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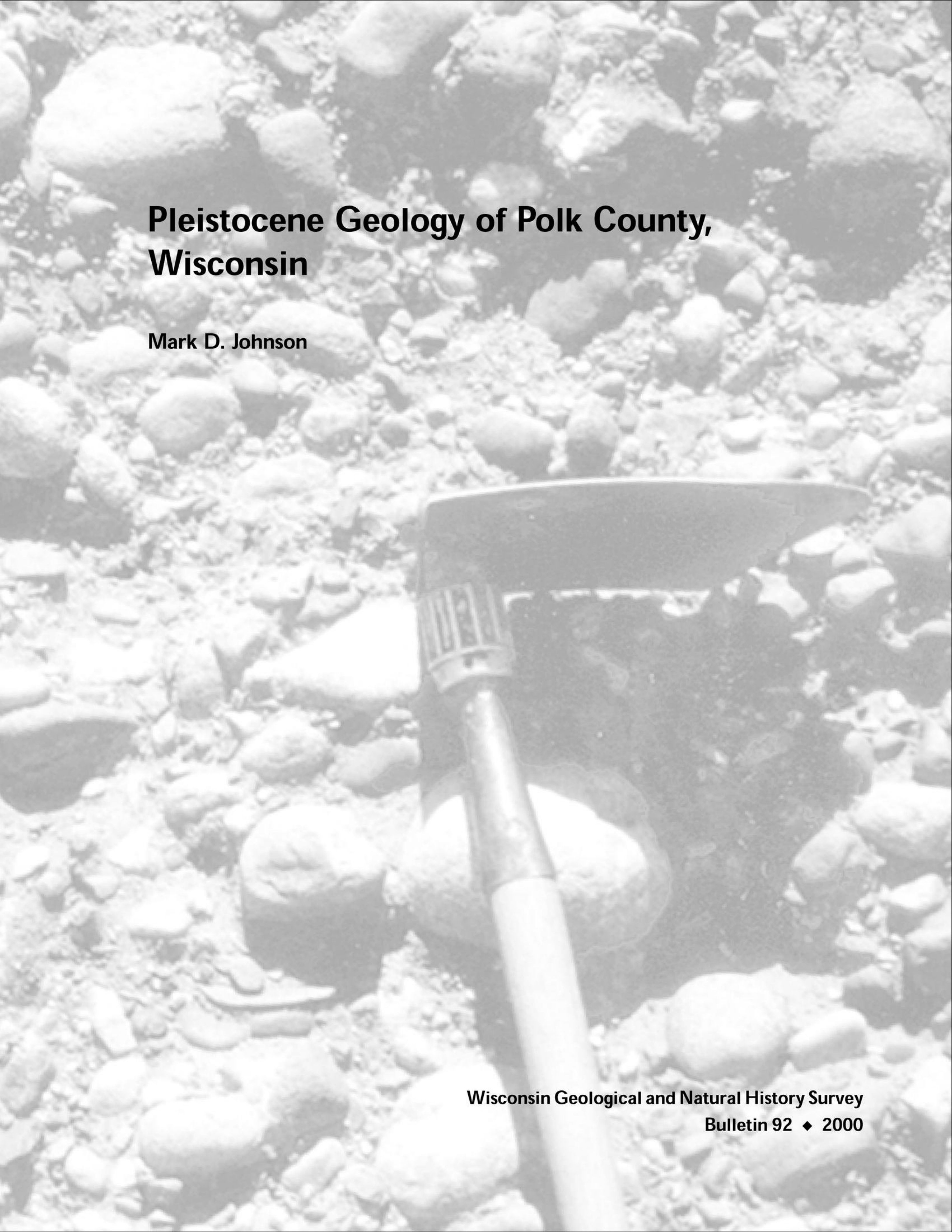
Pleistocene Geology of Polk County, Wisconsin

Mark D. Johnson



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Bulletin 92 ◆ 2000

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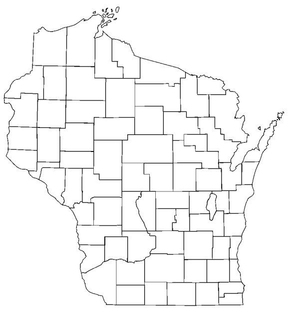

Pleistocene Geology of Polk County, Wisconsin

Mark D. Johnson

With an appendix naming the Trade River Formation, Falun Member of the Trade River Formation (by Mark D. Johnson and Chris Hemstad), and the Sunrise Member of the Copper Falls Formation

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FIGURES

TABLES

Pleistocene Geology of Polk County, Wisconsin

Mark D. Johnson

ABSTRACT

Polk County was glaciated several times during the Pleistocene, but the topography and surficial sediment are associated primarily with advances of the Superior Lobe and Grantsburg Sublobe during the last part of the Wisconsin Glaciation.

The earliest known glacial advance into Polk County probably occurred more than 730,000 years ago during the Reeve Phase of the Des Moines Lobe. This lobe deposited gray loam till of the Pierce Formation, which is overlain in places by reddish-brown sandy loam till and outwash of the River Falls Formation, probably deposited more than 130,000 years ago during the Baldwin Phase of the Superior Lobe. The Superior Lobe advances that occurred during the last part of the Wisconsin Glaciation began with the Emerald Phase. Deposits from this phase are at the surface underneath the gently rolling topography of the southeast corner of Polk County. The St. Croix Phase of the Superior Lobe and later advances are represented by at least 12 former ice-margin positions within the county. During these events, the Superior Lobe left behind reddish-brown sandy loam till and outwash of the Copper Falls Formation as well as striations, grooves, outwash plains, outwash fans, tunnel channels, eskers, hummocks, ice-walled-lake plains, ice-dammed-lake plains, end moraines, and the Spooner Hills of northeastern Polk County. As the Superior Lobe retreated north of Polk County, glacial Lake Lind formed in the preglacial St. Croix River valley and lasted at least 776 years; this time span is based on the number of varved silt and clay couplets found in lake sediment of the Sunrise Member of the Copper Falls Formation.

The Grantsburg Sublobe, an offshoot of the Des Moines Lobe, advanced during the Pine City Phase across a fluvial plain that developed on top of glacial Lake Lind sediment. The Grantsburg Sublobe deposited gray loam till of the Trade River Formation and left behind end moraines, till plains, ice-marginal channels, and ice-dammed-lake plains. Glacial Lake Grantsburg was dammed in front of the advancing ice and lasted approximately 100 years; this length is based on the number of varved silt and clay couplets of the Falun Member of the Trade River Formation. The location of the lake's outlet is unknown.

Many drainage events from ice-dammed Lake Superior created the potholes in the basalt around St. Croix Falls and caused the St. Croix River to incise its valley. An interruption in these drainage events allowed a large sand surface to develop in northwestern Polk County. Dunes later developed on this surface.

INTRODUCTION

Polk County, Wisconsin, has been glaciated several times; the deposits at the surface throughout the county date from the last part of the Wisconsin Glaciation. Processes associated with glaciers, streams, and lakes, with some modification by wind and hillslope processes, resulted in deposition of sediment and creation of landforms in the county; the geologic map (plate 1) shows their distribution, character, and age.

General setting

Polk County lies in the St. Croix River drainage basin and is part of the region covered by the southern part of the Superior Lobe during the last part of the Wisconsin Glaciation; part of the county had also been covered by the eastern part of the Grantsburg

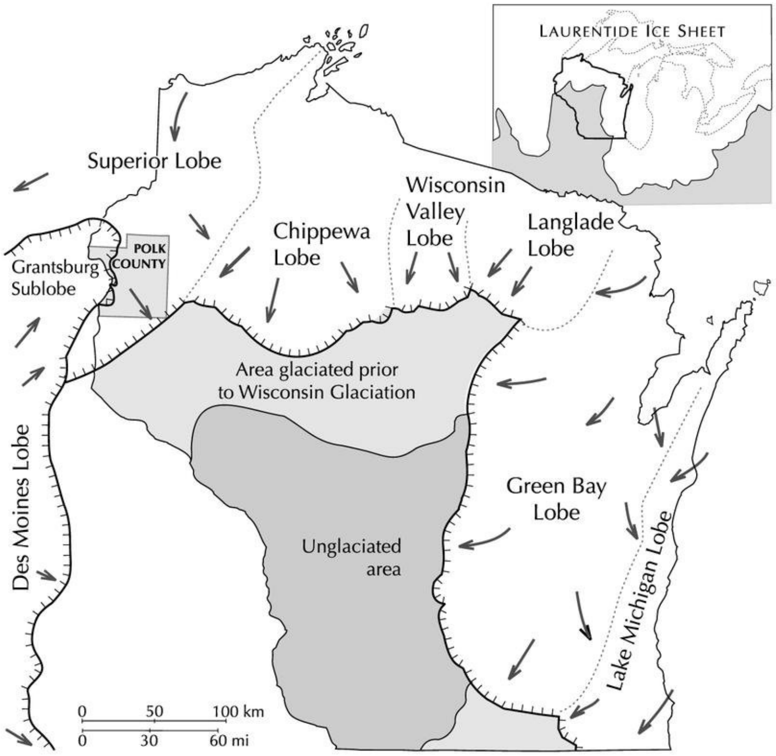

Figure 1. *Location of Polk County, Wisconsin, in relation to the maximum extent of the Laurentide Ice Sheet. Arrows indicate direction of ice movement.*

Sublobe (fig. 1). Most of the county lies at elevations between 300 and 400 m; a fire lookout just southeast of Frederic has an elevation of more than 430 m, and elevation of the St. Croix River, in the southwestern corner of the county, is approximately 207 m. Relief is as great as 90 m along parts of the St. Croix River valley.

The St. Croix River valley in the western edge of the county is bounded by cliffs of Paleozoic sandstone and dolomite near Osceola and by rounded knobs of Precambrian basalt near St. Croix Falls. In this basalt the famous potholes of the region have been formed. Farther north, the valley sides contain till and stream and lake sediment.

The physiography of Polk County can be divided into six distinct landscape regions (fig. 2).

- **Sand-dune terrace.** Several terraces are present along the St. Croix River; for example, an areally prominent (fig. 2) pine-covered sand barrens of northwest Polk County extends northward into central Burnett County. The fine- to medium-grained sand that constitutes the surface sediment of this terrace has been shaped into irregular transverse dunes.
- **Osceola bench.** Another terrace-like surface, which I refer to as the Osceola bench, covers 50 km^2 in the area east and south of Osceola, Wisconsin (fig. 2). A variety of material is exposed at the surface: Till deposited by the Grantsburg Sublobe, sandy to bouldery stream sediment, and Ordovician dolomite crop out in places on the bench surface.
- **Trade River till plain.** The Trade River till plain covers a region just east of the sand barrens (fig. 2). This area, underlain by till deposited by the Grantsburg Sublobe, is flat to pitted; some ice-collapse pits, such as Manitou Lake, are as much as 30 m deep.
- **Hummocky ridge with basalt knobs.** A broad, hummocky ridge studded with basalt knobs forms a prominent drainage divide in the county and extends from Farmington Township in the southwestern part of the county northwesterly in an arc through St. Croix Falls, Frederic, and Clam Falls (fig. 2). This ridge separates drainages flowing east and south into the Apple and Willow Rivers from those flowing west and north into the St. Croix, Trade, Wood, and Clam Rivers. In places stream piracy has shifted the divide southeasterly. Precambrian basalt crops out in places (see plate 1), but much of this forested ridge is underlain by thick glacial and stream deposits.
- **St. Croix Phase hummocky outwash plains.** South and east of the hummocky ridge, the county is a mosaic of outwash plains, hummock tracts, and ice-walled-

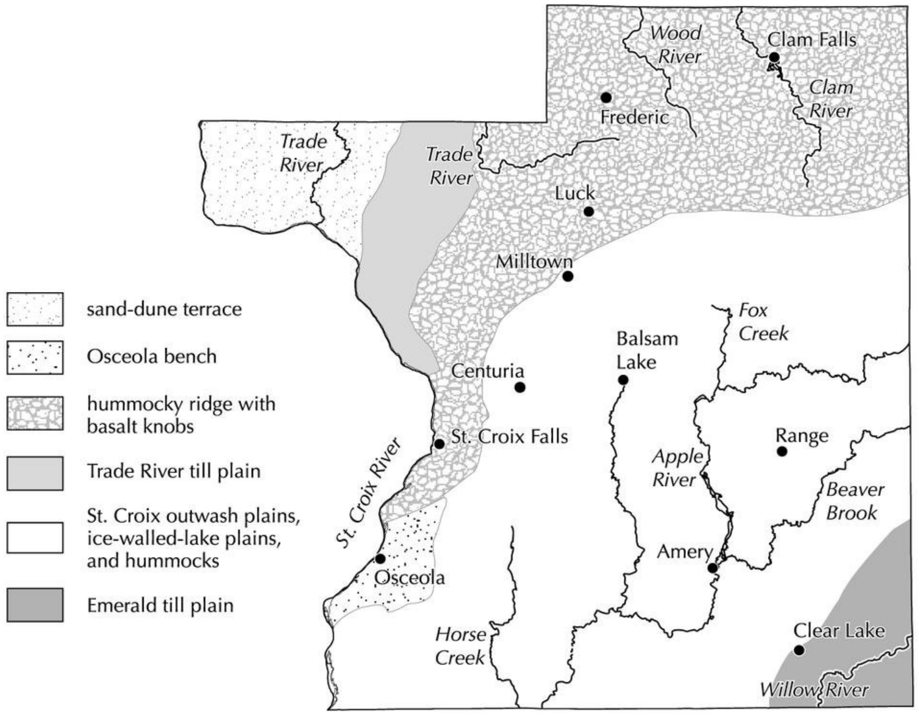

Figure 2. *Landscapes, towns, and major drainages of Polk County.*

lake plains composed of sediment left by the Superior Lobe glacier during the St. Croix Phase and later phases. This is the largest physiographic region in the county, and the dominant material is sand. Hummock tracts are composed of till and stream sediment and are forested. The ice-walled-lake and outwash plains, composed of stream and lake sediment, are cultivated.

- **Emerald till plain.** East of Clear Lake, in the southeastern corner of the county, the topography is gently rolling and exhibits a well defined dendritic drainage network. This part of the county is underlain by till deposited during the Emerald Phase of the Superior Lobe.

Sources of information

U.S. Geological Survey maps (7.5-minute series, topographic) served as the primary base maps for field work. I spent a total of five months in the field during the summers of 1988, 1989, and 1990. The outcrops that I examined were primarily in gravel pits, roadcuts, and building excavations. I examined aerial photographs (scale 1:20,000), but the county had been photographed when trees had leaves and the photographs were not very useful. I inspected more than 1,000 well constructor's reports, on file at the Wisconsin Geological and Natural History Survey, but terminology differences and probable errors made these logs useful only to a degree. Subsurface information was supplemented with 105 holes drilled by the Wisconsin Geological and Natural History Survey crew and by me in Polk and neighboring St. Croix and Burnett Counties. Kissinger (1979) described soil parent material in Polk County.

Samples of till and stream, lake, gravity-flow, and wind sediment were analyzed in the Quaternary Laboratory, Department of Geology and Geophysics, University of Wisconsin–Madison. Grain size was determined using sieve and hydrometer techniques. In this report, I use U.S. Department of Agriculture (USDA) terminology to describe the general grain size of the less-than-2-mm fraction of the till samples, although fraction boundaries are slightly different from those used by USDA. Magnetic susceptibility was measured with a Bison 3101A magnetic susceptibility meter. Pebbles for pebble counts were sieved from large bulk samples in the field and include pebbles generally between 8 and 16 mm; between 75 and 250 pebbles per sample were obtained in this manner and counted. Pebble fabrics consist of the measured orientation of 25 pebbles with long to short axis ratio greater than 1.5:1.

Early geologic investigations in the Polk County area have resulted in a broad understanding of the stratigraphy, origin, provenance, and geologic history of Pleistocene deposits in the region (Strong, 1880; Chamberlin, T.C., 1883; Berkey, 1897, 1905; Chamberlin, R.T., 1905, 1910). Subsequent research has added detail, but has not significantly changed the interpretations of these early workers. Refinements in the stratigraphy have been made by Baker and others (1983), Mickelson and others (1984), Johnson (1984, 1986), and Attig and others (1988). Several somewhat dissimilar interpretations of the position and nature of the southern margin of the Superior Lobe during the last part of the Wisconsin Glaciation have been made (Leverett, 1932; Mathieson, 1940; Black, 1959; Berg, 1960; Wright, 1972; Wright and others, 1973; Johnson, 1984, 1986; Johnson and Savina, 1987; Mooers, 1989). The history of the glacier-dammed lakes (glacial Lake Lind and glacial Lake Grantsburg) occupying the St. Croix, Clam, and Yellow River drainage basins has been discussed by several workers (Berkey, 1905; Hansell, 1930; Burkhead, 1931; Butz, 1931; Cooper, 1935; Johnson, 1992, 1994; Addis and others, 1996; Johnson and Hemstad, 1998; Johnson and others, 1999). A regional understanding of the details of the last glacial period has been aided by large-scale geologic mapping of Pleistocene deposits in the Lake Superior region (Clayton, 1984), the Twin Cities region (Meyer, 1985), Barron County, Wisconsin (Johnson, 1986), Hennepin County, Minnesota (Meyer and Hobbs, 1989), Dakota County, Minnesota (Hobbs and others, 1990), Washington County, Minnesota (Meyer and others, 1990) and Ramsey County, Minnesota (Patterson, 1992).

Reliability of map and cross sections

The reliability of the geologic contacts on plate 1 is primarily a function of the sources of information, the number of outcrops, and the distinctiveness of landforms on U.S. Geological Survey topographic maps and aerial photographs. Contacts far from roads or gravel pits were interpreted from topography and nearby exposures; these contacts may be inaccurate in places.

The cross sections (plate 1) are drawn along east–west lines through the middle of townships. I used information from well constructor's reports and drillhole records within 2 km north or south of the line. These cross sections are not actual representations of the material below the surface; they are designed to give a generalized interpretation of the materials in that part of the county. Surface topography was taken from the U.S. Geological Survey topographic maps.

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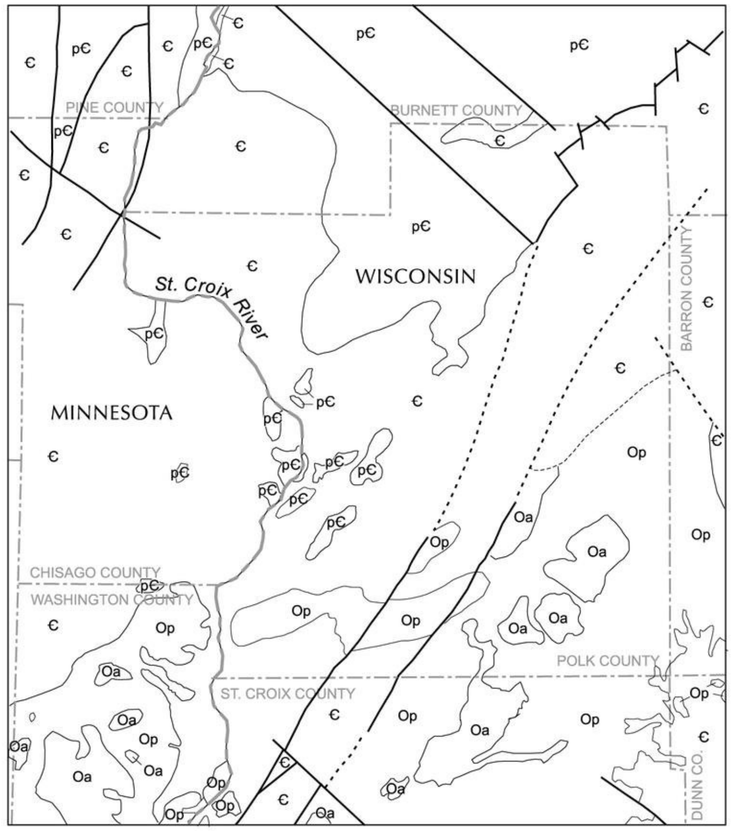


Figure 3. *Bedrock geology of Polk County and vicinity (from Mudrey and others, 1987; Morey and others, 1981).*

Hanson, Brian Hess, and Adam Hogan for drilling; Gary Meyer for unpublished information on Chisago County, Minnesota; Arthur Bettis and Edwin Hajic for unpublished information on the history of the middle Mississippi valley; Andrew Nichols for help with figures; Rodney Stevens and the Geology Department at Chalmers Tekniska Högskola/Göteborg Universitet, Gothenberg, Sweden, for support during the writing stages; D.L. Patterson for production of plate 1; and Susan Hunt for layout and production of the final report.

PRE-PLEISTOCENE GEOLOGY

The Pleistocene deposits in Polk County cover a bedrock surface of high relief (more than 100 m in places) Precambrian basalt and Paleozoic sedimentary rock (fig. 3).

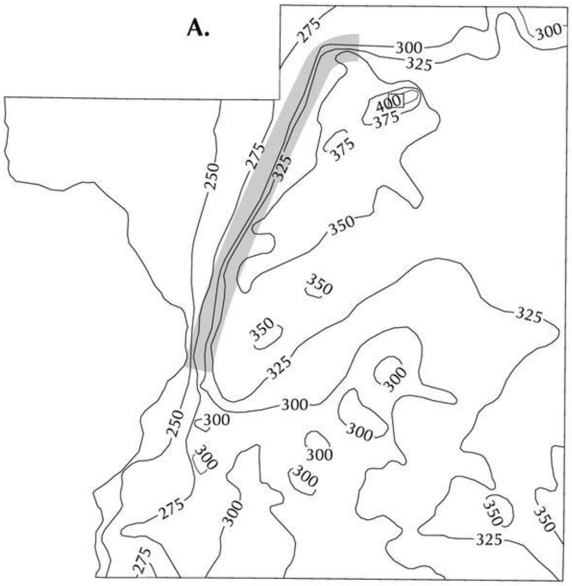
Outcrops of basalt are common along a line from St. Croix Falls through Frederic and east to Clam Falls. In these places, the basalt crops out as oak-forested knolls that have up to 30 m of relief. The Keweenawan basalt of the Chengwatana Group is well exposed in the St. Croix River valley and makes up the famous St. Croix Dalles.

The basalt erupted from numerous fissures oriented parallel to the Midcontinent Rift System during the Proterozoic, about 1.1 billion years ago (Green, 1982; Van Schmus and others, 1982). Following emplacement, the basalt was uplifted as part of the St. Croix Horst, a prominent structure that lies roughly coaxial with the St. Croix River. The contact of the basalt with the overlying Paleozoic and Pleistocene units is irregular. Near Centuria, for example, wells within 3 km of one basalt outcrop intersected basalt at depths of 15 m, 28 m, 35 m, and 80 m. Evidently, the high relief existing during the Cambrian was somewhat similar to present-day relief.

Outcrops of basalt have been glacially sculpted; however, striations in many locations have been removed by weathering. The line of basalt hills likely affected ice movement during glaciation. The steep, buried escarpment on the north side of the basalt ridge (fig. 4A) was probably shaped by repeated glacial scouring and may have directed ice flow southwesterly. Paleozoic rock to the southeast of the ridge in central Polk County may have been protected from erosion because it was on the lee side of the ridge, and it was overridden by ice somewhat thinned after crossing the basalt ridge.

The distribution of Paleozoic units, which are primarily marine sandstone and dolomite, is shown in figure 3. The few outcrops of Paleozoic rock have a less pronounced influence on the geomorphic character of the present-day landscape than the

A.



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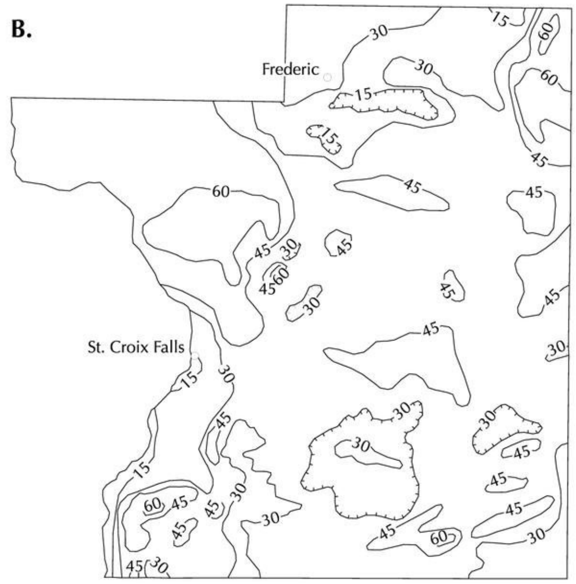
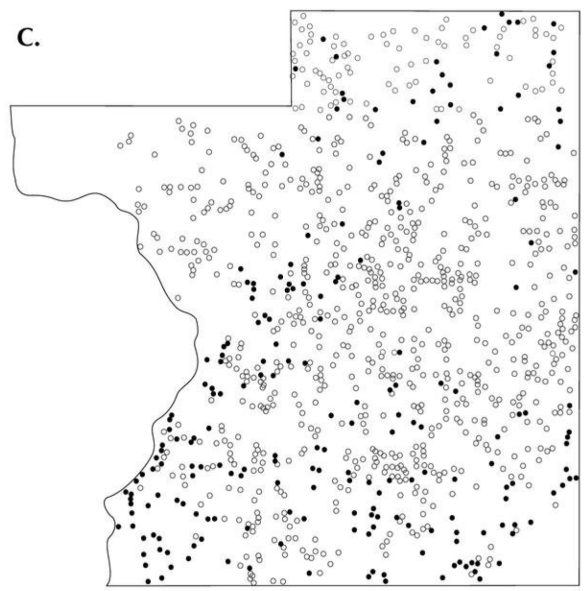


Figure 4. A: *Elevation of bedrock in Polk County. Bedrock elevation was determined from well constructor's reports; contour interval, 25 m. Shaded region indicates location of a steep, buried escarpment.* **B:** *Thickness of Pleistocene sediment in Polk County determined from well constructor's reports; contour interval, 15 m.* **C:** *Locations of wells used to determine bedrock elevation (A) and Pleistocene sediment thickness (B). Closed circles represent wells that penetrate bedrock; open circles represent wells that do not penetrate bedrock.*

C.



basalt. Resistant units crop out as cliffs along the St. Croix River, an outcrop of Prairie du Chien dolomite is between Nye and Horse Creek in Horse Creek valley, and small surface exposures of dolomite are in the southwestern part of the Osceola bench.

PLEISTOCENE DEPOSITS

Pleistocene deposits in Polk County are commonly between 30 and 45 m thick (fig. 4B). Along the basalt ridge near Frederic and in the St. Croix River valley south of St. Croix Falls, the deposits are thin; in some other parts of the county, they are more than 60 m thick. Pleistocene deposits consist of till, river, lake, gravity-flow, and windblown sediment that are included in four formations: the Pierce, River Falls, Copper Falls, and Trade River Formations (table 1). Differentiation of these formations is based primarily on lithology, texture, and color.

Pierce Formation

The Pierce Formation in Polk County is found only in the subsurface and consists of dark-gray loam till. In the area around the type section at Woodville, St. Croix County, Wisconsin, the Pierce Formation consists of two till and two lake-sediment members (Baker and others, 1983; Mickelson and others, 1984; Baker, 1988a, 1988b). Lake sediment has not been found in Polk County; it is not clear whether one or both till members are present. The following description is based on samples from Polk County and northernmost St. Croix County (see table 2).

Table 1. *Pleistocene lithostratigaphy in Polk County.*

Formation	Member	Estimated age
Trade River	Falun	14,000 BP
Copper Falls	Sunrise	14,000–15,000 BP
	Sylvan Lake	15,000–18,500 BP
	Poskin	15,000–25,000 BP
River Falls		>125,000 BP
Pierce		>730,000 BP

Pierce till

Pierce till is slightly gravelly loam; a few samples contained clay loam and sandy loam. Gravel content is less than 5 percent. Typically, this till has a sand:silt:clay ratio of 42:34:23 (fig. 5). The till is dark gray (5Y 4/1 on the Munsell scale) where unoxidized, and yellowish brown (10YR 5/4 on the Munsell scale) where oxidized. The average magnetic susceptibility of the till is 1.1 x 10^{-3} (SI units) (fig. 6). The minerals in the clay fraction of samples from the type area and in Barron County are dominated by expandable clay (Baker and others, 1983; Johnson, 1986).

Pierce till was found in samples from four drillholes (fig. 7) in the southern part of Polk County and the northern part of St. Croix County. The Pierce till in these samples is 3 to 20 m thick; the upper surface of the till lies 5 to 10 m below the land surface. However, if the "yellow clay" and "blue clay" shown in figure 7 are Pierce till, the till is typically buried 20 m below the surface. According to drillhole samples and well constructor's reports, sediment likely to be that of the Pierce Formation overlies bedrock.

Two of the samples did not contain the oxidized part of the till present elsewhere, suggesting that a weathering profile formed in the upper part of the till has been subsequently eroded. Pierce till with and without the weathered profile has been found beneath till of the River Falls Formation in Polk and Barron Counties (Johnson, 1986), implying that weathering and erosion of the weathered profile occurred before deposition of the River Falls till.

Table 2. *Summary of characteristics of till and gravity-flow sediment in Polk County, with some samples of sediment of the River Falls and Pierce Formations in northernmost St. Croix County.*

Lithostratigraphic unit	Number of samples	Sand:silt:clay (%)	Magnetic susceptibility (SI units)	Munsell color
Trade River Formation till	38	50:30:20	2.1 x 10^{-3}	brown, dark brown, yellowish brown, to dark yellowish brown (7.5YR 4/4, 10YR 4-5/4)
Copper Falls Formation	138	65:25:10	3.8 x 10^{-3}	reddish brown to dark reddish brown (5YR 3-4/4)
Copper Falls silty till	10	50:37:13	3.1 x 10^{-3}	
Sylvan Lake Member till	80	68:23:9	3.8 x 10^{-3}	
Sylvan Lake Member gravity-flow sediment	13	65:25:10	4.2 x 10^{-3}	
Poskin Member till	35	64:26:10	3.9 x 10^{-3}	
River Falls Formation till	26	66:21:14	1.2 x 10^{-3}	reddish brown (5YR 4/4)
Pierce Formation till	25	42:34:23	1.1 x 10^{-3}	dark gray (5Y 4/1) (unoxidized) yellowish brown (10YR 5/4) (oxidized)

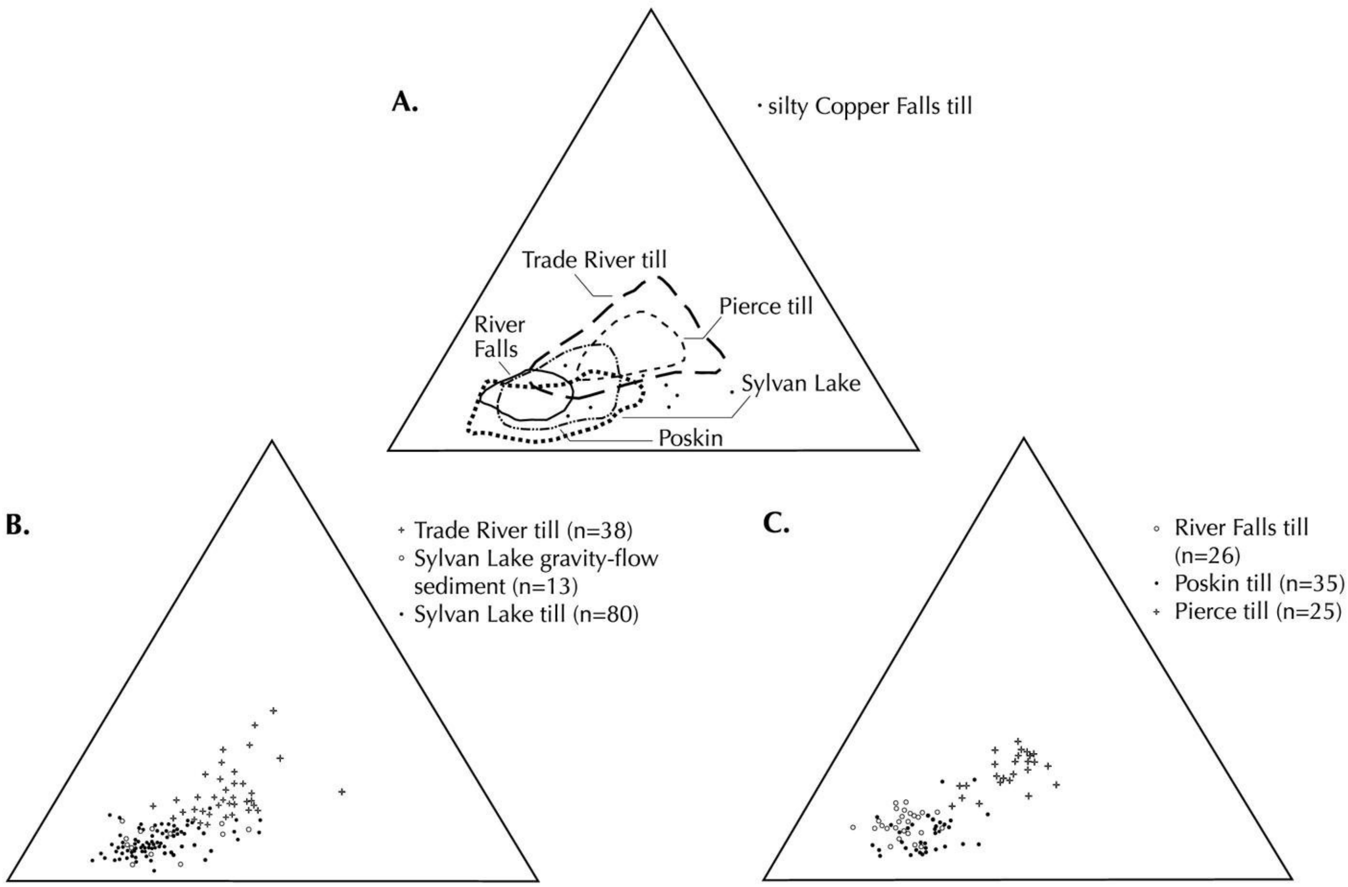


Figure 5. *Grain-size distribution of the less-than-2-mm fraction of till and gravity-flow sediment in Polk County (sand: 0.0625–2.0 mm; silt: 0.002–0.0625 mm; clay: less than 0.002 mm).* **A:** *Range of grain size for each of the five till units. Dots are individual samples of silty Copper Falls material.* **B:** *Grain-size distribution of Trade River till, Sylvan Lake till, and Sylvan Lake gravity-flow sediment and the number of individual samples.* **C:** *Grain-size distribution of River Falls, Poskin, and Pierce till and the number of individual samples.*

Although well constructor's reports near drillhole sites report "yellow clay" or "blue clay," which may indicate the presence of Pierce till, most well constructor's reports do not mention this distinct unit, and samples from most drillholes do not contain Pierce till. Thus, it appears that the distribution is patchy (see cross sections, plate 1).

