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CONTRIBUTIONS TO QUATERNARY STUDIES IN MINNESOTA

Carrie J. Patterson and H.E. Wright, Jr. Editors

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FOREWORD

Contributions to Quaternary studies in Minnesota is a collection of papers that summarizes advances in our understanding and approaches to the study of Quaternary glacial sediments, and the history of ice movement across Minnesota and adjacent regions. Contributors include geologists from the Minnesota Geological Survey and faculty and students from a number of academic institutions in the region including the University of Minnesota (Twin Cities, Duluth, and Morris campuses), the University of Wisconsin (River Falls and Madison campuses), and Gustavus Adolphus College. The authors form a community of researchers that regularly exchange ideas at formal meetings such as North-Central GSA and Midwest Friends of the Pleistocene, informal meetings such as FOSLAGS (Friends of the Superior lobe and Grantsburg sublobe), field meetings held in conjunction with Research Experience for Undergraduates (REU) programs, and Minnesota Geological Survey mapping reviews.

The volume starts with a paper by H.E. Wright, who provides a concise summary of the history of work on Quaternary sediments in Minnesota prior to publication of this volume. His summary is followed by three papers that address the extent and style of deposition associated with the Late Wisconsinan Superior lobe. The first paper, by Johnson and Mooers, is based on regional mapping in Minnesota and Wisconsin. Their correlation of ice-margin positions provides a regional framework and perspective, and highlights the asymmetry of the Superior lobe. They also document three additional phases of the Superior lobe and comment on the different styles of moraines and their implications for ice-lobe dynamics. The second paper, by Knaeble, is based on field mapping in Stearns County. He uses twenty-two thoroughly investigated field sites to document glacial thrusting in the St. Croix Moraine by Superior-lobe ice. In the third paper, Quinn focuses his investigation of glacial landforms — especially tunnel valleys — on a six-quadrangle area (1:24,000) centered on Anoka, Minnesota. His purpose in mapping was to delineate hydrogeologic facies for a groundwater investigation.

The next two papers describe features in the same (east-central) part of the state but their focus is on glacial lakes that developed adjacent to the Superior lobe and the Grantsburg sublobe of the Des Moines lobe during the Late Wisconsinan. Meyer interprets the history of lakes in the Stacy Basin by integrating field mapping at a variety of scales and considering subsurface data. He presents his conclusions in a series of useful paleogeography diagrams. Johnson and Hemstad concentrate on evidence for the history of Glacial Lake Grantsburg. Using detailed sedimentologic descriptions of exposures and cores they document the lake's hundred-year history, substantiate the rapid advance of the Grantsburg sublobe, and explain the unusual red and brown laminae in part of the sequence. The authors of both of these papers have done an excellent job ferreting out obscure but useful references. The papers differ slightly in their interpretation of events — Meyer calls for the Superior lobe to advance into Glacial Lake Lind during its Automba phase, whereas Johnson and Hemstad see no evidence for this.

Moving to the west-central part of the state, Goldstein focuses on sediments associated with the Wadena lobe, commenting also on the Superior lobe to the east and the Des Moines lobe to the west and south. He uses field observations to constrain the sequence of glacial and meltwater events of the three ice lobes and comments on ice-lobe dynamics and the alternating dominance of ice-accumulation centers in Canada. Other papers in this volume follow up on some of the issues he first brought to light including the source of carbonate in the Wadena-lobe till and the relationship of the Wadena lobe to the Rainy lobe. Carney and Mooers restrict their mapping to a portion of the Itasca Moraine, which represents the fourth and final phase of the Wadena lobe in Goldstein's scheme. Carney and Mooers favor a slightly younger age for the moraine and recognize a gradual change in the till lithology, which they relate to a shift in ice-flow from the northeast (Wadena-source) to the northwest (Koochiching-St. Louis-sublobe source). As with Quinn's work, their mapping was conducted in order to relate glacial facies to groundwater recharge.

Rittenour, Geiger and Cotter turn our attention to a proglacial lake that fronted a late phase of the Des Moines lobe. Glacial Lake Benson was of greater extent and duration (over 40 varves have been counted) than previously interpreted. Harris, West and Tipping contribute a paper on an interesting subglacial drainage feature recognized during a regional mapping project in the Red River valley. Images of the shape and nature of the material filling a buried tunnel valley are created with drillers' logs of water wells and resistivity data. The particular tunnel-valley of the Red River lobe is well documented because it forms an aquifer, and is probably one of many such features associated with nearby ice margins.

The next three papers unravel the drainage history of two major streams in Minnesota — the Mississippi and Minnesota Rivers. Baker, Knox, Lively and Olsen use varying lines of evidence (geomorphic relationships, uranium-series dates on speleothems in caves near the river, and the paleomagnetic signature of lake sediments within parts of the buried channel) to substantiate the early entrenchment (prior to 790 ka, and possibly prior to 2.1 Ma) of the upper

Mississippi River valley. Johnson, Davis and Pederson consider the entire length of the present Minnesota River valley and show how difficult even local correlations among terraces are. Strath terraces dominate in the upper reaches of the Minnesota River valley, and fill terraces in the lower reaches. They augment their observations with facies analysis of extensive exposures in a fill terrace near Kasota, Minnesota. They recognize a deep downcutting period followed by rapid infilling of the 15 m-deep stream and a second deep downcutting period. They also recognize that phases of downcutting and infilling were not contemporaneous along the length of the river. Wright, Lease and Johnson look at the Mississippi River valley downstream of its confluence with the Minnesota River, and concentrate on the late-glacial and Holocene history of Lake Pepin. They are able to constrain the timing and sequence of events associated with the draining of Glacial Lake Agassiz and the demise of Glacial River Warren, by linking radiocarbon dates obtained from organic material in cores from Lake Pepin and other nearby lakes with evidence for vegetational changes as recorded by pollen.

Lusardi investigates the till stratigraphy preserved in a road cut near Henderson, Minnesota. She documents and identifies the till units and deformational features, and suggests that the sequence in the road cut does not match that recognized elsewhere in the region. The sequence has been affected by post-glacial downhill slumping or glacial thrusting. Pirkl, Kuglin and Cotter examine a pre-Wisconsinan lacustrine unit, the "Gastropod Silts" at 3 localities to better define its paleoenvironmental setting, and assess evidence for correlation between these gastropod-bearing silt units in the upper Midwest. The pollen and beetle assemblage and amino acid racemization dates indicate that these sediments are correlatable, are of Late Illinoian age, and contain subarctic species.

The last three papers treat methods that are commonly used to interpret the provenance of tills. Gowan statistically evaluated different methods of discriminating among till samples and identifying unknown samples. She determined that the commonly used combination of matrix texture and sand-grain composition does not discriminate among tills as well as matrix geochemistry does. Her statistical analysis also shows that the New Ulm Till and Granite Falls Till are similar, and that the Hewitt Till of the Wadena lobe fits best with tills of northeastern provenance. Harris correlates till units in North Dakota and northwestern Minnesota using the traditional combination of matrix texture and sand-grain composition. He uses an interactive computer program which assists in identifying statistically significant clusters in large data sets. Hobbs' contribution is a user's guide to the identification of 1–2-mm grains, which includes a map showing the sources for these different detrital-grain types. He describes in detail the characteristics used to identify grains, and the lithologic groupings that he has found most useful for different parts of Minnesota. All three papers emphasize that the data need to be consistent to be of use, and that the techniques used should be tailored to the problems and questions in a given study area.

Preparation of this volume has required decisions regarding terms commonly used in glacial geology (e.g. till, drift, moraine), as well as temporal terms (e.g. Wisconsin, Wisconsinan), geographic-temporal terms (e.g. Glacial Lake Agassiz, Glacial River Warren), and stratigraphic and geomorphic terms (e.g. New Ulm Till, St. Croix Moraine). We recognize that the style and terminology chosen may not be agreed upon by all workers, and may even be cause for healthy discussion. Regardless of any debate, the basic data presented in this volume represent a valuable contribution to Quaternary studies in Minnesota. The *Quaternary History of Minnesota* (Wright, 1972) has until now been the primer for glacial geologists working in Minnesota. It presents a history of late-glacial events and may be the reference most frequently cited in studies of glacial sediments in Minnesota. The authors of papers in this volume, *Contributions to Quaternary studies in Minnesota*, repeatedly emphasize that while they are adding detail and making minor changes, Wright's (1972) basic framework remains accurate. We hope this volume will be as useful to the glacial-geologic community as Wright's original article and will be used in conjunction with it.

I would like to thank G.B. Morey for suggesting that I organize this volume, the authors for their hard work and patience, the reviewers for thorough and thoughtful comments (John Attig, Howard Hobbs, Mark Johnson, Charlie Matsch, Gary Meyer), Kate Pound for her heroic editing effort and outsider's insight, Phil Heywood for drafting many of the figures, and Lynn Swanson for her editorial work in the early stages of preparation, as well as Herb Wright for his editorial acumen and laying the foundation for this work.

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NOTE ON MEASUREMENTS USED IN THIS REPORT

Although the metric system is preferred in scientific writing, certain measurements are still routinely made in U.S. customary units. For example, distances on land are usually measured in miles, and the contour interval on the U.S. 7.5-minute series topographic maps is 10 ft. Depths in drill holes are also routinely measured in feet. In this volume every attempt has been made to ensure consistent use of units of measure within each contribution, although preference is given to retaining the units (S.I. [metric] or U.S. Customary) in which measurements were originally made. To assist readers, conversion factors for some of the common units of measure are provided below.

Metric units to U.S. customary units:

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

U.S. customary units to metric units:

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

A SKETCH OF THE HISTORY OF GLACIAL INVESTIGATIONS IN MINNESOTA

H.E. Wright, Jr.

During the Late Wisconsinan glaciation the southern margin of the Laurentide Ice Sheet in the Great Lakes region was marked by distinct ice lobes. Their location (Figs. 1 and 2) was largely controlled by preglacial lowlands, the morphology of which was determined by the stratigraphy and structure of the bedrock. In Minnesota the Superior lobe advanced to the southwest along the Lake Superior basin, which was eroded in down-faulted late Precambrian red sandstone and slate bounded by resistant volcanic rocks. In the west the Des Moines lobe occupied the shallow lowland eroded in gray Paleozoic carbonate rocks and Cretaceous shales. These two lobes thus carried strongly contrasting rock types, and their deposition tells much about the nature of subglacial processes of erosion and deposition. Central Minnesota, however, was not marked by such prominent lowlands, and there the margin of the ice sheet was controlled in its expansion mostly by the morainic barriers built during previous glaciations as well as by the interaction of minor protuberances of the ice front. Central Minnesota was dominated by the Rainy lobe; the associated enigmatic Wadena lobe was confined largely to uplands in northern and north-central Minnesota.

Concepts of the glacial history of Minnesota have evolved in stages since the pioneer explorations of Winchell and Upham (1888), who correctly interpreted the conspicuous red and gray glacial sediments as being derived from the Lake Superior basin and the Red River lowland respectively. Winchell delineated the extent of Glacial Lake Agassiz and traced the development of Glacial River Warren and the formation and retreat of St. Anthony Falls. In the second stage, Leverett's (1932) much more detailed work, carried out on horse and foot with F.W. Sardeson in the 1910's, resulted in a map of the entire state that emphasized the red and gray glacial sediments. He identified the Wadena drumlins, but he considered that the ice flowed from the southwest rather than the northeast. He also delineated the Grantsburg and St. Louis sublobes of the Des Moines lobe. In a separate monograph he described the strandlines around Lake Superior (Leverett, 1929). In the same period Sardeson independently wrote many papers on local problems including the classification of the glacial periods, the formation of loess and sand dunes, and the drainage history. Most of these were published in the maverick journal Pan American Geologist—a fascinating story of geopolitics in the 1920's and 1930's recounted by Weiss (in press). In the same period a completely independent project on the Anoka Sandplain was carried out by Cooper (1935), a University botanist who started out to study the vegetation of the sand dunes that Sardeson had described. Cooper ended up making a comprehensive analysis of the geologic development of the area; he attributed most of the geomorphic features to shifting stream patterns, with eolian activity having only a minor impact.

A third stage in the history of investigations, carried out with modest support of the Minnesota Geological Survey, came in the 1950's and 1960's when newly available aerial photographs and topographic maps permitted the delineation of drumlin fields, moraines, tunnel valleys, eskers, and lake plains (Wright, 1972a). Of equal importance was the availability of new road cuts and other exposures, making it practical to study the glacial history by differentiating till types as well as by using geomorphic features. Clast counts of tills and gravels became widely used for distinguishing between tills of the different lobes, and for mapping their distribution and stratigraphic relations. The Rainy lobe was identified as occupying the upland northwest of the Superior lobe on the basis of landforms as well as till composition and texture. Four separate phases were distinguished for the Superior lobe on the basis of moraines and the reworking of proglacial lake clays. The calcareous tills in the western part of the state were differentiated into those of the Des Moines lobe (which contains fragments of Cretaceous shale) and those of the Wadena lobe (in which Cretaceous shale is absent). Three

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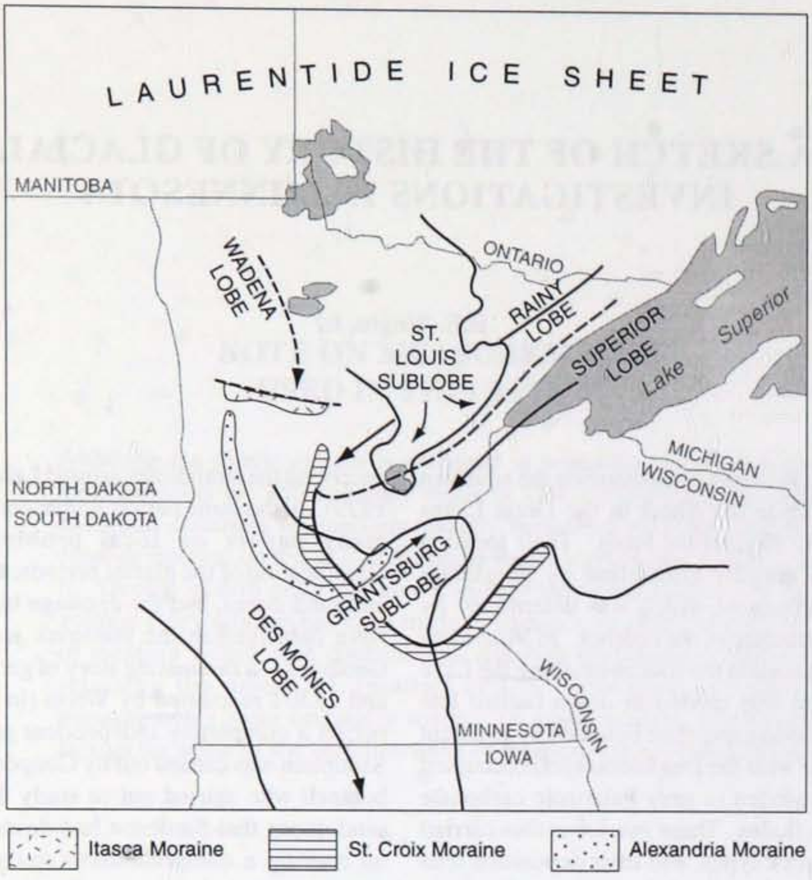

Figure 1. Minnesota and adjacent regions, showing probable extent of the Laurentide Ice Sheet during the Late Wisconsinan, and the maximum extent of associated ice lobes. Position of the Alexandria, Itasca and St. Croix Moraines also shown. Solid lines show known extent of ice lobe; dashed lines indicate uncertainty. Solid arrows indicate known direction of ice advance; dashed arrows indicate some uncertainty in inferred ice-movement direction.

major drumlin fields were delineated—the Wadena drumlins of west-central Minnesota, the Toimi drumlins of the northeast, and the Pierz drumlins in the center of the state (Fig. 2). Drumlins elsewhere in the state aided in tracing the course of the several ice lobes. The fan-shaped pattern of tunnel valleys and eskers associated with the Superior lobe led researchers to question the controls on the glaciological dynamics of major ice lobes. A series of small maps was prepared to show the interrelations of the ice lobes and the sequence of glacial events.

A synthesis of this fieldwork (Wright, 1972a) included results of local studies by Sharp (1953a,b) in northeast Minnesota, by Schneider (1961) in central Minnesota, and by Matsch (1971, 1972) in southwest Minnesota. It was followed by the preparation of a colored map of the glacial deposits of the entire state (Hobbs and Goebel, 1982) which adopted the previous interpretations of ice lobes and utilized regional soils maps that were based on a regional geomorphic classification (Wright, 1972b).

Since my 1972 synthesis of the glacial history, three doctoral dissertations have been undertaken independent of the Minnesota Geological Survey, and have elaborated or revised the picture. First, the cause of the distinctive interbedding of the Superior lobe (red) and Des Moines lobe (gray) glacial sediments in the Minneapolis area was examined by Chernicoff (1980, 1983), who showed unequivocally that the interbedding resulted from erosion and redeposition rather than from contemporaneous existence of the two ice lobes, as Leverett had believed.

Second, Goldstein (1985, 1989, this volume) undertook a thorough study of the Wadena drumlin field, which largely delineates the southern extent of the Wadena lobe. He proposed a major revision of the interpretation that I had made. The Wadena drumlins are rich in carbonate and form a well developed fan pattern, indicating ice flow to the southwest despite the inferred source of carbonate in the Winnipeg area to the northwest. Carbonate content in the Wadena drumlins increases to

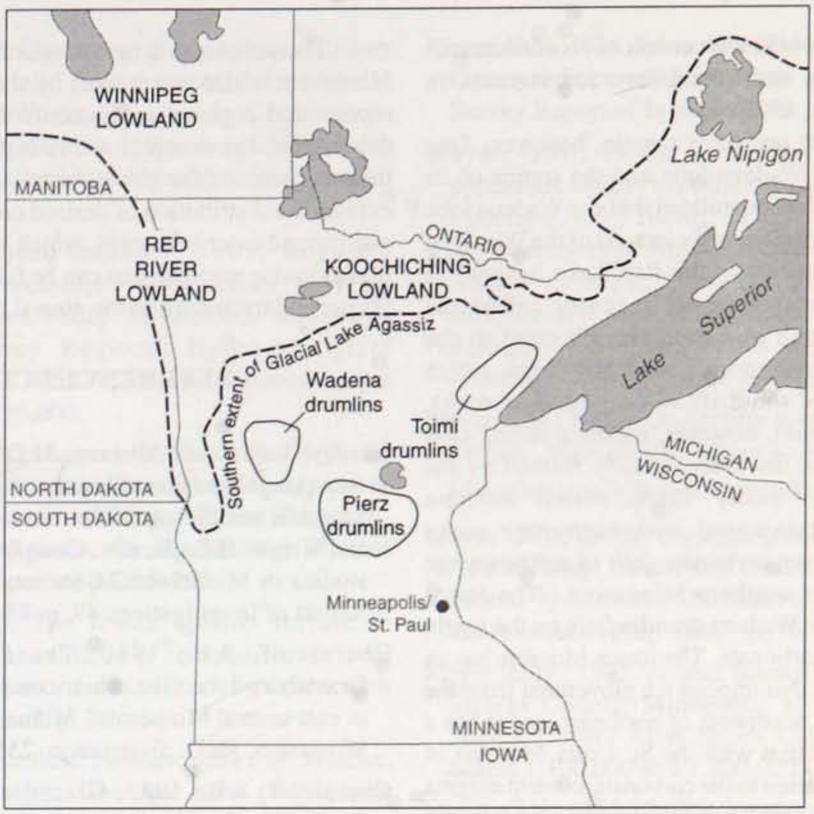

Figure 2. Location of geographic and geomorphic features discussed in the text.

the southwest. Either the ice came from the Paleozoic limestone terrane in the Winnipeg area to the northwest and was diverted to the southwest by encountering the Rainy lobe, which contaminated it with noncarbonate particles, or it was actually a deposit of the Rainy lobe contaminated by older carbonate drift that it overrode. I chose the former explanation, and Goldstein chose the latter on much more extensive lithologic analysis (Goldstein, this volume).

Third, relations between the Superior and Rainy lobes were investigated in central Minnesota in a comprehensive study by Mooers (1988), which included assessments of the significance of glacial thrust masses (Mooers, 1989a), tunnel valleys (Mooers, 1989b) and drumlins (Mooers, 1989c), as well as the identification of a sequence of retreatal ice-margin positions (Mooers, 1989d).

In recent years the Minnesota Geological Survey has expanded its activities in surficial geology and hydrogeology in response to county and state needs for land-planning and water-resource programs (e.g. Meyer, 1995). Four glacial geologists currently head projects in different areas. Hobbs (1983) sorted out the drainage connections among Glacial Lakes Agassiz, Aitkin, Upham, and the Lake Superior predecessors in northern Minnesota, as well as for lakes that preceded Glacial Lake Agassiz. He integrated the results of thesis studies in the interlobate area of the Superior and Rainy lobes in northeastern Minnesota (Hobbs and others, 1988). In southeastern Minnesota Hobbs (1993, 1995) worked on the complex of pre-Late Wisconsinan glacial deposits that extends southward beyond the Late Wisconsinan moraines, as well as on the development of the Iowan erosion surface by periglacial and eolian processes. Lithologic studies of deep cores by Meyer (1986, 1993a,b,c and 1996), in cooperation with the Minnesota Department of Natural Resources, have provided a picture of the distribution and correlation of glacial units that pre-date the Late Wisconsinan in central and northern Minnesota, and an evaluation of their influence on the texture and composition of the surficial glacial deposits. Meyer (this volume) also reinterpreted the history of the Anoka Sandplain, which he attributes to an essentially lacustrine origin, in contrast to Sardeson's eolian and Cooper's glaciofluvial models for its origin. Harris (1995) concentrated on the glacial stratigraphy in the Red River Valley and the use of computer-assisted lithostratigraphy. Research by Patterson has focused on the deposits and dynamics of the Des Moines lobe, especially in the southwestern part of the state (Patterson, 1996). She emphasizes the differentiation of the deposits into bands of subglacial and supraglacial (stagnation) materials and has identified short tunnel valleys and associated outwash on both margins of the lobe. Her work also deals with the mechanisms of ice flow in the context of recent research on surging glaciers and on modern ice streams in Antarctica (Patterson, 1998).

Some important problems remain, however. One is the concept of the Wadena lobe and the source of its carbonate content. I had postulated that the Wadena lobe eroded the Paleozoic carbonate rocks west of the Winnipeg lowland, flowed southeast to the Red Lake lowland of northwestern Minnesota (more recently called the Koochiching lowland), and then was diverted to the southwest by the contemporaneous Rainy lobe, which locally contaminated the drift with crystalline rocks. Goldstein (this volume), however, makes a strong case that the Wadena drumlins were actually formed by the southwest-flowing Rainy lobe, which became progressively contaminated with carbonate rocks contained in underlying carbonate drift of unknown age that covered most of northern Minnesota. The Itasca Moraine truncates the Wadena drumlin field on the north, and it is also rich in carbonate. The Itasca Moraine has an east-west orientation that implies ice movement from the north rather than the northwest or northeast, and it has a clear interlobate junction with the St. Croix Moraine of the Rainy lobe. A solution to the carbonate-content enigma is suggested in one contribution to this volume (Carney and Mooers). They suggest that the carbonate content of the Wadena drumlins and the Itasca Moraine is derived from the Hudson Bay lowlands rather than from the Winnipeg lowland. Much of this area of northern Minnesota is obscured by shale-bearing glacial sediments of the St. Louis sublobe of the Des Moines lobe, and by sediments of Glacial Lake Agassiz. Glacial sediments in the Ontario portion to the north contain less than 5 percent carbonate in their matrix (Dredge and Cowan, 1989), whereas the Itasca Moraine has as much as 40 percent. Until the problem of the carbonate source is solved, the status of the Wadena lobe is uncertain. Meyer (1997) supports Goldstein's (1987) model, in which much of the calcareous till of the Wadena lobe results from incorporation of older, carbonate-rich deposits, because deep cores show such contamination at the contacts between till units. Meyer (1997) attributes the enigmatic directional trends of the moraines and drumlins in this area to obstructions provided by the Giants Range and other bedrock protuberances. However, until this area in both northern Minnesota and adjacent Canada is more thoroughly studied, the concept that the Wadena lobe is represented by the Wadena drumlin field and the Alexandria Moraine is best retained. The term Rainy lobe should be restricted to ice associated with the St. Croix Moraine and its successors.

The accelerated rate of glacial investigations in Minnesota is also represented by the portions of county reports and regional assessments that show how such detailed local geomorphic and stratigraphic studies reveal the intricacies of the glacial history. These reports also explain the distribution of desired construction materials and groundwater resources, which are practical aspects of continuing research that can be fully elucidated with a proper understanding of the glacial history.

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ICE-MARGIN POSITIONS OF THE SUPERIOR LOBE DURING LATE WISCONSINAN DEGLACIATION

Mark D. Johnson[1] and Howard D. Mooers[2]

ABSTRACT

Recent mapping in the region covered by the Late Wisconsinan advance of the Superior lobe has revealed previously unidentified ice-margin positions that can be added to the 4-fold chronology proposed by Wright (1972) and Wright and others (1973). We present a map that synthesizes information on Superior-lobe ice-margin positions from Minnesota and Wisconsin. We recognize the following phases of the Superior lobe (in chronological order): Emerald, St. Croix, Automba, Split Rock, Nickerson, Porcupine, and Lakeview. The Emerald phase occurred between 20,000 and 25,000 yrs B.P. and the Lakeview at 9900 yrs B.P. We offer a hypothetical correlation map that shows that the Superior lobe had an asymmetrical recessional pattern because of a topographic high in western Wisconsin where Keweenawan basalt crops out, and a topographic low in eastern Minnesota along the former course of the St. Croix River.

INTRODUCTION

In this paper we present maps showing Superior-lobe ice-margin positions in Minnesota and western Wisconsin during Late Wisconsinan deglaciation. These maps are built upon work summarized by Wright (1972) and Wright and others (1973) and reflect recent field work in the region by Johnson (1986, and in press) and Mooers (1989, 1990). Parts of the maps show ice-margin positions interpreted from Hobbs and Goebel (1982) and Patterson (1994). We use the term "ice-margin position" for a former position of the ice margin as defined by a variety of geomorphic features which may include moraines.

Wright's overall framework (Fig. 1) for the history of the Superior lobe identifies the St. Croix-, Automba-, Split Rock-, and Nickerson-phase ice-margin positions (Wright, 1972; Wright and others, 1973). Subsequent mapping in Minnesota and western Wisconsin has increased understanding of the multiple phases of the Superior lobe. However, Wright's overall framework still accurately describes the history of the lobe. In this paper we summarize some of the details added during the last twenty years. We present a map showing ice-margin positions (Fig. 2), a map showing a hypothetical correlation of these margins (Fig. 3), and a brief synopsis of the sequence of Superior-lobe phases.

SUPERIOR LOBE ICE-MARGIN POSITIONS

The ice-margin positions interpreted for the Superior lobe (Fig. 2) are based on prominent geomorphic features that can be interpreted as indicating distinct ice-margin positions. These features are tunnel-valley mouths, tunnel-valley/outwash-fan pairs, outwash heads, discontinuous moraine ridges, abrupt boundaries of hummock tracts, and till-sheet margins. Each feature or group of features can be traced for several kilometers laterally; they represent stillstands, advances, or sedimentologic events that record the location of the ice margin (for example, the tunnel-valley/outwash-fan pairs clearly indicate the position of the ice margin but do not require an ice-margin stillstand or readvance). The

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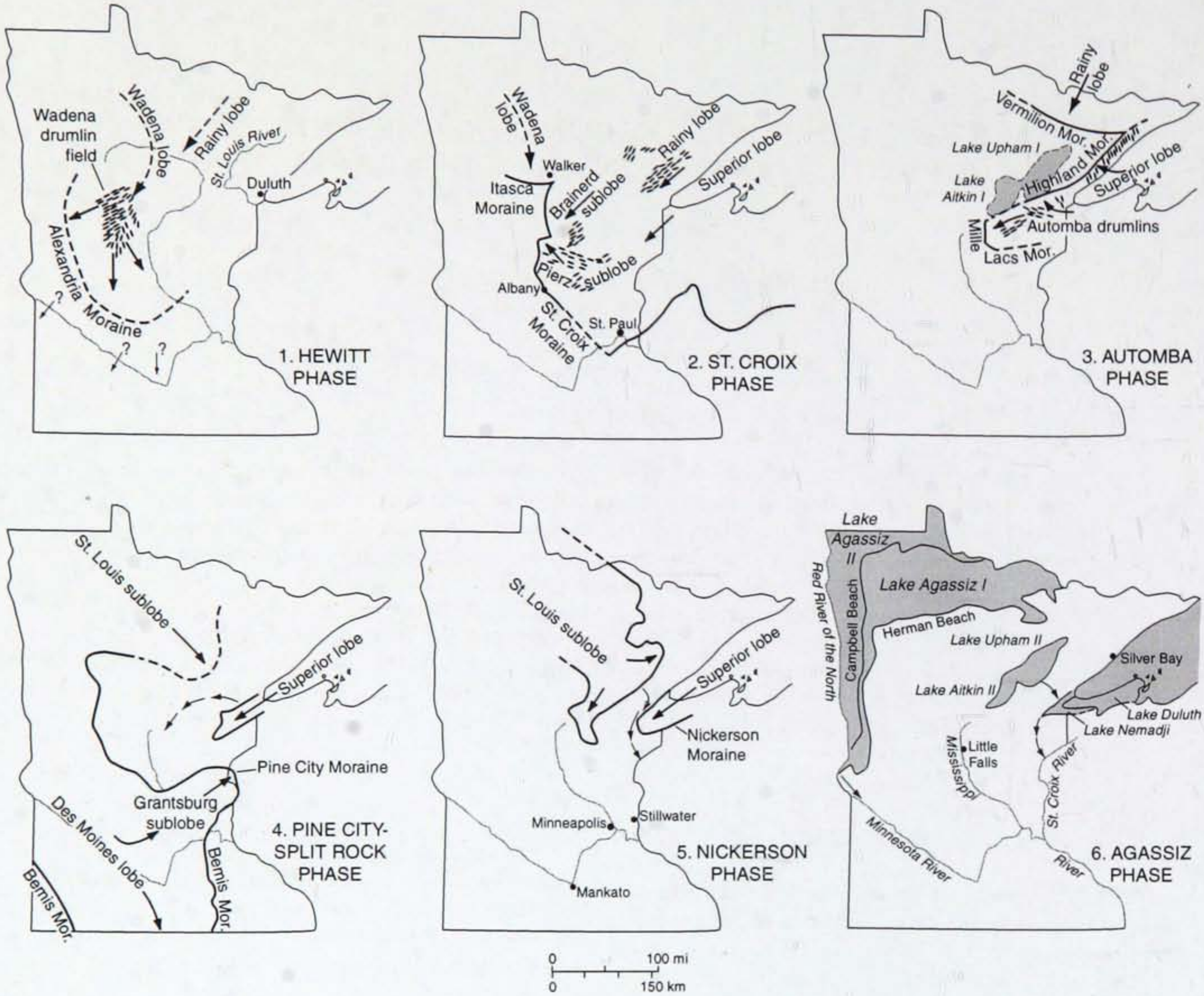

Figure 1. Sketch maps from Wright and others (1973) showing their interpretation of the sequence of ice-margin positions formed during overall retreat of the Superior lobe. Arrows indicate direction of ice flow; dashed where uncertain. Heavier black lines indicate ice-margin positions as determined from moraines; dashed where uncertain. Extent of glacial lakes shown by stipple; dashed margins indicate that extent or location is uncertain. Redrawn from Wright and others (1973).

sources for the ice-margin positions are shown in Table 1. Figure 2 represents an updated version of the map presented in Mooers and Johnson (1994).

Figure 3 shows a hypothetical correlation of the ice-margin features shown in Figure 2. This may be a false correlation, because we do not believe it necessary that ice-margin landforms were necessarily synchronous along the perimeter of the Superior lobe. It is probable that construction of ice-marginal landforms may shift from one part of the lobe to another during overall retreat. Nonetheless, we feel that presentation of this hypothetical correlation is helpful in revealing what we think to be the overall shape of the Superior lobe during retreat.

PHASES OF THE SUPERIOR LOBE

The events occurring during overall deglaciation of the Superior lobe, including construction of ice-marginal landforms, are referred to as "phases." Wright and Ruhe (1965) defined a phase as "...an informal unit of geologic time that is identified or defined on the basis of either morphologic or stratigraphic features...." The use of phases has since been adopted regionally (for example Clayton and others, 1992; Attig and others, 1985). The ice-margin positions shown in Figures 2 and 3 include features formed during the St. Croix, Automba, Split Rock, and Nickerson phases (Wright, 1972; Wright and others,

Table 1. Sources of information for Superior-lobe ice-margin positions.

GEOGRAPHIC AREA	ICE-MARGIN POSITIONS	SOURCE
Western Wisconsin	Centuria, Emerald, Fox Creek, Frederic, Hertel, Indian Creek, Luck, McKinley, St. Croix, West Sweden, and several unnamed margins in Polk County, Wisc.	Johnson (1986, in press), Johnson and Savina (1987)
Northwestern Wisconsin	Tiger Cat and several unnamed margins in Douglas County, Wisc.	Clayton (1984), **this paper**
Eastern Minnesota	Emerald, Ramsey, St. Croix, and several short ice-margin positions in Hennepin, Wright, and Sherburne Counties, Minn.	Hobbs and Goebel (1982), Johnson and Savina (1987), Meyer and others (1990), Patterson (1994)
Central Minnesota	Ann Lake, Beroun, Knife Lake, Mille Lacs, Nokasippi, Outing, Platte River, Pleasant Lake, Rum River, St. Croix, Stewart Lake	Schneider (1961), Wright (1972); Wright and others (1973), Mooers (1988, 1989)
Northeastern Minnesota	Cloquet, Nickerson, Sandy Lake, Sawyer, Thompson, Wright	Wright (1972), Wright and others (1973)

1973) as well as the Emerald phase (Johnson, in press). The Lakeview and Porcupine phases of the Superior lobe (Clayton, 1984; Clayton and others, 1992) post-date the Nickerson phase. Geomorphic features attributed to the Lakeview and Porcupine phases are not shown on Figures 2 and 3. We do not make an attempt in this paper to define other phases, although our increased database of ice-margin information indicates that other phases may be definable.

Emerald Phase

The term "Emerald phase" replaces the term "Early St. Croix Advance" used by Johnson (1986) for the first record of a glacial advance associated with the Superior lobe during the Late Wisconsinan. The Emerald-phase ice margin lies mostly in Wisconsin and in easternmost Minnesota. The extent of ice during the Emerald phase is shown by the distribution of several geomorphic features as well as the extent of the Poskin till (Johnson, 1986). Several collapsed valleys, small areas of hummocky topography, areas of deranged drainage, and a few ice-block depressions occur in central Barron County and northern St. Croix County, Wisconsin, and Dakota County, Minnesota (Johnson, 1986, in press; Johnson and Savina, 1987). No equivalent to the Emerald-phase ice margin is known west of the St. Croix Moraine in central Minnesota. The Emerald phase is considered by Johnson (1986, in press) to have occurred around 20,000–25,000 yrs B.P.

St. Croix Phase

The next youngest ice-margin position is the St. Croix-phase ice margin (following Wright, 1972). Much of the length of the St. Croix Moraine is not characterized by morainic ridges, but consists of hummock tracts, outwash plains, and tunnel-valley/outwash-fan pairs. We admit to loose usage of this helpful term in this report by referring to landforms built within 15 km of the St. Croix-phase ice-margin position as the St. Croix Moraine. The contemporaneity of the St. Croix Moraine in central Minnesota and the St. Croix-phase deposits in the Twin Cities area and western Wisconsin is not disputed in this paper, but we point out that this has not been proven either.

The St. Croix Moraine was named by Berkey (1897) for a north-south band of hummocks immediately east of the town of St. Croix Falls, Wisconsin. Leverett (1932) transferred the name St. Croix Moraine to the hummocky deposits that marked the edge of the Superior lobe in western Wisconsin and in central Minnesota. Upham (Winchell, 1888) mapped the glacial geology of several central Minnesota counties, which resulted in the first description of the major glacial features associated with what is now known as the St. Croix phase in Minnesota. Leverett (1932) used Upham's detailed descriptions and county maps in his mapping of the Superior lobe in Minnesota. Wright and Ruhe (1965) called the event that made these features the St. Croix phase. Recognizing the complexity of the Wisconsinan glacial sequence, Wright (1972) and Wright and others (1973) modified interpretations of the glacial history of central Minnesota, formerly thought by Leverett to be a simple invasion of the Patrician Ice Sheet, into the chronology depicted in Figure 1.

The timing of the St. Croix phase is uncertain. A radiocarbon date of 20,500 yrs B.P. ± 400 (I-5443) (Wright 1972; Wright and others 1973) was obtained from disseminated organic matter in lake sediments at Wolf Creek in central Minnesota. This lake is behind the St.

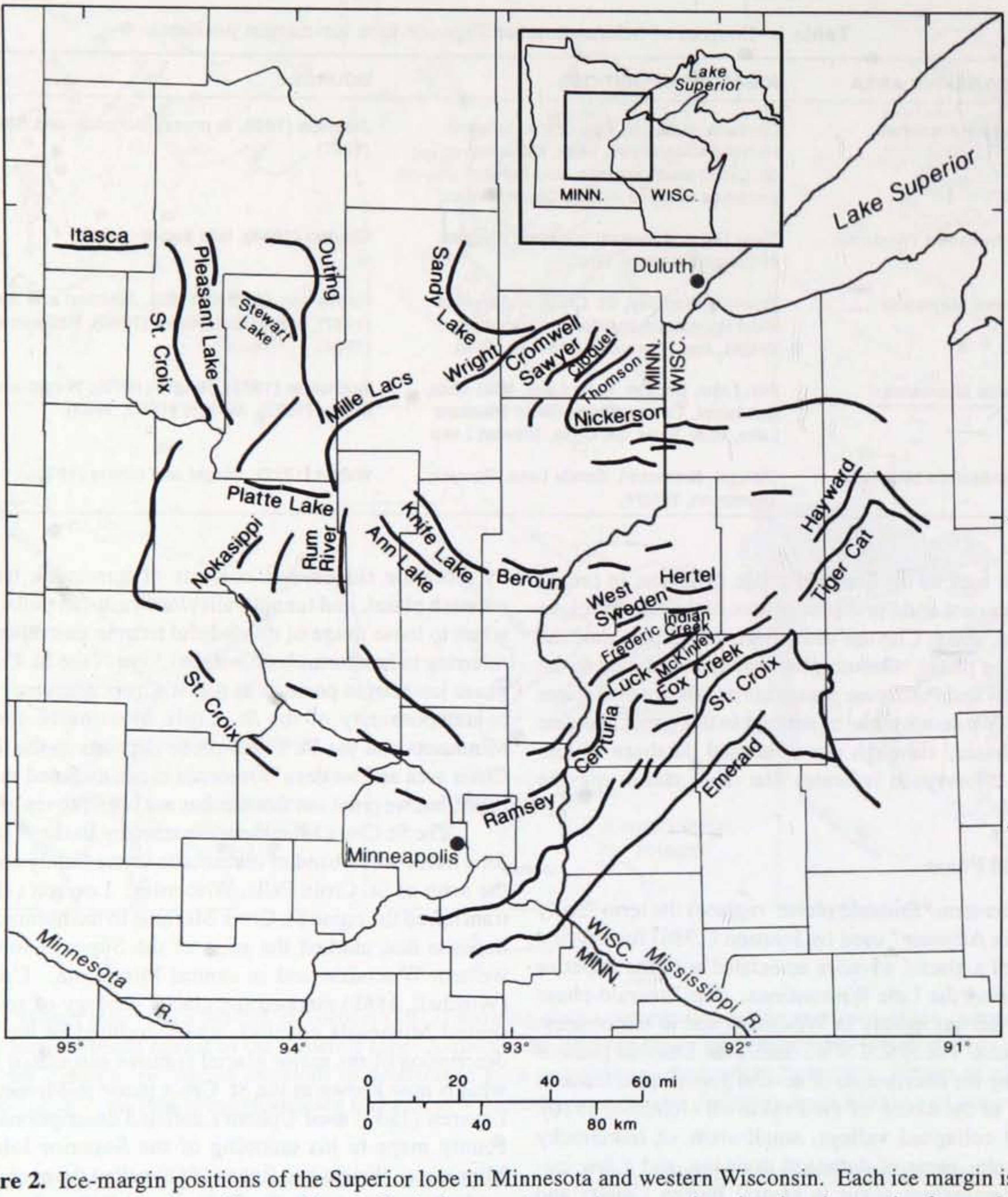

Figure 2. Ice-margin positions of the Superior lobe in Minnesota and western Wisconsin. Each ice margin is taken from prominent geomorphic or sedimentologic features that are interpreted as showing the precise former location of the Superior-lobe ice margin. Inset shows location of Figures 2 and 3.

Croix Moraine and would not have been ice-free until the ice margin had retreated 60 km from the maximum limit, possibly post-dating the St. Croix-phase maximum by hundreds of years. There is also a possibility that lake sediment was contaminated by old carbon, and the date may not be reliable. Clayton and Moran (1982), Mickelson and others (1983), Attig and others (1985), and Johnson (1986) suggest a somewhat younger age for the St. Croix phase, approximately 18,000 to 15,000 yrs B.P. Their chronologies are based on dates from wood in other regions, where there is less chance of contamination.

Ice-Margin Positions Formed Between the St. Croix and Automba Phases

Numerous ice-marginal landforms were formed along the southern margin of the Superior lobe in western Wisconsin and eastern Minnesota following the St. Croix

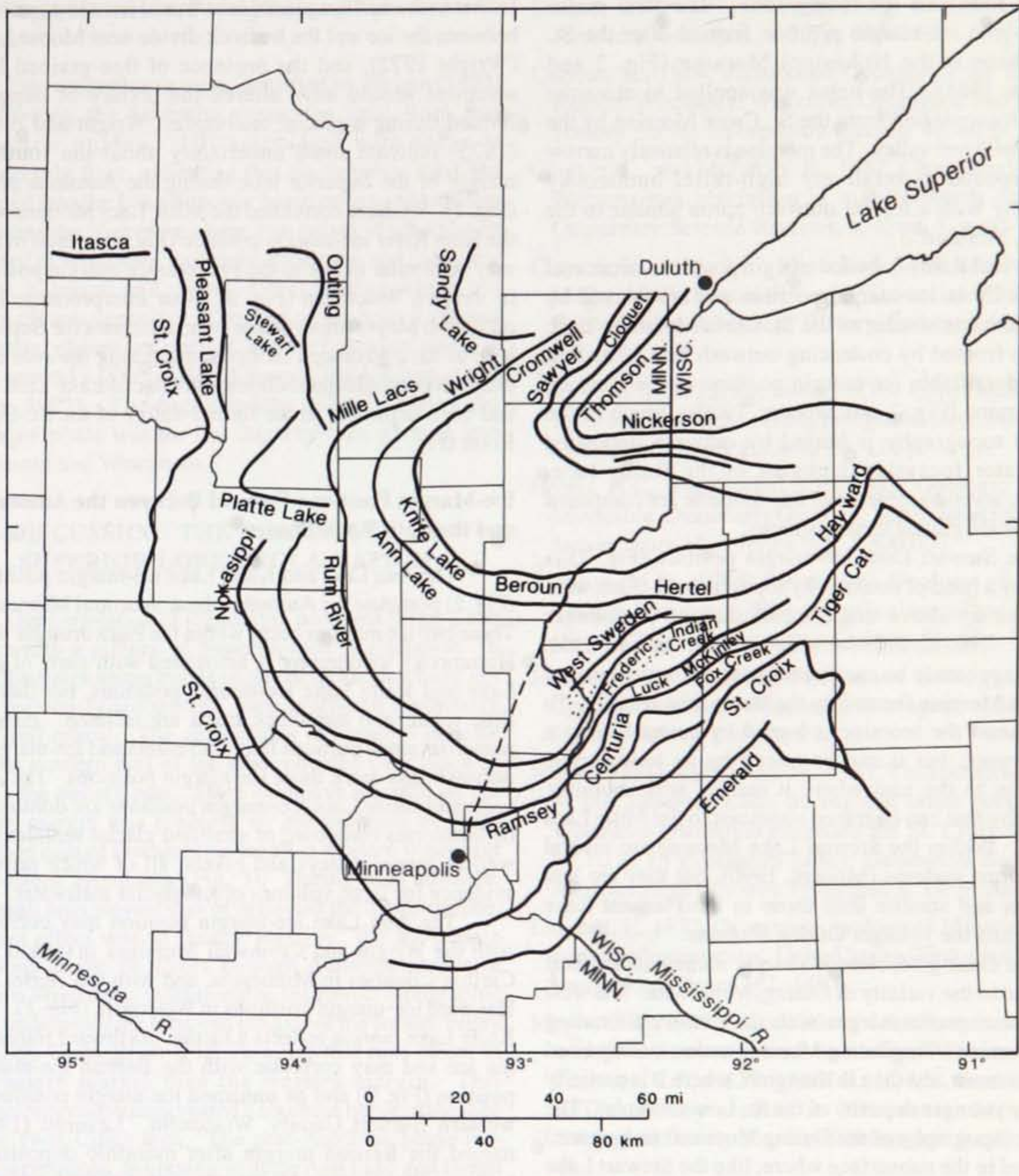

Figure 3. Hypothetical correlation of ice-margins shown in Figure 2. See text for discussion. Dashed line is former path of the St. Croix River (Cooper, 1935). Stippled area is outcrop region of basalt hills in Polk County, Wisconsin (Johnson, in press). See Figure 2 for location.

phase. The most prominent of these is a series of ice-margin positions that include the Tiger Cat, Fox Creek, McKinley, Luck, Centuria, Ramsey, and several unnamed ice margins that are identified by tunnel-valley/outwash-fan pairs in Hennepin, Wright, and Sherburne Counties, Minnesota (Patterson, 1994). The rough contemporaneity of these ice-margin positions is indicated not only by their geometry, but also by the fact that they all consist of landforms constructed of subglacially discharged outwash. Tunnel-valley mouths, outwash heads, and outwash fans occur along these margin positions, and some of the most extensive outwash plains in this region head in these ice-margin positions. The large amount of outwash associated with these ice-margin positions suggests an increase in meltwater production in the Superior lobe.

During retreat of the ice from the St. Croix Moraine in central Minnesota, the ice that formed the St. Croix Moraine subdivided more clearly into two lobes, the

Superior lobe and the Rainy lobe. The first major Superior-lobe ice-margin position formed after the St. Croix phase is the Nokasippi Moraine (Fig. 2 and Schneider 1961). The name was applied to morainic topography separated from the St. Croix Moraine by the Mississippi River valley. The moraine is relatively narrow and composed of relatively high-relief hummocky topography with a frontal outwash apron similar to the St. Croix Moraine.

Several Rainy-lobe ice-margin positions occur east of the St. Croix ice-margin position and are marked by hummock tracts similar to the St. Croix Moraine. Each margin is fronted by coalescing outwash fans. The first readily identifiable ice-margin position is the Pleasant Lake moraine (Fig. 2 and Mooers, 1990). Much of the morainic topography is buried by outwash deposited during later recessional phases of the Rainy lobe. However, several segments of this moraine are composed of large-scale glacial thrust systems.

The Stewart Lake ice-margin position (Fig. 2) is marked by a band of hummocky topography 2–3 km wide that sticks up above thick accumulations of younger outwash. The northwestern end of the Stewart Lake Moraine appears to be continuous with the eastern end of the Itasca Moraine formed by the Itasca lobe (Fig. 2). To the southeast the moraine is buried by outwash from a later advance, but it can be traced by its topographic expression to the east where it merges with morainic topography that can be traced southeast to the Mille Lacs Moraine. Within the Stewart Lake Moraine are several glacial thrust systems (Mooers, 1990), but they are less numerous and smaller than those in the Pleasant Lake Moraine and the younger Outing Moraine.

The Outing Moraine is sharply arcuate and is best developed in the vicinity of Outing, Minnesota. The west end of the moraine merges with the east-west-trending Itasca Moraine. The Outing Moraine makes a sharp bend to the southeast and then to the south, where it is partially buried by younger deposits of the St. Louis sublobe. The morainic topography of the Outing Moraine can be traced southward in the subsurface where, like the Stewart Lake Moraine, it appears to merge with the Mille Lacs Moraine.

Automba Phase

Wright's (1972; Wright and others, 1973) second phase of the Superior lobe is called the Automba phase (Fig. 1). The maximum extent of the Superior lobe during the Automba phase was determined to be the Mille Lacs morainic system along the west side of Lake Mille Lacs. Prior to this readvance, the Superior lobe apparently retreated no more than 150 km. If the ice had retreated farther to the north, a glacial lake would have been ponded between the ice and the bedrock divide near Moose Lake (Wright 1972), and the presence of fine-grained lake sediment should have altered the texture of deposits formed during a glacial readvance. Wright and others (1973) indicate some uncertainty about the southern margin of the Superior lobe during the Automba phase (Fig. 1). We have correlated the Mille Lacs Moraine with the Rum River ice-margin position (Fig. 2), which in turn may be similar in age to the Frederic ice-margin position in western Wisconsin (Fig. 3). Our interpretation is at odds with Meyer (this volume) who interprets the Superior lobe to have advanced farther south during the Automba phase over proglacial sediments of Glacial Lake Lind that had been deposited in the former valley of the St. Croix River (Fig. 3).

Ice-Margin Positions Formed Between the Automba and the Split Rock Phases

The Ann Lake and Knife Lake ice-margin positions (Fig. 2) post-date the Automba phase in central Minnesota. These two ice margins occur within the Pierz drumlin field. Hummocky topography is associated with parts of Ann Lake and Knife Lake ice-margin positions, but there is little relief, and hummock tracts are isolated. Instead, numerous small outwash fans with eskers and ice-marginal outwash fans mark these ice-margin positions. The Ann Lake and Knife Lake ice-margin positions are dominated by landforms composed of stratified glacial sediment, as well as tunnel valleys and eskers, all of which provide evidence for large volumes of subglacial meltwater.

The Ann Lake ice-margin position may correlate with the Wright and Cromwell Moraines in Aitkin and Carlton Counties in Minnesota, and with the Hertel and Hayward ice-margin positions in Wisconsin (Fig. 3). The Knife Lake margin reflects a further northward retreat of the ice and may correlate with the Beroun ice-margin position (Fig. 2) and an unnamed ice-margin position in western Burnett County, Wisconsin. Leverett (1932) named the Beroun margin after morainic deposits in southern Pine County, Minnesota. Some of the landforms that Leverett cited are used by us to map the Beroun ice-margin position, but our reconstruction differs in shape from Leverett's.

Several ice-margin positions are shown in northern Pine County, Minnesota and southwestern Douglas County, Wisconsin (Fig. 2). These ice margins are interpreted from lines of hummocks that stretch across the streamlined landscape of this region. Some of these may correlate with either the Split Rock- or Nickerson-phase margins.

Split Rock, Nickerson, Porcupine, and Lakeview Phases

Two other phases were identified by Wright (1972) as following the Automba phase: the Split Rock and Nickerson phases. Till associated with these is considerably finer, indicating that the Superior lobe had retreated into the Lake Superior basin prior to advancing. Following the Nickerson phase, two pulses of ice advance occurred in Wisconsin, called the Porcupine and Lakeview phases (Clayton and others, 1992), during which red clayey till was deposited. The ages of the Split Rock and Nickerson phases are unclear, but the Lakeview phase is dated around 9,900 yrs B.P. (Clayton, 1984; Clayton and others, 1992). The Superior-lobe advance during the Lakeview phase was the last Superior-lobe advance into Minnesota and Wisconsin.

DISCUSSION: THE CHARACTER OF SUPERIOR LOBE DEGLACIATION

Our correlation of ice-margin positions (Figs. 2 and 3) provides a picture of Superior-lobe deglaciation. It also illustrates some trends in deglaciation that have not been previously recognized, particularly the asymmetry of overall retreat. The correlations in Figure 3 indicate that the western part of the lobe retreated over twice as fast as the eastern part. More extensive advance on the eastern margin was hindered by the presence of high-elevation hills of Precambrian basalt in western Wisconsin and eastern Minnesota (Fig. 3). During each advance, the basalt hills slowed and/or deflected the Superior lobe. The net effect was to "bunch together" the ice-margin positions of the St. Croix through Automba phases in western Wisconsin. Additionally, the lowest topographic point underneath the lobe was the axis of the former valley of the St. Croix River (Fig. 3), a line that runs closer to the eastern margin than the western margin. This topographic constraint created a southern bulge in the lobe in the Twin Cities area. The post-Automba phase ice-margin positions, beginning with the Ann Lake and Hertel ice-margin positions (Fig. 3), have a geometry unaffected by the higher ground in Wisconsin and are more concentric with the western end of Lake Superior.

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SUPERIOR-LOBE GLACIAL THRUSTING OF SEDIMENT AND BEDROCK ALONG THE ST. CROIX MORAINE, STEARNS COUNTY, MINNESOTA

Alan R. Knaeble

ABSTRACT

Glacial thrusting of sediment and bedrock played an important part in the development of the St. Croix Moraine in Stearns County, west-central Minnesota. The ice-thrust features formed as Late Wisconsinan Superior-lobe ice advanced southwest across Stearns County. Evidence for glacial thrusting is documented from 22 sites between Avon and Kimball. At the Powder Ridge borrow pit near Kimball, thrust slabs of Cretaceous bedrock, a variety of old till units and Superior lobe-derived sediments dip 30°–60° northeast, in what would have been the up-glacier direction. Folding and streaking are common along thrust-block boundaries. At other sites (Avon Ridge, Fifth Lake, Merden Esker and St. Benedict), glacial deposits are structurally overlain by Cretaceous bedrock. Saprolithic material derived from Precambrian basement overlies glacial deposits at some locations, and older tills structurally overlie Late Wisconsinan Superior-lobe tills at some localities. Superior-lobe ice excavated, transported, deformed, and stacked preglacial, proglacial and subglacial materials to form many of the prominent topographic features of the St. Croix moraine complex. Theoretically, glacial thrusting took place where there was sufficient ice-flow velocity, the subglacial pore-water pressure was elevated, and permafrost conditions extended into subglacial material and bedrock.

INTRODUCTION

The importance of glacial thrusting in the development and modification of glacial landforms has been recognized in Alberta and Saskatchewan in western Canada (Kupsch, 1962; Christiansen and Whitaker, 1976). Bluemle and Clayton (1984) suggested that in North Dakota "thrusting of subglacial material was widespread and that glacial thrusting was the single most important geomorphic process in some parts of the North American midcontinent region." Glacial thrusting of sediment and bedrock is here interpreted to have played a significant role in the development of landforms within the St. Croix Moraine in Stearns County, Minnesota.

The data and interpretations presented in this paper represent observations and interpretations made during preparation of the Stearns County geologic atlas in 1993-1995 (Meyer, 1995; Meyer and Swanson, 1996). Stearns County lies in west-central Minnesota (Fig. 1). Elevation ranges from about 1,450 to 950 ft. Drainage is to the southeast along the Sauk and Crow Rivers and east along the Clearwater River. These rivers empty into the Mississippi River, which flows southeast and forms the eastern boundary of the county (Fig. 1).

Glacial thrusting is interpreted from field observations made at surface exposures; these observations are complemented by data obtained from samples collected at surface exposures in road cuts, river cutbanks, and gravel and borrow pits (Fig. 2 and Table 1). Samples and data were also collected from four shallow hand-auger borings (which extend 4 feet below the surface), and 97 Giddings-probe borings (which extend from 8 to as much as 56 ft below the surface). In addition, seven Rotasonic drill holes ranging from 95 to 200 ft deep were logged and sampled. A total of 650 samples were collected and analyzed in the laboratory to determine textural composition. Grain-count identifications (Hobbs, this volume) were completed for about 400 of the samples. Seismic refraction profiles were obtained from 15 sites, and magnetic susceptibility

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values were determined for samples from the Powder Ridge borrow pit and for Rotasonic core samples; however, neither of these methods provided information useful for interpreting thrust features. Stearns County water-well drilling logs (unpublished Minnesota Geological Survey files) provided additional data, as did Minnesota Highway Department bridge-boring logs. Data from Mooers (1988) assisted in the initial location of thrust sites and their interpretation.

REGIONAL GEOLOGIC SETTING

The surface geology of Stearns County is composed almost entirely of glacial sediments. Precambrian bedrock beneath the sediments includes Archean schist and gneiss as well as Proterozoic volcanic and metasedimentary rocks, schist, and coarse-grained intrusive rocks. The Precambrian rocks protrude through the glacial sediments

Table 1. Summary of information for each of the 22 glacial thrust sites studied within Stearns County.

Location Name	T-R-S §	Primary Data Source	Background Data
Powder Ridge borrow pit	122-29-27	3 water-well logs	WWL
		1 borrow pit exposure	S, 6 GB, SP; T; GC; R*; MG
Avon Ridge	124-30-17,18	1 water-well log	WWL
		2 Giddings-probe borings	GB; S; T; GC
	125-30-34	1 Giddings-probe boring	GB; S; T; GC
Fifth Lake	124-31-2	1 gravel pit exposure	S; T; GC
	124-31-3	1 outcrop exposure	visual
Merden Lake Esker	124-30-25	1 gravel pit exposure	S; T; GC
St. Joseph	124-29-16	1 Giddings boring	3 GB; R; S; T; GC
Other Sites	122-29-29	2 Giddings-probe borings	2 GB; S; T; GC
	123-29-29	2 water-well logs	WWL
	123-29-31	3 outcrop exposures	S; T; GC
	123-30-24	1 water-well log	WWL
	124-31-1	1 Giddings-probe boring	GB; S; T; GC
	125-30-20	1 outcrop exposure	visual

WWL - interpreted water-well log; GB - Giddings-probe boring; S - sample; T- textural analysis; GC - grain count; R - Rotasonic core; MG - magnetic susceptibility; * - Rotasonic core 1.5 mi south of Powder Ridge borrow pit was used for interpretation. § - sites are located using the township, range and section system.

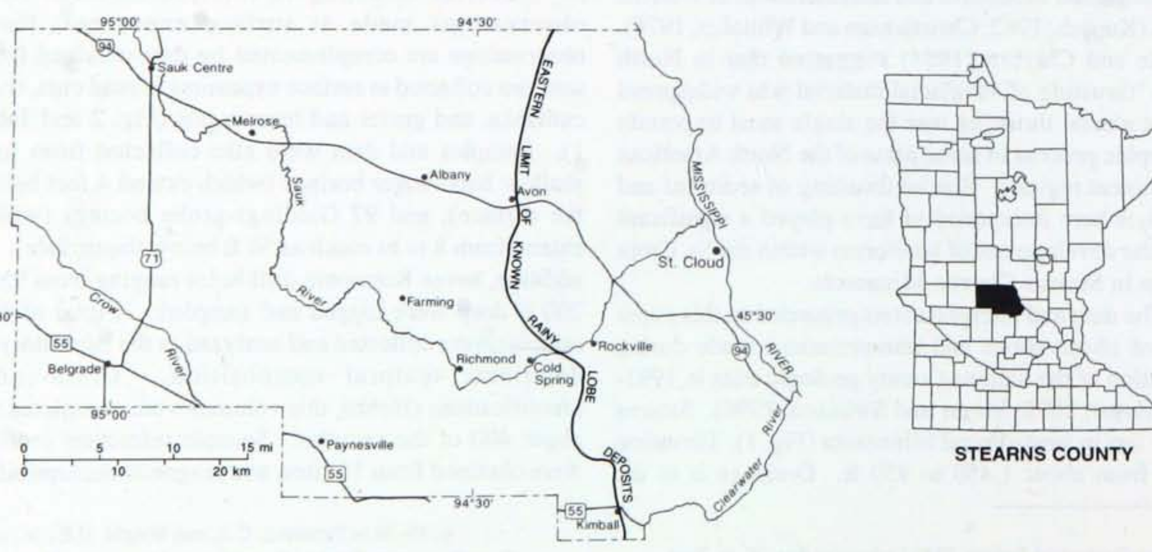

Figure 1. Geographic features mentioned in the text, and known extent of Rainy-lobe deposits. Location of Stearns County shown on inset.

in and around Waite Park, St. Cloud, Rockville, and Cold Spring (Boerboom, 1995). Late Cretaceous shale forms a thin veneer, commonly less than 100 ft thick, which is preserved within Precambrian bedrock lows in east-central and southeastern Stearns County (Setterholm, 1995).

Glacial deposits blanket the bedrock countywide except for the isolated knobs of Precambrian basement in east-central Stearns County. Glacial deposits reach a maximum thickness of 500 ft in the southwest corner of Stearns County. Numerous pre-Wisconsinan till units overlie bedrock, but are only rarely exposed at the surface. In the subsurface, the pre-Wisconsinan till units are widespread yet discontinuous; this is a result of erosion and deformation during subsequent glacial advances. The pre-Wisconsinan till units contain evidence for the many pulses of ice advance into Stearns County since the onset of the Pleistocene Epoch. Clast types within the pre-Wisconsinan tills indicate (Meyer and Knaeble, 1996) the dominant source to be the Winnipeg lowland (gray clayey carbonate-rich till), with only rare evidence for till of Superior basin source (red sandy carbonate-poor till).

Surficial glacial deposits (Meyer and Knaeble, 1995) consist predominantly of Late Wisconsinan sediment deposited by the successively younger Rainy, Superior, and Des Moines lobes of the Laurentide Ice Sheet. Rainy-lobe deposits of northeast source

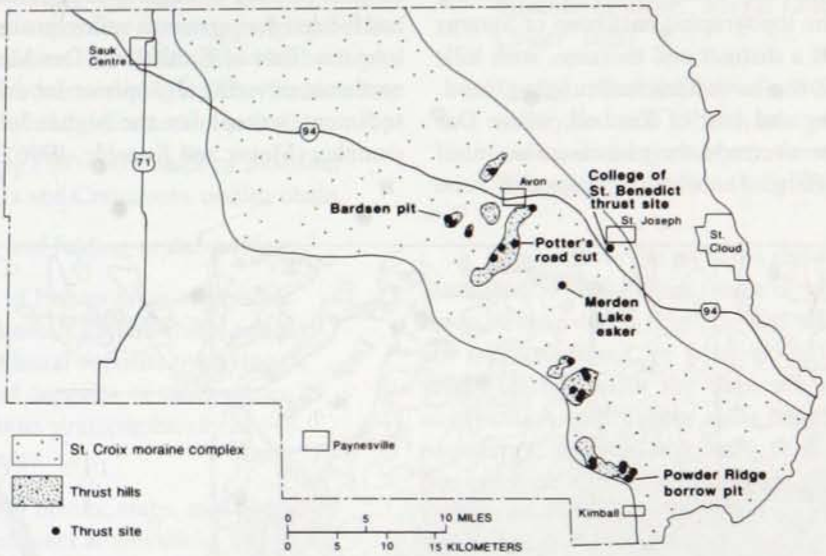

Figure 2. Stearns County showing location of the St. Croix Moraine and sites examined and interpreted to have formed through glacial thrusting.

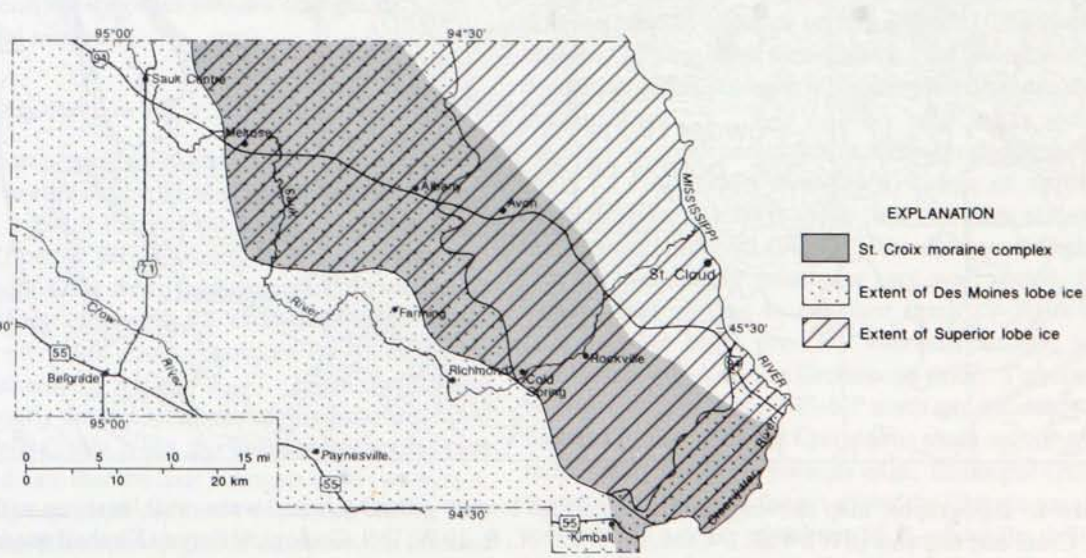

Figure 3. Stearns County showing the current surface extent of the St. Croix Moraine, and the inferred extent of Superior-lobe ice during deposition of the St. Croix Moraine. The extent of the later Des Moines-lobe ice is also shown.

stratigraphically underlie Superior-lobe and Des Moines-lobe deposits and are exposed only rarely at the surface in cut banks of existing or abandoned river channels. Rainy-lobe deposits are well documented in the subsurface in the western three-quarters of Stearns County (Fig. 1).

Superior-lobe ice advanced from the northeast prior to 16,150 yrs B.P. (Birks, 1976), possibly contemporaneously with the Rainy lobe or soon after Rainy-lobe ice began to retreat. The Superior-lobe deposits form the discontinuous St. Croix moraine complex (Meyer and Knaeble, 1996), which is 10–20 mi wide. In Stearns County it trends southeast from just east of Sauk Center to northeast of Kimball (Fig. 3). The western edge of the moraine complex between Farming and Kimball forms the topographic backbone of Stearns County; it consists of a distinct end moraine, with hills standing up to 300 ft above the surrounding land. Northwest of Farming and east of Kimball, where Des Moines-lobe ice later overrode the end moraine, relief becomes subdued (Fig. 3). Relict Superior-lobe subglacial tunnel-valley channels as wide as 2 miles breach the moraine in places and are now occupied by streams, lakes and lowlands. The Superior lobe formed two recessional moraines during its northeasterly retreat (Meyer and Knaeble, 1996).

Des Moines-lobe ice advanced from the northwest, covering the Rainy lobe deposits, and overrode the St. Croix Moraine between Sauk Center and Farming (Fig. 3). Thin ice-marginal deposits west of Avon mark a north-south-trending line, showing where the lobe appears to have stagnated. Between Farming and Kimball, the St. Croix end moraine blocked the advance of the Des Moines ice, although sediments were deposited by meltwater streams flowing through open gaps in the moraine, which had formed during tunnel-valley erosion beneath Superior-lobe ice. East of Kimball the Des Moines lobe extended northeast, covering all Superior-lobe deposits with glacial sediment, except for the higher hills of the moraine complex (Meyer and Knaeble, 1996).

