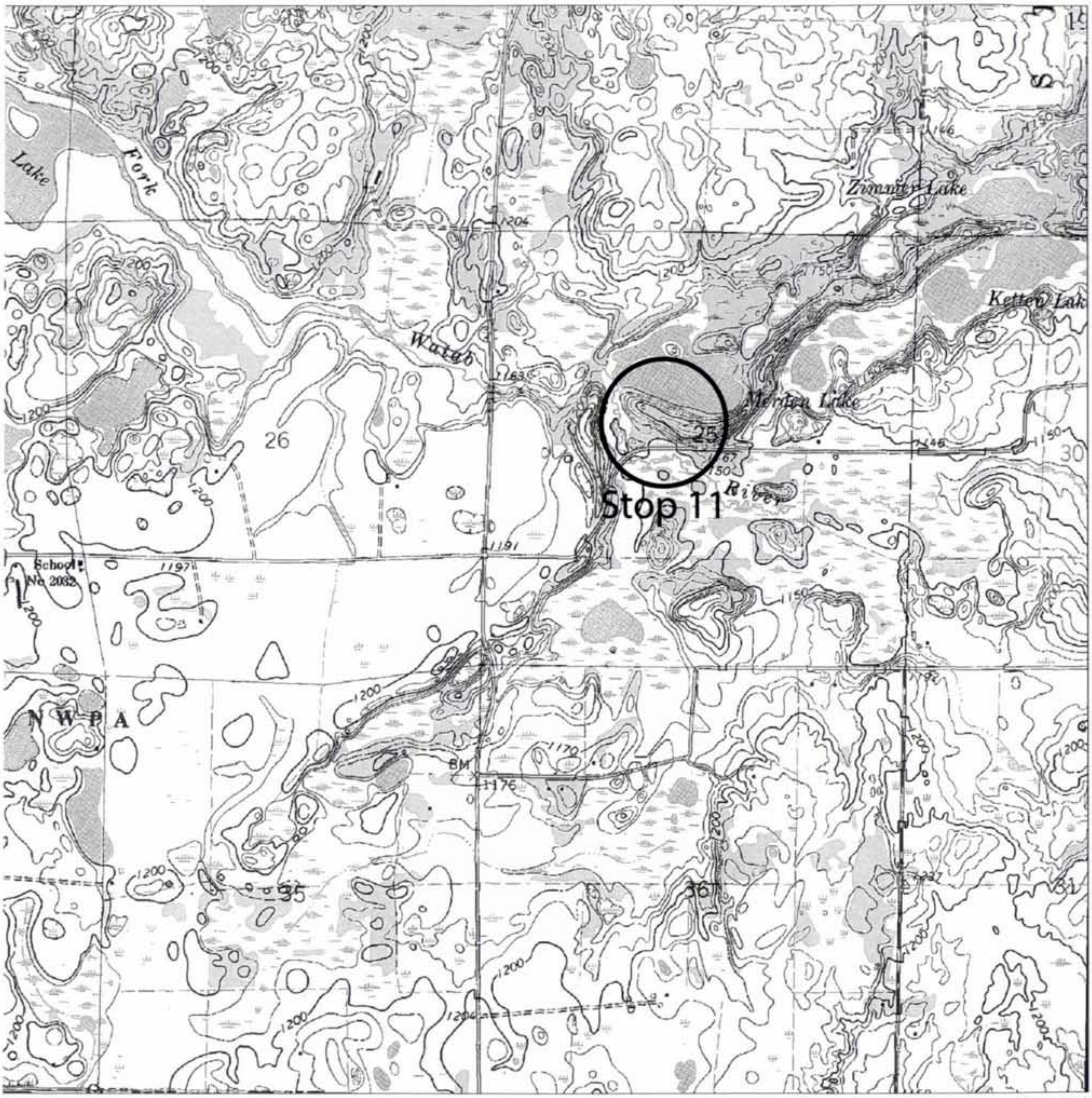


Figure 25. Topographic map showing Stop 11—Merden Lake esker with an outwash fan deposit west of the esker (SE1/4SE1/4NW1/4, sec. 25, T. 124 N., R. 30 W.; U.S.G.S. Avon quadrangle, 7.5-minute series, 1979).

component. These clasts are derived from the upper weathering profile of the Precambrian igneous and metamorphic saprolith (Setterholm, 1996). Their presence in the esker deposits suggests that erosion the weathered bedrock surface was occurring up-ice to the northeast. Another indicator that bedrock was being eroded up-ice is the presence of older till and Cretaceous sediment in the Superior till. A readvance of the Superior-lobe ice apparently excavated older drift and Cretaceous bedrock up-ice from the esker and subsequently smeared it over the top of the esker as ice readvanced and overrode the older feature (Knaeble, 1998).

Beverage break.

7.2 0.0 Exit from pit by turning left and continuing east on CR 160.