Pierce till is distinguished from other units in the county by color and texture (table 2). It is easily distinguished from the red sandy till of the River Falls and Copper Falls Formations. It is similar to till of the Trade River Formation, but it lacks the distinctive Cretaceous shale clasts found in the Trade River till. The Pierce till has been correlated to the "old gray drift" of southeastern Minnesota (Mickelson and others, 1984) and the Medford Member of the Marathon Formation of central Wisconsin (Baker and others, 1987; Attig and Muldoon, 1988).

River Falls Formation

The River Falls Formation in Polk County consists of reddish-brown, sandy loam till and associated stream sediment. River Falls sediment is not common in Polk County, and I did not find it exposed at the surface, although isolated deposits may exist in streamcuts in the extreme southeastern part of the county. The following description is based on samples from Polk County and northern St. Croix County (see table 2).

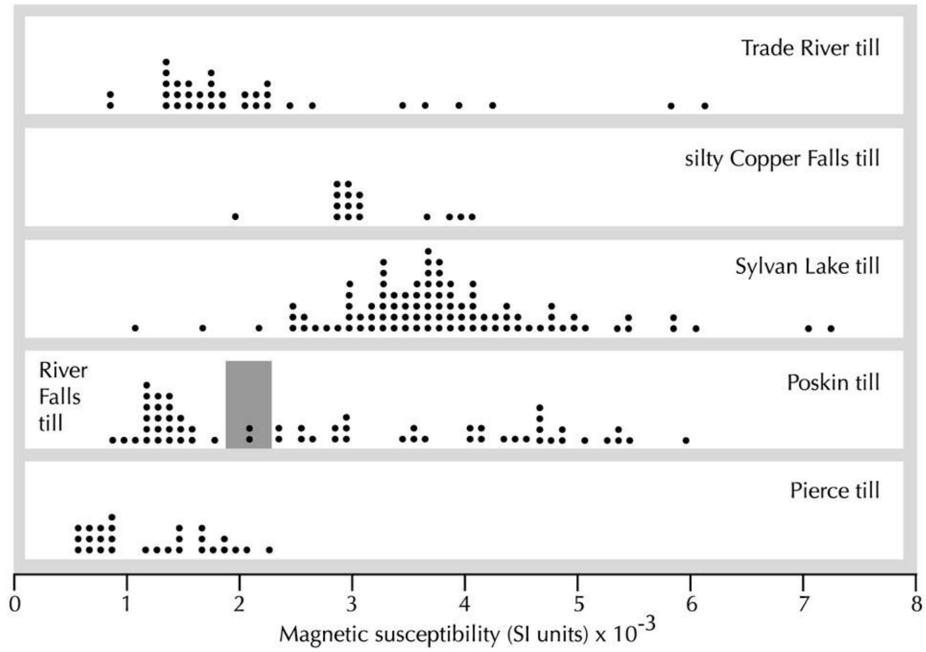


Figure 6. *Magnetic susceptibility (SI units) of till in Polk County; some samples of Poskin and River Falls till are from northern St. Croix County. Each dot represents one sample. Till that has values similar to Sylvan Lake till (>2.0 x 10^{-3}) was assumed to be Poskin till; till that has lower values (<2.0 x 10^{-3}) was assumed to be River Falls till. Shaded area is the boundary between River Falls and Poskin values; values falling within this range are difficult to assign to either unit.*

River Falls till

River Falls till is slightly gravelly to gravelly, sandy loam with less than 15 percent pebbles. The dominant lithologies in the pebble fraction are sandstone, fine-grained mafic rock, and rhyolite of Keweenawan age, and granitic gneiss (table 3). Average sand:silt:clay ratio of River Falls till is 66:21:14 (fig. 5); matrix color is reddish brown (5YR 4/4 on the Munsell scale); average magnetic susceptibility is 1.2 x 10^{-3} (SI units) (fig. 6).

Till of the River Falls Formation is nearly identical in character to till of the Poskin Member of the Copper Falls Formation (table 2), both of which are at the surface south of the limit of sediment of the Sylvan Lake Member of the Copper Falls Formation. Poskin and River Falls till can be distinguished on the basis of magnetic susceptibility and clay mineralogy (Johnson, 1986) and soil development (Baker and others, 1983). Differentiation between Poskin and River

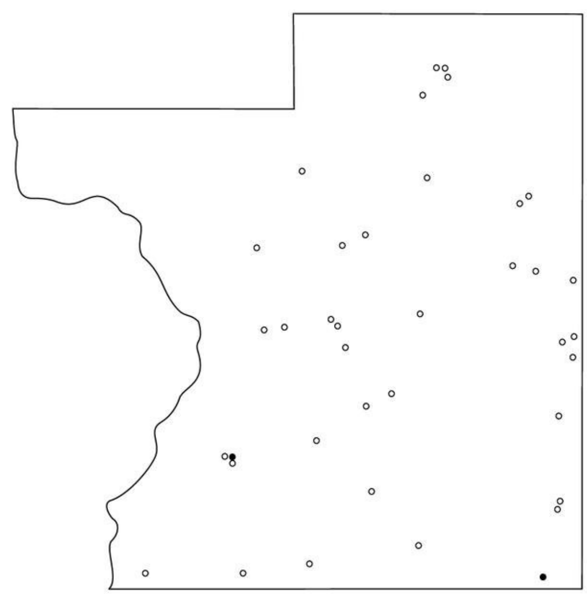


Figure 7. *Map of Polk County showing locations of drillholes containing Pierce till (closed circles) and of well constructor's reports that described "yellow clay" or "blue clay" at depth (open circles).*

Table 3. *Percentages of pebble types in till and stream sediment in Polk County.*

Lithostratigraphic unit (number of samples)	Fine-grained mafic	Granite/ gneiss	Coarse-grained mafic	Precambrian sandstone	Cambrian sandstone
Trade River stream sediment (12)	41	13	5	8	3*
Sylvan Lake till (3)	48	6	9	19	1*
Sylvan Lake stream sediment (13)	55	8	10	7*	3*
Sylvan Lake stream sediment south of Prairie du Chien subcrop (5)	34	5	3	7	3
Horse Creek Channel sediment (4)	52	8	6	11	3*
Poskin stream sediment (1)	33	7	9	23	5
River Falls till (1)	28	9	4	29	1

Falls till in Polk and St. Croix Counties is made on the basis of magnetic susceptibility (fig. 6). Most values of magnetic susceptibility for River Falls till were less than 2.0 x 10^{-3} (SI units); those for Poskin till were generally greater than 2.0 x 10^{-3} (SI units) (fig. 6). Thus, those samples of till that lie close to 2.0 x 10^{-3} (SI units) are difficult to assign with confidence to either till unit. (See discussion in the section entitled *Emerald Phase* under *Pleistocene History*.)

River Falls stream sediment

Stream sediment of the River Falls Formation is sand, slightly pebbly sand, and pebbly sand. The sediment is predominantly horizontally bedded, but is cross-bedded in places. Deposits of this sediment crop out beneath Copper Falls till in the southeastern part of the county. Some buried sand units shown in the cross sections on plate 1 may belong to the River Falls Formation.

Copper Falls Formation

The Copper Falls Formation is at the surface throughout the county, except the northwestern corner. The type section is in Copper Falls State Park, Ashland County, Wisconsin (Mickelson and others, 1984). In Polk County, the Copper Falls Formation includes the Poskin, Sylvan Lake, and Sunrise Members (table 1). The Sunrise Member is named in this report (see appendix for formal description).

Copper Falls till

Copper Falls till typically has an average sand:silt:clay ratio of 65:25:10 (fig. 5), a gravel content of generally less than 5 percent, and an average magnetic susceptibility of 3.8 x 10^{-3} (SI units) (fig. 6); the members of the Copper Falls Formation have only slightly different values (table 2). The till is reddish brown (5YR 4/4 on the Munsell scale), but is dark reddish brown (5YR 3/4) in places. It is difficult to distinguish between till of the Sylvan Lake Member, found in the hummocks and till plains northwest of the St. Croix ice-margin limit (map units **gsn**, **usn**, and **ush**, plate 1), and till of the Poskin Member, found beneath the rolling stream-dissected topography southeast of the limit (map unit **gpn**, plate 1). In Barron County, the Poskin till is slightly redder where both till units are in the same outcrop (Johnson, 1986), but I did not observe this distinction in Polk County; I mapped the distribution on the basis of topography. Copper Falls till in

Dolomite†	Limestone	Shale	Quartzite	Rhyolite	Other
7*	2*	1*	1*	13	6
0	0	0	1*	6*	6
0	0	0	1*	13	4
33*	0	0	1*	10	6
0	0	0	1*	15	6
0	0	0	2	11	10
0	0	0	4	12	13

† Dolomite in Trade River stream sediment probably comes from Ordovician outcrops in the Winnipeg lowland; dolomite in Sylvan Lake stream sediment south of Prairie du Chien subcrop is of local origin.

* Some of the samples for this particular unit did not contain this rock type.

southern Burnett County had an average sand:silt:clay ratio of 50:37:13 (table 2; fig. 5). Although this till would not generally be considered silty, it is in comparison to typical Copper Falls till, and I refer to it in this paper as silty Copper Falls till. Till similar to this silty till is present, but not well exposed, in the northernmost parts of Polk County and parts of Chisago County, Minnesota (Gary Meyer, Minnesota Geological Survey, written communication).

Copper Falls stream sediment

The most common type of sediment in Polk County is Copper Falls stream sediment, which consists primarily of sand, slightly gravelly sand, and gravelly sand, with much of the gravel in the pebble fraction. The Copper Falls stream sediment that was deposited within 1 km of former ice-margin positions is commonly much coarser, more poorly sorted, more crudely horizontally bedded, and contains more cobbly gravel and some boulders (note locations of cobble-rich outwash, fig. 8) than stream sediment deposited in more distal positions. Farther from former ice-margin positions, the stream sediment is dominated by sand in horizontal and cross-bedded layers. Copper Falls stream sediment was deposited in pitted outwash plains (map unit **ssp**, plate 1), in hummocks (map units **ssh** and **ush**, plate 1), in parts of some till plains (map unit **usn**, plate 1), in the edges of ice-walled-lake plains (map unit **nsi**, plate 1), and in channel and valley bottoms (map unit **ssv**, plate 1).

Gravel in Copper Falls till and stream sediment is composed primarily of mafic rocks, granite, gneiss, rhyolite, and sandstone (table 3). This assemblage is typical of sediment derived from the Lake Superior basin. In the southern part of the county, south of the subcrop contact with the Prairie du Chien dolomite (fig. 3), coarse gravel in eskers and fans that formed at the mouths of tunnel channels contains up to 50 percent dolomite. Copper Falls till in the southern part of the county is not as dolomite rich, in-

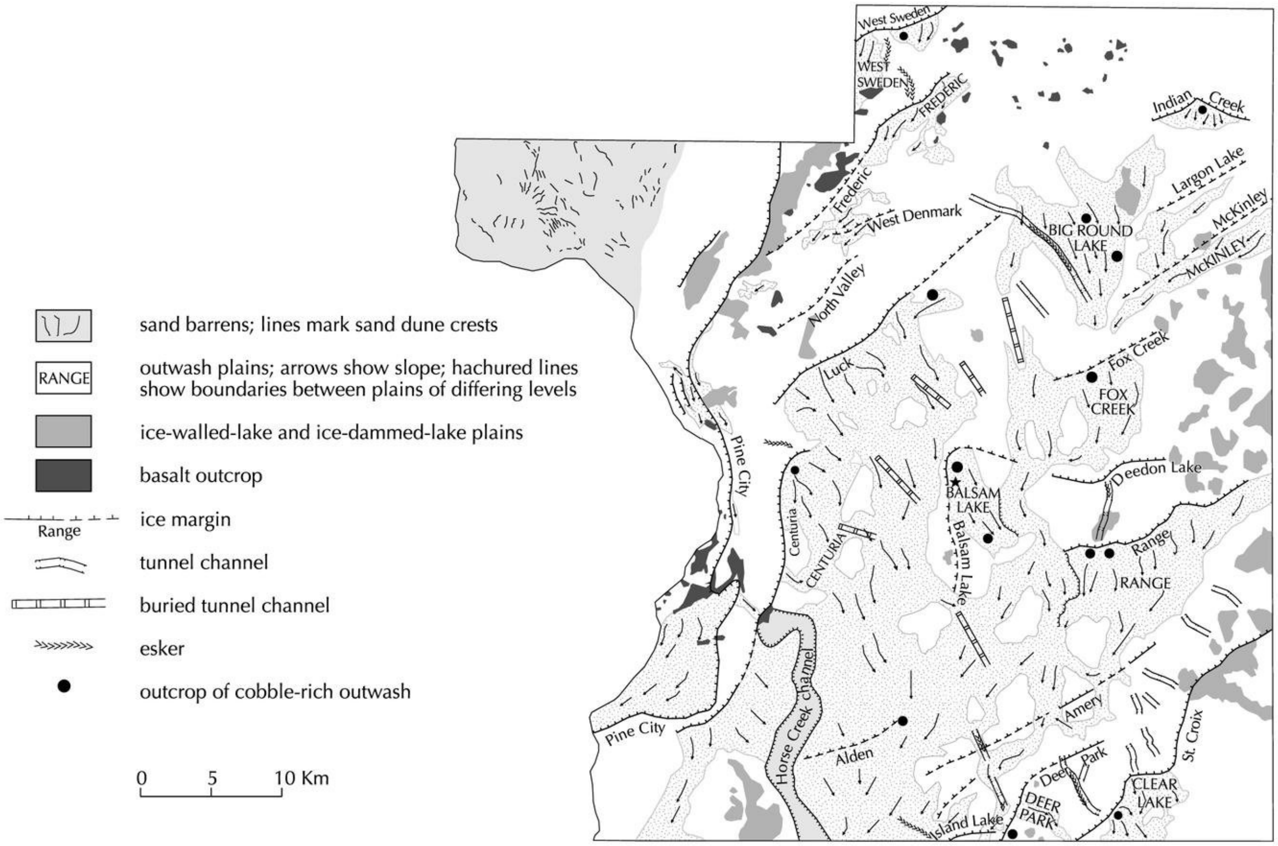


Figure 8. *Selected geomorphic features of Polk County. Names of ice-margin positions are shown with upper- and lower-case letters; outwash plains, with upper-case letters. Regions not identified are predominantly upland areas consisting of hummocks and till plains. Tunnel channels shown are those that have distinct channel shapes; most are in till-covered upland areas. Buried tunnel channels shown are those interpreted from elongate collapse depressions; most are found in outwash plains. Many of the areas shown as outwash plains on this map are actually extensive regions of hummocks composed of outwash.*

dicating that most of the dolomite was eroded by subglacial meltwater close to the ice margin.

Copper Falls gravity-flow sediment

Copper Falls gravity-flow sediment is nearly identical to Copper Falls till in color, grain size, and magnetic susceptibility (fig. 5; table 2). Unlike the till, gravity-flow sediment is interbedded with water-sorted material and has a weak pebble fabric. Copper Falls gravity-flow sediment is not as common as Copper Falls till and is found in hummocks (map unit **ush**, plate 1), in till plains (map unit **usn**, plate 1), in the edges of ice-walled-lake plains (map unit **nsi**, plate 1), and in the up-slope margins of outwash plains.

Copper Falls lake sediment

The Copper Falls Formation includes lake sediment deposited in ice-walled lakes, small ice-dammed lakes, and glacial Lake Lind. Ice-walled-lake plains, common in Polk County (fig. 8), represent ice-walled lakes that formed in the Superior Lobe after the glacier stagnated and as it melted. Stream- and wave-sorted sand and gravel was deposited along the margins of the ice-walled lakes (map unit **nsi**, plate 1). In places this sediment is interbedded with till-like gravity-flow sediment that flowed from adjacent stagnant ice into the lake. Coarse sediment is restricted to the margins of the lake; much of the interior is underlain by silt (fig. 9; map unit **osi**, plate 1). Samples from a

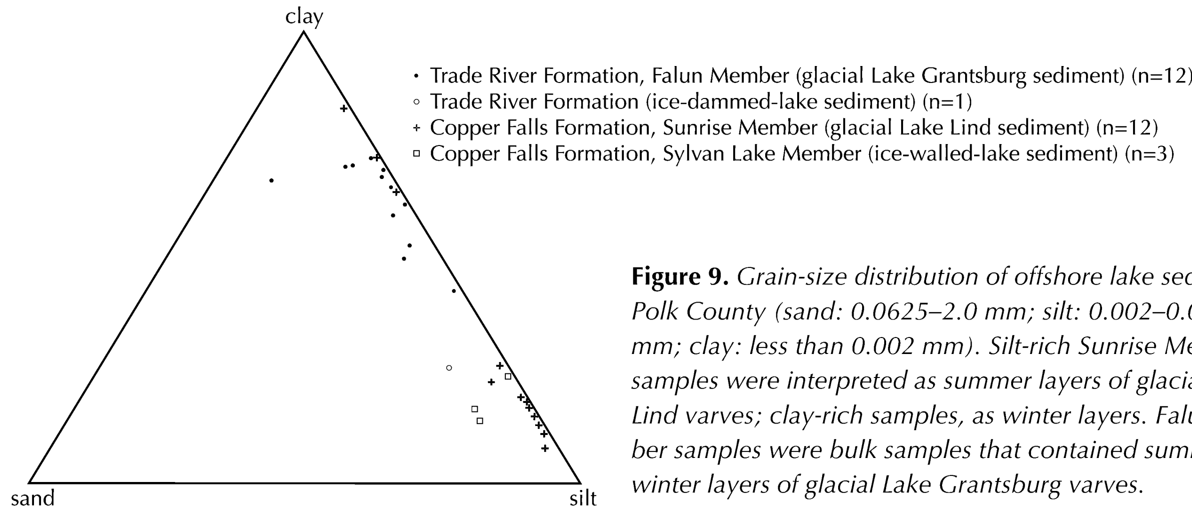


Figure 9. *Grain-size distribution of offshore lake sediment in Polk County (sand: 0.0625–2.0 mm; silt: 0.002–0.0625 mm; clay: less than 0.002 mm). Silt-rich Sunrise Member samples were interpreted as summer layers of glacial Lake Lind varves; clay-rich samples, as winter layers. Falun Member samples were bulk samples that contained summer and winter layers of glacial Lake Grantsburg varves.*

drillhole in the center of the large ice-walled-lake plain just west of Cedar Lake in the southwestern part of the county contained 20 m of medium silt with very fine-grained sand near the top (fig. 10). The silt is calcareous below 1 to 2 m and is brown to dark brown (10YR 4/3 on the Munsell scale in the upper part, 7.5YR 3/2 in the lower 3 to 4 m). The lake sediment overlies Sylvan Lake till. Small ice-dammed-lake plains are near Clayton in southeastern Polk County (map units **osi** and **nsi**, plate 1). The sediment deposited in these lakes was not analyzed as part of this study, but it is probably similar to sediment in the ice-walled-lake plains.

Lake sediment deposited in glacial Lake Lind is included in the Sunrise Member (see appendix) and consists of varved (anually layered) clay and silt and nonvarved sand and silt. The Sunrise Member has been noted only in the northwestern corner of Polk County, primarily in the subsurface. Elsewhere, outcrops can be found as far north as the mouth of the Clam River in Burnett County and as far south as along the Sunrise River, Chisago County, Minnesota. Subsurface information indicates that this unit extends to the southwest nearly as far as the Mississippi River near Anoka, Minnesota (Helgesen and Lindholm, 1977). In Polk County, outcrops of varved lake sediment lie along the St. Croix River and the streams that dissect the sand barrens of northwest Polk County (map unit **st**, plate 1).

The varved part of the Sunrise Member is slightly calcareous and consists of couplets of reddish-brown (5YR 4/4 on the Munsell scale) clay and dark reddish-gray (5YR 4/2) silt (fig. 9). The maximum number of varves counted in this unit was 776 at the type section, but Berkey (1905) described a site at Grantsburg, Wisconsin, where he estimated 1,680 couplets, implying that the lobe lasted at least 1,680 years. Varve couplets are generally 0.5 to 3.0 cm thick, although in places anomalously thick silt and clay beds (up to 11.0 cm thick) can be present.

Varved sediment is 7 m thick at the mouth of the Wood River in Burnett County, where it overlies Copper Falls till. A drillhole in northwestern Polk County penetrated more than 10 m of varved sediment, and a drillhole near Sunrise, Minnesota, penetrated nearly 30 m. The variation in thickness likely represents variations in lake-floor topography, sediment sources, and depositional processes and subsequent erosion.

A 3- to 5-m thick coarsening-upward transitional sequence is at the top of the varved part of the Sunrise Member. Silt and fine-grained sand predominate in this sequence and contain thin clay laminations interpreted to be winter layers.

Above the coarsening-upward sequence is a 20-m thick layer of fine- to medium-

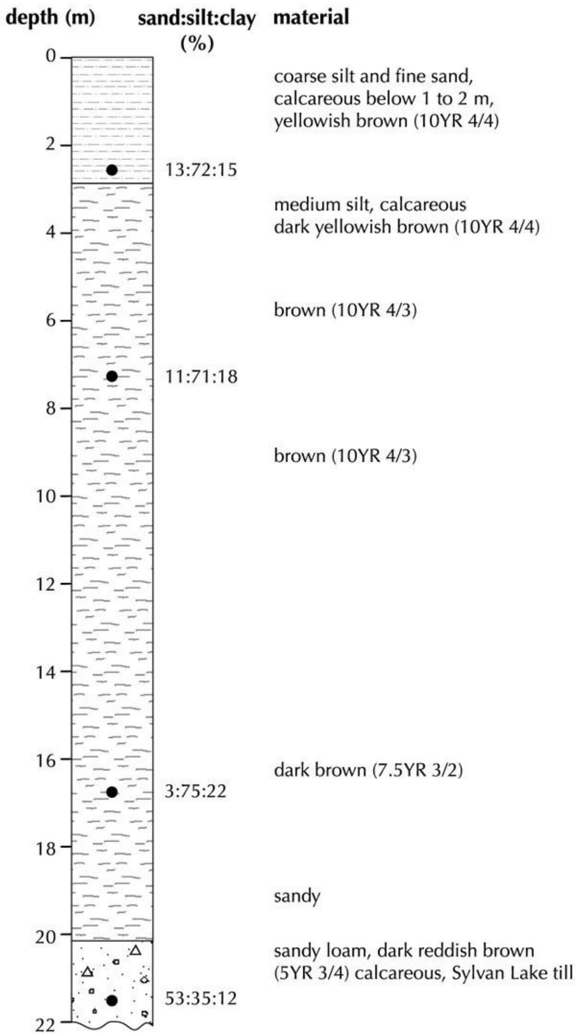


Figure 10. *Grain size of sediment from a drillhole in the center of an ice-walled-lake plain in southwestern Polk County on the border with St. Croix County (SE¼SW¼SW¼ sec. 33, T32N, R18W). (See fig. 21 for location of drillhole.)*

grained sand, which is noncalcareous and yellowish red (5YR 5/6 on the Munsell scale). In some exposures and in split-spoon samples, the upper few meters of the sand are horizontally laminated with well segregated dark minerals that may be beach laminations. Elsewhere, bedding suggests a fluvial origin. This sandy part of the Sunrise Member is preserved underneath the till and lake sediment of the Trade River Formation in southern Burnett County. The sequence was likely present in northwestern Polk County, but was eroded during the entrenchment of the St. Croix River following the Pine City Phase. In this area, varved clay is overlain by a gravel lag, which is in turn overlain by the fluvial and aeolian sand that make up the sand barrens (map unit **st**, plate 1). The sand in the sand barrens is not assigned to any lithostratigraphic unit and is younger than the Trade River Formation.

Trade River Formation

The Trade River Formation is found in the pitted to hummocky till plain of western Polk County (map unit **gth**, plate 1) and in the few end moraines formed at the Pine City ice-margin limit (map unit **gtm**, plate 1). This formation includes till and lake sediment and stream sediment composed of debris left by the Grantsburg Sublobe during the Pine City Phase. The type section in Polk County is approximately 4 km west–northwest of Eureka Center. The till of the Trade River Formation is equivalent to the Twin Cities Formation as defined by Stone (1966). The Trade River Formation is named for the first time in this report and formally described in the appendix.

Trade River till

The till of the Trade River Formation is calcareous, slightly gravelly loam; it has an average sand:silt:clay ratio of 50:30:20 (fig. 5; table 2) and less than 5 percent gravel. Samples of Trade River till at and near the surface were oxidized and are brown, dark brown, and yellowish brown to dark yellowish brown (7.5YR 4/4, 10YR 4–5/4 on the Munsell scale). Generally, the brown samples (with hues of 7.5YR) were closer to the eastern edge of the Trade River till plain (fig. 2). This difference in color is probably due to the incorporation of Copper Falls sediment at the margin of the Grantsburg Sublobe as it advanced, as suggested by Chernicoff (1983). Unoxidized Trade River till is present in the subsurface in poorly drained settings and is dark gray (10YR 4/1). At the type section (see appendix), the lower 1 m of the till is redder (7.5YR 4/4) than the upper 3 m (10YR 4/4). The redder layer is interlaminated with the overlying gray layers, similar to laminations described for the Twin Cities Formation of Minnesota (Cooper, 1935; Wright, 1953; Stone, 1966; Chernicoff, 1983).

The average magnetic susceptibility of Trade River till is 2.1 x 10^{-3} (SI units) (fig. 6). The pebble fraction of the till contains a variety of rock types, but it is distinct from other units in the county because of the abundant clasts of soft Cretaceous shale from the Red River valley and limestone and dolomite from Manitoba. Lignite clasts are not uncommon. The till ranges from 4 to 15 m thick, as shown by outcrops, well constructor's reports, and samples from drillholes.

Trade River stream sediment

Trade River stream sediment is not widespread in western Wisconsin. It is slightly gravelly to gravelly sand, has horizontal beds and cross-beds, and is found in pitted plains and terraces (map unit **stv**, plate 1) and on the Osceola bench (map unit **sto**, plate 1). Near former ice-margin positions, the pebble rock types are nearly identical to those of the till. In these areas, the pebbles consist of fine-grained mafic rock, granite, gneiss, and rhyolite, with significant, but small amounts of dolomite, limestone, and shale (table 3). Farther from the Pine City margin, the pebble rock types of Trade River stream sediment are different because meltwater from the Grantsburg Sublobe eroded preexisting Copper Falls sediment. In St. Croix River terraces equivalent to or younger than the Grantsburg Sublobe (map unit **t**, plate 1), pebble rock types are mixed.

The Trade River Formation includes lake sediment deposited in glacial Lake Grantsburg and other smaller ice-dammed lakes. Glacial Lake Grantsburg did not extend into Polk County, although it is likely that the outlet for glacial Lake Grantsburg passed through western Polk County. (See next section.) Many small ice-dammed lakes existed in Polk and Burnett Counties (fig. 8; map unit **oti**, plate 1); sediment that was deposited in them is predominantly silt, although sand and gravel is present at former lake margins (fig. 9). The silt is dark yellowish brown (10YR 4/4 on the Munsell scale) where oxidized and dark gray (10YR 4/1) where unoxidized. The lakes received a significant amount of reworked Copper Falls sediment derived from highlands to the east.

PLEISTOCENE HISTORY

Little is known about the pre-Pleistocene landscape in Polk County. The basalt knobs in the northern and western part of the county (discussed earlier in the Pre-Pleistocene geology section) were high elements in the landscape during the Cambrian; at times they were islands in the Cambrian sea. Since the Cambrian, the basalt knobs probably have periodically been high elements in the landscape. The relatively uniform thickness of Pleistocene deposits over most of the county (fig. 4B) suggests that regional slopes and local relief were similar prior to the Pleistocene. Before the Pleistocene, the basalt ridge would have formed a prominent drainage divide, and streams in central Polk County would have flowed southerly, as they do today.

However, the path of the ancestral St. Croix River was most likely different than it is today. A number of bedrock valleys are present in western Wisconsin and eastern Minnesota (Schwartz, 1936; Olsen and Mossler, 1982); these valleys could have served as routes for earlier versions of the St. Croix River. Berkey (1897), Upham (1900), Martin (1932), and Cooper (1935) suggested that the preglacial St. Croix River flowed

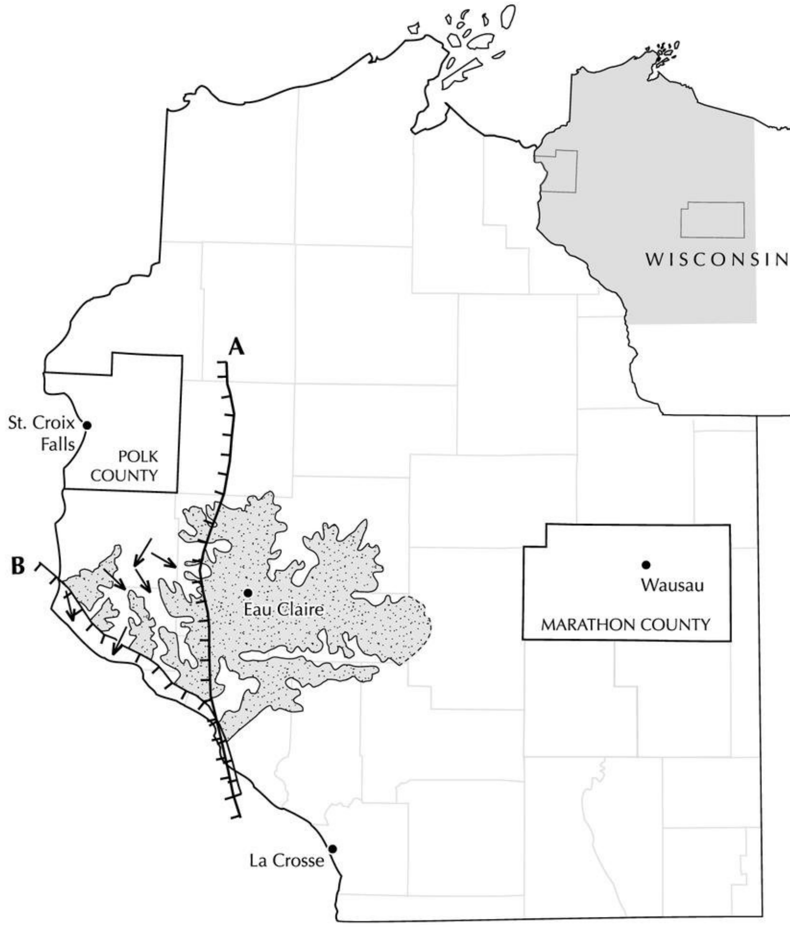


Figure 11. *Ice-margin positions (hachured lines), ice-flow direction from pebble fabric (arrows), and ice-dammed lakes (stippled area) associated with the Reeve Phase of the Des Moines Lobe in western Wisconsin. Pebble-fabric data and lake distribution is from Baker and others (1983); ice margin A, from Johnson (1986) and Baker and others (1983). Ice margin B shows the hypothetical position of the Des Moines Lobe when lake sediment of the Pierce Formation was deposited (Baker and others, 1983). The Des Moines Lobe may have advanced as far east as Marathon County (Baker and others (1987).*

southwesterly, toward what is now the Twin Cities, and that the river's present-day course, through what is now the St. Croix Dalles, was established at some time during the Pleistocene. Cooper (1935) suggested that, at least prior to the latest Wisconsin advances, the position and flow of the St. Croix River were similar to what they are today in western Burnett County and northwestern Polk County. From there, Cooper suggested that the river flowed southwest, toward what is now Minneapolis. The deposits of glacial Lake Lind (please refer to fig. 24, p. 36) outline a buried lowland that extends to the southwest along the route described by Cooper. The stratigraphic and geomorphic relationships outlined in this report support the conclusions of earlier researchers that the present-day course of the St. Croix River along the western edge of the county dates from the latest part of the Wisconsin Glaciation; I suggest the present-day course developed during the Pine City Phase. (See section entitled *Drainage of Lake Superior and the entrenchment of the St. Croix River*.)

Climate records from deep-sea cores indicate that about two dozen glacial episodes occurred during the Pleistocene; many of the glaciers may have covered Polk County. However, the deposits in Polk County and the surrounding area provide evidence for only a few of these episodes.