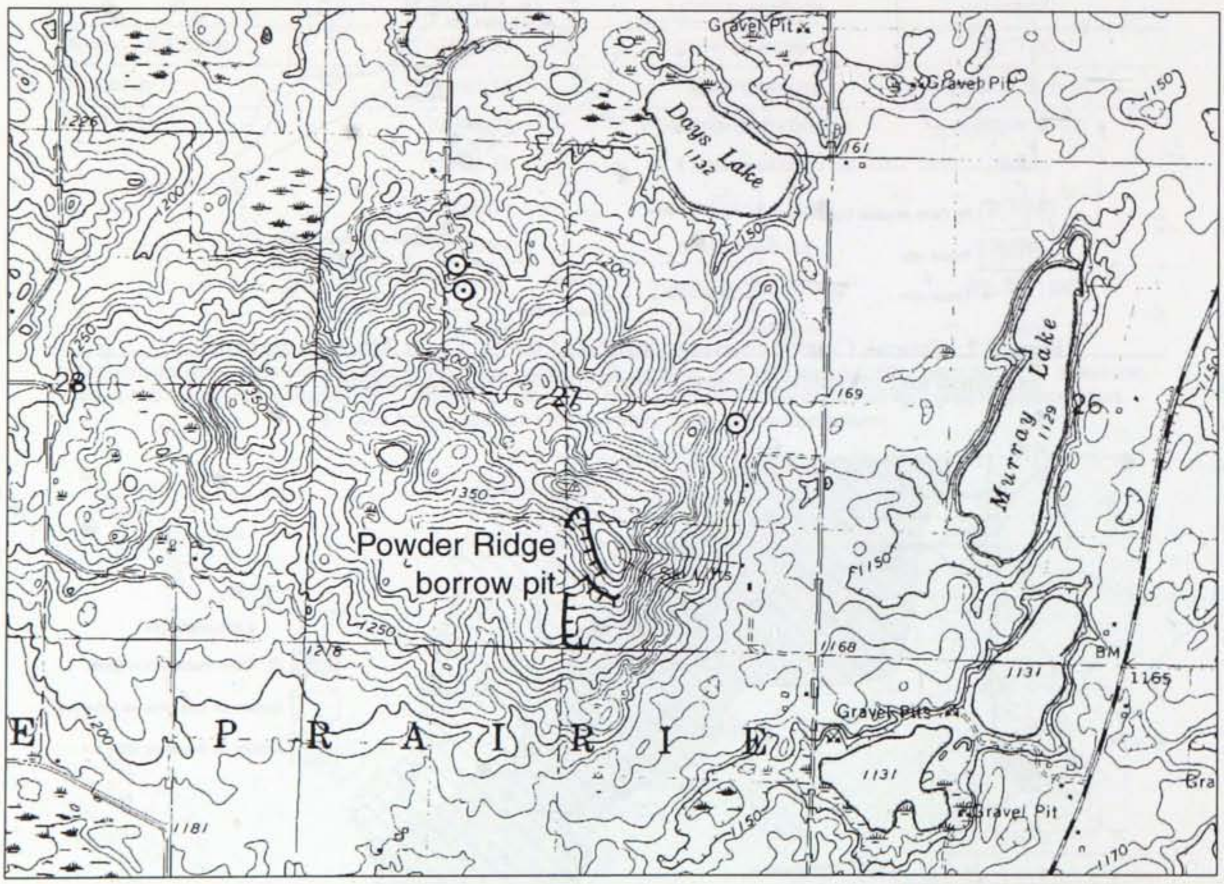

Figure 4. Topographic map showing the Powder Ridge borrow pit and selected water-well locations within the St. Croix end moraine (SW1/4 SE 1/4, sec. 27, T. 122 N., R. 29 W; U.S. Geological Survey Kimball quadrangle, 7.5 minute series, 1967). Area shown is 2.4 miles wide; contour interval is 10 ft. Lines with tick marks delineate scarps; ticks point down-scarp. Circled dots show the location of selected water wells. Lakes now fill larger depressions that were probably the local source for thrust material.

GLACIAL THRUST SITES IN STEARNS COUNTY

Mooers (1988, 1990a, 1990b) recognized and described glacial thrusts in Stearns County. From field evidence he concluded that glacial thrusting took place during the Itasca/St.Croix phase (Wright, 1972) within recessional moraines deposited by Superior- and Rainy-lobe ice, both north of Stearns County and near the Superior-lobe St. Croix end moraine in Stearns County. In this paper, detailed evidence for glacial thrusting caused by the southwest advance of Superior-lobe ice is presented. Glacial thrusting is interpreted from twenty-two sites that lie within the St. Croix Moraine (Fig. 2 and Table 1). Eight of the sites are surface exposures at outcrops, gravel pits, or borrow pits; seven sites are Giddings-probe borings, and seven of the sites are well logs. The features or characteristics used to infer deformation include:

1. Steeply dipping (30°– 60°) slabs of stratified glacial deposits and Cretaceous marine shale.
2. Shear mixing and folding at slab contacts.
3. The presence of Precambrian saprolithic material, Cretaceous marine shale, and pre-Wisconsinan glacial deposits overlying younger glacial deposits, or the presence of marl or coal units stratigraphically above glacial sediments.
4. The presence of blocks, slabs, and streaks of Cretaceous sediment at elevations 100 ft or more above the top of the surrounding Cretaceous bedrock surface.
5. Repetitive sequences of color changes in glacial materials.

Powder Ridge Borrow Pit

The best evidence for glacial thrusting is recorded four miles northwest of Kimball in the Powder Ridge borrow pit, west of the Powder Ridge ski hill (Fig. 2). This large borrow pit is located in the St. Croix end moraine, about 225 ft above the surrounding outwash plain of the Des Moines lobe (Fig. 4). The pit is oriented north-south and provides good exposures on its northern, western and eastern walls (Fig. 5). Six texturally and compositionally distinct sedimentary units are recognized in the pit walls (Table 2, Fig. 6). Textural and grain-count analyses indicate that the four youngest units (wt-w, st-x, wt-x and st) represent sediment deposited during four separate Late Wisconsinan glacial advances. In inferred stratigraphic order, from oldest to youngest, the units exposed in the pit walls are:

1. Unit K : Cretaceous marine shale contains septarian concretions and large selenite crystals
2. Unit S : pre-Late Wisconsinan sands
3. Unit wt-w : Unoxidized dark grey clayey till (Winnipeg provenance; informally named the "Elmdale till" by Meyer, 1986)
4. Unit st-x : Unoxidized dark red-brown till (Superior provenance, "Old Red Till")
5. Unit wt-x : Oxidized yellow-brown or unoxidized grey silty till (inferred to be Illinoian or older "Meyer Lake" and "Sauk Center" tills)
6. Unit st : Reddish brown sandy till, subdivided into till (st), lake sediments (sl) and sand and gravel (so); these are Late Wisconsinan Superior-lobe sediments

Exposures in the pit walls show these sediments to form slabs 50–150 ft thick, some of which extend laterally for more than 400 ft (Fig. 5). The slab contacts dip 30°–60° north-northeast, in what would have been the up-glacier direction for the Superior lobe. The internal stratification within these slabs largely subparallels slab boundaries, although two zones, each 50–100 ft thick, are intensely deformed; the sediments are sheared, streaked, and mixed, and display distorted overturned folds. Based on comparisons with the stratigraphic sequence observed in apparently undeformed areas, sediments within the pit can be divided into at least 6 thrust blocks. Each thrust block contains two or more distinct units, which are differentiated by color or texture or both. The youngest till unit (st) caps each thrust block. Ice associated with deposition of this youngest till is interpreted to have caused the thrusting.

At the south end of the pit, Cretaceous marine shale (unit K) structurally overlies a wedge of deformed Superior-lobe till 10 ft thick that contains streaks of incorporated older till (Fig. 5). The deformed Superior-lobe till structurally overlies a very well sorted, finely bedded unit of fine to medium sand 25–30 ft thick interpreted to be of pre-Late Wisconsinan age, which stratigraphically overlies Cretaceous shale. The contacts between these units dip 30°–60° north and indicate south-directed thrusting of the Cretaceous shale and overlying sedimentary units over younger units. Rotasonic drill core from the south end of the pit shows the Cretaceous shales to extend to a depth of at least 56 ft, where the drill core ended. The elevation at the top of these Cretaceous sediments is 1300 ft, although well logs show the highest

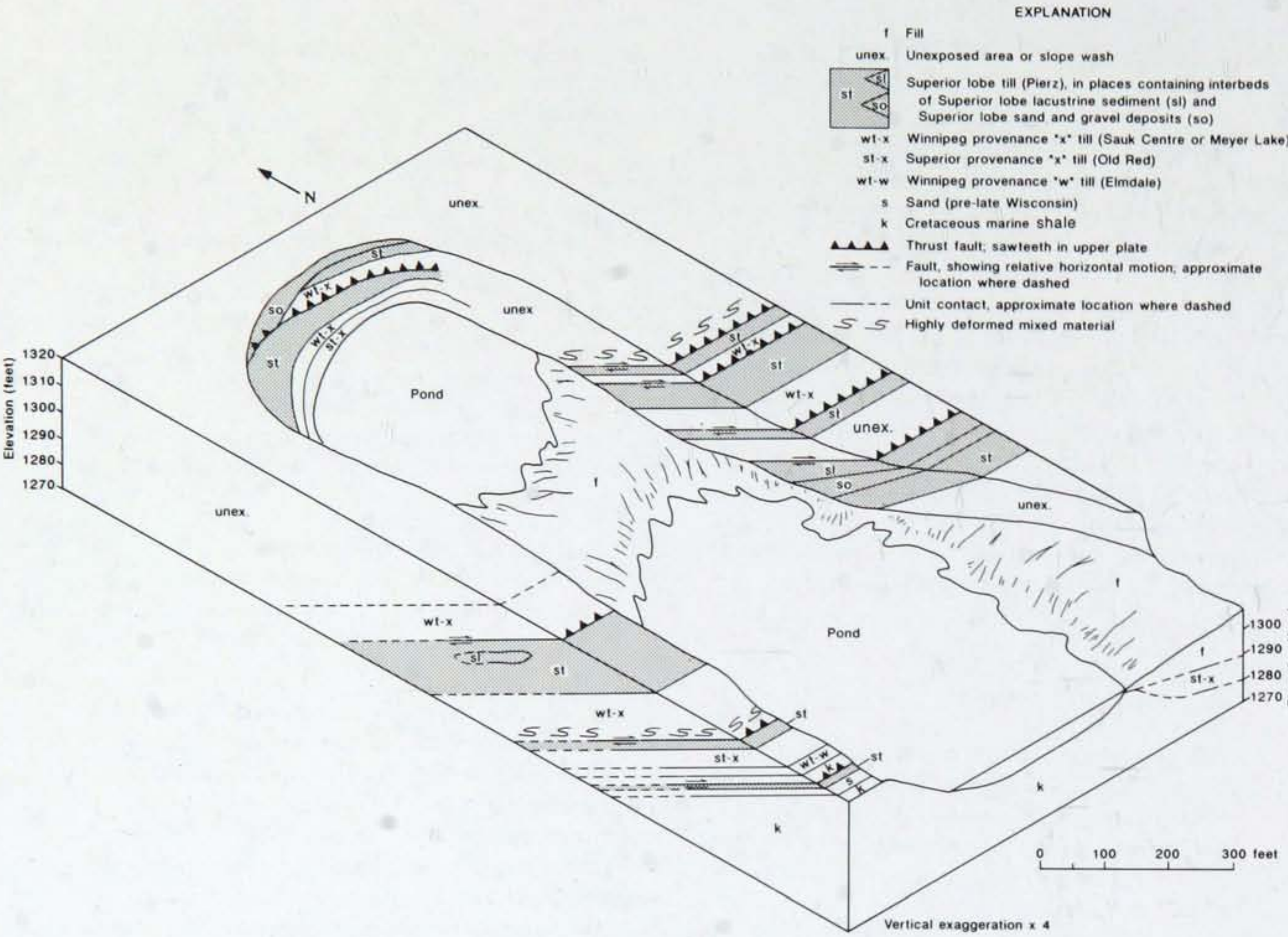

Figure 5. Block diagram of the Powder Ridge borrow pit showing stratigraphic units and interpreted thrust surfaces. Quaternary sediments and Cretaceous shales are exposed on the north, east and west walls of the pit; the exposure on the west wall has been extended through to the outside face of the block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

undisturbed Cretaceous bedrock in the region to be less than 1100 ft above sea level. The Cretaceous shale is interpreted to have been emplaced over younger sediments as a thrust sheet during glacial advance.

The St. Croix end moraine is 1–2 mi wide at the Powder Ridge borrow pit. Records for three water wells (Fig. 4) located on the flanks of the end moraine (two for wells about a half mile northwest of the pit, one located about a quarter mile northeast of the pit) also describe materials that appear to be thrusted (i.e. Cretaceous shales overlying till, and repetitive sequential color changes in the till units). A broad tunnel-valley channel 2 mi wide lies directly east of the end moraine in which the Powder Ridge borrow pit is located. This tunnel-valley channel runs northeast, following highway 15 along a series of lake depressions (Fig. 4).

Bardsen Pit

The Bardsen pit is located on a hill immediately south-southwest of Fifth Lake, five miles southwest of Avon in the middle of the St. Croix moraine complex (Figs. 2 and 7). Exposures at the Bardsen pit provide evidence for "hill-depression" thrusting (Bluemle and Clayton, 1984). The hill south-southwest of Fifth Lake is encircled by Des Moines-lobe till that incorporates varying amounts of underlying Superior-lobe material. In contrast, the east wall of the Bardsen pit, located on the west face of the hill, shows Superior-lobe till to overlie dark gray Cretaceous shale, which structurally overlies a pre-Wisconsinan silty, shale-free, carbonate-rich till of Illinoian age or older (the Sauk Center or Meyer Lake Tills of Meyer and Knaeble, 1996). The pre-Wisconsinan till includes an upper brown oxidized unit, and a lower gray unoxidized unit (Fig. 8). The north-facing wall at

Table 2. Matrix texture for till units in the Powder Ridge borrow bit (stratigraphic units are from Fig.5).

Unit	No. of samples	Cumulative percentage of Sand	Silt	Clay
wt-w	4	29	40	31
st-x	6	41	34	25
wt-x				
Meyer Lake	5	28	57	15
Sauk Centre	8	41	41	18
st	20	58	29	13

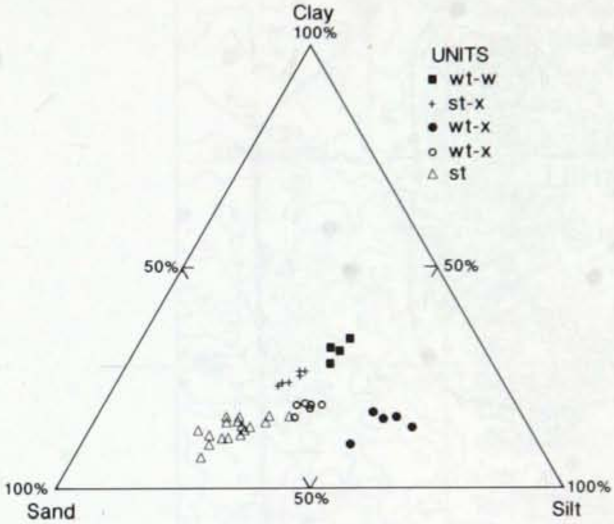

Figure 6. Triangular plot showing matrix texture for till units in the Powder Ridge borrow pit (see Table 2 and Fig. 5).

the southern end of the pit shows deformed streaks of red, yellow, and white saprolithic material together with minor gray Cretaceous shale, both of which are included and apparently folded within deformed sand, gravel and till of uncertain age. The Cretaceous shale and overlying Superior-lobe till were thrust over the Sauk Center and Meyer Lake Tills, which themselves probably form the upper portion of a thrust block. The sand and gravel of uncertain origin includes lenses of deformed saprolithic material and Cretaceous shale, and probably represents a zone of deformation associated with southwest-directed glacial thrusting. One-half mile directly south of the Bardsen pit, an outcrop in a farm field on the east side of the gravel road (Fig. 7) shows layers of dark gray Cretaceous shale 5–10 ft thick interlayered with sandy red Superior-lobe deposits. Bedding in all of these units strikes northwest and dips northeast in what would have been the up-glacier direction for the Superior lobe. Fifth Lake is interpreted to occupy the depression from which the material that forms the hill directly to the southwest was derived by the advancing Superior-lobe ice (Fig. 7).

Avon Ridge

Additional evidence for glacial thrusting is observed just south of Avon. An elongate ridge (T. 124 N., R. 30 W., and T. 125 N., R. 30 W.) one mile south of Avon extends southwest for 5 miles, terminating immediately northeast of Big Fish Lake and Long Lake (Fig. 2). The ridge stands 200–300 ft above the surrounding terrain and is probably a recessional moraine. The southwestern tip of the ridge lies three miles east of the St. Croix end moraine. The northeastern end of the ridge was bored with a Giddings probe at a locality where the surface elevation was 1225 ft. Five feet of sand and gravel overlie a layer of brown and gray Cretaceous shale. The Cretaceous shale extended to the bottom of the bore hole at a depth of 25 ft. Logs for wells located north, east, and west of the site (but not on the ridge) indicate that the Cretaceous bedrock surface reaches elevations no greater than 1050 ft.

At another site on the ridge (labeled "Potter's roadcut" on Fig. 2), one-quarter mile west of Big Watab Lake (NW1/4, sec. 16, T. 124 N., R. 30 W.), a 10-ft road cut exposes Cretaceous shale at a surface elevation of 1340 ft. A supplementary boring adjacent to this exposure shows Cretaceous shale to extend 5 ft below the surface, where it overlies old glacial sediment and sand and gravel. A boring 18 ft deep one mile west of Potter's roadcut (eastern half of sec. 18, T. 124 N., R. 30 W.) on a township gravel road showed streaking and deformation of interlayered tills. A well log from a nearby well 233 ft deep (Table 3) documents more than a dozen color changes within the sediments, including layers of "black clay" and "coal" overlying "glacial deposits." All of the observations at or near Avon Ridge provide evidence for probable repeated thrusting of older units over younger units during a recessional phase of the Superior lobe.

St. Benedict

Further evidence for thrusting is documented one mile southwest of St. Joseph (Fig. 2) in the wooded hills on the College of St. Benedict campus (NW1/4, sec. 16, T. 124 N., R. 29 W.). At a surface elevation of 1115 ft, a Giddings-probe boring 20 ft deep revealed 9 ft of brown and gray Cretaceous shale over oxidized glacial sediment. A quarter of a mile southwest of this locality a Rotasonic drill hole with a surface elevation of 1100 ft penetrated 200 ft of undisturbed Cretaceous marine shale. Cretaceous shale within the Rotasonic drill core is interpreted to represent in situ "bedrock," whereas the Cretaceous shale from the Giddings-probe locality represents Cretaceous shale bedrock thrust over glacial sediment.

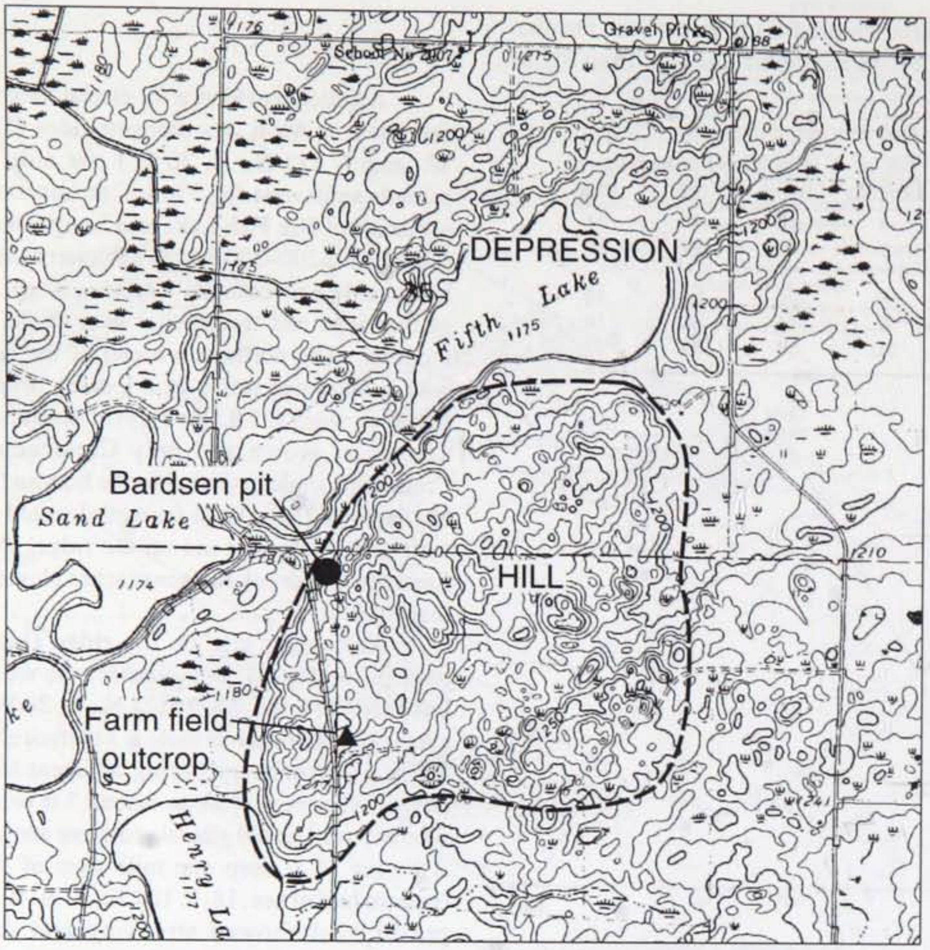

Figure 7. Topographic map showing location of the Bardsen pit near Fifth Lake, and the farm field outcrop. The dashed line indicates the approximate extent of thrusted material that lies to the southwest of the topographic depression, which was the source. The area shown is 1.75 mi wide; the contour interval is 10 ft. (U.S. Geological Survey Farming quadrangle, 7.5- minute series, 1965).

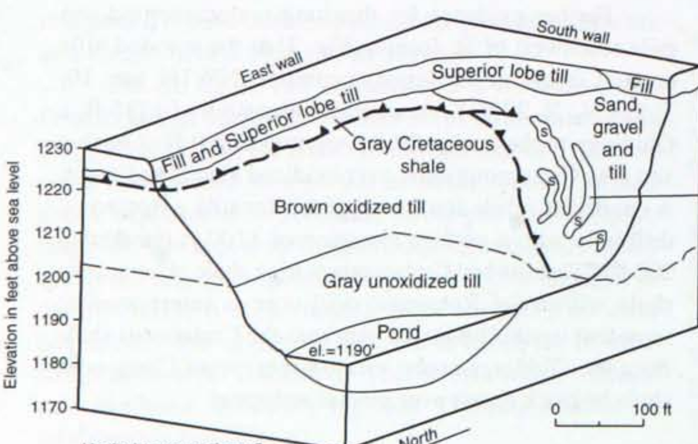

Figure 8. Block diagram of Bardsen pit (Fig. 7) looking to the southeast. Shows units observed on the east and south walls of the pit. Dashed fine lines indicate inferred contacts between units. Heavy dashed line with tick marks shows interpreted position of thrust surface; tick marks are on the base of the thrust slab. S indicates saprolite bodies or lenses.

Table 3. Tabulated summary of well-driller's and geologist's descriptions of materials penetrated during water-well drilling south of Avon on the thrust ridge. The log shows numerous color changes in the glacial units, and Cretaceous "black clay" and "coal" overlying glacial deposits.

Transcribed Water Well Record
Minnesota Unique Well Number 146795
Stearns County, Collegeville Township,
T. 124 N., R. 30 W., Sec 18, NW1/4 SE1/4 SE1/4 SE1/4
Elevation 1339 ± 5 ft
Completed 10-2-78

Geologist's Interpretation of Well Record	FORMATION LOG	COLOR	HARDNESS	DEPTH (FEET)
Elev. 1339 ± 5 ft				
Quaternary	Clay-Sand-Rocks	Brown	M	0–44
	Clay & Sand	Red	S	44–53
	Sticky Clay	Gray	S	53–62
	Clay	Brown	S	62–78
	Clay	Gray	S	78–104
	Clay	Red	S	104–108
	Clay	Brown	S	108–120
	Clay	Gray	S	120–122
	Clay	Yellow	S	122–133
	Clay	Gray	S	133–135
	Clay	Blue	S	135–145
	Clay	Gray	S	145–169
Elev. 1170 ± 5 ft				
Cretaceous	Clay & Coal	Black	S	169–181
	Clay	Gray	S	181–189
	Clay & Coal	Black	S	189–192
	Clay	Gray	S	192–204
	Clay & Coal & Brown Sand	Black	S	204–218
	Clay & Coal	Gray & Black	S	218–221
	Clay	Gray	S	221–225
	Sand & Mud	Brown	S	225–226
	Clay	Gray	S	226–229
Elev. 1110 ± 5 ft				
Quaternary	Sand & Gravel	Brown	S	229–230
	Sand & Gravel	Gray	S	230–232
	Sand & Gravel	Brown	S	232–233
	Clay	Gray	S	233
Elev. 1110 ± 5 ft				

Merden Lake Esker

A gravel pit in the Merden Lake esker provides evidence for small-scale thrusting that is not associated with end-moraine formation (Fig. 2). The northwest wall of the pit exposes the core of the esker, which is composed of Superior-lobe sand and gravel. Covering this core is a 5–10 ft cap of Superior-lobe till that has incorporated in it a large (approximately 5 ft thick) slab of "Elmdale Till" of Meyer (1986). A 1 ft-thick layer of deformed dark gray Cretaceous shale is present near the base of the Superior-lobe till cap. The presence of older sedimentary units overlying Superior-lobe esker sands and gravels is attributed to subglacial removal of these older units from regions up-ice, and their subsequent emplacement as thrust blocks on top of the already-deposited esker.

GLACIAL THRUSTING PROCESSES

The widely accepted model for the development of thrust systems in glacial environments is summarized below. The important physical processes and conditions that contribute to thrusting at the ice margin (Fig. 9), and some of their resulting features are:

1. The presence of subglacial frozen beds or permafrost that "attach" unlithified subglacial sediment or unlithified bedrock to the glacier's base (Mackay and Mathews, 1964; Clayton and Moran, 1974; Bluemle and Clayton, 1984; Aber, 1988).

2. An increase in pore-water pressure in the underlying sediment, reducing intergranular friction as the pore space becomes saturated with water. This aids slipping along the base of the permafrost thrust blocks (Clayton and Moran, 1974; Bluemle and Clayton, 1984; Aber, 1988).

3. Ice-flow velocities high enough to provide the shear force to excavate the frozen substrata (Clayton and Moran, 1974; Aber, 1988).

4. The plucking of frozen subglacial slabs from their original sites, and the transportation and stacking of these slices in front of the glacier (Clayton and Moran, 1974; Aber, 1988).

5. Deformation of thrust blocks during transport, stacking, and in some cases, overriding by glacial ice (Aber, 1988).

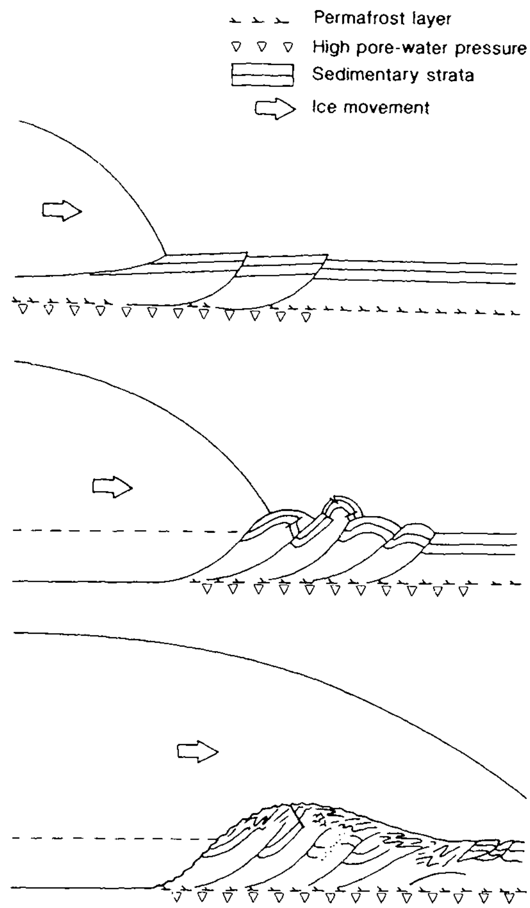

Figure 9. Model illustrating the processes contributing to the structural deformation produced by glacier advance over permanently frozen unlithified sedimentary strata. Modified from Aber (1988, Figure 11-2).

DISCUSSION

All 22 thrust sites are located within a section of the St. Croix Moraine that runs from near Avon southeast to Kimball. Exposures at the Powder Ridge borrow pit, the Bardsen pit, and Avon Ridge provide substantial evidence that glacial thrusting was a significant factor contributing to the development and modification of the materials within this portion of the St. Croix Moraine.

At the Powder Ridge borrow pit, bedded fluvial sediments and varved lacustrine deposits within the thrust slabs have retained their primary sedimentological features, despite having been transported. Deformation is usually restricted to thrust-block boundaries. The thrust blocks at the Powder Ridge borrow pit range from 50–250-ft thick. These features indicate that there was a frozen subglacial environment. The number of thrust blocks documented decreases up-ice (to the northeast) from the end moraine, probably due to the diminishing thickness of the permafrost in that same direction (Clayton and Moran, 1974). Red sandy Superior-lobe till caps each thrust block. This pattern indicates that the Superior-lobe till cap probably represents the subglacial sediment load frozen to the top of the substrata, and that thrust blocks were removed consecutively and were transported and stacked near the ice front. Another interpretation might suggest that Superior-lobe ice may have readvanced, and in the process it may have pushed and stacked some of its earlier deposits.

Gaps in the moraine such as those near the Powder Ridge borrow pit locality and the area southwest of Rockville, formed as Superior-lobe subglacial tunnel valleys, and are typically adjacent to thrust hills in the end moraine. The presence of subglacial tunnel valleys appears to have fostered thrusting; subglacial pore-water conditions favored the removal of blocks of subglacial material to become thrust blocks (Bluemle and Clayton, 1984). Thrusting nearer the eastern margin of the St. Croix moraine complex, such as that documented for Merden Lake Esker and the hills southwest of the College of St. Benedict campus may have resulted from activity along the ice front as the Superior lobe retreated.

CONCLUSIONS

On the basis of field investigations within the St. Croix moraine complex and analysis of compiled subsurface data, the following conclusions are offered:

1. Processes leading to the formation of glacial thrust blocks within the St. Croix moraine complex include pushing (Lehmann, 1992), thrusting, and deformation of preglacial and proglacial material, as well as the excavation and transport of large frozen slabs from beneath the toe of the glacier to the ice margin, where the thrusted (and commonly deformed) material was stacked.
2. Tunnel-valley stream channels commonly lie in an up-glacier direction from morainic material in which evidence for glacial thrusting has been documented.
3. Thrust hills are often located in what would have been the down-glacier direction from topographic depressions.
4. Thrusting of frozen subsurface material played a significant part in the genesis of landforms along sections of the St. Croix moraine complex.

ACKNOWLEDGMENTS

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TUNNEL VALLEYS AND OTHER GLACIAL FEATURES NEAR ANOKA, MINNESOTA

John J. Quinn

ABSTRACT

The topography and surficial geologic deposits of east-central Minnesota result primarily from the Late Wisconsinan advances of the Superior lobe and the Grantsburg sublobe of the Des Moines lobe. Detailed geologic mapping in a 300 mi^2 region centered around Anoka, Minnesota, indicates the locations of six tunnel valleys and a significant tunnel-valley fan. The arrangement, character, and interrelations of these landforms are described, their glacial sedimentary facies are identified, and their glacial history is interpreted. The identification of glacial sedimentary facies has application for the development of hydrogeological interpretations.

INTRODUCTION

The purpose of this work was to map glacial features (especially tunnel valleys and eskers) at a resolution finer than that available in currently published geologic maps, so that regional glacial sedimentary facies and geologic history could be interpreted. The study was driven by a need to characterize the regional sedimentary facies characteristics and relations in the area adjacent to a landfill in the Anoka region. A 23-mi^2 area surrounding the landfill was studied in detail to produce a ground-water flow model and a model showing the three-dimensional geostatistical distribution of glacial aquifers and confining units (Quinn, 1992; Quinn and others, 1992; Quinn and others, 1994).

Geologic mapping is critical in the development of sedimentologic and hydrogeologic facies models, both of which assist in understanding ground-water conditions. Facies models serve as a framework for both interpreting and predicting the geology of a given sedimentary environment (Walker, 1984). Glacial facies models are generalized assemblages of sediments that are representative of certain glaciological depositional environments (Eyles, 1983). Glacial-geologic facies models are useful in determining large-scale trends and distributions of different glaciogenic units (Eyles and Miall, 1984). Recent studies have emphasized the hydrogeological importance of such models (Fraser and Bleuer, 1987; Anderson, 1989). Knowledge of the facies relations within surficial and buried sedimentary units provide one with the ability to predict the arrangement of aquifers and confining units. Such studies are commonly concerned with landform-scale facies variations because of the difficulties in evaluating small-scale heterogeneities within facies (Anderson, 1989).

This study involved detailed landform-scale mapping of a 300-mi^2 region covered by six 7.5-minute U.S. Geological Survey topographic quadrangles (Anoka, Nowthen, Elk River, Rogers, Coon Rapids, and Cedar) centered around the town of Anoka, Minnesota. The resulting map covers parts of Anoka, Hennepin, Sherburne, and Wright counties (Fig. 1), and is useful in interpreting both the glacial history and hydrogeology of the area.

BACKGROUND AND PREVIOUS WORK

The surficial geology and landforms of east-central Minnesota primarily result from the Late Wisconsinan advances of the Superior lobe from the northeast, and the advance of the Grantsburg sublobe of the Des Moines lobe from the southwest. A detailed overview of the character of the ice lobes, their geographic extent and origins, and the timing of events is provided by Wright (1972a, 1972b, 1973) and Wright and others (1973).

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p. 27–34 *in* Patterson, C.J., and Wright, H.E., Jr., eds., Contributions to Quaternary studies in Minnesota: Minnesota Geological Survey Report of Investigations 49 (1998)

The Superior Lobe

Tunnel valleys and eskers commonly occur together in areas covered by Superior lobe ice. Cooper (1935) was the first to recognize tunnel valleys in Minnesota, noting that oversized valleys containing eskers may be "tunnel valleys formed beneath the ice." Wright (1973) suggested that cold ice in the upper part of the glacier prevented supraglacial meltwater from reaching the base of the ice, and that meltwater accumulated subglacially by geothermal or frictional heat. In order to have the high volume of meltwater flow required to erode the valleys, Wright suggested that the basal meltwater collected for thousands of years in an area extending beneath the ice sheet to the Hudson Bay area, until it broke through an opening in the frozen toe of the Superior lobe, resulting in the catastrophic incision of the tunnel valleys. Eskers formed when the ice thinned and the hydrostatic head decreased, resulting in the deposition of sand and gravel.

Mooers (1988, 1989) noted a lack of tunnel valley and esker complexes within the northern portion of the St. Croix Moraine. He suggested that at its maximum the Superior lobe may have been a subpolar glacier with a frozen toe; the ice would have been too cold to allow supraglacial meltwater to reach the base of the glacier.

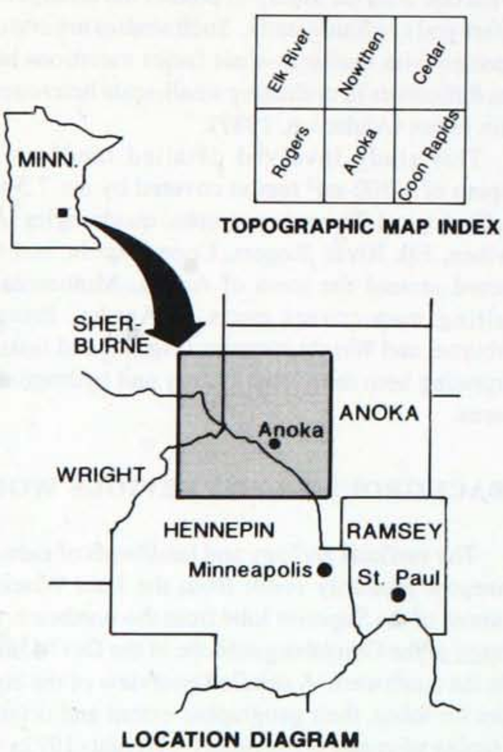

Figure 1. Location of study area in east-central Minnesota. Topographic map index shows the six 7.5-minute U.S. Geological Survey topographic quadrangles covered in this study (Fig. 2).

At recessional ice margins of the Superior lobe, tunnel valleys and eskers are more prevalent. Mooers (1989, 1990) documented that some eskers commence at kame deposits and terminate at the recessional ice margins in subaerial outwash fans. These landforms imply that during retreat the Superior lobe had changed to a temperate glacier without a frozen toe. Drumlins associated with the Superior lobe indicate that the ice had fanned out across east-central Minnesota (Wright, 1973), requiring an extensional regime in which longitudinal crevasses would have been common. Supraglacial meltwater may have flowed into the crevasses of this temperate glacier and penetrated to its base. Mooers (1989, 1990) reasoned that the headward growth of tunnel valleys would be accomplished by up-glacier crevasses intercepting the surface meltwaters of the wasting ice. As the lobe narrowed during retreat, the number of tunnel valleys would decrease because of merging subglacial streams. During the summer melting season, the water table within the glacier probably rose, increasing the hydrostatic pressure on the water in the tunnel valleys; channels were enlarged and in some places flow was driven uphill (Mooers, 1989). Mooers did not ignore the possibility of basally derived meltwater, but he contended that it was insignificant compared to the volume of water derived from surface melt.

Eskers within the tunnel valleys were deposited by waning meltwater flow and represent the position of the subglacial stream as the deforming ice constricted water flow. The eskers are much narrower than the tunnel valleys; two or more subparallel eskers may be present within a tunnel valley. Tunnel valleys in the Anoka region are normally straight or slightly curved and trend to the southwest. This trend is oblique to the regional slope of the land surface, but parallels the inferred ice gradient and is in the direction of decreasing hydrostatic head (Wright, 1973). Locally, the tunnel valleys were incised by water flowing uphill, a result of flow being driven by high hydrostatic pressure. At some locations in eastern Minnesota, tunnel-valley erosion may have etched the bedrock (Wright, 1973). Tunnel valleys associated with Superior-lobe ice range in width from less than 590 ft to more than 3,300 ft, with an average of about 980 ft (Wright, 1973), and they are about 33 ft deep. They vary greatly in length (Wright, 1973), although most segments are 6–12 mi long (Mooers, 1989). The eskers are normally discontinuous features within or along the sides of the tunnel valleys. The crests of the eskers are usually equal in elevation to the adjoining till plain (Wright, 1973). Typically, the fairly continuous esker segments are less than 2.5 mi in length (Mooers, 1989).

In east-central Minnesota Patterson (1994) and Meyer and others (1993) document large ice-contact fans as marking the termini of many tunnel valleys. These ice-contact fans represent periodic stable locations of the Superior-lobe ice margin during the construction of the St. Croix Moraine and during retreat of the ice from the St. Croix Moraine. The ice-contact fans now dominate the local topography, particularly in comparison to the flat tunnel valleys with low elevation. The elevation of the ice-contact fans is attributed to the high hydraulic head of the sediment-laden waters conveyed by the tunnel valleys (Patterson, 1994).

The Grantsburg Sublobe

Following the retreat of the Superior lobe, the Grantsburg sublobe of the Des Moines lobe moved across the region from the southwest. It overran the St. Croix Moraine and advanced northeastward across Superior-lobe deposits. Tunnel valleys and eskers are not associated with the Grantsburg sublobe (Chernicoff, 1980, 1983). As the Grantsburg sublobe stagnated, the ice margin moved back to the southwest, and the glacial Mississippi River shifted its course, distributing outwash over an area of 850 mi^2 (Farnham, 1956; Meyer, this volume). The resulting outwash plain is known as the Anoka Sandplain. Most of the surficial portion of this unit is lake sand (Stone, 1966; Meyer and others, 1993).

In the area that was covered by both the Grantsburg sublobe and the Superior lobe, the base of the Grantsburg till typically includes a zone of interlayered red and gray glacial sediments. This was first described by Winchell (1888) and interpreted to mean that the Grantsburg sublobe and the Superior lobe were contemporaneous. More recent studies (Wright and others, 1973; Johnson and Hemstad, this volume) have shown that the interlayering is caused by the incorporation of Superior-lobe tills by overriding Grantsburg-sublobe ice. Superior-lobe tills were entrained at the frozen margin of the Grantsburg sublobe (Chernicoff, 1980, 1983); the contamination of Grantsburg-sublobe till with Superior-lobe till is most recognizable at the margins of the sublobe. The Grantsburg sublobe is interpreted to have had a warm-based, basally sliding interior and a frozen marginal zone about 6 miles wide (Chernicoff, 1980, 1983).

Numerous kettle lakes and other depressions dot the regions covered by ice during the advance of the Superior lobe and the Grantsburg sublobe. The melting of buried ice produced these topographic lows, which are now typically occupied by peatlands, swamps or lakes. Blocks of Superior-lobe ice buried within the sediments persisted during the advance of the Grantsburg sublobe and deposition of Grantsburg till and the Anoka Sandplain. The distinctive topographic features of the eskers and tunnel valleys formed by Superior-lobe ice (Wright, 1972a, 1972b) are largely preserved by stagnant ice despite activity by the Grantsburg sublobe.

MAPPING PROCEDURES

Detailed mapping of glacial sediments is best accomplished by integrating information from aerial photographs, topographic maps, and soil surveys with field data. In this study low-altitude (1:20,000-scale) black-and-white aerial photographs (stereo-pairs) provided a valuable mapping tool. In suburban areas, aerial photographs taken prior to extensive development are the most useful for identification of glaciogenic features. Tunnel valleys, eskers, kettles, dunefields, and paleodrainageways can be effectively mapped by combining the information from stereo-pair photographs with that from topographic maps.

County soil surveys by the U.S. Department of Agriculture Soil Conservation Service and the University of Minnesota Agricultural Experiment Station indicate the distribution of various soil types, from which the parent glacial materials may be inferred. The soil surveys were used in this study to validate aerial-photograph interpretations; they allowed distinction between the alluvial soils and the muck soils typical of former meltwater drainageways or peaty kettles. Soil surveys are also useful for identifying the contacts between outwash and till units, and the contacts between Grantsburg-sublobe till and mixed Grantsburg-sublobe / Superior-lobe till. For this study the glacial features were initially mapped on 7.5-minute U.S. Geological Survey topographic quadrangles (scale 1:24,000) and then transcribed onto a 1:100,000 base map.

The glacial geologic map (Fig. 2) illustrates the main components of the Quaternary glacial cover for the Anoka region. The map represents units that have been identified by the methods followed in this text. These units have been distinguished from each other by compositional factors, time of formation, and specific depositional environments and/or mechanisms. This has produced a glacial-geologic map that has assisted in interpretation of the geologic history and the hydrogeologic framework of glacial sediments in the region.

Because of similarities in topographic expression and soil types, the kettles, tunnel valleys, paleodrainageways, and present-day floodplains are grouped together as undifferentiated Holocene lowlands and depicted together (Fig. 2). Linear depressions or rows of kettles indicate the location of former drainageways associated with either the Superior lobe or the Grantsburg sublobe. These drainageways were filled with dead ice during deposition of younger sediments. The presence of eskers in a linear lowland indicates the position of a Superior-lobe tunnel valley (Fig. 3).

Other glacial-geologic maps that include the study area have been published since this project began, including coverage of Anoka County (Meyer and others,

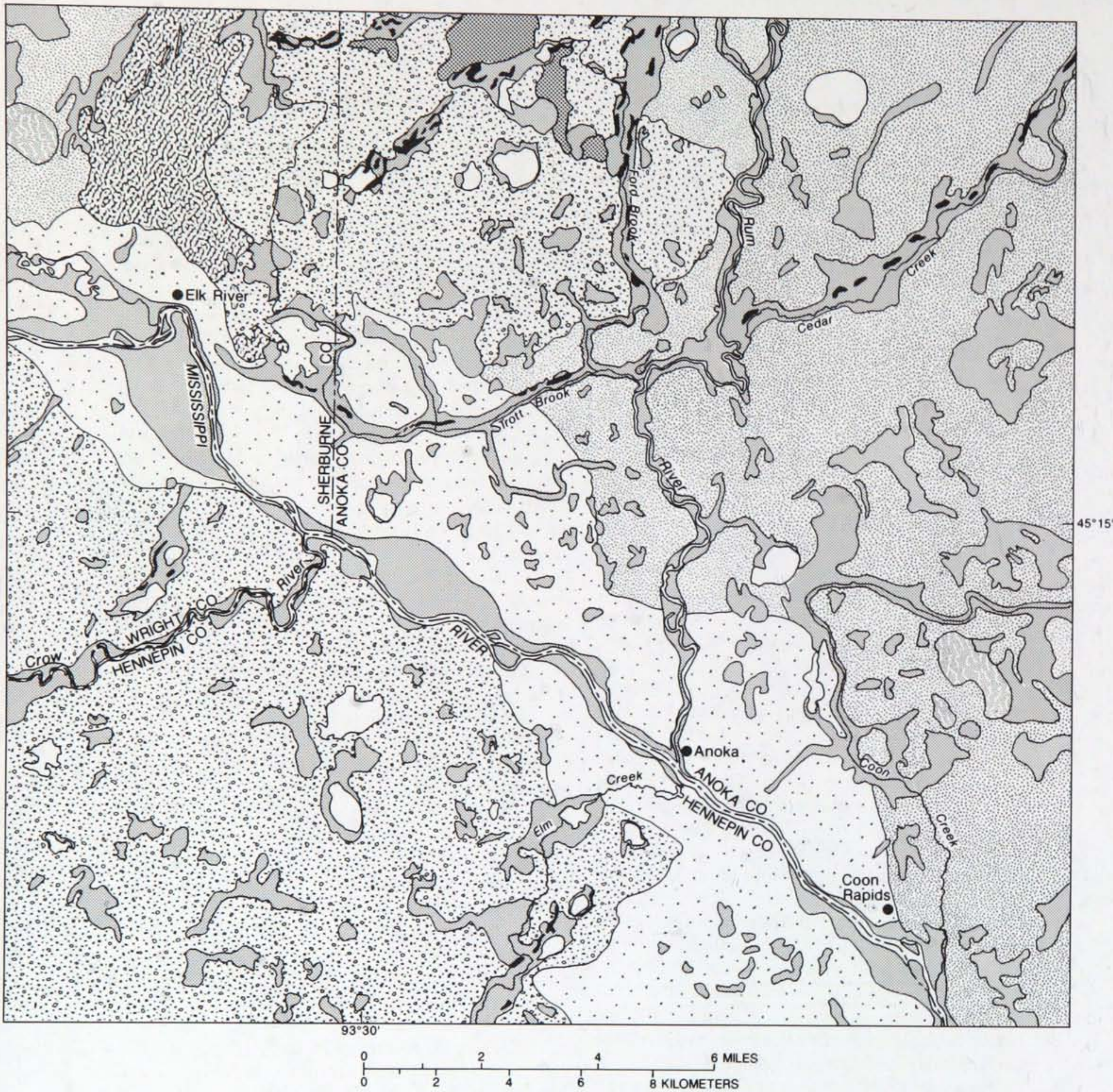

Figure 2. Glacial geology of the Anoka region (see Fig. 1 for location, and Fig. 3 for position of tunnel valleys). See p. 31 for explanation.

1993), Sherburne County (Meyer and others, 1993; Meyer and Hobbs, 1993), Wright County (Lehr, 1991). Meyer and Hobbs (1989) presented a surficial geology map for Hennepin County. Although these maps provide detailed information, they do not delineate tunnel-valley boundaries or esker locations at the same resolution as Figure 2.

MAPPED LANDFORMS

Tunnel Valleys and Eskers

Six tunnel valleys were mapped in the Anoka region (Figs. 2 and 3); five of these (#1–5 of Fig. 3) extend beyond the mapped area. Tunnel valleys are identified from the topographic map as linear depressions that may contain sinuous, discontinuous ridges interpreted as eskers. The

EXPLANATION FOR FIGURE 2

Holocene sand dunes—Eolian planar cross-bedded sand.

Undifferentiated lowlands—Topographically low areas occupied by wetlands, lakes, peat bogs, and floodplains of creeks and rivers. Unit includes some former tunnel valleys (see inset).

Mississippi Valley train—Sand deposited by the glacial Mississippi River. Large braided channels are visible on aerial photographs. Valley train elevation is about 20 ft higher than the current Mississippi River floodplain, and 5–10 feet lower than the Anoka Sand Plain.

Anoka Sand Plain—Outwash sand and gravel deposited by the glacial Mississippi River as the Grantsburg sublobe wasted southwestward. Typically includes a cap of lacustrine sand.

Fan complex—Topographic highs contain sands and gravels deposited as tunnel-valley fans associated with the Superior lobe. Fan sediments are overlain by a veneer of outwash derived from the Grantsburg sublobe. This unit includes adjacent regions that are blanketed with fan sands and gravels.

Ground moraine of the Grantsburg sublobe—Gently undulating topography in the north-central portion of the mapped area. Gray to buff fine-grained till. In the southwest portion of the mapped area, this till blankets the undulating to steep Superior-lobe till of the St. Croix moraine.

Mixed ground moraine—Till of the Grantsburg sublobe mixed with red, coarse-grained till of the Superior lobe. Topography is gently undulating.

Esker—Linear or serpentine ridges of sand and gravel deposited in tunnel valleys of the Superior lobe.

Lake

tunnel valleys are oriented primarily southwest; one valley however, trends south (#3) and another trends almost due west (#1). The presence of eskers helps distinguish the subglacially formed tunnel valleys from other paleodrainageways. Despite the eskers in the Anoka area being mantled by Grantsburg till and/or sediments of the Anoka Sandplain (Quinn, 1992), they are clearly identified on aerial photographs and topographic maps by their morphology and by their location within long depressions. The tunnel valleys within the Anoka area range from 0.15 to 0.5 mi in width. Most of them are at least 5 mi long and extend out of the map area. The eskers range in width from 200 to 500 ft. Continuous esker segments are commonly about 0.5 mi long. Esker morphology is well preserved, and the eskers commonly meander within the tunnel valleys. Pitting of the river valleys and till plains indicates that Superior-lobe dead ice filled the tunnel valleys of the Anoka area during advance of the Grantsburg sublobe, and deposition of sediments forming the Anoka sandplain.

Figure 3. Location of the 6 tunnel valleys in the area mapped (see Fig. 2). Numbers refer to discussion in text.

The southwestern part of the Anoka region (Figs. 2 and 3) is dominated by ground moraine of the Grantsburg sublobe. Two tunnel valleys (#5 and 6 in Fig. 3) are also identified in this area; they contain discontinuous esker segments. The eskers in the southwest are blanketed by Grantsburg tills; soils collected along the crests of the eskers consist of silty till to depths of at least 3 ft (Quinn, 1992). Other eskers may be present in this region but burial by deposits of the Grantsburg sublobe masks them.

Relations between the location of the tunnel valleys and the present day drainage of the Anoka region are varied. Some of the longer valleys (e.g. #4 in Fig. 3) that originated as tunnel valleys now contain creeks, but many are now closed depressions. As the drainage system developed, the Rum and Crow Rivers may have followed former tunnel valleys, in part at least. The larger meandering rivers would have eroded most of the eskers.

Elk River Fan

In the northwestern part of the Anoka region, the topography is dominated by a fan complex termed the Elk River Fan (Patterson, 1994). The fan complex reaches elevations of 50-150 ft above the neighboring Anoka Sandplain and till plain associated with the Grantsburg sublobe. Well logs indicate that sand and gravel of this unit is roughly 150 ft thick near the southern extent of the fan complex, where several immense sand and gravel pits are located. The uppermost 30 ft of sand and gravel within the fan complex contains shale clasts indicative of a Grantsburg-sublobe source (Patterson, 1994). The southern end of the fan complex is the highest, with a maximum elevation of about 1,100 ft. The edges of the fan are not distinct. Information in the Sherburne County soil survey (Grimes, 1968) suggests that sand was eroded from the fan and redeposited as a veneer on the lower, adjacent areas.

The Elk River fan complex has been variously interpreted. Warren Upham (in Winchell, 1888) worked without the help of aerial photographs, present-day topographic maps or soil surveys and referred to the feature as "kame-like hills and ridges of modified drift, trending from north to south and ranging from 40 to 100 feet in height." Leverett and Sardeson (1919) label the feature as sandy moraine. Cooper (1935) proposed the name "Elk River Morainic Area" for the area occupied by the fan complex and the adjacent tills, all of which he mapped simply as Keewatin (Grantsburg) drift. Farnham (1956) labeled the fan as Superior-lobe gravel. Wright (1956) described this feature as a perched outwash fan, deposited in a deep reentrant at the margin of the Grantsburg sublobe. The perched effect would have been produced by the eventual melting of adjacent ice. Wright (1972b) then described the fan as "an esker complex related to the St. Croix phase of the Superior lobe overlain by till of the Grantsburg sublobe, and this by outwash that forms a pitted plain, bordered by ice-contact slopes on three sides, which slopes northward to grade into the Anoka Sandplain." Hobbs and Goebel (1982) refer to it and the Grantsburg and Superior tills to the east as "Grantsburg end moraine; the topography of this unit reflects the underlying St. Croix Moraine." They also labeled the fan with an esker symbol.

The Elk River fan complex is interpreted here (and by Patterson, 1994) to have formed adjacent to the ice, at a stable ice-margin position of the retreating Superior lobe. The fan was built with sediment disgorged from the tunnel valleys, including at least two (#1 and #2) of those shown in Figure 3. The fan probably continued farther to the south and may have received sand and gravel from the long tunnel valley (#4 of Fig. 3). Any southern extension of the fan complex would have been eroded by the glacial Mississippi River. During the advance of the Grantsburg sublobe, the southern part of the fan complex probably formed a topographic barrier, deflecting Grantsburg-sublobe ice, but allowing deposition of Grantsburg outwash within a north-trending reentrant. This interpretation is similar to that of Wright (1956), but it allows for the bulk of the feature to be a Superior-lobe fan. On the western edge of the fan distinct troughs and ridges with relief of more than 50 ft trend north-south in a strip 0.5 mi wide; these were probably formed by meltwater streams associated with the Grantsburg sublobe. In addition to ice-contact sands and gravels, the fan complex also contains till units (Patterson, 1994). The surface of the fan complex slopes to the north for a distance of about 10 mi and finally merges with the Anoka Sandplain at an elevation of about 1,000 ft in the vicinity of Blue Lake immediately north of the Elk River quadrangle.

Small kames are present southeast of the fan complex. No other tunnel-valley fans, such as those noted in the investigations of Patterson (1994), Meyer and others (1993), or Mooers (1988, 1990,), were noted in the study area. However, because they are positive topographic features, relatively small fans could have been deposited in this region and modified during advance of the Grantsburg sublobe.

Grantsburg Ground Moraine and Anoka Sandplain

Grantsburg ground moraine covers much of the north-central part of the Anoka region, and includes several small zones of mixed till, which represent Superior-lobe deposits incorporated by Grantsburg ice. Cooper (1935) suggested that the ground moraine comprising this area did not become covered by sediments of the Anoka Sandplain because the fan complex protected the stagnant ice in the area from east-flowing meltwater streams as the Grantsburg sublobe wasted. The Anoka Sandplain dominates the eastern part of the Anoka region. The long tunnel valley traversing it remains a distinct morphologic feature, indicating that deposition of Anoka Sandplain sediments did not mask the tunnel valley and esker systems.

Mississippi River

The glacial Mississippi River eventually reached its present position along the east side of the St. Croix Moraine by cutting through the moraine at Minneapolis (Cooper, 1935; Wright, 1972b) and by finding a new pathway south of the Elk River fan complex (Cooper, 1935). At this time meltwater would no longer have followed the route around the north side of the fan-complex, but would have taken the shorter, southern route. This route resulted in a stream of higher gradient and greater erosive capability, which resulted in formation of the Mississippi valley train.

The Mississippi valley train is distinguished on aerial photographs by large braided patterns. The downcutting resulted in a surface that slopes from an elevation of 900 ft near Elk River to 860 ft near Coon Rapids, leaving the Anoka Sandplain as a slightly higher terrace. Due to the high velocity of the valley-train outwash streams, sands deposited on the train are generally slightly coarser than those of the Anoka sandplain. Numerous kettles within the valley train indicate that blocks of stagnant ice remained buried during the formation of the valley train. During the Holocene, flow decreased in the Mississippi River, leaving the valley train as a terrace.

Eolian Dunes

Several dune areas are mapped in northwestern and southeastern parts of the Anoka region. Keen (1985) also noted several minor sites of eolian deposition within the Anoka region. For simplicity, only the prominent and more laterally extensive areas were mapped in the present study. Lake-sediment analyses suggest that the probable cause of the eolian activity was climatic change, and that the time of major dune formation was 4,000–8,000 yrs B.P. (Keen, 1985; Keen and Shane, 1990).

SUMMARY

Mapping of glacial landforms and facies in the 300 mi^2 region around Anoka, Minnesota, has allowed interpretations to be made about their origin, and about the Superior lobe and Grantsburg sublobe. Six well-preserved Superior-lobe tunnel valleys are delineated. These valleys have widths of about 0.25 mi, and most extend beyond the area mapped. Eskers typically have lengths of 0.5 mi, and are commonly located in the tunnel valleys. The tunnel valleys fed sediment to the southern part of the Elk River fan complex. The fan complex provided a topographic obstacle to the Grantsburg sublobe, and Grantsburg-sublobe outwash was deposited atop the fan complex.

Delineation of the glacial landforms and facies has been useful (1) in developing a hydrogeologic facies model for ground-water modeling, and (2) in determination of model boundary conditions and the distribution of infiltration, especially when combined with an inspection of subsurface data from private well logs (Quinn, 1992; Quinn and others, 1994). The Grantsburg-sublobe ground moraine and associated mixed ground moraine of the Anoka area are interpreted as underlying the Anoka Sandplain and Mississippi valley-train sands.

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GLACIAL LAKES OF THE STACY BASIN, EAST-CENTRAL MINNESOTA AND NORTHWEST WISCONSIN

Gary N. Meyer

ABSTRACT

The Stacy basin is a depression in the bedrock that underlies most of Anoka and Chisago Counties in Minnesota, and extends into Burnett and Polk Counties, Wisconsin. This depression controlled the formation of several glacial lakes during Late Wisconsinan glaciation. Glacial Lake Lind formed when meltwater from the retreating St. Croix-phase Superior lobe was trapped within the Stacy basin by the St. Croix Moraine, which formed a barrier to the west, south, and east. During the Automba phase, the southwestward readvance of the Superior lobe across the Stacy basin either caused complete drainage of Glacial Lake Lind or forced it to extend back up the Mississippi valley. Retreat of ice after the Automba phase led to formation of a second lake within the area previously covered by Glacial Lake Lind. The subsequent northeast-directed advance of the Grantsburg sublobe across the Stacy basin led to the formation of Glacial Lake Grantsburg north of the basin. Following drainage of Glacial Lake Grantsburg during the early stages of the retreat of the Grantsburg sublobe, Glacial Lake Anoka formed in the Stacy basin when meltwater from the stagnant Grantsburg sublobe became dammed at the St. Croix valley outlet by the Barrens fan. Glacial Lake Anoka underwent a series of major drainage events, first down to the Hugo level, and then to the Fridley level, before the lake drained completely when an outlet opened at Minneapolis, establishing the present course of the Mississippi River above its confluence with the St. Croix River.

INTRODUCTION

A succession of Late Wisconsinan glacial lakes (Fig. 1) formed over a southwest-trending depression on the Paleozoic bedrock surface, herein named the Stacy basin (Fig. 2). The basin is defined roughly by the 800-ft bedrock topographic contour (Mossler, 1983) and is bounded on the southeast by an escarpment formed in the Ordovician Oneota Dolomite (Jirsa and others, 1986). The basin is floored by Cambrian sandstone and shale, which rise gradually to the northwest and form the base and remaining margins of the basin. The Blaine and Amelund sub-basins are defined by the 700-ft contour (Fig. 2 and Mossler, 1983) and are near the two major outlets of the Stacy basin (to the St. Croix valley and the Phalen channel; Meyer, 1992). Both outlets, and other minor ones, were plugged by sediment of the Cromwell Formation which was deposited during the Late Wisconsinan by the northeast-derived Superior lobe (Wright and others, 1970) as the advancing ice stalled atop the Oneota escarpment (Fig. 2).

The St. Croix Moraine

The maximum age for the advance of the Superior lobe into east-central Minnesota during the St. Croix phase is 32,300 ± 2000 yrs B.P. (Table 1, Beta-40098). This age is based on a radiocarbon date obtained from wood fragments in a core sample taken below 130 ft of Cromwell Formation sand and gravel in Ramsey County, Minnesota (Meyer, 1992). As the front of the Superior lobe stabilized at its maximum, it formed the St. Croix

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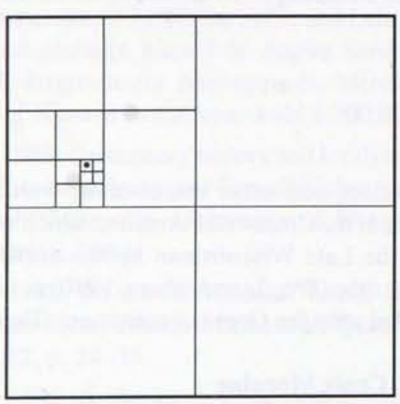
p. 35–48 *in* Patterson, C.J., and Wright, H.E., Jr., eds., Contributions to Quaternary studies in Minnesota: Minnesota Geological Survey Report of Investigations 49 (1998)

Table 1. Radiocarbon dates determined from organic material in sediments of the Stacy basin area.

[The W-series dates are from the U.S. Geological Survey in Washington, D.C., as reported in Wright and Rubin (1956). The Beta-series dates were determined by Beta Analytic Inc. of Miami, Florida, for the Minnesota Geological Survey. NA, not available; yrs B.P., years before present.]

General location and sample description	T-R-S*	Sample No.	Age (yr. B.P.)
Loring Park, Minneapolis, Hennepin County. Peat from sand of Mississippi valley train.	NA	W-445	10,200 ± 300
Stacy, Chisago County Wood from Glacial Lake Anoka sand.	T. 34 N., R. 21 W., Sec. 17BBB	Beta-37418	11,710 ± 80
Loring Park, Minneapolis, Hennepin County. Wood from same sand as W-445.	NA	W-454	11,790 ± 200
Cedar Creek Bog Lake, Isanti County. Gyttja just above Glacial Lake Anoka sand.	NA	W-466	11,830 ± 200
Shafer, Chisago County. Wood from base of New Ulm Till.	T. 33 N., R. 19 W., Sec. 16DCD	Beta-47059	11,850 ± 60
Shafer, Chisago County. Wood from organic silt below New Ulm Till.	T. 33 N., R. 19 W., Sec. 16DCD	Beta-47804	11,900 ± 70
Maple Grove, Hennepin County. Wood from kettle fill just above New Ulm Till.	T. 119 N., R. 22 W., Sec. 14CDA	Beta-23746	11,930 ± 60
North Branch, Chisago County. Wood from Glacial Lake Anoka sand.	NA	W-354	12,030 ± 200
North Branch, Chisago County. Peat from same horizon as W-354.	NA	W-389	12,700 ± 250
Arden Hills, Ramsey County. Wood from silt below Cromwell Fm sand and gravel.	T. 30 N., R. 23 W., Sec. 16DCA	Beta-40098	32,300 ± 2000
St. Michael, Wright County. Organic debris in sand and gravel just below New Ulm Till.	T. 120 N., R. 24 W., Sec. 12BCB	Beta-23745	38,040 ± 1360
Lino Lakes, Anoka County. Wood from Glacial Lake Anoka sand.	T. 31 N., R. 22 W., Sec. 19BBA	Beta-33498	41,800 ± 1000



**** Diagram to illustrate the process of locating a drill hole (bullet) within a section by means of the abbreviated subsection system***

The location of drill holes in Tables 1 and 2 is described by township number (T), range number (R), section number (Sec.), and subdivisions of sections by quarters. The system used by the Minnesota Geological Survey to subdivide a section (one square mile) assigns letters to the quarters of a section where A is the NE1/4, B is the NW1/4, C is the SW1/4, and D is the SE1/4. Each quarter is then subdivided into four more quarters using the letter system. In listing quarters the largest subdivision is given first and each quarter of a quarter is given in succession. In the example above the subdivisions of the section would read BCDAB.

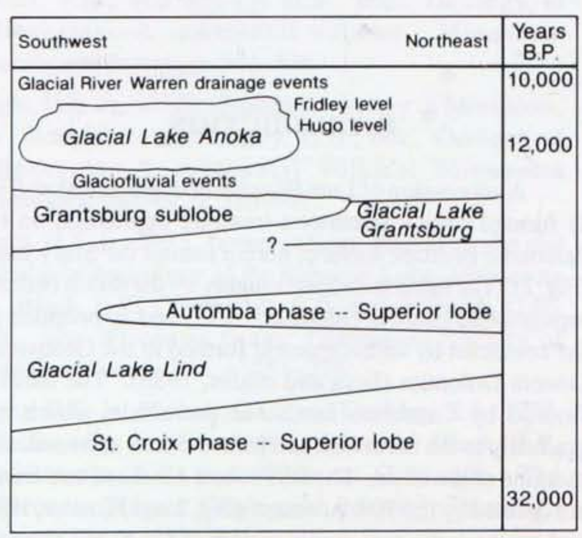


Figure 1. Time-distance diagram showing the Late Wisconsinan events recorded by sediments of the Stacy basin area.

Moraine, a complex linear series of high hills enclosing the Stacy basin on the west, south, and east (Hobbs and Goebel, 1982). During the eventual retreat of the ice front, meltwater issuing from the Superior lobe flowed through channels in the moraine (Fig. 3). The North Ramsey mounds (Patterson, 1992) mark a retreatal position of the Superior lobe in northern Ramsey County at the edge of the Stacy basin and form the northern flank of the St. Croix moraine complex.

Glacial Lake Lind

As the Superior lobe retreated north over the increasingly lower terrain of the Stacy basin, meltwater was no longer able to pass readily through outlets in the ice-cored St. Croix moraine complex (Fig. 4) and it became ponded to form Glacial Lake Lind (Johnson, 1992 and in press). Reddish varved silt and clay exposed in central Chisago County and in nearby Wisconsin are interpreted to represent seasonal depositional cycles indicating that Glacial Lake Lind existed for about a thousand years. This varved sediment has previously been interpreted to have been deposited in the younger Glacial Lake Grantsburg (Cooper, 1935; Wright, 1972). The extent of Glacial Lake Lind as depicted in Figure 4 is

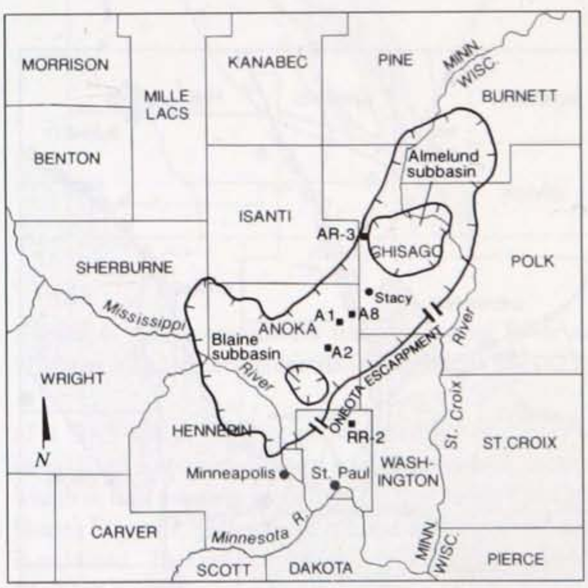


Figure 2. Location of the Stacy basin, which includes the Almelund and Blaine sub-basins. The Stacy basin is named for the centrally located town of Stacy. Extent of Stacy basin shown by hachured line; position of the Oneota Escarpment is indicated. Major pre–Wisconsinan outlets are indicated by thick parallel bars. Location of Minnesota Geological Survey test holes (listed in Table 2) indicated by bullet with number .

Table 2. Location of Minnesota Geological Survey test holes discussed in text.

[See footnote to Table 1 for description of abbreviated subsection system]

Hole	Unique No.	Location
A-1	243177	T. 33 N., R. 22 W., Sec. 22CBBCCA
A-2	243178	T. 32 N., R. 22 W., Sec. 18ADCCDA
A-8	243184	T. 33 N., R. 22 W., Sec. 13BDAAAC
AR-3	247207	T. 35 N., R. 21 W., Sec. 19ACBBBC
RR-2	247131	T. 30 N., R. 22 W., Sec. 16BCCBDC

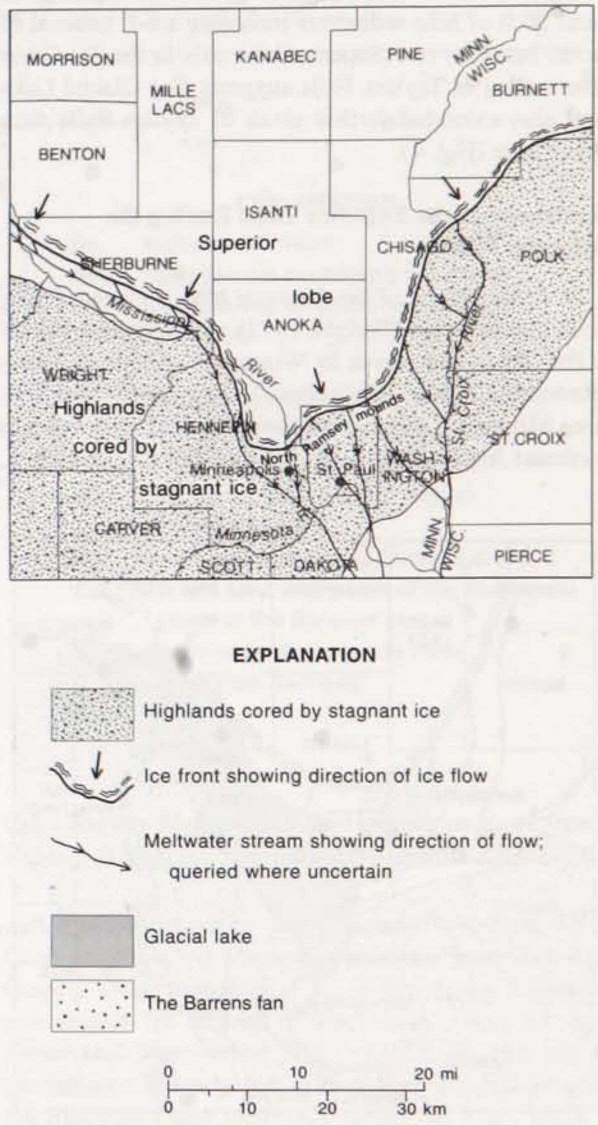


Figure 3. Glacial history of the Stacy basin: The St. Croix phase. Shows position of Superior lobe just prior to northward retreat of the ice front across the Stacy basin. The North Ramsey mounds mark the north-facing flank of the St. Croix Moraine. Explanation is for Figures 3, 4, 5 and 7–17. The present courses of the Mississippi, Minnesota and St. Croix Rivers are labeled to assist the reader with location.

based primarily on logs from test holes augered by the U.S. Geological Survey (Helgesen and Lindholm, 1977). On the basis of exposed lake sediments and the absence of kettle holes in areas presumed to have been covered by the lake, Johnson (in press) extended the bounds of Lake Lind well into southern Pine County, Minnesota, and central Burnett County, Wisconsin. Reddish laminated silt and clay exposed along the Mississippi River near Monticello in Wright County, together with subsurface data, indicate that the areal extent of the lake may have been greater than shown here (Fig. 4). An exposure of about 20 ft of lake sediments including a 6-ft interval of varves between two Superior-lobe tills in the St. Croix River valley at Taylors Falls suggests that Glacial Lake Lind also extended farther south of Taylors Falls than shown here (Fig. 4).