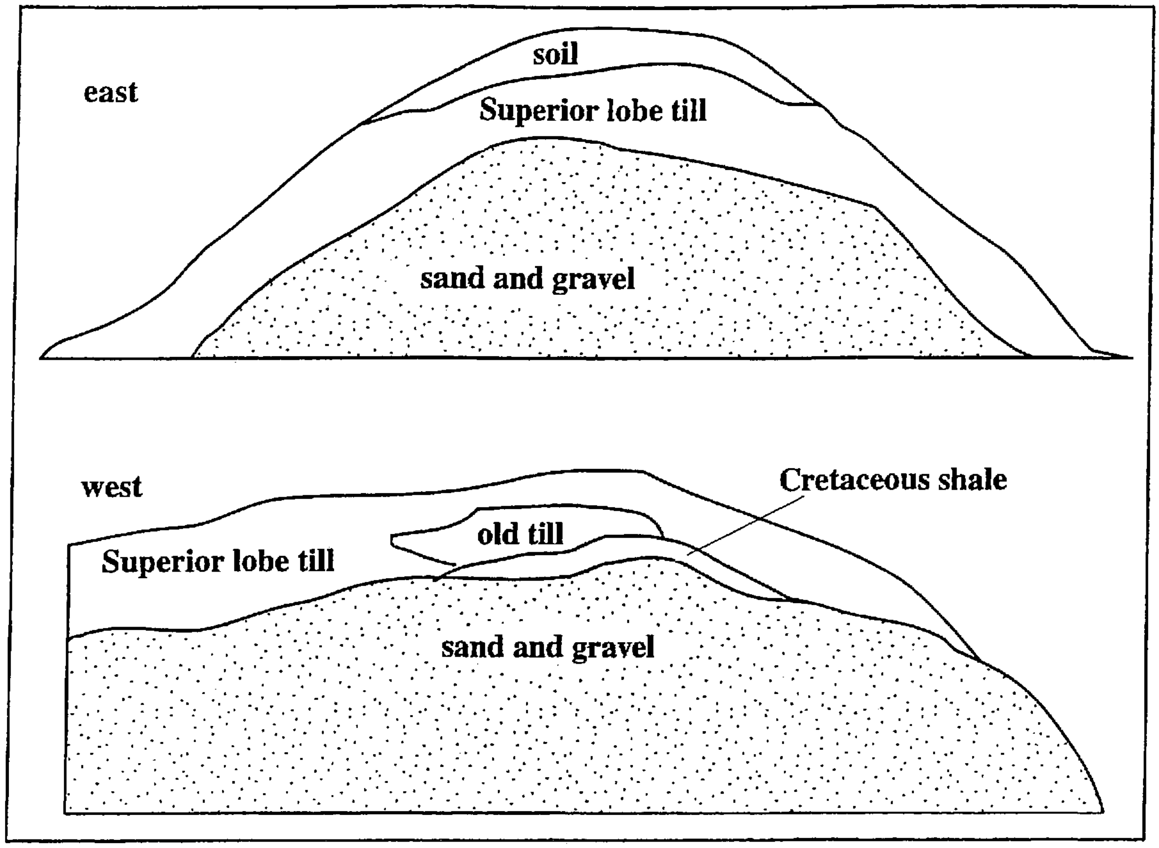


Figure 26. Diagrams showing the east and west pit exposures of the Merden Lake esker.

8.8	1.6	Descend into South Fork of the Watab River channel. This channel carried Des Moines-lobe meltwater, which flowed to the northeast, away from the ice margin, which was located approximately 8 miles (12.8 kilometers) to the southwest.
9.1	0.3	Turn right (south) on CH 2.
9.9	0.8	Turn left (east) on CR 139.
10.8	0.9	Turn right (south) following CR 139.
12.1	1.3	View of the St. Croix moraine in the distance to the south.
13.2	1.1	Granite bedrock outcrops on the left (east) side of road in the Sauk River valley.
13.4	0.2	Turn left (east) on Sauk River Rd.
13.8	0.4	Turn right (west) on Broadway Street (old State Hwy 23).
14.2	0.4	Turn left (south) on CH 8.
16.4	2.2	Grand Lake is on the left (east) and the St. Croix moraine is on right (west). Materials in the hills that make up the St. Croix moraine have been identified as pre-Late Wisconsinan drift and have been interpreted as having been deposited by Superior-lobe ice (Meyer and Knaeble, 1995). This ice advanced from the northeast, excavated sediments from the Grand Lake basin, and stacked them to form the moraine. This is probably an example of a hill-hole pair.