Reeve Phase

During the middle part of the Pleistocene, the Des Moines Lobe advanced into western Wisconsin and deposited dark-gray loam till and lake sediment of the Pierce Formation. Because Pierce Formation sediment has reversed magnetic polarity, Baker and others (1983) suggested that the Reeve Phase (Johnson, 1986) occurred before 730,000 BP, during the Matuyama Reversed Polarity Epoch, or perhaps during a short reversal approximately 460,000 BP.

Leverett (1932) suggested that the Des Moines Lobe at this time reached a maximum position as far east as the boundary between St. Croix and Dunn Counties. Baker and others (1983) and Johnson (1986) suggested that the maximum extent was farther east, in the center of Barron and Dunn Counties (ice margin A, fig. 11). On the basis of lithostratigraphic correlation of the Pierce Formation with the Marathon Formation (Attig and Muldoon, 1988), Baker and others (1987) suggested that the Des Moines Lobe may have advanced as far east as Marathon County during the Reeve Phase (fig. 11).

The presence of two till units of the Pierce Formation at the type locality near Woodville, Wisconsin, which lies 17 km south of the Polk County's southern border, indicates two ice advances (Baker, 1988b). During my field work in Polk County, I found no exposures that contained these two till units; therefore, it is not clear whether or not both advances covered Polk County, although it is probable given the proximity of Woodville.

Because of the Pierce Formation's patchy distribution well below the present-day land surface, no geomorphic features in the county are associated with this advance. The weathered profile in the Pierce till, even where it is buried by River Falls till, suggests that a significant period of subaerial exposure and soil formation followed the Reeve Phase (Johnson, 1986). The scarcity of this unit in the subsurface (fig. 7) suggests that much of it has been removed by erosion.

Baldwin Phase

After an interglacial period sufficiently long enough to weather the Pierce till, the Superior Lobe advanced into eastern Minnesota and western Wisconsin and deposited the River Falls Formation. This advance, known as the Baldwin Phase (Johnson, 1986), left behind deposits that include reddish-brown, sandy loam till.

The margin of the Superior Lobe reached a position south of Polk County during this phase (fig. 12) because River Falls till, which was deposited by the Superior Lobe during this phase, is present in northern Dunn County and parts of St. Croix and Pierce Counties (Baker and others, 1983). The southern limit is difficult to locate accurately because the present-day relief is great in the terminal region, and hillslope erosion was extensive after the Baldwin Phase, probably intensified by the presence of permafrost during the Wisconsin Glaciation. Present-day topography is characterized by a well integrated drainage network, and little glacial topography remains. However, the limit of the Baldwin Phase may coincide with the feature referred to as the "Hampton moraine" of Dakota County, Minnesota (Ruhe and Gould, 1954) (fig. 13).

Almost no sediment from this advance was discovered in Polk County during my study because it is buried. Most of the samples analyzed for figures 5 and 6 were collected in northern St. Croix County. It is likely that the thick sequence of unlithified material throughout Polk County contains some of this sediment at depth (see cross sections, plate 1).

River Falls till has a normal magnetic polarity (Baker and others, 1983) and is more deeply weathered than till deposited during the Wisconsin Glaciation (Johnson, 1986). On the basis of this evidence, the Baldwin Phase probably occurred after 730,000 BP, the beginning of the epoch of normal polarity, and prior to 130,000 BP, which is approximately the beginning of the long, warm Sangamon

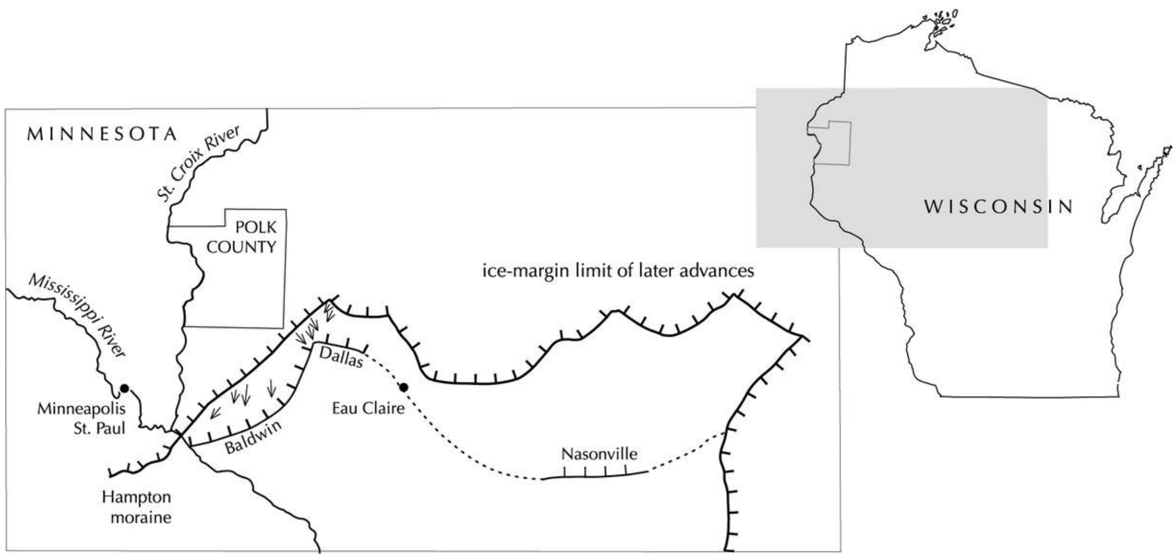


Figure 12. *Ice-margin positions (hachured lines) and ice-flow direction from pebble fabric (arrows) during the Baldwin Phase of the Superior Lobe in west-central Wisconsin (from Baker and others, 1983; Johnson, 1986). The position of the Hampton moraine is from Ruhe and Gould (1954); the Nasonville Phase ice margin, from Clayton and others (1991). Although the ice-margin limits of the Baldwin, Dallas, and Nasonville Phases and the Hampton moraine are connected in this figure, their contemporaneity has not been proven.*

interglacial period immediately preceding the Wisconsin Glaciation.

This advance occurred at about the same time as the Dallas Phase in Barron County (Johnson, 1986) and is similar in age to the Nasonville Phase of central Wisconsin (Attig and Muldoon, 1989) (fig. 12).

Emerald Phase

Toward the end of the Wisconsin Glaciation, the Superior Lobe advanced into western Wisconsin, completely covered Polk County, and reached its maximum position in central St. Croix and southern Barron Counties (fig. 13). Till deposited during that time is reddish-brown sandy loam and is included in the Poskin Member of the Copper Falls Formation. This advance is known as the Emerald Phase. (The term "Emerald Phase" replaces the term "Early St. Croix Advance" used by Johnson, 1986.)

The extent of ice during the Emerald Phase is shown by the distribution of several geomorphic features as well as by the extent of the Poskin till, but the limit is not marked by a prominent feature on the landscape. Several collapsed valleys, small areas of hummocky topography, examples of deranged drainage, and a few ice-block depressions are evident in central Barron County and northern St. Croix County (fig. 13) (Johnson and Savina, 1987). Poskin till is nearly continuous in Barron County and southeastern Polk County behind the Emerald Phase ice-margin limit, but its distribution in northern St. Croix County is discontinuous (fig. 13). Five of 16 till samples collected in this area have magnetic susceptibility values similar to River Falls till (fig. 6). The Poskin till may have been thinner originally in southern Polk and northern St. Croix Counties or subsequent hillslope erosion has been intense. Where the Poskin till is at the surface, the land surface is gently rolling and has a well established dendritic drainage pattern; this suggests that significant surface erosion has occurred.

Other than an ice-dammed-lake plain in Barron County (Johnson, 1986), no geomorphic features mark the maximum ice-margin limit, although an ice-margin limit similar to the position of the Emerald margin was described by Berg (1960) and referred to as the "Emerald moraine" after the town of Emer-

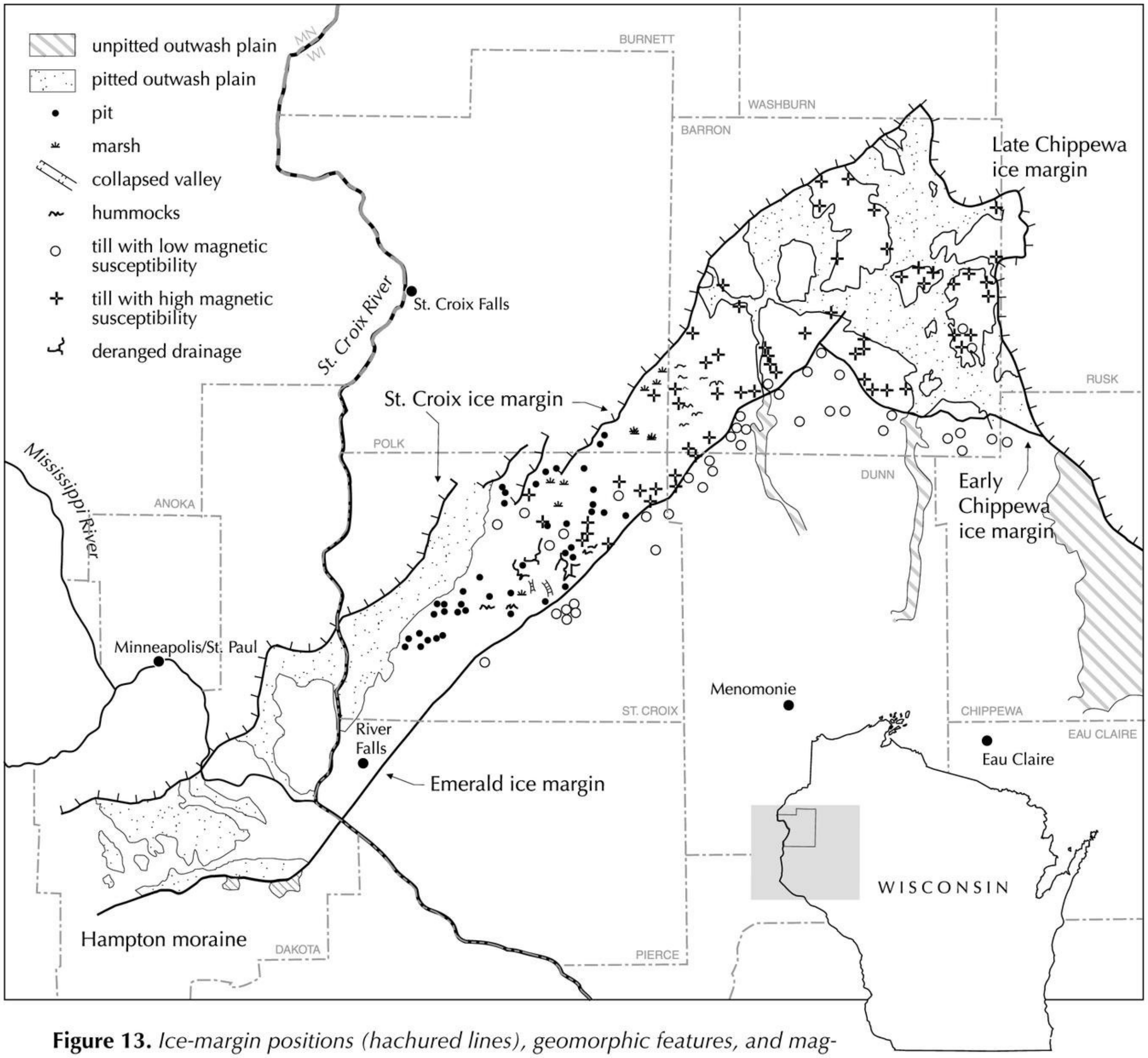


Figure 13. *Ice-margin positions (hachured lines), geomorphic features, and magnetic susceptibility values of till associated with the Emerald Phase of the Superior Lobe. Geomorphic features interpreted from topographic maps of southern Polk County, St. Croix County, western Pierce County, northern Dunn County, and Dakota County, Minnesota, by Johnson and Savina (1987); St. Croix ice-margin position in Minnesota from Hobbs and Goebel (1982). High magnetic susceptibility in Barron County (from Johnson, 1986) is represented by values greater than 5.0 (arbitrary magnetic susceptibility units); high magnetic susceptibility values in Polk and St. Croix Counties are those greater than 2.0 x 10^{-3} (SI units) (see fig. 6).*

ald in northeastern St. Croix County. Little outwash that can be attributed to the Emerald phase is present at this former ice-margin position. Johnson and Savina (1987) suggested that the climate was much colder during this phase. Because of this, the Superior Lobe may have had less debris, and meltwater would not have flowed through the glacier to the glacier bed from the surface of the ice. Meltwater streams may have carried less sediment and hence did not aggrade at this time. (See section entitled *Characteristics of the Superior Lobe during the Emerald and St. Croix Phases.*)

On the basis of mineralogic and geomorphic evidence, the Emerald Phase occurred during the latter part of the Wisconsin Glaciation, which Clayton and Moran (1982) suggested began after approximately 25,000 BP. The magnetic susceptibility and kaolinite:illite ratio of the Emerald Phase Poskin till is similar to that of Sylvan Lake till deposited during the St. Croix Phase, but distinct from till of the River Falls Formation deposited during the Baldwin Phase (Johnson, 1986). This evidence suggests that the River Falls till is deeply weathered, and therefore old. The Poskin till, which shows little change attributable to weathering, is similar in age to the Sylvan Lake till and therefore is young.

Furthermore, collapse pits in outwash plains that grade to the St. Croix margin indicate that buried ice from the Emerald Phase remained frozen until after the St. Croix Phase (fig. 13). Although glacial deposits interpreted to have been deposited during the early part of the Wisconsin Glaciation are present in central Wisconsin (Stewart and Mickelson, 1976; Attig and Muldoon, 1989), it is unlikely that this buried ice could have been deposited during the early Wisconsin Glaciation in western Wisconsin and could have survived the relatively warm period during the middle part of the Wisconsin Glaciation. This suggests that the Emerald Phase occurred during the latter part of the Wisconsin Glaciation, perhaps a few thousand years prior to the St. Croix Phase.

St. Croix Phase and later Superior Lobe phases

Following the Emerald Phase, the margin of the Superior Lobe melted back some unknown distance to the north and then readvanced to a position 10 to 15 km north of the Emerald ice-margin limit. This readvance of the Superior Lobe deposited till of the Sylvan Lake Member and is known as the St. Croix Phase.

The use of the name "St. Croix" in association with glacial features in western Wisconsin was originally applied to the band of hummocky topography running north–south immediately east of St. Croix Falls. This was called the "St. Croix moraine" by Berkey (1897). In this report, I have called the glacial event that formed this feature the Centuria Phase (note Centuria ice margin, fig. 8). Chamberlin (1905) used the term "St. Croix moraine" in the same sense as Berkey and recognized several other features in Polk County that he called moraines, including the "Alden moraine" (name retained for use as Alden ice margin; see fig. 8).

The name was first applied to landforms farther southeast by Leverett (1932), and it is this hummocky region that geologists generally refer to as the "St. Croix moraine" or "St. Croix Moraine." Although Leverett recognized Chamberlin's other moraines (such as the Alden), he did not recognize the "St. Croix moraine" in the sense defined by Berkey (1897) and used by Chamberlin (1905). Leverett gave no explanation for the name change. Wright and others (1973) referred to the ice advance that made this landscape the "St. Croix Phase." In this report, "St. Croix Phase" replaces the term "Late St. Croix Advance" as used by Johnson (1986) and Johnson and Savina (1987).

Sylvan Lake till overlying Poskin till was found at three localities in Barron County (Johnson, 1986), which indicates a retreat prior to readvance, but no exposures with these stratigraphic relationships were found within Polk County. Well constructor's reports in central Polk County commonly describe a thick, complex stratigraphy of interlayered till and outwash units, which suggests that many advances and readvances may have occurred during the overall retreat of the Superior Lobe.

During and after the St. Croix Phase, the Superior Lobe left behind a landscape sharply contrasting with that of the Emerald Phase and consisting of the extensive outwash plains, collapsed topography, numerous lakes, and deranged drainage that characterize much of Polk County. Several prominent former ice-margin positions are apparent; the St. Croix ice margin and the Centuria–McKinley ice margins are most conspicuous. The ice margins shown in figure 8 reveal the shape of the glacier as it retreated from Polk County. The deposits left during these events are predominantly sandy outwash and reddish-brown sandy loam till included in the Sylvan Lake Member of the Copper Falls Formation.

Striations and grooves

On the basis of the orientation of striations, till fabric, eskers, tunnel channels, and ice-marginal features, the ice-flow direction of the Superior Lobe during the St. Croix Phase was to the southeast. Striations are well preserved on the basalt knobs in the northern part of the county (fig. 14B); numerous crag-and-tail striations can be found where the basalt is amygdaloidal.

Striations as well as grooves in basalt indicate an earlier ice-flow direction to the southwest (fig. 14A), first noted by Hansell (1930). The grooves cut into the basalt are 1 to 5 cm deep, 20 to 50 cm wide, and up to 2 m long (fig. 15). Although some grooves oriented northwest–southeast are present (fig. 14B), most are oriented northeast–southwest. The grooves are broadly U-shaped in cross section and have, in places, a slight sinuosity and smoothness that gives them a waterworn appearance. Striations also are found within the grooves. The grooves do not form a network; they appear as a series of unlinked segments. It is likely that the grooves were cut subglacially because their orientation is nearly always southwest regardless of the slope of the basalt knob on which they are found. The grooves appear similar to Nye channels described by Walder and Hallet (1979) beneath the Blackfoot Glacier in Montana. Walder and Hallet interpreted these grooves to have been cut subglacially by intermittent flow of water and later striated by ice flowing back into the channels.

It is not clear when these southwest-trending grooves and striations were formed (fig. 14A), but in the places where they are found with the southeast-trending set, they are older than the southeast set of striations. The grooves are as fresh as the younger set of striations, which suggests that they were formed by ice movements during the Emerald or St. Croix Phases, and that they could not be as old as the Baldwin Phase.

I suggest that the grooves were formed during surging of the Superior Lobe, and that the younger striations were made by later sliding along radial flow lines. This idea is supported by the conclusions of Clayton and others (1985), who suggested that Pleistocene ice lobes in the Midwest surged during the latter part of the Wisconsin Glaciation. If the Superior Lobe surged, it may have exhibited plug flow (flow to the southwest) rather than the radial flow implied by the southeast flow indicators. High discharge rates of sediment-rich subglacial meltwater are associated with modern surging glaciers (Kamb and others, 1985). The subglacial water produced during flow to the southwest could have cut the grooves. Radial flow would have ensued following surge flow and then cut the younger, more prevalent southeast set of striations.

The striations running east–west at Z in figure 14C are the youngest set in the county and I interpreted them to have been formed by the Superior Lobe when it stood at the Centuria ice margin. Chamberlin (1905) attributed similarly oriented striations in this

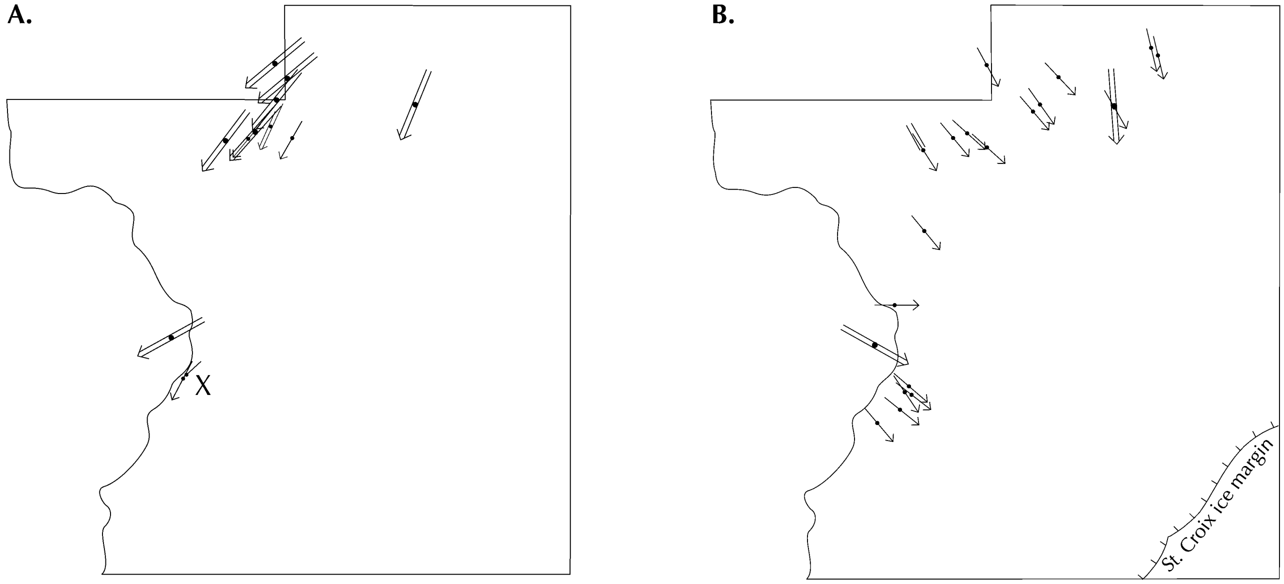
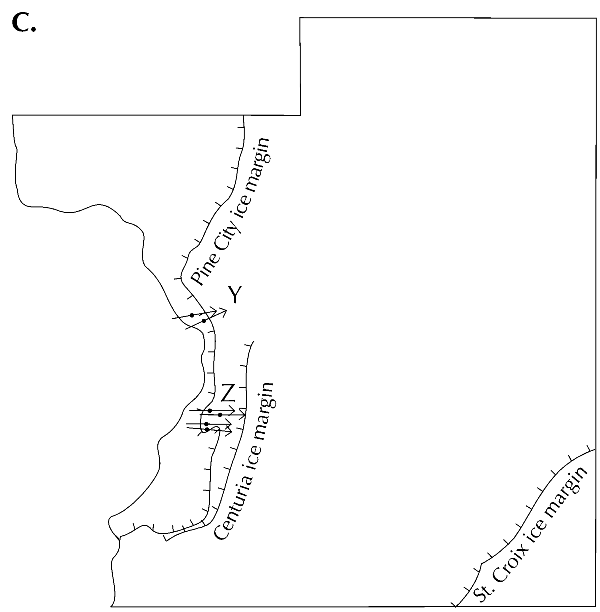


Figure 14. *Striations (single arrows) and grooves (double arrows) in Polk County.* **A:** *Orientation of grooves and striations showing ice flow to the southwest. In most places, cross-cutting relationships were apparent and always showed striations and grooves in this orientation to be older than those shown in B. Striations at X are striations and crag-and-tail striations atop Eagle Peak and Observation Rock in Interstate State Park.*
B: *Prominent southeast striations and grooves.*

area to work of the Grantsburg Sublobe, which advanced into Polk County from the west. (See section entitled *Pine City Phase*.) However, it is unlikely that these striations are Grantsburg Sublobe striations for the following reasons:

- The striations are on basalt at elevations between 323 and 329 m. The highest elevations of nearby Grantsburg Sublobe deposits are 314 m, along the Pine City Phase end moraine in St. Croix Falls (map unit **gtm**, plate 1).
- The striations are 1 km directly east of a knob (elevation 347 m) covered with Superior Lobe deposits. This hill would have to have been crossed for the east–west striations to have been cut. Because of the elevation, it is unlikely the Grantsburg Sublobe crossed this knob. In addition, there is no evidence of Grantsburg Sublobe material on this knob, only on its western flanks and below an elevation of 305 m. The striations



C: *Striations showing easterly flow and Pine City and Centuria ice-margin positions. The group at Z is interpreted to have been cut by the Superior Lobe later than striations at the same site shown in 14B. The group at Y was interpreted by Chamberlin (1905) to have been formed by the Grantsburg Sublobe.*

Figure 15. *Photograph of basalt outcrop that has grooves. The ice-flow direction when the grooves were cut was roughly left to right. Outcrop is in SW¼SW¼ sec. 11, T36N, R18W in Laketown Township.*

at Y (fig. 14C) may have been cut by northeast-flowing ice of either the Grantsburg Sublobe or the Superior Lobe.

Outwash plains and fans

Outwash plains cover much of Polk County and constitute one of the most common landforms remaining there from the Wisconsin Glaciation (map unit **ssp**, plate 1). These plains were built by meltwater streams emanating from the melting Superior Lobe. Exposures of sand and gravel exhibit sedimentary structures typical of braided streams, although channels and bars characteristic of braided streams are not discernible on aerial photographs. The outwash plains are commonly pitted as a result of the melting of buried ice blocks. Elsewhere, buried ice has been extensive enough to leave no planar portions uncollapsed (map unit **ssh**, plate 1).

Outwash plains are clearly associated with former ice-margin positions; the positions of former Superior Lobe ice margins have been interpreted partly on the basis of the sharp northern and western up-slope limits of the outwash plains (figs. 8 and 16). As shown in figure 17, outwash deposited close to former ice-margin positions is coarser than outwash deposited distally. Near former ice-margin positions, the slope of the outwash plains is relatively steep: It ranges from 2.0 to 4.0 m/km on the plains near Centuria, Big Round Lake, and Frederic, Wisconsin, but in places may be as high as 8.5 m/km, such as on the plain just west of Range, Wisconsin. In more distal positions, the slope is less pronounced. The outwash plain north of New Richmond, Wisconsin, near the southern border of Polk County, has a slope of 1.1 m/km.

Figures 8 and 16 show that the outwash plains in Polk County formed at different times as the Superior Lobe melted back; the outwash fan and plain at Clear Lake are the oldest (fig. 18). The most extensive outwash

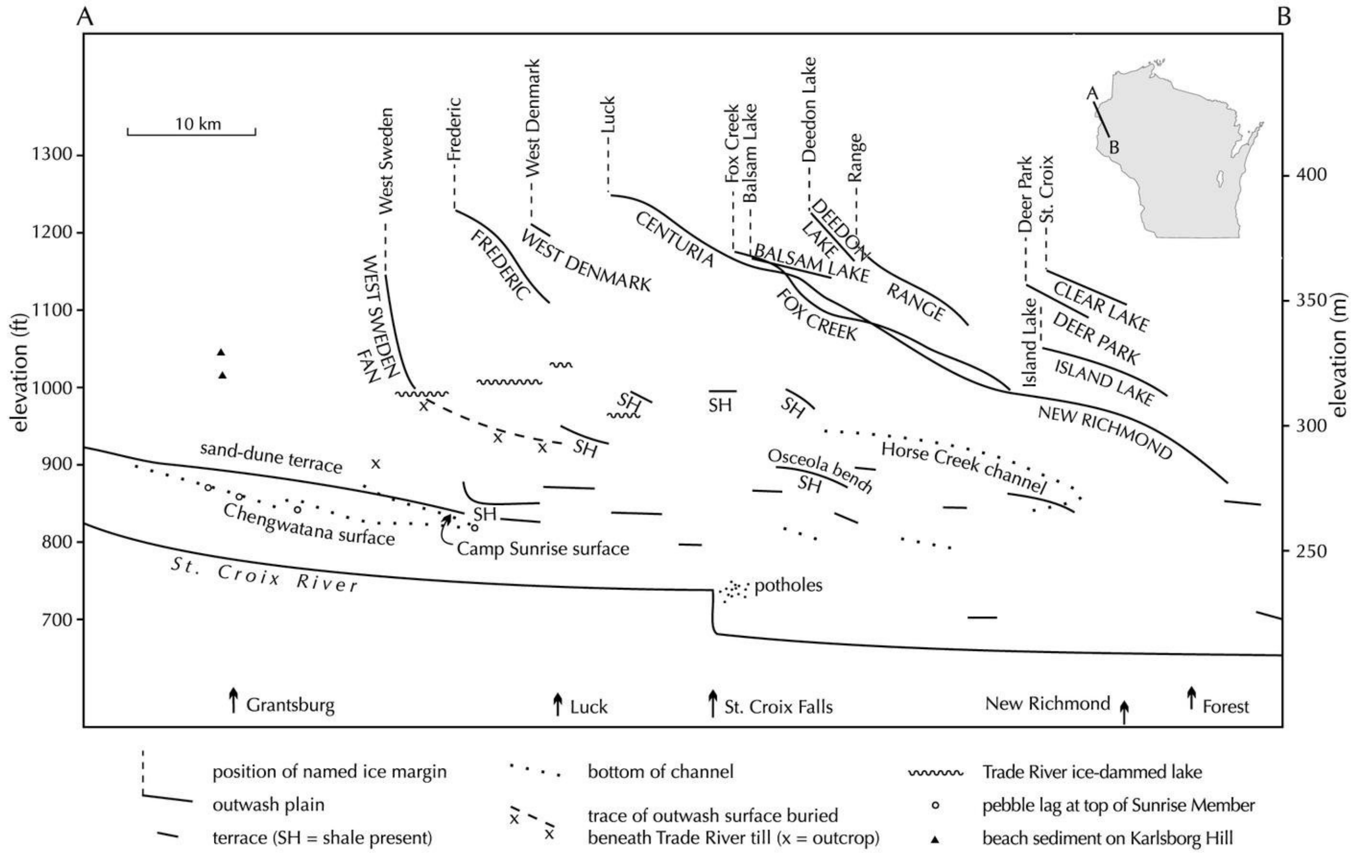


Figure 16. *Outwash-plain profiles, terrace profiles, channel profiles, and ice margins projected onto a line (A–B) oriented north–northwest through Burnett, Polk, and St. Croix Counties. Elevations were taken from U.S. Geological Survey topographic maps. Vertical exaggeration approximately 200 times. Some slope changes and slope reversals (such as along the Horse Creek Channel) are an artifact of projection. Not all outwash plains or ice margins are represented. Terraces with shale (SH) indicate presence of western-source shale derived from the Grantsburg Sublobe.*

plain in the county was formed during the Centuria–McKinley Phases. The Centuria and Fox Creek outwash plains were formed about the same time during these phases and are up-slope extensions of the large outwash plain that begins at Star Prairie in southern Polk County, underlies New Richmond, and continues to the St. Croix River at Hudson (fig. 16).

A significant amount, if not most, of the outwash in the outwash plains was derived from tunnels discharging meltwater and sediment underneath the Superior Lobe. In several places in the county, the outwash plains have fan shapes at former ice-margin positions that have apexes coincident with the mouths of a tunnel channel or an esker. It is clear in these cases that the tunnel system underneath the ice, now indicated by the tunnel channels and eskers, was the source for the sediment that composes the outwash plain. Perhaps the best example of this relationship in the county is the tunnel channel and outwash fan 3 km southwest of Clear Lake (fig. 18). Other examples of subglacial outlet points are at the head of Rock Creek valley (5 km north–northwest of Centuria) and at Frederic, where an esker at the north edge of town shows the location of the subglacial tunnel (fig. 19). Such a relationship between subglacial meltwater, tunnel channels, and outwash plains is common along the late Wisconsin ice margin elsewhere in the Midwest (for example, in Wisconsin

B.

A.

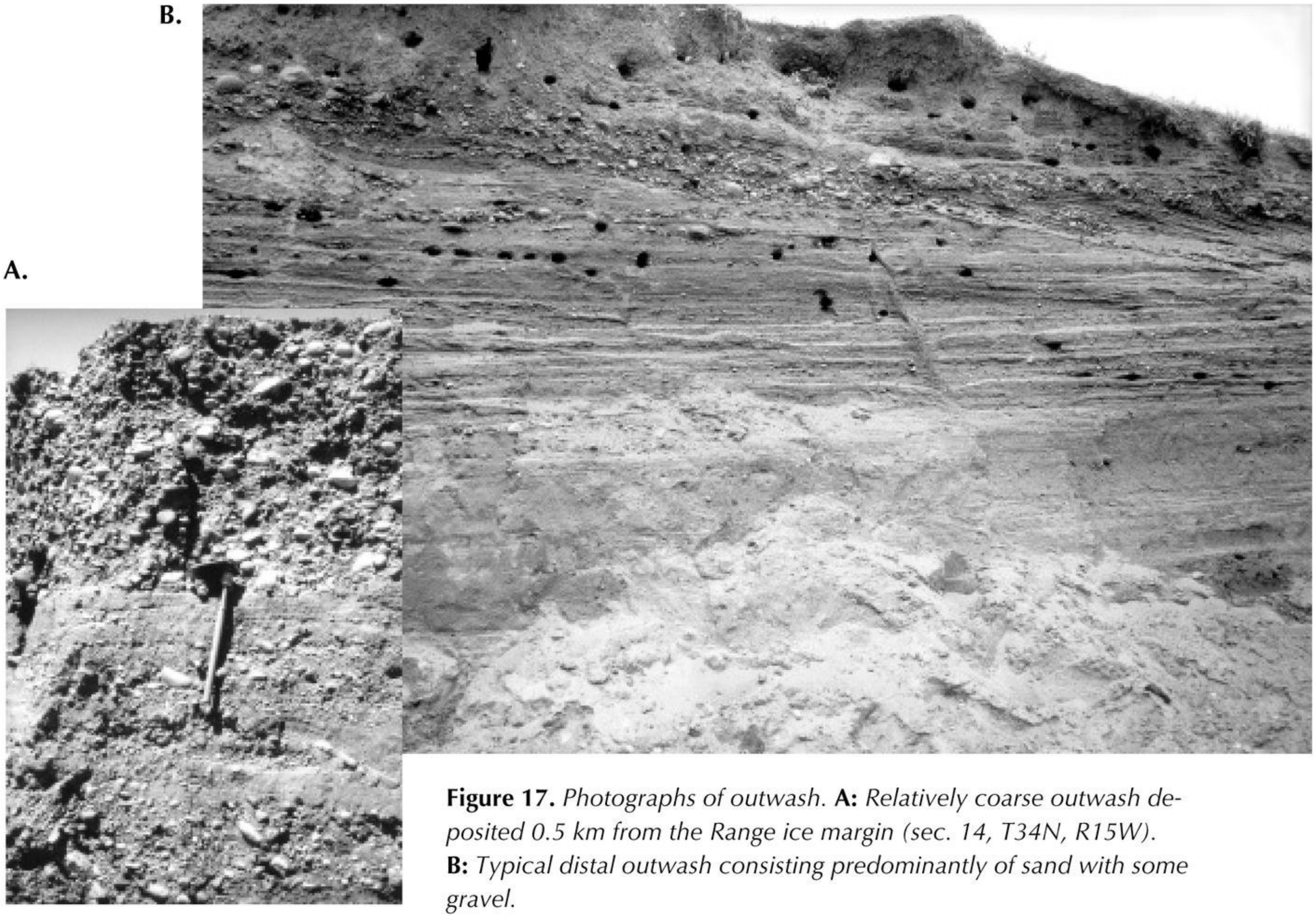


Figure 17. *Photographs of outwash.* **A:** *Relatively coarse outwash deposited 0.5 km from the Range ice margin (sec. 14, T34N, R15W).* **B:** *Typical distal outwash consisting predominantly of sand with some gravel.*

[Clayton, 1986; Johnson, 1986; Attig and others, 1989] and in central Minnesota [Mooers, 1989]). Erosion by subglacial meltwater, subglacial transport in tunnels, and the formation of outwash plains with fans at tunnel mouths has been reported for the Malaspina Glacier in Alaska (Gustavson and Boothroyd, 1987).