Readvance of the Superior Lobe During the Automba Phase

A readvance of the Superior lobe occurred during the Automba phase (Wright, 1972), which was equivalent to the Tiger Cat phase in Wisconsin (Clayton, 1984; Johnson and Mooers, this volume). Split-spoon cores from three Minnesota Geological Survey (MGS) test holes in northeast Anoka County (Fig. 2 and Table 2, holes A-1, A-2, A-8) as well as data from Minnesota Department of Transportation (MnDOT) logs of borings at Coon Rapids in southwest Anoka County which show that reddish clayey till overlies varved lake sediments. The till records the Automba-phase readvance of Superior-lobe ice into the Stacy basin (Figs. 5 and 6). The readvance probably involved a thin, narrow tongue of ice that followed the topographic low now occupied by the Kettle River. The "red drift clay" once mined along Coon Creek at Coon Rapids by the Minnesota Paving Brick Company (Grout and Soper, 1919) is also believed to record this readvance. This till, like other deposits of the Automba phase of the Superior lobe (Wright and others, 1970), is part of the Cromwell Formation and is herein informally named the Coon Creek till. The clayey texture of the Coon Creek till is due to incorporation of the underlying clayey Lake Lind sediment as Superior-lobe ice moved south across the Stacy basin. Siltier Superior-lobe till noted in Wisconsin down-ice from the sediments of Glacial Lake Lind (Johnson, in press) may be equivalent to the Coon Creek till in Minnesota.

The upper part of the Coon Creek till as documented at two sites (Anoka County test hole A8 and MGS core from North Oaks, hole RR2; Table 2) has the typical sandy-loam texture of Cromwell Formation till (Wright and others, 1970). At the North Oaks site the lower half

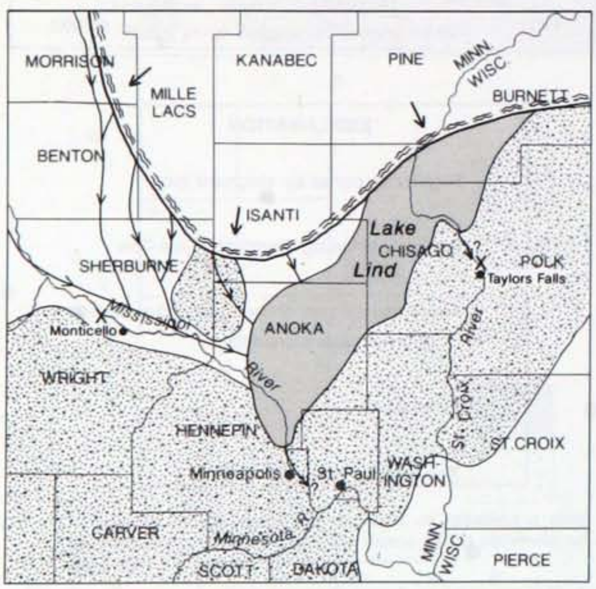


Figure 4. Glacial history of the Stacy basin: Formation of Glacial Lake Lind. Exposures of reddish lake sediments (shown by X) at Monticello and Taylors Falls indicate that Glacial Lake Lind may have been larger than depicted here. See page 37 for explanation of map symbols.

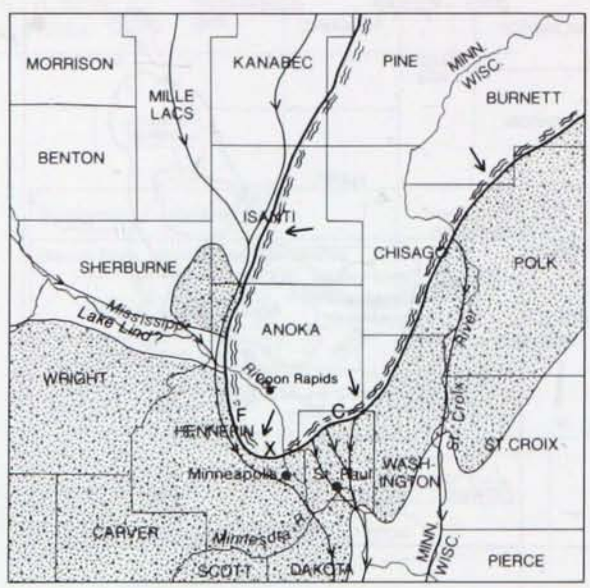


Figure 5. Glacial history of the Stacy basin: Automba phase readvance of the Superior lobe. Shows maximum position of the Superior lobe during the Automba phase, based on (1) drill core from North Oaks at C; (2) red clayey till exposed at X; and (3) a fan deposit (shown by F) at Maple Grove. See Figure 6 for cross section along Minn. Hwy 610 at Coon Rapids. See page 37 for explanation of map symbols.

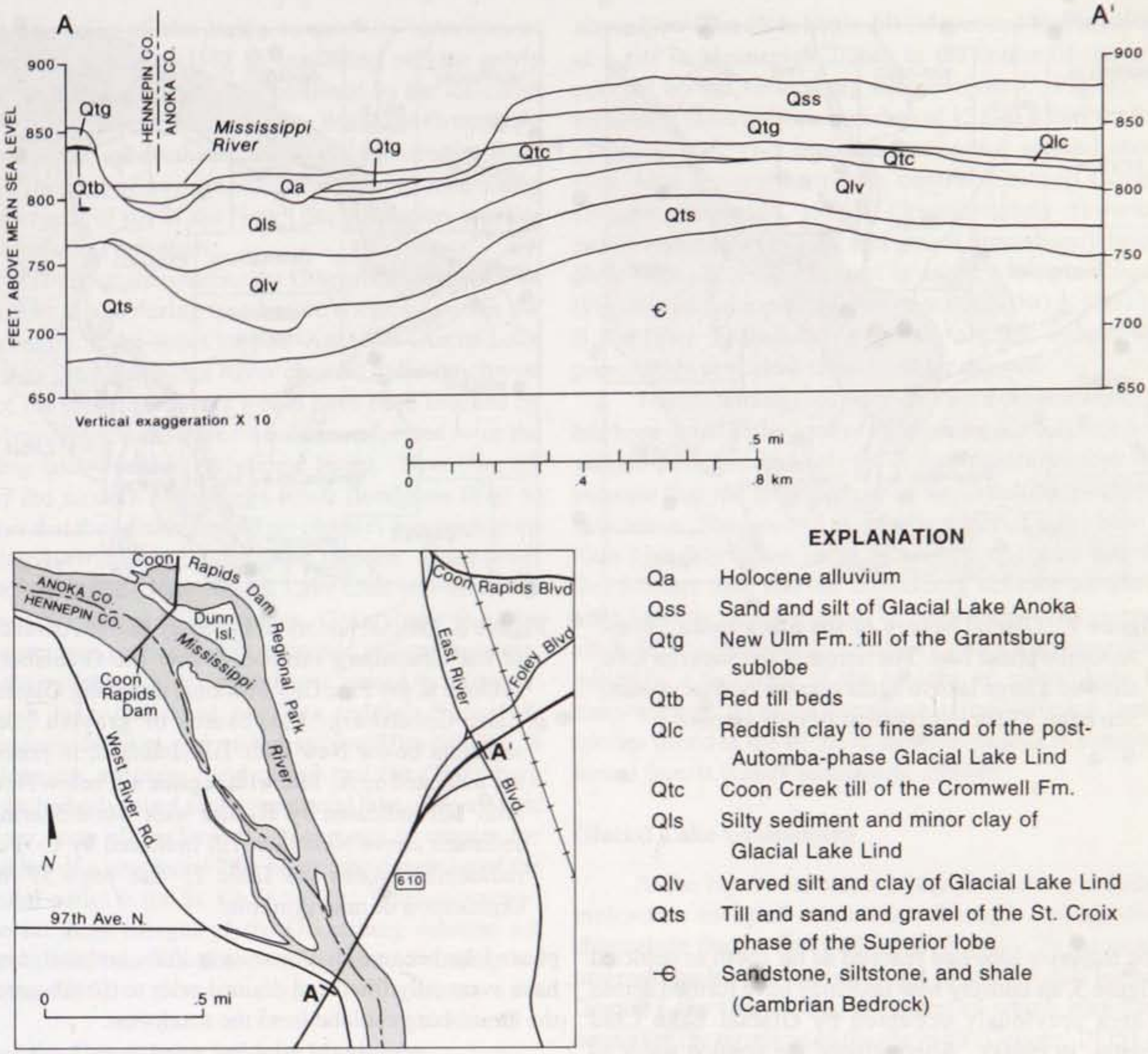


Figure 6. Cross section for the Mississippi River area at Coon Rapids, Minnesota, based mainly on more than 40 Minnesota Department of Transportation (MnDOT) borehole logs from test drilling along Minnesota Highway 610.

of a 50-ft-thick Superior-provenance till is clayey and unoxidized and overlies about 1 ft of clayey lake sediment, which in turn overlies more than 50 ft of sandy (St. Croix-phase) Superior-provenance till, the upper part of which is oxidized. This section at North Oaks, together with (1) MnDOT borehole logs and exposures at Coon Rapids in southern Anoka County (Fig. 6) that include clayey to silty till overlying lake sediments, and (2) red clayey till exposed in northeast Hennepin County (Fig. 5, location X) all indicate that the readvance of the Superior lobe across the Stacy basin reached at least the inside flank of the St. Croix Moraine. Because the clayey till overlies more than 100 ft of lake sediment at Coon Rapids, including more than 50 ft of varved silt and clay, it is unlikely that the till was deposited by a local readvance during the initial retreat of the Superior lobe from the St. Croix Moraine. At Maple Grove in northeast Hennepin County (Fig. 5, location F), a low-lying Superior-provenance fan deposit is overlain in places by thick Cromwell Formation till. Although the till is predominantly sandy, it may have been deposited during the Automba-phase readvance across the Stacy basin, if the ice flowed northwest of the clayey sediments of Glacial Lake Lind (Helgesen and Lindholm, 1977).

Post-Automba Phase Lake

Following the retreat of the Superior lobe to the north after the Automba phase, a lake again formed within the Stacy basin (Fig. 7). If the Automba-phase advance

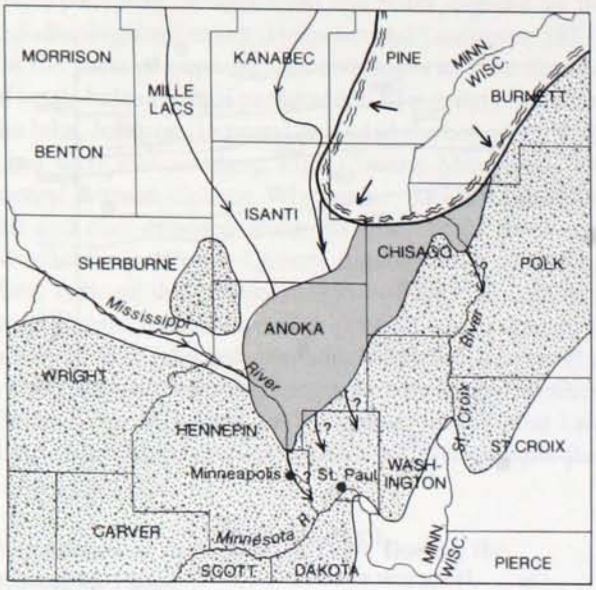


Figure 7. Glacial history of the Stacy basin: Post-Automba phase lake. The retreat of the Superior lobe allowed a large lake to again occupy the Stacy basin. See page 37 for explanation of map symbols.

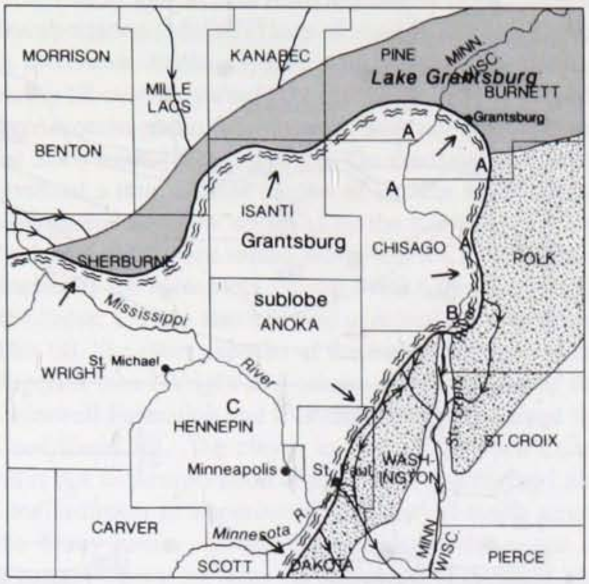


Figure 8. Glacial history of the Stacy basin: Advance of the Grantsburg sublobe. Shows the Grantsburg sublobe at the Pine City Moraine, damming Glacial Lake Grantsburg. Exposures of grayish lake sediment below New Ulm Till (Johnson, in press) are indicated by A. Site with organic silt below New Ulm Till indicated by B. Site with wood-bearing sediment above New Ulm Till indicated by C. For radiocarbon dates see Table 1. See page 37 for explanation of map symbols.

of the Superior lobe had reached as far south as depicted in Figure 5, an entirely new lake may have formed across the area previously occupied by Glacial Lake Lind (Johnson, in press). Alternatively, the ponded water of Glacial Lake Lind may have been forced north up the Mississippi valley during the Automba-phase advance, accounting for reddish lake sediment in the vicinity of Monticello in Wright County (Fig. 4). Sediments thought to be deposited in the post-Automba-phase lake are observed or documented (1) in central Chisago County, (2) above the Coon Creek till in MGS test hole A-2 in northeast Anoka County, (3) in a few Minnesota Department of Transportation logs in southwest Anoka County (Fig. 6), and (4) in MGS core hole AR-3 near North Branch in central Chisago County (Table 2). Lake sediments above the Coon Creek till include some clayey sediment, but they are coarser and lack the characteristic varves of lake sediments below the till, implying that the post-Automba-phase lake was shallower. Exposures in Chisago County as well as core AR-3 (Table 2) show that thick, very well sorted, fine-grained sand containing clasts of red clay caps the lake sediments above the Coon Creek till. This coarser sediment indicates that the post-Automba phase lake became shallower over time, and that it may have eventually filled and drained prior to the advance of the Grantsburg sublobe from the southwest.

Advance of the Grantsburg Sublobe of the Des Moines Lobe

The Grantsburg sublobe was a northeast-flowing offshoot of the south-flowing Des Moines lobe of northwestern source. Unlike deposits of earlier ice advances into central Minnesota from the northwest, Des Moines lobe deposits are characterized by an abundance of Cretaceous Pierre Shale fragments. Deposits of the Grantsburg sublobe of the Des Moines lobe are included in the New Ulm Formation (Meyer and Patterson, 1997).

Just as the stagnant-ice-cored St. Croix Moraine hindered escape of Superior-lobe meltwater out of the Stacy basin, the St. Croix Moraine also likely impeded the advance of Des Moines lobe ice into the basin. After initially bulging onto the relatively high ground of western Sherburne County (Meyer and Hobbs, 1993), the flank of the Des Moines lobe was eventually able to override the St. Croix Moraine at the western end of the Stacy basin. The ensuing sublobe probably moved rapidly northeast along the axis of the basin toward its terminus at Grantsburg, Wisconsin (Fig. 8), expanding over the gently rising surface to the north, but confined by the ice-cored St. Croix Moraine to the southeast. While the Grantsburg sublobe advanced northeast, ice was likely receding from the high ground of western Sherburne County, where only a thin veneer of till of the New Ulm Formation overlies the Cromwell Formation.

It is uncertain whether the Grantsburg sublobe was fronted by a lake during its advance northeast within the Stacy basin. If the outlet for post-Automba Glacial Lake Lind was the Mississippi River channel at the southwest end of the basin, the outlet would have been blocked by the advancing ice and a lake would have formed — or the existing lake would have become larger. New Ulm till below the modern Mississippi River floodplain (Fig. 6) implies that the Mississippi River channel was open prior to being overrun by the Grantsburg sublobe. If the outlet to post-Automba-phase Glacial Lake Lind was down the present St. Croix River valley, Grantsburg-sublobe meltwater was probably able to escape without ponding, until the outlet was blocked as the ice neared its terminus. Grayish lake sediment overlies reddish Superior-provenance deposits and underlies New Ulm till (Fig. 8 and Johnson, in press), indicating that the Grantsburg sublobe had advanced into a proglacial lake. These sites, however, may all be far enough east not to require the formation of a proglacial lake before the damming of the potential outlet at the St. Croix valley. "Push moraines" at the northern margin of the Grantsburg sublobe are composed of lake silt deformed by the advancing ice (Cooper, 1935).

Age of the Grantsburg Sublobe Maximum

The maximum extent of the Grantsburg sublobe is marked to the north by the Pine City Moraine (Hobbs and Goebel, 1982). The southeastern margin of the Grantsburg sublobe rested against the ice-cored St. Croix Moraine, so no distinct moraine formed. At a site near the eastern margin of the sublobe in southeastern Chisago County (Fig. 8, site B), organic silts overlie Cromwell Formation sediments and underlie more than 25 ft of New Ulm Formation till. Wood from the base of the New Ulm till at this location is radiocarbon dated at 11,850 ± 60 yrs B.P. (Table 1, Beta-47059) and wood from the organic silts provides a radiocarbon date of 11,900 ± 70 yrs B.P. (Table 1, Beta-47804). Both of these dates are considerably younger than Wright's (1972) estimate of 16,000 yrs B.P. for the time at which the Grantsburg sublobe reached its terminus, and slightly younger than Clayton and Moran's (1982) estimate of 12,300 years B.P.

The radiocarbon dates from wood in the organic silt and New Ulm till are very close to the date of 11,930 ± 60 yrs B.P. (Table 1, Beta-23746) obtained from wood just above New Ulm till in kettle-fill (Meyer and Hobbs, 1989) at a site in Hennepin County in the center of the area covered by the Grantsburg sublobe (site C, Fig. 8). A somewhat older radiocarbon date of 12,030 ± 200 yrs B.P. (Table 1, W-354) is reported from wood in sand above New Ulm Formation till in central Chisago County (Wright and Rubin, 1956). Organic debris (reworked peat?) sampled from sand and gravel immediately below New Ulm till at St. Michael in eastern Wright County (Fig. 8) yielded a radiocarbon date of 38,040 ± 1360 yrs B.P. (Table 1, Beta-23745); this organic debris was presumably reworked from an older deposit.

To summarize, the two sites where organic material has been dated at the base of Grantsburg-sublobe till have yielded dates that are likely either much older or somewhat younger than the probable age of the Grantsburg-sublobe maximum. The scarcity of organic material at the base of New Ulm Formation till in Minnesota suggests that the Des Moines lobe and the Grantsburg sublobe advanced across terrain largely devoid of vegetation. The organic silt at the site in southeast Chisago County may have been buried by a late surge of the sublobe or, more likely, by mass-wasting following stagnation of the active ice; insect species found in the silt have modern analogs in southern boreal forests (Garry and others, 1994).

Glacial Lake Grantsburg

At the maximum extent of the Grantsburg sublobe, meltwater escaped southward through pre-existing channels in the St. Croix Moraine (Fig. 8). To the north, however, meltwater was dammed by the ice and formed Glacial Lake Grantsburg, the outlet of which may have been over the terminus of the ice itself (Cooper, 1935), or possibly underneath the ice, as no other outlet is apparent. Deposits of lacustrine silt and clay thin rapidly to the north away from the Pine City Moraine. A recent study of varves in sediments of Glacial Lake Grantsburg provides an estimate of only about 100 years (Johnson, 1994; Johnson and Hemstad, this volume) for the duration of Glacial Lake Grantsburg.

When the Grantsburg sublobe began to retreat, Glacial Lake Grantsburg was drained as channels through the St. Croix Moraine became readily accessible (Fig. 9). Ice-marginal ridges and ice-contact fans formed as the sublobe stabilized during the early stages of retreat. The flow of new ice to the Grantsburg sublobe was apparently then cut off, and it was transformed into a large stagnant ice mass across most of the Stacy basin. Initially not all the meltwater was able to escape eastward to the St. Croix valley, and large ice-walled lakes formed. Not much glacial till was deposited by the Grantsburg sublobe in the middle of the Stacy basin (Helgesen and Lindholm, 1977) because of the sudden stagnation of the relatively

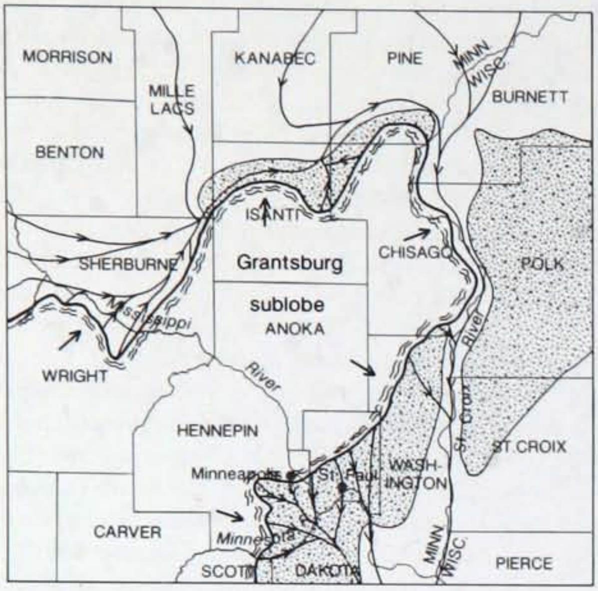


Figure 9. Glacial history of the Stacy basin: Recession of the Grantsburg sublobe. Showing recessional position of Grantsburg sublobe following the draining of Glacial Lake Grantsburg. See page 37 for explanation of map symbols.

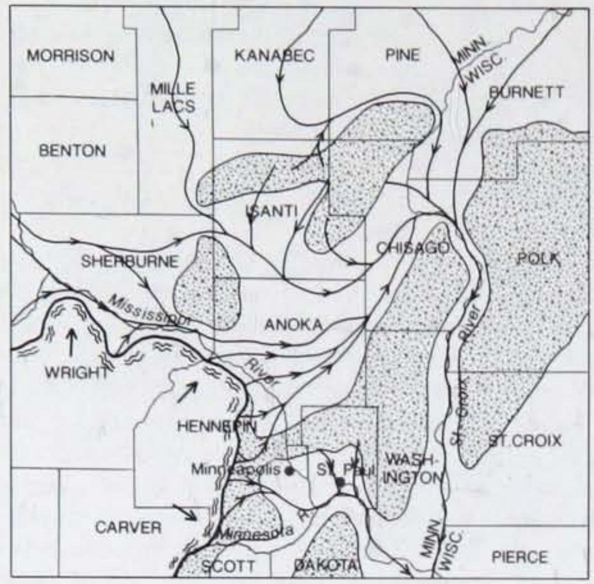


Figure 10. Glacial history of the Stacy basin: Stagnation of the Grantsburg sublobe. Map shows meltwater drainage across the Stacy basin following stagnation of the Grantsburg sublobe. Much of the flow was over and around stagnant ice. See page 37 for explanation of map symbols.

clean ice at the middle of the sublobe; meltwater coursing through the area subsequently removed much of the till that had been deposited (Fig. 10).

Glacial Lake Anoka

The large volume of Grantsburg-sublobe meltwater moving out of the Stacy basin through the St. Croix valley became blocked by an alluvial fan (the Barrens fan, Fig. 11 and Meyer and others, 1993) deposited by meltwater from the Superior lobe, which at this time had probably readvanced to the Nickerson Moraine (Wright, 1972; Clayton, 1984). The dammed meltwater formed Glacial Lake Anoka (Meyer, 1993), which extended over most of the Stacy basin. Sediments that infilled Glacial Lake Anoka form much of the Anoka Sandplain. A modern analog is Lake Pepin, formed by the damming of the Mississippi River by an alluvial fan at the mouth of the Chippewa River (Zumberge, 1952).

The Anoka Sandplain was considered by Cooper (1935) to have formed entirely as an outwash plain, until Stone (1965, 1966) recognized lacustrine sediments within the sand plain in northern Ramsey, southeastern Anoka, and northwestern Washington Counties. Mapping projects by the MGS (Meyer, 1985; Meyer and Hobbs, 1989; Meyer and others, 1990; Meyer and others, 1993; Meyer, 1993; Patterson, 1992) and the Minnesota Department of Natural Resources (Lehr, 1992) have gradually extended the area covered by Glacial Lake Anoka to that depicted in Figure 11.

New Ulm Formation till is locally overlain by fluvial sand and gravel that underlies sediments of Glacial Lake Anoka within the Stacy basin. This stratigraphic sequence suggests that meltwater was initially able to flow across the basin and down the St. Croix valley following the stagnation of the Grantsburg sublobe, prior to the development of the fan at the northeast end of the Stacy basin. The area north of the St. Croix valley outlet in Wisconsin is now occupied by a sandy area known as "the Barrens." The Barrens is interpreted as a remnant of the alluvial fan that dammed Glacial Lake Anoka. Its surface was lowered by fluvial erosion following drainage of Glacial Lake Anoka, and was modified by eolian activity. The reddish sand of the Barrens fan is derived from the Superior lobe and contrasts with the yellowish sand and silt deposits of Glacial Lake Anoka that are derived from the Des Moines lobe.

Meltwater flowing from the stagnant ice of the Grantsburg sublobe and the retreating margin of the Des Moines lobe filled the generally shallow Glacial Lake Anoka with mostly fine-grained sand. Much of the land surface adjacent to and beneath the lake was higher than at present because melting of buried stagnant ice has

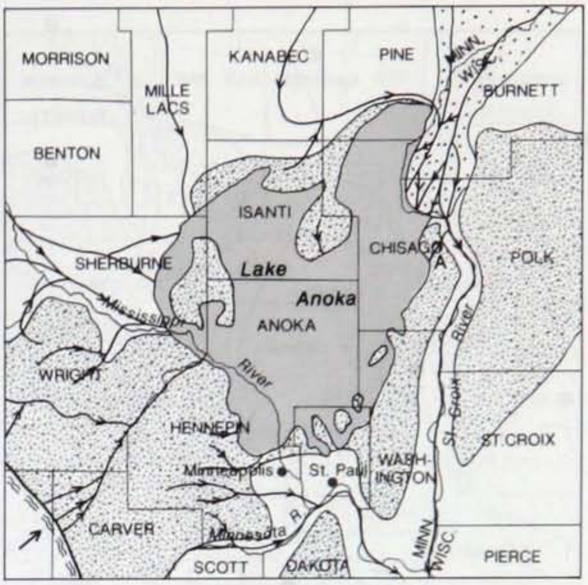


Figure 11. Glacial history of the Stacy basin: Glacial Lake Anoka. Map shows approximate maximum extent of Glacial Lake Anoka, dammed by the Barrens fan. An early secondary (overflow?) outlet is shown at A. See page 37 for explanation of map symbols.

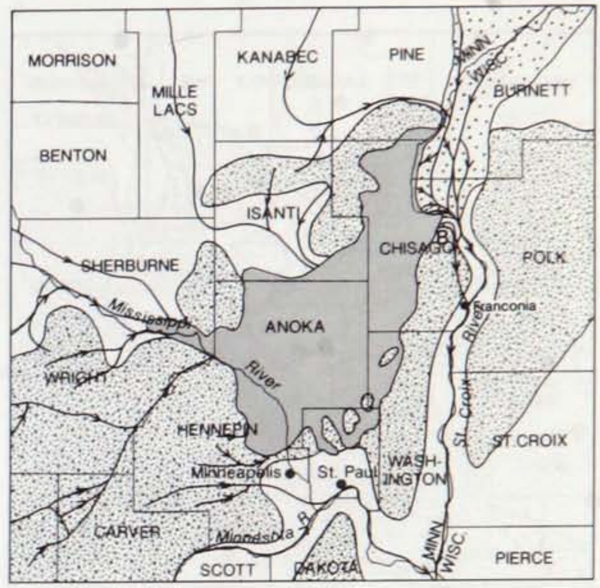


Figure 12. Glacial history of the Stacy basin: Glacial Lake Anoka at the Hugo level. Map shows extent of Glacial Lake Anoka at the Hugo level, following catastrophic drainage at outlet B. See page 37 for explanation of map symbols.

produced extensive lowlands, thus the lake's boundaries are now difficult to distinguish in places. Lake sediments at high elevations in the northern part of Glacial Lake Anoka may have experienced post-depositional uplift due to isostatic rebound still in effect from the off-loading of Superior-lobe ice. In many places the surface of the New Ulm till was only slightly modified by wave action and is now overlain by widely scattered, generally thin deposits of fine sand. During the early high stages of Glacial Lake Anoka, at least one outlet was present south of the Barrens fan (Fig. 11, outlet A). Other outlets may have existed in the southern part of the lake, serving to gradually lower the lake level, but if so, none was able to divert all flow from the Barrens fan outlet.

Stone (1966) identified sand waves and cross-bedding in exposed Glacial Lake Anoka sediments in northern Ramsey County. He interpreted these features to indicate that the lake dried up and streams occupied the lake bed for a short time prior to again being inundated. This exposure, tens of feet below the early levels of Lake Anoka, is in a narrow depression within the North Ramsey mounds and may represent drainage events in the early stages of, or prior to, the formation of the Barrens fan-dammed lake. Alternatively, the sedimentary structures Stone noted may have been formed by high-energy currents flowing along the bottom of a deep, narrow bay of Glacial Lake Anoka.

Hugo Level of Glacial Lake Anoka

Geomorphic evidence in southeastern Chisago County indicates that following development of the Barrens fan, a new outlet (Fig. 12, outlet B) close to the Barrens fan outlet opened and caused a catastrophic draining of the lake to the 940-ft "Hugo" level (Eginton, 1975; Meyer and others, 1990; Meyer, 1993). This new outlet must have become available as sediment-mantled ice in a buried valley melted, collapsing the overlying surface. A broad water-washed area west of the St. Croix valley from outlet B south to Franconia (Fig. 12; Meyer, 1993) is evidence that the valley was initially unable to handle all the water released during this event. Glacial Lake Anoka stabilized at the Hugo level long enough for a recognizable plain to form, confined primarily to the Stacy basin. Outlet B was short-lived, however, as deep ice-block melt-out depressions now distort the surface expression of the outlet, indicating that ice blocks still remained within sediments underlying outlet B. The sediment mantling the ice blocks was evidently more resistant to erosion than that of the Barrens fan, which was eventually incised, leading to the abandonment of outlet B following the initial drainage of Glacial Lake Anoka to the Hugo level.

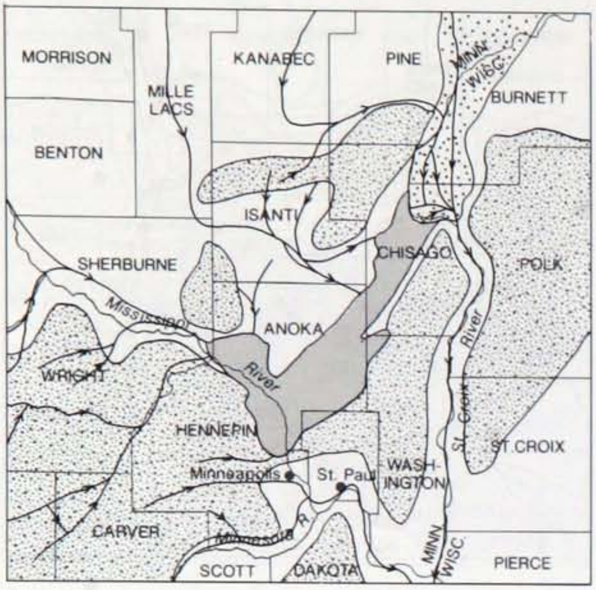


Figure 13. Glacial history of the Stacy basin: Glacial Lake Anoka - Fridley level. Map shows extent of Glacial Lake Anoka following drainage to the Fridley level. See page 37 for explanation of map symbols.

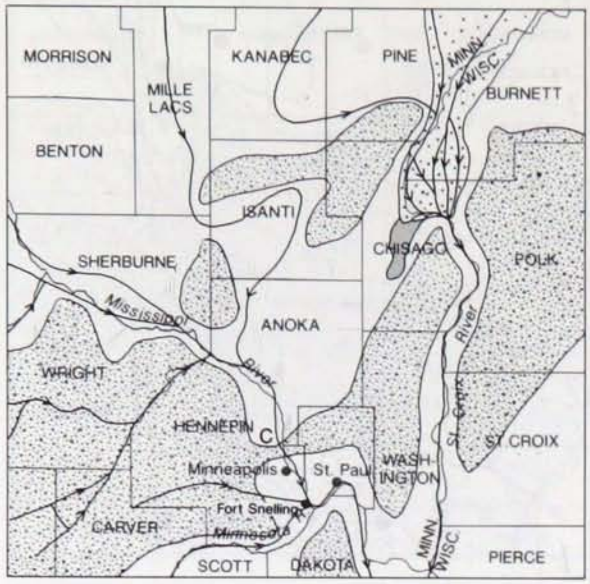


Figure 14. Glacial history of the Stacy basin: Establishment of the Course of the Mississippi River. Map shows course of Mississippi River above Fort Snelling, following drainage of Glacial Lake Anoka from the Fridley level at outlet C. See page 37 for explanation of map symbols.

Fridley Level of Glacial Lake Anoka

Glacial Lake Anoka was lowered next to the 915-ft "Fridley" level, restricting the lake primarily to central Chisago and southern Anoka Counties (Fig. 13) (Stone, 1965, 1966; Meyer and others, 1990; Meyer, 1993). The drop from the Hugo level to the Fridley level was presumably related to downcutting by the major stream draining the Des Moines lobe as the ice continued its northwestward retreat. The lowered base level and the increased gradient of the tributary St. Croix River, which formed the outlet stream for Glacial Lake Anoka, resulted in drainage of the lake to the Fridley level.

Wood in sand below the Fridley level in central Chisago County, recovered during drilling of a water well, yielded an age of 11,710 ± 80 radiocarbon years B.P. (Table 1, Beta-37418), somewhat younger than the date 12,030 ± 200 radiocarbon years B.P. (Table 1, W-354) reported by Wright and Rubin (1956) from wood at a nearby site also within the Fridley plain. A wood sample taken from a deep exposure below the Fridley level in Anoka County was dated at 41,800 ± 1,000 radiocarbon years B.P. (Table 1, Beta-34583). Presumably these wood fragments, like adjacent lignite and Cretaceous shale clasts, were reworked. Although wood, "peat," and "coal" layers have been noted in places by water well drillers, mollusk shells have not been recognized in deposits of Glacial Lake Anoka.

Establishment of the Present Courses of the Mississippi and St. Croix Rivers

Glacial Lake Anoka finally drained when a southern outlet opened in north Minneapolis (outlet C on Fig. 14; Meyer and Hobbs, 1989), establishing the present course of the Mississippi River above its confluence with the St. Croix River. This southern outlet likely became available when melting stagnant ice preserved in a buried valley produced a channel below the Fridley level. Isostatic rebound may have contributed to the shift from the northern outlet at the St. Croix valley to the southern outlet at the Mississippi valley. A small remnant of Glacial Lake Anoka probably remained dammed by the Barrens fan (Fig. 14) until continued downcutting of the Mississippi valley by Des Moines-lobe meltwater caused further incision of the fan outlet, finally allowing the lake to drain completely.

The courses of the Mississippi and St. Croix Rivers initially varied widely across the flat outwash and lake plains of the Anoka Sandplain, leaving behind a wide, high upper terrace (Fig. 15). The upper terrace is particularly wide above the Glacial Lake Anoka outlets. The surface of the Barrens fan was further lowered and incised during this period. When the Des Moines lobe retreated north of the continental divide, Glacial Lake Agassiz formed in northern Minnesota and adjacent areas

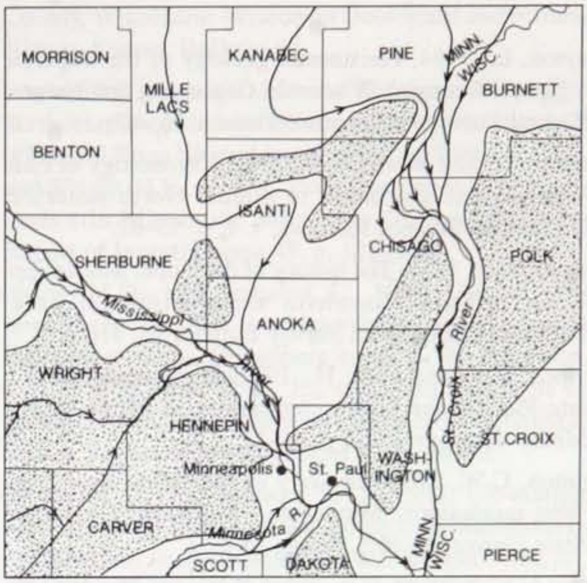


Figure 15. Glacial history of the Stacy basin: Upper terrace level of the Mississippi River. Map shows the course of the major meltwater streams at the upper terrace level. See page 37 for explanation of map symbols.

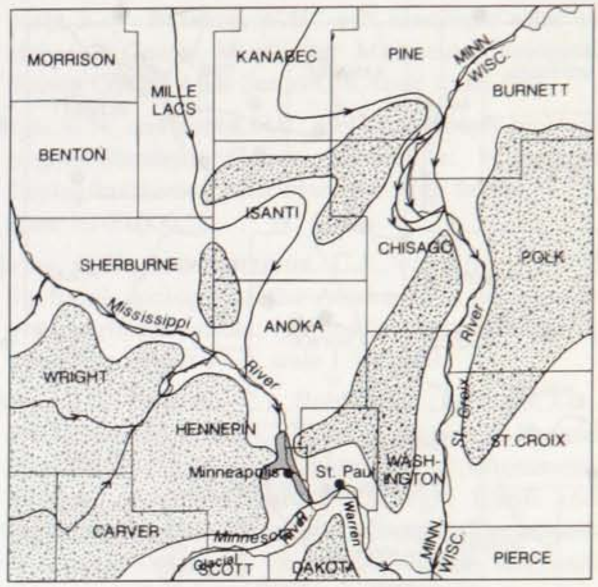


Figure 16. Glacial history of the Stacy basin: Middle terrace level of the Mississippi River. Map shows course of major meltwater streams at the middle terrace level. See page 37 for explanation of map symbols.

of North Dakota and Canada. Glacial River Warren formed the southern outlet for Glacial Lake Agassiz (Johnson and others, this volume; Wright and others, this volume), and became the dominant stream draining Minnesota. Glacial River Warren cut what is now the Minnesota River valley, and the Mississippi valley below Fort Snelling.

The Mississippi River above Fort Snelling was a tributary of Glacial River Warren during the drainage of Glacial Lake Agassiz. At this time the Mississippi River became restricted to the middle terrace level as its upper terrace became incised to match the downcutting master stream, Glacial River Warren (Fig. 16; Meyer and Hobbs, 1989). The gray laminated clay and silt mined for brick-making in the past (Grout and Soper, 1919), extends from downtown Minneapolis to southernmost Anoka County and was probably deposited in slackwater ponded within the Mississippi River floodplain (Fig. 16) by Glacial River Warren floods during this period (Meyer, 1996). Wood collected in 1923 by Cooper and Foot (1932) "at a depth of 3 to 12 feet" at the edge of these slackwater deposits was later radiocarbon dated at 11,790+ 200 yrs B.P. (Table 1; W-454). Peat collected at the same time from the site yielded a much younger radiocarbon date of 10,200 ± 300 yrs B.P. (Table 1, W-445). Wright and Rubin (1956) suggest the peat date may be inaccurate due to contamination. It is possible, however, that the wood was reworked from older deposits, and the peat gives the more reliable date.

The St. Croix River became restricted primarily to the Minnesota side of the St. Croix valley immediately north of the Barrens outlet during formation of the middle terrace levels. Terrace levels within the St. Croix valley are more numerous and complex than those of the Minnesota and Mississippi valleys, because the St. Croix valley was affected not only by the continued downcutting of Glacial River Warren but also by periodic flooding resulting from the release of water from proglacial lakes fronting the Superior lobe in the Lake Superior basin (Clayton, 1984). Subsurface data indicate that flow within the St. Croix valley during at least one such episode exceeded that of Glacial River Warren (Todd, 1942).

The formation of St. Anthony Falls, a by product of the entrenchment of Glacial River Warren, led to the establishment of the modern floodplain of the Mississippi River north of Fort Snelling. Glacial River Warren and the St. Croix River, more restricted now within their entrenched valleys, built the lower terrace levels (Fig. 17), such as Grey Cloud Island and the Bayport and Lakeland terraces (Meyer and others, 1990). Gray clay and silt lie beneath parts of downtown St. Paul and extend northward in a tributary valley (Meyer, 1992; Mossler and Walton,

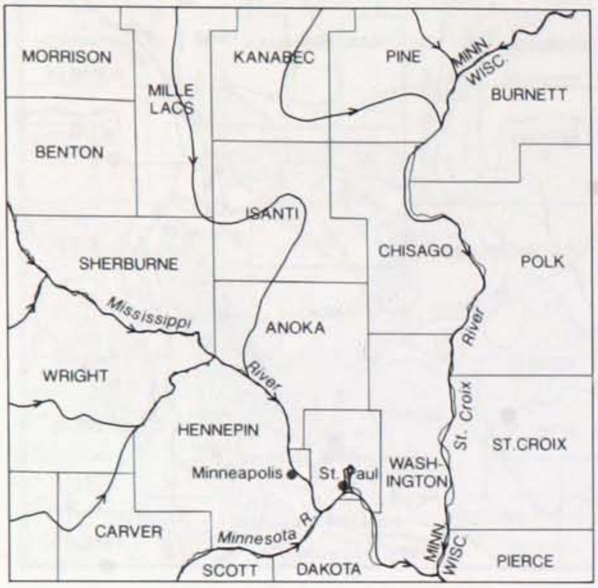


Figure 17. Glacial history of the Stacy basin: Lower terrace level of the Mississippi River. Map shows course of major meltwater streams at the lower terrace level. See page 37 for explanation of map symbols.

1979). This lacustrine sediment (Fig. 17) was deposited in slackwater ponded by Glacial River Warren during flow at the lower terrace level. Most buried stagnant glacial ice, at least in the vicinity of the major streams, had probably melted by this time. Both Glacial River Warren and the St. Croix River were subsequently entrenched more than 100 ft below the lower terraces before ceasing to serve as outlets for Glacial Lakes Agassiz and Duluth (Johnson and others, this volume). Their valleys are now being filled with alluvium, whereas the low-lying portions of the Glacial Lake Anoka basin continue to fill primarily with organic debris. During an extended dry period in the Middle Holocene beginning about 8,000 years ago, the surface of the lake basin, as well as that of the Barrens fan, was modified by wind; sand dunes formed in some areas (Keen and Shane, 1990).

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GLACIAL LAKE GRANTSBURG: A SHORT-LIVED LAKE RECORDING THE ADVANCE AND RETREAT OF THE GRANTSBURG SUBLOBE

Mark D. Johnson[1] and Chris Hemstad[2]

ABSTRACT

Glacial Lake Grantsburg formed as the Grantsburg sublobe advanced to the northeast in east-central Minnesota and dammed the ancestral St. Croix River. The St. Croix River flowed on a broad sand plain, which formed by the infilling of Glacial Lake Lind with prograding deltas and braid plains. Exposures show that Glacial Lake Grantsburg silt and clay overlie the deltaic and fluvial sand, which in turn overlies red varved clay of Glacial Lake Lind. The red varves were not deposited in Glacial Lake Grantsburg, as suggested by earlier authors.

Varved silt and clay is a common feature in Glacial Lake Grantsburg deposits. Overridden lake sediments and varve sedimentology indicate that the Grantsburg sublobe took 13–17 years to advance to the Pine City ice margin, suggesting an ice-advance rate of 3–7 km/yr. Varved sediment exposed at one site indicates that Glacial Lake Grantsburg was a short-lived lake, lasting perhaps only about 100 years. The outlet of Glacial Lake Grantsburg changed at least twice, and it was probably through the ice itself when it stood at the Pine City Moraine.

INTRODUCTION

This paper presents new ideas about the extent and duration of Glacial Lake Grantsburg, which existed in the St. Croix River drainage basin (Fig. 1). The data and interpretations are based on recent fieldwork (Johnson, 1992, and in press) and include detailed descriptions of the sediments deposited in Glacial Lake Grantsburg (see also Meyer, this volume). The new ideas presented are that (1) gray varved clays are common in Glacial Lake Grantsburg deposits and indicate that the lake was short-lived (perhaps around 100 years); (2) the red varved clays described by Berkey (1905) belong to a long-lived (over 1000 years) glacial lake (Glacial Lake Lind) and not to Glacial Lake Grantsburg, as was suggested by Cooper (1935); and (3) overridden varves indicate that the Grantsburg sublobe advanced at surging rates.

REGIONAL GLACIAL GEOLOGY

The St. Croix River basin was glaciated at least four times during the Pleistocene, as shown by stratigraphy preserved in valley-wall exposures and drill holes throughout the region (Berkey, 1897; Chamberlin, 1905, 1910; Leverett, 1932; Mathieson, 1940; Black, 1959; Wright, 1972; Wright and others, 1973; Baker and others, 1983; Chernicoff, 1983; Clayton, 1984; Johnson, 1986, and in press). Surface features in eastern Minnesota and western Wisconsin were formed primarily during the Wisconsinan Glaciation. During the last part of the Wisconsinan Glaciation, the Superior lobe advanced towards the southwest through the study area and melted back, leaving several clear ice-margin positions (Figs. 1A and 2; see also Johnson and Mooers, this volume), as shown by tunnel-channel mouths, tunnel-channel/outwash-fan pairs, outwash heads, discontinuous moraine ridges, abrupt boundaries of hummocky tracts, and till-sheet margins (Meyer, 1985; Meyer and others, 1990, 1993; Johnson, 1986, and in press; Mooers, 1989; Johnson and Mooers, this volume). The till of the Superior lobe deposits is reddish brown (5YR 4/4), slightly gravelly to gravelly sandy loam, with an average sand:silt:clay ratio of 65:25:10 (Johnson, 1986, and in press).

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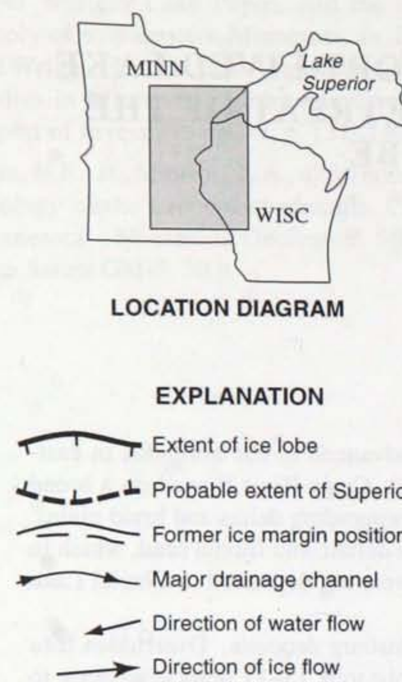
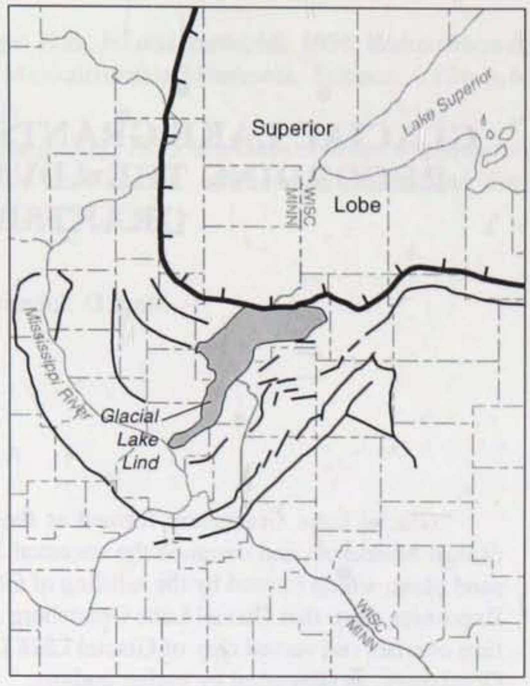
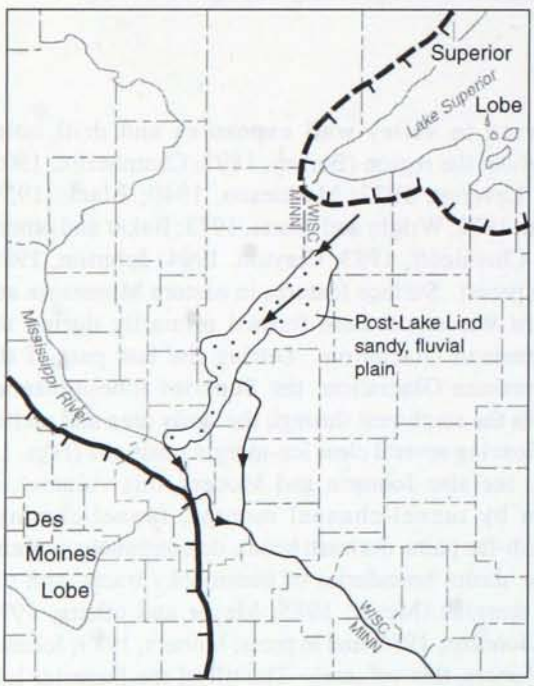
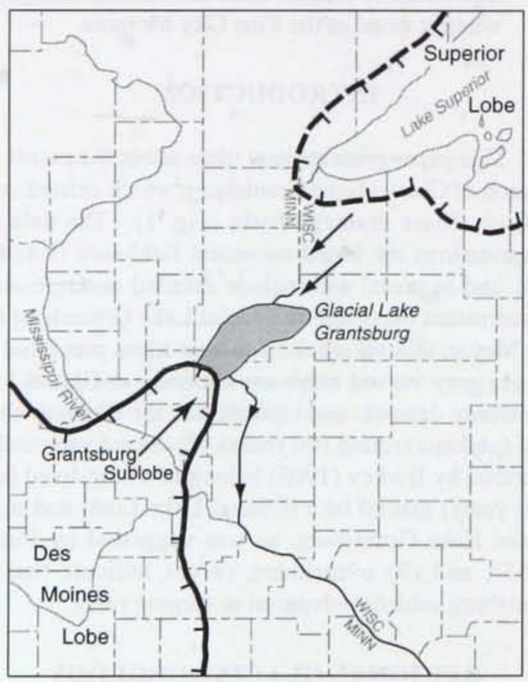




1A—Glacial Lake Lind formed in the lowland of the former St. Croix River. The Superior lobe at this time is shown by the heaviest line; the medium lines mark former Late Wisconsinan ice-margin positions of the Superior lobe (see Johnson and Mooers, this volume).



1B—Glacial Lake Lind filled in with sand deposited in prograding deltas and fluvial plains.



1C—The Grantsburg sublobe advanced across the sand plain, dammed the St. Croix River and the Mississippi River, and formed Glacial Lake Grantsburg. We suggest that an initial outlet of Glacial Lake Grantsburg would have formed the modern St. Croix River valley in the Taylors Falls area.

Figure 1. Sketch maps of the study area showing selected Late Wisconsinan events.

1D—The Grantsburg Sublobe continued to advance to the Pine City ice margin (shown here) and Glacial Lake Grantsburg expanded. The role of the Horse Creek channel as a possible outlet at this time is explained in the text. The Superior lobe may have still been in the drainage basin at this time.

1E—Glacial Lake Duluth drained through the study area along the St. Croix River via the Kettle River and then the Brule River.

Figure 1. *continued*

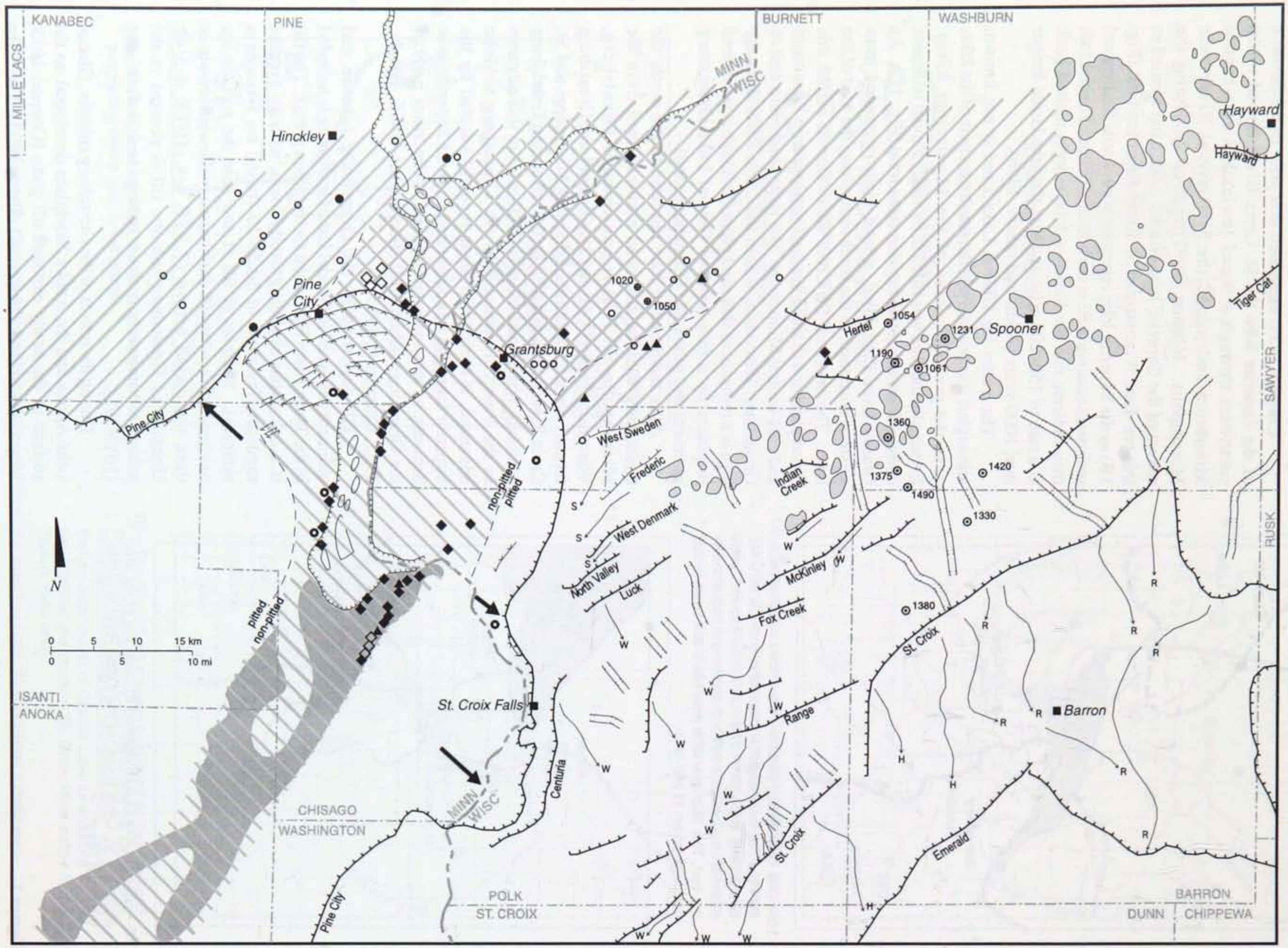
Cooper (1935) suggested that prior to the advance of the Superior lobe the St. Croix River flowed to the southwest through a broad lowland in east-central Minnesota and joined the Mississippi River near Minneapolis. Johnson (1992) showed that during the retreat of the Superior lobe Glacial Lake Lind formed in this pre–Late Wisconsinan St. Croix River lowland (Fig. 1B) as the Superior lobe retreated northward. Red varved sediments accumulated at the bottom of Glacial Lake Lind; they indicate that the Superior-lobe margin melted back at a rate of 150–200 m/yr and that the lake lasted longer than 1000 years (Addis and others, 1996).

The outlet for Glacial Lake Lind is not known, although it was probably in the southwest part of the lake, near the present course of the Mississippi River. Eventually the lake was filled in by sandy fluvial sediment derived from the retreating Superior lobe (Fig. 1C). As Glacial Lake Lind filled, a sand plain prograded from western Wisconsin to the southwest, along the axis of the lake. The ancestral St. Croix River flowed across this broad plain and drained much of northwestern Wisconsin and east-central Minnesota. The large sand plain east of Grantsburg, Wisconsin, within the Clam River drainage area is a remnant of this sand plain (although it is covered in places by a thin layer of Glacial Lake Grantsburg sediment and post-Lake Grantsburg sand).

After the Superior lobe retreated to the north, the Grantsburg sublobe advanced northeastward from the Minneapolis–St. Paul region towards Grantsburg, Wisconsin (Figs. 1D, 1E and 2). Glacial Lake Grantsburg formed when the southward draining Mississippi and St. Croix Rivers were dammed by the advancing Grantsburg sublobe. Wright and others (1973) refer to this advance as the Pine City phase. As the Grantsburg sublobe advanced, it reoccupied areas recently vacated by the Superior lobe, and it incorporated some of Superior-lobe deposits, as shown by redder hues in the lower parts of the Grantsburg-sublobe till sheet (Stone, 1966; Wright, 1953; Chernicoff, 1983).

Till deposited by the Grantsburg sublobe and sediment deposited in Glacial Lake Grantsburg is included in the Trade River Formation (Johnson, in press). The till is a calcareous slightly gravelly loam, with an average sand:silt:clay ratio of 50:30:20 (based on Wisconsin samples). Samples of till at and near the surface are oxidized and are brown, dark brown, yellowish brown, or dark yellowish brown (7.5YR 4/4, 10YR 4-5/4). Unoxidized Grantsburg-sublobe till is present in the subsurface in poorly drained settings and is dark gray (10YR 4/1).

During the retreat of the Grantsburg sublobe, Glacial Lake Anoka and the Anoka Sandplain developed on the surface of the newly exposed till plain (Cooper, 1935; Meyer, this volume; Meyer and others, 1993). Later, the



KANABEC
MILLE LACS
PINE
BURNETT
WASHBURN
SAWYER
RUSK
MINN
WISC
Hinckley
Hayward
Pine City
Grantsburg
Spooner
Tiger Cat
Hertel
West Sweden
Frederic
West Denmark
North Valley
Luck
Indian Creek
McKinley
Fox Creek
St. Croix
Range
Centuria
Emerald
St. Croix Falls
Barron
non-pitted
pitted
pitted
non-pitted
1020
1050
1054
1231
1190
1061
1360
1375
1490
1420
1330
1380
N
0 5 10 15 km
0 5 10 mi
ISANTI
ANOKA
CHISAGO
WASHINGTON
POLK
ST. CROIX
BARRON
DUNN
CHIPPEWA

EXPLANATION

- 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; ticks point up-ice
- County boundary
- Spooner Hills
- Outcrop of Glacial Lake Grantsburg massive clay
- 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 Superior lobe till
- Town

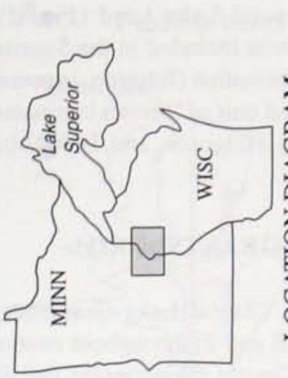


Figure 2. Portion of east-central Minnesota and northwestern Wisconsin showing features associated with the most recent glacial events (modified from Johnson, in press). Pine City ice margin in Minnesota from Cooper (1935) and Hobbs and Goebel (1982). Location of Glacial Lake Grantsburg and Glacial Lake Lind sediment in Minnesota from Chris Hemstad and Johnson (unpublished data) and Gary Meyer (oral commun. 1996). Extent of Glacial Lake Grantsburg in Minnesota is in part from Cooper (1935). Till fabric measurements in Minnesota from Chernicoff (1983). Pitted and non-pitted portions of the field area are interpreted to indicate the extent of Glacial Lake Lind, because permafrost and remnant ice blocks beneath Glacial Lake Lind were melted; pits remain only outside the lake margin.

Superior lobe retreated into the Lake Superior Basin, forming Glacial Lake Duluth. Spillway water from Glacial Lake Duluth drained through outlets at Moose Lake, Minnesota and at Brule, Wisconsin and cut the deep channel through which the modern St. Croix River now flows (Fig. 1F).

The age of Glacial Lake Grantsburg, as well as the ages of glacial events in western Wisconsin and east-central Minnesota are poorly constrained. Few radiocarbon dates exist, leading to different interpretations of the regional chronology (Wright and others, 1973; Clayton and Moran, 1982; Meyer, this volume). Based on the available interpretations, Johnson (in press) suggested that Glacial Lake Grantsburg formed around 14,000 yrs B.P., and that Glacial Lake Lind formed earlier, perhaps as early as 18,500 yrs B.P.

PREVIOUS WORK ON LAKE DEPOSITS IN THE ST. CROIX RIVER VALLEY

Lake sediment was first noted in the St. Croix valley by Berkey (1905) who described a unit of laminated red clay 1.5–12 m thick overlying Superior-lobe till. Berkey (1905) noted that the clay consisted of alternating laminations of red clay and brown silt, and he argued that each couplet of clay and silt represented one year's deposition. He also noted that the clay had been overridden by ice near Grantsburg, Wisconsin

Using the thickness of exposed silt and clay couplets, Berkey extrapolated the number of annual layers that would be present in the entire thickness of the laminated clay (as estimated from drill-hole logs) and concluded that the lake clay was deposited in about 1700 years. Berkey noticed that at Grantsburg the varves increase in thickness upwards towards a till cap, which led him to interpret the 1700 years as representing an interglacial period, with the thicker varves deposited as a glacier approached. Grout (1910) extended the known distribution of the clay.

In northwestern Wisconsin, Hansell (1930) mapped "varved clay" (as he called Berkey's laminated red clay) as well as a slightly younger "laminated clay" that consisted of "thicker layers of brown clay alternating with thin beds of reddish clay." He considered both these clay units to have been deposited in a postglacial lake called "the Barrens Lake," which he considered to be contemporaneous with Duluth-level shorelines in the Lake Superior basin.

Cooper (1935) described lake sediment he considered to have been deposited in a lake dammed by the Grantsburg sublobe, which he called Glacial Lake Grantsburg, a name originally used by Martin (1932). Cooper (1935) described the lake sediment as primarily gray silt forming a layer about 1 m thick, although locally

Figure 3. Glacial Lake Grantsburg varved silt and clay from a backhoe pit in southern Pine County, Minnesota (NW1/4 SE1/4 sec. 25, T. 39 N., R. 22W.). The blade of the trowel is 20 cm long.

it may form patches as thick as 10 m. He estimated the elevation of Glacial Lake Grantsburg to be 320–335 m, and he outlined the retreat of the Grantsburg sublobe and the development of the Anoka Sandplain. Cooper (1935) considered Berkey's red varves to be an older phase of Glacial Lake Grantsburg deposited in the lake as the Grantsburg sublobe advanced. Similarly, Wright and others (1973) considered the laminated red clay to represent an earlier phase of Glacial Lake Grantsburg, and the gray silt to represent a short later phase of the lake.

Recent field work (Johnson, 1992) reveals that the red-clay varves of Berkey were formed in an earlier lake, Glacial Lake Lind (Figs. 1B and 2). The stratigraphic basis for the separate identity of Glacial Lake Lind and Glacial Lake Grantsburg is that the red varves are separated from overlying Grantsburg-sublobe till and Glacial Lake Grantsburg sediment by lacustrine and fluvial sand 12–45 m thick. Numerous outcrops identified by Johnson (1992) and Addis and others (1996) helped determine the extent of Glacial Lake Lind (Fig. 2). Berkey's red clay varves are now included in the Sunrise Member of the Copper Falls Formation (Johnson, in press) and are equivalent to the buried unit of "brown laminated lake sediment" described by Helgeson and Lindholm (1997), and shown in Fig. 2.

GLACIAL LAKE GRANTSBURG

Sediment deposited in Glacial Lake Grantsburg occurs at the surface (Figs. 1E and 2) throughout central and southwestern Burnett County (Wisconsin) and in southern Pine County, southern Kanabec County, central Mille Lacs County, and parts of Benton County (Minnesota). In Minnesota, the distribution of Glacial Lake Grantsburg sediment is patchy, with thicknesses ranging from 1 to 5 m. The sediment is thickest in low swales between upland areas near the Pine City ice margin; it is commonly absent on hilltops and slopes. The topography north of the Pine City ice-margin position and within the area covered by Glacial Lake Grantsburg is essentially that left by the Superior lobe, with only slight modification by lake action.

In Wisconsin, Glacial Lake Grantsburg extended across the flat sand plain of Burnett County and western Washburn County (Fig. 1E). The eastern margin of the lake was against the Spooner Hills (Fig. 2, and Johnson, in press), where some strandlines are preserved. In Burnett County approximately 1 m of sand commonly overlies less than 1 m of Glacial Lake Grantsburg clay, which in turn overlies several meters of sand. The underlying sand grades downward into the fine-grained deposits of Glacial Lake Lind. Similar stratigraphic relations are recorded along the Clam River, in several drill holes, and in the gas pipeline trench discussed below.

Based on our observations of lake sediment (Figs. 1E and 2), the areal extent of Glacial Lake Grantsburg at its highest level is essentially that reported by Cooper (1935). A more precise depiction of its extent is difficult because (1) shorelines were not well-developed at the lake's northern boundary because of the lake's short duration (see section on duration), (2) nearshore beach sand is difficult to differentiate from the fluvial sand common in the region, due to lack of sedimentary structures, (3) sediment distribution is patchy, and (4) the northern margins of Glacial Lake Grantsburg were probably located in regions underlain by buried Superior-lobe ice, which later melted and would have collapsed any shoreline topography. These problems were clearly recognized by Cooper (1935) and Wright and others (1973).