19.2	2.8	View of the St. Croix moraine to south and west.
19.3	0.1	Continue straight at stop sign on CH 48.
21.2	1.9	Turn left (southeast) on CR 147.
23.2	2.0	Turn right (south) on 93rd Avenue.
23.7	0.5	On the right (east) Des Moines-lobe meltwater channel sediments and on the left (west) the St. Croix end moraine. Superior-lobe ice advanced from the northeast forming an end moraine of mostly thrusted materials. Subglacial meltwater excavated a tunnel valley, which is about a mile wide, located on the east side of the moraine. After Superior-lobe ice left the area the Des Moines-lobe ice advanced to its terminal ice margin located about 2 miles to the southwest (the St. Croix moraine was blocking any further advance). Meltwater from the Des Moines lobe flowed northeast, reusing the Superior-lobe tunnel valley and depositing a thick sequence of outwash sand and gravel (Meyer and Knaeble, 1995).
24.6	0.9	Turn right (west) at the Powder Ridge entrance sign.
24.8	0.2	Continue past gate straight into parking lot.

Stop 12—Powder Ridge Ski Hill (Fig. 27).

This extensive borrow pit is located near the top of the Superior-lobe St. Croix end moraine, about 225 feet (75 meters) above the surrounding outwash plain of the Des Moines lobe. The pit is approximately 1/4 mile long, trending north-south. It was excavated to supply material to build up the summit of the ski hill and regrade existing ski runs. Till, as well as glacio-lacustrine, and glacio-fluvial deposits are exposed in at least 6 thrust blocks. Most blocks are greater than 50 feet (16.6 meters) thick, the largest being approximately 250 feet (83.3 meters) thick, and their width, where unit correlation can be made, is greater than 400 feet (133.3 meters; Fig. 28). These slabs are tilted 30-60° and dip north-northwest in what would have been the up-ice direction for the Superior lobe. Two zones 50 to 100 feet (16.6 to 33.3 meters) thick show deformation so intense that materials are sheared, streaked, and mixed or lie in distorted overturned folds. Most slab boundaries and some unit contacts within slabs show less intense folding, faulting, and streaking features (Fig. 29).

Each thrust block contains two or more distinct units differentiated by color, texture, lithology or all three. Texture and very coarse grained (1-2 millimeters) sand fraction analyses indicate the presence of till and related deposits from at least four separate glacial advances. The oldest till belongs to the (w) sequence and was deposited by a pre-Late Wisconsinan ice lobe that advanced out of the Winnipeg lowland (Fig. 7). A younger, unoxidized dark red-brown, pre-Late Wisconsinan till of the (x) sequence was deposited by ice that advanced out of the Lake Superior basin. Still younger ice interpreted to be Illinoian Stage or older in age advanced (and possibly readvanced) from the northwest and deposited two similar tills, both belonging to the (x) sequence. They are silty, oxidized yellow-brown, or sometimes unoxidized gray. Finally, Late Wisconsin Superior-lobe ice advanced from the northeast and deposited the youngest red-brown sandy till, which caps each thrust block. This ice advance caused the thrusting.

At the south end of the pit two Cretaceous marine clay deposits containing septarian concretions and large selenite crystals are separated by a thin 10 foot-thick (3.3 meters) layer of streaky, deformed Superior-lobe till containing streaks of incorporated older till, and a very well sorted, finely bedded unit of fine to medium sand 25 to 30 feet (8.3 to 10 meters) thick (Fig. 28). These layers and the upper Cretaceous deposit are tilted 30-60° similar to other thrusted glacial units. The lower southernmost Cretaceous deposit was drilled and is continuous to a depth of 56 feet (18.6 meters). The boring ended in this unit. The top of these Cretaceous deposits is 1300 feet above sea level, yet in the area surrounding the moraine well logs show the highest Cretaceous bedrock in place to be less than 1100 feet above sea level.