Regions of collapsed outwash (map unit **ssh**, plate 1) owe their origin to extensive stagnant ice that was buried by meltwater-stream sediment. Some collapsed outwash tracts are on the north and west sides of prominent uplands—for example, the area south of Balsam Lake and just west of the region of map unit **ush** (plate 1) and the large area to the west and south of Lake Wapogasset. In these areas, the adjacent uplands associated with each would have caused the obstruction of meltwater flow directly away from the glacier, and sedimentation would have occurred on the thin ice at the ice margin. With further retreat, meltwater would flow more freely away from the glacier, and less marginal ice would become buried.

The extensive area of map unit **ssh** (plate 1) running from St. Croix Falls north–northeast to the county line (at the margin of material deposited during the Centuria Phase) probably formed in this way as well. This extensive hummocky area contains some isolated planar remnants (secs. 25 and 26, T36 N, R18W, and secs. 4 and 5, T35N, R18W) that represent fragments of kame terraces formed between the upland divide that runs between Milltown and Frederic and the retreating Superior Lobe to the west. When the ice was east of this divide, meltwater drainage was to the southeast into the Willow River system; when the ice was west of this divide, meltwater flowed along the ice margin to the southwest and outwash would

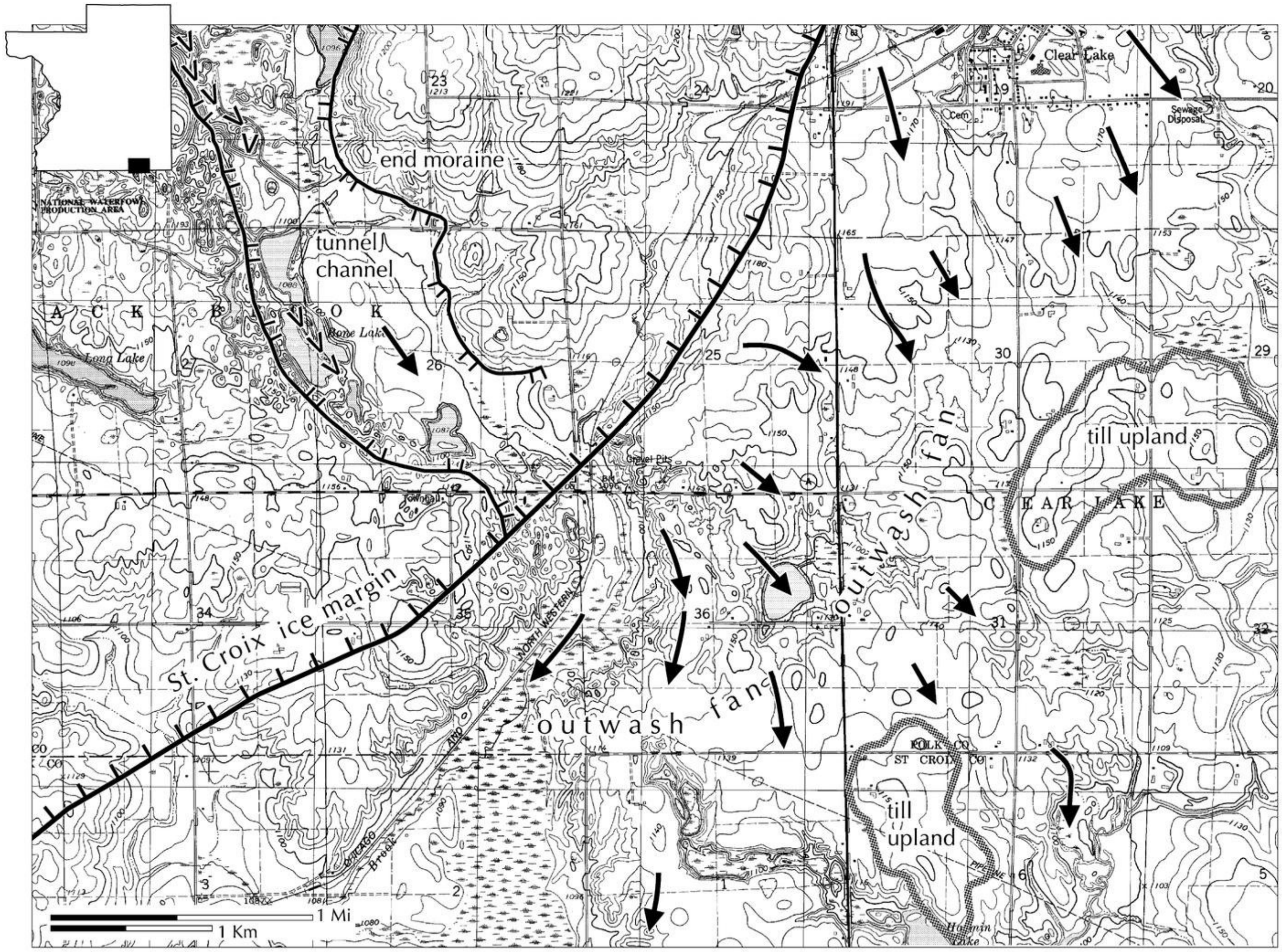


Figure 18. *Part of Forest Quadrangle, Wisconsin (U.S. Geological Survey, 7.5-minute series, topographic, 1975), showing tunnel channel, esker (arrowheads), outwash fan, and ice-margin association near Clear Lake. Meltwater and sediment were transported to the ice margin through the subglacial tunnel now represented by the tunnel channel and esker. Sediment was subsequently deposited in the outwash fan at the mouth of the tunnel channel. Arrows show slope and shape of outwash fan; arrows around Clear Lake are on an outwash fan that was fed by a tunnel channel just north of the area covered by this map. Gravel pits at fan apex contain cobbly sand and gravel with a few boulders as large as 0.5 m; gravel pits 2 km from the apex contain primarily slightly pebbly sand. The broad upland on either side of the tunnel channel may be an end moraine. Contour interval = 10 ft.*

have been deposited in places on marginal ice. Some hummocks in this north–south band may represent collapsed proximal outwash deposited when the Centuria outwash plain was formed.

Two broad regions of collapsed outwash (map unit **ssh**, plate 1) are in the northern part of the county: One is south of Clam Falls along McKenzie Creek, and the other is in the extreme northeast corner of the county along Sand Creek. These two valleys contain hummocks composed predominantly of sand, and the hummock tops decrease in elevation to the north. These broad valleys may have been the locations of tunnel channels when active ice was present (the Sand Creek area is connected to the tunnel channel whose mouth is at Cumberland), but later they became the pathway for northward-flowing meltwater from stagnant ice that melted in the northern part of the county following overall ice retreat. These surfaces grade northward to the sand plains of central Burnett County.

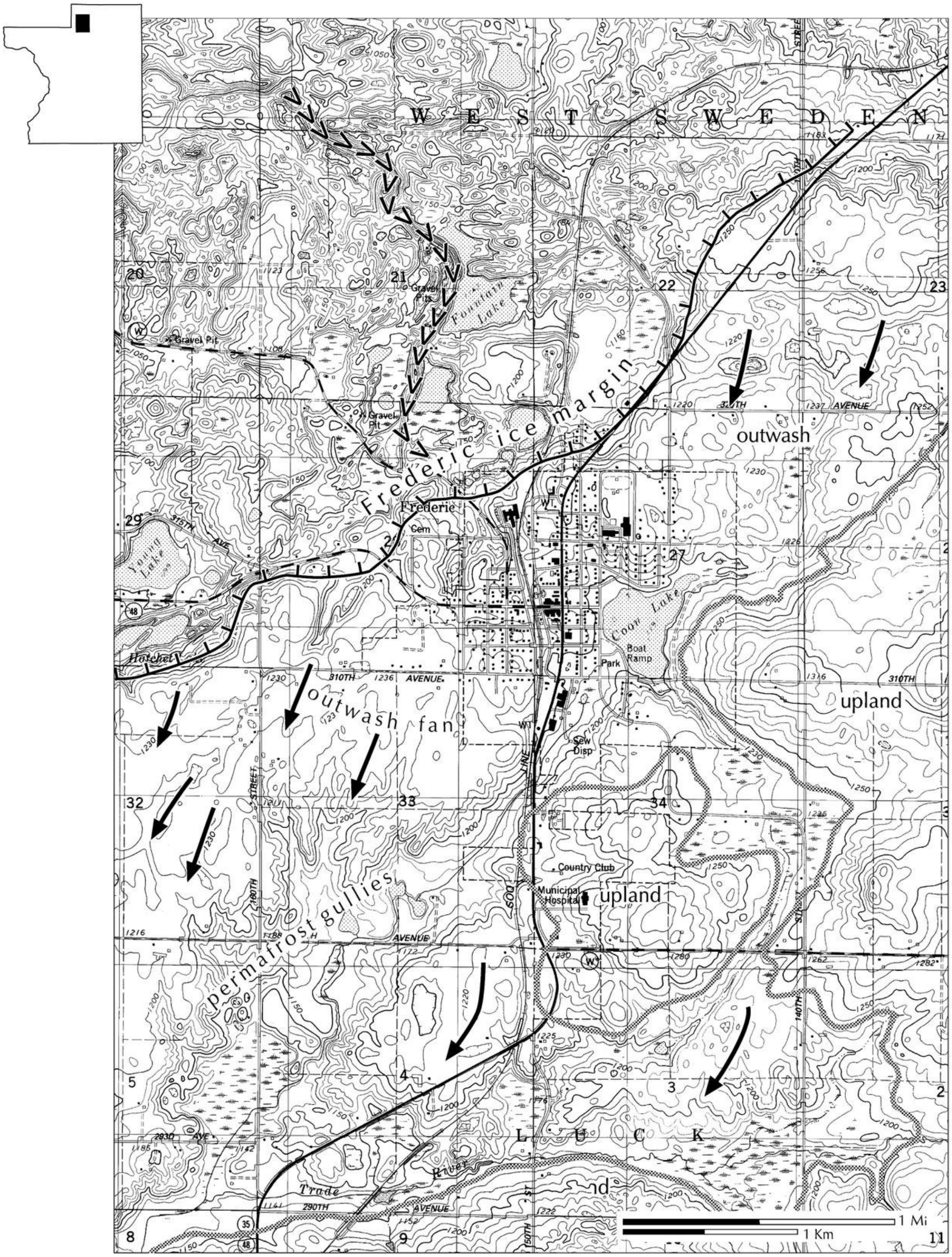


Figure 19. *Part of the Frederic Quadrangle, Wisconsin (U.S. Geological Survey, 7.5-minute series, topographic, 1983), showing esker (marked by arrowheads), outwash fan, ice-margin position, and permafrost gullies. Meltwater and sediment were transported to the Frederic ice margin in the tunnel now represented by the esker; meltwater subsequently flowed southwest. I interpret the well developed dendritic gullies in the pebbly sand to reflect low infiltration rates because of the presence of permafrost. Contour interval = 10 ft.*

Tunnel channels and eskers

Tunnel channels are common in Polk County; many are shown on plate 1. The greatest number is associated with the St. Croix ice margin, where nine tunnel channels are mapped (a part of one is shown in fig. 18). Half the tunnel channels in the county contain eskers (see fig. 8); the best example of an esker within a tunnel channel can be seen on the U.S. Geological Survey Big Round Lake quadrangle (7.5-minute series, topographic, 1983) (fig. 20). The tunnel channels mapped on plate 1 terminate at former ice-margin positions (see also fig. 8). As mentioned above, many tunnel channels are associated with proglacial outwash fans (fig. 18). However, this relationship is lacking in the five tunnel channels mapped between Clear Lake and Clayton.

Numerous other linear features in the county (lakes, marshes, collapse pits, and valleys) probably also represent tunnel channels. A series of elongate lakes (including Wapogasset Lake, Deer Lake, Loveless Lake, Boston Bay in Balsam Lake, Half Moon Lake, and Bone Lake) in the center of the county oriented generally northwest–southeast is likely a site of tunnel channels as well (buried tunnel channels, fig. 8). In these locations, the tunnel channels became filled with ice and were later buried deeply by outwash. With the melting of buried ice, an elongate kettle lake was formed. The tunnel channels mapped on plate 1 are better defined because they were formed in more upland positions and did not become buried later by outwash.

In addition to these buried tunnel channels, an esker and a string of collapse pits near Milltown indicate the location of former glacial tunnels. Because of its proximity to the outwash fan on the Centuria outwash plain, the valley of Rock Creek in western Polk County is probably the location of a former glacial tunnel as well. It is likely that more of these tunnels existed and that no geomorphic evidence remains of their existence.

Tunnel channels that formed underneath the Superior Lobe were first described by Wright (1973). He believed these to have been formed when subglacially derived meltwater was forced under cryostatic pressure toward the margin of the Superior Lobe. Because he believed the margin to have been frozen to the bed, the breakthrough of the meltwater must have been sudden and catastrophic. Mooers (1989) suggested that the long tunnel channels in Minnesota described by Wright (1973) could not have formed along their whole length simultaneously, but were formed in segments near the ice margin and lengthened in a headward fashion during ice retreat, and that the water to cut them came from surface melting of the glacier. In Polk County, it is possible to link together tunnel-channel segments into a network with some channel systems as long as 40 km (for example, see Attig and others, 1989). However, breaks in the tunnel-channel sequences, development of outwash plains of different ages graded to different parts of the same tunnel-channel sequence, and the presence of the best-developed tunnel channels next to former ice-margin positions suggest that the tunnel channels in Polk County were formed as relatively short segments near former ice-margin positions.

The association of eskers within the tunnel channels is common and indicates two levels of discharge during subglacial drainage. A large discharge is shown by the large size of the tunnel channel as well as the fact that it is an erosional feature. According to Wright (1973) and Attig and others (1989), the tunnel channel represents an initial, short-lived burst of subglacial meltwater, perhaps under hydraulic head built up be-

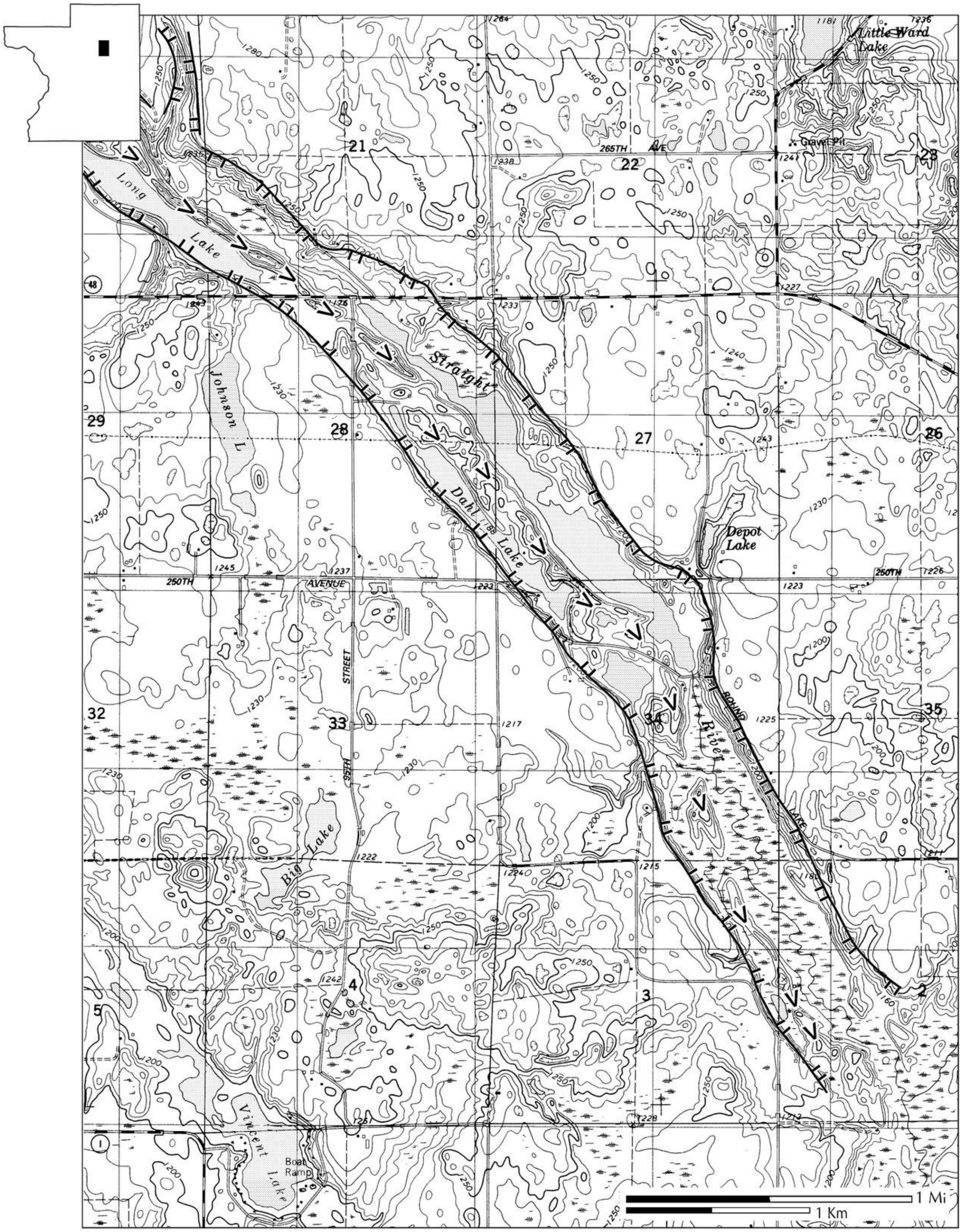


Figure 20. *Part of the Big Round Lake Quadrangle, Wisconsin (U.S. Geological Survey, 7.5-minute series, topographic, 1983), showing tunnel channel and esker (arrowheads). Water flow during tunnel-channel formation was to the southeast. Material bordering this tunnel channel is relatively thin outwash over till. Contour interval = 10 ft.*

hind a frozen margin. As discharge abates, the subglacial meltwater pathway is maintained at a smaller size. This smaller tube later becomes filled with stream sediment and becomes an esker upon melting of the surrounding ice.

Eskers not in tunnel channels are also present in the county. The largest is in northwest Polk County and has its terminus at the apex of the large outwash fan upon which Frederic lies (fig. 19). The elevation of this esker rises from 329 m near West Sweden to 366 m at its terminus, indicating that the sediment in this esker was deposited as water flowed up the regional slope. Other prominent eskers include one at the St. Croix County line, locally referred to as "The Hogsback," and one revealed in a large collapse pit 3 km north of Centuria.

Hummocks

Hummocky topography left by the Superior Lobe characterizes the upland surfaces in many parts of the county (fig. 21). Hummocky topography is believed to be created by sediment collapse during the melting of buried, stagnant ice (Gravenor and Kupsch, 1959; Clayton, 1967). The irregularly shaped hills interspersed with the ice-walled-lake plains, kettle lakes, swamps, and deranged drainage that lie within the hummock tracts in Polk County support the hypothesis that the hummocks formed during the melting of stagnant ice.

The various hummock tracts shown on plate 1 (map unit **ush**) are commonly associated with former ice-margin positions. Distinct regions of hummocks lie along the St. Croix, Range, Balsam Lake, Centuria, and Luck ice margins. Elsewhere, the boundaries of hummock tracts bear little relation to local former ice-margin positions, such as in the area just west of Bone Lake (plate 1).

Hummocks composed primarily of sand and gravel (map unit **ssh**, plate 1) were discussed in the *Outwash plains and fans* section of this paper. Many other hummocks are composed of a variety of sediment types, including sorted clay, silt, and sand and gravel (mostly fluvial and lacustrine sediment) and significant amounts of nonsorted sediment (gravity-flow deposits and till) (map unit **ush**, plate 1). A complete gradation exists in the county between hummocks composed primarily of sorted sediments (mostly sand and gravel) to hummocks composed entirely of nonsorted gravity-flow sediment or till. Figure 22 is a sketch of a cut through a hummock formed near St. Croix Falls behind the Centuria ice margin. This hummock contains outwash and nonsorted sediment interpreted to be meltout till on the basis of its strong fabric, faint stratification, and presence in a hummock.

The extensive hummock tracts in Polk County indicate widespread ice stagnation following the St. Croix and later ice advances. As a glacier melts, sedimentation processes on the glacier's surface rework glacial debris and produce sequences of fluvial sediment and gravity-flow deposits on top of the ice near the edge of the glacier (for example, Paul, 1983). However, the preservation of meltout till in many hummocks behind the St. Croix ice-margin limit suggests that debris released supraglacially from the melting ice was fairly stable and was only partly reworked by slumping and meltwater activity. For a more complete discussion of hummocks composed of meltout till in western Wisconsin, see Johnson and others (1995). The concentration of hummocks near former ice-margin positions reflects the greater amount of debris in the glacier near the margin. Enhanced compressive stress near the margin of glaciers is thought to be responsible for shearing basal debris up to englacial positions. In addition, extensive

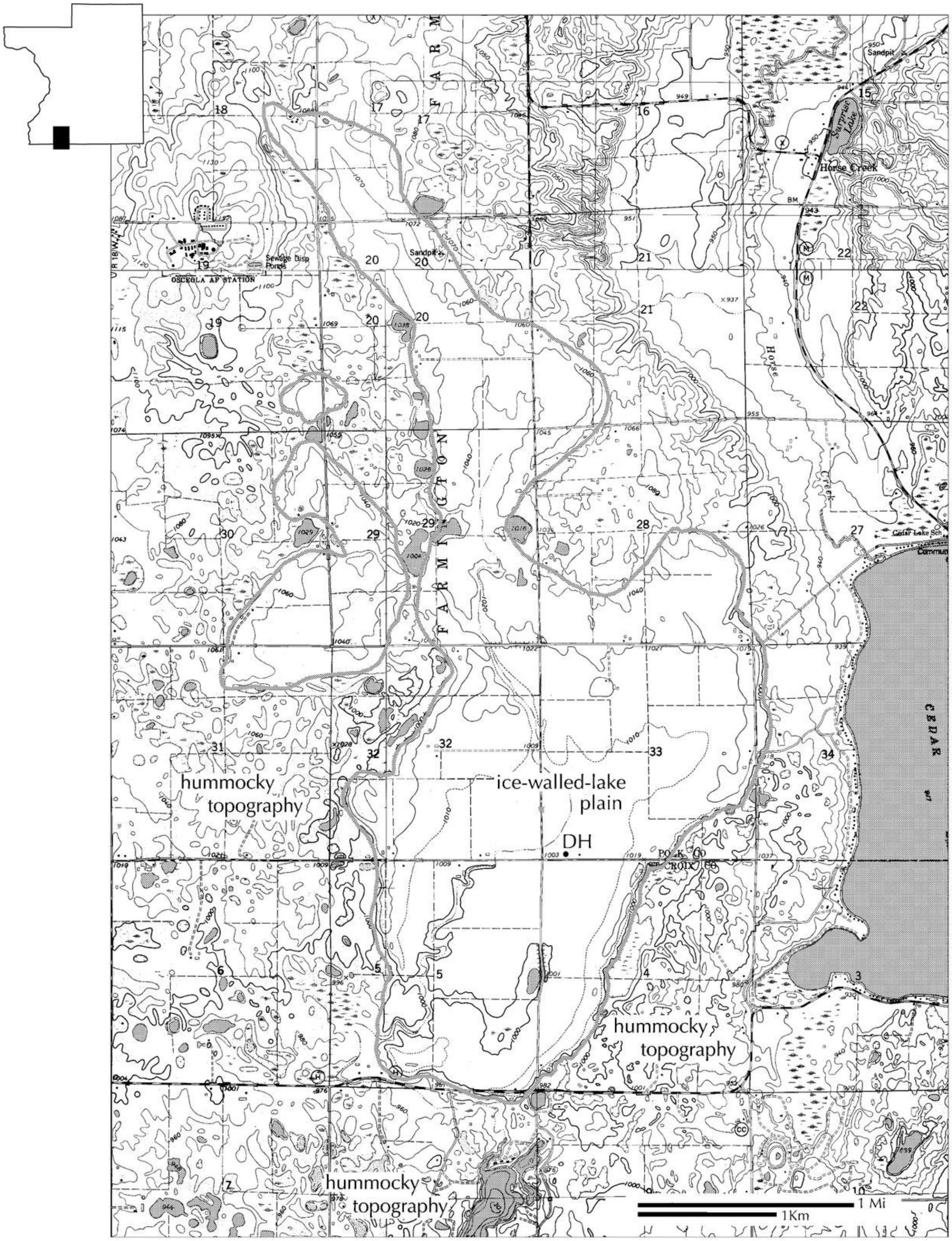


Figure 21. *Parts of New Richmond North, Nye, Osceola, and Somerset North Quadrangles, Wisconsin and Minnesota (U.S. Geological Survey, 7.5-minute series, topographic, 1974, 1978, 1993, and 1974, respectively), showing ice-walled-lake plain on the Polk–St. Croix County line surrounded by hummocky topography. Contour interval is 10 ft, except in the southwestern part, where it is 20 ft. Hummocks in this region contain Sylvan Lake till, gravity-flow deposits, outwash, and lake sediment. Note higher elevation of the rim of the ice-walled-lake plain. DH = location of drillhole depicted in figure 10.*

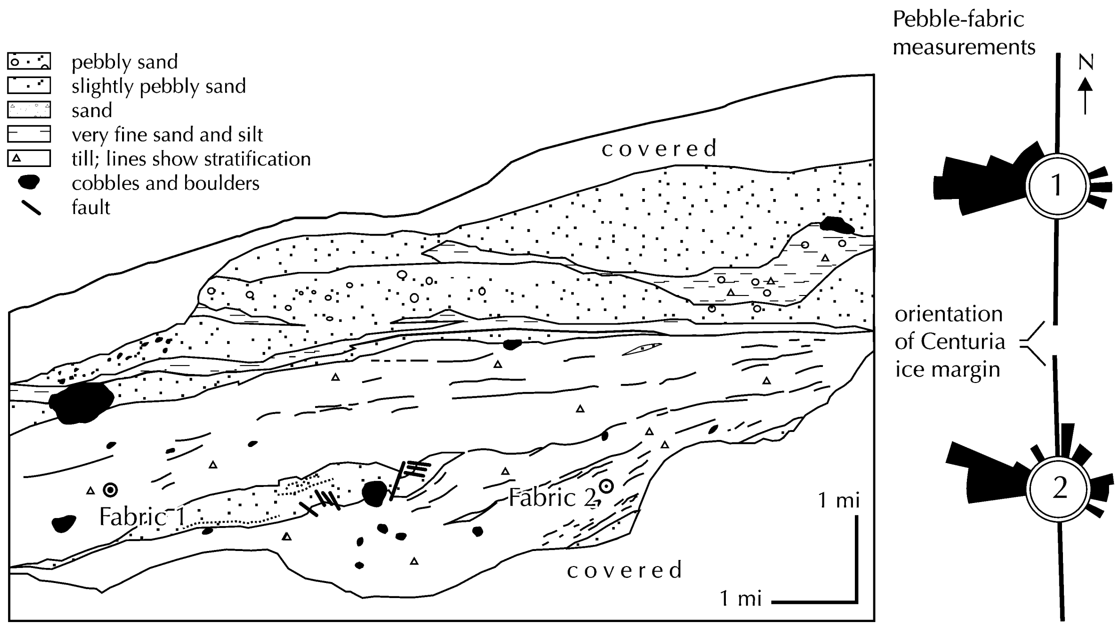


Figure 22. *Sketch of an outcrop in a hummock just east of St. Croix Falls associated with the Centuria Phase (NW¼NW¼SW¼ sec. 28, T34N, R18W). The hummock is composed of till, silt, sand, slightly pebbly sand, pebbly sand, cobbles, and boulders. Two pebble-fabric measurements were from the bedded till at the base of the cut. Note that the pebbles are strongly unimodally oriented and in a direction perpendicular to the Centuria ice margin. Bedding within this lower till consists of subtle color banding and thin (<0.5 cm) sand lenses. The small lens of till-like material in the upper right has variable texture and is interpreted to be a gravity-flow deposit.*

freezing of material at the glacier bed near the margin may occur during surging (Clapperton, 1975) and greatly increase debris content. (See section entitled *Characteristics of the Superior Lobe during the Emerald and St. Croix Phases.*)

Ice-walled-lake and ice-dammed-lake plains

Ice-walled-lake plains form as a result of sedimentation in ice-walled lakes. The plain forms as the surrounding stagnant ice melts and a dish-shaped plateau composed of lake sediment results (fig. 21). The ice-walled-lake plains in Polk County are easily recognizable on topographic maps. These plains support agriculture, which is not possible in the swampy, bouldery, hummock tracts that border the plains. The well preserved shape of the ice-walled-lake plains suggests that little ice was beneath the lakes when they existed. I did not identify any area of pervasively collapsed ice-walled-lake sediment in Polk County; the higher heat capacity of the lake water and convective heat loss in the lake water must have caused most of the ice beneath the lake to melt so that lake sediment was deposited directly on ice-free sediment.

All but two of the nearly 40 ice-walled-lake plains in Polk County (map units **osi** and **nsi**, plate 1) lie within areas of hummocky topography (map unit **ush**, plate 1). Although ice-walled-lake plains can be found throughout the county, the highest concentration of them is in the east-central part of the county between Turtle Lake and McKinley (fig. 8). This band continues eastward into Barron County (Johnson, 1986). Ice-walled-lake plains also characterize Superior Lobe landforms in the Twin Cities area (Meyer, 1985; Meyer and others, 1990).

The ice-walled-lake plains in Polk County range in size from 1 to 13 km^2; typically, they are approximately 2 km^2. The largest lake plain, near McKinley, lies on the border with Barron County. Turtle Lake, Wisconsin, lies on an ice-walled-lake plain that is 9 km^2. The large ice-walled-lake plain pictured in figure 21 is 11 km^2 and lies on the border with St. Croix County southeast of Osceola.

It is clear from their geomorphology that ice-walled-lake plains are stagnant-ice features. Some ice-walled-lake plains cross known former ice-margin positions, indicating that the ice that walled the lake came from two separate advances (for example, the Fox Creek and Deedon Lake ice margins, fig. 8).

Ice-dammed-lake plains form proglacially along a glacier's margin when the glacier impounds water in a proglacial drainage basin. When the Superior Lobe was at the St. Croix margin, water was ponded in three small basins near Clayton in the southeast part of the county (map units **nsi** and **osi**, plate 1). The spillway for these lakes was the South Fork Hay River in the southwestern corner of Barron County.

End moraines and till-covered uplands

Several till-containing broad ridges that can be interpreted as end moraines are at the St. Croix, Deer Park, Island Lake, and Amery ice-margin positions in southeastern Polk County, are parallel to the trend of former ice-margin positions, and are included within map unit **gsn** (plate 1). The ridges are 1 to 2 km wide, can be traced for several kilometers, and have a gently rolling, nonhummocky surface (fig. 18). The ridge at the St. Croix Phase ice-margin limit can be traced through Clear Lake and Clayton for a distance of 7 km. The ridges are cut by tunnel channels in places, indicating that the ridges were formed prior to the cutting of the tunnel channels. Few large exposures exist in these ridges, but Copper Falls till is present in small roadcuts. A gravel pit 2 km north of Clear Lake exposes a thick sequence of sand and gravel below a cap of till. The ridges may contain complex stratigraphy because they represent a significant buildup of sediment from the elevation of the adjacent rolling surface to the south. The ridge at Clear Lake reaches an elevation of 396 m; older till surfaces 2 km to the south reach an elevation of 354 m, suggesting that as much as 42 m of sediment was piled up to form this ridge.

Till-covered uplands other than end moraines elsewhere in the county (map unit **gsn**, plate 1) are gently rolling, nonhummocky surfaces underlain by thick homogeneous till. In places, they display streamlined topography, but no well developed drumlin fields are found in Polk County.