It is clear that Glacial Lake Grantsburg began to exist soon after the Grantsburg sublobe started to advance, because gray lake sediment, typical of Glacial Lake

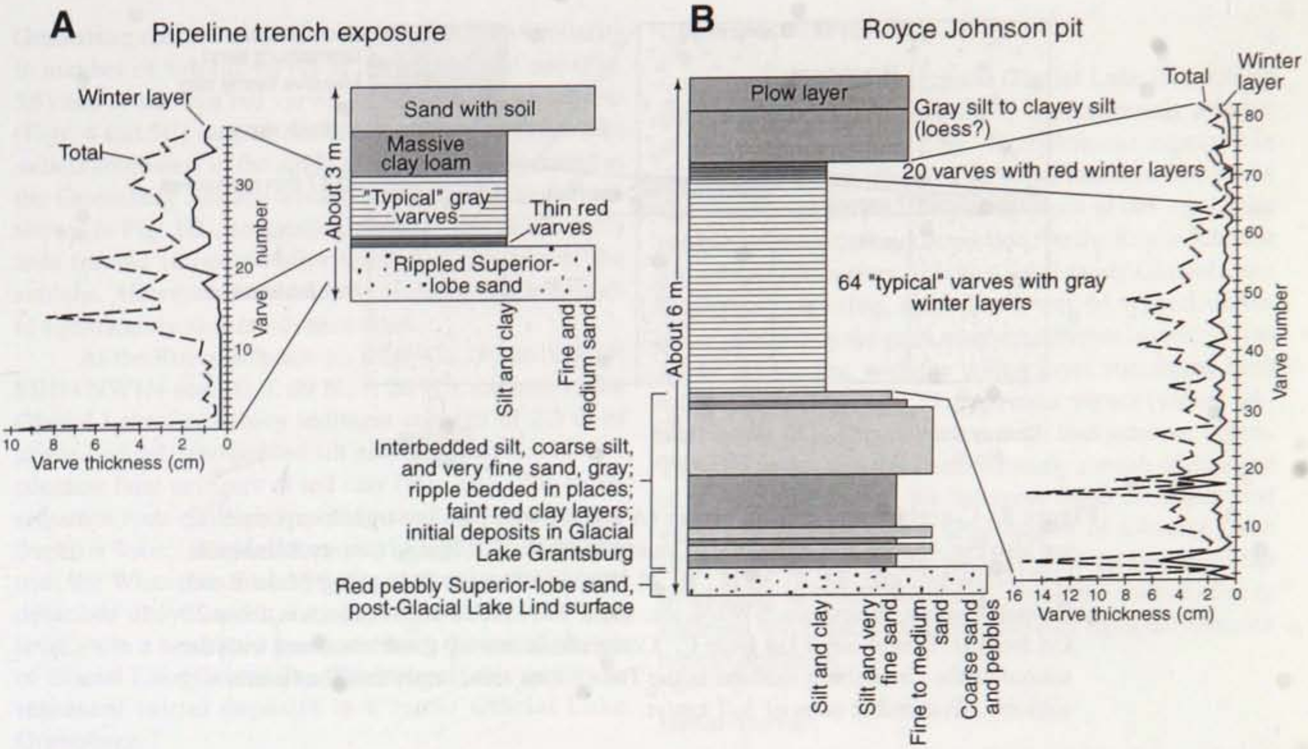


Figure 4. Varve thicknesses and sediment logs for two locations with Glacial Lake Grantsburg sediment; at both sites, Grantsburg varves overlie fluvial sediment derived from the Superior Lobe. **A.** The pipeline trench exposure (Burnett County, Wisconsin, NE1/4 NW1/4 NE1/4 sec. 19, T. 38 N., R. 18 W.) contains thin red varves, which are interpreted to represent the initial sediments of Glacial Lake Grantsburg, deposited while the Grantsburg sublobe advanced. The beginning of the thicker, "typical" varves is interpreted to represent the time when the Grantsburg sublobe is at the Pine City Moraine. **B.** The Johnson pit (NE1/4 SE1/4 NW1/4 sec. 10. T. 39 N., R 20 W.) contains sediment interpreted to represent deposition throughout the entire duration of Glacial Lake Grantsburg, which lasted perhaps as little as 100 years. See text for explanation.

Grantsburg, occurs directly below the till in several locations (Fig. 2). Furthermore, Cooper (1935) describes push ridges in the Pine City Moraine to be composed of lake sediment. We suggest that during an early stage of Glacial Lake Grantsburg, the lake level may have risen to the level of Superior-lobe outwash surfaces in the area of Wild River State Park, Minnesota, and Wolf Creek, Wisconsin, and formed an outlet to the south, down the present valley of the St. Croix River (Fig. 1D). Numerous authors have suggested that the present course of the St. Croix south of Sunrise, Minnesota was established after the retreat of the Superior lobe (Upham, 1900; Cooper, 1935) and that the present St. Croix River valley was deepened by drainage from Glacial Lake Duluth. The continued advance of the Grantsburg sublobe to the Pine City ice-margin position eventually blocked this initial outlet, at which time the lake level would have risen significantly. We suggest that Glacial Lake Grantsburg drained over, under, or through the Grantsburg sublobe, when the ice was at the Pine City ice-margin position (see discussion below).

We agree with Cooper's (1935) conclusions that Glacial Lake Grantsburg formed as a result of an advance of the Grantsburg sublobe. We also concur with his estimation of the lake's extent (Fig. 2) and likely outlet. However, we present new sedimentological data for Glacial Lake Grantsburg, which indicate that the lake had a duration of approximately 100 years. The new data are derived from eleven backhoe pits dug in localities with thick Grantsburg lake sediment (Fig. 2), and a gas pipeline trench dug during the summer of 1992 along Wisconsin State Highway 70, east of Grantsburg, Wisconsin.

CHARACTER OF GLACIAL LAKE GRANTSBURG SEDIMENT

Cooper (1935) stated that the evidence for Glacial Lake Grantsburg is a "discontinuous body of silt," and he emphasized that it is silt (not clay) that makes up most of the deposits. Cooper reports that "varving is rare, having been found in but three places." We discovered that the sediment of Glacial Lake Grantsburg contains a significant

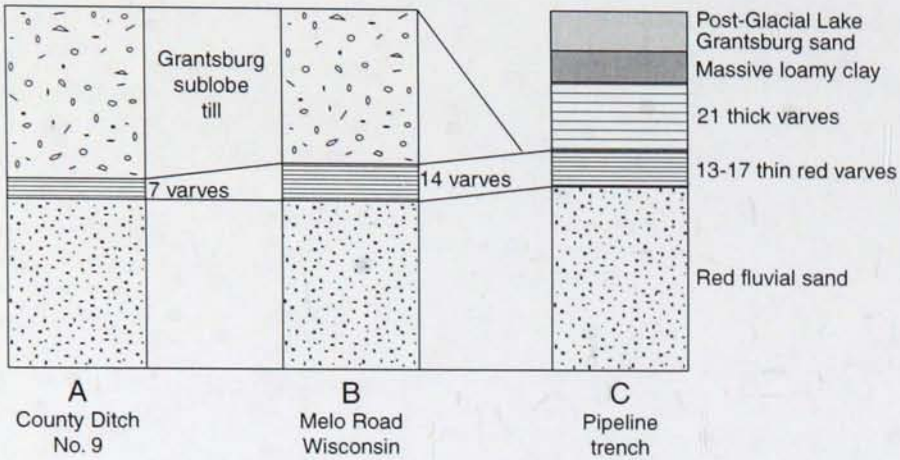


Figure 5. Correlation of sub-till varves (A and B) with pipeline trench exposure (C; see also Fig. 4). Section A is along a County Ditch No. 9, Chisago County, Minnesota, NW1/4SW1/4, sec. 11, T. 36 N., R. 21 W.), and Section B is along Melo Road, Burnett County, Wisconsin, SW1/4, sec. 19, T. 37 N., R 18 W. Section A is about 20 km from B; B is about 9 km from C. Correlations among these sites, and with the source of the Grantsburg sublobe in the Twin Cities area, imply that the Grantsburg sublobe advanced at rates of 3–7 km/yr.

amount of clay, and commonly displays rhythmic bedding that we interpret as varves (Figs. 3 and 4). Sediment deposited in Glacial Lake Grantsburg consists predominantly of gray calcareous rhythmically laminated to rhythmically bedded to massive clay and silty clay. It is easily distinguished from sediment of Glacial Lake Lind by its color (Glacial Lake Lind comprises red clay and brown silt) and its stratigraphic position. Glacial Lake Grantsburg sediment is 1–5 m thick and sharply overlies sand, sand and gravel, or diamicton composed of Superior-lobe lithologies (Fig. 4). Locally, sand occurs within sediments of Glacial Lake Grantsburg, and it is likely that the extensive sand near the northern margin of the lake was deposited in the lake, although this sand is difficult to confidently assign to Glacial Lake Grantsburg.

Varve Thickness

Near the inferred ice margin, varves are commonly 3–6 cm thick but range up to 15 cm in places. They thin to 1 cm at a site 13 km from the ice margin (SE1/4 sec. 22, T. 39 N., R. 23 W.) and to around 2.5 cm at a site 30 km from the ice margin (SE1/4 sec. 18, T. 39 N., R. 15 W.). We measured varve thicknesses at 11 sites and constructed varve-thickness diagrams (two are shown in Fig. 4), but were not able to correlate varve thickness among sites.

Bottom Varves

Varved sediment near the base of the Glacial Lake Grantsburg sequence directly overlies rippled Superior-lobe sand. In a pipeline trench (Fig. 4A) close to the Pine City ice margin near Grantsburg, Wisconsin (Burnett County, Wisconsin, sec. 19, T. 38 N., R. 18 W.), 13 to 17 varves were counted. They range from 0.5 to 8.0 cm thick, with thin (0.2 cm) winter layers composed entirely of red clay (10R 5/6) and summer layers that are coarser and yellowish brown (10YR 5/4). We interpret these varves to indicate that local sources (predominantly Superior-lobe sediment derived from nearby melting stagnant ice) dominated the early years of Glacial Lake Grantsburg in Wisconsin. Because the trench site is east of the proposed initial outlet (the St. Croix River), we suggest that gray Glacial Lake Grantsburg sediment would have been shunted south through the outlet before it could reach this location. Later, when the Grantsburg sublobe reached the Pine City Moraine, the initial outlet was blocked, the lake level rose, and the ice was closer, all of which resulted in producing thicker gray varves ("typical varves") described in the next section (Figs. 3 and 4).

If this interpretation is true, the Grantsburg sublobe lasted 13–17 years from the time the lake first formed to the time it reached the terminus (or at least the initial outlet). An exposure in western Wisconsin (Melo Road cut, SW1/4, sec. 19, T. 37 N., R 18 W.) contains 12–14 red and gray varves underneath Grantsburg-sublobe till (Fig. 5B), showing that the lake existed for 12–14 years before the sublobe reached western Wisconsin. To achieve this, the Grantsburg sublobe must have advanced at a velocity of 3–7 km/yr, a rate similar to that suggested by Clayton and others (1985) for surging lobes in the Midwest. Erosion of the overridden varves by the

Grantsburg sublobe may have occurred, but the similarity in number of sub-till varves at the Melo Road site (Fig. 5B) and of the thin red varves at the pipeline trench site (Figs. 4 and 5C) suggest erosion was limited. Other lake outlets southwest of the study area may have operated as the Grantsburg sublobe advanced (even prior to the one shown in Fig. 1D), suggesting that the lake in the study area formed sometime after the initial advance of the sublobe. However, consideration of this would not result in significantly slower advance rates.

At the Royce Johnson pit (Pine Co., Minn., NE1/4 SE1/4 NW1/4 sec. 10. T. 39 N., R 20 W.), the base of the Glacial Lake Grantsburg sediment consists of 2.3 m of ripple-bedded, interbedded silt and fine sand that locally contains faint stringers of red clay (Fig. 4B). The entire sequence rests on slightly pebbly sand derived from the Superior lobe. The Johnson site is higher in elevation than the Wisconsin sites with the thin, red winter layers described above, and it may have been above the lake level, or in a nearshore position during the initial phases of Glacial Lake Grantsburg. We interpret this section to represent initial deposits in a lower Glacial Lake Grantsburg.

Typical Varves

The dominant or typical varves that characterize the middle portion of the Glacial Lake Grantsburg sequence are the most common type of varve found within the lake deposits. The summer layers are primarily silty clay (with a small percent sand) and contain horizontal laminations (see Fig. 2 for sites with varved clay). These silty clay layers are dark yellowish brown to yellowish brown (10YR 4-5/4); in places they are mottled. The sand fraction includes abundant organic matter (broken-up grains of Cretaceous lignite) and sand-sized calcite concretions. Sorted quartz-rich sand is present in summer layers at some locations, but in all cases this sand is locally derived from lake-floor knobs composed of Superior-lobe deposits.

The finer winter layers consist of ungraded clay and 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). The redder color occurs either at the bottom of the winter layer or the top of the winter layer. Upper and lower contacts between summer and winter layers are equally sharp, sometimes disturbed. In many places, the winter layers consist of subrounded breccia-like clasts of clay surrounded by reddish-brown matrix; the clasts have sharp boundaries. This clast-like fabric is best developed in the winter layers that are gray, and it is lacking in those dominated by red clay. The origin of these features is not clear; they may represent clay alteration, bioturbation, post-depositional deformation, loading, or erosion by bottom currents.

Uppermost Varves

At most sites the typical Glacial Lake Grantsburg varved sediments are overlain by approximately a meter of massive clay or silty clay. In continuous exposure in the pipeline trench, clearly this upper massive clay was a disturbed zone formed by pedogenesis at the top of the typical varves of the middle portion. At the Royce Johnson pit, a total of 84 varves overlie a basal sandy Glacial Lake Grantsburg unit (Fig. 4B). The lower 64 typical varves are dominated by the gray, coarser, summer layers; varves 40–64 are thicker, with the winter layer containing both red and gray clay. The 20 uppermost varves (varves 64–84) consist of red winter layers with thin summer layers. The change in varve thickness is mostly a result of thinning of the summer layer. We interpret these 20 uppermost varves to represent the final stages of Glacial Lake Grantsburg caused by the beginning of the retreat of the Grantsburg sublobe. With this retreat, the source of gray sediment was reduced, allowing red clay from the Superior lobe to dominate.

Distal Varves

Varves deposited far from the margin of the Grantsburg sublobe in distal portions of Glacial Lake Grantsburg are documented at a site east of Webster, Wisconsin (SE1/4 sec. 18, T. 39 N., R. 15 W.), approximately 30 km from the ice margin. The 12 varves at this site comprise alternating reddish and brownish laminated clay. The red clay represents winter layers and the brown clay summer layers. During the summer, brown sediment-rich meltwater was introduced at the margin of the Grantsburg sublobe directly into the lake below the lake surface as cold, turbid (0°C) underflows or interflows. This sediment would have settled out from a position near the lake bottom during the summer. At the same time red clay entered the lake from meltwater streams derived from the distant Superior lobe. The meltwater from the more distant source would have been warmer (5°C), and would have entered the lake at the surface. The clay would have been trapped in the epilimnion until winter freezing permitted deposition as the winter layer in the couplet. This is apparently the clay described by Hansell (1930) as "brown laminated clay." Cooper (1935) interpreted these clays to have been deposited in Glacial Lake Grantsburg distal to the ice margin.

Massive Clay

The Glacial Lake Grantsburg clays are varved in most places with a thin, massive upper portion (likely the result of pedogenesis). However, at three of the backhoe sites, massive silty clay similar in overall color and texture to the typical varves (Fig. 2) is present and occupies the same stratigraphic position. The sites are 1, 9, and 19 km from the Pine City ice margin. The massive clay is predominantly dark grayish brown (10YR 4/2) with wisps of blue, purple, and red zones. The site close to the former ice-margin position contained no pebbles, no layers of flow till, and no clear deformation features, suggesting that it was not a product of deposition from the ice or deformation by the ice. The site most distal to the ice margin contains several distinct varves at the base, some of which have been tilted, indicating deformation. It is not clear why the clays are predominantly varved but locally massive. Water depth at the sites where massive clay is recorded would have been 20–35 m, so iceberg drag seems an unlikely cause for the massive clay.

"Cooper's Silt"

A surface layer of silt, similar to that described and interpreted as lake sediment by Cooper (1935), occurs within the area studied. It is possible that the silt is loess. Cooper does not address this question. Thin loess caps on Late Wisconsinan deposits have been identified in the region (Johnson, 1986). Furthermore, silt caps till north of Cooper's designated shoreline and is at elevations too high for Glacial Lake Grantsburg. These observations, plus the discovery of extensive varved clays, suggest that the silt may be lake sediment only in part and thus not suitable for tracing the extent of the lake.

Hinckley "Delta" Deposits

Dating of Pine City phase by Wright and others (1973) and Clayton and Moran (1982) is based on a geomorphic interpretation that the plain of sand and gravel underlying Hinckley, Minnesota is an outwash plain and/or delta that graded to Glacial Lake Grantsburg. Wright and others (1973) and Clayton and Moran (1982) tie this sand and gravel surface not only to Glacial Lake Grantsburg but also to the margin of the Split Rock Advance, a Superior lobe ice margin that Wright and others (1973) consider to be around 16,000 yrs old and that Clayton and Moran (1982) consider to be around 12,300 yrs old. Wright and others (1973) recognize that a part of the Hinckley surface is an outwash plain, but suggest 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 that we examined in the Hinckley surface reveal medium cross-bedded pebbly sand and slightly pebbly sand throughout the length of the surface, features equally consistent with an outwash-plain interpretation as well as a delta-topset-bed interpretation. No part of the Hinckley surface has clear deltaic characteristics, indicating that its use for correlation is questionable. The chronological position of the Hinckley surface is unclear, but it is most likely to be an outwash plain related to the Superior lobe.

DURATION OF GLACIAL LAKE GRANTSBURG

Previous workers have implied that Glacial Lake Grantsburg and the Grantsburg sublobe were of short duration. Chamberlin (1905) suggests that the Grantsburg sublobe was short-lived and explained that striations and geomorphic features could not have been formed from "...so transient an ice advance." Cooper (1935) stated that "the lake was of brief duration...," a fact further substantiated by the nature of the Grantsburg sublobe's deposits. Cooper (1935) says "the weakness of [the Grantsburg sublobe's] terminal deposits indicates that maximum extension was followed almost immediately by the initiation of decline."

The backhoe exposure at the Royce Johnson site (Fig. 4B) provides evidence for Glacial Lake Grantsburg having a duration of as little as 100 years. The 84 varves at the Johnson site represent both the initial stages and final stages of the lake. Other sites provide a record of only a few dozen varves. The lake clearly lasted longer than 84 years, because the silt below the varves at the Royce Johnson site may have taken several years to form. Although the youngest varves likely formed during the final stages of the lake, it is possible that the massive sediment overlying the uppermost red varves represents the last several years of accumulation in the lake. We did not find any evidence at the Johnson site for the varves being truncated by erosion.

THE OUTLET FOR GLACIAL LAKE GRANTSBURG

It is likely that one or more outlets formed during the advance of the Grantsburg sublobe (Fig. 1D), but there is no obvious outlet for Glacial Lake Grantsburg when the glacier stood at its maximum position (Fig. 2). Cooper (1935) suggests 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 suggests that "evidently 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 calculation of basin size, precipitation rates, and melting rates suggest that the lake would have filled in just a year or two. Because of 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 occurs at the margin, and several smaller ice-dammed lake plains occur at the margin indicating that through-flowing drainage did not exist (Fig. 1E, and Johnson, in press). Alternative explanations include the following two possibilities, but neither of these is fully satisfactory.

1. Drainage was around the eastern edge of the glacier as it stood at the Pine City ice 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 develop. Because the Grantsburg-sublobe till is relatively thin, it seems likely that such a large channel would be palimpsest today and detectable.

2. Drainage was through the ice in englacial channels and flowed south out of the glacier near Osceola, Wisconsin. No evidence would remain of this outlet because the ice has melted.

However the lake drained, it 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, Wisconsin and cut the Horse Creek channel (Fig. 1D). The timing constraints indicated by the geomorphic relationships (Johnson, in press) indicate that the Horse Creek channel was cut during the period of time in which 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. The channel head is too high for Glacial Lake Lind and perhaps too high for Glacial Lake Grantsburg. Furthermore, there is no channel connecting the Horse Creek channel with the closest Glacial Lake Grantsburg deposits, a distance of 40 km. Chamberlin (1905), who was not aware of Glacial Lake Lind or Glacial Lake Grantsburg, suggests that water ponded between the deposits of the Centuria ice margin (Fig. 2) and the retreating Superior-lobe ice, and water in this lake used the low spot at Dresser as a spillway. No evidence of this lake exists (it would be older than Glacial Lake Lind), but it is a reasonable alternative. Lastly, it is not impossible to imagine supraglacial or englacial lakes on or in the Superior or Grantsburg sublobes, that may have been of sufficient size and have drained quickly enough to cut the Horse Creek channel.

With the difficulties mentioned above, we can do no better than Cooper, and we agree that drainage of Glacial Lake Grantsburg was likely over, under, or through the ice when the Grantsburg sublobe stood at its maximum position.

CONCLUSIONS

Our observations show that varved silt and clay is a common feature within sediments of Glacial Lake Grantsburg. Varve counts show that Glacial Lake Grantsburg was a short-lived lake, probably persisting for only 100 years. Evidence indicates that the outlet of Glacial Lake Grantsburg changed at least twice during the existence of the lake, and it was likely through the ice itself. We conclude that the red varves described by Berkey (1905) stratigraphically underlie deposits of Glacial Lake Grantsburg and belong to an older glacial lake, Glacial Lake Lind.

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QUATERNARY STRATIGRAPHY AND HISTORY OF THE WADENA DRUMLIN REGION, CENTRAL MINNESOTA

Barry S. Goldstein

ABSTRACT

A study of the area in central Minnesota that includes the early Late Wisconsinan Wadena drumlin field has led to a reinterpretation of the dynamics and history of the Wadena lobe. There were four main phases of the lobe: Granite Falls, Alexandria, Hewitt and St. Croix. The lobe was most extensive during the first two phases. During the third (Hewitt) phase the dynamics of the ice sheet changed significantly, promoting enhanced erosion of the glacier bed and drumlin formation. The ice stagnated at the end of this phase. During the succeeding St. Croix phase the Itasca Moraine was formed. It was while the Wadena lobe was at the Itasca Moraine that the St. Croix and Rainy lobes advanced into the region. After all three of these northeastern lobes retreated, the Osakis sublobe (defined herein) of the Des Moines lobe advanced from the southwest. The rearrangement in position of these ice lobes also forced a series of changes in the drainage relationships in the region.

The sedimentology of the till deposited during the drumlin-forming Hewitt phase changes systematically in the down-ice direction. This suggests that the glacier progressively incorporated local material as it advanced. Contrary to the previous interpretation that the Wadena lobe advanced from the northwest, it is suggested here that the Wadena lobe advanced from the northeast and incorporated underlying northwest-provenance Browerville Till. The deformable nature of the Browerville Till may also have assisted in drumlin formation.

INTRODUCTION

In this paper the Quaternary stratigraphy, history, and geomorphology of the Wadena drumlin area and parts of the surrounding complex of glacial and postglacial landforms in west-central Minnesota (Figs. 1, 2 and 3) are presented.

Previous Work

Wright (1962) succinctly summarized the history of investigations through the early 1960's on the origin of glacial sediment in west-central Minnesota (see Figs. 1 and 2 in Wright, this volume). The results of his own investigations are given in detail in a later work (Wright, 1972). A more recent overview (through the early 1980's) of studies on the glacial geology and soils in the region may be found in Goldstein (1986). Since then, Meyer (1986) and Gowan (1993) have contributed to our understanding of the complex glacial stratigraphy of the area, and Mooers and Johnson (1994) have shed some light on the late-glacial drainage history of the upper Mississippi River basin. The majority of this paper is drawn from Goldstein (1986), in which site locations, detailed descriptions of key localities, and complete sedimentologic data for approximately 200 samples are presented. A brief summary of the glacial history of the Wadena drumlin region is presented in field-guide form in Goldstein (1987). A detailed discussion of the sedimentology of the drumlin till, and its glaciological implications may be found in Goldstein (1989).

Several aspects of the geology of the Wadena drumlin region remain to be resolved. They include: (1) details on the distribution, geometry, and ages of the Wadena-lobe deposits; (2) the nature and cause of the

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p. 61–84 *in* Patterson, C.J., and Wright, H.E., Jr., eds., Contributions to Quaternary studies in Minnesota: Minnesota Geological Survey Report of Investigations 49 (1998)

variability in till properties of the drumlin region; (3) the contrasting evidence for the apparent northwestern source of some of the till in the drumlins and the northeastern source of the ice responsible for shaping them; (4) the subsurface stratigraphy of the area; (5) the uncertain post-drumlin-forming glacial and post-glacial history of the region.

Terminology

In this paper the terminology used essentially follows that of Wright (1972) and Wright and Ruhe (1965). In this paper the term lobe is used for tongues of ice that move across the terrain from different ice-accumulation centers. Where the lobes (Wadena, Rainy, Superior, Des Moines) are associated with the deposition of a particular till unit (even if the till is in part derived from the underlying substrate, as is the case of the Wadena-lobe till) the term lobe is used in the till name, hence use of the term Wadena-lobe till. In this paper a new sublobe (the Osakis sublobe) is identified for the Des Moines lobe.

The term phase was introduced by Wright and Ruhe (1965), and was defined as "...an informal unit of geological time that is identified or defined on the basis of either morphologic or stratigraphic features...." In this paper four phases are recognized for the Wadena lobe. These are the Granite Falls, Alexandria, Hewitt and St. Croix phases. The Granite Falls, Hewitt and St. Croix phases are slightly modified from Wright's original usage (see Fig.1 in Johnson and Mooers, this volume); Alexandria is a newly introduced informal phase name.

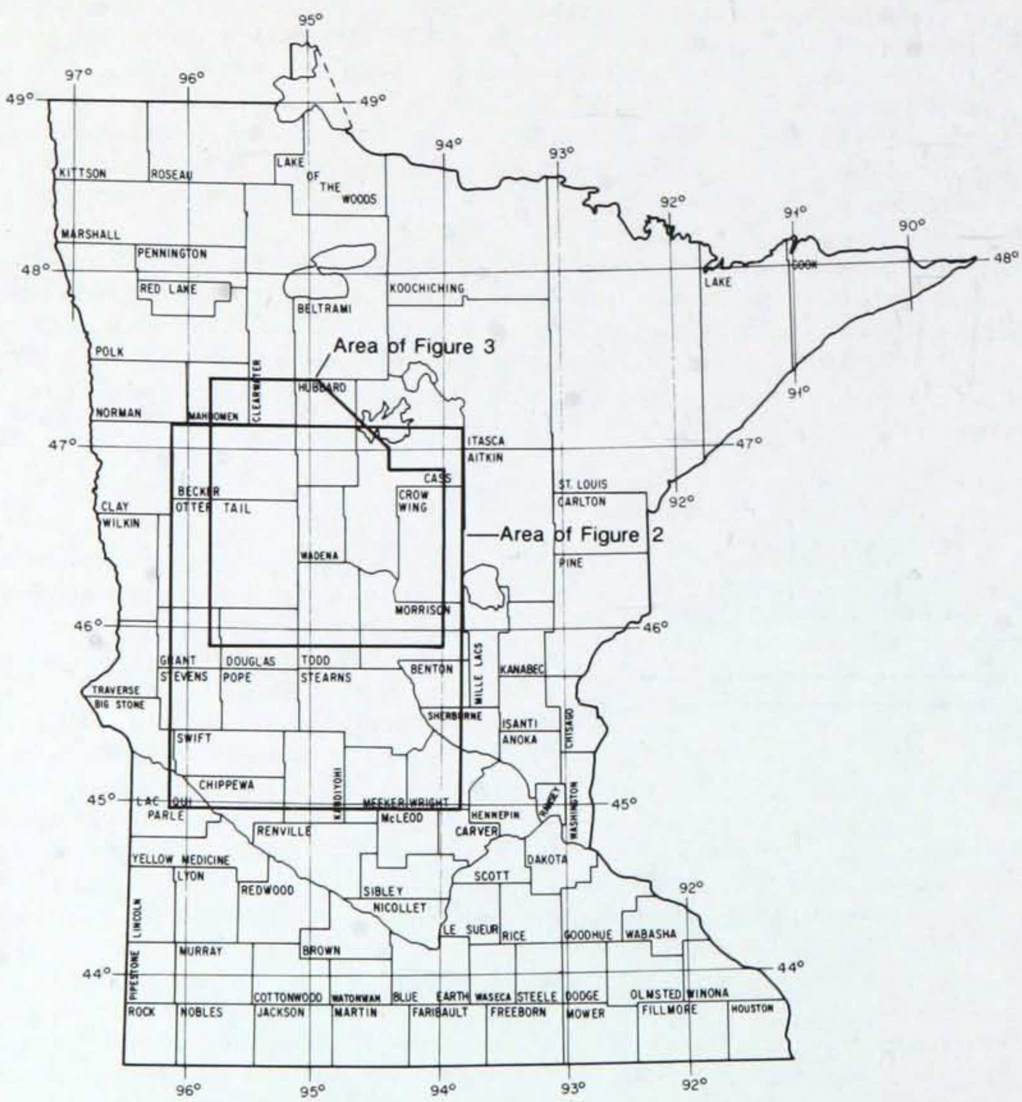


Figure 1. Location of Minnesota counties mentioned in the text, and location of Figures 2 and 3, which portray the generalized geology of the Wadena drumlin region and surrounding areas in west-central Minnesota.

Study Area

The main surface exposure of the Wadena drumlins is bounded by moraines and frontal outwash plains (Fig. 2). To the north and east, respectively, the Itasca and St. Croix Moraines and outwash deposits of the St. Croix phase blanket the drumlins, whereas on the south and west till and outwash of the Des Moines lobe cover the drumlins.

Sedimentologic data and regional stratigraphic relations in the Wadena drumlin region have allowed the variations in till composition to be assessed. The processes that acted at or near the base of the Laurentide Ice Sheet and resulted in significant variations in the composition of the tills have been recognized. Similarly, the evolving topography had a varying effect on the deployment of the thin marginal areas of the ice lobes, particularly on the direction of meltwater flow and distribution of proglacial lakes.

The Wadena drumlin field extends 7500 km^2 (Figs. 2, 3 and 4) across west-central Minnesota. Based on Wright's (1962) previous count of 1200 drumlins within an area of 3000 km^2, and assuming a constant density of drumlins per unit area, the area may include up to 2000 drumlins. The drumlin field is approximately 90 km wide, with a fan curvature of about 90°.

Relief within the drumlin field is low, reflecting in part the low height of the drumlin forms—generally less than 15 m, and in part the extensive filling of interdrumlin swales by outwash. Elevations of drumlin crests range from 475 m in the northwest to 390 m in the southeast. Between these extremes is an undulating surface rather than an even grade. The surrounding moraines provide the greatest elevation and relief, with elevations as high as 620 m in the western part of the Itasca Moraine and local relief of as much as 100 m.

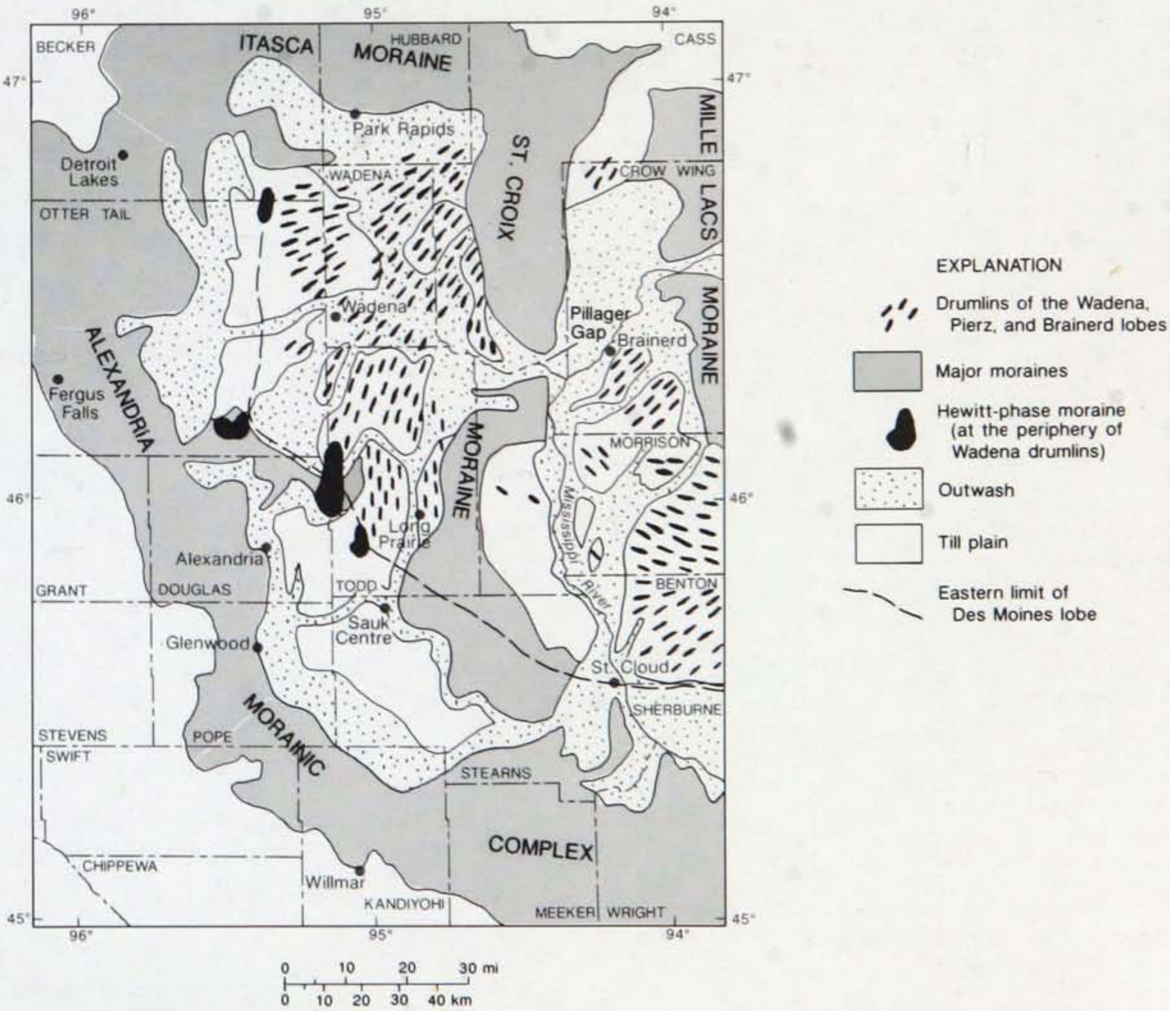
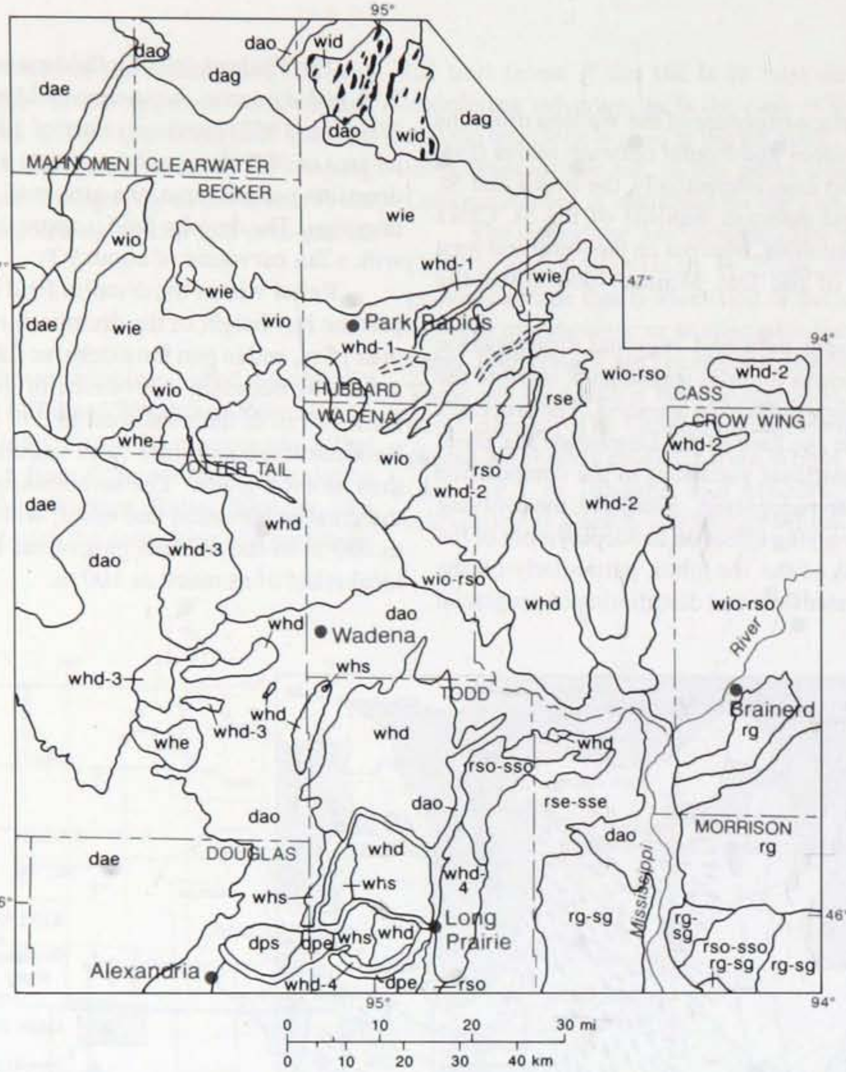


Figure 2. Generalized glacial geology of the Wadena drumlin region. All of the features except the Hewitt-phase moraine and the core of the Alexandria Moraine are younger than the Wadena drumlins, and thus they obscure the true extent of the drumlin field. Note the great distance from the margin of the Wadena drumlins to the Alexandria Moraine. For location see Figure 1. Modified from Wright (1962).



EXPLANATION

ALTAMONT PHASE

Des Moines lobe

dae .... Alexandria end moraine
dag .... Ground moraine
dao .... Outwash

PINE CITY PHASE

Des Moines lobe

dpe .... End moraine
dpo .... Outwash
dps .... Stagnation ground moraine

ST. CROIX PHASE

Wadena lobe

wie .... Itasca end moraine
wio .... Outwash derived from the Itasca moraine
wid .... Drumlins associated with the Itasca moraine

Rainy lobe

rg .... Drumlinized ground moraine
rso .... Outwash
rse .... St. Croix end moraine

ST. CROIX PHASE ctd.

Superior lobe

sg .... Drumlinized ground moraine
sso .... Outwash
sse .... St. Croix end moraine

HEWITT PHASE

Wadena lobe

whd .... Drumlins
whd-1 ..... Drumlins with variable cover of unit wio
whd-2 ..... Drumlins with variable cover of units rso and rse
whd-3 ..... Drumlins with variable cover of unit whs
whd-4 ..... Drumlins with variable cover of units dpo and dpe
whd-5 ..... Drumlins with variable cover of units sso and sse
whe .... End moraine
whs .... Stagnation ground moraine

Spillway

Linear ridges (drumlins?) north of Itasca moraine (within unit wid)

Figure 3. Glacial geologic map of the Wadena drumlin region, west-central Minnesota. The small unit of whs in extreme northwestern Todd County is Mt. Nebo, a large kame 3 km north of Hewitt. See Figure 1 for location of the map area.

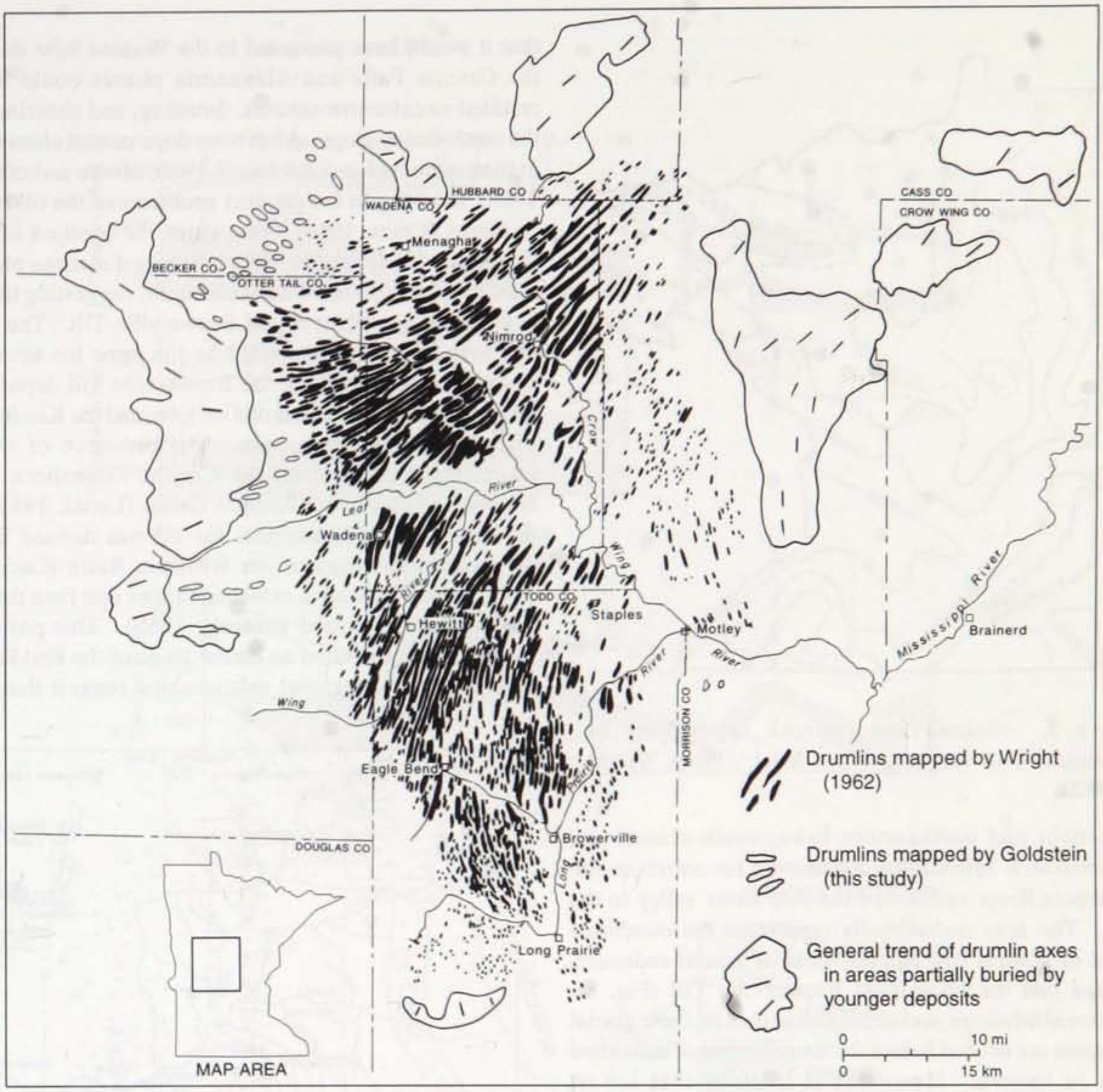


Figure 4. Drumlin distribution and orientation in the Wadena field, west-central Minnesota. Modified from Wright (1962).

Bedrock topography (Fig. 5) controlled the passage of discrete ice lobes into Minnesota from the northeast, north, and northwest. Till of the Wadena drumlin field overlies a thick (as much as 100 m) accumulation of Quaternary sediments (Meyer, 1986), which overlie bedrock. Together, these underlying units form a subsurface highland with relief of 35–50 m (Figs. 5 and 7). The present-day Long Prairie River marks the approximate southern and eastern borders of the subsurface highland, and the Leaf River marks its northern extent (Fig. 6).

Background: Pre-Wisconsinan Advances

Advances of ice from the northwest dominated pre-Wisconsinan events in central Minnesota (Fig. 10). These advances and associated deposits are discussed here; their place in the interpretation of the sequence of events is dealt with in the section on Quaternary History, p.73–79. This interpretation is based on consideration of a sequence of grey, calcareous, fine-grained tills and interbedded outwash and lacustrine units that lies beneath and includes the pre-Wisconsinan Browerville Till in central Minnesota. The sequence may exceed 100 m in thickness, particularly where the subdrumlin highland capped by the Browerville Till overlies a bedrock valley (Fig. 7). The stratigraphy of this sequence has yet to be worked out in detail, but it appears to represent several episodes of ice advance south within the Winnipeg lowland (Fig. 10) and across northwestern Minnesota (Meyer, 1986). The areal extent of the deposits includes the region bounded by northeastern Minnesota (Vermilion district), southwestern

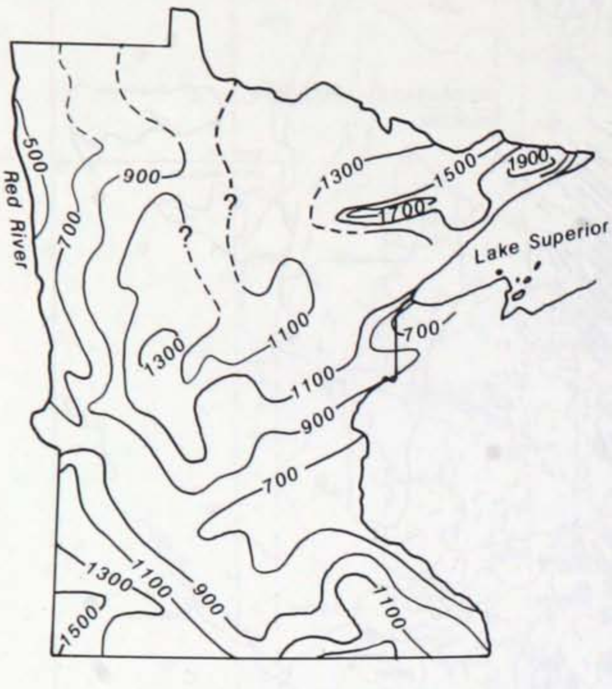


Figure 5. Generalized bedrock topography of Minnesota, in feet above sea level. From Wright (1972).

Wisconsin and northeastern Iowa, south-central and southwestern Minnesota at least as far south as the Minnesota River valley, and the Red River valley to the west. The area undoubtedly represents the combined extent of several overlapping units of glacial sediment, and not just the uppermost Browerville Till (Fig. 8). Additional lithologic and stratigraphic data on these glacial sediments are needed before the lateral extent of individual units is known. However, it is clear that ice of northwestern origin predominated in Minnesota throughout much of the Pleistocene. The reason for the paucity of northeastern-derived glacial sediment in these older deposits, representing the inability of the ice from the Superior basin to advance significantly beyond its margins, is unclear. Caution must be exercised, however, because of the potential for the identity of one or more of the units of old northeastern-derived glacial sediments to be masked in much the same manner as glacial sediments deposited by the Wadena lobe.

The most recent of these pre-Wisconsinan advances from the northwest deposited (1) the Browerville Till in the area of the drumlin field, and (2) the lithologically similar Kandiyohi Till in the area of the later Alexandria Moraine (Fig. 10). The distribution and orientation of the till in north-central Kandiyohi County north of Willmar suggests that the Kandiyohi Till may have contributed a considerable amount of relief to the moraine before the Alexandria phase (Crum, 1984). The topographic barrier that it would have presented to the Wadena lobe during the Granite Falls and Alexandria phases could have resulted in extensive erosion, thrusting, and shearing on the north-facing slope, as has been documented elsewhere in the prairie region (Chernicoff, 1980; Moran and others, 1980), resulting in the disjunct geometry of the till body in places (Crum, 1984). Elsewhere the position of the Kandiyohi Till in presumably undisturbed sections places it directly beneath the Wadena-lobe till, suggesting that it is a lateral equivalent of the Browerville Till. The two tills may have been deposited by the same ice advance from the northwest, with the Browerville Till deposited at the eastern margin of a broad ice lobe, and the Kandiyohi Till at the western margin. The presence of shale fragments derived from the Carlile, Greenhorn and Niobrara units of the Colorado Group (Lerud, 1982) in the Browerville Till suggests the till was derived from the easternmost edge of the Williston Basin (Carlson, 1973), which may have extended farther east then than it does today (Teller and Bluemle, 1983). This position would have constituted an earlier stage of the Red River valley. In turn, regional relationships suggest that the

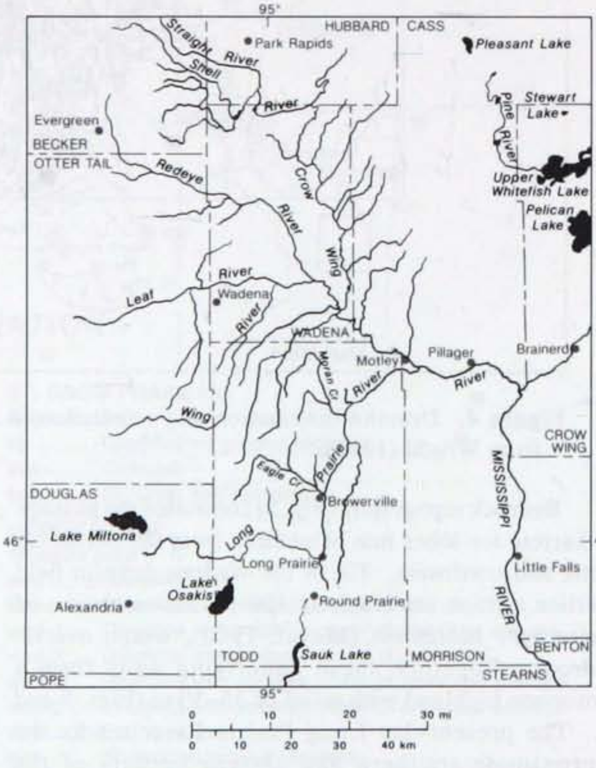


Figure 6. Drainage patterns in the Wadena drumlin region, west-central Minnesota. The trends of the tributary streams reflect the fan-shaped pattern of the drumlins. The present-day Long Prairie River flows northward between Long Prairie and Motley, but barbed tributaries such as Eagle Creek at Browerville indicate a former southerly drainage.

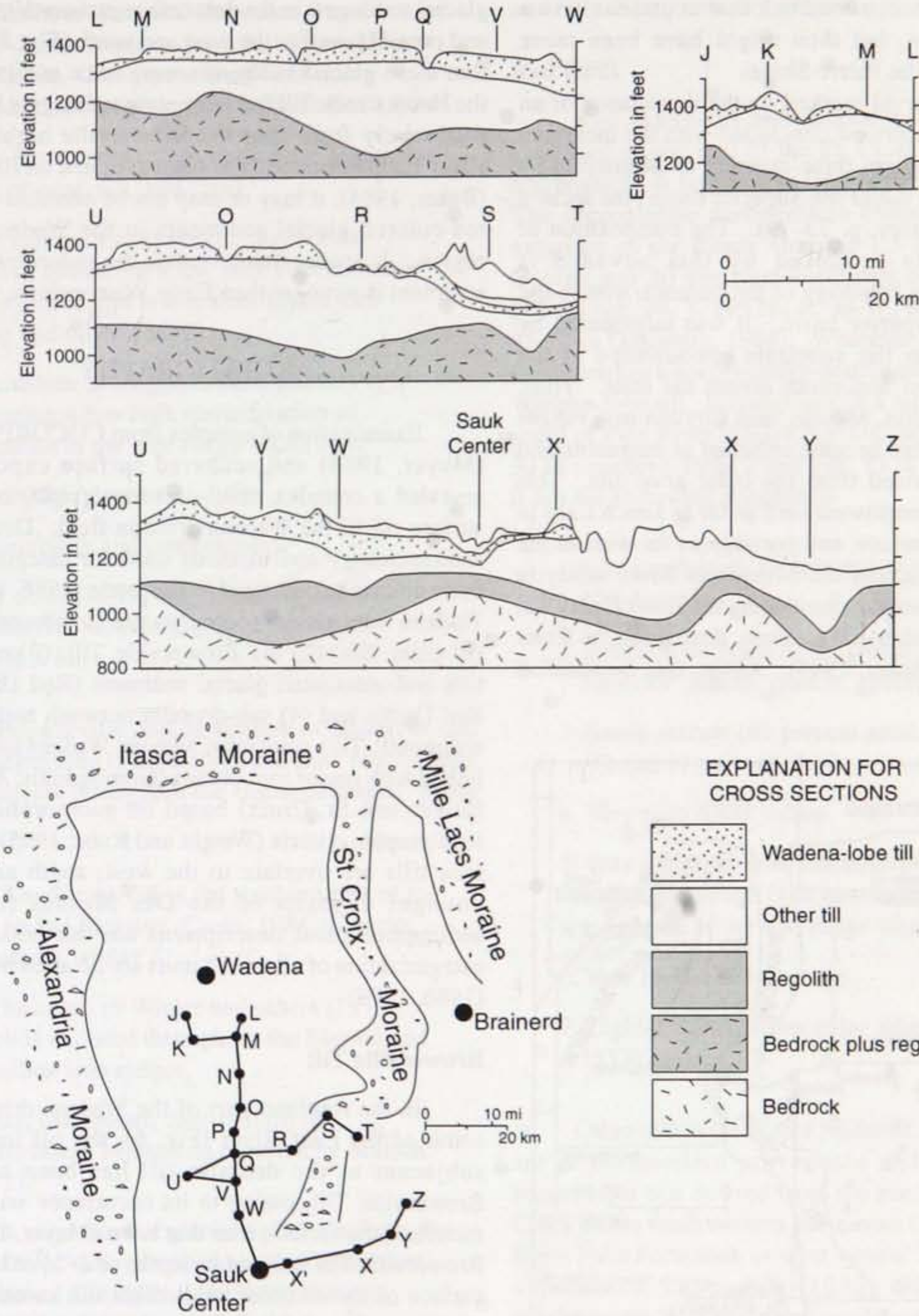


Figure 7. Topography and generalized subsurface stratigraphy of the Wadena drumlin region. Letters indicate locations of Minnesota Geological Survey drill holes that reached bedrock. Stippled unit is the Wadena-lobe till. A complex stratigraphy (not shown), lies between the bedrock surface and the bottom of the Wadena-lobe till. In the section U–T, the Wadena-lobe till is buried east of hole R by two units within the St. Croix Moraine. The section U–Z shows the thin deposits of the Osakis sublobe of the Des Moines lobe mantling the Wadena-lobe till south of drill hole W; a thick regolith unit overlies bedrock in section U–Z. The St. Croix Moraine is presumed to represent the ice-margin position during the St. Croix I phase. The Mille Lacs Moraine is presumed to represent the ice-margin position during the St. Croix II phase. Data from Meyer (1986).

Pierre Shale would have been incorporated into the Kandiyohi Till. Instead, the shale content of the Kandiyohi Till may have been derived largely from more local sources of nonmarine Cretaceous bedrock that at present have a patchy distribution, but then might have been more continuous east of the Pierre Shale.

The long interval marked by the dominance of an ice divide to the northwest concluded with the incursion in much of the southern three-quarters of Minnesota by an ice lobe moving out of the Superior basin (see section on Quaternary History, p. 73–79). The composition of glacial sediments produced by this advance is characteristic of the lithology of the bedrock within and adjacent to the Superior basin. It was augmented by contributions from the substrate encountered in the passage of ice west and south across the state. Thus, beyond the Vermilion, Mesabi, and Cuyuna iron ranges the red sandy till also became enriched in magnetite and in components derived from the older gray tills. This advance extended northwestward as far as Leech Lake in north-central Minnesota, and possibly as far west as the Red River valley, across the Minnesota River valley in southwestern Minnesota—producing the Hawk Creek Till (Matsch, 1971), and into Wisconsin, depositing the River Falls Formation (Baker, 1984). Again, this distribution may actually represent more than one advance, but on the basis of similar stratigraphic positions these units are assigned to a single unit. The presence of red-colored glacial sediments in the subsurface just north of Brainerd, and possibly well to the west and south (Fig. 8), suggests that these glacial sediments were once continuous with the Hawk Creek Till but were removed largely by erosion, particularly from atop the Browerville highland. The River Falls Formation has been assigned an Illinoian age (Baker, 1984); it may or may not be correlative with the red-colored glacial sediments in the Wadena drumlin region. It seems unlikely that the red-colored glacial sediment is younger than Early Wisconsinan.

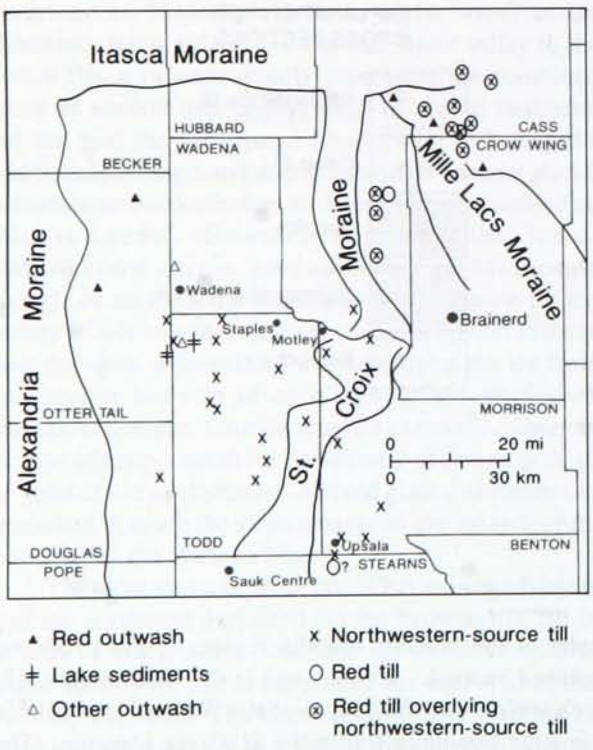


Figure 8. Distribution of pre-Hewitt-phase deposits encountered in drill holes and surface exposures. For location, consult Figure 1.

STRATIGRAPHY

Examination of samples from COCORP drill holes (Meyer, 1986) and scattered surface exposures has revealed a complex multi-unit stratigraphy beneath the surface till in the Wadena drumlin field. Details of the sedimentology and methods used for categorization of these units is summarized in Goldstein (1986, 1989). Pre-Wadena lobe glacial sediments are (in ascending order) (1) older tills; (2) the Browerville Till; (3) red-colored tills and associated glacial sediment (Red Drift or Old Red Drift); and (4) sub-drumlin outwash and lacustrine sediments. Tills associated with the Wadena lobe are each linked with one of four phases (Granite Falls, Alexandria, Hewitt and St. Croix) based on geomorphologic and stratigraphic criteria (Wright and Ruhe, 1965). Wadena-lobe tills are overlain to the west, south and east by younger deposits of the Des Moines lobe. The sedimentological descriptions and methods used for categorization of all the till units are detailed in Goldstein (1986, 1989).

Browerville Till

In the southern part of the Wadena drumlin field, south of the Leaf River (Fig. 6), the till immediately subjacent to the drumlin till has been named the Browerville Till, owing to its occurrence within a few meters of the surface near that town (Meyer, 1986). The Browerville Till is found at depths of 2–25 m beneath the surface of the drumlin field. This till, or other similar tills that are located beneath it within the drumlin field, is also documented east and northeast of the St. Croix Moraine at depths as great as 50 m (northwestern tills of Figure 8). It is also recorded in places below an intervening Red Drift of northeastern derivation. The Browerville Till is characterized by the following:

1. High carbonate content (25–30 percent) in the less-than-62μ fraction.

2. High content of Paleozoic carbonate granules (greater than 40 percent) in the 1–2-mm fraction, and a low percentage of Cretaceous nonsiliceous shale and limestone fragments in the 1–2-mm fraction, probably derived from the Carlile, Greenhorn, and Niobrara Formations that underlie the Pierre Formation.

3. Clay-loam texture (approximately 33 percent each of sand, silt, and clay).

4. Low values of anhysteretic magnetism (ARM), indicating a low bulk concentration of magnetite that is less than 10μ in size (King and others, 1982).

5. Low values of magnetic susceptibility (χ), indicating a low bulk concentration of magnetite in the size range 10μ–100μ.

6. Low ARM /χ ratios.

7. Nonfriability and compactness.

8. Gray color (10YR 5/1) when dry and unoxidized, very dark gray when moist (10YR 3/1).

The Browerville Till is similar in character and stratigraphic position to a variety of pre-Late Wisconsinan glacial sediments throughout the Upper Midwest. These include:

1. The Kandiyohi Till in the southern part of the Alexandria Moraine (Crum, 1984; Giencke and others, 1984).

2. The basal till of Winter and others (1973), which is exposed throughout the Mesabi and Vermilion iron ranges.

3. A gray, calcareous, clay-rich till in southwestern Minnesota reported by Matsch (1971).

4. Thick sequences of glacial sediments from the Red River valley in northwestern Minnesota (unnamed unit 2); eastern North Dakota (Tiber Formation, unit LFtR-50); southeastern Manitoba (Woodmore Formation), as described by Harris and others (1974), Moran and others (1976), Teller and Fenton (1980), and Teller and Bluemle (1983); the Pierce Formation of west-central Wisconsin (Baker, 1984); the Wolf Creek Formation of Iowa (Hallberg, 1980); and till of the Bridgeport terrace of the Wisconsin River in southwestern Wisconsin (Knox and others, 1982).

Although these units contain material derived from the northwest, correlation is uncertain owing to the lack of sufficient drill-hole data, surface exposures, age control and lateral discontinuity of units.

Red Drift

Red sandy till and related outwash have been identified in and east of the St. Croix Moraine (Fig. 8), and possibly as far south as Upsala (east of Sauk Centre). The approximate northwestern extent may be near an exposure in the Itasca Moraine 1.5 km south of Lake George and 30 km west-northwest of Walker (NE1/4, NW1/4 sec. 34, T. 143 N., R. 34 W.; see also Fig. 9, site 83-12 in Goldstein, 1986). Wherever it occurs, the Red Drift overlies a northwestern-source till and underlies the Wadena-lobe till. It is exposed in a large gravel pit 5 km south of Pine River (SE1/4, SW1/4 sec. 13, T. 137 N., R. 30 W.; see also Table 2 and Fig. 13 in Goldstein, 1986). It has the following properties:

1. Little carbonate (7 percent) in the less-than-62μ fraction.

2. Pebble rock types of the North Shore of Lake Superior (felsite, granite, gabbro).

3. Sandy texture (69 percent sand, 20 percent silt and 11 percent clay).

4. Very high ARM values.

5. Very high magnetic susceptibility (χ) values, indicating a high bulk concentration of magnetite in the size range 10μ–100μ.

6. Very high ARM /χ ratios.

7. Light-reddish-brown color when dry (5YR 6/4).

Other tills in the Upper Midwest, like the Red Drift, are of northeastern provenance and postdate a thick sequence of tills derived from the northwest. The Hawk Creek Till in southwestern Minnesota (Matsch, 1971), the River Falls Formation in west-central Wisconsin (Baker, 1984), and Leverett's (1932) Old Red Drift of southwestern Wisconsin and southeastern Minnesota are all characterized by rock types and texture that suggest transport from the Lake Superior basin.

Subdrumlin Outwash and Lacustrine Deposits

In a few localities in the western part of the Wadena drumlin field, buried calcareous outwash and lacustrine sediments lie immediately beneath the drumlin till (Fig. 8). The yellow color of the outwash suggests that it has been oxidized, either through the action of near-surface groundwater or when exposed at the surface. The latter possibility is favored, because overlying outwash interbedded with the drumlin till is not oxidized (Figs. 19, 49, and 50 in Goldstein, 1986). Therefore, the older deposits were probably exposed subaerially prior to burial by the drumlin till. The position of the finer-grained sediments to the west of the sand and gravel suggests westward meltwater drainage and damming.

WADENA-LOBE TILLS

Wadena-Lobe Tills: Granite Falls, Alexandria, and Hewitt Phases

The till at the surface in the drumlin field is overlain by younger deposits to the west, south, and east. This surface till is recognized throughout the region by its sandy texture, presence of Paleozoic carbonate-rock fragments, and lack of Cretaceous shale. Most significant, however, is locally derived material that constitutes a major proportion of the drumlin till. The content of locally derived material diminishes rapidly upwards in any given vertical section, to be replaced by an assemblage representing a mixture of farther-travelled components (Fig. 32 in Goldstein, 1989). The dominance of this local contribution also diminishes longitudinally in the direction of ice flow (to the southwest within the drumlin field), extending no more than a few kilometers from the site of incorporation before being succeeded by new material. Because much of the drumlin till is underlain by glacial sediments rich in components derived from the northwest, the characteristics of the till also vary considerably across the extent of the field (for more information, see Figs. 8–20 in Goldstein, 1989).

In the northeastern part of the field, the till has the following characteristics:

1. Very pale brown (10YR 7/3) when dry, and light olive brown (2.5Y 5/4) when moist. Toward the southwestern part of the drumlin field, the till becomes progressively more like the Browerville Till.
2. Sandy texture (71 percent sand, 18 percent silt, 12 percent clay).
3. Low content of Paleozoic carbonate granules in the 1–2-mm fraction.
4. Low carbonate content (2–5 percent) in the less-than-62μ fraction.
5. High values of anhysteretic magnetism (ARM), indicating a high bulk concentration of magnetite less than 10μ in size.
6. High values of magnetic susceptibility (χ), indicating a high bulk concentration of magnetite in the size range 10μ-100μ.
7. High ARM /χ ratios.

A variety of tills throughout Minnesota resemble the drumlin till. They include the Granite Falls Till in western and southwestern Minnesota (Matsch, 1971), the Marcoux, Vang, and LFtR-40 Formations (Moran and others, 1976), and the stratigraphically higher Lower Red Lake Falls Formation (Harris and others, 1974) along the Red River valley, and the New York Mills Formation of Anderson (1976), which is located between the Alexandria Moraine and the northwestern part of the drumlin field. In addition, till found throughout the Alexandria Moraine (Crum, 1984; this study), the Itasca Moraine, and near Wabedo (about 15 km southeast of Leech Lake in northern Cass County) has been assigned to the Wadena lobe. Other notable local deposits are the tills that occupy what appear to be moraine remnants scattered along the periphery of the Wadena drumlin field. These tills lie to the northwest in the vicinity of Collett Lake near Evergreen (south-central Becker County); to the west in the Black Peak area near Henning (east-central Otter Tail County), and in the southeast as a buried surface between Upsala (Morrison County) and Sauk Centre (Stearns County) (Fig. 3, unit whe). These areas are topographically lower than the main Alexandria Moraine and lie within it on the north and east or are separate from it. The tills are assigned to the Hewitt phase of the Wadena lobe on the basis of field relations and the model developed below.

Recognition of patterns of regional variation in the Wadena-lobe till has led to a broad definition for the unit. Intrinsic to this revised view is the validity of the model of progressive incorporation and mixing of a variety of substrate materials beneath the drumlin-forming Hewitt phase of the Wadena lobe (Goldstein, 1989). For the Wadena drumlin field, these considerations are of primary importance regarding the history and source of the Wadena lobe. Instead of being of northwestern (Wright, 1962) or polygenetic (Perkins, 1977) origin, the drumlin till is regarded here as the product of progressive mixing of a northeastern-source till with the substrate, which was predominantly the Browerville Till. This model adequately explains the regional variations in the drumlin till. It also simplifies the history of the deployment of the ice lobes in Minnesota by eliminating the requirement for an active ice center to the northwest at a time when the main accumulation centers were apparently to the northeast.

An enhanced understanding of the origin of Wadena-lobe glacial sediments must also include a consideration of the age relationships of this geographically widespread deposit. It is proposed here, and will be discussed more fully later, that as many as four phases of the Wadena lobe can be recognized. From oldest to youngest, they are:

Granite Falls phase—Responsible for the Granite Falls Till and its correlatives that lie outside (west and south) of the Alexandria Moraine.

Alexandria phase—The bulk of the moraine was built during this phase, possibly over a core of older Kandiyohi Till.

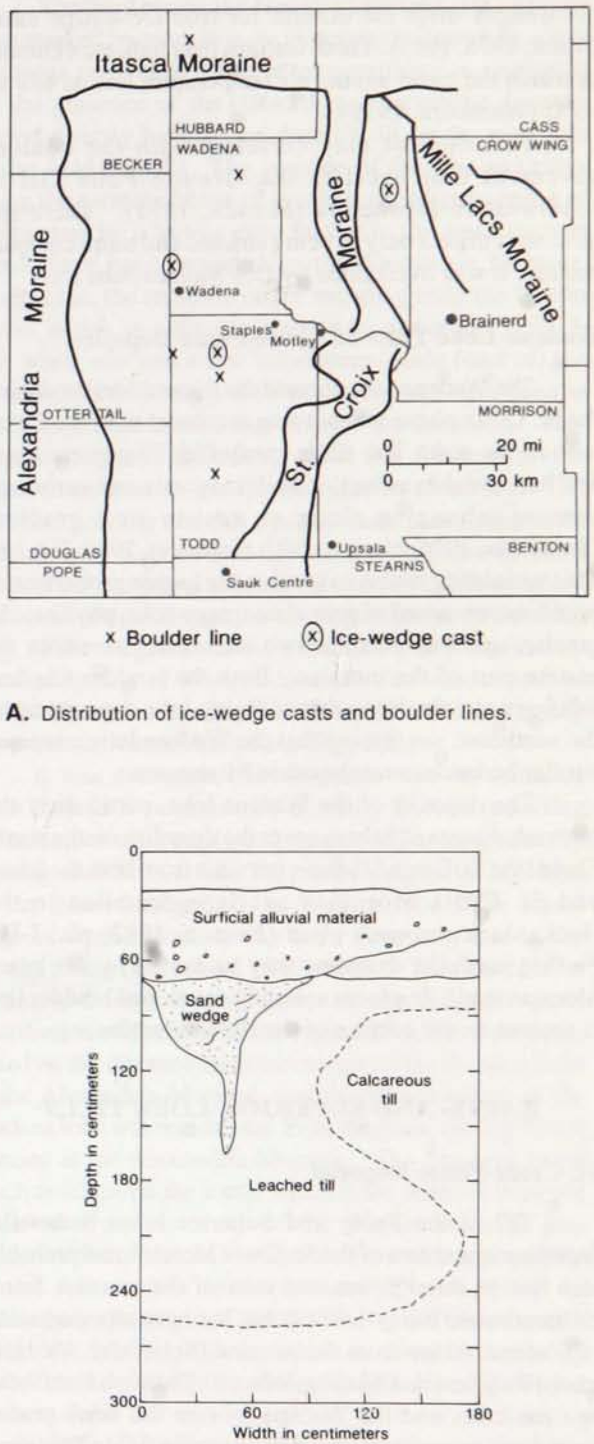
Hewitt phase—The drumlin field and surrounding low moraines were built during this phase.