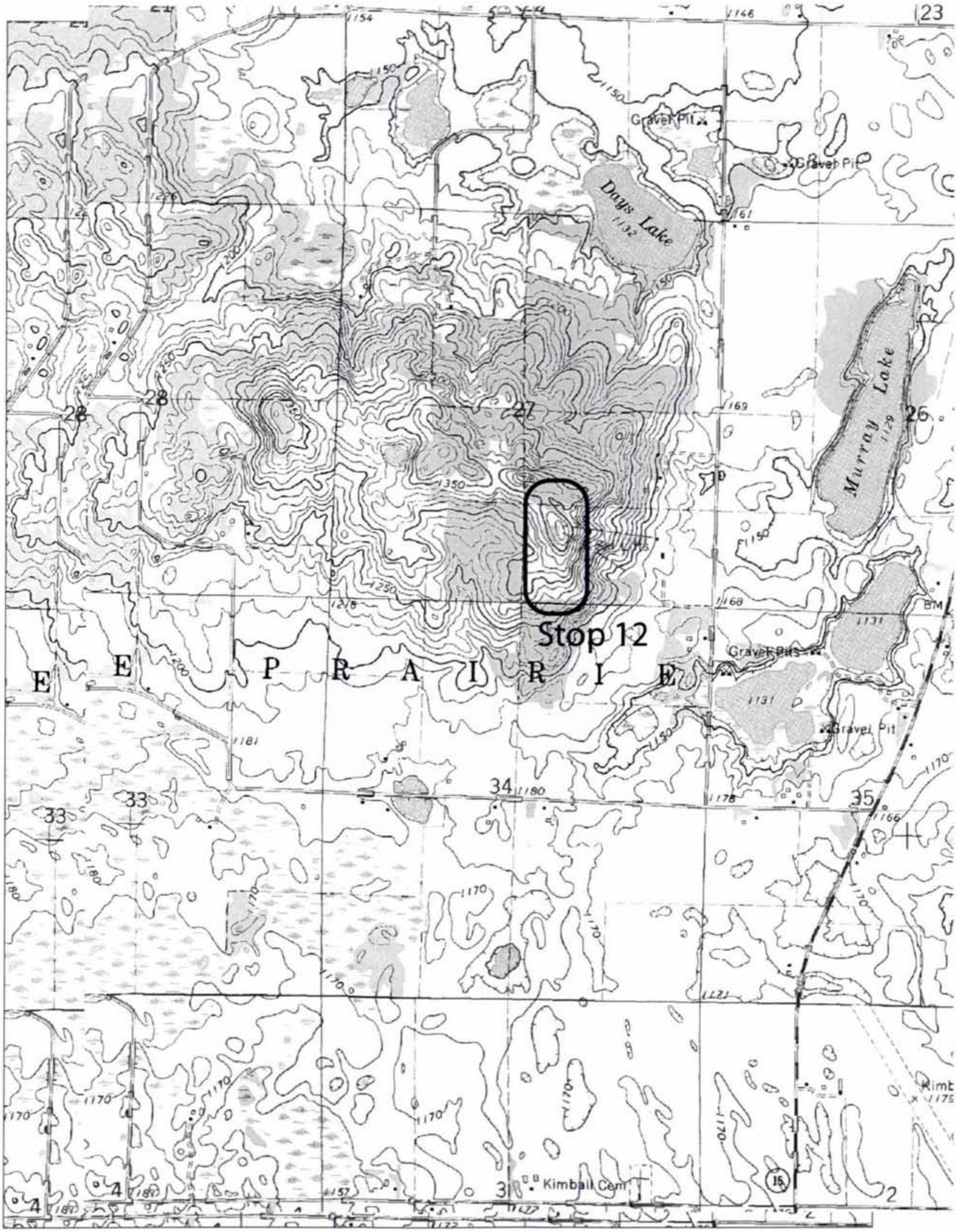


Figure 27. Topographic map showing Stop 12—Powder Ridge Ski Hill pit site, shown on top of St. Croix moraine with tunnel valley channel east of the moraine, located 2 miles (3.2 kilometers) northwest of Kimball (SW1/4SE1/4, sec. 27, T. 122 N., R. 29 W.; U.S.G.S. Kimball quadrangle, 7.5-minute series, 1967).