The Spooner Hills

Many upland areas near Polk County's northern border with Burnett County are underlain by Precambrian basalt, but in the northeastern corner and continuing in a band to the northeast lies a line of high-relief hills that contain unlithified sediment. These hills are distinct from any other landscape region in northwestern Wisconsin and represent a landform type not commonly described in glaciated regions (fig. 23). I refer to these hills as the Spooner Hills after the village of Spooner, Wisconsin, which lies in the center of the band of hills.

The Spooner Hills range in area from 1 to 5 km^2 and exhibit relief as high as 60 m. Hilltop elevations in the Spooner Hills generally increase from the northwest to the southeast. They are roughly equidimensional, but a number of them are elongate to the southeast, parallel to the direction of regional ice flow. The regional distribution of the Spooner Hills is shown in figure 24.

Drillholes, exposures, and well constructor's reports show that the Spooner Hills are composed of unlithified sediment,

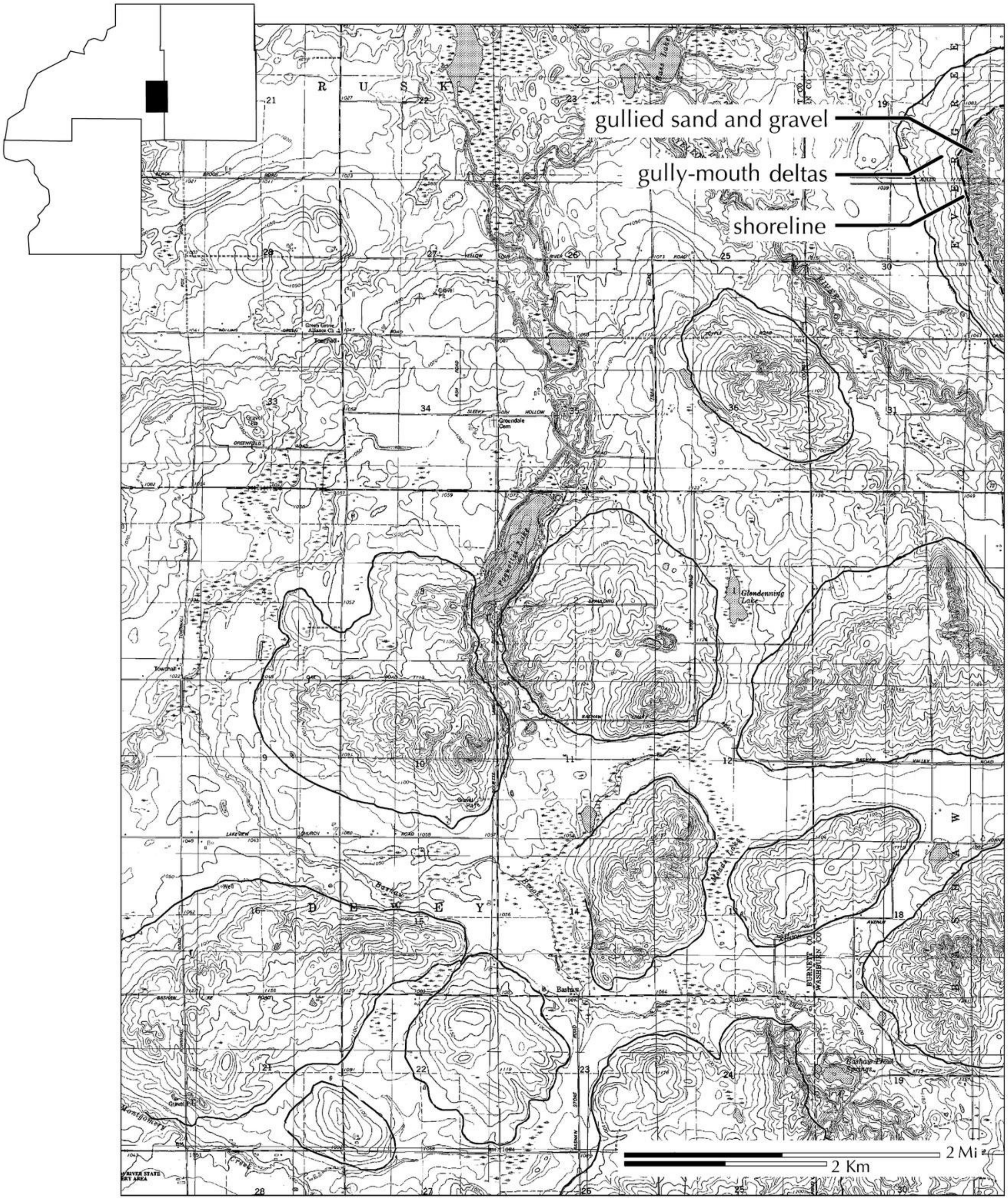


Figure 23. *Part of Poquettes Lake Quadrangle, Wisconsin (U.S. Geological Survey, 7.5-minute series, topographic, 1982), showing the Spooner Hills; the Spooner Hills are outlined. The hill in the northeast part of the map is composed primarily of sand at the surface and shows a well developed shoreline. The gullies in sand above the shoreline were formed when the lake was present. The depth and spacing of the gullies implies that permafrost was present as well. Accumulations at gully mouths below the shoreline are delta-like accumulations that were deposited when the lake was present. It is most likely that the shoreline was cut by glacial Lake Grantsburg, given the elevation of the shoreline. Contour interval = 10 ft.*

including till as well as sorted sediment. Most surface exposures and material from shallow drillholes contain Sylvan Lake till, but samples from a drillhole in northeastern Polk County (NE¼, NE¼, NE¼, sec. 14, T37N, R15W) contained 30 m of slightly pebbly sand. A gravel pit in southeastern Burnett County (SE¼, SE¼, sec. 10, T38N, R14W) exposes several meters of meltwater-stream sediment overlying red sandy loam till that may be Copper Falls or River Falls till. Well constructor's reports from northeastern Polk County show a variety of sequences of unlithified sediment.

The valley floors between the hills are flat, sandy plains, as shown in figure 23, but elsewhere are hummocky with collapsed outwash. Some of the margins of the glacial lakes that existed in the Clam–Yellow River lowland were around the Spooner Hills. Their shoreline features are well developed (fig. 23). Some sandy deposits between the Spooner Hills are likely associated with these lakes.

On the basis of this information, I offer the following hypothesis as an explanation for the formation of the Spooner Hills. Because the hills contain a variety of sediment types representing a variety of depositional environments, and because the sediment may predate the most recent glaciation, it is likely that the Spooner Hills are erosional features. Several lines of evidence suggest that the erosion occurred subglacially. The Spooner Hills are commonly covered with the till of the most recent glaciation and are somewhat streamlined in a direction parallel to the regional ice-flow direction of the most recent glaciation. In addition, the orientation of the band of the Spooner Hills parallels the St. Croix ice margin, suggesting that they are related (fig. 24). The inter-hill valleys form a branching network that, in some places, connects with prominent tunnel channels. I suggest that these valleys were excavated by subglacial meltwater and the tunnel channels represent the outlets for meltwater and sediment. However, this connection cannot be shown convincingly along the entire Spooner Hills chain. The water and sediment were released at the glacial margin and the sediment was deposited proglacially in large outwash fans and outwash plains. In this scenario, the Spooner Hills would have formed when the ice was at the St. Croix ice margin or the Tiger Cat–McKinley ice margin (fig. 24).

Two published descriptions of landforms similar to the Spooner Hills support the suggestion that subglacial meltwater erosion may have created them. Clayton (1986) described till ridges in Portage County, Wisconsin, that have similar characteristics to the Spooner Hills. He suggested that they may have been cut by subglacial meltwater. Booth and Hallet (1993) described hills in the Puget Lowland, Washington, that have a size and shape similar to the Spooner Hills. The hills in the Puget Lowland are among channels that have been interpreted as cut by subglacial meltwater.

Alternatively, the primary form of the Spooner Hills may be a result of preglacial subaerial erosion. Drainage of proglacial lakes dammed up against the Spooner Hills chain may have cut a few of the inter-hill valleys. For a more complete discussion of the Spooner Hills, see Johnson (1999).

Deglacial sequence

The Superior Lobe ice-margin positions shown in figure 8 were drawn on the basis of tunnel-channel–outwash-fan relationships (fig. 18), esker–outwash-fan relationships (fig. 19), distribution of proximal- and distal-outwash facies (fig. 8), end moraines (fig. 18), and the margins of regions of hummocky topography. Each ice margin represents the extent of the Superior Lobe at a point in time,

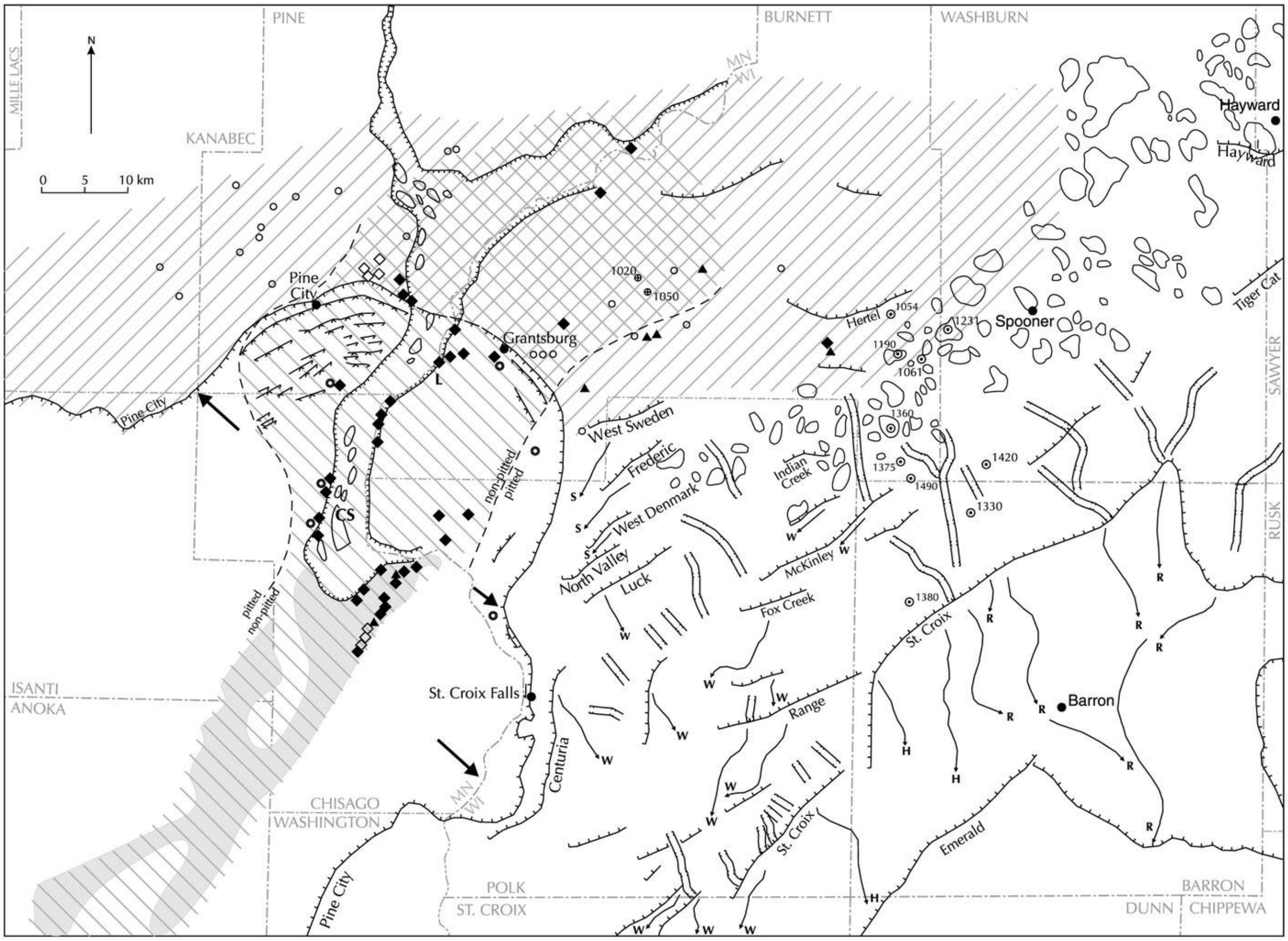


Figure 24. *Part of northwestern Wisconsin and adjoining Minnesota showing features associated with the most recent glacial events. Spot elevations are included to show that elevations increase from central Burnett County to the St. Croix ice margin. On the basis of their relative positions, the Centuria, Luck, Fox Creek, and McKinley ice margins are correlated with the Tiger Cat ice margin of Clayton (1984). Tiger Cat and Hayward ice margins from Clayton (1984) and Attig and others (1985). Emerald, St. Croix, Early Chippewa, and Late Chippewa ice margins are from Johnson (1986). Pine City ice margin in Minnesota is from Cooper (1935) and Hobbs and Goebel (1982). Locations of glacial Lake Grantsburg and glacial Lake Lind varved clay in Minnesota are from Chris Hemstad and M.D. Johnson (unpublished data) and Gary Meyer (Minnesota Geological Survey, written communication). Only tunnel channels in Wisconsin are shown. Extent of the glacial Lake Grantsburg in Minnesota is in part from Cooper (1935). Till fabric measurements in Minnesota from Chernicoff (1983). CS (in eastern Minnesota) = location of Camp Sunrise. L = Lind, Wisconsin.*

but it is not clear whether each ice margin represents a 1) stillstand during gradual ice retreat, 2) a readvance, or 3) an event, such as sudden tunnel-channel drainage, that left geomorphic and sedimentologic evidence. Some named ice-margin positions probably represent readvances because thick deposits of interbedded till and sorted sediment are found in the central part of the county and, if the deposits are all Copper Falls sediment, could have only accumulated through multiple advances.

The lateral discontinuity of several of the ice margins suggests that hypothesis 3 is correct. For example, at the St. Croix ice-margin position in southern Polk County, shown in distribution of buried red and brown laminated lake sediment of Helgesen and Lindholm (1977)

extent of glacial Lake Lind

extent of glacial Lake Grantsburg

ice-flow direction of Grantsburg Sublobe inferred from till fabric

low-relief Grantsburg Sublobe moraines

Kettle River and St. Croix channel with bars on the Chengwatana surface

tunnel channel

boundary between pitted and non-pitted topography

dominant meltwater drainage route
- **R** Red Cedar River
- **H** Hay River
- **W** Willow River
- **S** flows to the southwest

ice-margin position

county boundary

Spooner Hills

outcrop of glacial Lake Grantsburg varved clay

outcrop of glacial Lake Grantsburg varved clay exposed beneath Trade River till

outcrop of glacial Lake Lind varved clay

outcrop of glacial Lake Lind near-shore sediment

1050 location and elevation of glacial Lake Grantsburg wave-washed gravel

1490 selected spot elevations

outcrop of silty Copper Falls till

town

---

figure 13, there are several en echelon segments that could not have formed contemporaneously. The ice-margin position is marked by geomorphic features produced at different times as the ice margin retreated. Similarly, the Centuria, Luck, Fox Creek, and McKinley ice margins (fig. 24) are roughly the same age because their outwash plains grade to a similar level (fig. 16), but they cannot be confidently connected laterally. On the basis of the distribution of the outwash plains, the Centuria margin must be in part slightly older than the Luck margin. Likewise, the Fox Creek margin must be slightly older than the McKinley margin.

Although it is difficult to correlate individual former ice-margin positions with each other in the county, some approximate correlations can be made. The large amount of outwash associated with the Centuria, Luck, Fox Creek, and McKinley ice margins (fig. 8) suggests an increase in meltwater production in the Superior Lobe. Clayton (1984) used a similar large outwash surface and head to identify the Tiger Cat ice margin in Sawyer County (fig. 24). On the basis of the general lateral connection of former ice-margin positions and the similar dynamic events associated with them (increased meltwater production), I suggest that the Centuria, Luck, Fox Creek, and McKinley ice margins correlate to the Tiger Cat ice margin.

In front of the Hayward ice margin (fig. 24) (Clayton, 1984) is a prominent drainage channel that slopes to the west. This drainage could operate only when the Superior Lobe had retreated to some position in Burnett County. Thus, the Hayward ice margin is younger than any ice-margin position in Polk County.

Correlation of ice-margin positions with those to the west in Minnesota is difficult because of the intervening deposits of the Grantsburg Sublobe. The St. Croix Phase ice margin is correlated to the St. Croix moraine in central Minnesota, which was formed during the St. Croix Phase of Wright (1972) and Wright and others (1973). All Superior Lobe ice margins in Polk County are older than the Automba Phase ice margin of Wright (1972) and Wright and others (1973). The Centuria, Luck, Fox Creek, and McKinley ice margins correlate to the Ramsey ice limit in Ramsey and Washington Counties (Patterson, 1992). Mooers (1989, 1990) showed four former ice-margin positions behind the St. Croix moraine of central Minnesota, the youngest of which is likely younger than any ice margin in Polk County. The remaining three are roughly correlative to the younger ice margins in Polk County. If these correlations are correct, ice-retreat rates for the Superior Lobe in Minnesota were nearly 1.5 times faster than for the Superior Lobe in Wisconsin. For a more complete discussion of ice-margin correlations between Wisconsin and Minnesota, see Johnson and Mooers (1998).

As the Superior Lobe ice margin retreated northwestward through the county, the route of meltwater drainage was dominantly toward the southeast into the Willow River system (fig. 24). Beginning with the time the ice was at the North Valley and West Denmark ice margins (fig. 24), meltwater began to flow southwest. When the Superior Lobe ice margin retreated to the West Sweden ice margin, meltwater streams formed an outwash plain that was later partly buried by Grantsburg Sublobe till. Large blocks of stagnant Superior Lobe ice were buried in this outwash and numerous collapse pits later formed. This buried ice did not melt until after the Pine City Phase, indicating that ice remained buried for at least 1,000 years.

A silty till and a younger advance

Till of the Copper Falls Formation that is similar in color and lithology to Sylvan Lake till but siltier (fig. 5) is found in southern Burnett County and eastern Minnesota (fig. 24). This silty till was seen at the base of the glacial Lake Lind varve sequence at the mouth of the Wood River, in material from a drillhole near Sunrise, Minnesota (Gary Meyer, Minnesota Geological Survey, written communication), and in several outcrops along the Sunrise River in Minnesota (Gary Meyer, Minnesota Geological Survey, written communication). In no locality was the silty till found overlying Sylvan Lake till. The finer texture suggests that the Superior Lobe readvanced into glacial Lake Lind early in the history of the lake and incorporated lake sediment into the glacier. A pebble-fabric measurement in this till in southern Burnett County indicates ice movement to the south. Several outcrops of slightly finer-textured till also are found in the northern tier of townships in Polk County, but the sediment is thin and of variable texture, and interpretation is difficult.

If the silty till represents a readvance of the Superior Lobe into the Lake Lind basin, the ice advanced at least to the northern boundary of Polk County. If some of the previously mentioned outcrops in northern Polk County are from this advance, the ice may have advanced at least as far as the Frederic or Indian Creek ice margins (fig. 24).

Permafrost features and ventifacts

Several ice-wedge casts are north of the St. Croix Phase ice-margin limit. One ice-wedge cast was discovered in Polk County during this study on the outwash fan developed in front of the West Sweden ice margin (east-facing roadcut, SE¼SE¼NE¼ sec. 9, T37N, R17W). Because this former ice-margin position is the northernmost ice margin in the county, permafrost conditions must have existed throughout the deglaciation of the county. In addition, one ice-wedge cast is in northwest St. Croix County and several are on Karlsborg Hill in central Burnett County. Permafrost conditions are known to have been present during the St. Croix Phase because ice-wedge casts are developed in Barron County outwash that grades to the St. Croix ice margin (Johnson, 1986). Attig and Clayton (1986) suggested that permafrost ex-

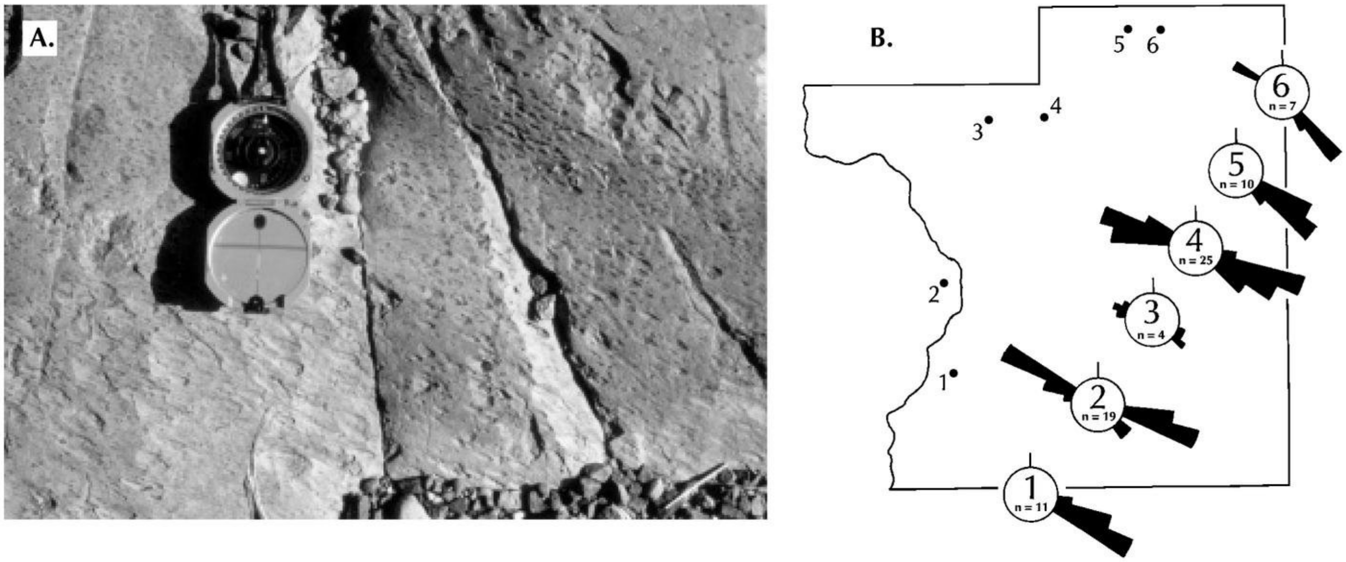


Figure 25. A: *Photograph of ventifacted basalt surface, SE¼NW¼ sec. 18, T36N, R17W. Compass arm points north. Here, vesicular basalt has been pitted by wind from S65°E. Elsewhere at this outcrop, the basalt is amygdaloidal and the ventifacts have a stoss and lee relationship. This outcrop also has ventifacts that show a northwest wind direction.* **B:** *Rose diagrams and locations of ventifacted basalt outcrops in Polk County. Blackened area indicates source of the wind and thus shows winds predominantly from the southeast, but also from the northwest; n = number of measurements. Photograph in A from site 4.*

isted in northern Wisconsin until somewhat after 13,000 years ago.

Gullied terrace scarps are found in places in Polk County and are interpreted to represent geomorphic evidence of permafrost activity (fig. 19). Well developed dendritic gullies in pebbly sand are interpreted to reflect low infiltration rates due to the presence of permafrost. The increased runoff, coupled with movement of the active layer, is responsible for the development of the gullies.

Several basalt outcrops in Polk County bear the marks of wind abrasion. The ventifacted surfaces are distinct from glacially striated surfaces and show a more scalloped form than the straight, glacially formed striations (fig. 25A). Differential erosion of the vesicular to amygdaloidal basalt has developed a stoss and lee relationship that allows inference of wind direction. Measurements from several sites revealed that wind blew predominantly from the southeast (fig. 25B). The freshness of the ventifacts and their close relationship with striated surfaces suggest that they formed after deglaciation. Thorson and Schile (1995) showed that glacial-anticyclonic winds developed during the retreat of the Laurentide Ice Sheet; in western Wisconsin, these would have been southeast winds. I suggest that these winds formed the ventifacts.

Ventifacts are buried beneath beach gravel on Karlsborg Hill in Burnett County. If the ventifacts on Karlsborg Hill are the same age as those on the basalt, and if I am correct in suggesting the beach gravels are from glacial Lake Grantsburg, the wind abrasion of the basalt knobs occurred before or during the advance of the Grantsburg Sublobe and after the Superior Lobe left the northern part of Polk County. The landscape of Polk County following deglaciation would have experienced periglacial conditions with little vegetation to interfere with aeolian transport of abrading silt and sand.

Age

The date of the St. Croix Phase and the advances represented by the other former ice-margin positions of the Superior Lobe in Polk County is not well known, but likely oc-

Table 4. *Comparison of landforms created during the Emerald and the St. Croix Phases.*

Emerald Phase landforms	St. Croix and later phases landforms
few hummocks	many hummocks and ice-walled-lake plains
few collapse depressions	many collapse depressions
—	many tunnel channels, some with eskers as well as the Spooner Hills
few, small outwash plains	extensive outwash plains

curred between 15,000 and 18,500 BP. No radiocarbon dates exist for these events in western Wisconsin because few or no trees would have grown during this period of extensive permafrost.

Wright (1972) and Wright and others (1973) argued that the St. Croix Phase in central Minnesota (which I assume to have been contemporaneous with the St. Croix Phase in western Wisconsin) occurred before 20,500 BP; this date is based on a radiocarbon date from lake sediment overlying the till of the moraine. Clayton and Moran (1982) argued that the lake sediment may be contaminated with older carbon and suggest the St. Croix Phase (their margin W13) occurred around 15,000 BP or as much as a few thousand years earlier. Johnson (1986) adopted Clayton and Moran's rationale and suggested the St. Croix Phase occurred around 15,000 BP.

However, on the basis of the following assumptions, the St. Croix Phase could have occurred as early as 18,500 BP. Assuming reasonable retreat rates, and noting that several readvances of the Superior Lobe may have occurred, it may have taken as much as 2,500 to 3,000 years for ice to retreat from the St. Croix ice-margin position to the center of glacial Lake Lind, where thick varve sequences are found. By adding this figure to the number of varves in glacial Lake Lind (at least 776 varves and perhaps as many as 1,500) and to the age of the Pine City Phase (around 14,000 BP; see section entitled *Pine City Phase*), I conclude that the St. Croix Phase may have occurred as early as 18,500 BP. Indeed, the earliest known appearance of significant amounts of red clay in the terrace sediments of the Mississippi River valley has been estimated at shortly after 18,000 BP. (Arthur Bettis and Edwin Hajic, Iowa Geological Survey, written communications). Because more evidence exists for extensive meltwater activity during the St. Croix Phase than the Emerald Phase, it is likely that this clay represents drainage during the St. Croix Phase.

Characteristics of the Superior Lobe during the Emerald and St. Croix Phases

The landforms left behind during the Emerald Phase of the Superior Lobe are distinct from those formed during the St. Croix and later phases. (See summary in table 4.) Features formed by widespread stagnant ice (hummocks and ice-walled-lake plains) and extensive discharge of subglacial meltwater (tunnel channels, eskers, and outwash plains) dominate the landscape left by the St. Croix Phase, but are absent or rare in the landscape left by the Emerald Phase. I interpret these phases to have occurred during the last part of the Wisconsin Glaciation and that the difference in the landform suites is due to a change in character of the Superior Lobe at the beginning of the St. Croix Phase. I suggest that the Superior Lobe changed from a cold, nonsurging glacier during the Emerald Phase, to a less cold, surging glacier during the St. Croix Phase.

The landforms of the Emerald Phase (table 4), the thin to patchy cover of the Poskin till (deposited during the Emerald Phase), and the presence of well developed permafrost features suggest that the climate was colder during the Emerald Phase than during the St. Croix Phase. The absence of tunnel channels indicates that less subglacial meltwater was present during this phase, perhaps because cold conditions prevented meltwater from draining through the glacier to the bed. Meltwater formed predominantly superglacially, flowed for the most part over clean ice, and had a low sediment load. Ice flowed into pre-Emerald Phase valleys that later became collapse depressions when warming allowed buried ice to melt. Following retreat of the ice margin, permafrost conditions helped to allow rapid development of a dendritic drainage network, and it is likely that much surface till was eroded. The drainage network may have been inherited partly from the pre-Emerald Phase surface because it would not have been deeply buried by Poskin till.

During the St. Croix Phase, large-scale subglacial drainage of the Superior Lobe began and formed tunnel channels and eskers. As mentioned previously, much of the meltwater-stream sediment in the outwash plains of Polk County can be traced to tunnel-channel mouths. Additionally, the Spooner Hills are thought to be the result of erosion by subglacial meltwater. The increase in subglacial meltwater features is accompanied by the presence of widespread stagnant ice features.

Johnson and Savina (1987) suggested that the Superior Lobe surged during the St. Croix and later phases, and Clayton and others (1985) suggested that many lobes of the Laurentide Ice Sheet surged. Increased subglacial discharge of meltwater is associated with surging (Kamb and others, 1985), and surging can leave large amounts of stagnant ice that melts to form hummocks (Wright, 1980). Clapperton (1975) suggested that large amounts of debris are frozen on to the base of the glacier during surging. A thick, basal, debris-rich layer in a mass of stagnant ice would produce high-relief hummocks like those in Polk County (map unit **ush**, plate 1). Surging is a periodic characteristic of glaciers; the size and geometry of the tunnel channels indicate that they operated only for a short time and that they were not all operating at the same time (Attig and others, 1989; Patterson, 1994).

On the other hand, the hummocks may simply indicate cold conditions rather than surging. Many researchers have suggested that hummocks are produced by nontemperate glaciers (glaciers with ice colder than 0°C) (Boulton, 1972; Paul, 1983; Möller, 1987; Sollid and Sørbel, 1988; Attig and others, 1989; Mooers, 1990). These authors have described freezing on of debris at the base of the glacier as meltwater generated where the bed that is at 0°C moves subglacially toward the margin and encounters ice colder than 0°C. This process produces a thick, basal, debris-rich zone. The margin of the cold glacier stagnates during melting, and the melting of the debris-rich ice produces hummocky topography. Evidence of permafrost in Polk County suggests that the hummocks may simply indicate a nontemperate glacier, and not necessarily a surging glacier.

It is not clear from evidence in Polk County whether the water that cut the tunnel channels melted from the bed or from the surface of the glacier. Wright (1973) stated that tunnel channels formed under the Superior Lobe because subglacial meltwater was held by a frozen margin of the glacier. Mooers (1989) argued that the Superior Lobe was temperate and that the tunnel channels indicate that meltwater from the surface of the glacier reached the glacier bed. Gustavson and Boothroyd (1987) documented a surficial source for subglacial meltwater on the temperate Malaspina Glacier, Alaska. The presence of ice-wedge casts behind the St. Croix Phase ice-margin limit suggests that the ice surface would have been well below 0°C and that little surface meltwater would have reached the glacier bed. How-

Figure 26. *Varved silt and clay of glacial Lake Lind from an outcrop along the Wood River, southwest Burnett County. Dark layers are clay and represent deposition in glacial Lake Lind during winter; light layers are silt and represent summer deposition. Approximately 13 years of sedimentation are shown here. Some bioturbation is evident at the tops of clay layers.*

ever, cold conditions were present during the Emerald Phase when no or few tunnel channels were formed.

I suggest that climate supported permafrost conditions during the Emerald and St. Croix Phases, but was gradually getting warmer. Ice-wedge casts outside the Emerald Phase ice-margin limit are numerous and well developed (Johnson, 1986); those behind the St. Croix Phase ice-margin limit are few and less well developed. During the St. Croix Phase, even though permafrost conditions were present, surface meltwater began to find pathways to the glacier bed. The presence of increased water at the bed caused the lobe to surge and tunnel channels to form, and left widespread stagnant ice.

Glacial Lake Lind

Thick, varved sediment, stratigraphically beneath sediment of the Trade River Formation in the St. Croix River valley, is evidence for a long-lived glacial lake predating the advance of the Grantsburg Sublobe and glacial Lake Grantsburg (fig. 26). The reddish-brown lake sediment was first described by Berkey (1905) and has been studied by several geologists (Grout, 1910; Hansell, 1930; Cooper, 1935; Wright and others, 1973). Berkey (1905) interpreted the laminated silt and clay couplets to represent annual layers deposited in a glacial lake, and, by extrapolation from exposures and thicknesses known from drillholes, suggested that nearly 1,700 years of sedimentation had occurred. He also recognized that the lake sediment was overridden by a glacier during a later advance. Hansell (1930) did not find till overlying the red clay and silt and thus believed the lake sediment to have been deposited in a large postglacial lake that he called Lake Barrens. Cooper (1935) and Wright and others (1973) considered the red varves to represent the initial deposits in glacial Lake Grantsburg. They suggested that as the Grantsburg Sublobe advanced from the southwest, it dammed the St. Croix River valley and created a lake in which the varved silt and clay were deposited.

On the basis of outcrops and drillhole records, it is clear in Polk County that the varved silt and clay are beneath Trade River till and thus were deposited in a glacial lake that predates the advance of the Grantsburg Sublobe (fig. 27). The coarsening-upward sequence at the top of the red silt and clay and the extensive overlying sand (see section entitled *Copper Falls Formation*) indicate that the lake filled in prior to the advance of the Grantsburg Sublobe during the Pine City Phase. These observations make it clear that the red silt and clay were deposited in a lake that was not connected to glacial Lake Grantsburg. I have given the name glacial Lake Lind to the lake in which this sediment was deposited (Johnson, 1992; Johnson and others, 1999). The rural locality of Lind, (fig. 24) lies approximately in the center of the region covered by glacial Lake Lind.