St. Croix phase—The Itasca Moraine formed during this phase.

Recession of the Hewitt-phase Wadena lobe was largely by stagnation, as exemplified by the numerous ice-block depressions across the drumlin field and by a morainic landscape west and southwest of Browerville but within the extent of the drumlin field (Fig. 3, unit whs). A further indication of this downwasting is Mt. Nebo, a large kame located 3 km north of Hewitt in extreme northwestern Todd County (secs. 4 and 9, T. 133 N., R. 35 W.) that formed during this stage. Semicircular in plan view, it is over one kilometer long, rises 25 m above the crests of nearby drumlins, and 45 m above the interdrumlin swales. It is composed of outwardly dipping beds of calcareous, shale-free sands and gravels. In addition, a thin cap of loose, stony ablation till may overlie the lodgement till of the drumlins (Antoine, 1970; Gamble and Mausbach, 1984), but this till is hard to distinguish from the subsequently formed solifluction deposits.

Wadena-Lobe Tills: Post-Hewitt Phase Slope Deposits

Where there are good exposures through drumlins, a boulder line is seen to extend across the form within 1–2 m of the surface, except where younger deposits create a thicker cap (Fig. 9A). The line is commonly one boulder thick in topographically high positions; the line thickens to a layer downslope and over local depressions, increasing from 0.15–0.25 m to 1.0–1.5 m thick. The boulders are mostly in contact, their long axes generally point downslope, and the voids between them are filled with a coarse, poorly sorted, sandy matrix. At a few sites, the line is interrupted by a vertical wedge filled by the same material as the line, or by a combination of that and the overlying material, usually sand (Fig. 9B). The wedges have a maximum depth of 1.0–1.5 m, and the long axes of the boulders within the wedges are oriented vertically.



A. Distribution of ice-wedge casts and boulder lines.

B. Sketch of an ice-wedge cast. Adapted from Gamble and Mausbach (1984).

Figure 9. Ice-wedge casts and boulder lines in the Wadena drumlin region.

The boulder line is interpreted as a solifluction residue that formed under permafrost conditions, whereas the wedges meet the criteria for true ice-wedge casts (Black, 1976, 1983). These features may indicate a climate in which the mean annual air temperature was as low as –5°C (Washburn, 1979).

This deposit may correlate with the boulder pavement that overlies the Granite Falls Till in southwestern Minnesota (Matsch, 1971). There the pavement differs only in being striated and more compact because it was overridden by Des Moines-lobe ice.

Wadena-Lobe Tills: St. Croix-Phase Deposits

The Wadena lobe formed the Itasca Moraine during the St. Croix phase when it was confluent with the Rainy lobe to the east. The till is sandy (65–75 percent sand) and has variable values of bulk magnetic and carbonate content, changing along an east-to-west gradient (Sackreiter, 1975; Norton, 1982; Goldstein, 1986, Fig. 18). This variability is also evident in the higher proportion of boulders composed of gray slate, graywacke, phyllite, and granite, some as much as two meters across within the eastern part of the moraine. Both the boulder size and lithology are similar to that of Rainy-lobe deposits far to the northeast, suggesting that the Wadena lobe traversed similar bedrock in northeastern Minnesota.

The deposits of the Wadena lobe, particularly the outwash discussed below, cover the drumlins on the north. East of the St. Croix Moraine, outwash from both the Itasca and St. Croix Moraines overlaps drumlins in the Hackensack outwash plain (Norton, 1982, pls. I-II). Farther north the drumlins may be buried by the Itasca Moraine itself. In places a weakly developed boulder line is present on the surface of the Itasca Moraine.

RAINY- AND SUPERIOR-LOBE TILLS

St. Croix-Phase Deposits

Till of the Rainy and Superior lobes buries the drumlins in and east of the St. Croix Moraine and probably also two to three kilometers west of the moraine front. Extramorainic Rainy-lobe till that has been reported north of Wadena, 40 km from the moraine (Schneider, 1961), is more likely leached Wadena-lobe till. Outwash from these two ice lobes and the Wadena lobe to the north grades southward, covering parts of the drumlin field. This sand cover was modified by later eolian activity to form dunes, and it provided the source material for the abrasion of wind-cut rock surfaces (Norton, 1982).

DES MOINES-LOBE DEPOSITS

Till deposited by the Des Moines lobe has the following characteristics in the study area:

1. High carbonate content (21–26 percent) in the less-than-62μ fraction.
2. Moderate amounts of Pierre Shale fragments (10–20 percent) in the 1–2 mm fraction.
3. Clay-rich texture (30–44 percent clay, 28-36 percent silt, 28–38 percent sand).
4. Low-moderate values of ARM.
5. Low–moderate values of χ.
6. Low–moderate values of ARM /χ.
7. 10YR 7/3 when dry; 2.5Y 5/4 when wet.

The Des Moines-lobe till caps the Wadena-lobe till (1) in the Alexandria Moraine, (2) in the Osakis till plain south and west of the drumlin field, (3) in some parts of the Hewitt-phase terminal moraine (Fig. 3, unit whe), and (4) north of Hennepin Lake in extreme northwestern Hubbard County. The northern border of the Osakis till plain is marked by a thin, narrow moraine (designated here as the Osakis Moraine) between Lake Osakis and Long Prairie (Fig. 3, unit dpe). The moraine reaches an elevation of 444 m. The Osakis moraine consists of interbedded Wadena- and Des Moines-lobe tills that were probably sheared together when the thin Des Moines-lobe ice moved up the 30-m, south-facing slope that marks the southern border of the drumlin field there (Fig. 7, section U-Z), precisely in the manner described elsewhere for the margin of the Des Moines lobe (Chernicoff, 1980). The Des Moines-lobe till extends northward as a progressively thinning cover—probably formed by mudflows off the ice front—until it disappears about one and one-half kilometers from the crest of the Osakis moraine. East of Long Prairie the tills and mudflows making up the Osakis moraine disappear abruptly, to be replaced northward by a kame moraine (containing the distinctive fragments of Pierre Shale) that reaches an elevation of 411 m three kilometers southeast of Browerville (Fig. 3, unit whd-4). South of Long Prairie the deposits are generally less than 1 m thick and have a patchy distribution.

The Osakis sublobe is the designation given here for the first time for this thin, narrow extension of the Des Moines lobe. During the early part of the Pine City phase it moved to the northeast as far as the St. Croix Moraine just southeast of Browerville, and to the northwest about as far as Lake Miltona in northern Douglas County. The till in the Osakis till plain and the

Alexandria Moraine is characteristically thin—commonly less than 1 m and rarely greater than 3 m in thickness. In fact, the Des Moines lobe may never have entirely overtopped the highest parts of the southern Alexandria Moraine in Kandiyohi and Meeker Counties, leaving those areas as nunataks composed of the older Wadena-lobe till and Kandiyohi Till.

Later Des Moines-lobe outwash deposits capped the Osakis till plain on the west and south and filled the valleys of the Long Prairie and Leaf Rivers, their tributaries, and numerous low areas between drumlins (Fig. 3, unit dao). This outwash is found along several terraces, the highest of which (1350 ft elevation) is responsible for the sand cap on the north side of the Leaf River valley, 1.5 km northwest of Wadena (Goldstein, 1986, Fig. 19).

QUATERNARY HISTORY OF THE WADENA DRUMLIN REGION: EARLY ADVANCES OF THE WADENA LOBE

A revised classification of the stages of the Wadena lobe and a new interpretation of its source region are suggested here, based on the results of this study. It is proposed, based on the conclusions drawn from the sedimentological data and an extension of the drumlin axes back toward their source, that the Wadena lobe advanced across northeastern Minnesota from the vicinity of Rainy Lake (Fig. 10C). The Wadena lobe is envisioned here as having been an early, expanded version of the Rainy lobe. Nevertheless, in this paper, the Wadena-lobe terminology is retained for those deposits and landforms created during pre-St. Croix-phase events (the Granite Falls, Alexandria, and Hewitt phases) by this northeastern-source ice mass, whereas the St. Croix phase marked the separation of this large ice lobe into two smaller, truly distinct lobes—the Wadena and Rainy lobes.

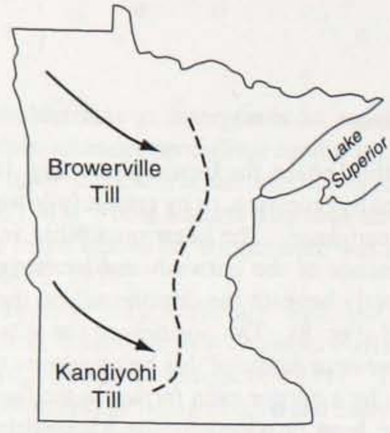
Granite Falls and Alexandria Phases

At least four stages can be identified for the Wadena lobe (Figs. 10C and 10D). The Granite Falls phase (Fig. 10C-1) was the earliest and most extensive, reaching as far as southwestern and westernmost Minnesota, and possibly to the Coteau des Prairies in northeastern South Dakota (Matsch, 1972). The ice then retreated and stabilized at the position of the Alexandria Moraine (Fig. 10C-2). This may already have been a topographic high underpinned primarily by the Kandiyohi Till, as discussed above. The location of the margin of the Wadena lobe during the Alexandria phase is still clearly evident in exposures along the axis of the Alexandria moraine complex from Otter Tail County to Meeker County, and the margin probably extended even farther eastward to the area south of St. Paul.

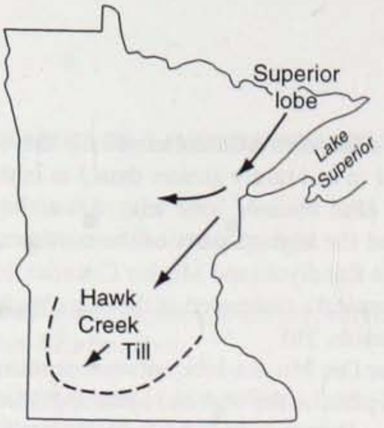
Hewitt Phase

The third phase, the Hewitt phase (Fig. 10C-3), was also marked by recession, or by retreat followed by a less vigorous readvance. The latter possibility is supported by the presence of the outwash and lacustrine deposits buried directly beneath the drumlin till on the west side of the field (Fig. 8). The position of the silts and clays along the western fringe of this belt suggests trapping of meltwaters by a barrier even farther to the west, such as would have been provided by the Alexandria Moraine. In any case, the restabilized ice margin during the Hewitt phase, which in places is marked by a moraine (Fig. 3, unit whe), was just a few kilometers inside (east of) the Alexandria Moraine on the west, but it may have been as much as 60 km behind the moraine on the south. This disparity suggests the strong effect that the Browerville highland exerted on the thinned Hewitt-phase ice. The highland not only acted as a partial dam, preventing more extensive ice flow toward the south, but it also diverted ice flow off its northern slope. As a result, the distribution and trend of drumlins in the northwest corner of the field (Fig. 4) show a greater arc of curvature than is marked by the distribution of Wadena-lobe till that was deposited within the area covered by the Alexandria Moraine during the previous Alexandria phase (Fig. 3).

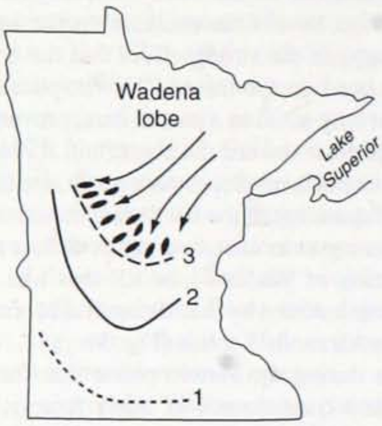
It was during the Hewitt phase that the drumlins were built as a consequence of many factors, including the influence of an easily deformable substrate (primarily the clay-rich Browerville Till) and a subglacial highland on the thinned margin of the Wadena lobe. The actual stage of drumlinization may have been very late in the Hewitt phase (Goldstein, 1987, 1989). This conclusion is derived from examination of the mapped areal distribution of features in the region (Fig. 3). I propose, based on the distance from the margin of the drumlin field to the Alexandria Moraine, that the Hewitt phase of the Wadena lobe was recessional from the phase during which it stood at the Alexandria Moraine. The gap may be as much as 60 km on the south, which is the distance between the oval drumlins north of the Osakis moraine and Wadena-lobe till found in stagnation moraine topography in the Alexandria Moraine near New London in northeastern Kandiyohi County. This region lies primarily within the Osakis till plain, which is composed of a cap of Des Moines-lobe till overlying Wadena-lobe till. Buried Wadena-lobe till may constitute, at least partially, a continuation of the drumlin field. However, on the basis of comparison with other drumlin fields, Wright (1962) placed the margin of the Wadena drumlin field where the drumlin forms become markedly less streamlined and more oval in shape, and this interpretation is adopted here as well. To the west, hilly uplands and lower topography have been termed, respectively, Hewitt-phase end moraine and Hewitt-phase ice-stagnation ground moraine (units



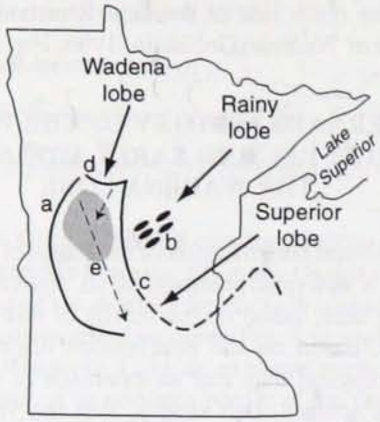
A. Pre-Wisconsinan advance from the northwest, which deposited the Browerville Till and Kandiyohi Till. Dashed line indicates uncertainty in ice-margin position.



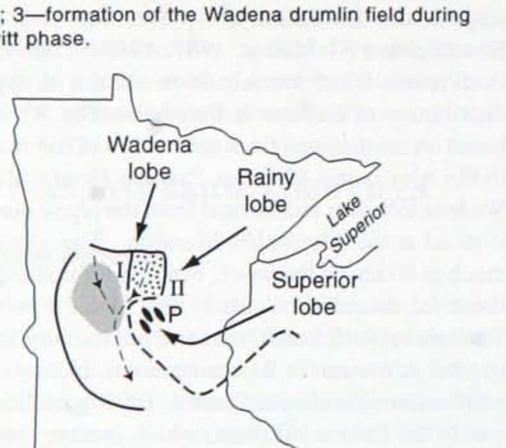
B. Pre- or Early Wisconsinan advance of the Superior lobe, which deposited the Hawk Creek Till in southwestern Minnesota and its equivalent in the area of the Wadena drumlin region. Dashed line indicates uncertainty in ice-margin position.



C. Granite Falls, Alexandria and Hewitt phases. Early advances of the Wadena lobe. 1—limit of deposition of the Granite Falls Till; 2—formation of the Alexandria Moraine; 3—formation of the Wadena drumlin field during the Hewitt phase.



D. St. Croix phase I. Advance of the Wadena lobe to the Itasca Moraine and of the Rainy and Superior lobes to the St. Croix Moraine, with southward transport of the outwash (thin dashed line) beyond the margin. Formation of the Brainerd drumlin field by the Rainy lobe actually occurred during *retreat* to the St. Croix II position. **a**—Alexandria Moraine; **b**—Brainerd drumlin field; **c**—Rainy- and Superior-lobe ice-margins at the St. Croix Moraine (dashed where uncertain); **d**—Wadena-lobe ice-margin at the Itasca Moraine; **e**—southward transport of outwash. Gray area shows position of the Hewitt-phase Wadena drumlin field.



E. St. Croix phase II. Retreat of the Rainy lobe and advance of the Superior lobe, which formed the Pierz drumlin field (**P**), temporarily entrapping meltwater behind the St. Croix Moraine to form Glacial Lake Brainerd (stipple); eventual erosion of Pillager gap. **I**—position of ice-margin during St. Croix phase I; **II**—position of ice-margin during St. Croix phase II, presumed to be at the Mille Lacs Moraine. Dashed line indicates uncertainty in ice-margin position. Gray area shows general position of the Hewitt-phase Wadena drumlin field.

F. Advance of the Des Moines lobe from the northwest, forming the Osakis Moraine and reversing the direction of drainage to the north and east out Pillager gap. **PG**—Pillager gap; **OM**—Osakis Moraine. Heavy dashed line indicates probable Superior-lobe ice-margin position during the preceding St. Croix phase.

Figure 10. Postulated sequence of glacial-geologic events in west-central Minnesota.

whe and whs, respectively, Fig. 3). These regions mark the approximate maximum extent of the drumlin field, although removal or covering by the effects of the younger Des Moines lobe may mask the true margin.

Where the Wadena-lobe till does occur in an upland position in the Alexandria Moraine, it is generally at least 25 km from the proposed margin of the drumlin field. These distances are significantly higher than the average range of 2-3 km given for many drumlin fields (Moran and others, 1980), but they may be similar to the greater distances found for some drumlin tracts in Sweden (Lundqvist, 1970). Such cases, including the Wadena drumlin field, may represent insignificant terminal-moraine construction at the margin of the ice sheet during the drumlinizing phase. The drumlin field in the southern Puget lowland (Crandell, 1963; Goldstein, 1994) and the Teeswater field in southern Ontario (Cowan, 1979) are marked by such an absence of terminal moraines. These situations may have occurred through trapping of most of the sediment load of the glacier behind the terminal position within the drumlins.

Finally, downwasting at the end of the Hewitt phase is recorded by the ice-stagnation ground moraine near, but within the margin of the Wadena drumlin field (Fig. 3, unit whs), as well as by the ice-block depressions located in the northeastern part of the field and by the kame at Mt. Nebo in extreme northwestern Todd County.

The variations in the character of the drumlin till reflect a variety of processes acting on scales as fine as individual grains, but are under the primary influence of the nature of the local substrate. The progressive incorporation and mixing of local materials with the far-travelled components in the Wadena-lobe till significantly altered the composition of the till over the length of the field (Goldstein, 1989).

This interpretation of the formation of the drumlin field and of a northeastern source for the Wadena lobe clarifies several problems raised by Wright (1972), such as the apparent mixing of Rainy-lobe till with the drumlin till, which did indeed occur, only in a sense opposite to that previously postulated. It also provides a simple answer to the question of why the Wadena lobe bypassed the Red River lowland. The lowland would have been a major pathway for ice flowing southward out of the Winnipeg lowland, and it should have diverted the motion southward along its axis instead of southeastward into the Red Lake lowland. In the interpretation presented here, the Wadena lobe entered the Red Lake lowland from the east or northeast, and not from the west. This is especially pertinent in light of the role that the Red River valley apparently played in the formation of the older Browerville Till, in contrast to the hypothesis that the valley did not exist until the development of the Des Moines lobe (Wright, 1972).

The Hewitt phase ended with frontal retreat and stagnation of the Wadena lobe. A low, discontinuous stagnation moraine within the Hewitt-phase margin (Fig. 3, unit whs) is succeeded in an up-glacier direction by other products of the downwasting process, most notably the kame at Mt. Nebo. Numerous blocks of stagnant ice were left in the swales between the drumlins as well, and these and the drumlins themselves were probably mantled with a thin cover of loose ablation till. A fringe of outwash was also deposited in front of the retreating margin, further blanketing and reducing the relief on the landscape. The result of these processes was a cover of variable thickness that mantled and insulated the stagnant ice blocks and aided their preservation. The primary cause for their persistence, however, must have been the maintenance of permafrost conditions throughout the entire interval of time from the end of the Hewitt phase until the St. Croix phase. In fact, the oldest sediments found in Cat Lake and Dog Lake, which are located in interdrumlin swales 10 km north of Motley, are only 12,000 yrs B.P., suggesting persistence of ice in those basins until that late date (Florin and Wright, 1969).

Timing of Wadena-Lobe Phases

The timing of these early phases of the Wadena lobe is uncertain. The drumlin till may have an age of more than 39,900 yrs B.P. (W-1232) (Wright, 1972), whereas wood from beneath the correlative or older Granite Falls Till has been dated at more than 34,000 yrs B.P. (GX-1309) and more than 40,000 yrs B.P. (I-4932). Although the validity of the various dates is unclear, the age of the Wadena drumlin field is certainly not greater than Middle Wisconsinan, based on the strong degree of preservation of the individual drumlin forms. The Hewitt phase is here considered to be early Late Wisconsinan.

Climatic Indicators

If the Hewitt phase is indeed as old as indicated by the radiocarbon dates, then the climatic amelioration of the Farmdalian interstadial in northeastern Illinois (Follmer, 1983) was unable to penetrate as far north as central Minnesota. This climatic limitation also extends the interval during which the drumlin slopes would have been subject to mass wasting by solifluction and the formation of ice wedges. A considerable amount of material was moved from the tops of the drumlins to low spots between them, resulting not only in a reduction of the general relief by several meters but the formation of a stone line as well. The concurrent development of ice wedges, to be filled later by slope wash and other deposits as the ice melted, indicates that the mean annual temperature was as low as –5°C during this time. This is consistent with the presence of tundra in ice-free areas at least during the latter part of this period (Cushing, 1967; Birks, 1976).

St. Croix Phase of The Wadena Lobe

The Wadena lobe readvanced to the Itasca Moraine during the St. Croix phase, which also marked the maximum Late Wisconsinan advance across Minnesota of the Superior lobe and the Rainy lobe (now distinct from the Wadena lobe) (Fig. 10D) at about 20,500 yrs B.P. (Birks, 1976). The confluence of the Rainy and Superior lobes at the St. Croix Moraine with the Wadena lobe at the Itasca Moraine constituted a continuous ice margin hundreds of kilometers long. The meltwater that was generated flowed southward, covering the drumlins north of the Leaf River to form the Park Rapids-Staples outwash plain of the Wadena lobe (Wright, 1962) and Oshawa outwash plain of the Rainy lobe (Norton, 1982). South of the Leaf River the meltwater was confined largely to the newly created valley of the Long Prairie River and the terrain east of it toward the St. Croix Moraine (Fig. 3, units wio and rso), thence south toward the Mississippi River through the valley now occupied by Sauk Lake (Fig. 6).

The outwash covered large parts of the drumlin field, particularly on the north and east, where stagnant ice of the Hewitt phase of the Wadena lobe filled interdrumlin swales. This permitted a more or less continuous blanket of sand to form over that landscape near the ice margin (within 2–3 km of the moraine front), whereas only the drumlin flanks and interdrumlin swales were covered farther to the southwest. It was this cover that was originally interpreted as the deposits of Glacial Lake Wadena by Leverett (1932), and its pebbly sand composition attributed to winnowing by wave action at shallow water depths (Wright, 1962).

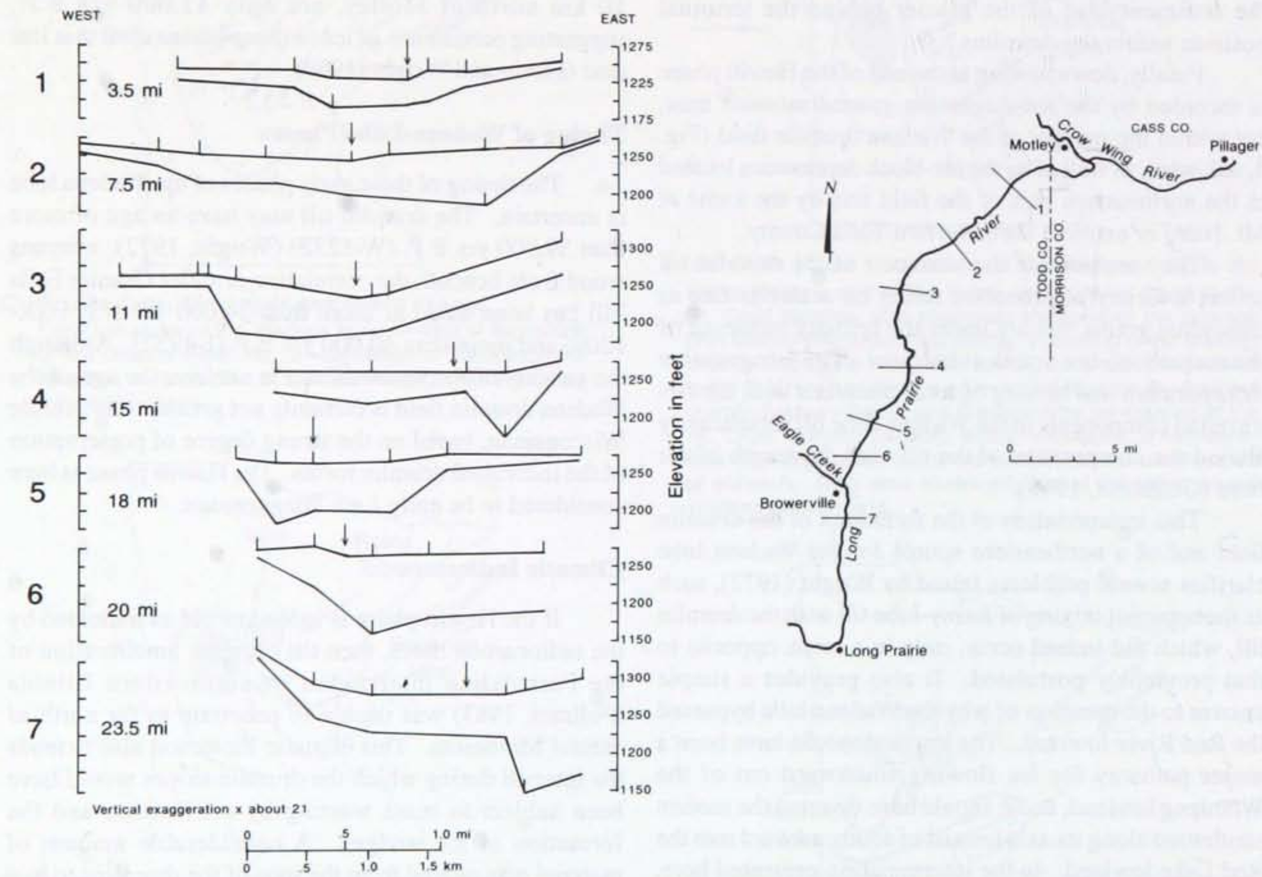


Figure 11. Sections across the Long Prairie valley. The upper line represents the present land surface (arrows indicate the location of the modern channel), which closely approximates the Grantsburg valley train. The lower line represents the St. Croix phase II valley as reconstructed from U.S. Geological Survey drill core (tick marks on upper line); the valley bottom is incised into the Browerville Till. Mileages indicate distance south of the present-day confluence with the Crow Wing River, which is 8 mi west of the Pillager gap.

These stagnant ice masses were preserved under the same permafrost regime that promoted the formation of the stone line and the ice-wedge casts (Fig. 9). The sand cover also provided additional insulation and protection for the ice masses until they began to melt, probably at about 12,000 yrs B.P. (Florin and Wright, 1969). Where the outwash is thickest nearest to the moraines, north of Menagha in northwestern Wadena County, a pitted outwash plain formed that has numerous lakes clearly controlled by the local drumlin orientation. Farther away, to the south and west, the thinner sand blanket was eventually let down without becoming noticeably pitted.

The St. Croix phase marked the first time that the Wadena lobe truly exhibited dynamics that marked it as an ice mass distinct from the main body of the Rainy lobe. This was presumably the result of the bedrock high in northeastern Minnesota (Fig. 5) exerting greater control on the thinned ice during the St. Croix phase than was possible during earlier phases, when the ice was thicker. This reorganization and subdivision into separate Rainy and Wadena lobes is shown by the shift from a trend of N 45° E – S 45° W for the Hewitt-phase drumlins to one of N 20° E – S 20° W for the linear ridges (drumlins? tunnel valleys?) north of the Itasca Moraine near Hennepin Lake in northwestern Hubbard County (Fig. 3, unit wid). Within the Itasca Moraine, gently arcuate ridges oriented N 65° W to S 65° E, and concave to the northeast, suggest ice flow from about N 25° E (Sackreiter, 1975; Norton, 1982). The ridges may be recessional moraines or thrust masses. The latter possibility is supported by the presence of a body of red till (Fig. 9, site 83-12A in Goldstein, 1986) that appears to have been thrust to the surface from a lower stratigraphic position. The strike (N 25° W) and dip (30°N) of this body conforms approximately to the morphology of the large ridges and is consistent with the hypothesis of ice flow from the northeast rather than the north or northwest. As in the earlier phases, however, there is some indication of erosion and mixing of older units by the Wadena lobe in constructing the Itasca Moraine. Westward the till becomes finer grained, richer in carbonate, and poorer in magnetite, and it contains large boulders of "white granite," reflecting the diminishing influence of northeastern bedrock and the increasing contribution of the Browerville Till substrate and other deposits in the west.

Another aspect of the St. Croix phase was the asynchronous behavior of the adjacent Superior and Rainy lobes, a pattern documented elsewhere in the Great Lakes region (Mickelson and others, 1983). Recognition of this has led to the subdivision here for the first time of the St. Croix phase into subphases I and II to account more accurately for the sequence of events. During the St. Croix I phase, the Wadena lobe started construction of the Itasca Moraine, whereas the Rainy and Superior lobes stood at the St. Croix Moraine (Fig. 10D).

After the St. Croix I maximum, the Rainy lobe retreated northeastward, apparently forming the poorly developed Pleasant Lake and Stewart Lake Moraines during brief recessional stillstands between the St. Croix I and the St. Croix II positions. The St. Croix II margin was most likely at the Mille Lacs Moraine near Outing in east-central Cass County (Fig. 10E; see also Mooers and Johnson, 1994, and Fig. 2 in Johnson and Mooers, this volume). The southwest-trending Brainerd drumlins (Fig. 10D), which consist of distinctive brown sandy carbonate-poor till (Schneider, 1961), also formed during this retreat (Mooers, 1989). The recession permitted the Superior lobe to advance into the now-vacated low ground south of Brainerd, where it formed the Pierz drumlin field (Fig. 10E).

The altered geometry may have also profoundly influenced the regional drainage. Meltwater flowing northward from the Superior lobe, westward from the retreated Rainy lobe, and southward from the eastern margin of the Wadena lobe would have become trapped east of the St. Croix Moraine, forming what is termed here Glacial Lake Brainerd. The lake would have extended from Brainerd on the south to Longville in central Cass County on the north, and from the St. Croix Moraine on the west to the St. Croix phase II position (Mille Lacs Moraine) on the east. With the moraine as its eastern boundary, Glacial Lake Brainerd would have covered about 1500 km2 (Fig. 10E).

The lake would have acted as a sediment trap, allowing the water that spilled over the moraine dam (and probably also seeped through the sandy, porous moraine) to excavate a channel at Pillager. Where this flow emerged west of the St. Croix Moraine, it turned southward down the Long Prairie valley train, eroding downward through outwash and drumlin till and into the underlying Browerville Till. The resulting valley was as much as 70 m deep below the crests of the surrounding drumlins (Fig. 11), and had an approximate final gradient of 0.5 m/km (Fig. 12), based on data obtained from cores drilled along the Long Prairie valley by the U.S. Geological Survey. The modern, greatly underfit valley south of Long Prairie and its continuation southward along the Sauk Lake trough attest to the degree of erosion during this interval of time.

Glacial Lake Brainerd was probably not long lived, and the loose material composing the moraine probably did not effectively retard the downcutting and broadening of the outlet at Pillager. When this occurred, the lake drained and outwash was transported southward along the young Long Prairie channel, where it was deposited as a new valley train. It seems likely that the 1350-ft terrace within the Crow Wing valley at Pillager formed at the

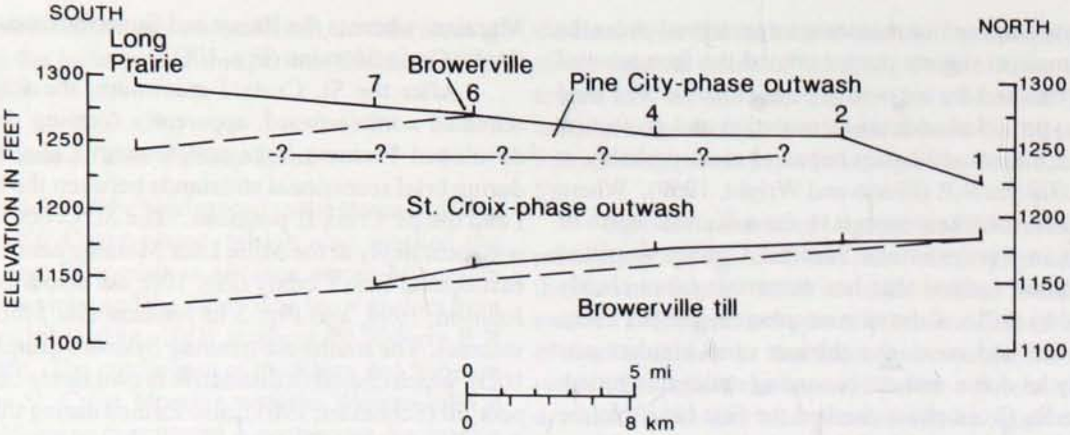


Figure 12. Longitudinal section along the Long Prairie River from the city of Long Prairie to the intersection of the Long Prairie River and section line 1 as shown in the index map in Figure 11. Stratigraphic relationships show Pine City–phase outwash (calcareous) overlying St. Croix–phase outwash, which in turn overlies Browerville Till. The position of the contact between the two outwash units north of Browerville is uncertain; the upper dashed line is the average slope. The lower dashed line is the average slope of the St. Croix valley floor.

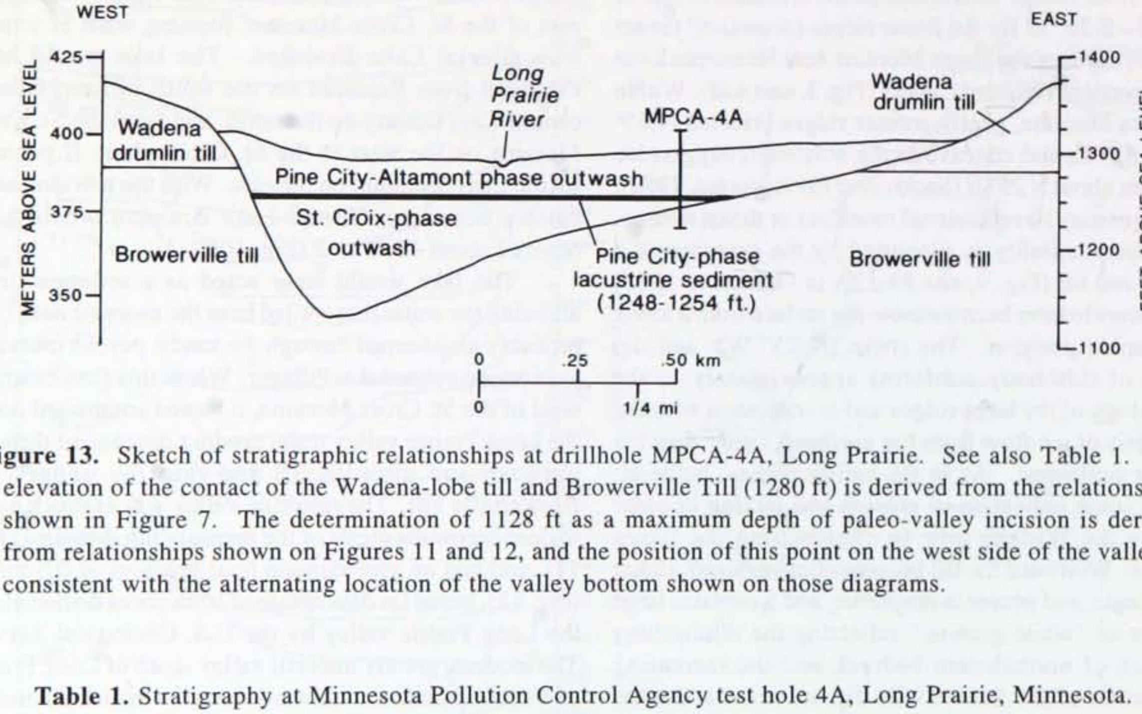


Figure 13. Sketch of stratigraphic relationships at drillhole MPCA-4A, Long Prairie. See also Table 1. The elevation of the contact of the Wadena-lobe till and Browerville Till (1280 ft) is derived from the relationships shown in Figure 7. The determination of 1128 ft as a maximum depth of paleo-valley incision is derived from relationships shown on Figures 11 and 12, and the position of this point on the west side of the valley is consistent with the alternating location of the valley bottom shown on those diagrams.

Table 1. Stratigraphy at Minnesota Pollution Control Agency test hole 4A, Long Prairie, Minnesota.
[T. 129 N., R. 33 W., sec. 17, SE1/4, SE1/4. See also Figure 13.]

Depth (m)	Elevation (ft)	Description
0–11.8	1293–1254	Gray outwash (fine to coarse shale-bearing sand); low magnetic susceptability
11.8–13.5	1254–1248.5	Gray silty clay containing 2 percent organic material, 13 percent carbonate, and *Picea* and *Artemesia* pollen
13.5–15.5	1248.5–1242	Gray outwash (medium to fine sand; no shale); high magnetic susceptability
15.5–18.2	1242–1233	Dark-gray silty loam till (Browerville) containing 30 percent carbonate, wood fragments of *Abies balsamea* and a juvenile specimen of an unidentified hardwood, probably *Acer* sp. or *Alnus* sp., located at top of the unit.

head of this valley train. It is difficult to trace this surface southward through most of the Long Prairie valley, but a reconstruction can be made at the town of Long Prairie on the basis of samples provided by the Minnesota Pollution Control Agency (MPCA). The presence of a buried contact that separates a lower outwash unit containing a strong component of Rainy-lobe derived sediment from the overlying Des Moines-lobe lacustrine and outwash deposits is inferred on the basis of contrasts in magnetic susceptibility and shale content (Fig. 13). Extension of the 1350-ft terrace at Pillager to the 1249-ft elevation marking the top of the Rainy-lobe outwash at Long Prairie yields a gradient of about 2.5 ft/mi, which is typical for many valley trains (Flint, 1971, p. 578-579). This elevation of the buried Rainy-lobe outwash at Long Prairie also represents a valley fill of about 121 ft there, because the depth of incision during the earlier downcutting phase was near 1128 ft (Fig. 12). The disparity between this elevation and the 1242-ft contact between the Rainy-lobe outwash and the underlying Browerville Till at MPCA test hole 4A is probably a consequence of the location of the hole along one of the valley sides, about a quarter of a mile east of the center of the channel (Fig. 13).

Although deposits of Glacial Lake Brainerd appear to partially bury parts of the Pleasant Lake and Stewart Lake Moraines (Mooers and Johnson, 1994; Johnson and Mooers, this volume), landforms from this ephemeral lake are generally not well developed. Besides the lake's short duration, the subsequent history of the area may have served to obscure its deposits. Sediment deposited in the lake would have been spread over a floor consisting of numerous stagnant ice blocks left during the recession of the Rainy lobe. Continued outwash production by the confluent Rainy, Wadena, and Superior lobes after the draining of the lake further filled the basin. The eventual collapse of the ice blocks resulted in a plain pitted by many depressions presently occupied by lakes such as Whitefish, Pelican, and Cross Lakes in northern Crow Wing County. This collapse would have certainly disrupted the (presumably) thin deposits of Glacial Lake Brainerd, possibly even focusing much of the sediment into the depressions developing over the melting ice blocks at the lake bed.

This interpretation is contrary to that of Leverett (1932), who based the presence of Glacial Lake Wadena along the west side of the St. Croix Moraine on the equivalence in elevation of the terrace at Pillager, presumably formed along the shore of the lake, to that of the pass south of Long Prairie. At the time of the events outlined above, however, the pass would not yet have existed, as it was formed by the younger Des Moines lobe and therefore could not have ponded any water during the St. Croix phase. The Pillager gap would have opened prior to the Pine City phase as well, preventing the formation of a lake north of that latitude, as postulated by Leverett (1932) to explain the sand draped over the drumlins in that region. Instead, the hypothesis adopted here invokes the spreading of St. Croix-phase outwash over a landscape dotted with stagnant ice masses, thus accounting for the sand cover.

A consistent feature along the contact between Browerville Till and Rainy- and Superior-lobe outwash throughout the Long Prairie area is the presence of numerous wood fragments (Michael Convery, written commun., 1984]. At MPCA test hole 4A (Fig. 13) these include *Abies balsamea* and an unidentified hardwood species, possibly a juvenile specimen of *Alnus* or *Acer* (James Bowyer, written commun., 1984). The presence of wood fragments at this contact in several wells and test holes suggests that the trees and shrubs were buried in place or were washed from nearby sources as the waters depositing the outwash flowed from the ice sheet itself. The presence of the wood fragments is contrary to the vegetational reconstruction of the region for this time, based on pollen evidence, which indicates the presence of a spruce/tundra community (Birks 1976). If the proposed history of the Long Prairie valley is accurate, then the fragments are the oldest macrofossils yet identified of woody species growing in central Minnesota during the Late Wisconsinan. Perhaps the trees grew on the west-facing slope of the deep Long Prairie valley as an isolated community. However, both the persistence of the wood layer at the great depth of the till-outwash contact throughout the area, and the stratigraphic and lithologic relationships (Fig. 13) argue for the interpretation presented here.

As the Wadena, Rainy, and Superior lobes retreated at the end of the St. Croix phase, the Crow Wing-Long Prairie channel was abandoned as a course for the southward-directed meltwater, and the integration of a nonglacial drainage network was initiated. This included the southeast-oriented parts of the Long Prairie River and Eagle and Moran Creeks (Fig. 6), which would have been tributaries to the southward-flowing Long Prairie River that drained at least as far south as the Sauk Lake channel.

THE DES MOINES LOBE: PINE CITY AND ALTAMONT PHASES

The 20,500-yrs-B.P. age for the St. Croix phase, if accurate, can now be regarded to be a true minimum date as it records the end of the St. Croix II phase during which the Pierz drumlins formed. Similarly, the 16,000-yrs-B.P. age for the advance of the Grantsburg sublobe of the Des Moines lobe is a minimum date as well, as it marks the time when the ice had already advanced across Minnesota to Grantsburg, Wisconsin, forming Glacial Lake

Grantsburg and the Pine City Moraine (Wright and others, 1973). Prior to that time, the Des Moines lobe had to advance 450 km southward from its source region in southeastern Manitoba along the Red River lowland and then an additional 350 km toward the northeast. The rapid advance of the lobe and its apparent low surface profile have led to its characterization as a surging glacier (Kemmis, 1981; Chernicoff, 1983). In its early stages it may have existed as a narrow tongue, the Osakis sublobe, that protruded northeastward through a topographic break in the Alexandria Moraine located between Glenwood and Brooten in southeastern Pope County. This area is 20 km wide and is characterized by subdued topography that generally lies 50 m below the moraine to the northwest and southeast.

Further advance of the lobe filled the lowland west of the drumlin field to a point north of Alexandria and enabled the ice to project onto the southern edge of the drumlin-capped upland between Lake Osakis and the town of Long Prairie (Fig. 10F). The thin Osakis Moraine was built within this region (unit dpe in southwestern Todd County, Fig. 3), with the ice reaching a maximum elevation of at least 444 m, and a thin cap of flow-till deposits spread as distant as 1.5 km northward from the ice edge. The Osakis Moraine formed by incorporation and mixing of underlying Wadena-lobe till with the thin load of Des Moines till at the terminus as the ice moved from the 404-m elevation of the Osakis till plain up the 30–40-m high south-facing escarpment of the Browerville highland, in a manner analogous to that described for the Pine City phase of the Des Moines lobe by Chernicoff (1983). The thin Des Moines-lobe ice also extended an additional 12 km northward to Browerville into the narrow tract of low ground between the east edge of the drumlins and the St. Croix Moraine, where it built a kame moraine reaching just above 412 m (Fig. 3, unit whd-4). Very thin and discontinuous patches of Des Moines-lobe till characterize the low interdrumlin regions of the Long Prairie region, and are by themselves not clear evidence for the extent of the ice at this stage. However, outwash bearing the distinctive Pierre Shale, diagnostic of the Des Moines lobe glacial sediment, marks the true northern extent of the ice lobe east of Browerville. The kame-moraine origin of this material is interpreted from the presence of gravel with cobble-sized clasts of the shale throughout the entire deposit. These clasts presumably would not have survived intact the vigorous fluvial transport along a valley-train system from Long Prairie, 12 km to the south.

The advance of the Osakis sublobe of the Des Moines lobe across the Long Prairie valley blocked the south-flowing river, creating a lake that extended up the valley as far north as Browerville. Nearly 2 m of calcareous lacustrine sediment accumulated at Long Prairie, largely derived from material released by the Des Moines lobe (Fig. 13; Table 1). This sediment overlies the St. Croix-phase Rainy outwash but thins northward and disappears at Browerville, marking the northern limit of the lake. The presence of *Picea* and *Artemisia* pollen characterizes this unit (Linda Shane, written commun., 1984). As the Des Moines lobe advanced to its final Pine City-phase position at 16,000 yrs B.P., and later to its maximum in Iowa at 14,000 yrs B.P. during the Altamont phase (Mickelson and others, 1983), its outwash continued to prograde northward along the Long Prairie valley. Eventually, the shale-bearing, magnetite-poor outwash (Fig. 13; Table 1) was built to a height great enough to reverse the drainage along the Long Prairie valley toward the north (Fig. 12), eventually escaping eastward out the Pillager gap, which formed during the earlier St. Croix II phase.

The growth of the Des Moines lobe during these latter stages permitted the ice to overtop the Alexandria Moraine north of Glenwood, but not the higher Itasca Moraine farther north. The contrast between the smooth, broad slopes of the Alexandria Moraine, mantled by the fine-textured Des Moines-lobe till, and the short, steep, bouldery slopes of the Itasca Moraine beyond the Des Moines overlap are evident both in the field and on aerial photographs. This contrast allows the maximum extent of the Des Moines lobe to be mapped (Fig. 3). As the Des Moines lobe advanced to this stage, greater volumes of outwash were shed from the ice front between Detroit Lakes and Henning eastward down the Leaf River valley train. This may have already been an established drainageway formed along a sag in the drumlin topography north of the Browerville highland. At least two terraces formed along this route; near Wadena the higher level reached almost 1350 ft in elevation and covered the lower, valleyward slopes of drumlins, mantling the stone line and ice wedges there (Goldstein, 1986, Fig. 19). This upper-level outwash was also high enough to fill the interdrumlin swales as backwater deposits as far as several kilometers north and south of the valley train. The lower terrace was deposited at about 1310 ft near Wadena. Outwash issuing from the ice margin near Miltona was transported eastward along the channel that had been tributary to the southward-flowing Long Prairie River prior to the Pine City phase, but that had become an ice-marginal channel north of the Osakis sublobe. This east-trending valley is the head of the modern Long Prairie River. Between the Leaf River and Long Prairie River valley trains, meltwater flowed north and east along interdrumlin swales. The meltwater intersected pre-existing channels at Eagle Bend on Eagle Creek and at the bend of Moran Creek. The meltwater first transported outwash southeast along these channels and then northward along the Long Prairie valley. Farther west the outwash was transported directly into the Leaf River channel, such as along the Partridge River. All of the Des Moines-lobe meltwater eventually passed eastward through the Pillager gap and then southward, contributing to the nascent Mississippi River system.

LATE-GLACIAL AND POSTGLACIAL ENVIRONMENTS

The late-glacial rise in temperature continued into the early Holocene, and by 7,000 yrs B.P. the trend to a warmer, drier climate reached its maximum (Wright, 1972). Accompanying this change, prairie vegetation advanced from the west onto the drumlin slopes, and the smaller lakes and marshes either dried up or dropped to lower levels. Another result of the climatic amelioration was the cessation of solifluction and the onset of soil formation, which may have been initiated as early as 12,000 yrs B.P. (Watts, 1983). The variable soils present on the drumlins today have resulted from continual pedogenesis since that time.

In the northeastern part of the drumlin field, leaching has reached as deep as 6 m on the sandy, carbonate-poor till. The progressively finer texture and higher carbonate content of the till to the west and south is characterized by shallower depths of leaching (Fig. 21 in Goldstein, 1986). However, the "fragipan" nature common to the B- and C-horizons of many of the soils throughout the region probably did not develop through soil formation, but rather was inherited from the original properties of the deposits (Antoine, 1970; Gamble and Mausbach, 1984). The contrast between these high-bulk-density horizons at depth and the looser material above resulted primarily from the effects of solifluction acting on the surface of the dense drumlin till from the end of the Hewitt phase until the climatic warming at the end of the Pleistocene. A variably thick cover of ablation deposits draped over the drumlins by the stagnating Hewitt-phase Wadena lobe contributed to this contrast. Deeper soils are occasionally located at mid- and toe-slope positions on the drumlins (Charles Saari, written commun., 1984), which result from the presence of thicker solifluction deposits at those positions, promoting better drainage and therefore more efficient soil-horizon development.

In places, exposed outwash surfaces have been modified by eolian action, either during the late-glacial or the Hypsithermal period (Keen and Shane, 1985), or both. Evidence of this kind of activity is recorded in the vicinity of Cat and Dog Lakes north of Motley, where poorly preserved low dune forms and ventifacts attest to the mobilization by wind of the exposed sands and silts of the Park Rapids-Staples outwash plain. For the Oshawa area 40 km to the north, Norton (1982) provides evidence that northwesterly winds formed the dunes preserved there. Part of the sandy blanket on the drumlins in this area of the drumlin field may therefore be attributed to these eolian deposits, although their development may be greatest against the St. Croix Moraine, which would have acted as a sediment trap for wind-driven sand.

As the Hypsithermal period of maximum warmth and dryness gave way to cooler and moister conditions after 7000 yrs B.P., the conifer-hardwood forest became reestablished. Peat began to develop in poorly drained lowland sites, particularly in interdrumlin swales. Today the peat bogs are five or more meters thick in places (H. C. Mooers, oral commun., 1984). The clearing of the land for agricultural use beginning in the mid-nineteenth century has undoubtedly accelerated the processes of slopewash and gully formation, which have been operating since deglaciation, and it marks the last stage in the modification of the topography of the Wadena drumlin field.

DISCUSSION

The sequence of events in Minnesota presented above highlights the variation in the direction of ice flow across the Upper Midwest on two distinct time scales. Deposits primarily of northwestern origin characterize the older parts of the stratigraphic record and indicate the dominance of a "Keewatin" ice center during the earlier glacial stages of the Quaternary through the time of the formation of the Browerville and Kandiyohi Tills. These deposits are succeeded by the Hawk Creek Till of possible Illinoian age and the complex of Wisconsinan deposits, including Wadena-lobe till, that record the more recent dominant control of ice flow from the northeast. In broad terms, this sequence has been correlated to deposits in the Dakotas, Iowa, and western Wisconsin and may even be represented by a similar transition found as far to the southeast as southern Illinois (Frye and others, 1965). The cause of this shift, if it is indeed real, is not understood. Furthermore, any attempt at explanation must first satisfy the fundamental requirements of more accurate regional correlation and assignment of absolute ages.

Within the last glacial stage, the Wisconsinan, the revised interpretation presented here indicates that ice flow into Minnesota was consistently from the northeast throughout all of the early and middle Late Wisconsinan, represented at various times by the Wadena, Superior, and Rainy lobes. The Wadena lobe is reinterpreted here as an early, expanded version of the Rainy lobe. It was only during the latest Late Wisconsinan that the Des Moines lobe entered Minnesota from the northwest. This is consistent with evidence from a broad region that ranges from Quebec (Hillaire-Marcel and others, 1980), across to the south and west sides of Hudson Bay (Shilts and others, 1979; Shilts. 1982), and to southeastern Manitoba

(Teller and Fenton. 1980). The relative dominance of ice flow from the Labradoran rather than the Keewatin ice dome determined glacial events in south-central Canada and the north-central United States for most of the Wisconsinan glaciation.

Nonclimatic factors have been postulated as causing the Late Wisconsinan fluctuations of the Superior lobe (Birks, 1976). The Late Wisconsinan shift in the position of main ice activity has also been attributed (Mayewski and others, 1981) to marine ice streams draining the eastern part of the Laurentide Ice Sheet. If and how this may have contributed to the growth of a western ice dome is speculative. Other nonclimatic mechanisms may have played a role in the late advance of the Des Moines lobe (Boulton and Jones, 1979). In any event, the time period within the Wisconsinan stage spanned by these events is inferred on geomorphic evidence to be longer than that of the reconstruction by Mickelson and others (1983). First, the well-developed stone line and ice wedges developed on the Hewitt-phase drumlins probably required more than just a very few thousand years to form. The persistence of stagnant Hewitt-phase ice masses through the St. Croix phase has already been discussed. Second, the drainage relationships clearly demonstrate that the age for the onset of the Des Moines-lobe advance into central Minnesota was younger than the retreat of the Superior, Rainy, and Wadena lobes from their positions during the St. Croix II phase, and was not synchronous with the advance of those lobes to their St. Croix maxima.

Thus the net result of the processes affecting the drumlins since their uncovering as subglacial landforms has been to reduce relief by about 10 m throughout much of the field, and by even greater amounts where post-Hewitt-phase deposits completely obscure them. Nevertheless, enough of the essential characteristics of the drumlins have been retained to permit presentation of the data and interpretations here. More work, some already in progress, is required with respect to the pre-Hewitt-phase deposits. Critical to these studies will be a much better understanding of their stratigraphic relationships and lithologic variation, because the Wadena drumlin field probably represents the oldest glacial deposit in Minnesota whose geomorphology will provide significant insights into the glacial history of the region.

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LANDFORM ASSEMBLAGES AND GLACIAL HISTORY OF A PORTION OF THE ITASCA MORAINE, NORTH-CENTRAL MINNESOTA

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ABSTRACT

Landform assemblages within the Itasca Moraine of north-central Minnesota suggest a new interpretation for the glacial history that involves the advance of the Wadena and Koochiching lobes during Late Wisconsinan glaciation. The Itasca Moraine initially formed as a stagnation complex during the recession of the Wadena lobe. Later, the Itasca Moraine marked the southern margin of the Koochiching lobe. The abundance of shale fragments in Koochiching-lobe deposits distinguishes them from Wadena-lobe deposits. The complex glacial topography of the Itasca Moraine includes landform assemblages containing proglacial, supraglacial, and subglacial deposits. Advance of the Koochiching lobe was previously thought to have been a result of the Wadena-lobe retreat, which opened a conduit allowing the Koochiching lobe to advance from the west. Results presented in this paper and in St. George (1994) suggest that the Wadena lobe never actually retreated from its position at the Itasca Moraine prior to the initial advance of the Koochiching lobe, but that the ice-flow center gradually switched from the north-northeast to the north, and eventually to the west-northwest. If a retreat of the Wadena lobe had occurred prior to the initial advance of the Koochiching lobe, a distinct stratigraphic contact would separate the shale-bearing deposits of the Koochiching lobe from the non-shale-bearing deposits of the Wadena lobe. The stratigraphic record shows that this contact is gradational, suggesting that the Koochiching lobe also contributed, to a certain degree, to the later-stage formation of the Itasca Moraine and associated landforms. This change in ice-flow direction would be contemporaneous with the retreat of the Rainy lobe, which opened an area into which the ice could flow and advance towards the southeast.

INTRODUCTION

Interpretations relating to the gradational shift in ice-flow direction of the Wadena lobe are made here as a result of the detailed study conducted in the Itasca moraine region of north-central Minnesota (Figs. 1 and 2). The initial study was related to a groundwater-recharge investigation (St. George, 1994) within the Itasca Moraine; it focused on the variations in spatial distribution of groundwater recharge among different landform assemblages. As a result of this study, a detailed Quaternary landform map was constructed (Fig. 3). This landform map prompted the reevaluation of ideas regarding the formation of the glacial deposits associated with the Itasca Moraine and directed attention to relations between deposits of the Wadena and Koochiching lobes (Fig. 4). Geological mapping also allowed assessment of the deposits immediately to the north of the Itasca Moraine, over which there has been debate by Martin and others (1989, 1991) and Meyer (1993) regarding the timing and extent of the advance of Koochiching-lobe ice.

The Itasca Moraine is a laterally extensive accumulation of glacial sediment that was interpreted by Wright (1972) and Wright and Ruhe (1965) to have been deposited by ice flowing from the north and northeast during Late Wisconsinan glaciation (Figs. 1 and 4).

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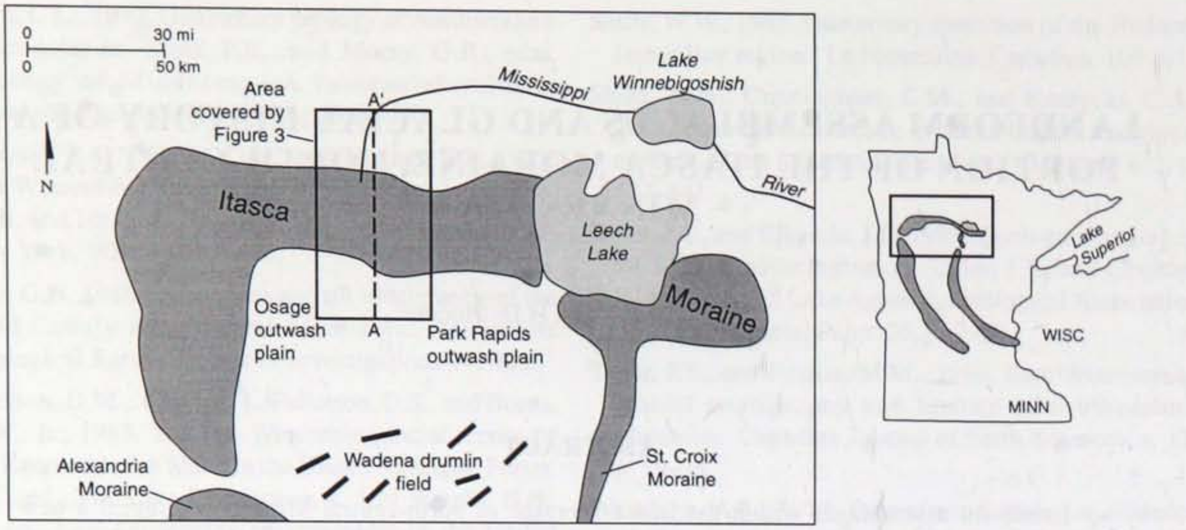


Figure 1. Location of the Itasca Moraine and associated landforms of north-central Minnesota. Portions of the previously formed Alexandria and St. Croix Moraines are also shown. Location of landform-assemblage map (Figure 3) is indicated. Dashed line (A-A') represents one possible location for generalized cross section (Figure 2).

Wright and Ruhe (1965) and Wright (1972) defined the Wadena lobe as ice originating in the Winnipeg lowland to the northwest. This ice mass then flowed toward the southeast into northeastern Minnesota, where it was diverted to the southwest by the advancing Rainy lobe. Therefore, the Wadena lobe entered central Minnesota from the northeast forming the Wadena drumlin field and the Alexandria Moraine. The Wadena lobe later retreated and stabilized forming the Itasca Moraine in north-central Minnesota. Recent investigations by Goldstein (1986, 1989, and this volume) and Meyer (1986) have shown that the Wadena lobe originated in the northeast. Meyer (1997) and Meyer and Knaeble, 1996) discontinued use of the term Wadena lobe. Mooers and Lehr (1997) have also discontinued use of Wadena-lobe terminology. There is, however, still considerable debate on abandonment of established terminology, and for the purposes of this investigation, usage of the term Wadena lobe is retained because an alternative has not been widely accepted.

Retreat of the Wadena lobe was followed by an advance of an eastern offshoot of the Des Moines lobe, which Leverett (1932) called the St. Louis sublobe after exposures in east-central Minnesota. Wright (1972) and Wright and Ruhe (1965) extended the use of St. Louis sublobe to eastward and southeastward-flowing ice north of the Itasca Moraine. Martin and others (1989, 1991) and Meyer (1993) now restrict usage of St. Louis sublobe to that portion of the ice south of the Mesabi Range; the term Koochiching lobe is used for northwest-derived ice that extended to the north of the Itasca Moraine. Several named phases of the Wadena and Koochiching lobe have been previously described (Wright, 1972; Wright and Ruhe, 1965; Martin and others, 1991) and are widely accepted. A historic synopsis will not be presented in this paper; refer to cited references for detailed phase descriptions.

The area studied encompasses approximately 1700 km^2 within the Anchor Hill, Big Basswood Lake, Heart Lake, Lake Hattie, Lake Itasca, LaSalle Lake, Osage, Park Rapids, Park Rapids NW, Schoolcraft Lake, Skunk Lake, and Two Inlets 7.5-minute quadrangles (Fig. 3). The rather strong topographic relief of the Itasca Moraine offered an ideal setting for the groundwater-recharge investigation conducted by St. George (1994) and resulted in the landform-assemblage definitions presented here.

BACKGROUND

The Itasca Moraine is roughly 150 km long and nearly 30 km wide and rises 100-200 m above adjacent areas to the north and south (Figs. 1 and 2). The Itasca Moraine is highest along its central axis; this high crest divides the Itasca Moraine into two regions of contrasting morphology and sedimentology. The proximal (up-glacier or northern) portion of the Itasca Moraine is a hummocky ice-stagnation complex represented by ablation till and isolated glaciolacustrine and glaciofluvial deposits (St. George, 1994). The distal (down-glacier or southern) portion of the Itasca Moraine is also characterized by ice-stagnation topography, but the suite of landforms is strikingly different (St. George, 1994). The southern

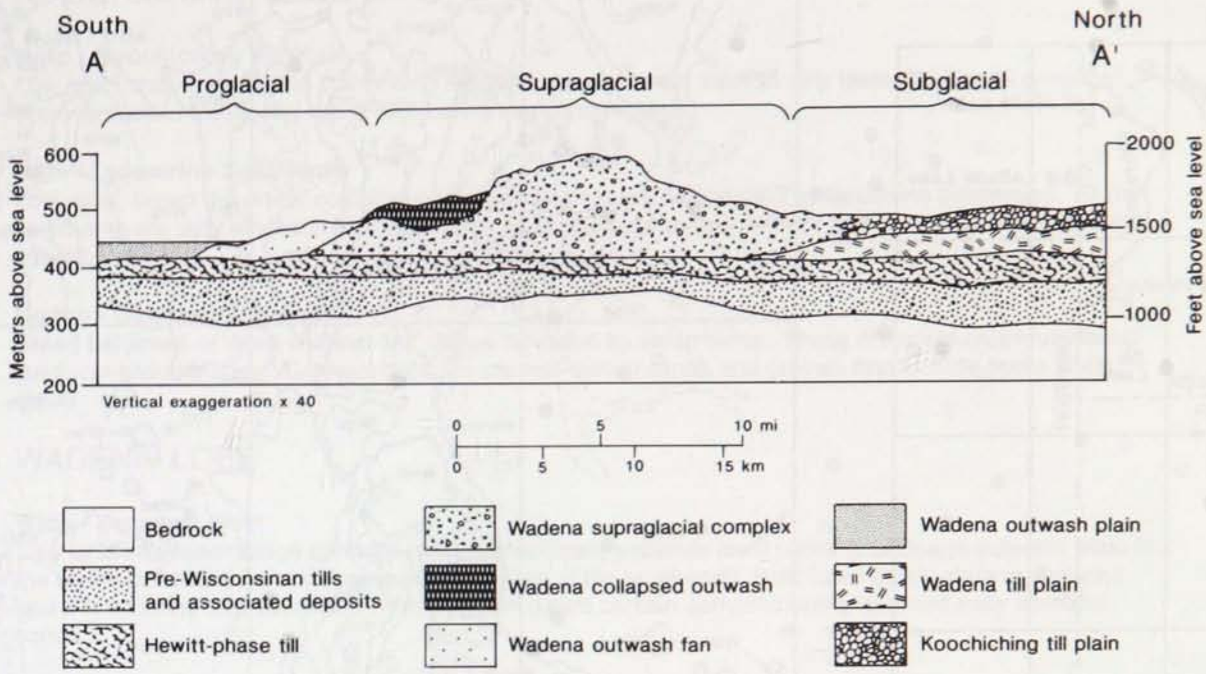


Figure 2. Generalized north-south cross section through the Itasca Moraine showing landform assemblages and their inferred relations (Fig. 1). Although the Wadena till plain and Koochiching till plain are shown as separate units with a distinct contact on this figure, there is a gradational contact between these two units. Bedrock elevation and sediment thickness were derived from well and geologic logs (St. George, 1994). Lacustrine, outwash channel and perched lake landform-assemblages are not shown in this figure due to limitations of scale. Vertical exaggeration is 40x.

portion of the Itasca Moraine contains an integrated drainage network composed of large meltwater channels and chains of ice-walled lake plains connected by rivers (St. George, 1994; Mooers and Norton, 1997). The southern portion of the Itasca Moraine is also crossed by numerous tunnel valleys, now expressed as chains of lakes, that reflect the englacial and subglacial drainage system that developed during and prior to Itasca Moraine formation (Wright, 1993).

The Park Rapids outwash plain lies to the south of the Itasca Moraine (Figs. 1 & 2). The outwash forms a gently sloping plain that grades from the distal portion of the Itasca Moraine southward, where the outwash apron breaks into fingers interpreted to result from water flowage between drumlins of the Wadena drumlin field (Goldstein, 1989 and this volume). The Wadena drumlin field was constructed during the earlier Hewitt phase of the Wadena lobe.

North of the Itasca Moraine we recognize 2 distinct tills within the till plain. They are associated with separate ice lobes, and are classified as separate landform assemblages. The eastern assemblage contains Wadena-lobe till, which is a stratigraphically older sandy loam, containing abundant metamorphic and igneous rock types derived from the Canadian Shield as well as abundant limestone, dolomite, and chert derived from Paleozoic carbonate rocks. Gowan (1993, and this volume) presented convincing evidence that the source area for the Wadena-lobe ice lay in the Hudson Bay region to the northeast, where Paleozoic carbonate rocks occur extensively. However, it has also been suggested that the carbonate in the sediments associated with the Wadena lobe may have had a source in the underlying carbonate-rich till, that was derived from the Winnipeg area to the northwest (Goldstein 1989, and this volume).

The western assemblage contains Koochiching-lobe till, which is younger, contains a suite of rock types similar to the Wadena-lobe till, but is slightly finer-textured, and contains abundant Cretaceous shale. This fine-textured till is compositionally and texturally similar to that of the later Koochiching-lobe tills of northwest-source (Meyer, 1993). The stratigraphic boundary between the two till units is gradational. The upward change in clast types suggests a reorientation of ice flow from a north-northeast source (Wadena lobe) to northwest source (Koochiching lobe) during the formation of the Itasca Moraine.

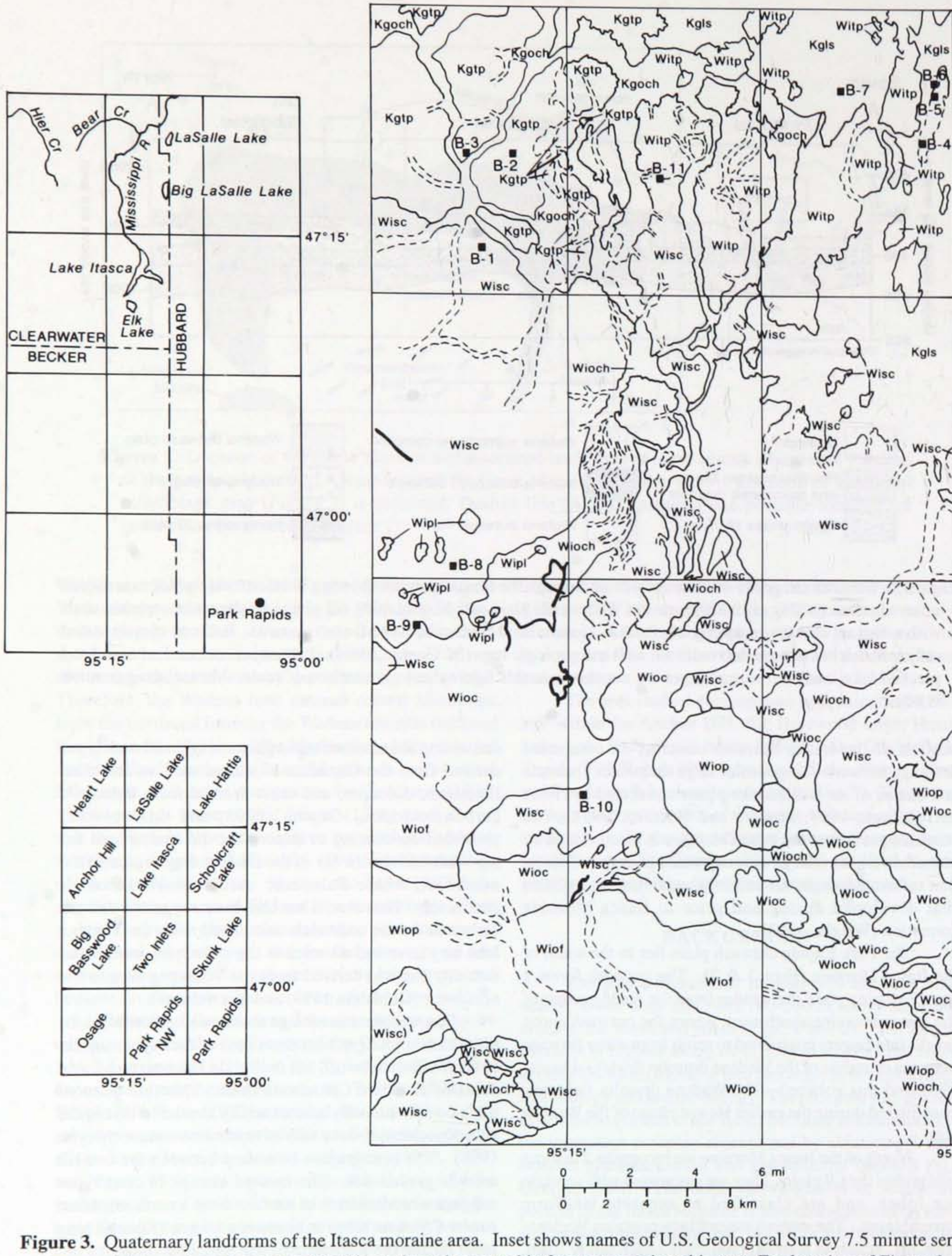


Figure 3. Quaternary landforms of the Itasca moraine area. Inset shows names of U.S. Geological Survey 7.5 minute series (topographic) quadrangles covered in this study and geographic features mentioned in text. For location of Figure 3 see Figure 1.