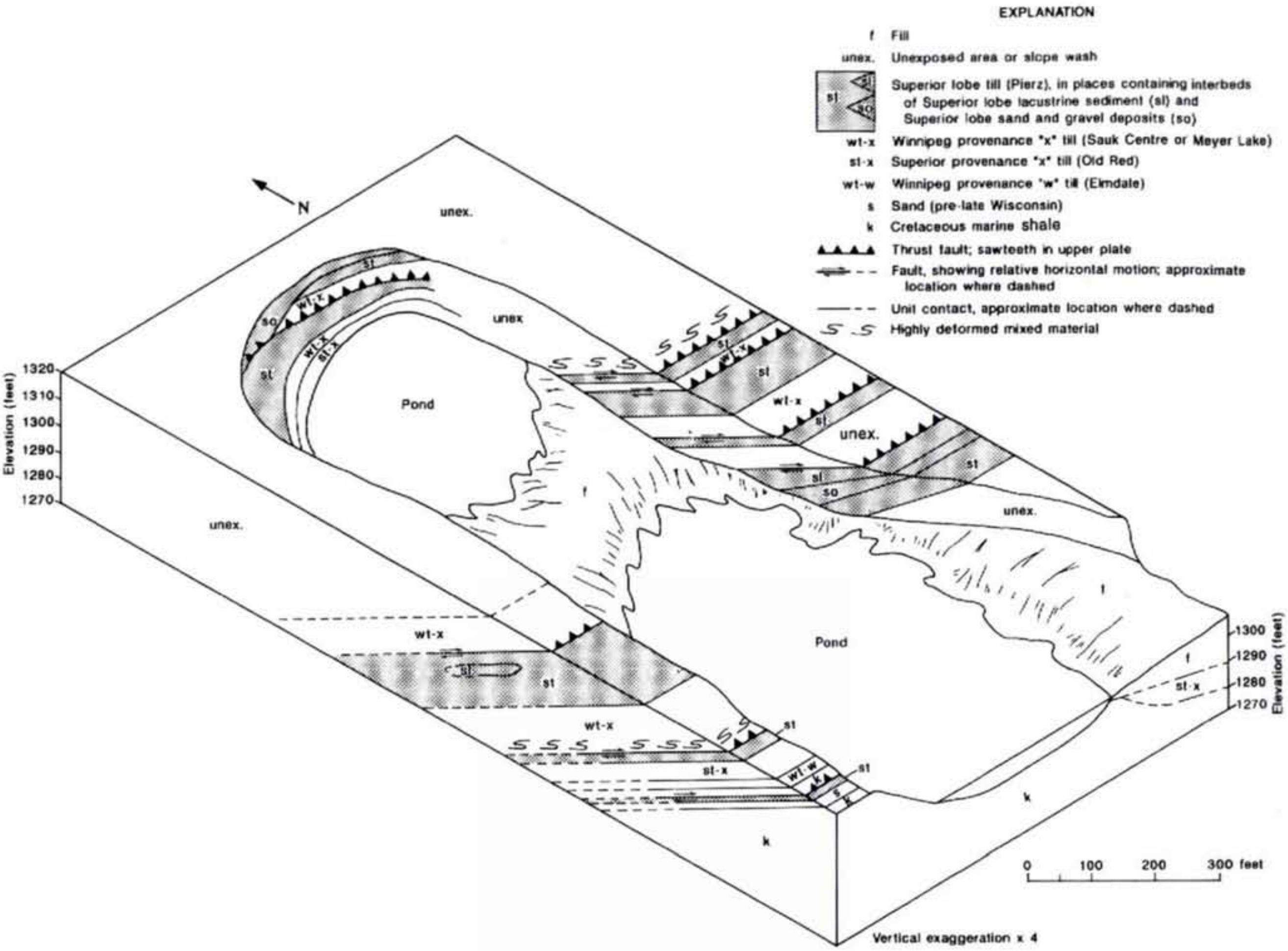


Figure 28. Block diagram of the Powder Ridge Ski Hill pit showing stratigraphic units and interpreted thrust surfaces. Quaternary sediments and Cretaceous shales are exposed on the north, east and west walls of the pit; the exposures on the west wall has been extended through to the outside face of the block diagram. Tick marks are on the base of each thrust sheet. Thrust direction is shown by small arrows. The explanation provides information on the stratigraphic units (Knaeble, 1998, Fig. 5).

Lunch—on top of Powder Ridge Ski Hill.

24.8	0.0	Exit parking lot heading east past entrance gate.
25.0	0.2	Turn left (north) on 93rd Avenue.
26.1	1.1	Turn left (west) on CR 147.
28.0	1.9	Turn right (north) on CH 48.
28.1	0.1	Continue straight at stop sign on CH 8.
33.4	5.3	Turn right (east) on Broadway Street (old State Hwy 23).
33.8	0.4	Turn left (north) on Sauk River Rd.
34.2	0.4	Turn right (north) on CR 139.

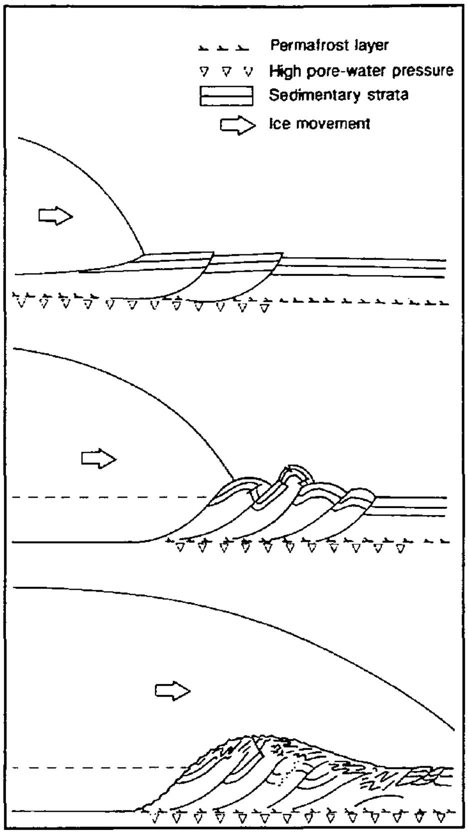


Figure 29. Model illustrating the processes contributing to the structural deformation produced by glacier advance over permanently frozen unlithified sedimentary strata. (Knaeble, 1998, Fig. 9; modified from Aber [1988]).

36.9	2.7	Turn left (west) and continue on CR 139.
37.8	0.9	Turn right (north) on CH 2.
39.0	1.2	Turn left (west) on CH 51.
42.1	3.1	Turn right (north) on CR 159.
43.6	1.5	Turn right (south) at stop sign on campus.
43.7	0.1	Turn right into Mary Hall parking lot.
43.8	0.1	Turn left into south end of parking lot.
43.8	0.0	**Trip completed!**

REFERENCES

Aber, J.S., 1988, Structural geology exercises with glaciotectonic examples: Winston-Salem, N.C., Hunter Textbooks, p. 81-84.

Anderson, C.A., 1976, Pleistocene geology of the Comstock-Sebeka area, west-central Minnesota: Grand Forks, N. Dak., University of North Dakota, M.S. thesis, 111 p.