The extent of glacial Lake Lind shown in figure 24 is based on the following four lines of evidence:

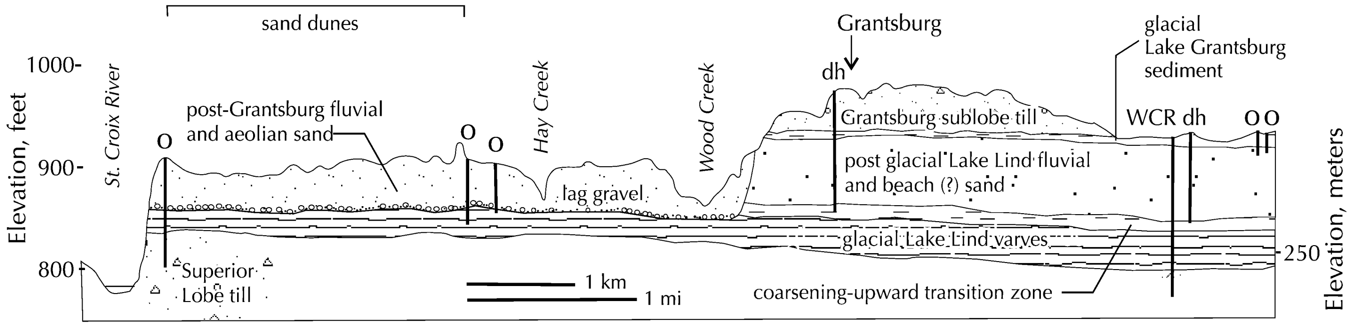


Figure 27. *East–west cross section from St. Croix River through Grantsburg, Wisconsin. Vertical lines show source of information; o = outcrop, dh = drillhole, WCR = well constructor's report. The geology shown between outcrops, drillholes, and well constructor's reports is inferred. Topography from Bass Creek and Grantsburg Quadrangles, Wisconsin–Minnesota (U.S. Geological Survey, 7.5-minute series, topographic, 1983 and 1982, respectively).*

- Outcrops of red varved silt and clay. The distribution of outcrops of red varves is shown in figure 24. Several exposures along the Snake and Sunrise Rivers in Minnesota reveal varves that have summer layers composed of sand in the form of oscillation ripples.
- Distribution of nearshore sediment. Thick, convoluted silt deposits are basinward of the sandy, rippled varves. These features suggest nearshore and/or rapid sedimentation conditions and are distinct from varve exposures found elsewhere in what would have been the deeper part of glacial Lake Lind. They are also distinct from varves directly above till and interpreted to have been deposited close to the retreating ice margin. Sediment representing "marginal facies" of the red laminated silt and clay along the Snake River was also noted by Berkey (1905).
- Distribution of buried red and brown laminated lake sediment. Helgesen and Lindholm (1977) found extensive red and brown laminated lacustrine clay under the Anoka Sand Plain in east-central Minnesota. Several outcrops of varved red silt and clay are within the region they outlined, suggesting that their lake sediment is Lake Lind sediment. If this correlation is accurate, glacial Lake Lind extended to the southwest as far as the present-day course of the Mississippi River.
- Extent of collapse pits in the St. Croix valley. The distribution of collapse pits within Polk County and the surrounding region can be explained by the presence of glacial Lake Lind and may in turn help define the lake's extent (see fig. 24). Lake sediment, as outlined above, is distributed within a region in which there are few or no collapse pits. However, there is much evidence for collapse pits outside the area containing Lake Lind sediment in Minnesota and Wisconsin, and almost all the collapse pits were caused by the melting of buried Superior Lobe ice. I suggest that permafrost conditions kept buried ice intact except where the land was covered by glacial Lake Lind. The high heat capacity of the lake water and convective currents would have allowed permafrost and buried ice to melt beneath the lake. In addition, ice retreating into glacial Lake Lind may have calved and not been buried. The buried ice remained intact in those areas outside of Lake Lind until the ice melted after the Pine City Phase. Thus, the western and eastern limits of glacial Lake Lind are marked by the boundary between pitted and nonpitted areas (fig. 24).

The northern extent of glacial Lake Lind is not known, although its northern edge throughout much of its existence was likely the margin of the Superior Lobe. More varves are exposed in the central part of glacial Lake Lind (as many as 776 varves at the type section) than in the northern part (170 varves at St. Croix State Park, Minnesota), suggesting that the lake expanded in the wake of the retreating glacier.

The extent of the glacial Lake Lind sediment outlines a buried lowland extending to the southwest from the northwest corner of Polk County to the Twin Cities. This lowland is likely the course of the St. Croix River prior to the Emerald Phase. Glacial Lake Lind formed when the Superior Lobe melted back and revealed the basin. Correlation of varve thicknesses among several sites indicates that the Superior Lobe retreated about 200 m/yr (Addis and others, 1996; Johnson and others, 1999). Drainage to the southwest was blocked by Superior Lobe stagnant ice, but it is likely that its outlet was in the southwest part of the lake. When the outlet stream cut through the stagnant ice, it was probably superposed on a bedrock high rather than excavating the valley of the ancestral St. Croix River. There is a possibility that the outlet was south, along the present-day course of the St. Croix River and perhaps along the Horse Creek Channel, but this contradicts cross-bed data that show southwesterly currents in sands that filled the lake (Hansell, 1930), and the elevation of the Horse Creek Channel head (between 305 and 332 m) seems too high for glacial Lake Lind. (See section entitled *Horse Creek Channel.*)

Although Berkey (1905) estimated that almost 1,700 years were represented by the Lake Lind sediment, this number was reached through extrapolation. Exposures and drillhole logs show that varve thickness varies considerably, and layers of thick, slumped silt and clay can interrupt the varve sequence, making accurate extrapolation impossible. The 776 varves at the type section along the North Branch Sunrise River (NW¼NE¼NW¼ sec. 19, T35N, R20W) are the greatest number of varves counted from the Lake Lind silt and clay and suggest that the lake lasted at least 776 years. This is a minimum length of time for the duration of glacial Lake Lind because a part of this cut was covered, the base was below river level, and the top had been truncated by erosion. On the basis of varve-thickness correlations, it is likely that glacial Lake Lind lasted at least 1,000 years (Addis and others, 1996; Johnson and others, 1999).

The lake-level elevation of glacial Lake Lind is not well known, although it is probably approximately 280 m in the study area. All exposures of glacial Lake Lind varves are below an elevation of 271 m. Rippled varves along the Snake River interpreted to represent nearshore sedimentation (and likely shallow water) lie at an elevation of 280 m. At several localities in eastern Minnesota and western Wisconsin, sand that has discrete horizontal laminations of heavy and light minerals overlies the varved silt and clay. The horizontal laminations were found at elevations of 274 to 277 m in material from a drillhole near Grantsburg, Wisconsin (fig. 27), and at 258 m along Goose Creek near Harris, Minnesota. This facies may represent beach sediment and thus indicate lake-level elevation. The variations in elevation likely indicate warping of the sediment due to postglacial isostatic rebound as well as a probable drop in lake level as a result of outlet incision several times during the history of glacial Lake Lind. Some sand above the varved sediment exposed along Goose Creek in Minnesota contains clay clasts eroded from glacial Lake Lind sediment, indicating a lower lake level and clay erosion.

As glacial Lake Lind filled, a sand plain prograded from western Wisconsin to the southwest along the axis of the lake. Because few data exist from Anoka County where the lake would have filled last, it is not known whether the lake completely filled prior to the advance of the Grantsburg Sublobe. It is clear, however, that glacial Lake Lind ceased to exist in western Wisconsin and eastern Minnesota before the Pine City Phase. The low-gradient, southwest sloping, sandy fluvial plain that developed following the deposition of the varved sediment in glacial Lake Lind was likely the pre-Pine City Phase location of the St. Croix River, which drained much of northwestern Wisconsin and east-central Minnesota.

The age of glacial Lake Lind is not known. On the basis of the age of the Pine City Phase and the number of varves in the Sunrise Member, glacial Lake Lind must have formed by 14,800 BP, but this is a minimum date and glacial Lake Lind probably formed earlier.

Pine City Phase

At some time after the filling of glacial Lake Lind, the Grantsburg Sublobe advanced, traveled approximately 110 km to the northeast along the axis of the former glacial Lake Lind basin, and stopped near what are now the locations of Pine City, Minnesota, and Grantsburg, Wisconsin (fig. 24). This advance was referred to as the Pine City Phase by Wright (1972) and Wright and others (1973). The Superior Lobe was still within the St. Croix drainage basin at this time, but its exact location is not clear.

The Grantsburg Sublobe was an offshoot of the Des Moines Lobe, and the till left by it in western Wisconsin and eastern Minnesota is nearly identical to that deposited in central Minnesota (New Ulm Till, described by Matsch, 1972) by the main body of the Des Moines Lobe. Through measurement of till fabric, Chernicoff (1983) was able to show that ice-flow direction was to the northeast in the center of the lobe and perpendicular to the margin along the edges of the lobe. Because the till has a strong fabric, it is likely that the till was deposited subglacially beneath the Grantsburg Sublobe. In northwestern Polk County, above the limit of glacial Lake Lind, the Grantsburg Sublobe advanced across a part of a Superior Lobe outwash plain. The flat to pitted shape of the till plain and the gentle southerly dip of the till–outwash contact reveal the shape of the buried outwash plain (fig. 16).

The Pine City Phase ice-margin limit crosses the Polk County line near Atlas and stretches to the southwest, running east of Cushing and west of Eureka Center. In this region, the margin is not expressed geomorphically, but can be clearly mapped by using the outer margin of the Trade River till sheet. Farther south, the margin turns to the southeast and is marked by a well developed end moraine that crosses Wisconsin Highway 87 approximately 7 km north of St. Croix Falls (sec. 36, T35N, R19W). Between the moraine in sec. 36 and St. Croix Falls, the margin is difficult to trace, primarily because it was against the west side of the zone of stagnant ice associated with the Superior Lobe's Centuria margin; it is also close to the edge of the St. Croix River valley where water flowing in the Lake Superior spillway, postglacial fluvial erosion, and mass wasting could have removed much of the Grantsburg deposits. A second end moraine and several patchy outcrops of Trade River till are within St. Croix Falls (E½ sec. 19, T34N, R18W).

South of St. Croix Falls, I believe that the margin was embayed around the basalt knob in sec. 6, T33N, R18W. (See argument in section entitled *Striations and grooves*.) Trade River till crops out in a few places on the flanks of this basalt knob. To the south, the ice margin is clearly marked by an outwash head at the west end of the valley running east from Dresser. Farther south, the ice margin in Polk County is along the eastern and southern edges of the Osceola bench (fig. 2). I found only one outcrop of Trade River till on the Osceola bench, although Chamberlin (1905) showed that Grantsburg till covers parts of this surface, and Muldoon and others (1990) found Trade River till in material from a drillhole on this surface, indicating that this surface was cut before the advance of the Grantsburg Sublobe.

The Trade River till in Wisconsin and Minnesota is beneath an extensive till plain that features a few low-relief ridges that may represent end moraines. These ridges, best developed in Minnesota near Pine City, are arcuate and concentric to the shape of the maximum ice-margin limit (fig. 24). The ridges are 0.5 to 1.0 km apart, have relief of 3 to 30 m, and are composed of till. It is likely that these ridges were formed near the margin of the Grantsburg Sublobe during ice retreat. An end moraine near Cushing (sec. 25 and 35, T36N, R1W) contains some Trade River sediment, but is composed primarily of Copper Falls stream sediment. It is likely that this ridge was formed by thrusting of the Grantsburg Sublobe; this thrusting pushed Copper Falls sand and gravel upward from the subjacent meltwater deposits.

In Polk County, the deposits of the Pine City Phase covered by the Grantsburg Sublobe collapsed in places because of the melting of buried Superior Lobe ice blocks. The relief of these pits in many places exceeds the thickness of the Trade River till sheet.

Chernicoff (1983) suggested that the margin of the Grantsburg Sublobe was frozen, but the glacier bed behind the margin was at the pressure-melting point. He interpreted the banded, red zone at the base of the Trade River till unit, common in the Twin Cities area (Stone, 1966) and at the type section (see appendix), to represent freezing-on of Superior Lobe till at the subglacial boundary between the frozen and the melting zones under the Grantsburg Sublobe. If this advance occurred 14,000 BP, permafrost was likely present (see Attig and Clayton, 1986). Permafrost gullies associated with glacial Lake Grantsburg shorelines (fig. 23) indicate permafrost was present when the lake, and thus the Grantsburg Sublobe, was present. However, ice-marginal lakes existed at the margin of the lobe, and outcrops of Trade River till overlying lake sediment (fig. 24) show that the ice would have been advancing into the lake. In this case, permafrost would have been present only along those parts of the margin that were above the lake level.

The Pine City Phase is marked by very few meltwater-stream deposits. Meltwater deposits are not extensive (map unit **stv**, plate 1). Outwash plains of a size similar to those deposited by the Superior Lobe did not develop because the debris in the Grantsburg glacier contained less sand, the glacier occupied the drainage basin for a short time, ice-dammed lakes formed at its margin, and drainage may have been, in part, through the ice. The only deposit of outwash containing abundant rock types that are indicators of the Grantsburg Sublobe (dolomite and shale) is at the head of the Horse Creek Channel (secs. 8, 16, and 17, T33N, R18W). Younger terrace deposits in Polk County contain these indicators, but in smaller proportions, indicating dilution of Grantsburg Sublobe debris with local material.

Ice-marginal channels are present but not extensive along what was the ice-margin limit of the Grantsburg Sublobe in Polk County. They are best developed in Eureka Township (T35N, R19W), where flow direction was to the south. The sequence of three ice-marginal channels in secs. 24, 25, 35, and 36 of this township shows that some meltwater flowed to the south along the ice margin as the ice retreated.

The characteristics and number of varves in proglacial Lake Grantsburg as well as beneath Trade River till suggest that it took the Grantsburg Sublobe approximately 15 to 20 years to advance from the Twin Cities area to the Pine City margin; this implies advance rates of approximately 5.0 to 7.5 km/year (Johnson, 1994; Johnson and Hemstad, 1998). The 75 thick gray varves beneath the glacial Lake Grantsburg lake plain indicate that the ice stood at the Pine City margin for about 75 years (Johnson, 1994; Johnson and Hemstad, 1998). These thick varves are overlain conformably by 19 red varves, which I interpret to show that the Grantsburg glacier had begun its retreat and the bulk of the gray sediment to the lake was cut off, perhaps diverted southerly. Cooper (1935) came to a similar conclusion, but for different reasons: "The weakness of [the Grantsburg Sublobe's] terminal deposits indicates that maximum extension was followed almost immediately by the initiation of decline."

In addition to forming glacial Lake Grantsburg (see next section), the Grantsburg Sublobe dammed several other tributaries and formed lakes. Sedimentation in these lakes produced the five ice-dammed-lake plains in the county represented by map unit **oti** (plate 1). The plains that remain from these lakes are around 305 m in elevation (fig. 16). (The presence of these lake deposits indicates that the valleys west of Frederic and Milltown were incised by the time of the Pine City Phase and were not significantly deepened afterwards.) Gradual retreat of the Grantsburg Sublobe is indicated by a later ice-dammed-lake plain that formed against the ice margin when it stood near Cushing (map unit **oti**, secs. 25, 35, and 36, T36N, R19W, plate 1). The ice-dammed-lake plains are surrounded by collapse topography, making it difficult to identify the lake outlets.

The Grantsburg Sublobe remained active throughout its retreat. This idea is supported by the few collapse features present, which indicate that large areas of stagnant ice, ice-dammed lakes along the margin as the ice retreated, ice-marginal channels along the ice margin as ice retreated, and many ridges, which may represent end moraines, were formed. This was thus not a glacier that advanced to its maximum position and stagnated in place.

The Pine City Phase occurred prior to 12,000 BP; wood overlying Trade River till is approximately 12,000 years old (Gary Meyer, Minnesota Geological Survey, written communication; Wright and Rubin, 1956). Wright (1972), Wright and others (1973), and Clayton and Moran (1982) suggested the Pine City Phase is the same age of the Split Rock Phase of the St. Croix Phase, which Wright (1972) and Wright and others (1973) considered to be around 16,000 years old and which Clayton and Moran (1982) considered to be approximately 12,300 years old. These authors based their correlations on the interpretation that the sand plain underlying Hinckley in eastern Minnesota is a delta that formed in Lake Grantsburg. Wright and others (1973) recognized that a part of the Hinckley surface is an outwash plain, but suggested that farther east, the outwash plain became a delta "at a point now deeply dissected by the St. Croix River." The surface gradient of the Hinckley surface is similar to outwash-plain gradients, and exposures in the Hinckley surface reveal medium-grained, cross-bedded pebbly sand and slightly pebbly sand throughout the length of the surface. A deltaic deposit should show more sorting along the axis of the deposit, including a smaller gravel fraction in the distal parts. This characteristic is not present on the Hinckley surface. Furthermore, no stratigraphic evidence shows that the Hinckley surface formed during Lake Grantsburg's existence. On the basis of these observations, I do not consider it valid to use the Hinckley surface to correlate Lake Grantsburg with the Split Rock Phase. The Hinckley surface is most likely an outwash plain related to the Superior Lobe, but its stratigraphic position is unclear.

The simplest interpretation is that the Pine City Phase is the same age as the well dated Des Moines Lobe advance to the Bemis margin in Iowa around 14,000 BP. (See Clayton and Moran, 1982, for a summary of the dates.) The reasons to accept this age, as suggested by Howard Mooers (University of Minnesota–Duluth, verbal communication) are the following:

1) The maximum extent of the glacier in Iowa would indicate the greatest thickness of ice in Minnesota, and ice should have reached its maximum extent in the Grantsburg Sublobe at the same time.
2) Wright (1972) suggested that the Grantsburg Sublobe is younger than the Bemis date because Grantsburg ice was held back by thick, stagnant, debris-rich ice left by the Superior Lobe. Only after some of the Superior Lobe ice melted was the Grantsburg Sublobe able to advance northeast. However, the Des Moines Lobe was able to flow over thick, stagnant, debris-rich ice in the Alexandria moraine, presumably during the advance to the Bemis margin. This observation does not prove that the Grantsburg Sublobe advanced at 14,000 BP, but it tends to weaken the Superior-stagnant-ice-dam hypothesis.
3) Later advances, such as the advances to the Altamont and Algona ice-margin positions, moved parallel to the ice margin rather than perpendicular to it.

To these suggestions one could add that geomorphically, the Grantsburg Sublobe landforms and sediment (end moraines, till plains, basal till) are more similar to the Bemis landforms and sediment (end moraines, subglacial minor moraines, basal till) than to the Algona landforms and sediment (hummocky topography, sediment-flow deposits).

Glacial Lake Grantsburg

The advancing Grantsburg Sublobe dammed the southwesterly draining St. Croix River and created glacial Lake Grantsburg (Cooper, 1935). Glacial Lake Grantsburg did not extend into Polk County; the extent shown in figure 24 represents the suggested extent of the lake when ice stood at the Pine City margin. The distribution is based on the extent of glacial Lake Grantsburg varved sediment (Falun Member of the Trade River Formation; see appendix) and on shoreline elevations in Burnett County, Wisconsin, and Pine and Kanabec Counties, Minnesota. An accurate depiction of Lake Grantsburg's extent is not possible because 1) shorelines are not well developed at the lake's northern boundary, 2) nearshore sediments are difficult to identify, 3) sediment distribution is patchy, and 4) the lake's edge probably was in regions underlain by Superior Lobe buried ice, which later melted and would have collapsed shoreline features.

It is clear that glacial Lake Grantsburg formed almost immediately as the Grantsburg Sublobe advanced and dammed the southwesterly flowing St. Croix River because lake sediment underlies the Trade River till in several locations (fig. 24). I suggest that in this initial stage of the lake, the lake level rose to the level of Superior Lobe outwash surfaces in the area of Wild River State Park, Minnesota, and Wolf Creek and Cushing, Wisconsin. It may have been at this time that the present-day course of the St. Croix River was first occupied. As the ice continued to advance, it eventually blocked this outlet, at which point the lake would have risen significantly in elevation.

Glacial Lake Grantsburg lasted for about 80 to 100 years. Material from a backhoe pit in eastern Pine County, Minnesota, 6 km north of the Pine City ice-margin limit, revealed a section of glacial Lake Grantsburg sediment that contained 82 varves. Five to ten thin red clay laminations beneath these 82 varves may be varves deposited in the initial stage of the lake and may represent the time when the glacier first began to advance. The 75 varves in the central part of the sequence are thick and dominated by gray colors. These varves represent deposition in the deeper phase of the lake when the Grantsburg Sublobe was at its maximum position. Parts of the winter-clay layer are red, indicating that the lake received some sediment from the Superior Lobe or from Superior Lobe deposits. The uppermost 19 varves are dominated by red clay winter layers with thin gray summer layers, suggesting that the Grantsburg Sublobe had begun to retreat, the source of gray sediment was cut off, and glacial Lake Grantsburg received mostly sediment from the Superior Lobe, lying at some unknown distance to the north (Johnson, 1994; Johnson and Hemstad, 1998).

The elevation of glacial Lake Grantsburg is not precisely known. Cooper (1935) concluded that the evidence for the elevation of the lake's shoreline ranges from 320 to 335 m. Beach gravel on Karlsborg Hill in Burnett County, likely deposited in Lake Grantsburg, is at elevations of 311 and 320 m (fig. 16). Shoreline features in eastern Burnett County are between elevations of 332 and 354 m (for example, fig. 23). Some of these shorelines were probably cut by glacial Lake Grantsburg, but some of the higher ones may have been cut by smaller ice-marginal lakes that existed along the Superior Lobe margin as it melted back.

Locating the drainage of glacial Lake Grantsburg has been a problem for many years; no obvious outlet is present. Cooper (1935) suggested that the drainage shifted as the ice advanced and was sometimes on top of the ice. When the ice was at the Pine City margin, Cooper suggested that "[e]vidently the flow must have followed the depression between ice and moraine, and very probably to a considerable degree it traveled upon the ice itself—which will explain in part at least the lack of satisfactory local evidence of its presence."

The lake must have had an outlet. Rudimentary calculations of basin size, precipitation rates, and melting rates suggest that the lake would have filled in just a few years. Because of the topography, it seems most likely that the water flowed around the eastern edge of the glacier as it stood at the Pine City margin. However, there is no geomorphic evidence for this. No channel is present along the trace of the former ice-margin position, although several smaller ice-dammed lakes were present, indicating that through-flowing drainage did not exist. Alternative explanations include the following, but neither of these is fully satisfactory:

- Drainage was around the eastern edge of the glacier as it stood at the Pine City margin, but the ice advanced a short distance just before overall retreat began. This would have buried the outlet and would not have allowed sufficient time for a newer outlet to have developed. Because the Trade River till is relatively thin, it seems likely that such a large channel would be a palimpsest today and detectable.

- Drainage was through the ice or under the ice and flowed south out of the glacier near Osceola. No evidence would remain of this outlet after disappearance of the ice.

However the lake drained, the drainage was most likely to the south. Wright and others (1973) and Bruck (1979) suggested that meltwater from glacial Lake Grantsburg may have reached the area of Dresser and cut the Horse Creek Channel; however, I consider this unlikely for reasons explained below.

The Horse Creek Channel

One of the most spectacular and unique features in Polk County's landscape is the large valley known as the Horse Creek Channel (Bruck, 1979) (fig. 28), which runs from Dresser, generally to the south, through Somerset, and to the valley of the St. Croix River. The several streams and lakes along the bottom of the channel include Lotus Lake, Behning Creek, Horse Lake, Horse Creek, Cedar Lake, Cedar Creek, and the Apple River, which enters the valley at Star Prairie. The valley is 45 km long and is nearly 50 m deep near its head at Lotus Lake, steadily decreasing to about 9 m near Somerset (fig. 29). Similarly, the cross-sectional area of the valley decreases from almost 40,000 m^2 at the head to approximately 10,000 m^2 at the mouth.

The origin of the channel is not clear, but several comments can be made about it that narrow the possibilities. The valley is clearly an erosional feature, it is in the shape of a channel, and it bears a marked resemblance to other known glacial-lake spillways in the Midwest. It is in places about the same size as the St. Croix meltwater channel, which was cut by spillway water from Lake Superior when it stood at higher levels. (By comparison, the cross-sectional area of the spillway valley of glacial Lake Agassiz is 100,000 to 200,000 m^2 in places.) A large meander bend is at the head of the Horse Creek Channel, whose wavelength is approximately 3,300 to 3,800 m. Leopold and others (1964) showed that streams with wavelengths of this size are cut by streams with discharge between 2,500 and 4,000 m^3s^{-1}. This suggests drainage by a large body of water or by a smaller body of water that drained over a short time.

The channel truncates the outwash plain that grades to the Centuria ice-margin limit of the Superior Lobe and thus must postdate that event. The channel also contains Trade River gravel with easterly dipping crossbeds near the outwash head at Dresser (fig. 29). (Oddly, dolomite and shale were not found in the many gravel pits down-valley in the bottom of the channel.) The channel must have been cut before or while the Grantsburg Sublobe was at the Pine City ice-margin limit. Several features show that buried ice was still in existence when the valley was cut. (Note the eskers near Lotus Lake and the kettle lakes, Horse and Cedar Lakes, on plate 1.) The bottom of the channel west of Somerset is pitted in places as well.

The mouth of the Horse Creek Channel is developed in dolomite and is graded to a level in the St. Croix River valley 58 to 67 m above the St. Croix River. This indicates that the St. Croix River gorge was not cut until at least after the Centuria Phase and likely not until after the Pine City Phase.

The timing constraints indicated by the geomorphic relationships indicate that the Horse Creek Channel was cut while glacial Lake Lind and glacial Lake Grantsburg existed. It is difficult, however, to trace a spillway from either of these two lakes to the head of the Horse Creek Channel.

It is impossible to know with certainty

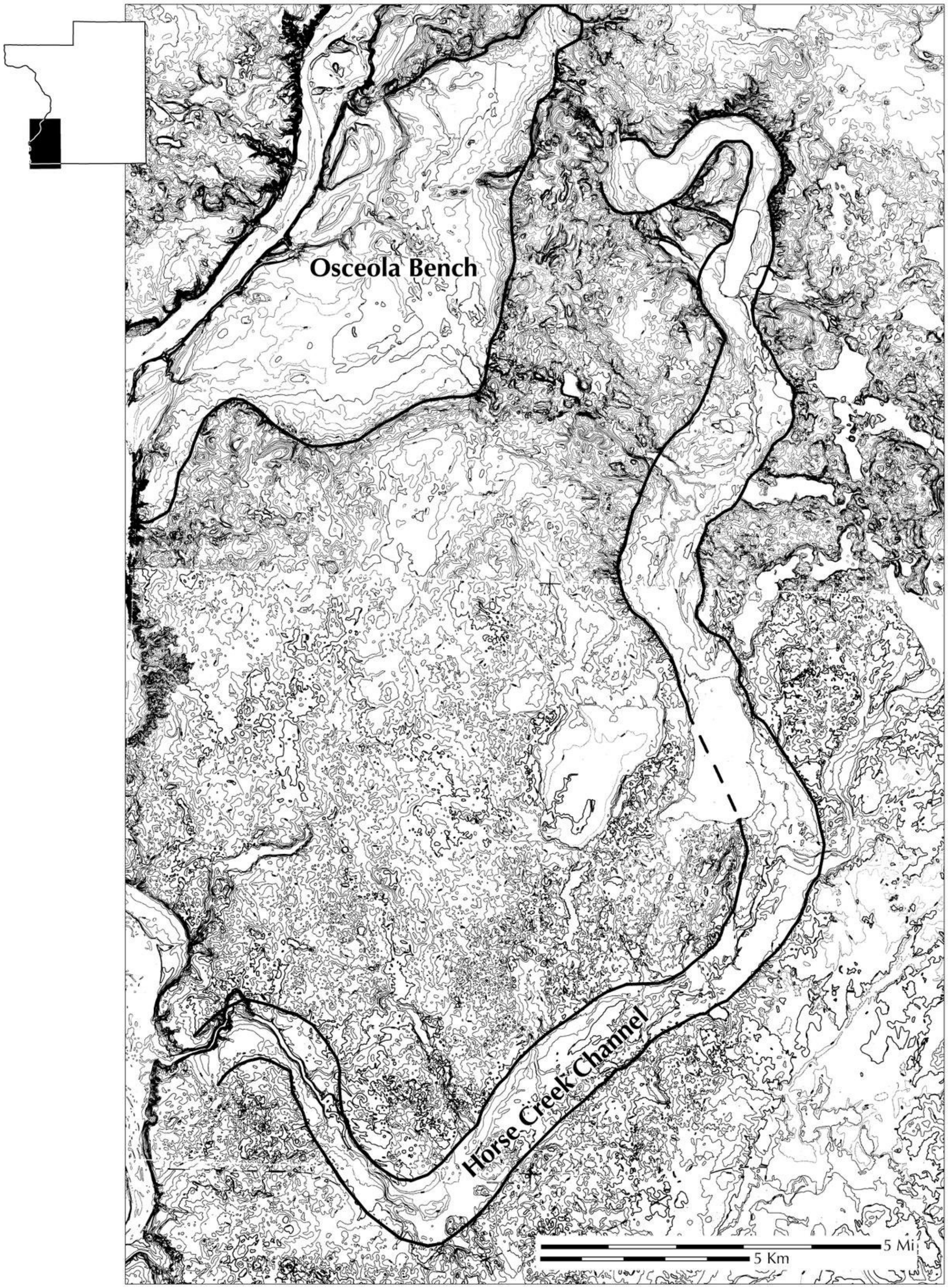


Figure 28. *Parts of Osceola, Nye, Somerset North, and New Richmond North Quadrangles, Wisconsin and Minnesota (U.S. Geological Survey, 7.5-minute series, topographic, 1993, 1978, 1974, and 1974, respectively) and parts of Somerset South and New Richmond South Quadrangles, Wisconsin and Minnesota (U.S. Geological Survey, 7.5-minute series, topographic, both 1974), showing the Horse Creek Channel and the Osceola bench. Contour interval = 20 ft, except for northern part of figure, where contour area is 10 ft.*

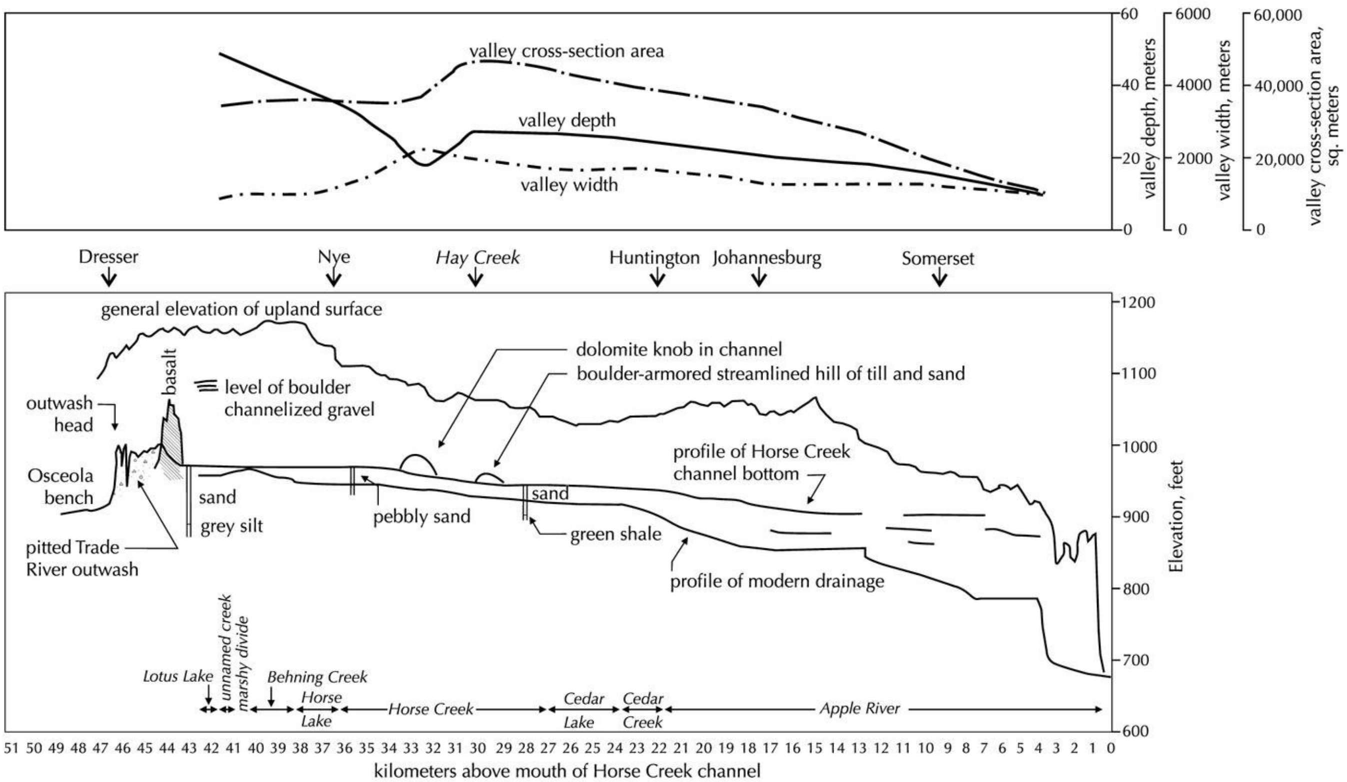


Figure 29. *Longitudinal profile of the Horse Creek Channel showing modern drainage, channel bottom, elevation of upland surface, valley width, depth, and cross-sectional area.*

the elevation of the head of the channel at the time cutting began. Elevations in the hummocky region behind the Centuria margin in this area reach 354 m; elevations were probably higher when buried ice was present. Because the area is hummocky, lower elevations certainly existed at the time the channel was cut, and meltwaters could have exploited one of these lower levels. A bouldery, channeled outwash deposit lies just east of the basalt knob at the head of the channel (fig. 29). This high-velocity stream deposit has elevations of 320 to 332 m. If this deposit represents an earlier stage in the cutting of the Horse Creek Channel, then it provides a minimum elevation for the water level of any lake that would discharge into it. Shorelines of glacial Lake Lind are below this level. Some of the possible shoreline elevations of glacial Lake Grantsburg are similar to those of the bouldery, channeled outwash deposit, but it is difficult to estimate the effects of isostatic uplift. It is not clear whether the level of glacial Lake Grantsburg would have been high enough to drain down the Horse Creek Channel.