EXPLANATION FOR FIGURE 3

KOOCHICHING LOBE

Kgtp - Koochiching Till Plain
Low relief undulating plains comprising light olive brown sandy loam to silty loam till. The till contains abundant shale clasts and has a high carbonate content.

Kgls - Lacustrine Sediments
Low relief, broad flat plains comprising sand and sandy loam deposited by lacustrine processes. All the sediments are very leached. The sediments have a low carbonate content and shale clasts are largely absent.

Kgoch - Outwash Channels
Broad flat areas or deep channel-like valleys bounded by steep sides. These channels crosscut other landform-assemblages. Channel deposits are well-sorted sands and gravels that include some shale clasts.

WADENA LOBE

Wiop - Outwash Plain
This landform assemblage contains two geographically separate level plains (the Osage outwash plain in the southwest and the Park Rapids outwash plain in the southeast). Both have gently sloping surfaces and a few closed depressions. These outwash plains contain compositionally and texturally identical sands.

Wiof - Outwash Fan
Narrow, low relief apron of moderately well sorted sand and gravel that slopes gently to the south and contains numerous small depressions. This unit is situated between the collapsed outwash of the stagnant ice field to the north and the broad flat outwash plains of the proglacial environment to the south.

Wipl - Perched Lakes
Isolated ice-walled lake plains (flat-topped hills) composed of silt that grades laterally and vertically into fine sand. The gradation reflects the proximity to the margin of an ice-walled lake. This landform-assemblage occurs within the western and southern parts of the supraglacial complex, and is not areally extensive.

Witp - Wadena Till Plain
Undulating plains marked by gently sloping swells, sags and depressions. This area is dissected by numerous stream valleys. The till is mainly a sandy loam and is light olive brown in color. Sediments have a high carbonate content and shale clasts are absent.

Wioc- Collapsed Outwash
Hummocky topography with relatively low relief and numerous closed depressions. Composed of weakly stratified loamy sand with gravel that is not always well sorted.

Wisc - Supraglacial Complex
Knolls, hummocks and closed depressions characterized by high relief and sharp, irregular surfaces. Comprises sandy loam (55%), poorly to moderately sorted sand and gravel (40%) and silts (5%). Tills are light olive brown and rich in carbonate. Cretaceous shale clasts are absent. Compositionally and texturally similar to the Wadena lobe till plain.

Wioch - Outwash Channels
Broad flat areas or deep channel-like valleys bounded by steep sides that crosscut other landform-assemblages. Channel deposits are well-sorted sands and gravels.

Scarps - interpreted as channel boundaries

Eskers

B-2 ■ Soil Boring Location

LANDFORM ASSEMBLAGE APPROACH

A landform-assemblage approach was used to evaluate the origin, structure, sedimentological complexity, and glacial history of the Itasca Moraine (St. George, 1994). Glacial terrains are composed of landforms such as hummocks, eskers, kettles, ice-contact forms, and outwash features. Each landform has developed due to a particular set of processes operating within the glacial system, and has similar relief, stratigraphy, and sedimentology. A landform assemblage is not limited by size; it can range from an extensive glacial outwash plain to long narrow channels, to small or large hummocky knobs, or large tracts of hummocks with similar topographic expression. A landform assemblage may be structurally and sedimentologically complex but the complexity is similar throughout the landform assemblage. Once the areal extent of a landform assemblage has been determined, the physical characteristics can be described from field observations, sample collection and laboratory analysis, and from compilation of stratigraphic data from borings.

Mapping of the landform assemblages was initially based on their topographic expression interpreted from maps and aerial photographs, and was compiled on 7.5-minute topographic quadrangles. Landform-assemblage types ranged from broad flat sand plains to complex glacial-morainic deposits, ice-stagnation features, till plains, and glaciolacustrine plains (Fig. 3). The landform assemblages were grouped into categories based on the glaciogenic environment in which they form.

Recognition of landform assemblages implies a genetic relationship among the assemblages and materials involved in their development (Flint, 1971; Sugden and John, 1976: Eyles, 1983; Eyles and Menzies, 1983). Based on identification of the landform assemblages and terrain type, the geometry and character of subsurface stratigraphies can be generalized for large areas. Eyles and Menzies (1983) describe three principal depositional environments: subglacial, supraglacial, and proglacial. Each depositional environment is associated with characteristic topographic expression, stratigraphy, and sedimentology. The landform assemblage associated with subglacial deposition and erosion generally results in undulating plains of low relief. Landform assemblages associated with supraglacial environments are generally characterized by blankets of debris on the ice surface that are left behind as the ice retreats. Retreating ice margins produce large tracts of hummocky supraglacial topography that frequently form arcuate belts (moraine complexes) several tens of kilometers wide (Eyles and Menzies, 1983). Landform assemblages associated with proglacial environments result from transport of sediments from the active ice surface, and their deposition by glaciofluvial or glaciolacustrine processes beyond the active ice margin.

Field Reconnaissance

The landform assemblage map (Fig. 3) was used to select areas for detailed study and to identify areas for collection of sediment samples. Field checking involved the classification of deposits associated with each landform assemblage on the basis of description of physical and chemical properties such as color, texture, structure, indicator grain lithology (shale, metamorphic, carbonate, etc.), relative density (i.e. compaction), caliche, mottling, gleying and reaction to dilute hydrochloric acid to determine presence of carbonate in all size fractions. Where possible, stratigraphic and sedimentological characteristics, and inferred depositional environments were noted. Field textures were confirmed by laboratory grain-size analysis using the method described by Folk, (1980) resulting in the percent of gravel, sand, silt, and clay. The resulting percentages of sand, silt and clay from each sample was applied to the US Department of Agriculture textural classification.

Because many portions of the study area are remote, most sediment descriptions are based on exposures in road cuts or borrow pits, or on samples obtained with a hand auger. Care was taken to distribute observations and sampling sites throughout the various landform assemblages and over a wide elevational range. A total of 498 sites were visited and described. The stratigraphy at 12 sites was assessed using core obtained with a Giddings probe.

DESCRIPTION OF UNITS

Landform assemblages were delineated primarily on the basis of topographic expression. Classification was further refined on the basis of sediment characteristics and inferred depositional mechanisms and interpreted glaciogenic origin. A total of eight separate landform assemblages were identified (Fig. 3). These eight landform assemblages are: till plain (Wadena lobe), till plain (Koochiching lobe), supraglacial complex, collapsed outwash, outwash plain, outwash fan, outwash channel, and lacustrine sediment. A generalized north-south cross section showing relations between these landform assemblages and their respective depositional environments is shown in Figure 2. The following is a detailed description for each of the landform assemblages, organized on the basis of glaciogenic environment.

Landform Assemblages of Subglacial Origin

Till Plain (Wadena Lobe) (Witp)

The Wadena lobe till plain, located on the northern margin of the Itasca Moraine, is characterized by low relief; undulating plains are marked by gently sloping swells, sags, and depressions with an apparently random pattern. The area has been dissected by streams and contains several remnant tunnel valleys such as those occupied by Lower LaSalle and Big LaSalle Lakes (see inset, Fig. 3). Grain size was analyzed for 11 samples collected from the Wadena-lobe till plain, and an additional 33 sites were visited and described. Three soil borings (B-4, B-5 and B-6, Fig. 3) were made to further assess the sedimentology and stratigraphy. Within the Wadena-lobe till plain approximately 90 percent of the sediment is subglacially deposited till, and 10 percent of the sediment is sand of glaciofluvial or glaciolacustrine origin. The tills are sandy loam (mean of 11 samples: 62 percent sand, 34 percent silt, 4 percent clay) and are light olive brown (2.5Y 5/4) in color. Pebbles within the tills are dominantly igneous, metamorphic, and carbonate. The till is calcareous, slightly compact and contains abundant secondary carbonate.

Till Plain (Koochiching Lobe) (Kgtp)

The till plain of the Koochiching lobe is located to the northwest of the Itasca Moraine (Fig. 3); it is also characterized by undulating plains with low relief, although it is slightly less dissected than the Wadena-lobe till plain. Two channels, now occupied by Hier Creek and Bear Creek (Fig. 3), are entrenched within the till plain and interpreted as tunnel valleys. Sediments of the Koochiching-lobe till plain are classified on the basis of grain-size analysis on 13 samples, together with observations at 34 additional sites. Two deep soil-probe borings (B-2 and B-3, Fig. 3) were also made. This till plain is primarily composed of subglacially deposited sediments. The landform assemblage contains 80 percent subglacially deposited till and 20 percent glaciofluvial-glaciolacustrine sediments. The subglacially deposited till is composed of 51 percent sand, 43 percent silt, and 6 percent clay; it is light olive brown (2.5Y 5/4) in color. The till contains a considerable amount of Cretaceous shale clasts as well as abundant carbonate clasts; shale is the predominant clast type. In some locations, handfuls of shale can be picked or scooped from the till and outwash deposits. This till is more compact than the till of the Wadena-lobe till plain, but like sediments of the Wadena-lobe till plain, it also contains secondary carbonate.

Lacustrine sediments within the Koochiching-lobe till plain have a loam to loamy sand texture. The lacustrine sediments were only inspected to a depth of approximately 0.5 m because they occur within topographically lower portions of the till plain where exposures are rare. The lacustrine sediments are dark olive brown (2.5Y 4/4) in color and are noncalcareous.

Landform Assemblages of Supraglacial Origin

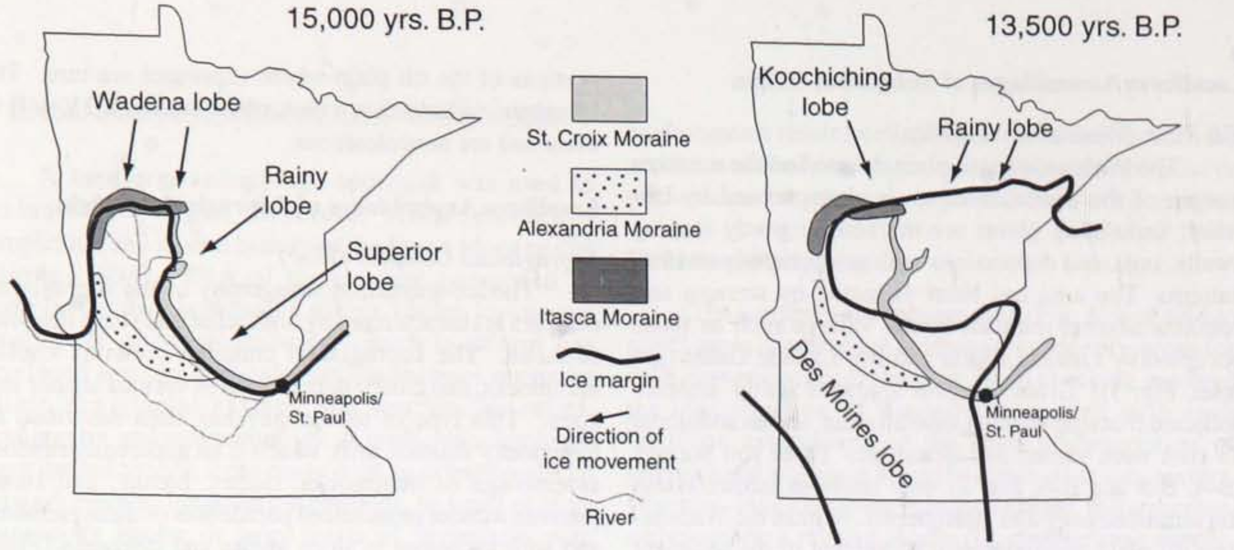
Supraglacial Complex (Wisc)

The ice-stagnation topography of the supraglacial complex is characterized by high relief and sharp irregular surfaces. The supraglacial complex contains knolls, hummocks, and closed depressions of various shapes and sizes. This type of topography has been described as hummocky ablation drift, which is an apparently random assemblage of hummocks, ridges, basins, and small plateaus without pronounced parallelism of these elements and with variations in slope angles and steepness (Flint, 1971). In the Itasca Moraine the supraglacial complex is cut by several large north-south trending channels interpreted as tunnel valleys (Wright, 1993), such as the one now occupied by Lake Itasca (see inset, Fig. 3). The supraglacial complex is structurally complicated, and stratigraphic continuity is very limited.

Deposits associated with the supraglacial complex are primarily composed of three sediment types. The most common sediment type within the landform assemblage (55 percent of the samples collected and analyzed for grain size) is a sandy loam till. Poorly to moderately sorted sand and gravel make up 40 percent of the assemblage, and lacustrine silt-loam accounts for about 5 percent of the samples collected and analyzed. These percentages are based on grain-size data for 85 samples (18 of which are from a study by Schulte, 1993). An additional 113 field observations, which include five shallow borings (B-1, B-8, B-9, B-10, and B-11, Fig. 3) were also made. The sandy loam till is light-olive brown (2.5Y 5/4) and rich in carbonate. The main clast types within the gravel fraction are igneous, metamorphic, and carbonate. Cretaceous shale clasts were not observed. This till is compositionally and texturally similar to that of the Wadena-lobe till plain, from which it is distinguished on the basis of its geomorphic expression and depositional environment. The sand and gravel component of these deposits is a result of fluvial deposition during moraine formation.

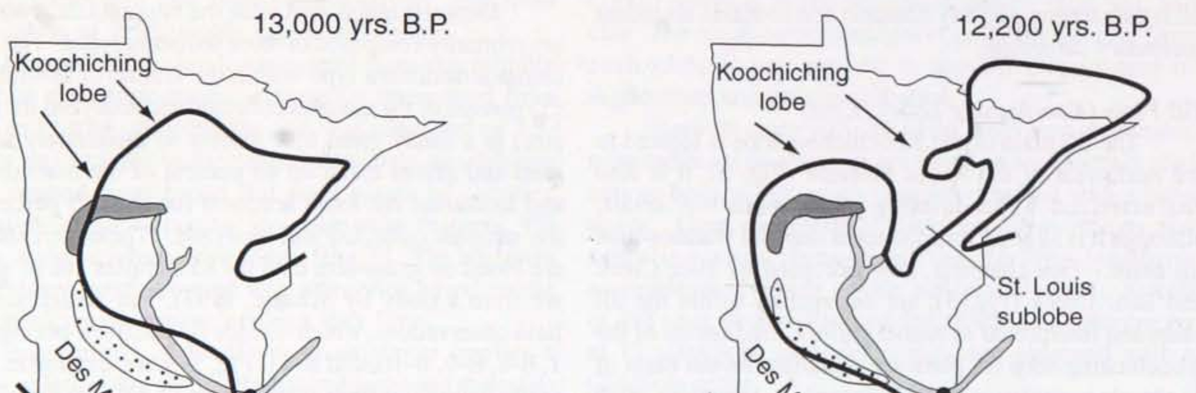
Collapsed Outwash (Wioc)

Areas of collapsed outwash are characterized by hummocky topography with frequent, relatively low relief, undulations and numerous closed depressions. This topography can best be described as low-relief mounds and shallow basins with gentle sideslopes. The material is weakly stratified; the stratification generally parallels the upper surface. The collapsed-outwash landform assemblage primarily occurs in the southern portion of the Itasca Moraine. Sediments within this assemblage



A. Advance of the Wadena lobe from the north was contemporaneous with advance of the Rainy and Superior lobes from the northeast approximately 15,500 years ago.

B. Wadena lobe remained at or near its terminal position as the Rainy and Superior lobes retreated to the northeast. Ice flow direction for ice terminating at the Itasca Moraine became more southeast-directed. At this point the northwest-sourced Des Moines lobe reached its maximum limit across south and central Minnesota.



C. Northward retreat (vs. stagnation) of Wadena-lobe ice as ice- flow direction became dominated by northwest-sourced, southeast-directed Koochiching-lobe ice.

D. Northwest-sourced, southeast-directed Koochiching-lobe ice extends across much of north and north-central Minnesota as the Des Moines lobe retreats.

Figure 4. Sequence of glacial events associated with the development of landform assemblages of the Itasca Moraine (Mooers, written communication, 1998). Dates are included for general reference only.

contain 85 percent sand and 15 percent sandy loam. Thirty-nine samples were collected and analyzed for grain size (23 of which are from Schulte, 1993); field observations were made at 15 additional sites. The sandy loam tills are poorly exposed; where they are exposed they represent portions of the stagnation complex that were not completely blanketed by the outwash that was deposited on top of stagnant ice after a slight recession of the ice margin. The outwash sand and gravel are often poorly sorted, reflecting their close proximity to their source. The collapsed outwash is distinguished from the adjacent outwash plains to the south on the basis of topographic expression.

Landform Assemblages of Proglacial Origin

Outwash Plain (Wiop)

Outwash plains are characterized by level, gently sloping surfaces with a few closed depressions. The outwash-plain sediments are moderately well sorted sands. Grain size analyses were completed for 19 samples (14 of which are from Schulte, 1993). The grain size of the sand shows an overall decrease away from former ice margins. Two geographically separate outwash plains are distinguished; the Osage outwash plain (Schulte, 1993) to the southwest, and the Park Rapids outwash plain (Norton, 1983) in the southeast (Fig. 1). Despite their geographic separation, these outwash plains are considered as a single landform assemblage.

Outwash Fan (Wiof)

An outwash fan is located south of the Itasca Moraine. It is characterized by an apron of low relief, the surface of which slopes gently to the south and contains numerous small depressions or closed basins. It was deposited at the terminus of a large esker, between the collapsed outwash of the supraglacial depositional environment and the outwash plain of the proglacial depositional environment to the south. Sediments in the outwash fan are moderately sorted sand with some gravel. Sixteen samples were collected for grain-size analysis (13 of which are from Schulte, 1993). The outwash fan bears stratigraphic and sedimentologic similarities to outwash plains, but is distinguished by its distinct fan shape and collapsed topography.

Outwash Channel (Wioch and Kgoch)

The outwash channels are defined on topographic maps as broad flat areas typically bounded by steep sides; the channels crosscut other landforms. The outwash channels result from glaciofluvial processes associated with melting ice. The outwash channels range from large or deep channels interpreted as subglacially carved tunnel valleys to flat-bottomed channels. A series of discontinuous valley-like features can be identified running north-south through the moraine, and are now occupied by a chain of lakes. Wright (1993) suggested these were tunnel valleys formed by subglacial meltwater. In many cases these valleys can be traced for up to 30 km from the subglacially deposited till plains through the morainic complex to the head of the outwash plain. Within the till plains, the channels often have broad flat bottoms, indicating they were occupied by subaerial streams. Most of the sediment within the channel deposits is well sorted sand and gravel. Till may be present in the middle or along the edge of the channels. The Wadena outwash channels (Wioch) can be distinguished from the Koochiching outwash channels (Kgoch) by the presence of shale clasts within the Koochiching outwash channels.

Lacustrine Sediment (Kgls)

The proglacial lacustrine sediment forms plains that occupy low portions of the till plain to the northeast of the Itasca Moraine. The sediments are predominantly moderately sorted medium to fine non-calcareous sand. The sand is occasionally interbedded with semi-calcareous silts. At one locality this lacustrine sediment is 2.7 m thick, and is underlain by till of the Wadena-lobe till plain (boring B-7, Fig. 3). Only the lower portion of the lacustrine sediment (below 0.75 m) in boring B-7 is calcareous. The upper portion of the lacustrine sediment (the top 0.75 m) is leached of calcareous material. The proglacial lacustrine sediments were deposited in a lake associated with the melting of the Koochiching lobe in the northeastern portion of the study area. The Koochiching-lobe meltwater ponded over the Wadena till plain between the Itasca Moraine and the retreating Koochiching lobe and deposited sands, silts, and clay.

INTERPRETATIONS

The traditional framework of glacial geology of the Itasca Moraine (Wright, 1957, 1962, 1972, 1993; Wright and Ruhe, 1965) has been modified to varying degrees by Sackreiter (1975), Harris (1975), Anderson (1976), Perkins (1977), Norton (1983), Goldstein (1986, 1989), Mooers (1988), and Gowan (1993). The development of the Late Wisconsinan geomorphic and sedimentologic features of the Itasca Moraine, and the sequence of events presented here (Fig. 4) are based in part on previous investigations as well as on the field studies of St. George (1994).

The advance of the Wadena lobe from the north was contemporaneous (Fig. 4A) with the advance of the Rainy and Superior lobes from the northeast during the Itasca / St. Croix phase (Wright, 1972; Wright and Ruhe, 1965) approximately 15,500 years ago (Clayton and Moran, 1982). Ice of the Wadena lobe may have persisted at the Itasca Moraine for a long time to account for the massive accumulation of drift (Wright, 1972). Evidence suggests (Fig. 4B) that the Rainy lobe retreated eastward from the St. Croix Moraine while the Wadena lobe remained at or near its position at the Itasca Moraine (Norton, 1983; Mooers 1988).

After the Wadena lobe retreated to its position at the Itasca Moraine, development of the moraine occurred in stages as the ice-flow center shifted to a northwest source. The heads of outwash of the Osage and Park Rapids outwash plains mark the maximum southern limit of the Wadena lobe during initial moraine formation. The presence of numerous tunnel valleys, which terminate at the heads of outwash (St. George, 1994; Wright, 1993) suggest that an integrated englacial and subglacial drainage system developed in the near marginal zone of the Wadena lobe. The southern extent of the Wadena- and Koochiching- lobe till plains marks the northern margin of the ice-stagnation complex.

The high central axis of the supraglacial complex apparently represents the area of maximum accumulation of debris on the glacier surface. As debris accumulated during retreat and stagnation, the active ice margin shifted northward. During this stage of formation, outwash draining from the ice surface was deposited over stagnant ice, and subsequent melting of the ice led to the formation of the collapsed-outwash landform assemblage. Evidence suggests that at this time there was a corresponding change in the nature of the englacial and subglacial drainage system. Several of the prominent tunnel valleys can be traced southward to the central axis of the moraine. At or slightly down-glacier from the moraine axis, these meltwater conduits flowed to the surface. Meltwater and sediment then flowed as surface streams over the stagnant ice in the proximal portion of the moraine to the Osage and Park Rapids outwash plains. One example of such a relationship is the tunnel valley now occupied by the western arm of Lake Itasca (Fig. 3). The tunnel valley can be traced from the Koochiching-lobe till plain into the supraglacial complex, along the western arm of Lake Itasca, and into the present basin of Elk Lake (Fig. 3). South of Elk Lake, a network of subaerial meltwater channels characterize the drainage system. It is likely that Elk Lake itself occupies the mouth of the channel.

Mooers (1988) suggested that the change in ice-flow direction from the north (south-flowing) Wadena lobe to the northwest (southeast-flowing) Koochiching lobe in the area of the Itasca Moraine was not punctuated by a retreat of the Wadena lobe. As the ice-flow center shifted and began to carry Cretaceous shale clasts from the west, the Rainy lobe began to retreat. The contemporaneity of these events allowed the Koochiching lobe to begin flowing toward the southeast and across the northern portion of the moraine (Figs. 4C and 4D). This conclusion is consistent with stratigraphic relations documented for the Itasca Moraine region (St. George, 1994). In the northern part of the Itasca moraine region, shale-bearing sediments that are representative of Koochiching-lobe deposits (origin from the northwest) overlie non-shale-bearing sediment that is representative of Wadena-lobe deposits (origin from the north). These two sedimentary packages are not separated by a sharp contact. In fact, there appears to be a gradational change from non-shale-bearing till to shale-bearing till (borings B-2 and B-3 in Fig. 3). If the Wadena lobe had retreated, one would expect the contact between these two tills to be sharper. One might even expect to see lacustrine or outwash deposits on the northern margin of the moraine, separating the two till units; these features were not observed within the Itasca moraine region. Meltwater and outwash from the Koochiching lobe reoccupied channels and tunnel valleys that formed during early phases of moraine development by the Wadena lobe. This relationship is inferred from abundant shale fragments in outwash sand and gravel, suggesting that ice flow from the northwest was occurring contemporaneously with moraine formation. Fragments of shale are also observed at the base of a sediment core taken from Elk Lake (Stark, 1976). In order for shale-bearing sediment to travel this far into the moraine these channels must have remained active while the Koochiching lobe was present north of the moraine. These relations suggest that within the Itasca moraine region, the Wadena lobe did not retreat prior to the advance of the Koochiching lobe, but that there was a shift in the ice-flow direction from south to southeast during the development of the Itasca Moraine (Fig. 4). This change in flow direction was contemporaneous with the retreat of the Rainy lobe, which allowed a conduit to open for further ice advance toward the southeast (Mooers, 1988). This reconstruction is consistent with interpretations presented by Dyke and Prest, 1987.

CONCLUSIONS

Based on the results of the detailed field studies of the Itasca moraine region (St. George, 1994), a modification to the accepted interpretation of the glacial history described by Wright (1972) is postulated. Wright (1972) states that ice of the Wadena lobe and St. Louis sublobe (Koochiching lobe) advanced separately; the Wadena Lobe advanced from the north, and retreated to its position at the Itasca Moraine approximately 20,000 years ago. He interprets the Wadena lobe to have then retreated and the St. Louis sublobe (Koochiching lobe) to have advanced from the northwest.

In this paper we suggest that the two events were not separated by a retreat. This interpretation is based on the gradational contact between the non-shale-bearing Wadena-lobe till and the overlying shale-bearing Koochiching-lobe till. Evidence for drainage channels within the moraine being occupied by meltwater from both ice lobes also supports this interpretation. The data indicate that there was a progressive shift in direction of ice-flow from a north-to-south direction during initial stages of the formation of the Itasca Moraine, to a northwest-to-southeast direction during the final stages of moraine and associated landform development (Fig. 4). Such a change would have caused a shift in the source of the deposits from the north to the northwest, which explains the change in sediment composition to include fragments of Cretaceous shale. This early phase of the Koochiching lobe has been termed the Guthrie phase (H.E.

Wright, Jr., oral communication 1992), based on exposures of shale-bearing Koochiching-lobe till overlying non-shale-bearing Wadena-lobe till near Guthrie, Minnesota.

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GLACIAL LAKE BENSON, WEST-CENTRAL MINNESOTA

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ABSTRACT

Glacial Lake Benson was a proglacial lake formed in the present Minnesota River valley during the Late Wisconsinan retreat of the Des Moines lobe (Diedrick and Rust, 1975). This study focuses on using the geomorphology and sedimentology of Glacial Lake Benson to determine lake geometry and history. A series of correlatable strandlines are mapped at an elevation 1075 ft, and an outlet channel (Chetamba Creek) has an elevation 1050 ft. Lake sediments, soil data, and varved clays indicate that a single large lake existed for at least four decades. Glacial Lake Benson drained southward when a proposed moraine dam in the area now occupied by the Minnesota River valley was breached. Subsequently, the Des Moines lobe retreated north of the Big Stone Moraine to form Glacial Lake Agassiz, which was later drained by Glacial River Warren.

GEOLOGIC SETTING

In west-central Minnesota the southeast-flowing Minnesota River occupies a bedrock lowland bordered to the northeast by the Alexandria Moraine and to the southwest by the plateau of the Coteau des Prairies. The bedrock lowland served as a conduit for the northwest-sourced Late Wisconsinan Des Moines lobe (Patterson, 1996). The axis of the Des Moines lobe coincided with the lowest portion of the bedrock valley. As the Des Moines lobe retreated, a series of proglacial lakes, collectively called Glacial Lake Minnesota (Ojakangas and Matsch, 1982), were created in the Minnesota River valley. One of these is Glacial Lake Benson (Figs. 1 and 2).

PREVIOUS WORK

Evidence for the presence of a glacial lake between Granite Falls and Ortonville in the Minnesota River valley was first recognized during soil surveys conducted by the Soil Conservation Service in Swift and Chippewa Counties (Diedrick and others, 1973). Analysis of the soils indicated that till was consistently present above 1050 ft, whereas well-sorted silts and clays were predominant below 1050 ft. Diedrick and Rust (1975) interpreted the fine-grained sediments (silts and clays) found at lower elevations as lacustrine. They also used the presence of deltaic sediments, and the contrast between hummocky topography and flat, low-lying topography to map the extent of a large lake with a surface area of about 1500 square miles; the lake had a shoreline elevation of 1050 ft, and was named Glacial Lake Benson. Hobbs and Goebel (1982) included Glacial Lake Benson on the Quaternary geologic map of Minnesota. Little additional work has since been done on the glacial-geologic history of Glacial Lake Benson.

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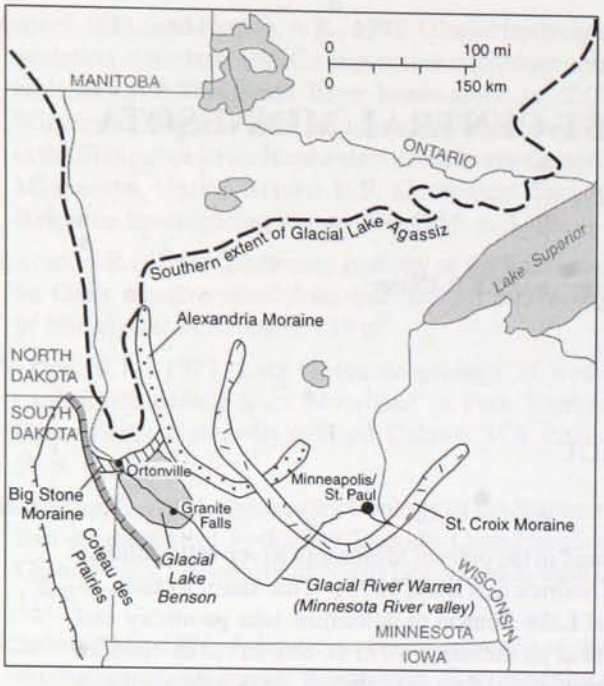

Figure 1. West-central Minnesota, showing locations discussed in text.

Diedrick and Rust (1975) suggested that Glacial Lake Benson began to fill after the Des Moines lobe had retreated northwest of Granite Falls. They indicated that the lake reached what they inferred to be its maximum size and level (1050 ft) when the Des Moines-lobe ice margin stabilized at the Big Stone Moraine to the north (Fig. 1). Glacial Lake Benson was fed by both meltwater and tributary flow from the southward draining Pomme de Terre and Chippewa Rivers, and many smaller streams. Diedrick and Rust (1975) interpreted the lake to have drained to the southeast down the Minnesota River valley when the moraine dam that blocked its spillway broke.

RESEARCH APPROACH

Beginning in the early 1980's, students and faculty of the University of Minnesota, Morris, started a detailed assessment of the glacial-geologic record of Glacial Lake Benson. The goal of this research was threefold: (1) to analyze sediments and landforms to interpret the depositional environments and history of the basin; (2) to determine the geometry and elevation of the lake or lakes; and (3) to determine whether the area of the Minnesota

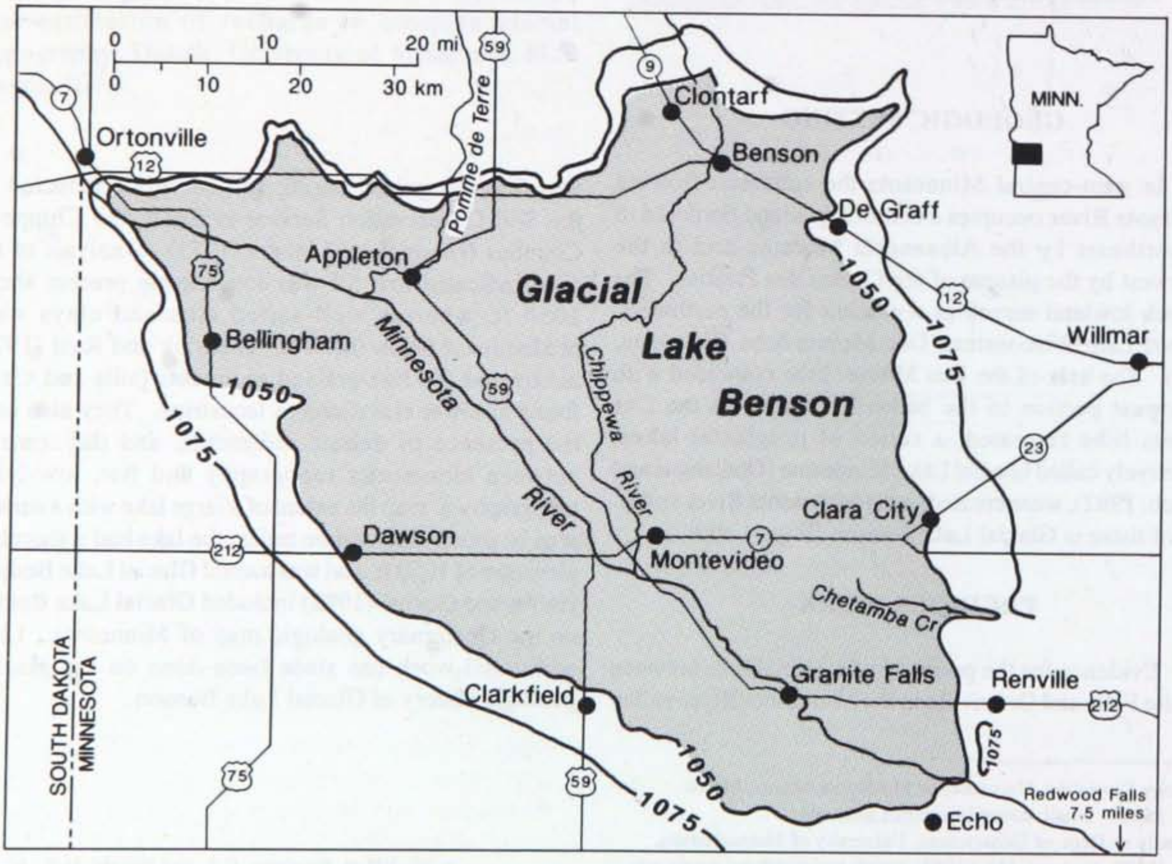

Figure 2. Location and geometry of Glacial Lake Benson. The areal extent of the lake shown here is based on the 1050-ft contour (after Diedrick and Rust, 1975), The position of the 1075-ft countour is also shown.

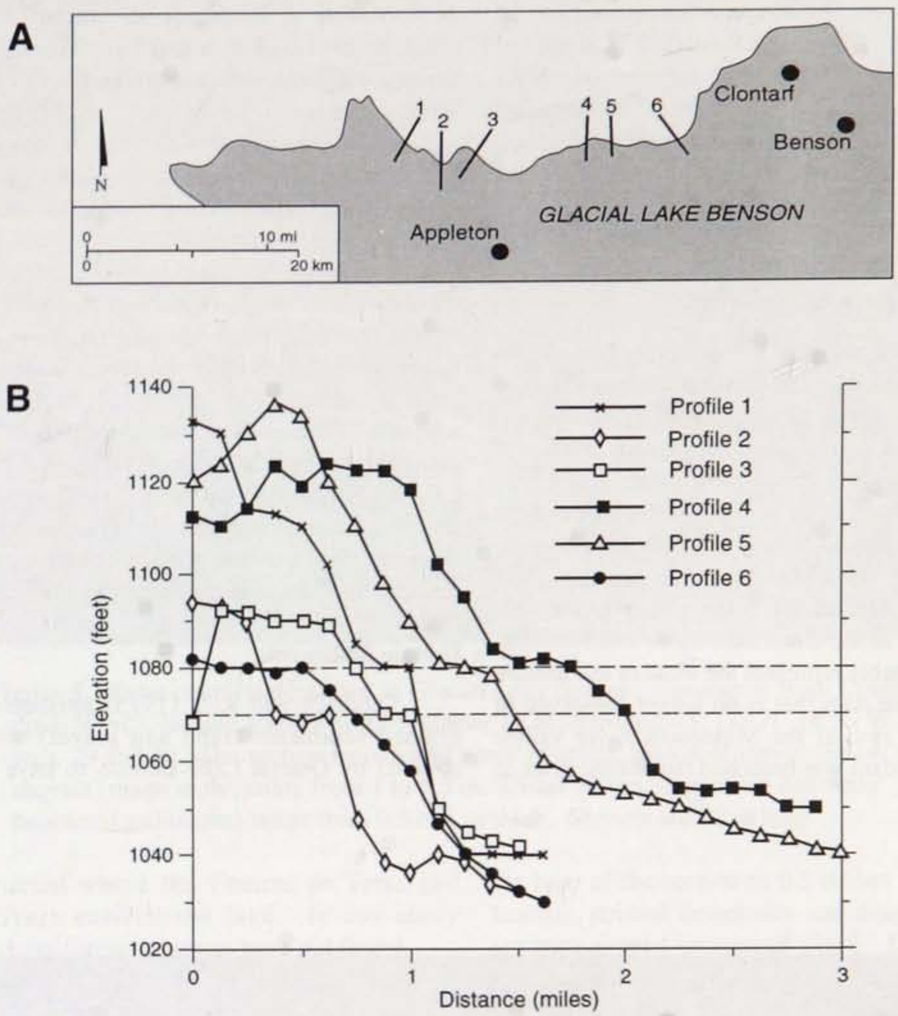

Figure 3. Topographic profiles for area mapped at the northern margin of Glacial Lake Benson. **A.** Northern margin of Glacial Lake Benson showing location of six profiles shown in (B). **B**. Profiles determined for six locations on the northern margin of Glacial Lake Benson A strandline is interpreted at approximately 1075 ft (based on a 10-ft contour interval).

River valley between Granite Falls and Ortonville was filled by a single, large glacial lake, or by a series of small short-lived proglacial lakes. Research methods included field mapping, use and interpretation of topographic maps and aerial photographs, outcrop studies and laboratory analysis of field samples.

The 1050-ft contour was initially plotted on a 1:100,000-scale map to delimit the shoreline of Glacial Lake Benson as interpreted by Diedrick and Rust (1975). The northern margin of the basin was studied in the field to determine if deltaic deposits were present where the Pomme de Terre and Chippewa Rivers enter the basin. Strandlines were mapped in the field, and sediments were analyzed to assist in determining the extent of the lake, and its depositional environments (Rittenour, 1994; 1995; Geiger, 1996). This work was further refined by detailed mapping at a scale of 1:24,000 (Rittenour, 1994; 1995), which resulted in a reevaluation of the strandline level.

RESULTS

Location and Elevation of Strand Lines

Strandlines, which are wave-cut benches marking former lake levels, are recognizable at the margins of the basin in which Glacial Lake Benson formed. Using 1:24000 scale topographic maps (which have a 10-ft contour interval) and aerial photographs, Rittenour (1994, 1995) mapped a well-defined strandline with an elevation between 1080 ft and 1070 ft in the northern portion of the basin (Swift and Big Stone Counties; Figs. 2 and 3). The 10-ft contour interval limits further resolution, so by convention we consider the lake level in this area to be 1075 ft. Although Diedrick and Rust (1975) suggested that the lake level was 1050 ft, their inferred lake level was based on soils maps. The 1075 ft strandline identified here (Figs. 2 and 3) roughly coincides with the mapped boundary of lacustrine and glacial soils (Diedrick and Rust; 1975) and is considered to represent lake level more accurately for the northern portion of the basin at least.

Location and Elevation of Spillways

Reconnaissance mapping indicates the channel now occupied by Chetamba Creek in northwestern Renville County (Figs. 1 and 2) was one of the Glacial Lake Benson spillways. The floor of the Chetamba Creek channel is 1050 ft above sea level. The 1050-ft contour probably approximates lake level in the southeastern portion of the basin. For the Chetamba Creek channel to have been an active spillway there must have been no topographic low where the current Minnesota River valley is located. Morainic remnants in the Clarkfield-Echo and Renville-Clara City area probably represent the western and eastern limbs of the moraine dam that is no longer preserved in the Echo-Renville area of the Minnesota River valley. When this moraine dam was breached (sometime prior to the formation of Glacial River Warren), the Chetamba Creek channel was abandoned and Glacial Lake Benson drained southeast down the area now occupied by the Minnesota River valley.

The difference between the proposed surface level of Glacial Lake Benson at the southeastern margin (spillway elevation: 1050 ft) and the northern margin (strandline elevation, 1075 ft) is not problematic. Placement of the lake level at the 1075-ft contour (Fig. 3) would extend the outlet of Glacial Lake Benson southeastward past Redwood Falls (Figs. 1 and 2). Additionally, a shoreline elevation change of 25 ft over a linear distance of 45 miles is readily explained by isostatic rebound. This rebound rate of 0.56 ft per mile is small compared to the 3.2 ft per mile rebound calculated for the Lake Agassiz basin. On the basis of basin floor drainage features, Diedrick and Rust (1975) suggested Glacial Lake Benson may have had additional spillways to the west and south. These spillways have not been identified.

Deltaic Sediments

Diedrick and Rust (1975) attributed the coarse-grained sediments (sand and gravel) within the area covered by Glacial Lake Benson to have originated as

Figure 4. Exposed varves in Swift County ditch 22 (branch 6, lateral 1 of County ditch no. 22, located 8 miles north-northeast of Montevideo - T. 118 N., R. 39 W., secs. 29 and 30). Culvert for scale; the ditch is approximately 12 ft deep.

Figure 5. Varve couplets deposited in Glacial Lake Benson; exposure is from County ditch No. 22, located 8 miles north-northeast of Montevideo - T. 118 N., R. 39 W., secs. 29 and 30. The section includes 44 varve couplets. Proximal varves (below the shovels) range in thickness from 1 to 5.5 in. Distal varves (uppermost distinctly laminated sediments) range from 0.5 to 1 in thick. Shovels are 20 in long.

deltas constructed where the Pomme de Terre and Chippewa Rivers entered the lake. In our study unequivocal topset-foreset contacts were not found.

Lacustrine Sediments

Diedrick and Rust (1975) mapped lacustrine silts and clays within the area covered by Glacial Lake Benson. More recently, interbedded silts and clays were described from the Bellingham area (Figs. 1 and 2) by Rittenour (1994, 1995), who interpreted them to have originated as a bottomset deltaic unit. Geiger (1996) examined a mile-long section exposed during excavation of Branch 6, Lateral 1 of County Ditch No. 22, located 8 miles north-northeast of Montevideo (T. 118 N., R. 39 W., secs. 29 and 30). She described a sequence of varved clays (Figs. 4 and 5), which she interpreted as lake sediments, that overlie a till unit. Assuming a lake-surface level of 1075 ft, and using the current elevation of the top of the varved clay unit, water depth in the lake would have been approximately 45 ft.

The varved sediments consist of pronounced laminae that form couplets representing annual deposition. The varves can be used to indicate the minimum length of time a sedimentary basin existed. Forty-four varves were counted and correlated from 3 sites across the exposure. Couplet thickness ranged from 5.5 inches near the base of the section to 0.5 inches at the top (Fig. 5). Locally, striated dropstones and diamict concentrations are over-draped by varved clays. During the 44-year history represented by this section increasingly thinner (more distal) summer layers are recorded, with fewer and fewer dropstones. These varves record the gradual northward retreat of the Des Moines lobe.

SUMMARY AND CONCLUSIONS

The geometry and sedimentology of Glacial Lake Benson was first described by Diedrick and Rust (1975), and has been documented in further detail in this paper. The lake had an areal extent of about $1{,}500^2$ mi, and an approximate maximum depth of 60 ft. Glacial Lake Benson existed for at least four decades. The dropstones and diamict concentrations within varved lake sediments indicate that a calving ice margin existed at the northwestern edge of the lake. The lake drained when a moraine dam at its southeastern boundary was breached, sometime prior to the formation of Glacial Lake Agassiz.

The interpretations and conclusions of Diedrick and Rust (1975) remain a solid departure point for recent studies of Glacial Lake Benson. Their results and those of this study indicate a single large lake occupied the Minnesota River lowland between Granite Falls and

Ortonville. Diedrick and Rust (1975) suggested that lake elevation was 1050 ft (on the basis of soil data), but we suggest a 1075 ft elevation in the northern portion of the basin (on the basis of strandlines). The difference appears inconsequential and may be explained by lake-sediment preservation and postglacial rebound. The varve section with dropstones exposed in County Ditch Number 22 provides strong evidence that Glacial Lake Benson was an ice-marginal lake of significant depth. The designation of a spillway (Chetamba Creek) and recognition of a southern moraine-complex dam (Clarkfield-Echo-Clara City) further clarifies the dynamics of the lake-outlet process.

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GEOLOGIC SETTING OF THE BUFFALO AQUIFER: A BURIED TUNNEL VALLEY OF THE RED RIVER LOBE

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ABSTRACT

The Buffalo aquifer was investigated as part of the Southern Red River Valley Regional Hydrogeologic Assessment (SRRV-RHA; Harris and others, 1995). The sediments forming the aquifer are exposed at the surface, but have little topographic expression on the low-relief Lake Agassiz plain. The Buffalo aquifer is a narrow body of sand and gravel 1000 ft to 2 mi wide, oriented north-south. It extends as much as 200 ft below the surface and is incised into sediments of Glacial Lake Agassiz and underlying glacial sediment as well as into the bedrock. A fan-shaped surficial deposit of sand and gravel is located at the southern extent of the Buffalo aquifer. Both channel and fan were partially buried by sediment deposited during a later phase of Glacial Lake Agassiz. Data from water wells, test wells, and a surface-resistivity survey were interpreted to develop detailed maps, cross sections, and computer images of the subsurface extent of the aquifer. The data show that the internal channel stratigraphy is complex, suggesting that it records more than one discharge event. The data also show that the base of the channel rises in elevation to the south, undulates vertically, and meanders horizontally. Sediments forming the Buffalo aquifer are interpreted to have been deposited in a tunnel valley that developed as basal meltwater discharged beneath the margin of the Red River lobe in the Red River valley during Late Wisconsinan deglaciation, recording the episodic southward discharge of water and sediment under great hydraulic pressure into a ice-marginal lake.

INTRODUCTION

Surficial geologic, airphoto, and lithostratigraphic mapping in the Red River valley (Fig. 1) have led to the identification of eight ice-margin positions for the Late Wisconsinan Red River lobe (Harris, 1987; Harris and Luther, 1991; Harris and others, 1995). Three of these ice margins extend across the Red River valley between Breckenridge, Minnesota and Grand Forks, North Dakota (Fig. 2). The ice-margin positions are interpreted to represent stable positions for the Red River lobe and are locally characterized by arcuate or linear areas of hummocky, high-relief morainic topography. Where this hummocky topography once extended across the Red River valley, it has been wave-washed (smoothed) and covered by lacustrine sediment so that it now forms very subtle, low-relief geomorphic features.

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Ice Margins and Aquifers

Lithostratigraphic boundaries associated with ice margins are coincident with discrete aquifers (the Buffalo and Hillsboro aquifers and unnamed large compaction ridges). The aquifers represent the deposits of subglacial streams that discharged meltwater at the ice margin. Compaction ridge (Bluemle, 1991) is a locally used term for a subtle ridge that indicates the probable location of coarse-grained fluvial sediment, mantled by fine-grained sediment. The fine-grained sediment has been compacted, whereas the coarse-grained sediment has not.

Moraines and Ice Margins

The best example of a wave-washed moraine is the Edinburg Moraine (Fig. 1, margin 1) which marks a stable position of the Red River lobe near Halstad, Minnesota

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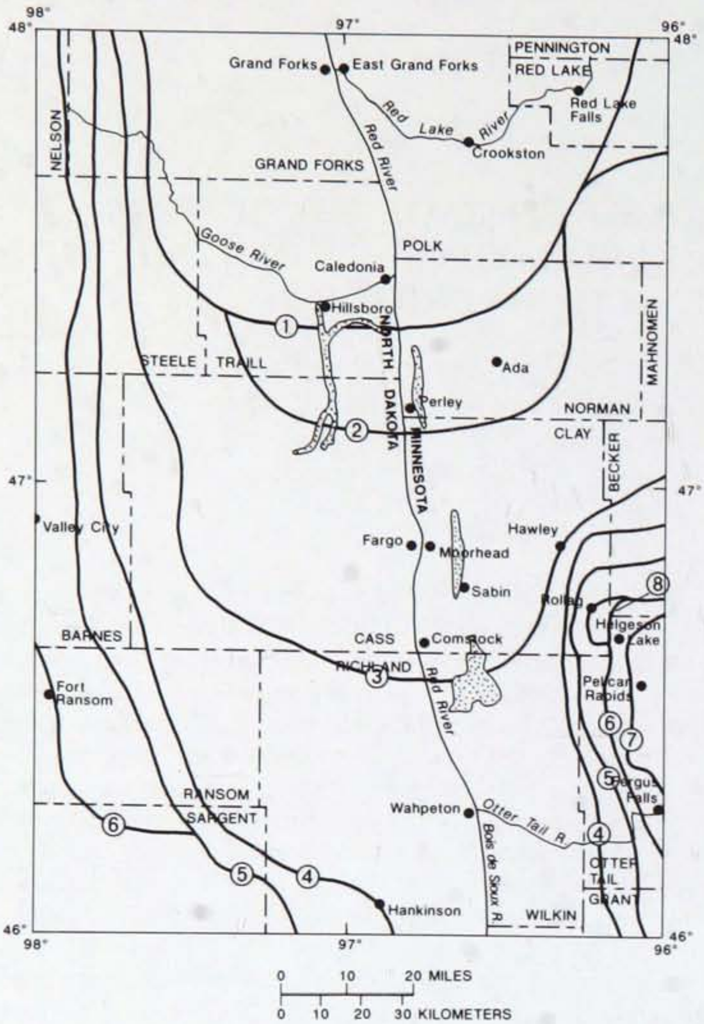

Figure 1. Southern Red River valley region showing ice-margin positions (numbered 1–8). Sands and gravels of the Buffalo aquifer and possible correlative deposits are shown in stippled pattern.

Table 1. Ice-margin positions and associated stratigraphic units and events (Modified from Harris and others, 1995).

Ice margin	Associated Group	Associated Formation*	Associated Ice Advance
1	Forest River group	Huot and Falconer Formations (RRV01 and RRV01)	Caledonia advance of the Red River lobe
2	Red Lake River group	Upper Red Lake Falls Formation (RRV03)	Perley advance of the Red River lobe
3	Red Lake River group	Lower Red Lake Falls Formation (RRV04)	Comstock advance of the Red River lobe
4	Goose River group	St. Hilaire Formation (RRV06 and RRV07)	Hankinson ice-margin position of the Red River lobe
5	Goose River group	Dahlen Formation and Heiberg till (RRV08 and RRV09)	Rollag ice-margin position of the Red River lobe
6	Lake Tewaukon group	Gardar Formation (RRV13 and RRV14)	Fort Ransom ice-margin position of the Red River lobe
7	Otter Tail River group	RRV10, RRV11 and RRV12	Pelican Rapids ice-margin position of the Rainy lobe
8	Crow Wing River group	Marcoux Formation (RRV15, RRV16 and RRV17) and RRV18	Helgeson Lake ice-margin position of the Rainy/Superior lobe

* Numbers prefixed by RRV correspond to till clusters identified as characteristic of the formation by Harris (this volume). Where a unit of formational status has not yet been identified, only the till cluster numbers are given. Some formations are represented by more than one till cluster number (Harris, this volume).

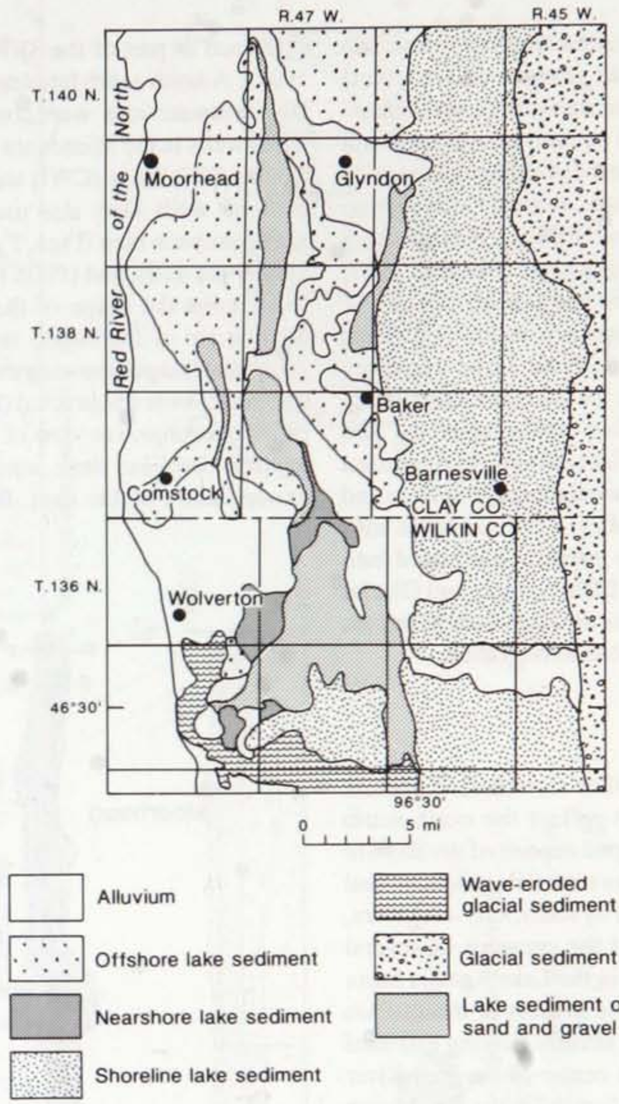

Figure 2. Surficial geologic map of the Buffalo aquifer region. For location, see Fig. 1. Modified from Harris and others (1995).

(Harris and others, 1974; Arndt, 1977; Clayton and Moran, 1982; Harris and Luther, 1991; Harris and others, 1995). The Edinburg Moraine marks the southern limit of the Huot and Falconer Formations in the Red River Valley (Fig. 1, Table 1 and Harris, this volume). It extends across the Lake Agassiz basin at the north end of the SRRV-RHA map area. The only indicator for the location of the moraine is the change in the character of the surface sediments, from clayey lacustrine sediment to clayey glacial till. There is no collapse topography marking the position of the moraine. Detailed field work and test borings were necessary to map the position of the Edinburg Moraine. West of the Lake Agassiz plain in Grand Forks and Walsh Counties of North Dakota, the Edinburg Moraine exhibits the collapse topography more characteristic of a lateral moraine.

Two other ice-margin positions were identified in the southern Red River valley. They extend across the valley near Perley in Norman County, Minnesota, and near Comstock in Clay County, Minnesota (Fig. 1, margins 2 and 3). These margins represent two stable ice-margin stillstand positions for the retreating Red River lobe and mark the southern boundaries of the Upper Red Lake Falls Formation (Perley ice-margin position) and the Lower Red Lake Falls Formation (Comstock ice-margin position). These ice margins are recognized on the basis of airphoto mapping; they are characterized by hummocky topography.

The Comstock ice-margin position is marked by glacial sediment of the Lower Red Lake Falls Formation in the lake plain and by the sands and gravels of the Buffalo aquifer. North of the Comstock ice margin the Buffalo aquifer forms an enlarged compaction ridge trending north-south. The Perley ice margin is less well documented; it extends east-west across the Lake Agassiz plain just south of an enlarged section of a north-south trending compaction ridge. The ridge is about 1 mi wide and 14 mi long. A similar feature, termed the Hillsboro aquifer, has been mapped in Traill County, North Dakota and extends south to the Perley ice margin (Bluemle, 1967; Clayton and others, 1980; Harris and Luther, 1991).

The lithostratigraphic sequence in the Red River valley indicates that the Red River Lobe retreated northward from the Comstock ice margin to the Perley ice margin. Each of the ice lobes that occupied the Red River valley during Late Wisconsinan deglaciation blocked the pre-existing northward drainage system and caused the flooding of the valley. The ice lobes also diverted pre-existing tributary streams southward into Glacial Lake Agassiz. Glacial Lake Agassiz and Glacial River Warren thus captured all the drainage from Manitoba and Saskatchewan east to the Red River valley.

Previous Work

Soil maps of Clay and Wilkin Counties, Minnesota (Nikiforoff and others, 1939) reflect the north-south channel and associated fan-shaped deposit of the Buffalo aquifer. Nikiforoff mapped these materials as loamy sand and fine sandy loam surrounded by loam, silty-clay loam, and clay. Winter (1967) noted the presence of several linear sand and gravel deposits in the Lake Agassiz basin and suggested that the sands and gravels of the Buffalo aquifer were deposited either by streams flowing eastward off a narrow lobe of ice in the center of the Red River Valley or by a river flowing in a "crack" in the ice. Moran and Clayton (1972) suggested that sands and gravels of the Buffalo aquifer were deposited by a river flowing across or under stagnant ice that separated two early stages of Glacial Lake Agassiz (Lake Climax and Lake Milnor). Arndt and Moran (1974) developed materials maps for land-use planning for Cass County, North Dakota and Clay County, Minnesota, and mapped the Buffalo aquifer as a composite unit including sand, clay and silt. Anderson (1976) mapped the Buffalo aquifer as fluvial sand and gravel. Perkins (1977) also mapped the Buffalo aquifer as fluvial sand and gravel and interpreted it to be a compaction ridge. Hobbs and Goebel (1982) show the Buffalo aquifer as Des Moines-lobe outwash on their Quaternary Geologic Map of Minnesota.

METHODS

The surficial geology of the Buffalo aquifer region (Fig. 2) was studied on aerial photographs and soil maps; samples collected from shallow borings were also examined as part of the SRRV-RHA (Harris and others, 1995). A north-south lithologic cross section and six east-west cross-sections were constructed with data from 272 water wells in the Minnesota Geological Survey's (MGS) County Well Index (CWI) and 60 USGS test wells. Logs of these wells were also used to construct a sand-and-gravel isopach map (Figs. 3 and 4). Data from the CWI, USGS test wells, and USGS resistivity surveys were used to examine the shape of the aquifer by estimating the distribution of the buried sand and gravel. Computer-generated images showing the distribution of buried sand and gravel were constructed (Figs. 5 and 6). These images provide an objective view of the geometry of the Buffalo aquifer. Because these images are based on computer extrapolation of the data, they do not show the exact

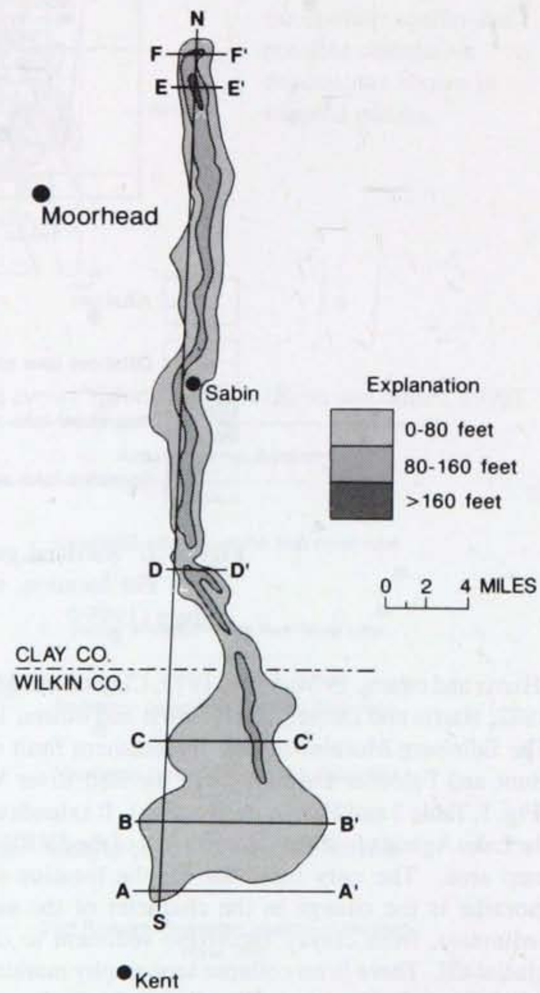

Figure 3. Isopach map of the Buffalo aquifer. Labeled lines show the approximate location of lithologic cross sections in Figure 4. Modified from Harris and others (1995).

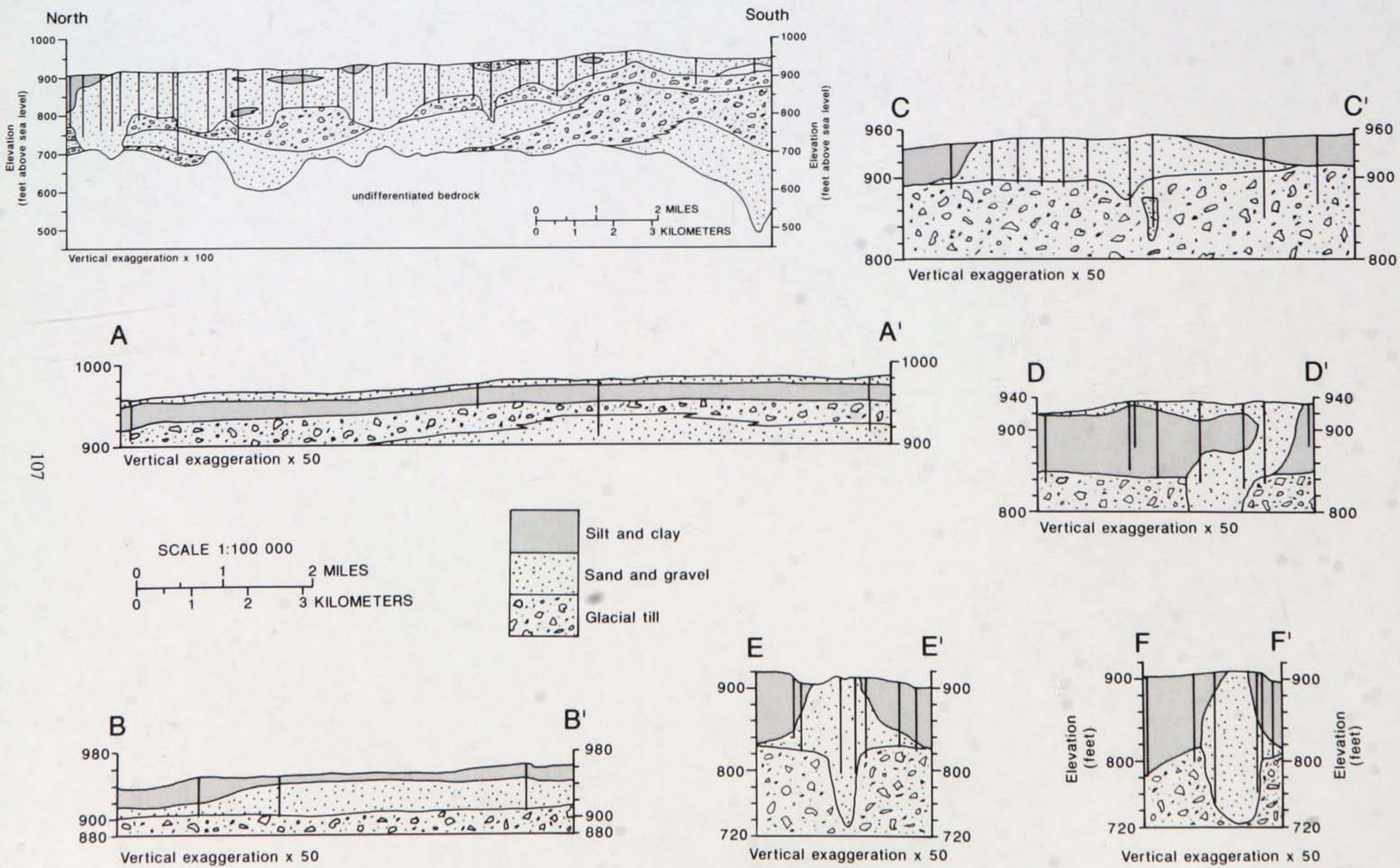

Figure 4 . Lithologic cross section of the Buffalo aquifer, based on water well records in MGS County Well Index. Location of cross sections is shown on Figure 3. Vertical lines indicate selected water-well records from the Minnesota Geological Survey County Well Index, as well as selected USGS test wells.

location of sands and gravels forming the aquifer, but they provide a qualitative look at the probable subsurface shape and extent of the aquifer.

RESULTS

The north-south orientation of the sand and gravel body forming the Buffalo aquifer, together with the fan shape of the sand and gravel unit at its southern end, are shown well on the surficial geology map of the region (Fig. 2). The sands and gravels of the aquifer form a subtle topographic high that is now mantled and surrounded by lacustrine and fluvio-glacial sediments.

At the northern extent of the Buffalo aquifer (Figs. 3 and 4, D–D', E–E' and F–F') the sands and gravels infill a channel that is incised into sediments (silts and clays) of Glacial Lake Agassiz as well as into the underlying glacial sediment. The lithologic cross-sections show the channel to vary in depth and width over its length. Stratigraphic relations suggest that the sands and gravels may represent several episodes of channel incision and infilling. In the southern portion of the Buffalo aquifer (Figs. 3 and 4, A–A', B–B', and C–C') the sand and gravel forms a nearsurface body 15–200 ft thick that is underlain by lake sediment and glacial till. Here, the sand and gravel body forming the Buffalo aquifer becomes thinner and wider to the south. The cross-sections show that sands and gravels of the Buffalo aquifer are generally present at the surface above the lacustrine sediments. The north-south lithologic cross section (Fig. 4) shows that the Buffalo aquifer consists of a complex mixture of sand and gravel, glacial till, and lacustrine sediment. The complex stratigraphy indicates multiple episodes of cut and fill; the sands and gravels of the channel fill generally rise in elevation and thin to the south.

The results of the modeling were stacked to produce a three-dimensional model (Fig. 5), which clearly shows a channel oriented north-south, with a fan marking its southern extent. Surface resistivity data were obtained for the Buffalo aquifer by the USGS (Zohdy and Bisdorf, 1979). Interpretations of the resistivity data (Zohdy, oral. commun. 1998) displayed a striking similarity to the airphoto geologic map (Fig. 2) developed of the Buffalo aquifer (Harris and others, 1995). We processed the resistivity data and determined a resistivity value that corresponded to the lithologic break between sand and gravel and till or clay (40 ohm-meters). Slice maps were then constructed from the resistivity data for a range of elevations, and the distribution of sand and gravel was displayed by stacking these maps (Fig. 6). They clearly show the subsurface extent of the Buffalo aquifer, the aggrading sand deposits in the fan, and the sinuous shape of the north-south channel.

DISCUSSION

The Buffalo aquifer is a deposit of sand and gravel incised into lacustrine sediments, glacial tills, and bedrock. Both the channel and fan sediments of the Buffalo aquifer are overlain by a veneer of lacustrine and fluvial overbank sediment.

The north-south cross section (Figs. 3 and 4) shows that the channel is actually a complex, multi-stage unit that rises to the south, recording multiple episodes of cut and fill. The presence of the sand and gravel fan suggests that the source of sediment was to the north, and that the sediment was transported by water and deposited on the floor of a lake as the discharged water lost its ability to transport the sand and gravel.

The three-dimensional geometry of the sand-and-gravel deposit forming the Buffalo Aquifer is shown in the computer-derived images (Figs. 5 and 6). The overall length of the channel and fan is 32 mi. The channel portion is about 24 mi long and rises in elevation toward the south. The channel portion clearly records cutting and filling at different elevations at different times. The maximum thickness of sand and gravel recorded from the available well data was 243 ft. The channel width ranges from a quarter of a mile to about 2 mi wide. All but the highest parts of the compaction ridge are overlain by thin lacustrine and fluvial overbank sediments. The fan measures about 8 miles from north to south and about 7 mi in width (east to west). It is a shallow, relatively thin, sand and gravel deposit that is veneered with lake and river overbank sediment, like the channel portion. The sand and gravel forming the Buffalo Aquifer is oriented north-south, perpendicular to and astride the Comstock ice margin position (Fig. 1). The channel portion of the feature extends north of the Comstock ice margin, and the fan extends south of that ice margin.