Bluemle, J.P., and Clayton, L., 1984, Large-scale glacial thrusting and related processes in North Dakota: Boreas, v. 13, p. 279-299.

Boerboom, T.J., 1996, Precambrian geology of Stearns County, Minnesota, *in* Meyer, G.N., and Swanson, L., eds., Text supplement to the geologic atlas, Stearns County, Minnesota: Minnesota Geological Survey County Atlas C-10, pt. C, p. 1-6.

Boerboom, T.J., Setterholm, D.R., and Chandler, V.W., 1995, Bedrock geology, plate 2 *of* Meyer, G.N., project manager, Geologic atlas of Stearns County, Minnesota: Minnesota Geological Survey County Atlas C-10, pt. A, 7 pls., scales 1:100,000 and 1:200,000.

Clayton, L., and Moran, S.R., 1982, Chronology of Late Wisconsinan glaciation in Middle North America: Quaternary Science Reviews, v. 1, p. 55-82.

Cooper, W.S., 1935, The history of the upper Mississippi River in Late Wisconsin and post-glacial time: Minnesota Geological Survey Bulletin 26, 116 p.

Dyke, A.S., and Prest, V.K., 1987, Late Wisconsinan and Holocene history of the Laurentide ice sheet: Geographie Physique et Quaternaire, v. 61, no. 2, p. 237-263.

Goldstein, B.S., 1985, Stratigraphy, sedimentology, and Late-Quaternary history of the Wadena drumlin region, central Minnesota: Minneapolis, University of Minnesota, Ph.D. dissertation, 216 p.

———1998, Quaternary stratigraphy and history of the Wadena drumlin region, central Minnesota, *in* Patterson, C.J., and Wright, H.E., Jr., eds., Contributions to Quaternary studies in Minnesota: Minnesota Geological Survey Report of Investigations 49, p. 61-84.

Gowan, A.S., 1998, Methods of till analysis for correlation and provenance studies in Minnesota, *in* Patterson, C.J., and Wright, H.E., Jr., eds., Contributions to Quaternary studies in Minnesota: Minnesota Geological Survey Report of Investigations 49, p. 159-178.

Harris, K.L., 1998, Computer-assisted lithostratigraphy, *in* Patterson, C.J., and Wright, H.E., Jr., eds., Contributions to Quaternary studies in Minnesota: Minnesota Geological Survey Report of Investigations 49, p. 179-192.

Harris, K.L., and Knaeble, A.R., 1999, Surficial geology, pl. 1 *of* Quaternary geology—Otter Tail area, west-central Minnesota: Minnesota Geological Survey Regional Hydrogeologic Assessment RHA-5, pt. A, 2 pls.

———2003, Surficial geology, pl. 3 *of* Harris, K.L., project manager, Geologic atlas of Pope County, Minnesota: Minnesota Geological Survey County Atlas C-15, pt. A, 5 pls., scale 1:100,000.

Harris, K.L., Knaeble, A.R., and Berg, J.A., 1999, Surficial geology, pl. 2 *of* Quaternary stratigraphy—Otter Tail area, west-central Minnesota: Minnesota Geological Survey Regional Hydrogeologic Assessment RHA-5, pt. A, 2 pls.

———2003, Quaternary stratigraphy, pl. 4 *of* Harris, K.L., project manger, Geologic atlas of Pope County, Minnesota: Minnesota Geological Survey County Atlas C-15, pt. A, 5 pls., scale 1:100,000.

Hobbs, H.C., 1998, Use of 1-2 millimeter sand-grain composition in Minnesota Quaternary studies, *in* Patterson, C.J., and Wright, H.E., Jr., eds., Contributions to Quaternary studies in Minnesota: Minnesota Geological Survey Report of Investigations 49, p. 193-208.

———2001a, Surficial geology of the Brainerd quadrangle, Cass and Crow Wing Counties, Minnesota: Minnesota Geological Survey Miscellaneous Map M-112, scale 1:24,000.

———2001b, Surficial geology of the Gull Lake quadrangle, Cass and Crow Wing Counties, Minnesota: Minnesota Geological Survey Miscellaneous Map M-113, scale 1:24,000.

Hobbs, H.C., and Goebel, J.E., 1982, Geologic map of Minnesota, Quaternary geology: Minnesota Geological Survey State Map S-1, scale 1:500,000.

Johnson, M.D., and Mooers, H.D., 1998, Ice-margin positions of the Superior Lobe during Late Wisconsinan deglaciation, *in* Patterson, C.J., and Wright, H.E., Jr., eds., Contributions to Quaternary studies in Minnesota: Minnesota Geological Survey Report of Investigations 49, p. 7-14.

Knaeble, A.R., 1996, Glaciotectonic thrusting along the St. Croix Moraine, Stearns County, Minnesota, *in* Meyer, G.N., and Swanson, L., eds., Text supplement to the geologic atlas, Stearns County, Minnesota: Minnesota Geological Survey County Atlas C-10, pt. C, p. 16-39.