On the other hand, the bouldery, channeled outwash deposit may not represent the early stages of channel downcutting, and thus the channel head can be assumed to have been lower. A line of features in this region (the valley filled with Trade River gravel just west of the basalt outcrop, Lotus Lake, the eskers east of Lotus Lake, Horse Lake, Big Lake, Church Pine Lake, and the marshes around Larsen Lake) outline the location of a possible tunnel channel. The bouldery, channeled outwash deposit may be associated with tunnel-channel deposits instead. Subsequent collapse of the tunnel may have left a lower gap in the hummocky deposits at the head of the Horse Creek Channel, leaving elevations that would have been lower than the level of glacial Lake Grantsburg. However, one is still left with the problem of finding a pathway for water to flow from glacial Lake Grantsburg to the head of the Horse Creek Channel, a distance of 40 km.

Chamberlin (1905), who apparently was not aware of glacial Lake Lind and glacial Lake Grantsburg, suggested another alternative for the formation of the Horse Creek Channel. According to Chamberlin, water ponded between the Centuria marginal deposits (his “St. Croix moraine”) and the retreating Superior Lobe ice, and water in this lake used the low spot at Dresser as a spillway. It would have been this smaller, ice-marginal glacial lake that would have drained to form the present-day shape of the Horse Creek Channel. Although no evidence of this lake exists, it is a reasonable alternative and is attractive in that it lacks the problems associated with requiring water from either glacial Lake Lind or glacial Lake Grantsburg to cut the channel.

Finally, it is possible to imagine supraglacial or englacial lakes on or in the Superior or Grantsburg glaciers that may have been of sufficient size or that drained quickly enough to have cut the Horse Creek Channel.

The Osceola bench

The Osceola bench (figs. 2 and 28) is a generally level surface bordering the St. Croix River near Osceola. The surface has a variable composition that indicates a complex history. Chamberlin (1905) and Muldoon and others (1990) found Trade River till covering parts of the surface, indicating that the Osceola bench existed at its present elevation prior to the Pine City Phase. Perhaps it was cut by meltwater from the Superior Lobe ice as it melted back from the Centuria margin. The association of Paleozoic dolomite at the surface in the southern part of the plain (plate 1) with coarse lag boulders suggests that it was exposed during erosion of this surface by a high-discharge flow. This indicates that much of the southern part of the bench is not a terrace, but merely exhumed bedrock. Gravel, pebbly sand, and slightly pebbly sand are in the northern part of the bench, and most outcrops of this sediment contain the dolomite and shale typical of Grantsburg deposits. The proportions indicate that the debris has been mixed with local sediment.

The slope of the Osceola bench suggests that some of the water flow came from the gap north of Dresser and from the north along the present-day course of the St. Croix River. The Osceola bench was incised in a stepwise manner by spillway water from Lake Superior. A large abandoned channel from this event is on the east side of Osceola.

Formation of the sand barrens

The sand barrens of northwest Polk County (fig. 2) extends northward into Burnett County between the St. Croix River valley and the Trade River till plain. Farther north, it merges into the large, flat, partly swampy sand plain of central Burnett County. In Polk County, the sand is 5 to 15 m thick and overlies varved glacial Lake Lind sediment. The sand and the red silt and clay are separated by a lag of pebbles and cobbles. Truncation of laminations in the red silt and clay indicates that this lag represents an erosional unconformity. The lag contains a few dolomite and limestone pebbles, presumably from the Grantsburg Sublobe; the lag is found only west of the Trade River till plain. These observations, in addition to the stratigraphic relationships shown in figure 27, indicate that the lag gravel was deposited after the Pine City Phase. The lag gravel is about the same elevation as the Chengwatana surface (fig. 16) and may have been cut at the same time. It may have also been cut earlier, perhaps by the drainage of glacial Lake Grantsburg.

Following this erosional event, sand began to aggrade on this surface. Pebbles and cross-bedding indicate fluvial deposition. Streams at this time were flowing to the south along the present-day course of the St. Croix River. The sand barrens formed about the same time as parts of the Anoka Sand Plain in Minnesota (Cooper, 1935). This period of aggradation in the St. Croix River basin suggests that Lake Superior did not exist at this time, the Superior Lobe was still within the drainage basin, and meltwater was carrying glacial debris. Because of the low gradients on the glacial Lake Lind/Lake Grantsburg deposits in central Burnett County and Pine County, Minnesota, the pebble fraction of the outwash was deposited farther upstream. This sand-bearing meltwater flowed to the south and southwest and built a delta-like surface in western Wisconsin.

As this delta-like surface prograded, it displaced the main stem of the St. Croix River westward. Ponded water (glacial Lake Fridley, Meyer and Hobbs, 1989) may have existed at this time in eastern Minnesota in a relationship not unlike the present-day relationship between the Chippewa River, the Mississippi River, and Lake Pepin. When Lake Superior subsequently drained down the St. Croix River, it incised its channel. The present-day channel of the St. Croix River thus marks the position of the westward displacement of the St. Croix by the prograding fluvial surface.

The sand barrens is now marked by irregular transverse dunes. Dune-crest and cross-bed orientations indicate that wind blew predominantly from the west and southwest. The dunes have a complicated shape that suggests vegetation and variable winds may have affected their development. Exposures in southern Burnett County indicate two periods of dune activity. Present-day dunes are in places composed of sand that throughout its thickness is iron stained, presumably by soil-forming processes. This suggests that the dunes were formed after a period of soil formation. Dunes formed by westerly to southwesterly winds were active between 8,000 and 4,000 BP in central Minnesota (Keen and Shane, 1990). The dunes in Polk County were probably active at this time as well. However, there are exposures in southern Burnett County that have non-stained sand with large-scale cross-beds, suggesting an earlier dune-forming period. This may have been immediately after glaciation, before vegetation was well established.

Drainage of Lake Superior and entrenchment of the St. Croix River

The deep gorge of the St. Croix River valley and its famous potholes formed most recently during the Pleistocene Epoch in Polk County. When the Superior Lobe retreated into Lake Superior, ice was covering the eastern outlet at Sault St. Marie, forcing the lake level to rise and find new outlets. Large channels indicate that this higher stage of Lake Superior had major outlets at Moose Lake, Minnesota, and at Brule, Wisconsin. The Moose Lake channel is slightly higher and was occupied only when the Brule outlet was ice covered.

Geomorphic and stratigraphic relationships in and surrounding Polk County show evidence for at least two drainage events. A scoured surface, marked by distinct lemniscate forms (Kehew and Lord, 1986), extends from the lower reaches of the Kettle River valley as far south as Sunrise, Minnesota. A lag of cobbles and boulders overlies till, lake sediment, or bedrock over much of this surface, although some of the bar-shaped forms are composed of sand. This surface, shown as the Chengwatana surface in figures 16 and 24, ultimately must have been cut by water flowing down the Kettle River from the Moose Lake outlet. As suggested above, the lag gravel underneath the sand barrens may have been deposited at the same time as the Chengwatana surface.

The Chengwatana surface is cut by a deeper channel that extends up the St. Croix River valley, indicating that the St. Croix valley is slightly younger than the Kettle River valley. This valley was cut by water from Lake Superior flowing out the Brule outlet. The potholes at International State Park were cut by this later event. The trace of the Chengwatana surface (fig. 16) grades to a level higher than the potholes. This indicates that the potholes were eroded not only by Lake Superior spillway water, but that they were also eroded during one of the latest phases of drainage.

These valleys were cut at the end of the Pleistocene between 12,000 and 9,000 BP, but the relationship of valley cutting to ice movements is difficult to interpret because the record of valley cutting is an erosional one. The movement of ice in and out of the Superior basin at the close of the Pleistocene indicates that water was ponded at high levels in the Lake Superior basin several times. Lake Superior would have existed and drained to the south before, in between, and after the advances that deposited the Barnum till (Wright, 1972) and the till of the Hanson Creek and Douglas Members (Need and Johnson, 1984). Additionally, smaller ice-marginal lakes (shown by Clayton, 1984) dammed against the retreating Superior Lobe may have had a significant enough discharge or hydraulic head to cut deep channels. The two or three flood events shown by the geomorphic and sedimentologic features in Polk County are certainly related to these drainage events, but an accurate correlation is not possible.

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APPENDIX: FORMAL DEFINITIONS OF NEW LITHOSTRATIGRAPHIC UNITS

Trade River Formation

Mark D. Johnson

Source of name. The Trade River in Polk and Burnett Counties, Wisconsin.

Location of type section. A gravel pit in northwestern Polk County in SE¼SW¼SE¼ sec. 10, T35 N, R19W, an area shown on the Cushing Quadrangle, Wisconsin and Minnesota (U.S. Geological Survey, 7.5-minute series, topographic, 1983; fig. A1).

Location of reference sections. Two outcrops along the Trade River in southwestern Burnett County. Reference section A is along the western bank of the Trade River near S½SE¼ sec. 19, T37N, R18W, approximately 150 m north of a barn shown on Trade River Quadrangle, Wisconsin (U.S. Geological Survey, 7.5-minute series, topographic, 1983; fig. A2). Reference section B is in the same section in a roadcut on the east side of Melo Drive, SW¼SE¼NW¼ sec. 19, T37N, R18W on the Trade River Quadrangle, Wisconsin (U.S. Geological Survey, 7.5-minute series, topographic, 1983; fig. A2).

Description of unit. The Trade River Formation contains till, lake sediment, and stream sediment derived from debris carried by the Grantsburg Sublobe. Trade River till is calcareous loam to clay loam (a few samples

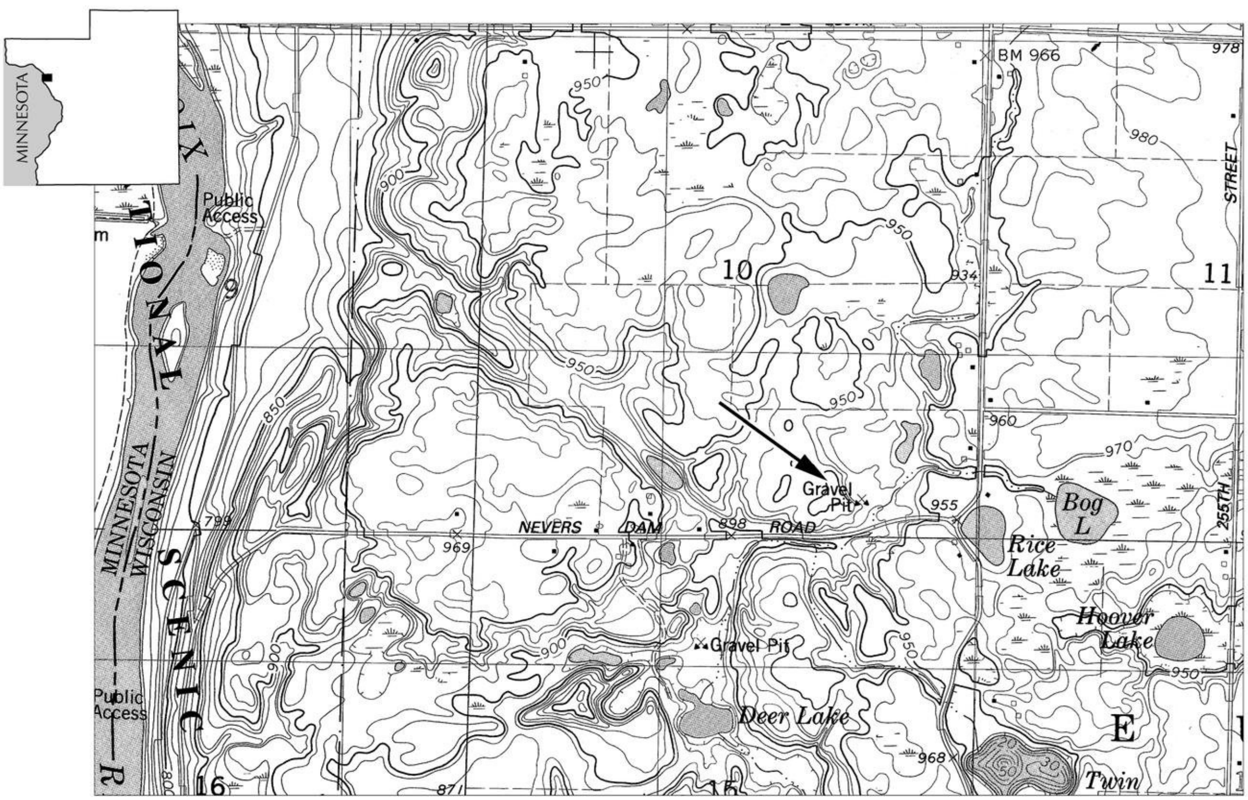

Figure A1. *Part of the Cushing Quadrangle, Wisconsin and Minnesota (U.S. Geological Survey, 7.5-minute series, topographic, 1983), showing the location of the type section of the Trade River Formation. Contour interval = 10 ft. Scale 1:24,000.*

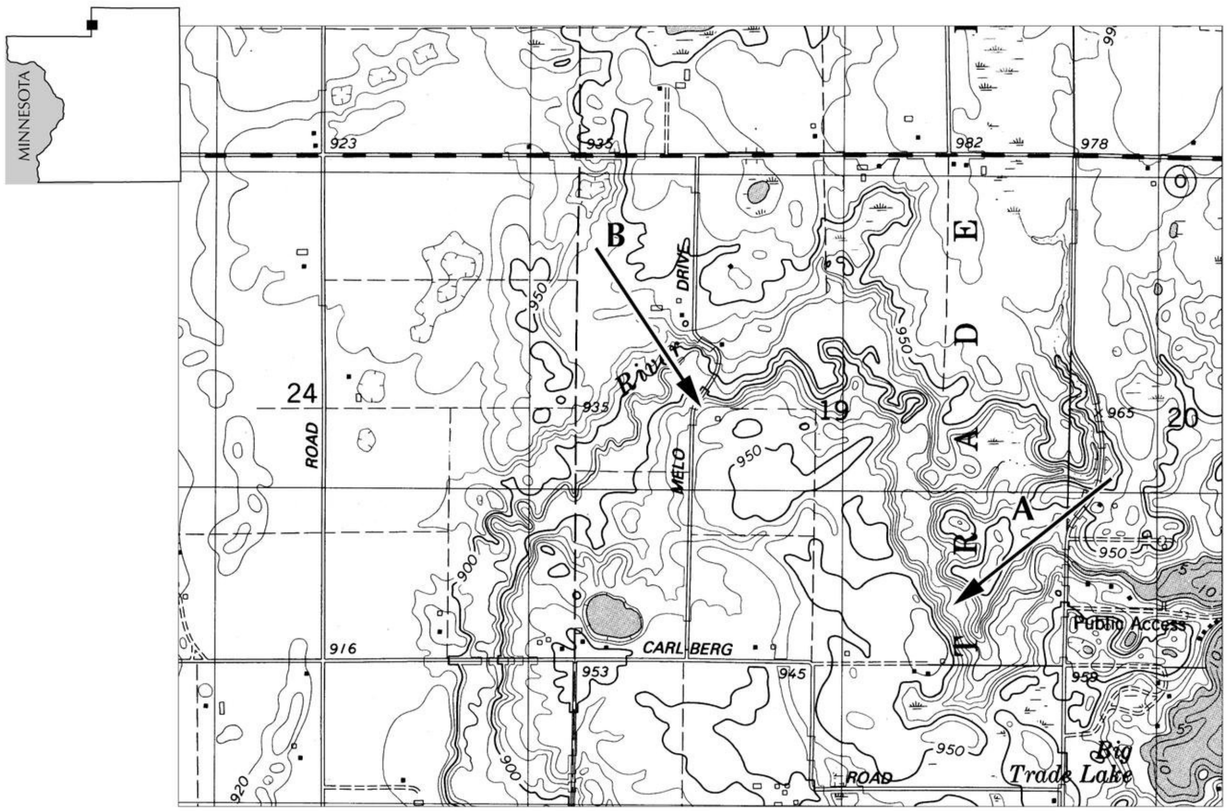

Figure A2. *Part of Trade River Quadrangle, Wisconsin (U.S. Geological Survey, 7.5-minute series, topographic, 1983), showing the location of the reference sections of the Trade River Formation. Contour interval = 10 ft. Scale 1:24,000.*

were sandy loam and sandy clay loam). The average sand:silt:clay ratio of 38 samples is 50:30:20; gravel content is less than 5 percent. The average magnetic susceptibility of 38 samples is 2.1×10^{-3} (SI units). Samples of Trade River till at and near the surface were oxidized and brown, dark brown, yellowish brown, to dark yellowish brown (7.5YR 4/4, 10YR 4-5/4). Generally, the redder samples (with hues of 7.5YR) are closer to the eastern edge of the Trade River till plain. In places, the lower part of the till unit is redder (7.5YR 4/4) and is interlaminated with the overlying grayer layers. Unoxidized Trade River till is present in the subsurface in poorly drained settings and is dark gray (10YR 4/1). The pebbles in the till contain a variety of rock types, but the abundant clasts of soft, Cretaceous shale from the Red River Valley area and limestone and dolomite from Manitoba are noteworthy. Lignite clasts are not uncommon.

Distinctly varved to massive silt and clay deposits in proglacial Lake Grantsburg are included in the Falun Member of the Trade River Formation (see next section). Silty and sandy lake sediment was also deposited in smaller ice-dammed lakes in northwestern Polk County. Trade River stream sediment is not extensive and in places its lithologic composition is different because of mixing with older sediment, mostly sediment of the Copper Falls Formation.

Nature of contacts. The base of the Trade River till overlies stream and lake sediment of the Copper Falls Formation in western Wisconsin. The contact is sharp everywhere. In places, several centimeters of Trade River lake sediment separate the Trade River till and underlying sediment.

Differentiation from other units. The till of the Trade River Formation is most similar to till of the Pierce Formation in western Wisconsin. It can be easily distinguished from the Pierce Formation primarily by the abundance of Cretaceous shale, but also by its stratigraphic position.

Regional extent and thickness. The Trade River till is at the surface in an arc-shaped band approximately 5 to 8 km wide and extending from Grantsburg, Wisconsin, south to a point a few kilometers north of St. Croix Falls. A few small patches of Trade River till are in St. Croix Falls and on the Osceola bench near Osceola, Wisconsin. On the basis of outcrops, drillholes, and well constructor's reports, the till is 4 to 15 m thick. Trade River stream sediment and lake sediment is thin and patchy.

Origin. The Trade River till was deposited underneath the Grantsburg Sublobe glacier as it advanced from the Minneapolis and St. Paul lowland to the northeast during the Pine City Phase.

Age and correlation. The Trade River Formation has been suggested to have been deposited as early as 16,000 BP. (Wright, 1972; Wright and others, 1973) and as late as 12,300 BP (Clayton and Moran, 1982). In this report, I suggest it was deposited around 14,000 BP. The till of the Trade River Formation is equivalent to the Twin Cities Formation as defined by Stone (1966) and is roughly the same age as the New Ulm till in southwest Minnesota (Matsch, 1972).

Description of type section. The type section exposes 4 m of Trade River till overlying 4 to 8 m of Copper Falls pebbly sand and sand. A drillhole at the type section contains 23 m of Copper Falls sand and pebbly sand. The lower 0.5 m of the till is redder and contains three or four faint laminations that show intermixing of the red with the overlying gray. Pebble fabrics are fairly strong and indicate ice movement to the east (in the lower red-laminated part) to N 60° E (in the gray part above). The till is massive and contains a few pods of sorted sand and a pod of red clay. The region around the type section is slightly hummocky and contains a number of kettle lakes.

Description of reference section. At reference section A (fig. A2), 15 m of oxidized and unoxidized Trade River till sharply overlies 2 m of Copper Falls stream sediment. At reference section B (fig. A2), 5 m of Trade River till overlies about 1 m of red and gray laminated (varved) lake sediment, which in turn overlies Copper Falls sand.

Previous usage. This name is used for the first time in this report.

Falun Member of the Trade River Formation

Mark D. Johnson and Chris Hemstad

Source of name. Falun in Burnett County, Wisconsin.

Location of type section. Back-hoe excavation (June 1992) on the south side of Wisconsin State Highway 70 approximately 3 km east of Grantsburg, Burnett County, Wisconsin, NE¼NW¼NE¼ sec. 19, T38N, R18W, an area shown on the Grantsburg Quadrangle, Wisconsin–Minnesota (U.S. Geological Survey, 7.5-minute series, topographic, 1982; fig. A3).

Location of reference sections. A) Gravel pit on the north side of M Y Road, Burnett County, Wisconsin, NW¼SW¼SW¼ sec. 3, T37N, R18W, an area shown on the Trade Lake Quadrangle, Wisconsin (U.S. Geological Survey, 7.5-minute series, topographic, 1983; fig. A4). B) Back-hoe excavation (June 1992) on the farm of Royce and Sue Johnson, Pine County, Minnesota, NE¼SE¼NW¼ sec. 10.

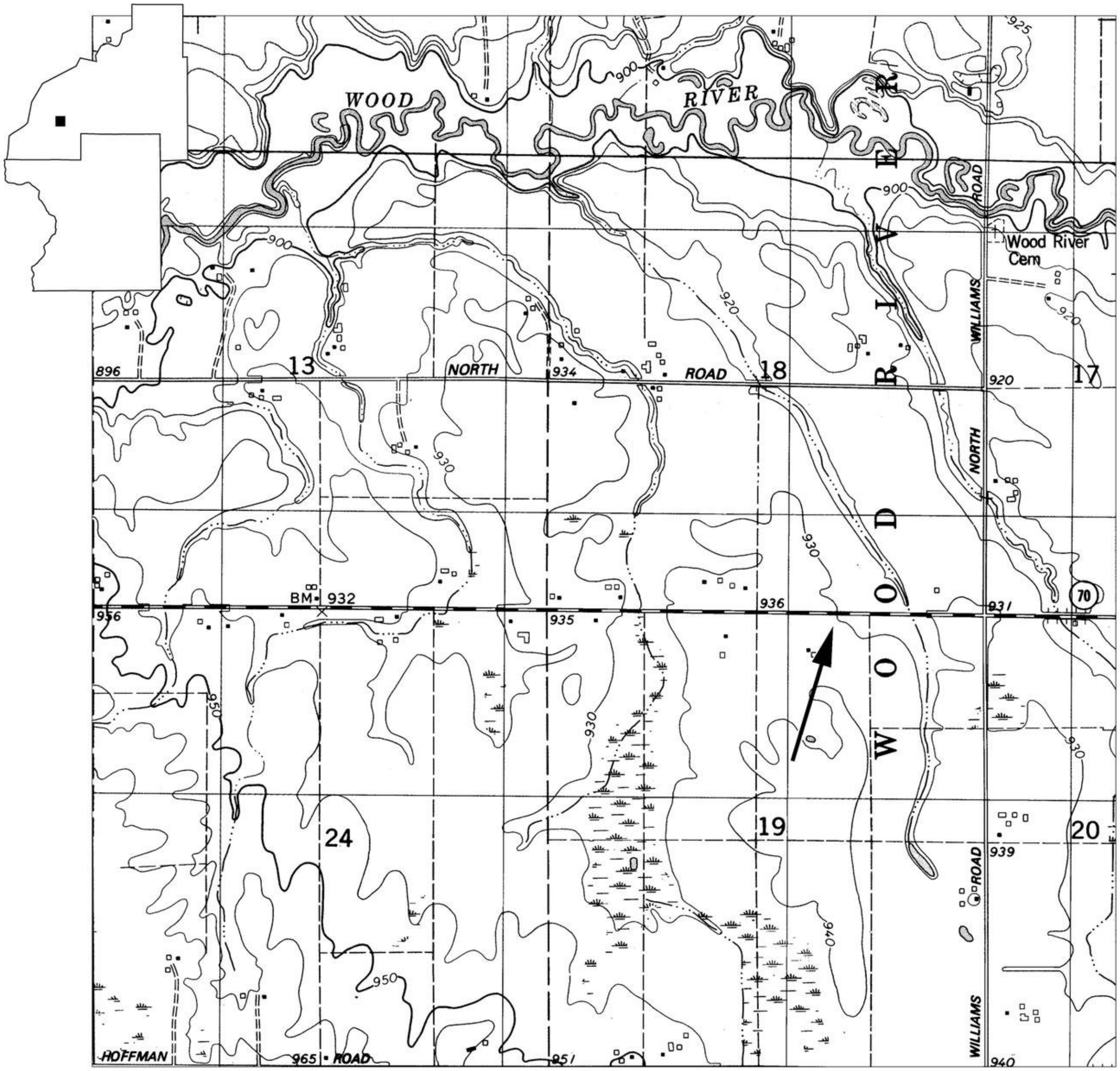

Figure A3. *Part of the Grantsburg Quadrangle, Wisconsin and Minnesota (U.S. Geological Survey, 7.5-minute series, topographic, 1982), showing the location of the type section of the Falun Member of the Trade River Formation. Contour interval = 10 ft. Scale 1:24,000.*

T39N, R20W, an area shown on the Cedar Lake Quadrangle, Minnesota (U.S. Geological Survey, 7.5-minute series, topographic, 1983; fig. A5).

Description of unit. The Falun Member consists predominantly of calcareous, rhythmically laminated, rhythmically bedded, massive clay and silty clay. At reference section B, the Falun Member includes silt and fine-grained sand at the base of the unit. In places, sand is found within the member. Silty clay layers are dark yellowish brown to yellowish brown (10YR 4–5/4), clay layers are predominantly dark grayish brown to dark brown (10YR 4/2 to 7.5YR 4/4), but in places are reddish brown (5YR 4/4).

Nature of contacts. The basal contact of the Falun Member is sharp and overlies red sand, slightly pebbly sand, and pebbly sand of the Copper Falls Formation. The Falun Member is at or near the surface and is in places overlain by sand up to a few meters

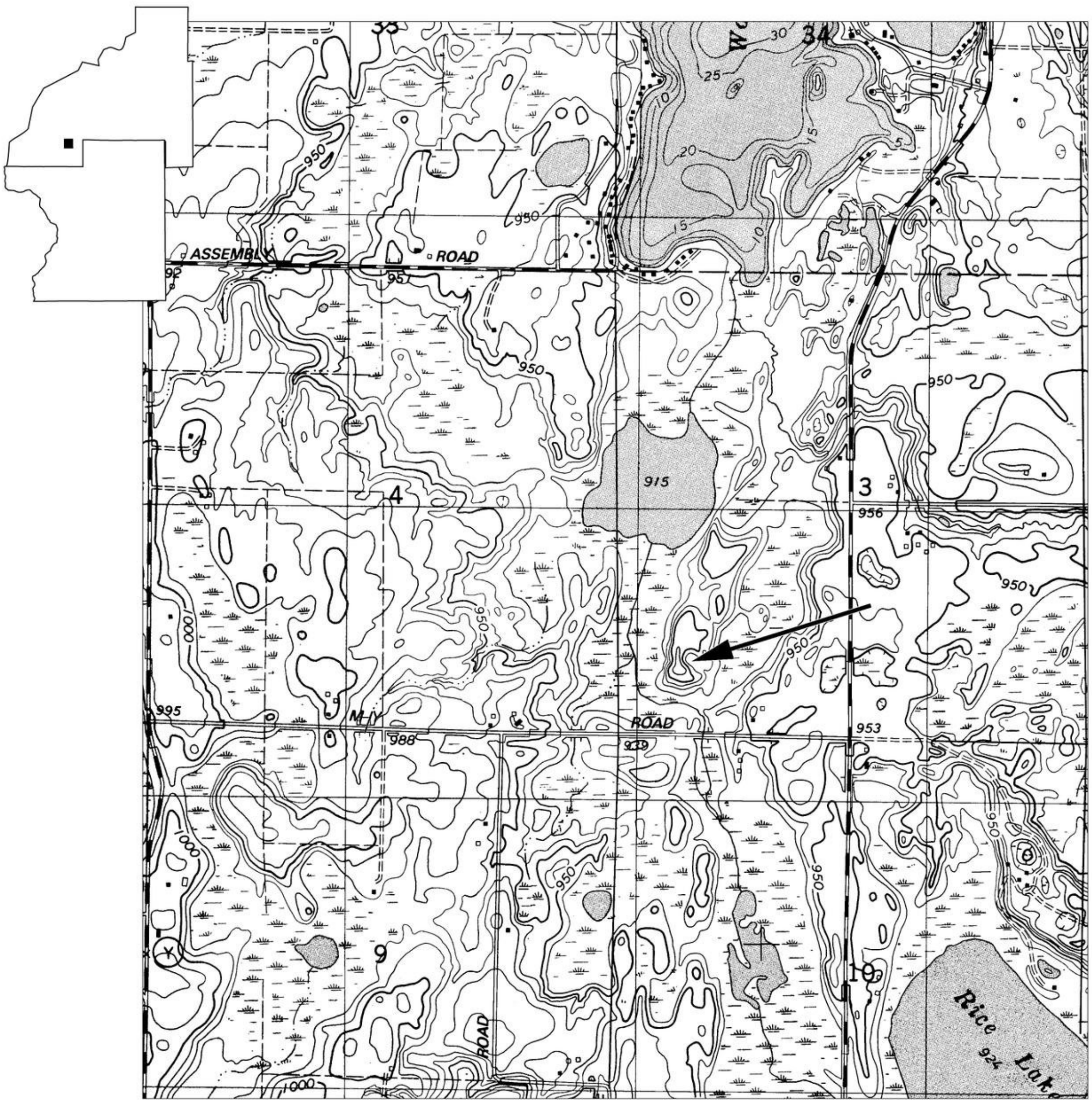

Figure A4. *Part of the Trade Lake Quadrangle, Wisconsin (U.S. Geological Survey, 7.5-minute series, topographic, 1983), showing the location of reference section A of the Falun Member of the Trade River Formation. Contour interval = 10 ft. Scale 1:24,000.*

thick or silt up to 0.5 m thick. The upper contact is in many places not as sharp, presumably because it is mixed with overlying sediment by soil-forming processes.

Differentiation from other units. The Falun Member is most similar to sediment of the Sunrise Member of the Copper Falls Formation (see next section), but can be differentiated easily from it because the Falun Member is gray and more calcareous than the Sunrise, has thicker beds and laminations, and occupies a higher stratigraphic position.

Regional extent and thickness. The Falun Member is near the surface throughout central and southwestern Burnett County, Wisconsin, in an east–west band in Minnesota between Pine City and Hinckley in Pine County, and continuing westward into southern Kanabec County. It probably extends farther west, but has not been mapped there. Thickness varies considerably from approximately 1.0 m up to 5.0 m. The Falun

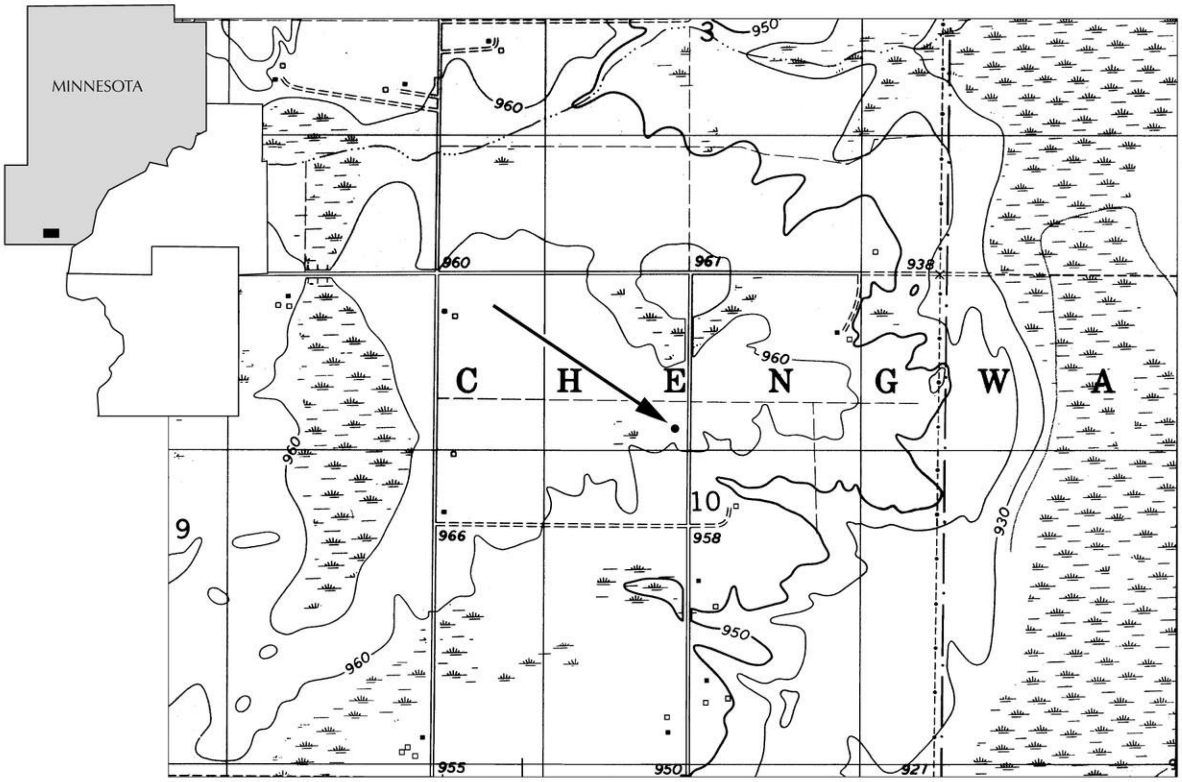

Figure A5. *Part of the Cedar Lake Quadrangle, Minnesota (U.S. Geological Survey, 7.5-minute series, topographic, 1983) showing the location of reference section B of the Falun Member of the Trade River Formation. Contour interval = 10 ft. Scale 1:24,000.*

Member is 1.2 m thick at the type section, 1.5 m thick at reference section A, and 5.2 m thick at reference section B. The unit is thickest near the Pine City ice margin and in low swales between upland areas. It is usually absent on hilltops and slopes.