The sand and gravel deposits of the Buffalo aquifer are interpreted to be part of the Lower Red Lake Falls Formation (Table 1; Harris and others, 1995). The sands and gravels were deposited beneath and in front of the ice lobe associated with deposition of the Lower Red Lake Falls Formation while it stood at the Comstock ice margin position. The Comstock ice margin does not mark the maximum extent of this advance, but rather it seems to mark a stable ice position that generally corresponds to the extent of Lower Red Lake Falls glacial sediment (Harris and others, 1995). Sands and gravels of the Buffalo aquifer fill a channel that is incised into pre-Wisconsinan glacial sediment and Cretaceous bedrock.

The Perley ice margin to the north (Fig. 1) marks a younger stable ice margin for the Red River lobe as it deposited the till of the Upper Red Lake Falls Formation, which overlies the Lower Red Lake Falls Formation. The only sediment that would have been deposited on the

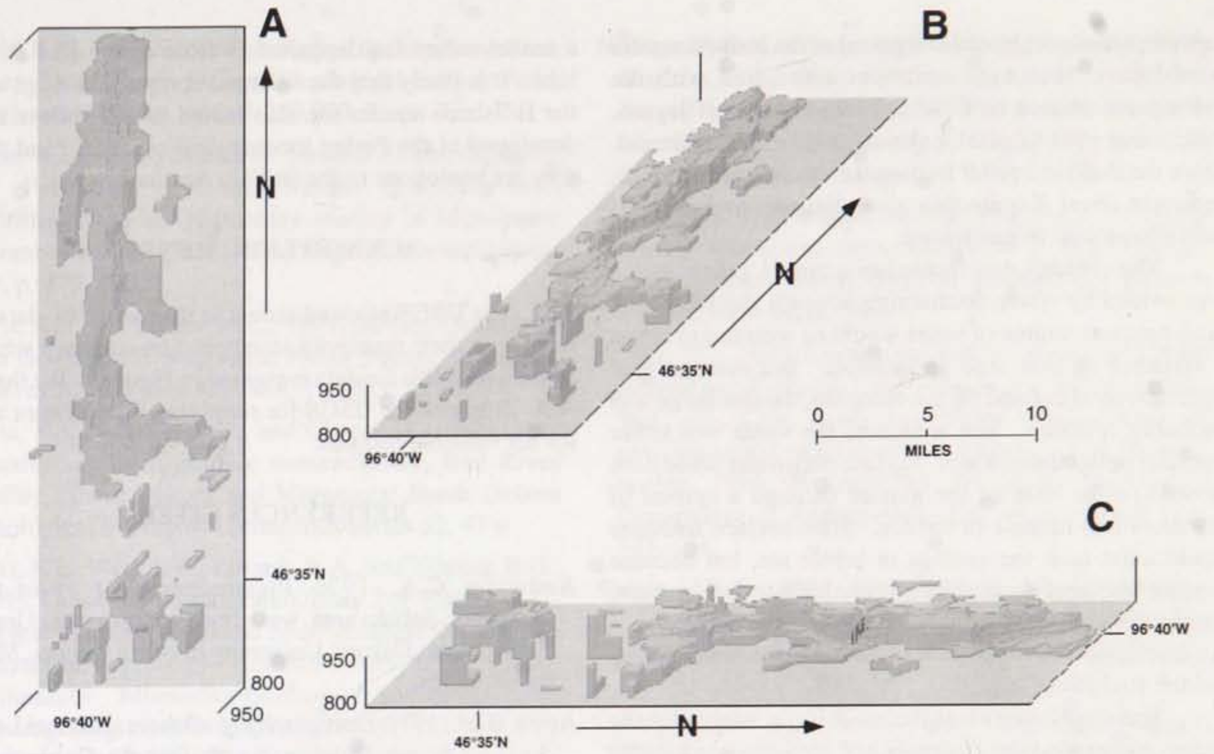

Figure 5. Computer-derived 3D images of the occurrence of sand and gravel in the Buffalo aquifer. Images based on water well records in MGS CWI. **(A)** birdseye view looking towards the north-northeast. **(B)** viewed from the southeast. **(C)** viewed from the east. From Harris and others (1995).

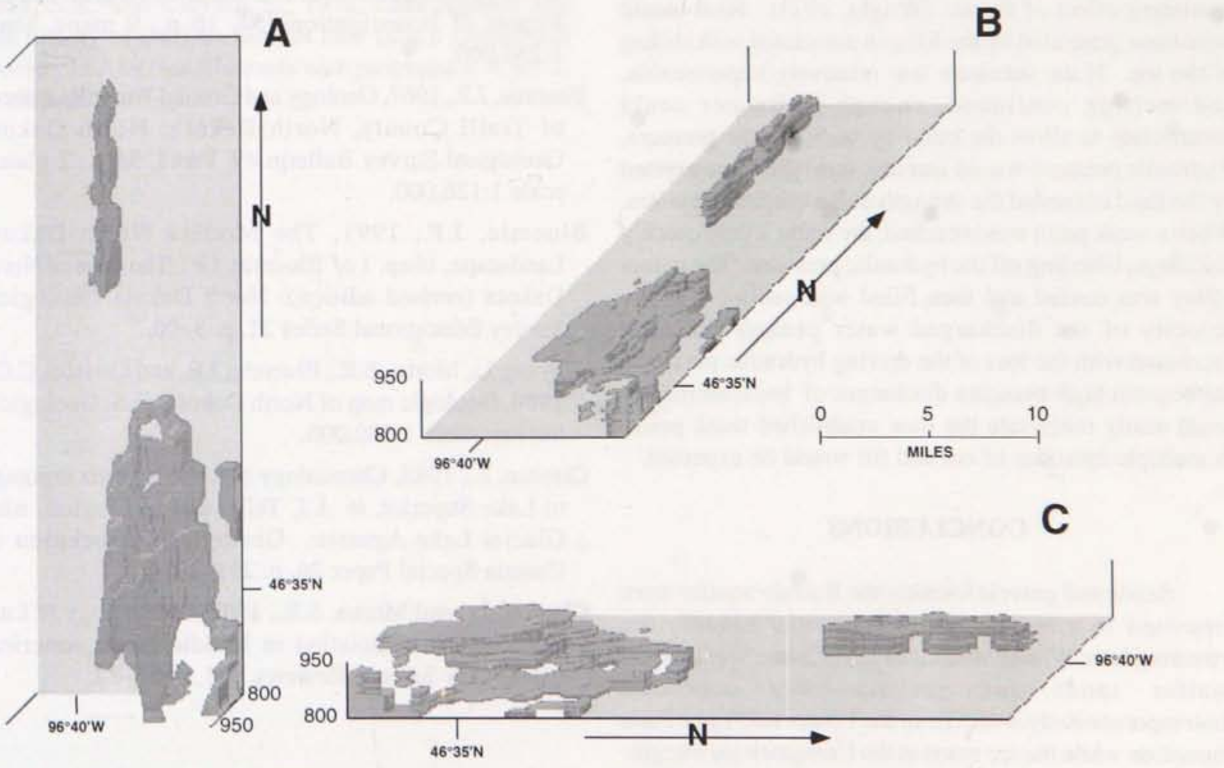

Figure 6. Computer-derived 3D images of the occurrence of sand and gravel in the Buffalo aquifer. Images based on USGS surficial resistivity surveys (Zohdy and Bisdorf, 1979). **(A)** birdseye view looking towards the north-northeast. **(B)** viewed from the southeast. **(C)** viewed from the east. From Harris and others (1995).

topographically high sand and gravel of the Buffalo aquifer would have been lake sediment associated with the subsequent phases of Glacial Lake Agassiz (Clayton, 1983) and post-Glacial Lake Agassiz river sediment. Since the Buffalo aquifer forms a subtle compaction ridge, sediment cover is quite thin along the axis and thickens laterally as well as northward.

The channel was formed as a tunnel valley, which was eroded by water discharging beneath glacial ice. A high-pressure source of water would be required to incise a channel of this size and shape. Because several generations of cut and fill are recorded, the discharge was probably episodic. The source of the water was either surficial or basal meltwater. Surface meltwater could have flowed to the base of the glacier through a system of fractures and tunnels in the ice. Such surface fractures could exist near the surface in brittle ice, but because surface fractures do not extend very far into deeper, more plastic ice it is unlikely that surface meltwater is the source for discharge beneath an active ice margin such as inferred for the Red River lobe.

Basal meltwater was the most likely source for the water that eroded the channels and then transported and deposited the sands and gravels that now constitute the Buffalo aquifer. Basal meltwater would have collected between the base of the ice and the relatively impermeable substrate (clay) due to terrestrial heat flow and the insulating effect of the ice (Wright, 1973). Heat would have been generated by the friction associated with sliding of the ice. If the substrate was relatively impermeable, and melting continued, enough meltwater could accumulate to allow the build up of hydraulic pressure. Hydraulic pressure would increase until the force exerted by the fluid exceeded the strength of the confining system. When a weak point was breached, the water would quickly discharge, bleeding off the hydraulic pressure. The tunnel valley was eroded and then filled with sediment as the velocity of the discharged water peaked and then decreased with the loss of the driving hydraulic pressure. Subsequent high-pressure discharges of basal meltwater could easily reactivate the now established weak point, so multiple episodes of cut and fill would be expected.

CONCLUSIONS

Sands and gravels forming the Buffalo aquifer were deposited in a tunnel valley excavated beneath the retreating Late Wisconsinan Red River lobe. The Buffalo aquifer sands and gravels were deposited contemporaneously with tills of the Lower Red Lake Falls Formation while the ice stood at the Comstock ice margin. The shallow, broad sand and gravel deposit to the south is a tunnel-valley fan deposited in front of the Red River lobe. It is likely that the enlarged compaction ridge and the Hillsboro aquifer are also buried tunnel valleys that developed at the Perley ice-marginal position, and that they are analogous to the Buffalo aquifer.

ACKNOWLEDGMENTS

The USGS allowed access to the resistivity data as well as to their resistivity interpretation software which formed the basis for data presented in Figure 6. We thank A.A. Zohdy of the USGS for supplying the software and for his valuable insights.

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EVIDENCE FOR EARLY ENTRENCHMENT OF THE UPPER MISSISSIPPI VALLEY

Robert W. Baker[1], James C. Knox[2], R.S. Lively[3] and Bruce M. Olsen[4]

ABSTRACT

The age of the earliest dissection of 150–200 m-deep valleys in the upper Mississippi watershed has been extensively debated. Interpretations regarding the age of deep bedrock dissection of the upper Mississippi watershed range from pre-Pleistocene to Late Wisconsinan. Uranium-series dates from speleothems in Paleozoic rocks and calcite cements in glacially derived sands and gravels in southeastern Minnesota indicate that an established fluvio-karst system drained toward the present course of the Mississippi River prior to 350 ka.

Valley incision prior to 350 ka is also interpreted from studies of glaciolacustrine sediments preserved within tributary valleys of the Mississippi in west-central Wisconsin. The glaciolacustrine sediments record a reverse-to-normal geomagnetic polarity transition, indicating that the tributary valleys were entrenched, and that sediment deposition had commenced prior to 790 ka. Additional geomorphic and paleomagnetic evidence from alluvial sediments in the lower Wisconsin River drainage shows that deep valleys were present there prior to 790 ka; these valleys were tributaries to the Mississippi River valley.

INTRODUCTION

For more than a century the causes and timing of deep entrenchment of the upper Mississippi River valley and its tributaries have been debated by scientists studying the Quaternary in the Upper Midwest (Fig. 1). Much of the early disagreement was due to the poor quality of stratigraphic information, combined with the fact that the bedrock surface is covered by a hundred meters or more of glacial sediment not readily datable by existing techniques. This paper (1) summarizes the results of recent investigations that provide new data, and (2) uses the data to show that major bedrock incision of the upper Mississippi River valley and its adjacent tributaries may have occurred in preglacial time (prior to 2.1 Ma), and certainly by the Early Pleistocene (790 ka).

PREVIOUS WORK

Without the benefit of suitable dating techniques, most early investigators believed that entrenchment of the upper Mississippi River valley into Paleozoic bedrock occurred prior to Pleistocene glaciation of the Upper Midwest. In the early 1900's Pleistocene glaciation was considered to have started about 1.5 million years ago. The early investigators reasoned that erosion of valleys as much as 200 meters below upland divides required extensive geologic time. Early investigators who supported preglacial entrenchment were Chamberlin and Salisbury (1885), McGee (1891), Trowbridge and Shaw (1916), Alden (1918), and Leverett (1921). Horberg (1945) appears to have been one of the few who continued to hold this opinion after the 1920's.

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Figure 1. Location of the upper Mississippi River valley between St. Paul, Minnesota and Dubuque, Iowa.

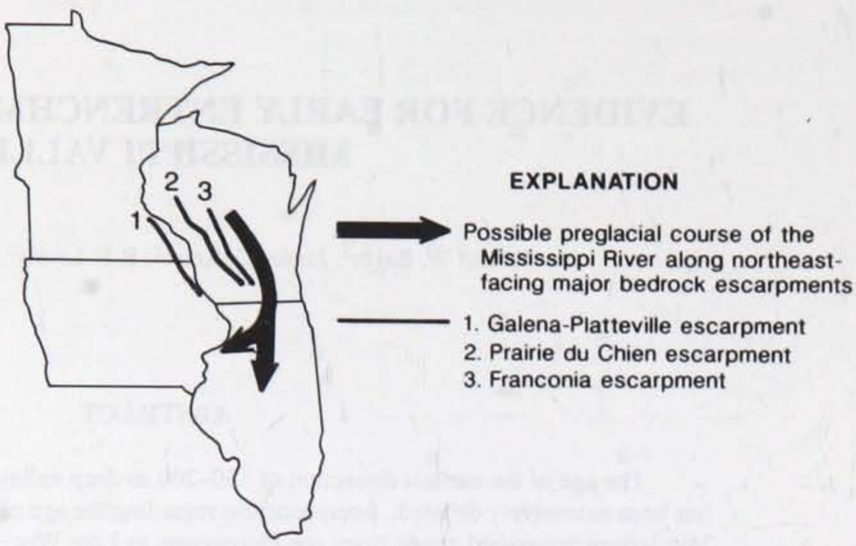

Figure 2. Possible preglacial course of the Mississippi River (shown by arrows). After Anderson (1988).

Although Trowbridge initially favored preglacial entrenchment, later field research in northeastern Iowa and southwestern Wisconsin led him to conclude that deep incision probably occurred during the early Pleistocene (Trowbridge, 1921, 1935, 1954, 1959, 1966). Additional support for early Pleistocene entrenchment was presented by Willman and Frye (1969, 1970). They identified high-level proglacial outwash gravel on the tops of bluffs in northwestern Illinois and concluded that the position of the present Mississippi River in northwestern Illinois and southwestern Wisconsin resulted from displacement of the river course by an Early Pleistocene ice front that had advanced from west to east. They suggested that the pre-Pleistocene landscape of the region was a low-relief Tertiary erosion surface without the Mississippi River drainage as seen today. They reasserted this interpretation several years later (Willman and others, 1989) proposing that (1) a northward drainage pattern characterized this area prior to the invasion of Early Pleistocene ice, and (2) a lake formed between the ice front and the Silurian escarpment to its south. Prior to 790 ka this lake overflowed and cut the present Mississippi River channel to a depth of about 150–180 meters.

Pleistocene ice advances undoubtedly influenced some characteristics of the upper Mississippi River drainage (Wright, 1985). Anderson (1988) speculated that the preglacial drainage in northeastern Iowa and southwestern Wisconsin may have been toward a master stream that flowed southeast along the north side of the Franconia and Prairie du Chien escarpments (Fig. 2). He suggested that the present course of the Mississippi River in this region resulted when a glacial forebulge in west-central Wisconsin diverted meltwater southward between the ice front and the uplifted low-relief preglacial land surface to the east.

A significantly younger age for deep valley incision has been suggested by Hallberg and Bettis (1985a, 1985b) and Hudak (1987) on the basis of field research in northeastern Iowa. Using valley-fill stratigraphy and relations between karst features, isotopic ages, and incised-drainage systems, Hallberg and Bettis (1985b, p. 40) suggested that "...the Mississippi River and its tributaries evolved within the middle Pleistocene, probably after the last glaciation to cover northeastern Iowa about 500,000 years ago . . . major stream incision probably began about 160,000 years ago . . . the major period of valley downcutting was in the Wisconsinan, and formed prominent bedrock-cored cutoff meanders...."

Although the suggestions of Hallberg and Bettis (1985b) are at odds with pre-Pleistocene or Early Pleistocene deep entrenchment of the upper Mississippi valley, it is possible that the record of bedrock dissection in northeastern Iowa may be an example of localized downcutting. Hallberg and Bettis (1985b) argued that significant downcutting did not occur until after the penultimate retreat of glacial ice from northeastern Iowa. We suggest that the entrenchment observed in northeastern Iowa may represent an adjustment of drainages on a previously protected upland surface to a preexisting Mississippi River valley that was entrenched prior to 500,000 years ago.

EVIDENCE FOR EARLY ENTRENCHMENT

Background

Bedrock mapping, stratigraphic relations, paleomagnetic dating of valley sediments from Wisconsin and Minnesota, and uranium-series dating of speleothems (calcite deposits formed by water dripping into caves) form the basis for the following discussion. Field investigations in west-central Wisconsin (Baker and others, 1983) have not provided direct evidence for any drainage system other than the southward-directed Mississippi Valley drainage system. General principles indicate that valley entrenchment must be older than the fill contained within a bedrock valley, and that tributaries drain into larger valleys. Mapping by Knox (Knox, 1982; Knox and Attig, 1988) in the Wisconsin River valley and nearby Mississippi River tributaries in extreme southwestern Wisconsin shows that (1) proglacial sediments drape from high on the western valley walls down into the adjacent major southward-flowing tributary drainages, and (2) these same proglacial sediments do not extend to the uplands and major interstream divides located on the eastern sides of the southward-flowing tributary drainages. These relations indicate that the tributary valley systems that drain into the present Mississippi River valley existed prior to the deposition of the high-level proglacial gravels.

Buried Valleys

Subsurface data in southern Minnesota, obtained primarily from water well and geophysical logs, indicate that the bedrock is cut by pre-Quaternary and even pre-Cretaceous valleys, and that the surface and subsurface drainage have been further modified by glaciation during the Pleistocene. In western Minnesota some valley systems appear to have drained westward into the Dakotas (Setterholm, 1990). Maps of bedrock topography suggest that most valleys in south-central and southeastern Minnesota drained toward the Twin Cities lowland and then south (Olsen and Mossler, 1982; Mossler, 1983; Jirsa and others, 1986; Swanson and Meyer, 1990). The bedrock topography does not indicate significant northward drainage. Furthermore, a pre-Quaternary bedrock surface sloping south-southeast and associated southward drainage is indicated by data recently obtained from Stearns County in central Minnesota (Setterholm and Cleland, 1995). A southward-sloping bedrock valley on the east side of Stearns County underlies the present Mississippi valley and appears to have drained a pre-Cretaceous basin. Data are not yet sufficient to indicate whether it connects with the entrenched Mississippi valley to the south, or whether it turns toward the west and the Cretaceous seaway. Buried valleys of unknown age on the western side of the Paleozoic plateau in southeastern Minnesota appear to have drained northeast to the Twin Cities lowland as tributaries to a major valley at the location of the modern entrenched Mississippi River valley, suggesting that an integrated drainage system existed prior to their burial (Olsen, 1985). In southern Minnesota some valleys contain over 180 meters of pre-Illinoian (and possibly Illinoian) till. Equilibrium uranium-series dates for calcite cements within gravels of a now-exposed buried valley segment in southeast Minnesota indicate that in that locality the Mississippi valley was entrenched prior to at least 350 ka (Lively and Olsen, 1986). Together, these data and the orientations of buried valleys in Paleozoic and older rocks in Minnesota and Wisconsin show that (1) active drainages were routed eventually into the Mississippi valley and then southward and (2) no evidence exists in the upper reaches of the Mississippi valley for the former northward drainage system suggested by Willman and others (1989).

Some cutoffs of bedrock-cored valley meanders developed during Wisconsinan time (Hallberg and Bettis, 1985b), while others appear to have formed earlier (Knox, 1982). At Boice Creek in southwest Wisconsin (Fig. 3), fill in a cut-off valley meander includes the Wisconsinan Peoria Silt and Roxana Silt, which overlie a strongly developed Sangamonian geosol in the surface horizon of the Loveland Silt (Knox and Leigh, 1990; Leigh and Knox, 1994). The Loveland Silt overlies lacustrine clays that are marked at the top by a strongly weathered geosol 2.2 m thick (Knox and Leigh, 1990). A radiocarbon date on charcoal in the middle of the Roxana silt provides an age of 36,900 ± 1200 yrs B.P. (AA5421) (Fig. 3). The age for the basal meander fill is unknown, but the radiocarbon-dated horizon in the Roxana silt is about 18 m meters above the bedrock floor of the cutoff-valley meander and about 70 m below the elevation of the adjacent upland divide. The presence of both the Sangamonian geosol in the Loveland silt below the dated horizon and the strongly weathered geosol at the top of the pre-Loveland lacustrine unit suggests that the Boice Creek incised-valley meander has considerable antiquity.

Uranium-Series Dating of Secondary Carbonate Precipitates

Paleozoic limestone and dolostone throughout the upper Mississippi River valley have been extensively weathered by solution to form a karst landscape for several hundred kilometers along both sides of the Mississippi River (Lively and Alexander, 1985). The isotopic ages of speleothems within the karst system, together with the vertical and horizontal distance of the speleothems relative to the valley floor, can be used to estimate both the minimum age and the amount of valley incision.

Valley incision within the Mississippi River valley watershed is the major factor in the lowering of the regional water table (Lively and Alexander, 1985). As the water table is lowered, solution cavities in carbonate rocks near or immediately below it are abandoned, and new solution cavities develop lower in the section. Some of the abandoned solution cavities in the Prairie du Chien dolostone are now located as much as 100 m above the present water table (Lively and Olsen, 1986). Dated periods of speleothem growth associated with karst development indicate that the fluvio-karst drainage system in southeastern Minnesota was established prior to the 350-ka limit of the dating method (Lively, 1990; Lively, 1984; Lively and Olsen, 1986).

Paleomagnetic Dating

In central Wisconsin pre-Illinoian ice extended eastward across the Mississippi River valley from Minnesota and blocked the drainage of a number of tributaries to the Mississippi River (Baker and others, 1987). As the ice retreated westward from its maximum position, the resulting lakes lengthened and formed an interconnected network of channels that covered over 6000 km² (Baker and others, 1983). More than 150 m of thinly laminated glaciolacustrine sediments (the Kinnickinnic Member of the Pierce Formation) accumulated in these lakes. Paleomagnetic analyses of these sediments indicate that their deposition spanned a transition from reversed to normal polarity (Baker and

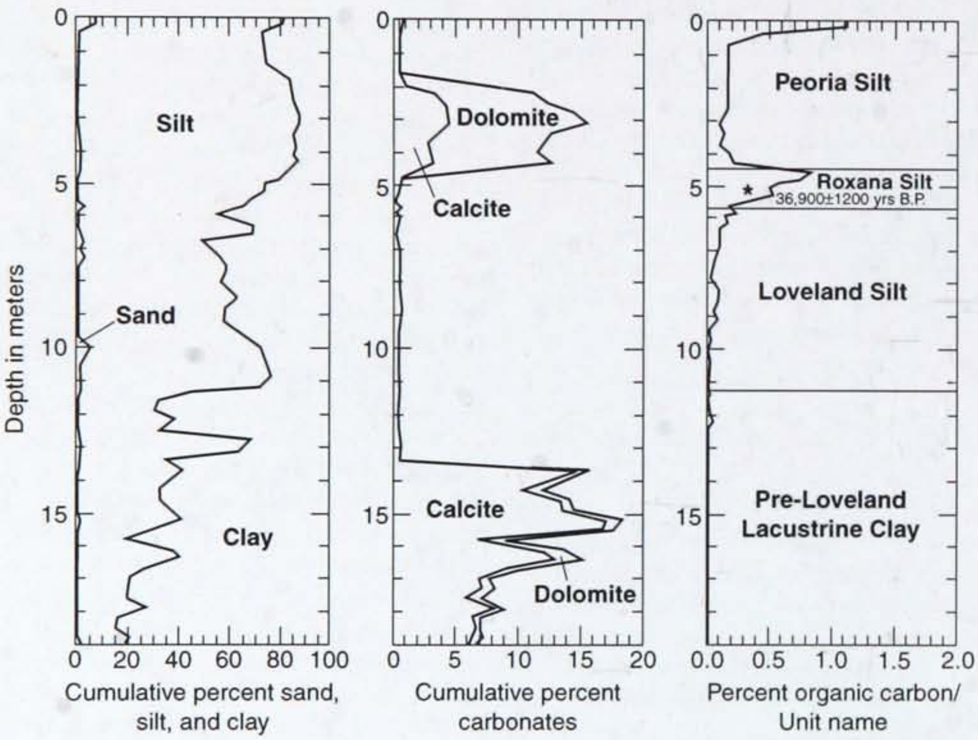

Figure 3. Stratigraphic relations between depositional units observed at Boice Creek, Wisconsin, located about 4.5 km east of the Mississippi River in Grant County, southwestern Wisconsin (after Knox and Leigh, 1990). The Boice Creek site is a cutoff-valley meander that is of pre-Illinoian age. The silt deposits include both *in situ* loess and colluvial silt derived from the Peoria, Roxana, and Loveland loess units. The antiquity of the cutoff-valley meander is illustrated by the presence of a well-developed Sangamonian geosol at the top of the Loveland unit and the presence of another well-developed geosol associated with carbonate leaching from the top 220 cm of the pre-Loveland lacustrine clay unit. The pre-Loveland unit is presumed to be younger than 790,000 yrs B.P., on the basis of normal remanent magnetization of sediments. However, correlation of its clay mineralogy with clay mineralogy of known pre-Illinoian deposits elsewhere in the region indicates at least a pre-Illinoian age. Offset drilling on the margins of the cutoff-valley meander indicates that the bedrock floor is located at a depth of about 23 m below the present ground surface.

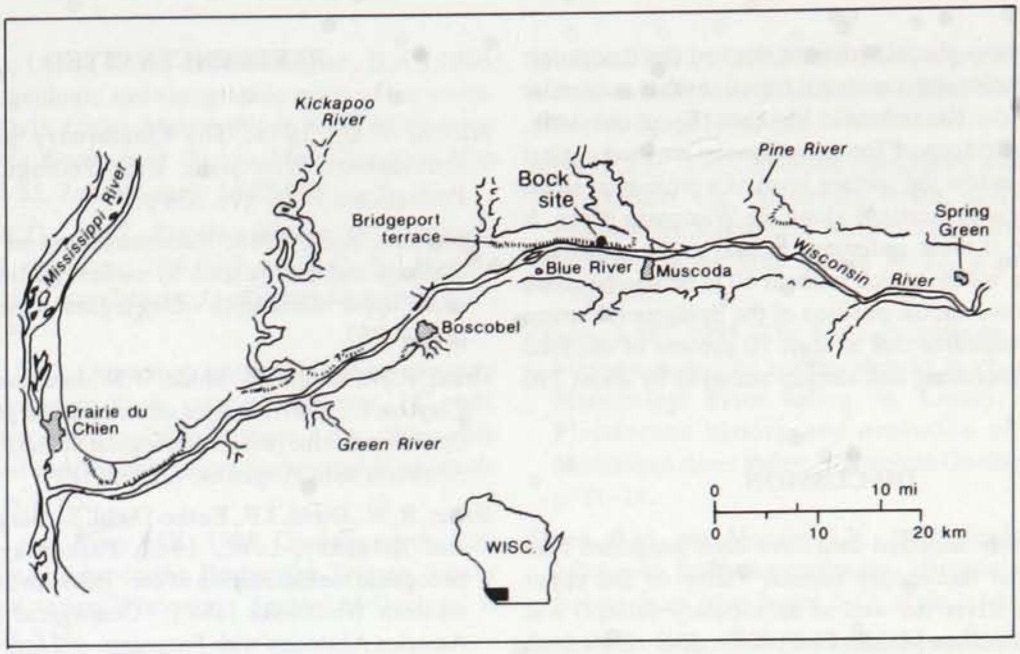

Figure 4. Location of the Bock site, Bridgeport terrace, lower Wisconsin River valley, Wisconsin. Proglacial silt associated with outwash entering the Wisconsin River valley from the west is associated with remnant magnetization having reversed polarity, suggesting that the valley was already deeply incised by at least 790 ka, because the terrace sediments lie between 125-150 meters below adjacent upland divides. After Knox and Attig (1988).

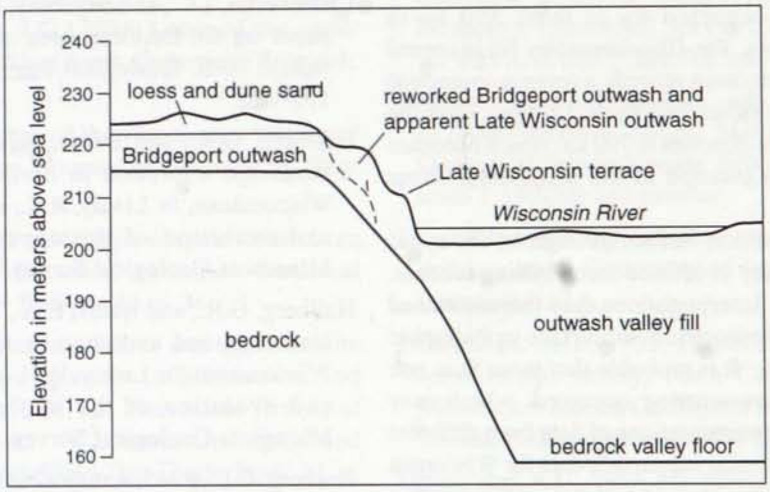

Figure 5. Schematic diagram of stratigraphic relations observed in the Bridgeport terrace deposits at the Bock Site, Wisconsin River valley. After Knox and Attig (1988).

others, 1982). It is not clear whether the transition represented by these glaciolacustrine sediments is the Matuyama-Brunhes transition, recently redated at 790 ka (Johnson, 1982; Izett and Obradovich, 1994), or the Matuyama-Reunion transition dated at 2.1 Ma (Baker and others, 1987). Regardless, the stratigraphic and geomorphic relations coupled with the paleomagnetic data indicate that tributaries to the Mississippi were deeply entrenched prior to at least 790 ka.

Pre-Illinoian entrenchment is also suggested by the reversed-polarity remanent magnetization of sediments found near the Bock site on the present floodplain level of the lower Wisconsin River valley (Fig. 4B). The sediments are about 125–150 m below adjacent upland divides in the Driftless Area of southwest Wisconsin. Here pre-Illinoian ice advanced from the west and blocked the mouth of the Wisconsin River (Knox 1982). Paleomagnetic analysis of water-laid silt units within the resulting fluvio-glacial sediment, termed the Bridgeport Terrace deposits, show reversed directions that are similar to those of the Kinnickinnic Member (Knox and Attig, 1988). The Bridgeport Terrace sediments are inset against and extend below the surface level of a prominent strath found at various locations along the Wisconsin River. It is unknown if these sediments extend to the maximum depth of the valley, which is about 60 m below the strath surface. However, the position of the Bridgeport Terrace sediments indicates that at least 70 percent of the total valley entrenchment had already occurred by about 790 ka.

DISCUSSION

Recently acquired data have been integrated here to show that the deeply incised valley of the upper Mississippi River (as well as its tributary valleys) was carved well before Middle Pleistocene time. Data from buried-valley systems that were tributaries to the Mississippi indicate that they were all part of a southward-draining network; this contradicts suggestions (Willman and others, 1989) that pre-Pleistocene upper Mississippi River drainage was northward. Uranium-series dates of speleothems and valley fill indicate that valley entrenchment had occurred by at least 350 ka in southeastern Minnesota. Pre-Illinoian valley fill in central and southwestern Wisconsin records a reverse-to-normal polarity transition, at either 790 ka or 2.1 Ma. Thus the minimum age for these deposits is 790 ka, which becomes the minimum age for incision of the Mississippi River valley.

Much of the bedrock surface throughout the upper Mississippi River valley is defined from drilling records, and is poorly known. Interpretations may therefore need to be revised as more bedrock and subsurface stratigraphic data become available. It is probable that more than one period of bedrock downcutting occurred, which may account for the varied interpretations of data from different parts of the region. Existing subsurface data for Wisconsin and Minnesota show that incised bedrock valleys with a southward drainage existed at least prior to the Middle Pleistocene. Extensive modification of this drainage occurred during Pleistocene glaciations and may have rerouted local reaches of the Mississippi River. Data suggest that in most areas the evolving Pleistocene drainage made use of a preexisting network of incised bedrock valleys.

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TERRACES OF THE MINNESOTA RIVER VALLEY AND THE CHARACTER OF GLACIAL RIVER WARREN DOWNCUTTING

Mark D. Johnson[1], David M. Davis[2], and Joel L. Pederson[3]

ABSTRACT

The Minnesota River Valley was cut by Glacial River Warren in as little as 400 years. The upper part of the valley contains boulder-strewn strath terraces cut in till. The lower part of the valley, downstream from Granite Falls, is characterized by fill terraces deposited during overall downcutting. One terrace exposure near Kasota records deposition of as much as 22 m of valley fill between major cutting episodes. Both strath and fill terraces are discontinuous within the valley, and terrace elevations and slopes are varied. Terrace surfaces cannot be correlated confidently with each other, nor can they be correlated with named Glacial Lake Agassiz strandlines, except within a few kilometers of the outlet. The sedimentology of terrace infill indicates rapid filling, with periods of greater stability during which streams approached a graded condition. The vertical and lateral distribution of strath and fill terraces reflects the complex response of cutting and filling to high discharges from Glacial Lake Agassiz.

INTRODUCTION

The Minnesota River Valley was formed by Glacial River Warren, which acted as the outlet for Glacial Lake Agassiz (Fig. 1) during the Lockhart phase (Clayton, 1983) and perhaps later during the Emerson phase (Clayton, 1983; Smith and Fisher, 1993). Numerous terraces and scoured bedrock surfaces within the valley record the progressive stages of valley formation (Fig. 2). Despite its significance as the outlet for Glacial Lake Agassiz, little work has concentrated on the geomorphology, sedimentology, and history of this spillway. In this paper we present evidence that significant filling as well as cutting occurred during the formation of the Minnesota River valley. We agree with earlier workers that cutting of the valley was episodic, but we differ with them in that we believe that correlation with individual lake phases as defined by the beach chronology is nearly impossible.

This paper presents a longitudinal profile (Fig. 2) showing the elevation and position of terraces and bedrock surfaces within the Minnesota River valley, as determined from 1:40,000-scale aerial photographs of the entire valley and from 1:24,000-scale topographic maps. Additional information was collected from soil surveys and from examination of gravel pits and quarries. We also present a detailed study of a well-exposed sequence of Glacial River Warren terrace sediments at Kasota. The longitudinal profile by Pederson and the terrace-sediment study by Davis (Davis and others, 1994) are combined with many years of observations by Johnson.

PREVIOUS WORK

The story of Glacial Lake Agassiz has been well documented (Upham, 1895; Mayer-Oakes, 1967; Teller and Clayton, 1983), but in recent years only Matsch (1983) and Kehew and Lord (1986) have written specifically on the Minnesota River valley's role as the spillway for Glacial Lake Agassiz, usually referred to as Glacial River Warren. Upham (1883, 1884a, 1884b, 1884c, 1884d, 1895) considered Glacial River Warren to

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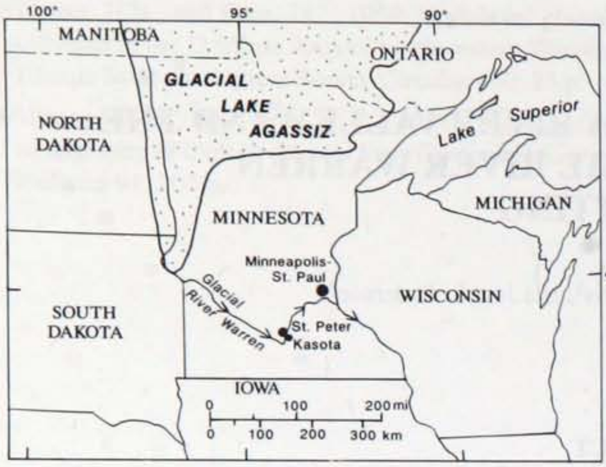


Figure 1. The Upper Midwest showing Glacial Lake Agassiz, Glacial River Warren, St. Peter, and Kasota.

be predominantly a downcutting stream. The fill terraces that are prominent in the lower reaches of the valley (Fig. 2) were interpreted by Upham to be composed of outwash deposited by meltwater streams of the Des Moines Lobe prior to the formation of Glacial Lake Agassiz. Matsch (1983) identified strath surfaces in the upper reaches of the valley and correlated them with different lake stages as defined by the beach chronology of Upham (1895) and Elson (1967). Episodic incision of the valley, which in turn controlled drops in lake level, has been attributed to several causes, including epeirogenic uplift (Upham, 1895), knickpoint migration (Chamberlin in Upham, 1895), and episodic removal of boulder-choked surfaces that developed during downcutting of till (Matsch and Wright, 1967). Weile and Mooers (1989a) suggested that Glacial River Warren flood events were caused by surging of the ice margin into Glacial Lake Agassiz. Kehew and Clayton (1983) suggested that episodic incision was due to periodic drainage of western glacial lakes into Glacial Lake Agassiz. Matsch (1983) used the Manning equation to estimate that Glacial River Warren had a discharge of 10^4–10^5 m^3/sec. Weile and Mooers (1989b) calculated the peak velocity of Glacial River Warren to be 3 x 10^5 m/sec. Kehew and Lord (1986) cited the Minnesota River valley as an example of their model for the development of glacial-lake spillways. Franco and Johnson (1997) interpreted fill-terrace sediments to represent either Glacial Lake Agassiz spillway deposits or pre-Glacial Lake Agassiz, Des Moines Lobe jökulhlaup deposits.

MINNESOTA RIVER VALLEY LONGITUDINAL PROFILE

A longitudinal profile of the Minnesota River and its terraces (Fig. 2) was constructed from 1:24,000 topographic maps of the valley from north of the outlet for Glacial Lake Agassiz to Hastings, Minnesota. The distance shown on the horizontal axis of the longitudinal profile is not river distance but distance along the valley axis. Flat to gently sloping portions of the river profile are due to alluvial infilling and ponding behind alluvial dams of tributary streams. Terrace identification was aided by inspection of 1:40,000 scale air photographs for the entire river valley, published soil surveys, and certain topographic features (topographic expression, gravel pits, quarries, and marshes marked on topographic maps). Differentiation of strath and fill terraces was based primarily on soil surveys. The profile has not been field-checked thoroughly, but soil descriptions, topographic character, and photographic expression are adequate to differentiate fill terraces composed of sand, boulder-strewn strath terraces cut in till, and exhumed bedrock knobs and benches. Some of the strath and fill terraces shown on the profile actually represent a number of smaller terrace segments. These smaller segments were combined on the profile to appear as one terrace. We identified several terraces (terraces between 780 and 880 ft, 300 miles from outlet, Fig. 2) that correlate in part with the three terrace levels mapped throughout the Twin Cities by Meyer and Hobbs (1989), Hobbs and others (1990), and Meyer and others (1990), but the terraces, as shown on our profile appear to represent more than three different levels, and correlation among them is difficult. The Glacial Lake Agassiz beaches shown on the profile (Fig. 2) are taken from Leverett's (1932) map of the outlet area.

The longitudinal profile also shows the bedrock profile beneath the Minnesota River floodplain. Points for this profile were taken from bridge-boring logs on file at the Minnesota Department of Transportation and, in part, through investigation of regional bedrock topography maps (Bloomgren and others, 1989, 1990; Patterson and others, 1990; Mossler, 1992). Care was taken to include only those bedrock elevations that were likely to have been cut during the time of Glacial River Warren. We have not included bedrock elevations that appear to represent pre-existing bedrock valleys. Several features are apparent from the profile:

1. Strath terraces are confined to the upper reaches of the valley, and fill terraces to the lower reaches. As we demonstrate below, the thickness of sediment in the fill terraces locally reaches 10–20 m.

2. Exhumed bedrock surfaces differ in topographic expression between the Precambrian metamorphic and igneous rocks and the Paleozoic sedimentary rocks. These surfaces are boulder-strewn in places and represent the base of cutting for Glacial River Warren. Erosion by Glacial River Warren was

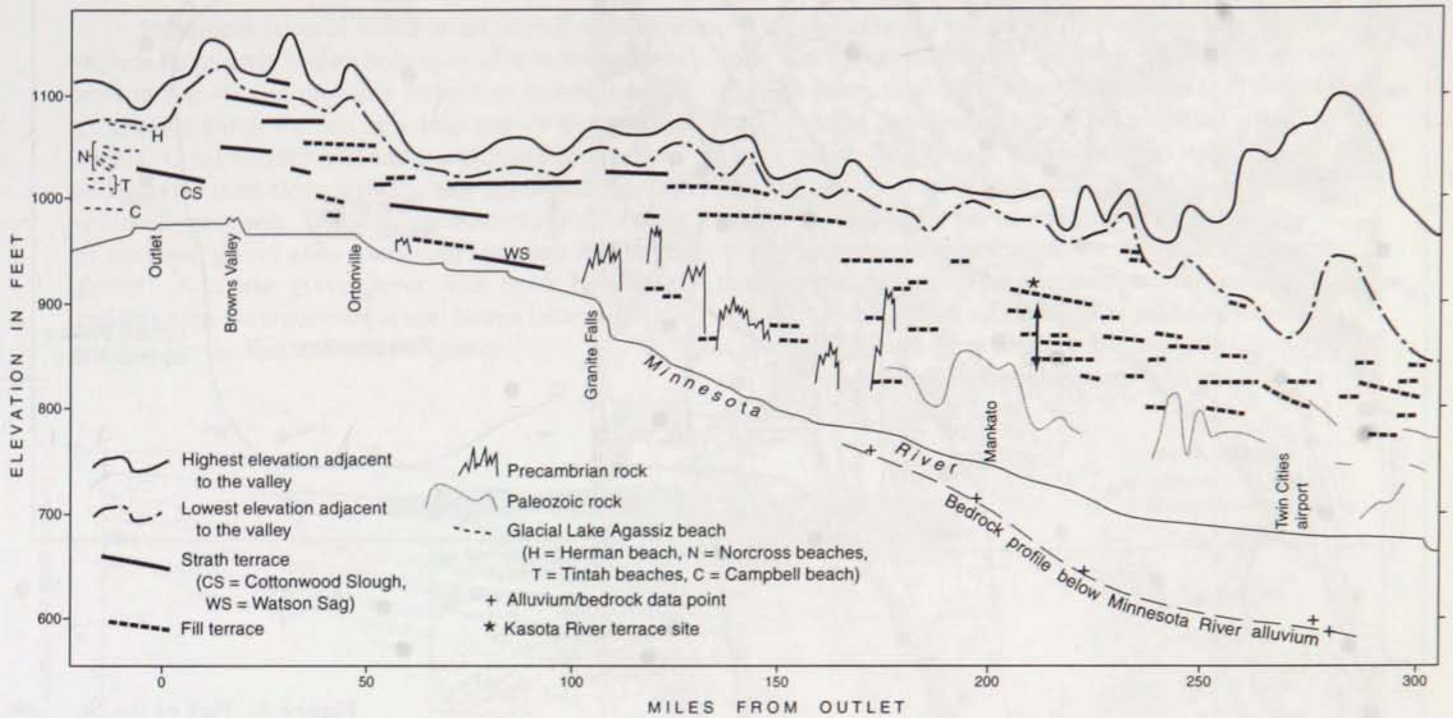


Figure 2—Longitudinal profile of the Minnesota River valley showing terraces and exhumed bedrock surfaces. Vertical exaggeration is 1320X. Strath and fill terraces shown are not as laterally extensive as indicated, and many consist of discrete segments that we have chosen to connect. The knobby appearance of the Precambrian rock is suggestive of the topography and not a true topographic representation. The asterix marks the location of the Kasota gravel pit (Figs. 3, 4, 5 and 6). The double-headed arrow indicates the depth of cutting and filling interpreted from the terrace sediments in the Kasota gravel pit.

minimal across these knobs and benches, and they should not be thought of as strath terraces. Numerous small fill terraces occur in the lee of these bedrock knobs.

3. Of eight prominent strath terraces, two are higher than the Herman beach, indicating valley incision prior to the Herman stage. Also included on Fig. 2 are profiles of the bottoms of Cottonwood Slough and Watson Sag, two large channels that had little subsequent filling. The profile indicates that Cottonwood Slough was used during the Herman and Norcross stages, but not during later stages.

4. The distribution of strath and fill terraces in the valley shows no obvious, correlatable relationship to the various Glacial Lake Agassiz beach stages.

5. The depth of Glacial River Warren scouring was 5–20 m below the modern Minnesota River floodplain in the lower reaches of the river.

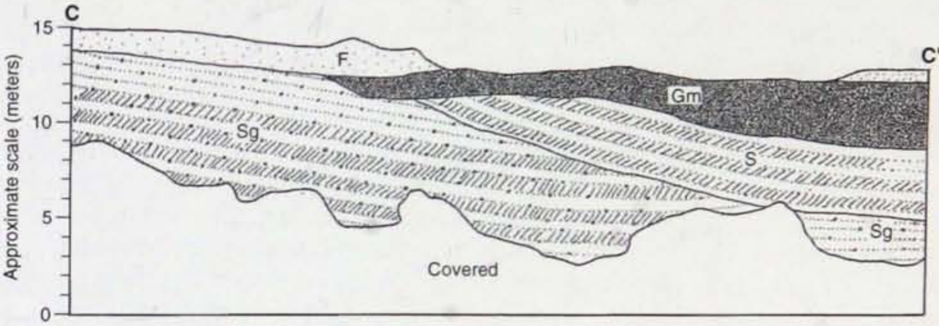
RIVER WARREN FLOOD DEPOSITS NEAR KASOTA, MINNESOTA

The fill terraces of the Minnesota River valley near the cities of St. Peter, Kasota, and Le Sueur are composed of sediment deposited during filling episodes of Glacial River Warren. A gravel pit one mile south of Kasota (Fig. 3) provides a 15-m-thick sequence through sediments interpreted to have been deposited by Glacial River Warren (Figs. 4, 5 and 6). The surface of the terrace is relatively flat and lies at roughly 271 m in elevation; a higher terrace 100 m to the east has an elevation of 277 m (Figs. 3, 4 and 5). The location of the exposure is noted on the longitudinal profile (Fig. 2).

Prominent features found in the terrace sediments include large-scale foreset beds up to 15 m in height (best seen in Fig. 4) that probably formed as part of a large, prograding bar at the bed of a deep and swiftly moving stream. Cross-bedded sand and gravel, plane-bedded sand and gravel, grain-flow deposits, and ripple-bedded sand are locally common. The terrace sediments consist largely of sand and gravel units containing less than 50 percent gravel. A coarse gravel layer with crude horizontal bedding caps the terrace sequence. Seven facies units are defined for the Kasota terrace sequence.

Facies Gs and Sg (Fig. 7) consist of cross-bedded sand and gravel containing less than 30 percent gravel (Sg) or more than 30 percent gravel (Gs). They are interpreted as deposits of dunes that migrated along the top or across the slip face of a high-relief migrating bar. Climbing-ripple stratification indicates that ripples formed on the slipface of the bar as it migrated.

Facies S consists of stratified sand containing less than 10 percent gravel and in many cases less than 1 percent gravel. Much of the sand is plane-bedded, but ripple bedding and cross bedding are common. Some of the large-scale foresets are composed of facies S.



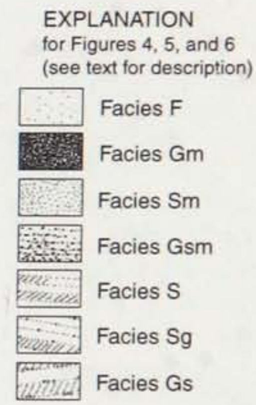


Figure 5. Outcrop sketch of B-B' (Fig. 3). Flow is to the right. Facies symbols are listed in the explanation and discussed in the text.

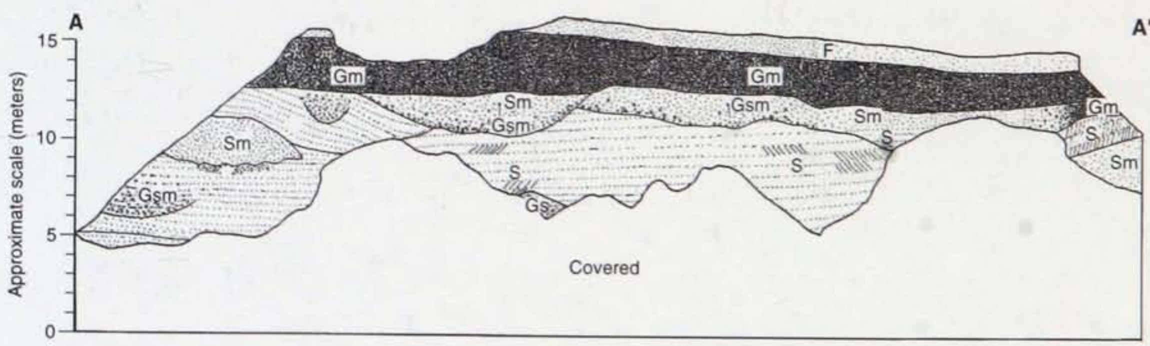
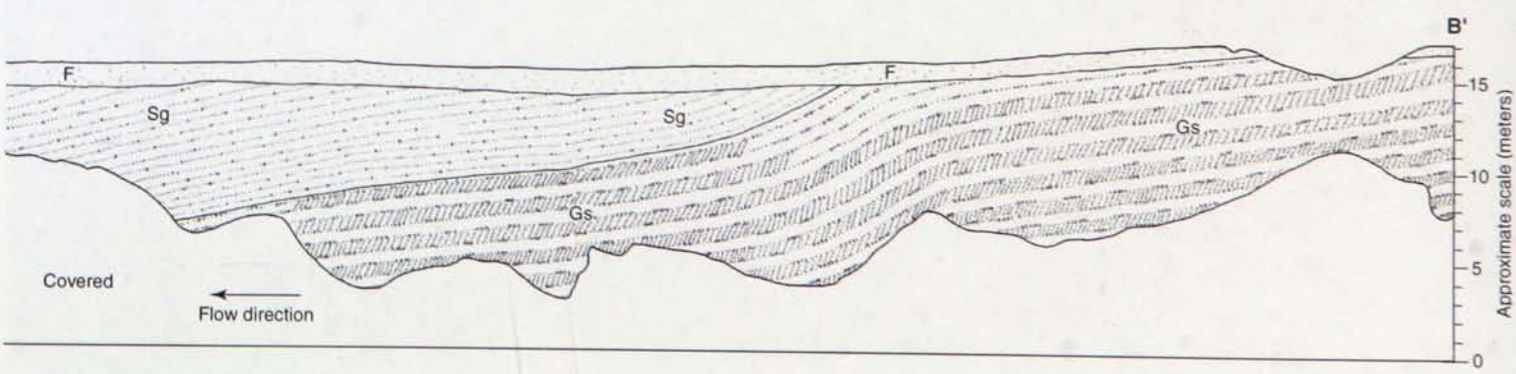


Figure 6. Outcrop sketch of A–A' (Fig. 3). Flow is into the page away from the reader. Facies symbols are given in the explanation and discussed in the text.



Facies Gsm consists of gravelly sand, which mantles or infills channel-like scours (Fig. 6). The gravelly sand typically fines upward; it contains 20–30 percent gravel near the base, and 0–5 percent gravel near the top of the unit. Facies Gsm is interpreted to represent fining-upward channel-fill deposits (with possible lateral overbank extensions). These are interpreted as grain-flow deposits resulting from failure of the foresets; they are only shown in Fig. 6, which is oriented perpendicular to paleoflow direction. Multiple fining-upward sequences are commonly present in each channel fill and are interpreted as multiple grain-flow pulses.

Facies Sm is a massive sand unit containing little or no gravel and little or no bedding. Facies Sm may represent grain flows down the slip face of the bar, perhaps related to facies Gsm. Alternatively, it may represent grain-fall deposits associated with plumes of sand being swept over the crest of the bar and deposited near the base of the foresets.

Facies Gm consists of poorly sorted, clast-supported sand and gravel interpreted as deposits of channel bars in a braided stream. It is much coarser than any of the other facies found in the study area; this is the result of the winnowing action of the braided stream, which removed much of the sand but not the coarser gravel.

Facies F consists of silt and fine sand grading upward into the modern soil profile and is interpreted either as overbank deposits of a braided stream or in part as loess.

The presence of facies Gm and F at the top of the sequence indicates a shallower stream than that responsible for the deposition of facies Gsm, Gs, Sg, Sm, and S, which appear to have been deposited in a deep swiftly moving stream.

The dip directions for foresets and cross beds are shown in Figure 8. The predominant dip direction of the foresets (Fig 8A) is north, corresponding to the assumed paleocurrent direction for Glacial River Warren. The dip direction of the cross-beds (Fig 8B) is to the east as well as to the north, indicating that dunes formed on foresets that were deposited by currents operating in the zone of separation in the lee of the bar.

Exposures in the Kasota gravel pit (Figs. 4, 5 and 6) indicate that a significant incision event was followed by channel filling and deposition of facies Gsm, Gs, Sg, Sm, and S. The sediments exhibit large-scale foreset-like geometry, indicating the channel filling was a relatively rapid event and that the stream was at least 15 m deep on the lee side of the bar. We speculate that the valley

Figure 7. Complex cross-bedded foresets of facies Sg exposed in a gravel pit 400 m east of the Kasota pit, during the summer of 1997. Water flow from left to right. The upper 1 m of the cut exposes sediment of facies Gm. The pit wall is 8 m high.

constriction just north of the site (Fig. 3), caused a hydraulic dam to develop, ponding water in the valley upstream. The foresets were deposited in a delta-like bar that prograded and filled this ponded reach.

Further evidence suggests that the stream responsible for these sediments was deeper than 15 m. Fig. 9 depicts a possible sequence of events leading to the formation of the terrace studied. It shows the period of channel incision (step 1) followed by rapid channel filling during which Gsm, Gs, Sg, Sm, and S were deposited (Step 2). As the flow of Glacial River Warren waned, a smaller braided stream flowed over what is now the terrace surface, depositing the massive gravel of facies Gm (Step 3). Thorough winnowing by this stream suggests a more-stable longitudinal profile occupied for a longer time than that indicated by the underlying foresets. This stream was able to downcut slightly, forming first the gravel cap on the 910-ft terrace and then the gravel cap on the 890-ft terrace (Step 4, see also Fig. 3). The higher terrace is capped with facies Gm, which is absent in Fig. 4 (B–B') because the site is on the slope between the two terraces and therefore was not covered with sediment when the stream was flowing over the lower surface. Therefore the channel must have filled to the level of the upper terrace, which is 6 to 7 m higher than the top of the 15 m foresets. From this it can be suggested that Glacial River Warren reached a depth of at least 22 m during an extreme flood event.

At some later time, another flood eroded the terrace (Step 5, see also Fig. 6), but this time not enough sediment was available in River Warren to result in a second filling episode. Thus we have evidence at this site for two major periods of downcutting interrupted with one major filling episode.

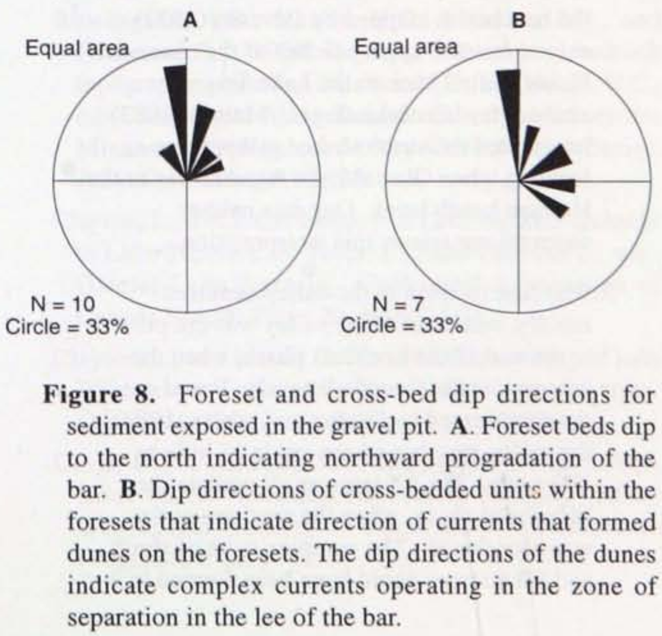


Figure 8. Foreset and cross-bed dip directions for sediment exposed in the gravel pit. **A**. Foreset beds dip to the north indicating northward progradation of the bar. **B**. Dip directions of cross-bedded units within the foresets that indicate direction of currents that formed dunes on the foresets. The dip directions of the dunes indicate complex currents operating in the zone of separation in the lee of the bar.

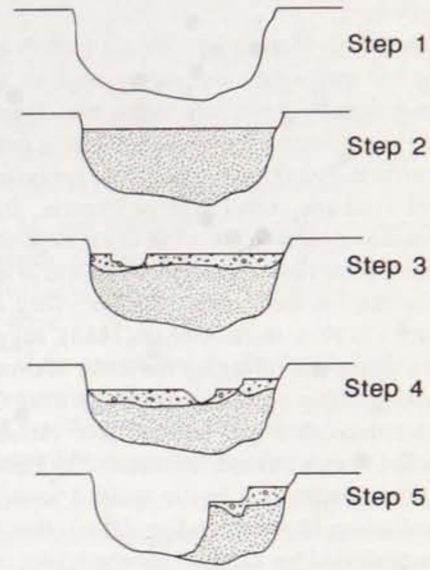


Figure 9. Sequence of events responsible for the stratigraphy exposed in the Kasota gravel pit. See text for explanation.

Fraser and Bluer (1988) described a similar terrace sequence in the Wabash River valley of northern Indiana. They used the term 'megasets' to describe cobble gravels in cross sets as much as 5 m thick. Fraser concluded that these were deposited by 'floods of extreme magnitude.' These were the result of rapid drainage of Glacial Lake Maumee, which occupied the Lake Erie basin. These flood events may have been similar to those of Glacial River Warren.

CUTTING OF THE MINNESOTA RIVER VALLEY

The longitudinal profile (Fig. 2) and the terrace sediments require the following interpretations about the cutting of the Minnesota River valley.

Strath terraces dominate in the upper part of the valley and fill terraces in the lower part. Fill-terrace surfaces cover deep valley incisions. Each episode of valley incision was characterized by downcutting throughout the valley, probably initiated in the lower reaches of the valley, where a knickpoint was formed. Knickpoints migrated upstream, perhaps rapidly, during periods of high discharge. As incision migrated upstream, the sediment removed would be transferred downstream, and filling would begin. The strath terraces in the upper part of the valley did not get covered with fill because the outflow from Glacial Lake Agassiz was not sediment-laden. This model suggests that incision and filling would have occurred in the valley simultaneously in different parts of the system.

We agree with Matsch and Wright (1967) that the main incision events were catastrophic, and we believe that this is indicated by the terrace sediments. The terrace sediments in the Kasota pit clearly indicate a period of incision down to the pit floor followed by a period of rapid deposition of sand and gravel in large foresets. Because the foresets seen in outcrop are 15 m thick, deposition of these structures took place in a stream that was at least 15 m deep. Elsewhere in the Minnesota River valley, terrace sediments are 12–30 m thick (Upham 1883), suggesting widespread cutting and filling by the River Warren.

Following filling episodes, discharge from Glacial Lake Agassiz decreased and became less variable. A braided, graded stream formed, represented by Facies Gm and F. Further adjustments in the braided stream after filling caused minor incisions and produced other terrace levels as exemplified by the two terrace levels cut into one fill sequence in the gravel pit. These minor, post-filling adjustments indicate that individual terraces in the lower part of the valley do not correspond, one-to-one, to discrete changes in stream discharge (or lake level), but represent a complex response to changes in discharge and sediment load (Schumm and Parker, 1973). The second major cutting episode at the Kasota site (Step 5 in Fig. 9) represents a later large discharge from Glacial Lake Agassiz, but it is difficult to determine if it occurred during the Lockhart phase or the Emerson phase.

Although we interpret the terrace at Kasota to have formed during the existence of Glacial Lake Agassiz, some of the fill terraces in the valley may be outwash terraces that formed as the Des Moines Lobe melted back. Comparison of radiocarbon ages for the advance of the Des Moines Lobe (14,000 yrs B.P., Clayton and Moran, 1982) with those for the initiation of Glacial Lake Agassiz (11,500 yrs B.P., Teller and Clayton, 1983) indicate that parts of the Minnesota River valley would have been ice-free for at least 1000 years prior to the formation of Glacial Lake Agassiz. The valley would have certainly been the path of outwash streams. Upham (1883) considered all of the fill terraces to be composed of outwash, and it is clear that the terraces of the Minnesota River valley in the Twin Cities region grade to the same level as outwash terraces of the Mississippi River.

However, a comparison of strath- and fill-terrace elevations (Fig. 2) indicates that it is unrealistic that all the fill terraces are outwash terraces. The scale of deposition seen in the Kasota exposures is not typical of "normal" outwash. We suggest that the majority of the fill terraces are composed of sediments deposited by Glacial River Warren. An alternative interpretation is that the large-scale foresets are jökulhlaup deposits formed in association with a surging Des Moines Lobe, that formed prior to the initiation of Glacial Lake Agassiz (Franco and Johnson, 1997). A sedimentologic comparison of several fill terraces may be able to test this hypothesis.

CORRELATION OF TERRACES WITHIN THE VALLEY AND TO LAKE AGASSIZ BEACH LEVELS

It is extremely difficult to correlate terraces down-valley from the outlet to Glacial Lake Agassiz. We suggest that the variations in elevation of the terrace fragments (Fig. 2) indicates that correlation is essentially impossible. It may be that high-resolution dates or specific sedimentologic characteristics may allow some far-removed terrace segments to be correlated, but correlation based on elevation is unlikely.

The strath terraces in the upper part of the valley are closest to the Glacial Lake Agassiz beaches, and thus most likely to correlate with beach levels. However, only a few correlations are certain:

1. Two strath surfaces occur above the level of the Herman beach and thus must relate to overflows from earlier lake stages (or perhaps even to pre-glacial-lake discharge, or discharge from the ice itself). Flow in these channels was down the Lake Traverse channel.

2. Cottonwood Slough (Fig. 2) clearly operated as a spillway when Glacial Lake Agassiz was at the Herman and Norcross levels, because the beaches as mapped by Leverett (1932) extend into the upper reaches of the channel. Flows shifted back to the Lake Traverse channel for later lake stages. Matsch (1983) interpreted the strath terrace at Appleton as forming when Glacial Lake Agassiz was at the Herman beach level. Our data neither supports nor rejects this interpretation.

3. The first incision in the valley occurred rapidly, and most of the valley was cut prior to the end of the Lockhart phase, when the lake was at the Campbell beach. Based on dates presented by Fenton and others (1983), the valley may have been cut in as little as 400 years. The fill terraces all predate the Moorhead phase, when the southern outlet was abandoned. The complex suite of strath and fill terraces could have been formed in a

short time; O'Conner (1993) describes features that show similar complexity in the Lake Bonneville spillway.

For these reasons, we think that it is unrealistic to apply Glacial Lake Agassiz beach phase names to erosional events within the valley. Fenton and others (1983) and Clayton (1983) state strongly that the beach sequence at the outlet is difficult to trace northward and that letting the outlet beaches determine major lake phases may be unrealistic. If the lake-phase chronology is uncertain, it gives all the more reason to avoid correlating beaches with events in the Minnesota River valley. Thus it is difficult to use the terrace sequence to evaluate the claim by Smith and Fisher (1993) that Glacial Lake Agassiz drained down the Clearwater-Athabasca spillway in Alberta and Saskatchewan at 9900 yrs B.P., rather than down the Glacial River Warren spillway.

ACKNOWLEDGMENTS

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GLACIAL RIVER WARREN, LAKE PEPIN, AND THE ENVIRONMENTAL HISTORY OF SOUTHEASTERN MINNESOTA

H.E. Wright, Jr.[1,2], K. Lease[1,3], and S. Johnson[1,4]

ABSTRACT

Lake Pepin was formed in the Mississippi River Valley when a dam was created by sediment from the Chippewa River after the outlet waters of Glacial Lake Agassiz ceased to flow down the Minnesota River valley. It is uncertain whether the outlet to Glacial Lake Agassiz was only active at 11,600–11,000 radiocarbon yrs B.P. or was also active more recently at 9500 yrs B.P. Wood from basal sediments in Lake Pepin provides an age of 9180 +/- 70 yrs B.P., which conflicts with a date of 9630 yrs B.P. from Lake St. Croix, which formed after Lake Pepin. Oxygen-isotope evidence for glacial meltwater in the Gulf of Mexico is equivocal. The rate of sediment deposition in Lake Pepin has increased 10-fold in the last 150 years. Pollen analysis of sediment from Lake Pepin indicates modest expansion of prairie vegetation in the Middle Holocene, but the site at Spring Valley on the upland to the southwest indicates that prairie was already extensive there by the Middle Holocene.

INTRODUCTION

Southeastern Minnesota and the Driftless Area of adjacent southwest Wisconsin were not covered by ice during the Late Wisconsinan glaciation, so any glacial lakes that were formed during previous glaciations have long since been filled or drained. Lake Pepin and a marsh near Spring Valley on the upland to the west of Lake Pepin are the only two sites in the region containing a nearly complete Holocene pollen record. Lake Pepin is an unusual natural lake in the Mississippi River valley. It formed after the outlet waters from Glacial Lake Agassiz in northwestern Minnesota ceased to flow and carry away the sediment supplied by tributaries; it is a result of the natural damming of the Mississippi River by an alluvial fan deposited where the Chippewa River enters the Mississippi River valley from Wisconsin (Figs. 1 and 2). The history of Lake Pepin records events in the development of the Mississippi River valley in the late stages of the last glacial period and during postglacial times. This review is an elaboration of an earlier account (Wright, 1990), which in turn drew on the analysis of Zumberge (1952). We highlight here the problems connected with interpreting the chronology of events for Glacial Lake Agassiz and its drainage.

The Spring Valley site (latitude 43°33'N., longitude 92°21'W.) is a marsh 12 mi southeast of the town of Spring Valley in Fillmore County, about 50 mi south of the site cored at Lake Pepin. The marsh probably formed by solution of the underlying Paleozoic carbonate bedrock. The cover of pre-Wisconsinan till and Wisconsinan loess inhibited underground drainage of the lake that originally occupied the site. The pre-settlement vegetation of the Spring Valley area consisted of oak woodland (Marschner map redrawn by Heinselman, 1974). The Spring valley core was collected from the middle of the depression that contains the marsh. The core is 580 cm long and contains peat underlain by lake sediments.