———1998, Superior-Lobe glacial thrusting of glacial sediment and bedrock along the St. Croix Moraine, Stearns County, Minnesota, *in* Patterson, C.J., and Wright, H.E., Jr., eds., Contributions to Quaternary studies in Minnesota: Minnesota Geological Survey Report of Investigations 49, p. 15-26.

———2001, Surficial geology of the Baxter quadrangle, Crow Wing, Morrison, and Cass Counties, Minnesota: Minnesota Geological Survey Miscellaneous Map M-111, scale 1:24,000.

Knaeble, A.R., and Meyer, G.N., 2004, Quaternary stratigraphy, pl. 4 *of* Setterholm, D.R., project manager, Geologic atlas of Crow Wing County, Minnesota: Minnesota Geological Survey County Atlas C-16, pt. A, 6 pls., scale 1:100,000.

Knaeble, A.R., Meyer, G.N., and Hobbs, H.C., 2004, Surficial geology, pl. 3 *of* Setterholm, D.R., project manager, Geologic atlas of Crow Wing County, Minnesota: Minnesota Geological Survey County Atlas C-16, pt. A, 6 pls., scale 1:100,000.

Larson, P.C., and Mooers, H.D., 2004, Glacial indicator dispersal processes: A conceptual model: Boreas, v. 23, no. 3, p. 238-249.

Leverett, F., 1929, Moraines and shorelines of the Lake Superior basin: U.S. Geological Survey Professional Paper 154A, 172 p.

———1932, Quaternary geology of Minnesota and parts of adjacent states: U.S. Geological Survey Professional Paper 161, 149 p.

Lusardi, B.A., 1998, Salisbury Hill road-cut: a deformed multiple-till section near Henderson, Scott County, Minnesota, *in* Patterson, C.J., and Wright, H.E., Jr., eds., Contributions to Quaternary studies in Minnesota: Minnesota Geological Survey Report of Investigations 49, p. 141-153.

Matsch, C.L., 1971, Pleistocene stratigraphy of the New Ulm region, southwestern Minnesota: Madison, University of Wisconsin, Ph.D. dissertation, 78 p.

———1972, Quaternary geology of southwestern Minnesota, *in* Sims, P.K., and Morey, G.B., eds., Geology of Minnesota—A centennial volume: Minnesota Geological Survey, p. 548-560.

Meyer, G.N., 1986, Subsurface and till stratigraphy of the Todd County area, central Minnesota: Minnesota Geological Survey Report of Investigations 34, 40 p.

———1997, Pre-Late Wisconsinan till stratigraphy of north-central Minnesota: Minnesota Geological Survey Report of Investigations 48, 65 p.

———2000, Contributions to the geology of Mower County, Minnesota: Minnesota Geological Survey Report of Investigations 50, p. 31-61.

Meyer, G.N., and Knaeble, A.R., 1995, Surficial geology, pl. 3 *of* Meyer, G.N., project manager, Geologic atlas of Stearns County, Minnesota: Minnesota Geological Survey County Atlas C-10, pt. A, scales 1:100,000 and 1:200,000.

———1996, Quaternary geology of Stearns County, Minnesota, *in* Meyer, G.N., and Swanson, L., eds., Text supplement to the Geologic atlas of Stearns County, Minnesota: Minnesota Geological Survey County Atlas C-10, pt. C, p. 16-39.

Meyer, G.N., Knaeble, A.R., and Ellingson, J.B., 2001, Surficial geology of the St. Cloud 30 x 60 minute quadrangle, central Minnesota: Minnesota Geological Survey Miscellaneous Map M-115, scale 1:100,000.

Meyer, G.N., Knaeble, A.R., and Tipping, R.G., 1995, Quaternary stratigraphy, pl. 4 *of* Meyer, G.N., project manager, Geologic atlas of Stearns County, Minnesota: Minnesota Geological Survey County Atlas C-10, pt. A, 7 pls., scales 1:100,000 and 1:200,000.

Mooers, H.D., 1988, Quaternary history and ice dynamics of the St. Croix phase of Late Wisconsin glaciation, central Minnesota: Minneapolis, University of Minnesota, Ph.D. dissertation, 200 p.

———1989a, Drumlin formation: A time transgressive model: Boreas, v. 18, no. 2, p. 99-107.

———1989b, On the formation of the tunnel valleys of the Superior lobe, central Minnesota: Quaternary Research, v. 32, no. 1, p. 24-35.

———1990a, Discriminating texturally-similar glacial tills in central Minnesota with graphical and multivariate techniques: Quaternary Research, v. 34, no. 2, p. 133-147.

———1990b, A glacial-process model: the role of spatial and temporal variations in glacial thermal regime: Geological Society of America Bulletin, v. 102, no. 2, p. 243-251.

———1990c, Ice marginal thrusting of drift and bedrock: Thermal regime, subglacial aquifers, and glacial surges: Canadian Journal of Earth Sciences, v. 27, p. 849-862.