Origin. The Falun Member was deposited in glacial Lake Grantsburg while the Grantsburg Sublobe stood at the Pine City Phase ice-margin limit. The rhythmically laminated layers are interpreted to be varves. Many rhythmites were probably deposited as the ice advanced to the Pine City margin and as the ice retreated from this margin.

Age and correlation. The age of the Falun Member is not well known, but it is approximately the same age as the till of the Trade River Formation. The Trade River Formation has been suggested to have been deposited as early as 16,000 BP (Wright, 1972; Wright and others, 1973) and as late as 12,300 BP (Clayton and Moran, 1982). In this report, I suggest it was deposited around 14,000 BP.

Description of type section. At the type section, the sediment of the Falun Member is overlain by 75 cm of tan to gray loose sand and a mixed zone of sandy gray loam at the contact; the Falun Member sediment is 115 cm and consists of 40 cm of massive clay and silt clay overlying 75 cm of rhythmically bedded clay and silty clay. The massive clay and silty clay are likely a result of soil-forming processes mixing the bedded clay. Thirty-eight varves are in the bedded part; the lowest 17 are quite thin (0.5 to 3.0 cm) and red. The 21 upper varves are thicker (2.5 to 4.0 cm) and grayer; the clayey winter layer is darker than the silty summer layer. Some of the winter layers in this section are slightly redder at their bases. The Falun Member is between 280 and 283 m in elevation.

The Falun Member overlies red, ripple-bedded to laminated, fine- to medium-grained sand of the Copper Falls Formation. Ripple-crest and cross-bed orientations show current flow to the west and northwest.

Description of reference section. At reference section A, a clayey, slightly pebbly till-like sediment about 1.0 m thick overlies 1.5 m of Falun Member sediment. Approximately 1.0 m is massive and 0.5 m is laminated. The laminations, 34 of which are present, are interpreted to be varves. The lowest 12 to 14 varves are red. The Falun Member sharply overlies several meters of pebbly sand of the Copper Falls Formation.

At reference section B, approximately 1 m of silt (loess?) overlies 3.0 m of rhythmically bedded silty clay and clay interpreted to be varves. Eighty-two couplets are present at this site and range in thickness from 1.0 to 15.0 cm; most are between 2.5 and 4.5 cm. The varves are predominantly gray, but a few thin red winter layers are among the first six varves. Above varve number 40, the winter layers begin to show redder colors, and varves 64 to 82 have reddish-brown (5YR 4/4) winter layers with relatively thin summer layers (0.5 cm). Within some of the summer layers in the central part of the sequence, fine laminations of coarse silt and very fine-grained sand are present. The varved part of the Falun Member at this site overlies 2.0 m of dark grayish-brown to strong brown (10YR 4/2 to 7.5-10YR 5/6), calcareous, coarse silt and fine-grained sand, which in places has slightly convoluted bedding. The lower part of this silt and sand has been oxidized and is brown to dark brown (7.5YR 4/4). The Falun Member sharply overlies red Copper Falls coarse sand.

Previous usage. This name is used for the first time in this report.

Sunrise Member of the Copper Falls Formation

Mark D. Johnson

Source of name. Sunrise in Chisago County, Minnesota.

Location of type section. The type section is in the east bank of the North Branch Sunrise River, outside of a meander bend, Chisago County, Minnesota, NW¼NE¼NW¼ sec. 19, T35N, R20W, and is shown on the North Branch Quadrangle, Wisconsin and Minnesota (U.S. Geological Survey, 7.5-minute series, topographic, 1983; fig. A6).

Location of reference sections. Reference section A is exposed in a ravine on the north side of Benson Road, Burnett County, Wisconsin, N½NE¼SE¼ sec. 7, T38N, R19W, and is shown on the Bass Creek Quadrangle, Wisconsin–Minnesota (U.S. Geological Survey, 7.5-minute series, topographic, 1983; fig. A7). Reference section B is exposed along the south bank of the Snake River, Pine County, Minnesota, SE¼NE¼NW¼ sec. 30, T39N, R20W, and is shown on the Pine City Quadrangle, Minnesota (U.S. Geological Survey, 7.5-minute series, topographic, 1983; fig. A8).

Description of unit. The Sunrise Member consists of rhythmically laminated sand, silt, and clay. The bulk of the sediment consists of couplets of slightly calcareous, dark reddish-brown (5YR 3/3) to dark reddish-gray (5YR 4/2) silt and slightly calcareous, dark reddish-brown (2.5-5YR 3/4) clay. The couplets range in thickness generally from 0.5 to 3.0 cm, although couplets as thin as 0.2 cm or as thick as 25.0 cm are present in places. Where the Sunrise Member overlies till, the sediment at the base of the unit near the contact consists of silt, sand, gravel, and till-like material interbedded with thin, widely

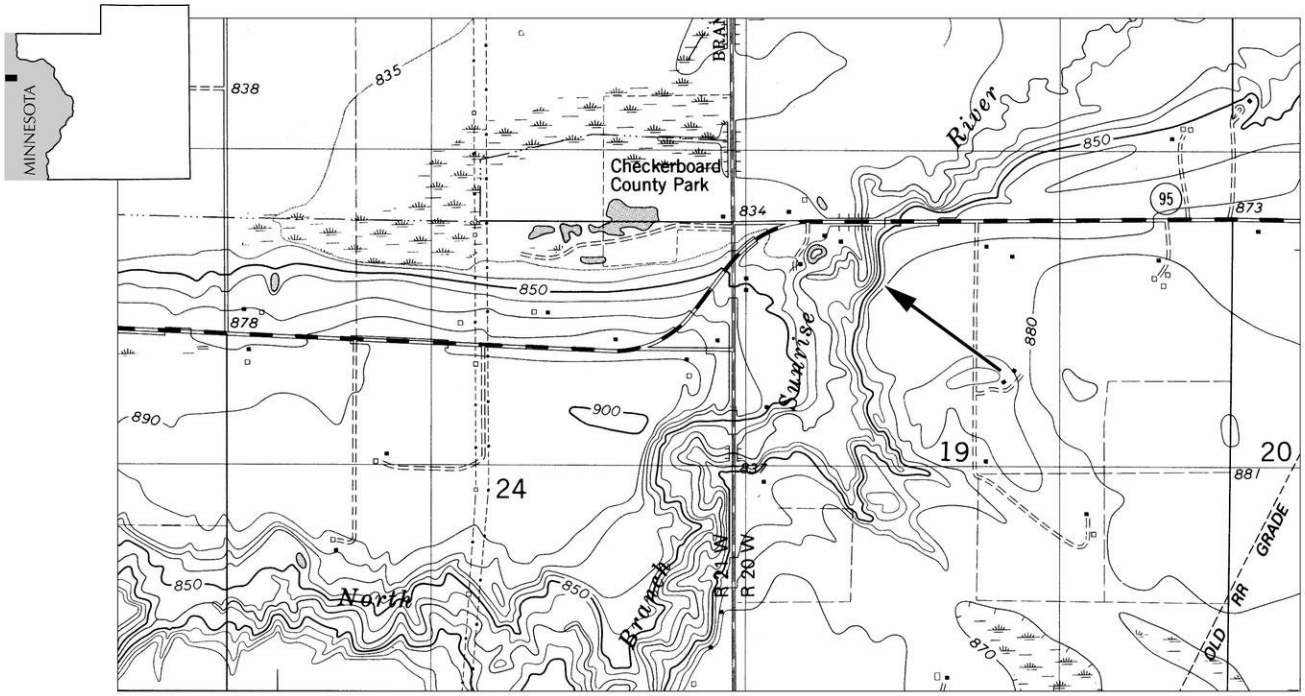

Figure A6. *Part of the North Branch Quadrangle, Wisconsin and Minnesota (U.S. Geological Survey, 7.5-minute series, topographic, 1983) showing the location of the type section of the Sunrise Member of the Copper Falls Formation. Contour interval = 10 ft. Scale 1:24,000.*

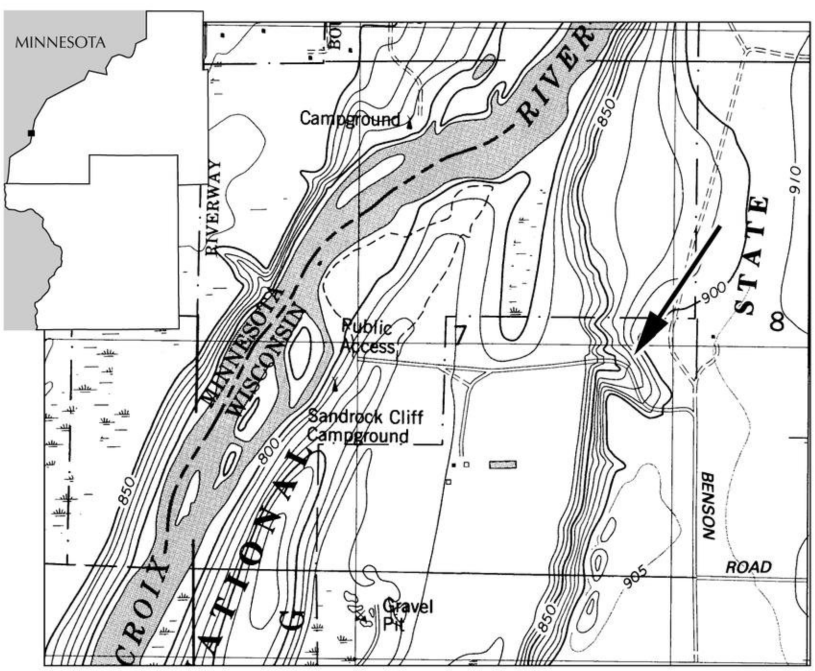

Figure A7. *Part of the Bass Creek Quadrangle, Wisconsin and Minnesota (U.S. Geological Survey, 7.5-minute series, topographic, 1983), showing the location of reference section A of the Sunrise Member of the Copper Falls Formation. Contour interval = 10 ft. Scale 1:24,000.*

separated clay layers. Near its eastern and western limits, the character of the Sunrise Member changes; thick beds of silt and sand, some of which are highly convoluted, are in places interbedded with pure clay.

In places, the laminated silt and clay grade upward into progressively thicker and coarser silt layers with intervening thin red clay beds. This sequence in turn grades upwards into sand, some of which has bedding that is characteristic of beach and fluvial sand. In places, the sand contains pebbles; some are red clay clasts derived from the laminated part.

Nature of contacts. Where observed, the lower contact of the Sunrise Member is sharp and overlies Copper Falls till. Beneath the sand barrens of Polk and Burnett Counties, Wisconsin, and parts of Chisago and Pine Counties, Minnesota, the upper contact is sharp and is overlain by a lag gravel and flu-

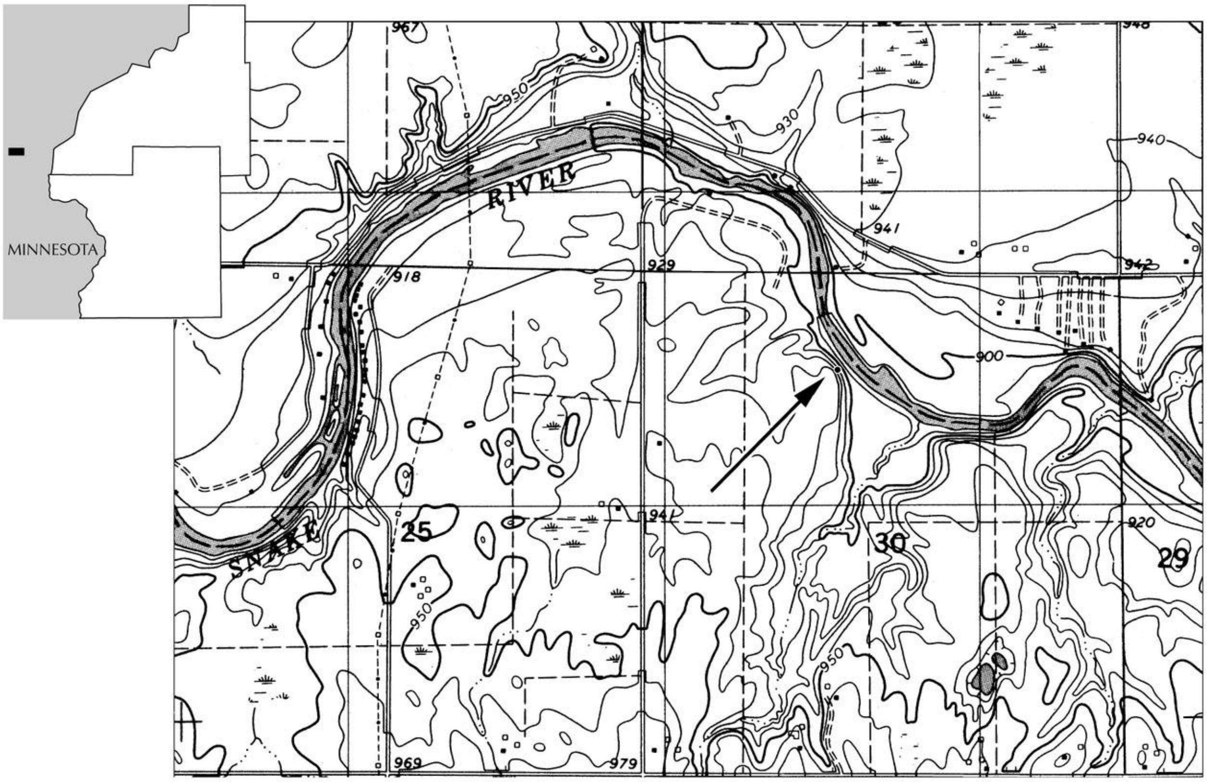

Figure A8. *Part of the Pine City Quadrangle, Minnesota (U.S. Geological Survey, 7.5-minute series, topographic, 1983), showing the location of reference section B of the Sunrise Member of the Copper Falls Formation. Contour interval = 10 ft. Scale 1:24,000.*

vial sand. Beneath the Trade River till plain in the same counties, the upper, sandy part of the Sunrise Member is overlain by Trade River till; a few centimeters of laminated gray clay are at the sharp contact.

Differentiation from other units. The Sunrise Member is most similar to the Falun Member of the Trade River Formation, but can be easily differentiated from it on the basis of color and stratigraphic position.

Regional extent and thickness. The Sunrise Member is exposed along the St. Croix River and its tributaries in northwestern Wisconsin and east-central Minnesota and is everywhere else present only in the subsurface. The southernmost outcrops are along the Sunrise River in central Chisago County, Minnesota; the northernmost, at St. Croix State Park, Pine County, Minnesota. The Sunrise Member is well exposed along the Wood, Clam, and Trade Rivers in Wisconsin and along Rock Creek, Goose Creek, and the Snake River in Minnesota. The thickness of the Sunrise Member varies from a few meters to as much as 30 m (found in material from a drillhole near Sunrise, Minnesota); most exposures contain 5 to 10 m. In places where the coarsening-upward sequence is preserved, the sand may be more than 20 m thick.

Origin. The Sunrise Member was deposited in glacial Lake Lind while the Superior Lobe was retreating from western Wisconsin and eastern Minnesota. The laminated sediments are interpreted to represent varves deposited in deep water away from strandlines. The coarser sediment at the base of the unit is interpreted to represent near-glacier sedimentation in the bottom of the lake as the Superior Lobe retreated and the lake expanded. Individual varve thickness is greatest above the till and becomes thinner upwards after 25 to 40 varves. Coarser sediment exposed along the Sunrise and Snake Rivers near the margins of the unit's extent are interpreted to represent near-shore sedimentation where sediment supply may have been higher and water depth was less. The coarsening-upward sequence preserved in places above the varved sequence is interpreted to represent deposition of deltaic and fluvial sand and a gradual filling in of the lake.

Age and correlation. The age of the Sunrise Member is not well known, but it was probably deposited between 14,000 and 16,000 BP. The Sunrise Member is probably correlative with a buried unit of red and brown lacustrine sediment in southern Chisago County and central Anoka County as mapped by Helgeson and Lindholm (1977). It is younger than fluvial and glacial deposits of the Copper Falls Formation elsewhere in Polk County and older than the sediment of the Trade River Formation.

Description of type section. Slightly pebbly sand that is 4.7 m thick overlies the Sunrise Member at the type section. Many pebbles and some cobbles lie at the contact and represent a lag gravel that truncates the top of the Sunrise Member. The laminated silt and clay beds of the Sunrise Member are 10.0 m thick and below the sand. The base of the silt and clay lies below river level and is not exposed, and some of the silt and clay is covered. Detailed observations at the site show that 776 varves are exposed, and that they range in thickness from 0.7 to 2.5 cm. Varve 536 above river level in the sequence we counted is 30 cm thick and could represent a mud-flow deposit rather than a varve.

Description of reference section. Reference section A contains several meters of sand overlying 6.5 m of Sunrise Member varved silt and clay; a gravel lag marks the contact. This cut contains 250 varves. Interbedded with the varved silt and clay are five thick (40 to 60 cm) silt and clay beds that are massive to graded. In places, these thick beds have discontinuous, convoluted silt beds. If these thick beds are traced across the outcrop, it is clear that they change in thickness significantly. These characteristics suggest that the thick units represent mud-flow or slump units.

Reference section B exposes several meters of sandy Sunrise Member sediment that is interpreted to represent sedimentation close to the western shore of glacial Lake Lind. From top to bottom the exposure contains 2.5 m of fine to coarse sand, 1.2 m of rippled sand with clay drapes, 0.3 m of red till-like material, 1.0 m of medium to coarse sand, and 3.0 m of red sandy till with some interbeds of sand. The rippled sand layer contains 50 clay drapes that are interpreted to be winter layers. In places the clay is truncated and present only in ripple troughs. The overlying sand is not clearly part of the Sunrise Member and may represent a Snake River terrace deposit.

Previous usage. This name is used for the first time in this report.

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Pleistocene Geology of Polk County, Wisconsin

2000

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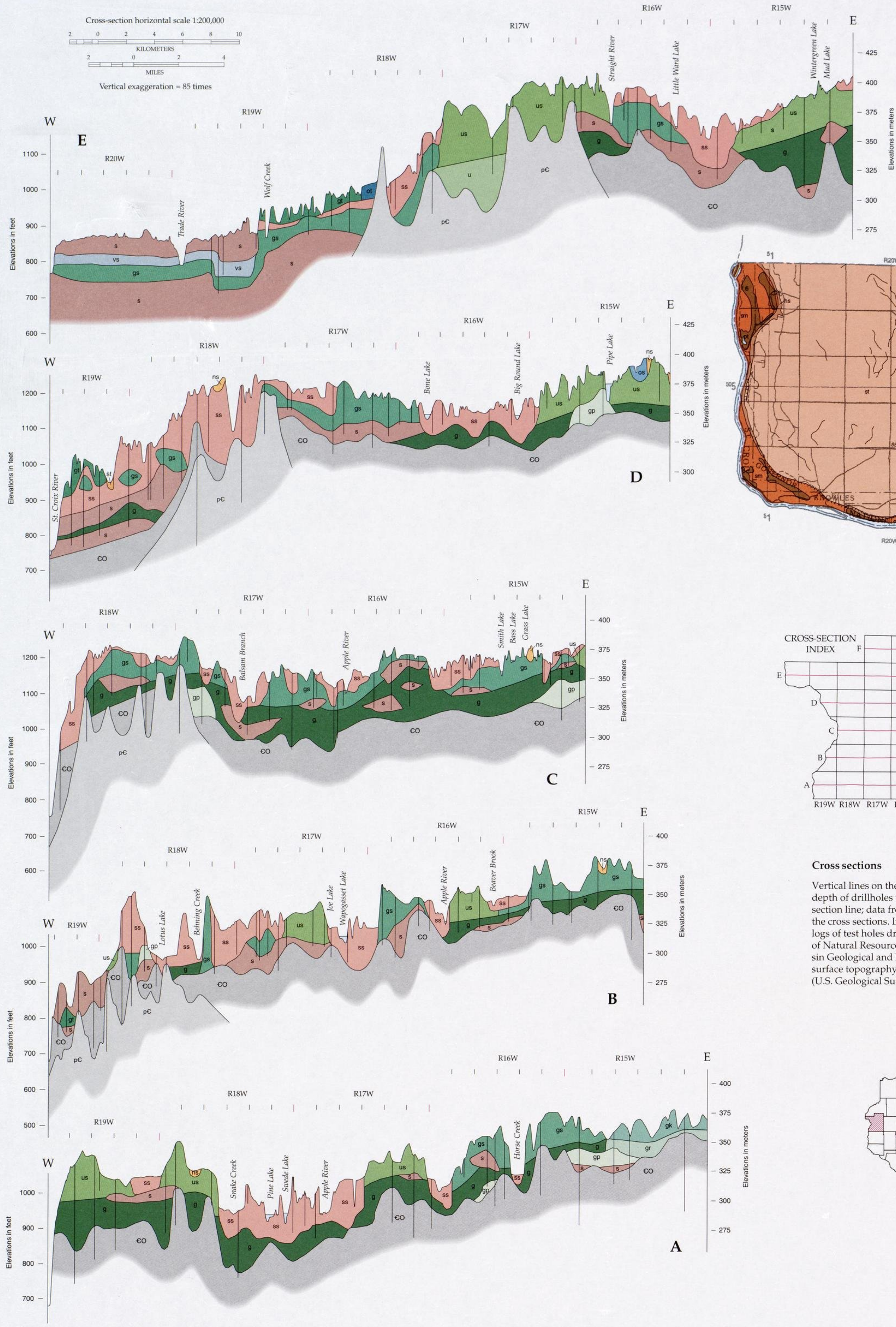
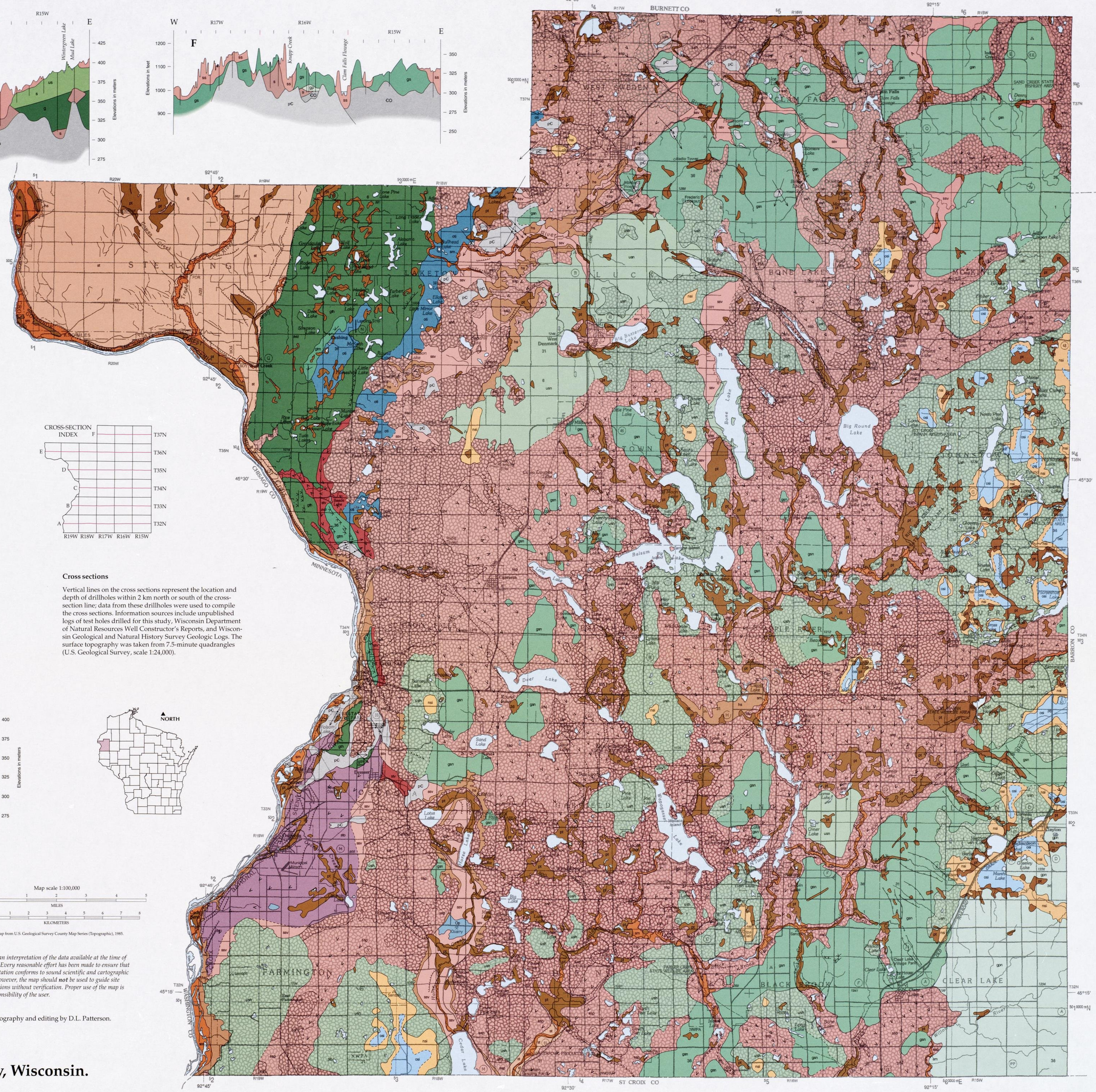
Cover: Gravel deposited by meltwater streams near to the Range ice-margin limit, eastern Polk County.





Cross sections

Vertical lines on the cross sections represent the location and depth of drillholes within 2 km north or south of the cross-section line; data from these drillholes were used to compile the cross sections. Information sources include unpublished logs of test holes drilled for this study, Wisconsin Department of Natural Resources Well Constructor's Reports, and Wisconsin Geological and Natural History Survey Geologic Logs. The surface topography was taken from 7.5-minute quadrangles (U.S. Geological Survey, scale 1:24,000).

Explanation

- s — Stream sediment, undifferentiated
- g — Till, undifferentiated
- u — Till and gravity-flow, stream, and lake sediment, undifferentiated
- ot — Lake sediment of the Trade River Formation
- gt — Till of Trade River Formation
- us — Till and gravity-flow, stream, and lake sediment of the Sylvan Lake Member of the Copper Falls Formation
- ns — Nearshore lake sediment of the Sylvan Lake Member
- os — Offshore lake sediment of the Sylvan Lake Member
- vs — Varved glacial Lake Lind sediment of the Sunrise Member of the Copper Falls Formation
- ss — Stream sediment of the Sylvan Lake Member
- gs — Till of the Sylvan Lake Member
- gk — Till of the Poskin Member of the Copper Falls Formation
- gr — Till of the River Falls Formation
- gp — Till of the Pierce Formation
- ЄO — Cambrian and Ordovician sandstone, dolomite, and shale
- pЄ — Precambrian basalt

Map scale 1:100,000

Base map from U.S. Geological Survey County Map Series (Topographic), 1985.

*This map is an interpretation of the data available at the time of preparation. Every reasonable effort has been made to ensure that this interpretation conforms to sound scientific and cartographic principles; however, the map should **not** be used to guide site specific decisions without verification. Proper use of the map is the sole responsibility of the user.*

Digital cartography and editing by D.L. Patterson.

Plate 1. Pleistocene geology and cross sections of Polk County, Wisconsin.

Wisconsin Geological and Natural History Survey
Bulletin 92
Pleistocene Geology of Polk County, Wisconsin
Plate 1

Mark D. Johnson
1998

Explanation

- pt — Marshes and wetlands composed of peat and muck.
- sm — Modern floodplains predominantly composed of noncalcareous sand, with some gravel and finer sediment deposited by modern streams.
- hs — Steep slopes with gullies and scarps along margins of St. Croix River valley and its tributaries and along the Horse Creek channel; composed predominantly of unlithified sediment. Paleozoic bedrock exposed along St. Croix River valley at Osceola and farther south; formed by fluvial and hillslope erosion.
- st — Terraces developed along the St. Croix River valley during postglacial valley incision; composed of sand and some gravel derived from Copper Falls and Trade River Formations. In the northwest, the terrace with transverse dunes is composed of noncalcareous sand derived primarily from the Superior Lobe and built initially by meltwater flowing from the north and later modified by westerly and southwesterly winds; sand between dunes is 5 to 15 m thick.
- Op — Outcrops of Ordovician dolomite of the Prairie du Chien Group.
- pЄ — Outcrops of Precambrian basalt of the Chengwatana Group; basalt is amygdaloidal and vesicular in places, and displays a high concentration of magnetic minerals in places; outcrops have high relief, are polished, grooved, striated, and weathered; potholes occur at St. Croix Falls.

Trade River Formation

- gth — Pitted to hummocky till plain underlain by calcareous, gray loamy Trade River till deposited by the Grantsburg Sublobe; shale, dolomite, limestone, and other rock types are present in till pebbles; till is several meters thick and underlain in most places by Copper Falls stream sediment that contained blocks of Superior Lobe ice that melted out after the Pine City Phase, collapsing the Trade River till and producing the collapse topography.
- gtm — Moraine ridges marking the edge of the Grantsburg Sublobe at its maximum extent and during its retreat; composed of Trade River till.
- stv — Trade River stream sediment occurring in ice-marginal channels and outwash plains; sediment is predominantly calcareous pebbly sand; in places, it contains significant admixtures of sediment eroded from the Copper Falls Formation; deposited by meltwater from the Grantsburg Sublobe.
- oti — Ice-dammed-lake plains occurring at the ice-margin limit of the Grantsburg Sublobe; composed of gravel, sand, silt, and clay; lake sediment is calcareous and includes sediment derived from the Grantsburg Sublobe as well as sediment that was eroded from the Copper Falls Formation and carried to the lakes by streams.
- sto — Osceola bench; composed of Trade River sand, pebbly sand, and coarse gravel, Trade River till, and Ordovician dolomite.

Copper Falls Formation

Sylvan Lake Member

- gsn — Gently rolling to streamlined upland areas underlain by thick, reddish-brown, sandy loam till of the Sylvan Lake Member; deposited by the Superior Lobe during the St. Croix and later phases.
- ssp — Pitted outwash plains composed of noncalcareous sand, slightly pebbly sand, and pebbly sand deposited by meltwater from the Superior Lobe; cobbles and boulders are common near former ice-margin positions; pits are as large a 1 km^2; abandoned channels and terrace scarps present in places.
- ssh — Hummocks composed of noncalcareous sand, slightly pebbly sand, and pebbly sand deposited by meltwater from the Superior Lobe; formed by extensive collapse of outwash plains as buried Superior Lobe ice melted; small marshes present in places.
- ssv — Broad, flat floors of St. Croix River tributary valleys in northwestern Polk County and the channel bottom of the Horse Creek Channel in southwestern Polk County; terrace scarps present in places; composed of sand to pebbly sand. Includes aprons of sandy hillslope sediment deposited at base of scarps. Valleys in northwestern Polk County were cut following retreat of the Superior Lobe ice and prior to the advance of the Grantsburg Sublobe; the Horse Creek Channel was cut during or after the Centuria Phase and prior or during the Pine City Phase.
- usn — Gently rolling, flat, to low-relief-hummocky landscape underlain by till and stream sediment of the Sylvan Lake Member. West of Luck, this unit overlies thick stream sediment. This unit is used also to represent a relatively young wave-cut surface around Bone Lake.
- ush — Hummocky topography underlain by till, gravity-flow sediment, stream sediment, and lake sediment of the Sylvan Lake Member; small marshes present in places.
- nsi — Nearshore deposits of ice-walled-lake plains and ice-dammed-lake plains; composed of silt, sand, pebbly sand, and unsorted material; deposited by streams, waves, and sediment gravity flow; deposited along the shorelines of ice-walled and ice-dammed lakes when stagnant ice of the Superior Lobe was present.
- osi — Offshore deposits of ice-walled-lake plains and ice-dammed-lake plains; composed primarily of silt with some sand and clay; deposited from suspension and by turbidity currents in the centers of ice-walled and ice-dammed lakes when stagnant ice of the Superior Lobe was present.

Poskin Member

- gpn — Gently rolling, stream-dissected landscape underlain by red, sandy loam till of the Poskin Member; deposited by the Superior Lobe during the Emerald Phase; outcrops of River Falls till may occur in this region.

Symbols

- Geologic contact, dashed where uncertain
- Slope of outwash surface
- Crest of transverse dune
- Ice-flow from striation measurement
- Esker
- Tunnel-channel margin
- Moraine ridge
- Stream-cut scarp

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