Mooers, H.D., and Lehr, J.D., 1997, Terrestrial record of Laurentide Ice Sheet reorganization during Heinrich events: Geology, v. 25, no. 11, p. 987-990.

Norton, A.R., 1983, Quaternary geology of the Itasca—St. Croix moraine interlobate area, north-central Minnesota: Minneapolis, University of Minnesota, M.S. thesis, 144 p.

Patterson, C.J., Knaeble, A.R., Setterhlom, D.R., and Berg, J.A., 1999, Quaternary stratigraphy, pl. 2 *of* Quaternary geology—Upper Minnesota River Basin, Minnesota: Minnesota Geological Survey Regional Hydrogeologic Assessment RHA-4, pt. A, 2 pls.

Perkins, R.L., 1977, The Late Cenozoic geology of west-central Minnesota from Moorhead to Park Rapids: Grand Forks, N. Dak., University of North Dakota, M.A. thesis, 99 p.

Prest, V.K., Donaldson, J.A., and Mooers, H.D., 2001, The Omar story: The role of Omars in assessing glacial history of west central North America: Géographie Physique et Quaternaire, v. 54, no. 3, p. 257-270.

Schneider, A.F., 1956, Pleistocene geology of central Minnesota, *in* Schwartz, G.M., ed., Glacial geology, eastern Minnesota: Geological Society of America, Annual Meeting, 1956, Guidebook for field trip no. 3, p. 25-52.

———1961, Pleistocene geology of the Randall region, central Minnesota: Minnesota Geological Survey Bulletin 40, 151 p.

Setterholm, D.R., 1995, Depth to bedrock and thickness of Cretaceous strata, pl. 5 *of* Meyer, G.N., project manager, Geologic atlas of Stearns County, Minnesota: Minnesota Geological Survey County Atlas C-10, pt. A, 5 pls., scales 1:100,000 and 1:200,000.

———1996, Geology of the Late Cretaceous strata and pre-Late Cretaceous weathering profile, Stearns County, Minnesota, *in* Meyer, G.N., and Swanson, L., eds., Text supplement to the geologic atlas, Stearns County, Minnesota: Minnesota Geological Survey County Atlas C-10, pt. C, p. 7-15.

Upham, W., 1881, Glacial drift and its terminal moraines: Minnesota Geological and Natural History Survey, 9th annual Report, p. 371-446.

———1896, Glacial Lake Agassiz: U.S. Geological Survey Monograph 25, 685 p.

Whitehill, M.F., 2002, Moraines of the Bonanza Valley, west-central Minnesota: University of Minnesota, M.S. thesis, 122 p.

Winchell, N.H., 1889, Geology of Minnesota: Minnesota Geological and Natural History Survey Final Report, v. 4, 695 p.

Winchell, N.H., and Upham, W., 1884, The geology of Minnesota: Minnesota and Geological Natural History Survey Final Report, v. 1, 697 p.

———1888, The geology of Minnesota: Minnesota and Geological Natural History Survey Final Report, v. 2, 695 p.

Wright, H.E., Jr., 1953, Interbedded Cary drifts near Minneapolis, Minnesota: Journal of Geology, v. 61, p. 465-471.

———1954, The Wadena Drumlin Field: Midwest Friends of the Pleistocene, Guidebook, Field Conference, Central Minnesota, May 1954, 45 p.

———1956, Sequence of glaciation in eastern Minnesota: Geological Society of America, Minneapolis Meeting Guidebook, pt. 3, p. 1-24.

———1957, Stone orientation in the Wadena drumlin field, Minnesota: Geography Annaler, v. 39, p. 19-31.

———1962, Role of the Wadena lobe in the Wisconsin glaciation of Minnesota: Geological Society of America Bulletin, v. 73, p. 73-100.

———1964, The classification of the Wisconsin Glacial Stage: Journal of Geology, v. 72, p. 628-637.

———1965, INQUA Upper Mississippi Valley: Guidebook for the Field Conference C, Day 5, p. 30-43.

———1972, Quaternary history of Minnesota, *in* Sims, P.K., and Morey, G.B., eds., Geology of Minnesota—A centennial volume: Minnesota Geological Survey, p. 515-547.

———1973, Tunnel valleys, glacial surges and subglacial hydrology of the Superior lobe, Minnesota, *in* Black, R.F., Goldthwait, R.P., and Willman, H.B., eds., The Wisconsinan Stage: Geological Society of America Memoir 136, p. 251-276.

Wright, H.E., Jr., and Ruhe, R.V., 1965, Glaciation of Minnesota and Iowa, *in* Wright, H.E., Jr., and Frey, D.G., eds., The Quaternary of the United States: Princeton, Princeton University Press, p. 29-41.

Wright, H.E., Jr., Matsch, C.L., and Cushing, E., 1973, Superior and Des Moines lobes, *in* Black, R.F., Goldthwait, R.P., and Willman, H.B., eds., The Wisconsinan Stage: Geological Society of America Memoir 136, p. 153-185.