The pollen stratigraphy of the sediment cores from Lake Pepin and the Spring Valley site, both of which are now dated by radiocarbon analysis, provides new

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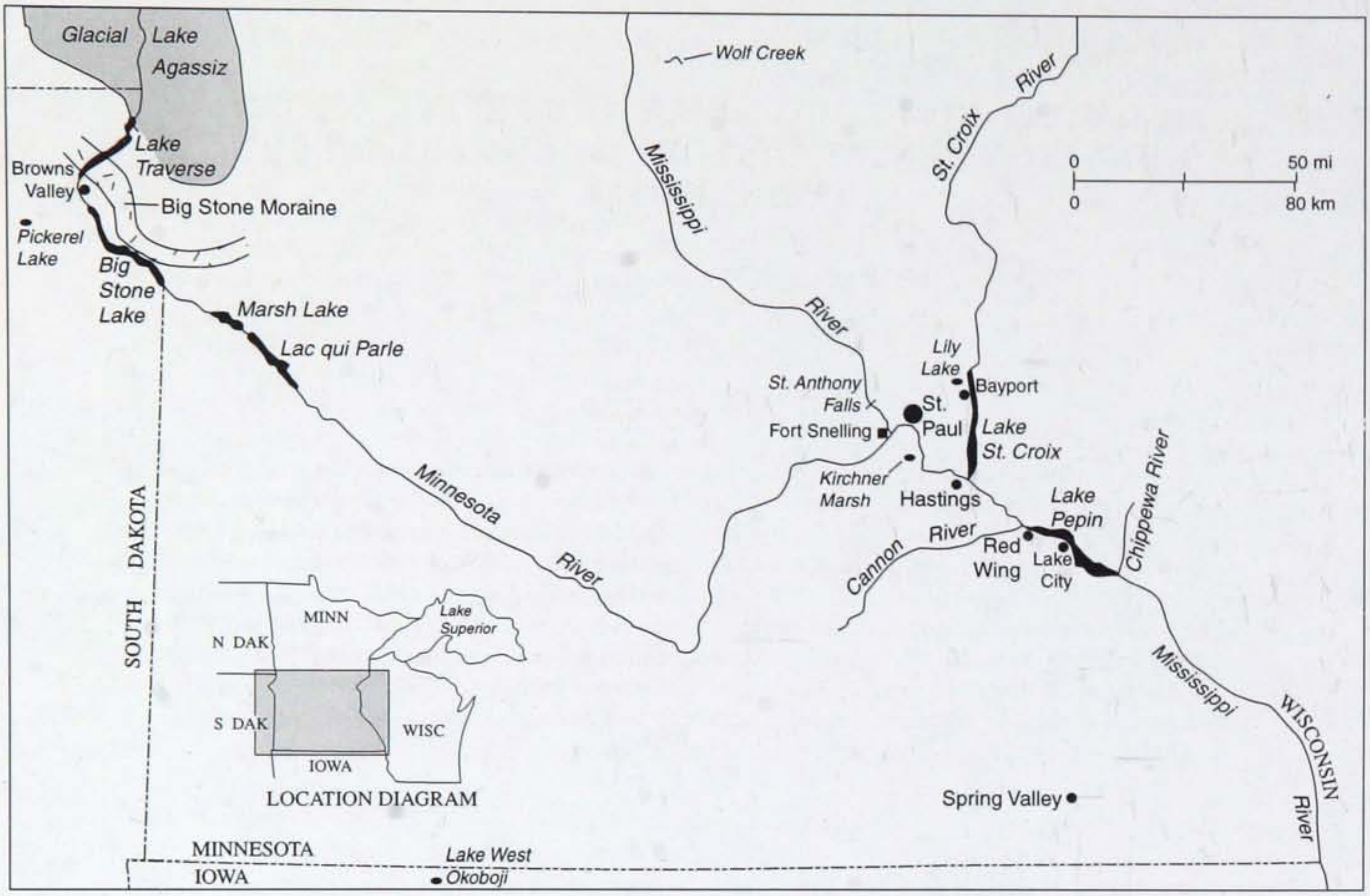

Figure 1. Minnesota and adjacent areas, showing localities and features mentioned in text.

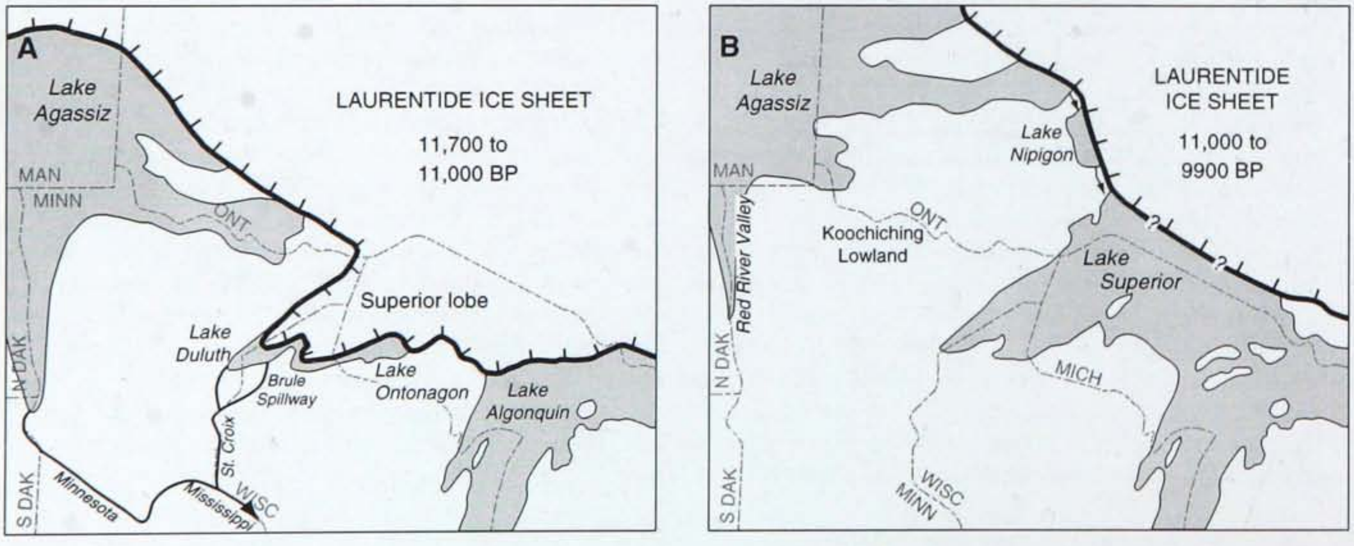

Figure 2. Extent of glacial lakes and contemporaneous ice margins at (**A**) 11,700 –11,000 yrs B.P. (Lockhart phase) and (**B**) 11,000 –9900 yrs B.P. (Moorhead phase). Modified from Farrand and Drexler (1985).

constraints on the time at which Lake Pepin formed, as well as a picture of the vegetational history of southeastern Minnesota.

GLACIAL LAKE AGASSIZ AND GLACIAL RIVER WARREN

Glacial Lake Agassiz formed in the Red River valley and Koochiching lowland of northwestern Minnesota and adjacent North Dakota and Manitoba when the Red River lobe of the Laurentide Ice Sheet retreated north across the continental divide near Browns Valley in Traverse County, western Minnesota (Figs. 1 and 2). The Des Moines lobe had previously covered this area, and it earlier reached its maximum extent in central Iowa about 14,000 yrs B.P. During its wastage it formed retreatal moraines, and its outwash followed the general course taken by what is now called the Minnesota River. At Fort Snelling, which marks the junction of this river with the Mississippi River, the Des Moines lobe outwash was joined by outwash derived from wasting ice lobes to the north (Cooper, 1935) and transported by the upper Mississippi River. The outwash surface is evident at the Metropolitan Airport near Fort Snelling, where it has an elevation of 820 ft. It can be traced as a terrace to Inver Grove Heights south of St. Paul, and thence downstream at decreasing elevation to Illinois. In the Lake Pepin area the terrace has an elevation of about 730 ft, or 60 ft above Lake Pepin. At the time the outwash terrace was being formed, glacial meltwater flooded back into tributaries, where it deposited backwater-lake sediment, forming flat alluvial floors that can be traced far upstream in the tributary valleys.

Retreat of the Des Moines lobe allowed the Red River lobe to advance in its place to the Big Stone Moraine, which is located on the present continental divide between the Minnesota River and the Red River (Figs. 1 and 2). Glacial Lake Agassiz formed in the Red River valley as a proglacial lake between that moraine and the retreating front of the Red River lobe (Lockhart phase, Fig. 2A). The first outlet for Glacial Lake Agassiz was south down the Minnesota River valley as Glacial River Warren, starting at about 11,700 yrs B.P., according to a radiocarbon date for the highest (Herman level) strandline (Teller, 1985). Glacial River Warren carried large volumes of water and was characterized by occasional catastrophic flooding (Johnson and others, this volume) associated with breaches of the outlet to Glacial Lake Agassiz.

Upstream of the confluence with the upper Mississippi River near Fort Snelling, Glacial River Warren cut through glacial sediments to flow across the underlying Ordovician Platteville Limestone. Downstream at St. Paul, this bedrock floor terminated abruptly at the western side of a north-south trending bedrock gorge that had been cut and infilled with glacial sediments during previous

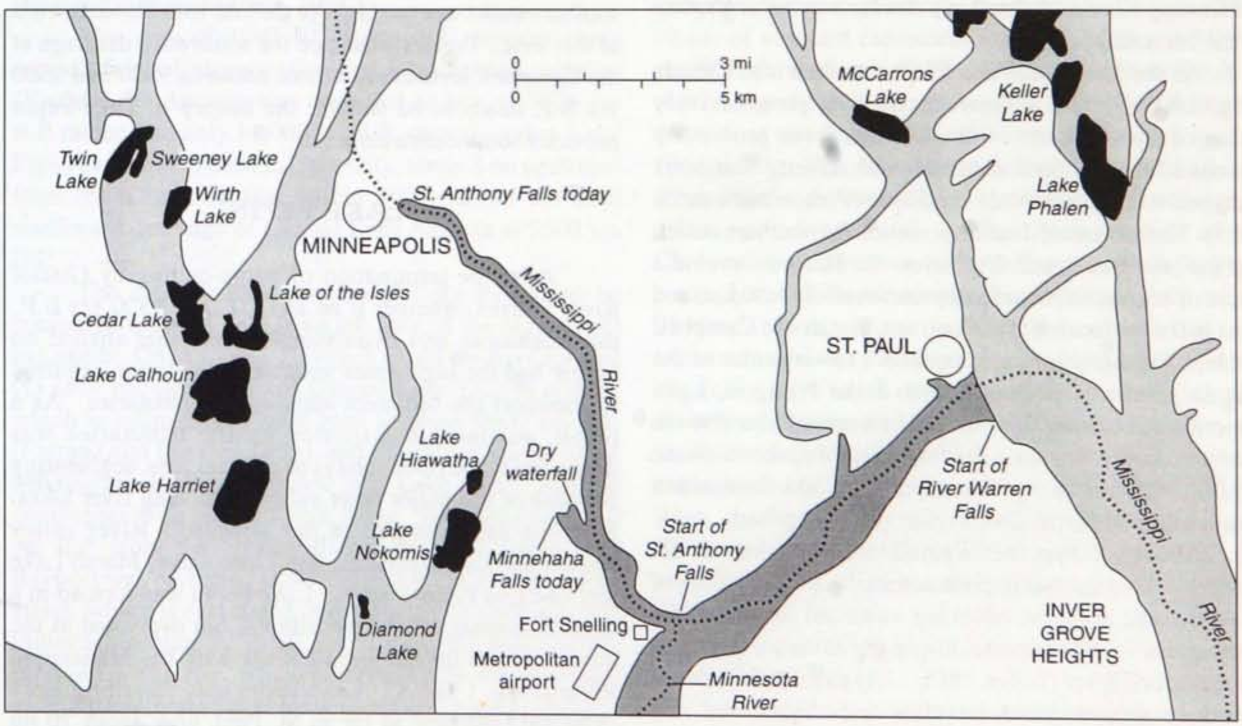

Figure 3. Minneapolis–St. Paul area, showing pre-existing gorges (light grey) infilled with glacial sediment. Location of valleys excavated during retreat of River Warren Falls and St. Anthony Falls are shown in dark grey. Current position of the Minnesota and Mississippi Rivers shown by dotted line (modified from Wright, 1990).

events (Fig. 3). Glacial River Warren eroded the glacial sediments from this pre-existing channel, and a waterfall formed where the superimposed channel entered the re-excavated gorge. The waterfall at St. Paul was about 200 ft high and 1 mi wide. The waterfall retreated upstream as the poorly cemented St. Peter Sandstone that underlies the Platteville Limestone was excavated.

At Fort Snelling the floor of the gorge had an elevation of 600 ft. It was incised 80 ft below the level of the present floodplain, and 220 ft below the glacial outwash terrace at the metropolitan airport. The outwash cover on the limestone bedrock at the airport is very thin, so the waterfall then was at least 200 ft high. It retreated about two miles upstream within the Minnesota River valley, where it encountered another gorge infilled with glacial sediment, now marked by a string of lakes in Minneapolis. The more resistant Platteville Limestone dips east and is not present on the western side of the previously existing bedrock gorge in Minneapolis, thus the waterfall ceased to exist at this point, and upstream erosion by Glacial River Warren progressed rapidly as the knickpoint of the former waterfall worked headward through glacial deposits and the underlying Paleozoic rocks. When the retreating waterfall of Glacial River Warren migrated past the confluence with the upper Mississippi River at Fort Snelling, St. Anthony Falls was formed; it has subsequently retreated about 7 mi to its present position in Minneapolis (Fig. 3). Minnehaha Falls in Minneapolis was formed in a similar way on a tributary of the Mississippi River.

As the Laurentide Ice Sheet retreated into Canada (Fig. 2A), Glacial Lake Agassiz was progressively enlarged by successive contributions from previously dammed lakes in Saskatchewan and Alberta that were marginal to the Laurentide Ice Sheet (Fenton and others, 1983). The increased discharge eroded the southern outlet, and the lake was lowered to below the Herman level in a series of stages, as recorded by successively lower strand lines in the outlet area (the Norcross, Tintah and Campbell levels). Further ice retreat opened a lower outlet to the east in northwestern Ontario to Lake Nipigon, Lake Superior and onward into the St. Lawrence River and the North Atlantic Ocean. During this Moorhead phase (11,000–9900 yrs B.P.) the portion of the lake floor within Minnesota and North Dakota was partly exposed.

About 9900 yrs B.P. a small lobe of the Laurentide Ice Sheet advanced southwest across the eastern outlet of Glacial Lake Agassiz, blocking eastward drainage and causing the lake to expand during the Emerson phase to the Campbell level (Teller, 1985). It is usually considered that the southern outlet was then re-occupied and was active until about 9500 yrs B.P., when ice retreat once again opened the eastern outlet. However, recent studies in western Canada suggest that at 9500 yrs B.P. Glacial

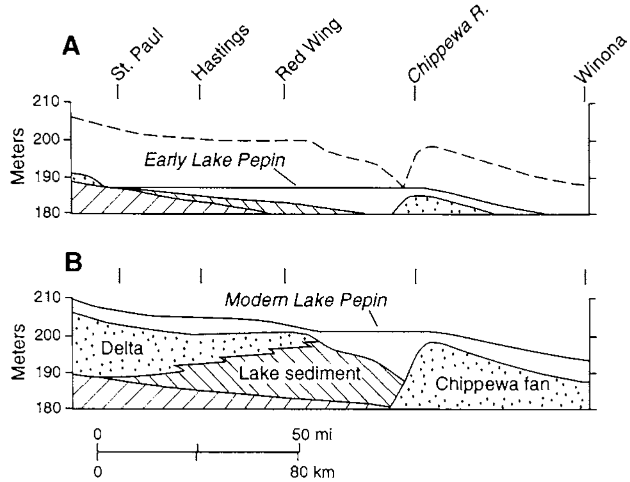

Figure 4. Longitudinal section of the Mississippi River Valley, from Lake Pepin upstream to St. Paul, showing the progressive advance of the delta, and the filling of the Lake Pepin. **A**. Early Lake Pepin; dashed line shows modern Mississippi River-bottom profile. **B**. Modern Lake Pepin. From Zumberge (1952).

Lake Agassiz was greatly enlarged due to ice retreat and extended into Manitoba and Saskatchewan, which had been depressed by the ice load, so that the lake actually drained instead to the northwest along the Laurentide ice front into the Mackenzie River and thence to the Arctic Ocean (Fisher and Smith, 1994). This implies that the southern outlet was too high for the lake to drain southward at this time. Further evidence for southward drainage at the Campbell level at some time between 9900 and 9500 yrs B.P. needs to be sought; the history of Lake Pepin provides some constraints.

LAKE PEPIN

After the termination of gorge-cutting by Glacial River Warren, whether it be at 11,000 or 9500 yrs B.P., the Minnesota and Mississippi Rivers that ensued no longer had the high water volume and velocity required to transport the sediment supplied by tributaries. As a result, sediment transported by the tributaries was deposited in the river valleys as alluvial fans, segmenting portions of the major river valleys into long river lakes. Near the upstream end of the Minnesota River valley system are Lake Traverse, Big Stone Lake, Marsh Lake and Lac Qui Parle (Fig. 1). Lake Pepin was formed in a similar manner behind the alluvial fan deposited at the confluence of the Chippewa River with the Mississippi River (Figs. 1 and 4). Lake Pepin may have originally extended upstream as far as St. Paul, now about 70 mi upstream from the Chippewa fan. This interpretation is based on the presence of 7 ft of lake sediments underlying 65 ft of alluvial fill at St. Paul (Zumberge, 1952). At

Hastings, 20 ft of lake sediment underlies 30 ft of alluvium. Near Red Wing, where the Cannon River enters the Mississippi River at the current northern extent of Lake Pepin, about 20 ft of lake sediment is present (H. Mooers, oral commun., 1998). Data from the Hastings, Red Wing and St. Paul localities indicate that the delta of the Mississippi River prograded southward into Lake Pepin and deposited fine clastic sediment throughout the lake. As the Lake Pepin delta prograded past the confluence with the St. Croix River, it deposited enough sediment to dam this river, which had cut a deep channel when it served as the outlet for Glacial Lake Duluth, at about the same time as Glacial River Warren drained Glacial Lake Agassiz (Eyster-Smith and others, 1991). Lake St. Croix was thereby formed.

Lake Pepin currently has a maximum depth of about 9 m. A sediment core taken from the center of the lake opposite Lake City (navigation mile 775; latitude 44°27'N, longitude 92°15'W) at a water depth of 8.5 m recovered 16 m of sediment. The sediment is homogeneous silt, with about 10% organic matter and 4–10 percent carbonate, based on a loss-on-ignition analysis. A piece of wood in alluvial sand at the base of the core was dated by radiocarbon analysis at 9180 +/- 70 yrs B.P. (Table 1). The date is consistent with the results of pollen analysis of the basal sediment, which is dominated by pine. The pine pollen zone begins in southeastern Minnesota at about 10,000 yrs B.P., when spruce pollen declines steeply (Eyster-Smith and others, 1991).

This date of 9180 +/- 70 yrs B.P. provides some support for the interpretation that the southern outlet of Glacial Lake Agassiz was occupied as late as 9500 yrs B.P. rather than only 11,000 yrs B.P., providing that Lake Pepin extended at least to Lake City, about 8 mi upstream from the Chippewa fan, within 300 years of the final southward drainage of Glacial Lake Agassiz at 9500 yrs B.P.

The date for the initiation of Lake Pepin can be compared with the date from the base of the organic silt in Lake St. Croix (Table 1), which could not have formed (1) until the outflow from Glacial Lake Duluth ceased, which is estimated to have been at about 9900 yrs B.P. (Farrand and Drexler, 1985), and (2) until the delta of the Mississippi River prograded into Lake Pepin past the confluence with the St. Croix River. The date of 10,610 yrs B.P. from the organic silts in Lake St. Croix near Bayport was corrected to 9630 yrs B.P. for the hardwater effect, which is calculated to be 980 yrs on the basis of a radiocarbon date of 1080 yrs B.P. at the level of the ragweed pollen rise, which marks the date for the end of early agricultural settlement at about 100 yrs B.P. (Eyster-Smith and others, 1991). The accuracy of the date is supported not only by the Glacial Lake Duluth outflow (9900 yrs B.P.), but also by the fact that the basal sediment at Lake St. Croix is in the pine-elm pollen zone, which starts at nearby Lily Lake at about 10,250 yrs B.P. (Eyster-Smith and others, 1991). However, this corrected date of 9630 yrs B.P. is incompatible with the termination of Glacial River Warren at 9500 yrs B.P., for it requires Lake Pepin to advance immediately from the Chippewa fan up at least to the mouth of the St. Croix River, so that Lake St. Croix could form and extend 20 miles up to the coring site near Bayport. Perhaps the "radiocarbon plateaus" (times of constant radiocarbon age) at 9600 and 10,000 yrs B.P. (Lowell and Teller, 1994) make it difficult to resolve the chronology. At any rate, the combination of dates does not support the 9500 yrs B.P. termination of Glacial River Warren. An earlier termination to Glacial River Warren downcutting at 11,000 yrs B.P. is favored, allowing at least 1400 yrs for the formation of the Chippewa fan, extension of Lake Pepin north to St. Paul, progradation of the Mississippi River delta past the mouth of the St. Croix River to form Lake St. Croix, and expansion of Lake St. Croix to Bayport. Perhaps this sequence of events was accomplished during the Moorhead phase of Glacial Lake Agassiz, when the southern outlet was abandoned and Lake Pepin was created and extended north to the mouth of the St. Croix River. In this case the renewed outflow of Glacial River Warren during the Emerson phase could remove the early sediment of Lake Pepin without destroying the dam that blocked Lake St. Croix, and sedimentation at Lake Pepin could be renewed at 9500 yrs B.P. when Glacial River Warren ceased to flow.

Another approach to the chronology of events associated with Glacial River Warren comes from the study of a sediment core from the Gulf of Mexico (Broecker and others, 1989). The oxygen-isotope content of

Table 1. Summary of radiocarbon ages referenced in the text.

Locality / Feature	Radiometric Age	Reference*
Lake Pepin wood in basal sediments 2425 cm	9180 +/- 70 yrs B.P.	CAMS-11058
Spring Valley elm-oak zone 385-387 cm	9120–9120 +/- 100 yrs B.P.	Y-2461
Spring Valley spruce zone 448-450 cm	9820 +/-120 yrs B.P.	Y-2460
Lily Lake basal sediment	11,770 +/-110 yrs B.P.	WIS-1450
Lake St. Croix organic silts	10,610 yrs B.P. (corrected to 9,630 yrs B.P. with hardwater effect)	A-1712

* Radiocarbon lab sample number. Y–Yale; A–Arizona; CAMS–Lawrence-Livermore; WIS–University of Wisconsin.

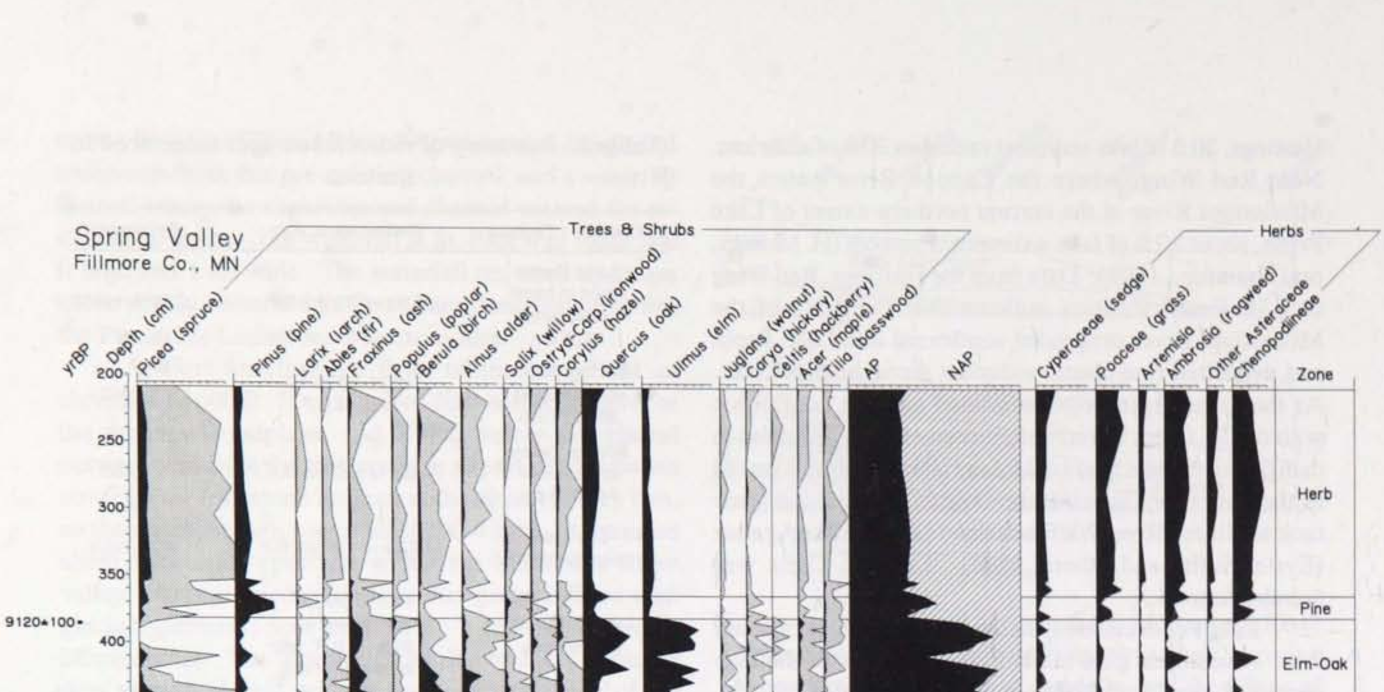

Figure 5. Pollen diagram for Spring Valley site, Fillmore County, Minnesota. Vertical axis shows depth from current soil surface. Percentages represent percentage of total pollen; stippled area shows pollen percentages exaggerated 10x. AP is arboreal pollen; NAP is non-arboreal (herbaceous) pollen. Analyst : K. Lease.

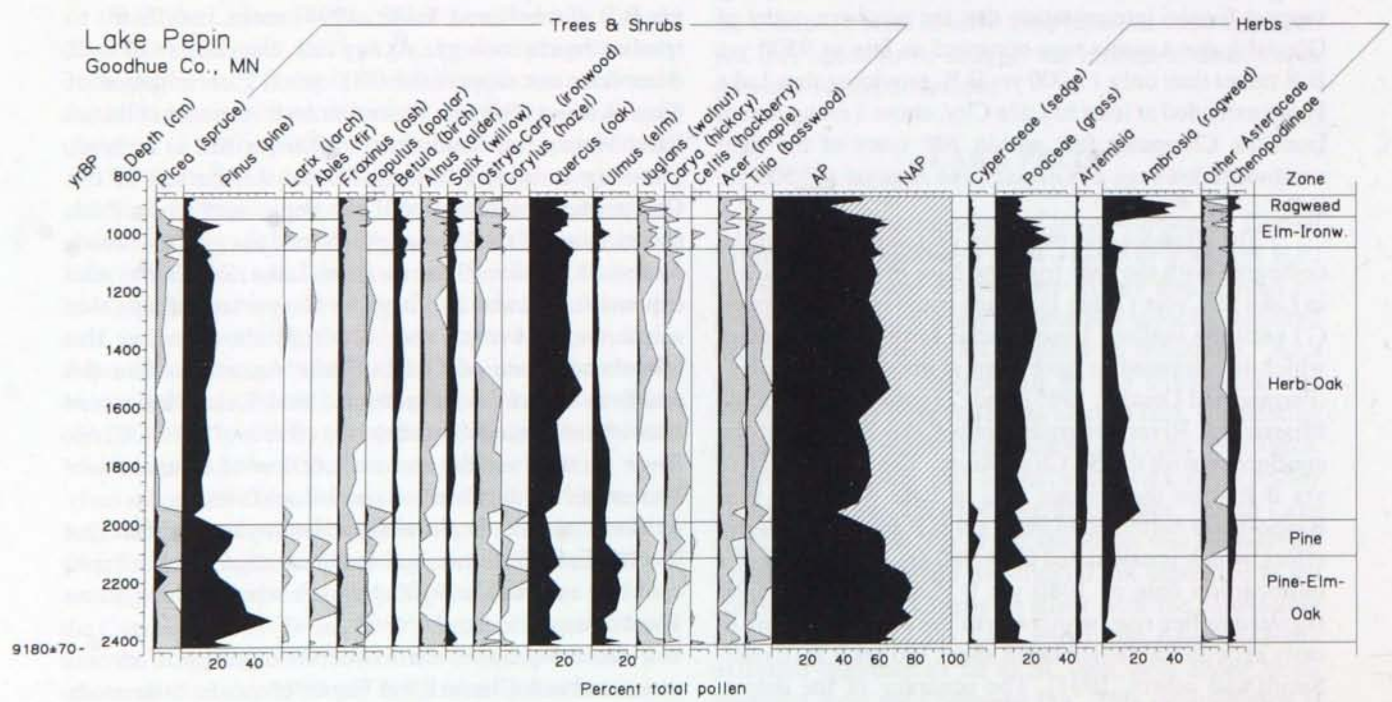

Figure 6. Pollen diagram for Lake Pepin site, Goodhue County, Minnesota. Vertical axis shows depth from current lake surface. Percentages represent percentage of total pollen; stippled area shows pollen percentages exaggerated 10x. AP is arboreal pollen; NAP is non-arboreal (herbaceous) pollen. Analyst : S. Johnson.

carbonate shells of foraminifera in marine cores reflects in large part the volume of water removed from the sea and stored on the continents as glacial ice. Snow that forms at high latitudes and altitudes has a composition isotopically lighter than the water left behind in the ocean because of isotopic fractionation during evaporation, transport, and precipitation. Thus when the Laurentide Ice Sheet melted it provided isotopically light meltwater to the Mississippi River and the Gulf of Mexico. The volume of meltwater supplied by the Great Lakes region started to increase at about 14,000 yrs B.P. as ice retreat accelerated, and it came to a maximum soon after 12,000 yrs B.P., with the outflow from Glacial Lake Agassiz. It left a distinct spike in the oxygen-isotope record in foraminifera of Gulf of Mexico cores, because of its distinctly different isotopic composition (Broecker and others, 1989). The oxygen-isotope spike terminates abruptly at about 11,000 yrs B.P., correlating with the diversion of Glacial Lake Agassiz outflow to the east. If the southern outlet was restored at about 10,000 yrs B.P., a second spike should be recorded. That seems to be the case with the isotopic record of one foraminiferal type, but in another the profile is equivocal. The interpretation is complicated by the fact that marine waters at this time were changing in temperature as a direct response to climatic change, and the isotopic composition is affected by salinity and temperature as well as by water source.

The sedimentation rate in Lake Pepin since agricultural settlement can be estimated from the abrupt increase in ragweed pollen from 5 to 35 percent of the total pollen in the uppermost 1.5 m of the Lake Pepin core. This increase reflects either local farming in the upland above Lake Pepin itself (starting perhaps about A.D. 1850), or extensive mechanized agriculture in the Minnesota River watershed (perhaps A.D. 1880). The date could be refined by lead-210 dating. In any case, the rate of deposition in the middle of the lake is more than 1 m/100 years, compared to one-tenth that rate for pre-agricultural time. The composition of the lake sediment also changed with the introduction of agriculture. This is indicated by the results of magnetic-susceptibility analysis, which reflect a major increase in the input of mineral sediment as a result of soil erosion related to forest clearance in the Minnesota and Mississippi River watersheds.

VEGETATIONAL HISTORY FOR SPRING VALLEY AND LAKE PEPIN

Local pollen-assemblage zones are designated for each of the two sites (Figs. 5 and 6) because of significant vegetational differences between the upland and lowland settings, as well as their different latitudes. The sequence at Spring Valley seems strange because of the late maximum of pine, but the radiocarbon dates clarify the relations and permit a correlation between the two sites, as suggested by the similarities in zone terminology. The early part of the sequence reflects the rapid climatic changes at the late-glacial/Holocene transition.

Spring Valley Pollen Record

The Spring Valley pollen record is substantially older than that for Lake Pepin, but it terminates much earlier, because pollen preservation in the dominantly peaty upper 2 m of core was inadequate to justify analysis. Thus the pollen diagram for Spring Valley does not extend to the surface of the sediment. The sequence (Fig. 5) starts with a spruce pollen zone in which temperate deciduous trees (ash, oak, elm) are represented as well as herbs. This anomalous late-glacial assemblage, not found today in the spruce forest, is attributed to the combination of (1) strong periglacial cooling favorable for spruce, along with (2) strong summer insolation (Wright, 1987). The ash (as much as 15 percent) is probably black ash (*Fraxinus nigra*), as recorded at other sites where the separation of pollen types has been made (e.g. Lily Lake). The relatively high values for herbs indicate openings in the spruce forest, which includes fir and larch. The high values for pine (as much as 5 percent) are unusual for the spruce zone in Minnesota and probably represent distant transport from the south, for pine was present at this time in Missouri.

The spruce zone at Spring Valley ends at 9820 yrs B.P. It is not replaced there by pine but rather by an assemblage designated as the elm-oak zone. The lower half of the elm-oak zone is marked by alder, hazel, and ironwood, which are temperate invader trees and shrubs that form a characteristic transitional pollen assemblage at the spruce/pine transition at many sites farther north, such as Kirchner Marsh and Wolf Creek (Amundson and Wright, 1979). At Spring Valley, however, pine did not arrive until significantly later at 9120 yrs B.P., and the early invader assemblage of the elm-oak zone is succeeded by the full mesic forest of elm and oak, together with maple, basswood, hazel, and even hickory and walnut. Such an assemblage is also found at Lake West Okoboji, which is 140 mi to the west (van Zant, 1979), in northwestern Iowa. The elm-oak zone at Spring Valley lasted from 9820 to 9120 yrs B.P. and is followed by a thin pine zone, which represents the late arrival of pine to the area, just before the expansion of prairie. At Lake Pepin (Fig. 6), the equivalent to the pine zone is more conspicuous; pine was a dominant in the preceding pine-elm-oak zone.

At Spring Valley the thin pine zone is followed by the herb zone, which extends to the top of the analyzed sediment section, above which the pollen preservation is poor. The herb zone includes grasses, ragweed, *Artemisia*, other composites and chenopods, which total about 60 percent of the total pollen. Some of these pollen types, as well as the sedges, may represent wet-ground weedy plants, as at Kirchner Marsh and nearby Lake Carlson 75 mi to the north; they may have spread over exposed lake floors at times of low lake levels (Watts and Winter 1966, Winter and Wright 1977). The persistent presence of spruce pollen (10 percent) in the herb zone, along with fir and larch, probably represents not outliers of spruce forest but rather erosion of spruce-zone sediment exposed around the lake edges at times of low lake level—a common phenomenon for lakes subject to water-level changes, e.g. Pickerel Lake in South Dakota (Watts and Bright 1968). The 5 percent pine pollen in the herb zone probably comes from distant transport.

Lake Pepin Pollen Record

The earliest pollen zone identified from sediments within Lake Pepin indicates sedimentation during the pine-elm-oak zone at 9180 yrs B.P., long after the regional decrease in spruce and its replacement as a dominant by pine. The pine-elm-oak zone here is correlated with the elm-oak zone at Spring Valley, with the major addition of pine. The unusual combination of elm and pine, for which no modern analogue exists in surface-sample collections, is documented (Wright, 1993) throughout central and even northern Minnesota. As with the spruce zone at Spring Valley, it may be attributed to the combined effects of periglacial cooling from the ice sheet (still in southern Canada) and the Milankovitch summer insolation maximum, which may have increased the summer rainfall favorable for elm. The deep Mississippi River gorge with its cooler air may have allowed pine to extend farther south than it did on the uplands near Spring Valley, which also is at a more southerly latitude. Similar relations are seen in the contrasting pollen diagrams for Lake St. Croix, which lies in a deep gorge, and the nearby upland Lily Lake (Eyster-Smith and others, 1991). The pine-elm-oak zone at Lake Pepin is succeeded by a relatively thin pine zone, and this by a herb-oak zone.

The herb-oak zone at Lake Pepin contains abundant ragweed, *Artemisia* , and chenopods of the prairie, but it also contains pollen from mesic trees such as elm (10 percent) and ironwood. This is a contradictory assemblage, but again it may reflect the fact that the pollen was drawn both from dry treeless uplands and from moist valley slopes as well as from the delta floodplain of the lake. The steep valley slopes presumably had a heavy forest cover, as they do today, at least on the west side—on the east side grassy areas result from high afternoon insolation. Conifer pollen brought by river transport from the north via the St. Croix River also had a masking affect on the herb percentages, as seen by the persistent 15–20 percent pine pollen as well as a few percent spruce up until recent time, even though these conifers do not occur locally today. Also, Lake Pepin is about 50 mi north of Spring Valley. In the upper half of the herb-oak zone at Lake Pepin the prairie herbs are less abundant than grasses, and elm and ironwood pollen are replaced in dominance by oak, birch, and ash. This interval is not covered in the Spring Valley diagram. At this time the upland pollen source for Lake Pepin probably included a mosaic of oak woodland and grass areas, i.e. an oak savanna.

At Lake Pepin the herb-oak zone is succeeded by a thin interval in which oak pollen dominance is reduced in favor of elm, ironwood, and ash, as well as hazel and hackberry. This thin elmwood-ironwood zone was identified in several pollen diagrams in south-central Minnesota by McAndrews (1968) and was discussed by Grimm (1983), who attributed it to an advance of mesic hardwoods (the "Big Woods") at the expense of oak, perhaps as a response to a moister climate related to the Little Ice Age of several centuries ago, and to a reduction in the frequency of prairie fires. Finally, there is a well-marked ragweed zone at Lake Pepin, which reflects woodland clearance for agriculture at the time of settlement in the middle of the last century.

SUMMARY AND CONCLUSIONS

Lake Pepin in the Mississippi River valley originated when Glacial River Warren, as the southern outlet for Glacial Lake Agassiz, ceased to exist, either after the first expansion of Glacial Lake Agassiz at about 11,000 yrs B.P. or after the second at about 9500 yrs B.P. It was formed when sediment from the Chippewa River dammed the Mississippi River. The date for the basal sediments suggests more recent formation, whereas evidence from the sediments of the associated Lake St. Croix points to an earlier end to the downcutting. Data from marine sediments in the Gulf of Mexico, where oxygen-isotope data are available, are not conclusive.

Pollen analysis of sediments from Lake Pepin combined with those from the upland Spring Valley site both show a distinctive early Holocene elm maximum after the sharp decline of spruce, particularly at the upland site, where pine made a late arrival and allowed the deciduous forest to expand beyond its pioneer invaders. The high elm pollen percentages were probably related to the early Holocene insolation maximum. The rest of the Holocene was dominated by prairie on the upland of the Spring Valley region and by forest in the Mississippi River gorge near Lake Pepin.

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SALISBURY HILL ROAD CUT: A DEFORMED MULTIPLE-TILL SECTION NEAR HENDERSON, SCOTT COUNTY, MINNESOTA

Barbara A. Lusardi

ABSTRACT

As many as five Quaternary tills are exposed in the Salisbury Hill road cut. All but one of the tills may be tentatively correlated with tills described from southern Minnesota. The order of the till units in the stratigraphic sequence at Salisbury Hill, however, does not match that established elsewhere in southern Minnesota.

Till unit 1 at the base of the section is a gray to brown calcareous loamy till that correlates with the old gray till described by Matsch (1971, 1972). Above this is a reddish sandy-loam till (till unit 2) that correlates with Matsch's Hawk Creek Till, as well as with other "red" tills identified across southern Minnesota and into South Dakota (Gilbertson, 1990; Patterson and Hobbs, 1995). Three tills (till units 3, 4 and 5) are present above this reddish sandy-loam till. It is apparent that these upper tills have been disturbed. At the "base" of this upper sequence is an olive-yellow calcareous loamy till that contains abundant shale (till unit 5). This till correlates with the Des Moines-lobe surface till that is described throughout southern Minnesota. Till unit 3 typically occurs at the "top" of the sequence; it is a sandy-loam shale-poor till that correlates with the Granite Falls Till of Matsch (1971, 1972). The intermediate till unit (till unit 4) does not correlate with tills described locally, although compositionally and texturally similar tills have been identified in southwestern Minnesota and eastern South Dakota (Matsch, 1971, 1972; Gilbertson, 1990; Lineburg, 1993; Patterson, 1995) and may represent till of the earliest Late Wisconsinan advance, dated at about 20,000–30,000 yrs. B.P. It is also possible that this intermediate till represents a zone of mixing between the upper till (unit 3) and lower till (unit 5). Complex folding and shearing observed at till-unit contacts at Salisbury Hill road cut are consistent with subglacial deformation by an advancing glacier and subsequent disruption of the original stratigraphic sequence.

INTRODUCTION

As many as five Quaternary till units are exposed in the Salisbury Hill road cut in Scott County along the Minnesota River valley in south-central Minnesota (Fig. 1). The till units record a complex glacial history and may not be in their original stratigraphic position. Correlation with established stratigraphic sections elsewhere in southern Minnesota (Table 1; Fig. 2) indicates that the till units at this site may have been deformed. The Minnesota River and its tributaries are incised as deeply as 85 m into the glacial uplands, which are covered by low-relief ground moraine attributed to the Altamont glacial phase of the Des Moines lobe (Hobbs and Goebel, 1982). In this study, the sediments were described and their stratigraphic relations mapped and assessed. The tills were sampled systematically for textural and grain-count analyses. The glacial stratigraphy of the five till units is interpreted here in the context of regional stratigraphic correlations that are based on till composition and texture.

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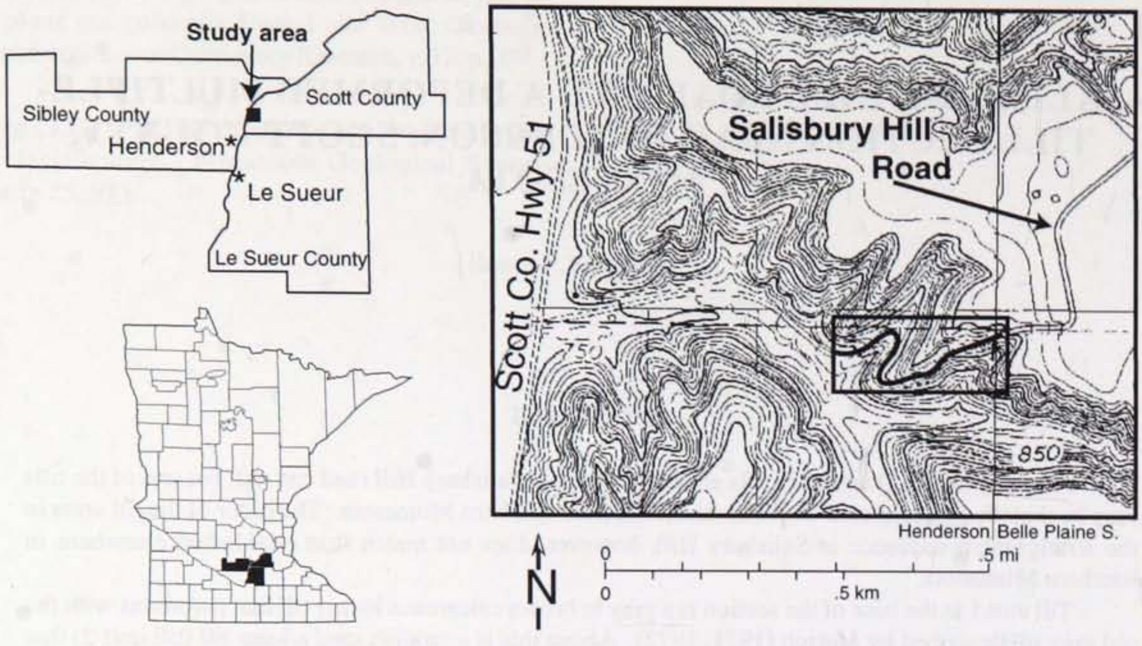

Figure 1. Location of Salisbury Hill Road study area in Scott County, Minnesota.

PREVIOUS WORK

South-central Minnesota was covered by ice many times during the Quaternary period. Glaciers advanced from the Keewatin and Labrador ice-accumulation centers in the northwest and the northeast (Fig. 3). The supply of ice from each of these centers fluctuated with time. Differences between the bedrock and the till cover within the regions traversed by the ice have contributed to the complex variations in till composition. The two source areas distinguished in this study are the Winnipeg lowlands and the Lake Superior basin (Fig. 3). The glacial sediments are best exposed along the Minnesota River valley, which served as the outlet for meltwater from Glacial Lake Agassiz during the last deglaciation. Glacial sediments and underlying bedrock are exposed in cutbanks along the length of the valley and within tributary streams.

The most recent investigations in south-central Minnesota were made by Matsch (1971, 1972), who examined surficial till in the New Ulm region (Fig. 2) and described four till units (Table 1). Matsch also did reconnaissance mapping within the Minnesota River valley and described a series of exposures containing "older tills." On the basis of these "older tills," Matsch inferred that at least four glacial advances took place during the Wisconsinan glaciation. The oldest till is a gray calcareous unit that contains very little shale. This "older till" is overlain by the Hawk Creek Till, which is a distinctive red-brown sandy-clay loam that contains material derived from the Lake Superior basin. The Hawk Creek Till is overlain by a calcareous till unit, the Granite Falls Till, that is yellow-brown to dark gray and contains only a trace of shale (less than 5 percent of the 1–2-mm fraction). The Granite Falls Till is overlain by the New Ulm Till; these two tills are separated either by a stone pavement, or by a thick sequence of sand and gravel. The New Ulm Till is an olive-brown clay loam to loam, with a distinctive high shale content (20–50 percent in the 1–2-mm fraction) that indicates derivation from the northwest. The New Ulm Till is the surface till over much of southern Minnesota. In Scott County it is mapped as stagnation deposits left by the Late Wisconsinan Des Moines lobe (Aronow and Hobbs, 1982).

A sequence of tills similar to that described by Matsch (1971, 1972) extends across southern Minnesota (Table 1). In northeastern South Dakota and the upper Minnesota River valley several pre-Late Wisconsinan and Late Wisconsinan tills have been correlated (Gilbertson, 1990) with tills defined by Matsch (1971, 1972). Tills in southeastern South Dakota (Lineburg, 1993), southwestern Minnesota (Patterson, 1995), and Rice County, Minnesota (Patterson and Hobbs, 1995) also fit into Matsch's general stratigraphic sequence (Fig. 2; Table 1).

METHODS

Salisbury Hill Road is located (Fig. 1) northeast of Henderson, Minnesota. It is a gravel road that climbs eastward up and around a ravine from Scott County

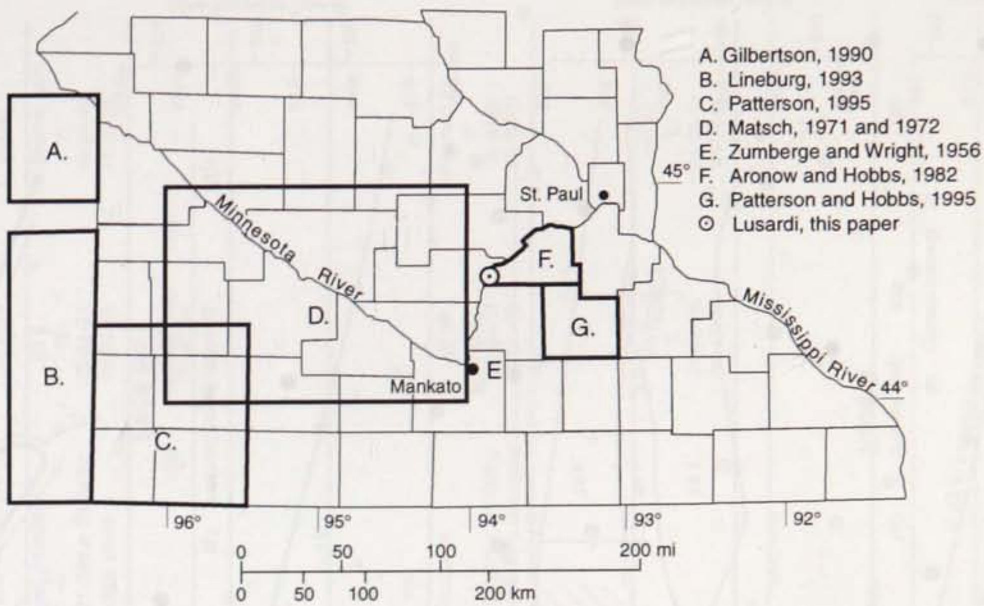

Figure 2. Location of previous studies on Quaternary till units in southern Minnesota.

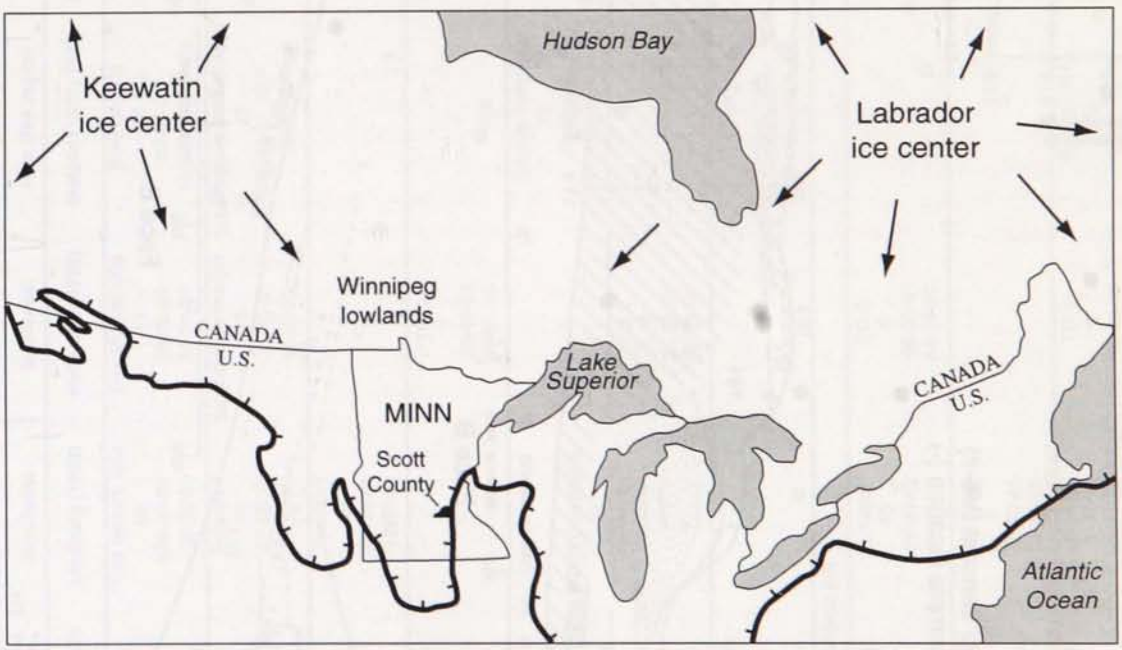

Figure 3. Late Wisconsinan ice margins (hachured line) in the Upper Midwest at approximately 14,000 yrs., showing the position of Scott County, Minnesota, and the location of the Lake Superior and Winnipeg lowland source areas, and the Labrador (northeast) and Keewatin (northwest) ice-accumulation centers. Modified from Meyer and Knaeble (1996).

Highway 51. The junction of Salisbury Hill Road and Scott County Highway 51 (Tyrone Township Road 2 in Le Sueur County) is 2.8 km north of State Highway 19 (T. 113 N., R 25 W., secs. 30 and 31, Henderson and Belle Plaine South 7.5-minute topographic quadrangles). The Salisbury Hill road cut provides 1.2 km of semi-continuous exposures of varying aspect, although landslides and slumping have modified the exposures. Samples were collected and analyzed in 1993-1994 after erosion provided clean, new exposures. In order to map and correlate sediments within and between the exposed faces of the Salisbury Hill road cut, the road was used as a

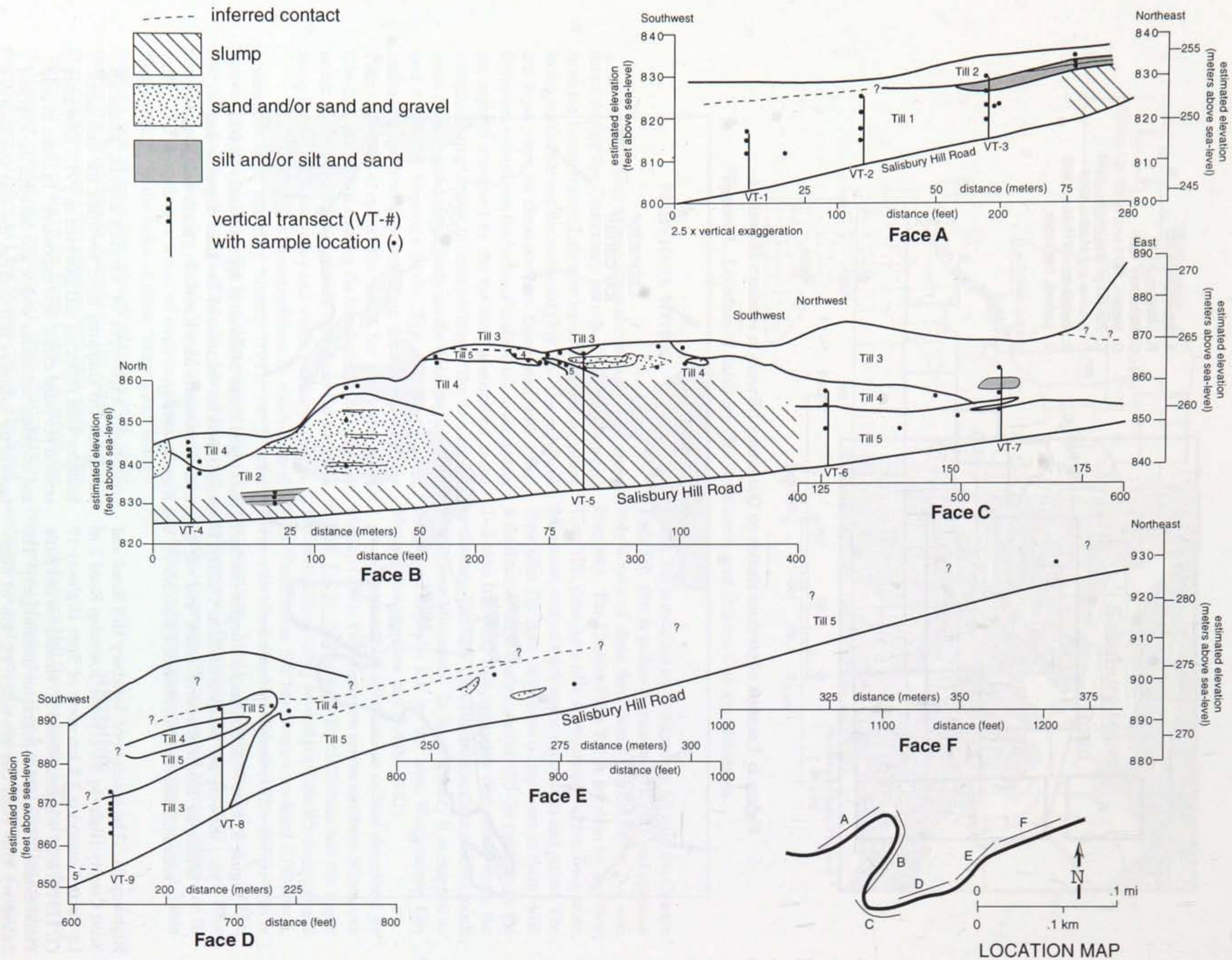

Figure 4. Mapped distribution and stratigraphic relations of till units exposed in the Salisbury Hill road cut. Vertical scale is given in feet and meters. Horizontal scale also given in feet and meters. See Figure 1 for location of the Salisbury Hill road cut.

Table 1. Summary of till-unit sequences and correlations across southern Minnesota and eastern South Dakota. Textural and compositional values are as reported by authors indicated.

	South Dakota		Minnesota				
	Grant County	Southeast	Southwest	New Ulm region	Mankato	Henderson	Rice County
	Gilbertson (1990)	Lineburg (1993)	Patterson (1995)	Matsch (1971, 1972)	Zumberge and Wright (1956)	This paper	Patterson and Hobbs (1995)
Till	New Ulm	Des Moines lobe	Des Moines lobe	New Ulm Till	Youngest (Mankato)	**till 5**	Des Moines lobe
No. of samples	131	59	13	30	–	**15**	5
sand-silt-clay	34-32-34	32-35-33	35-35-30	42-31-27*	32-53%s; 21-39%z; 23-34%c	**42-34-24**	46-38-16
xtlline-carb-shale^	50-22-28	38-38-31	53-29-18	16-34% carbonate	25-35% shale	**48-24-28**	47-26-28
Till	Toronto Till	Toronto II	Verdi ice margin	extra-morainic/Tazewell °	–	**till 4**	–
No. of samples	27	11	13	27		**21**	
sand-silt-clay	28-38-33	22-42-35	31-40-31	32-37-32 °		**45-37-18**	
xtlline-carb-shale^	55-28-17	42-39-20	42-35-22	39-40-21°		**58-24-18**	
Till	–	Toronto I	–	–	–	–	–
No. of samples		18					
sand-silt-clay		22-44-34					
xtlline-carb-shale^		42-37-21					
Till	–	–	TO 1	–	–	–	–
No. of samples			7				
sand-silt-clay			28-44-31				
xtlline-carb-shale^			45-41-13				
Till	Granite Falls Till	Drift Complex 5	–	Granite Falls Till	Middle till	**till 3**	unnamed till
No. of samples	37	28		17	–	**10**	6
sand-silt-clay	47-35-19	33-38-31		44-33-24*	17-46%s; 28-46%z; 24-36%c	**56-33-11**	44-40-16
xtlline-carb-shale^	61-32-07	60-25-15		44-44-12* (<5% shale)	3-5% shale; 36-47% dolostone	**62-29-09**	65-32-03
Till	–		TO 2	–	–	–	–
No. of samples			35				
sand-silt-clay			35-32-33				
xtlline-carb-shale^			73-21-04				
Till	Hawk Creek Till	–	–	Hawk Creek Till	–	**till 2**	red till
No. of samples	45			6		**5**	5
sand-silt-clay	55-29-16			55-22-23*		**51-33-16**	61-25-14
xtlline-carb-shale^	84-14-02			12-17% carbonate		**84-15-01**	76-24-00
	Gastropod Silt						
Till	Yellow Bank Till	Crooks	TO 3	–	–	–	–
No. of samples	7	65	5				
sand-silt-clay	30-29-41	28-30-42	25-33-41				
xtlline-carb-shale^	39-20-40	64-21-16	61-19-20				
Till	–	Big Sioux	–	–	–	–	–
No. of samples		5					
sand-silt-clay		25-30-45					
xtlline-carb-shale^		54-21-25					
Till	Whetstone Till	Brandon	TO 4	Kansan till °	Oldest till	**till 1**	old gray till
No. of samples	17	10	6	26	–	**12**	3
sand-silt-clay	39-33-28	25-39-36	19-29-51	29-27-44 °	–	**35-43-22**	44-35-21
xtlline-carb-shale^	60-25-15	49-27-24	43-26-31	65-30-05 °	3% shale; 3% dolostone	**43-52-05**	67-30-03

^ may be reported as Precambrian-Paleozoic-Cretaceous; * data from Matsch, 1971; ° data from Lucas, 1977;
%s = percent sand; %z = percent silt; %c = percent clay

Table 2. Location of till samples and results of textural and grain count analyses.

	Sample	Face	Texture (percent) Sand-Silt-Clay	Grain Count (percent) Crystalline-Carbonate-Shale	Normalized Silt	Normalized Crystalline
Till 1	91-1	A	35-44-20	41-53-06	69	44
	91-2	A	36-40-24	41-57-02	63	42
	91-3	A	36-42-22	36-60-04	66	38
	94- 1	A	36-42-22	47-48-05	66	49
	94- 2	A	34-43-23	41-54-05	65	43
	94- 3	A	34-43-23	40-55-05	65	42
	94- 4	A	37-42-21	46-49-05	67	48
	94- 5	A	34-43-22	46-50-04	66	48
	94- 7	A	35-43-22	52-46-02	66	53
	94- 8	A	34-43-23	44-50-06	65	47
	94- 9	A	34-43-23	41-54-05	65	43
	94- 6	A	34-42-24	53-44-03	64	55
Till 2	91-2	B	37-43-20	88-12-00	68	88
	91-6	A	55-32-13	84-16-00	71	84
	91-8	B	57-29-14	75-21-04	67	78
	94-11	A	53-36-12	88-12-00	75	88
	94-12	B	54-27-19	88-12-00	59	88
Till 3	94-26	B	52-38-10	66-24-10	79	73
	94-30	B	53-37-10	64-27-09	79	70
	94-36	C	49-40-11	59-33-08	78	64
	94-37	C	58-31-12	60-32-08	72	65
	94-38	D	60-29-11	61-29-10	73	68
	94-42	D	57-31-12	66-27-07	72	71
	94-43	D	58-31-11	64-28-08	74	70
	94-44	D	59-29-12	64-25-11	71	72
	94-45	D	57-30-12	59-33-08	71	64
	94-46	D	55-32-13	62-29-09	71	68
Till 4	91-1	B	44-35-21	52-29-19	63	64
	91-10	B	45-35-20	60-20-20	64	75
	91-13*	B	47-44-09	64-23-13	83	74
	91-15*	C	51-42-07	58-26-16	86	69
	91-18*	D	46-41-13	60-29-11	76	67
	94-14	B	46-34-21	65-21-14	62	76
	94-15	B	46-32-22	57-25-18	59	70
	94-16	B	46-36-18	63-27-10	67	70
	94-17	B	49-33-18	69-20-11	65	78
	94-18	B	41-35-24	52-29-19	59	64
	94-20	B	45-36-19	58-20-22	65	74
	94-22	B	47-33-21	56-26-18	61	68
	94-23	B	42-33-24	54-22-24	58	71
	94-25*	B	48-43-09	61-21-18	83	74
	94-27	B	40-33-27	43-17-40	55	72
	94-28*	B	48-43-08	65-25-10	84	72
	94-29	B	49-33-18	54-26-20	65	68
	94-31	B	48-32-21	64-23-13	60	74
	94-33	C	40-43-17	49-24-27	72	67
	94-34	C	37-56-08	61-30-09	88	67
	94-39	D	41-35-24	51-29-20	59	64
Till 5	91-12	B	41-33-26	51-18-31	56	74
	91-14	C	41-34-25	47-22-31	58	68
	91-16	C	41-33-26	50-23-27	56	68
	91-17	D	40-34-25	50-23-27	58	68
	91-19	E	43-35-22	44-32-24	61	58
	91-20	E	42-36-22	43-29-28	62	60
	91-21	F	44-36-20	47-27-26	64	64
	94-19	B	40-35-25	51-24-25	58	68
	94-21	B	46-31-23	50-22-28	57	69
	94-24	B	41-32-27	53-20-27	54	73
	94-32	C	41-34-25	48-25-27	58	66
	94-35	C	43-35-22	47-24-29	61	66
	94-40	D	39-37-24	44-34-22	61	56
	94-41	D	39-36-25	53-29-18	59	65
	94-47	D	41-32-27	46-26-28	54	64

normalized silt = (silt/(silt+clay))*100
normalized crystalline= (crystalline/(crystalline+carbonate))*100
* samples with texture more like till 3.

Table 3. Descriptive categories used for grain-count analyses.

Group	Components
Crystalline	granite and gneiss mafic igneous iron formation quartzite other metamorphic rhyolite and agate NE source red shale and sandstone
Carbonate	carbonate and dolostone limestone prism
Shale	gray speckled
Other	chert sedimentary pyrite lignite unknown secondary

base line. The lateral and vertical extent of each visually determined unit was mapped and plotted relative to this base line, as was the location of each sample (Fig. 4). Measurements and detailed sediment descriptions start 0.72 km east of County Highway 51.

Samples were collected in vertical transects. An extension ladder was used to collect samples between the base line up to a height of about 9 m, where the slope permitted. Where exposures were slumped or inaccessible by ladder, isolated samples were collected. Data include field descriptions of the sedimentary units and facies and their stratigraphic relations (Table 2). Samples were collected for textural analysis and grain-count analysis of the 1–2-mm sand fraction. Grain-count analyses were conducted following a method similar to that of Hobbs (this volume), using descriptive categories (Table 3). Computer-assisted lithostratigraphic techniques (Harris, 1987, and this volume) were also used to refine stratigraphic field observations; these techniques use interactive statistical methods for grouping till samples according to texture and detrital-grain type. Samples are characterized by four correlation parameters: (1) percentage of sand; (2) normalized percentage of silt; (3) normalized percentage of crystalline 1–2-mm sand grains, and (4) percentage of 1–2-mm shale grains. The parameters are graphed, and clusters of associated samples are identified (Fig. 5 and Table 2). Each cluster is refined to within two standard deviations of the mean. When all of the clusters are identified, defining parameters are compared to reduce overlap. In this study the technique provided five till groups, which were defined on the basis of average texture (sand, silt, clay) and detrital grain type (crystalline, carbonate, shale) (Table 4). With this procedure, 84 percent of the 70 till samples included in the analysis belonged to one of the five identified till groups.

The computer-assisted lithostratigraphic techniques are useful for corroborating field evidence. They also help identify units that look similar in the field but are distinct in texture and detrital grain type. Much of the exposure in the Salisbury Hill road cut is discontinuous or slumped, so it is difficult to determine stratigraphic relations and sequences, especially where the contacts are covered or disturbed.

DESCRIPTION OF STRATIGRAPHIC UNITS

Five till units (till unit 1 through till unit 5) are recorded from exposures in the road cut. Discontinuous silt, sand or sand and gravel bodies were also noted, but were not studied in detail. The characteristics of each till unit are summarized in Table 4; sample details are provided in Table 2. Maps of the exposures in the Salisbury Hill road cut are shown in Figure 4.

Till Unit 1 - Description

Till unit 1 is exposed at the lower, western end of face A (Fig. 4). The till has a loamy matrix, is calcareous and is gray brown (2.5Y 5/2) to light yellowish brown (2.5Y 6/4), although the color changes laterally as a result

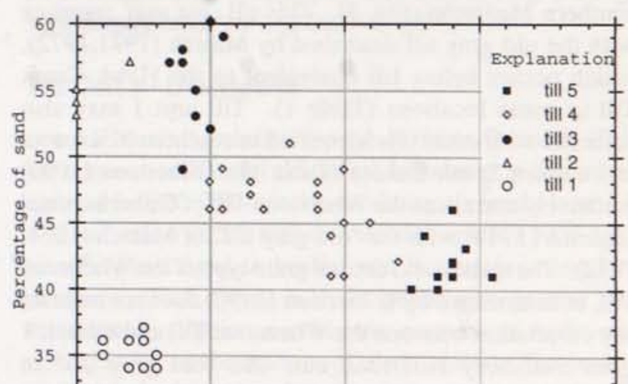

Figure 5. Graph showing sample clusters identified on the basis of computer-assisted lithostratigraphy. The criteria used are percentage of shale and percentage of sand. Not all of the samples listed in Table 2 were recognized as belonging to till clusters identified using computer-assisted stratigraphy.

Table 4. Summary description of till units described from Salisbury Hill road cut.

Till	Thickness	Color (wet)	Characteristics	Texture sand-silt-clay	Grain-Count crystalline-carbonate-shale
5	> 30 m	2.5Y 6/4 –6/6 light yellow brown to olive yellow; range 10YR 4/2 –5Y 5/2; lateral color variations possibly due to oxidation changes	Massive, blocky, pebbly, calcareous; contains lenses or pods of fine sand and gravel; contact is deformed	42-34-24	48-24-28
4	7.3 m	2.5Y 6/6 olive yellow; range 10YR 6/8 –5Y 5/2	massive, blocky, pebbly, calcareous; contact is deformed	46-37-17	60-24-16
3	> 12 m	2.5Y 6/6 –7.5YR 6/6 olive yellow to reddish yellow; range 7.5YR 6/6 –2.5Y 6/4	massive, pebbly, calcareous, extremely hard; irregular contact where visible	56-33-11	62-29-09
2	9 m (including sand)	10YR 6/4 light yellowish brown; range 10YR 6/6 –2.5Y 5/4; appears distinctly "red"	Massive, pebbly calcareous; includes a thick sequence of stratified sand and gravel and fine cross-bedded sand	55-31-14	83-16-01
1	8.5 m (exposed)	2.5Y 6/4 light yellowish brown; range 10YR 6/6 –5Y 3/1; lateral color variation possibly due to oxidation changes	massive, blocky, pebbly, calcareous	35-43-22	43-02-55

of oxidation. It is blocky when spaded, and oxidized along joint faces. Clast types include crystalline rocks (granite, gneiss), volcanic and metavolcanic rocks (basalt and greenstone), carbonate (limestone and dolostone) clasts, and minor amounts of shale. The texture and detrital grain types for till unit 1 are shown in Figure 6 and Tables 2 and 4.

Till Unit 1 - Interpretation

The abundance of carbonate clasts in till unit 1 suggests ice transport from the Winnipeg lowland in southern Manitoba (Fig. 3). This till unit may correlate with the old gray till described by Matsch (1971,1972), which occurs below till equivalent to the Hawk Creek Till in some locations (Table 1). Till unit 1 may also correlate with other tills identified in southern Minnesota and eastern South Dakota (Table 1). Gilbertson (1990) tentatively correlates the Whetstone Till of Gilbertson and Jensema (1987) with the "old gray till" of Matsch (1971, 1972). The texture and detrital grain type of the Whetstone Till, as determined by Gilbertson (1990) does not indicate any correlation between the Whetstone Till and till unit 1 from Salisbury Hill road cut. An "old gray till" in southwestern Minnesota (till TO4 of Patterson, 1995), as well as a deep till described from a Rotasonic drill core from Lonsdale in Rice County, Minnesota (Patterson and Hobbs, 1995), may correlate with till unit 1 (Table 1). Texture and grain type within each of these units varies, making definitive correlation difficult.

The Brandon Till of southeast South Dakota (Lineburg, 1993) has not been definitively correlated with any of the other tills listed in Table 1, although Patterson (1995) correlates till TO4 in southwestern Minnesota with

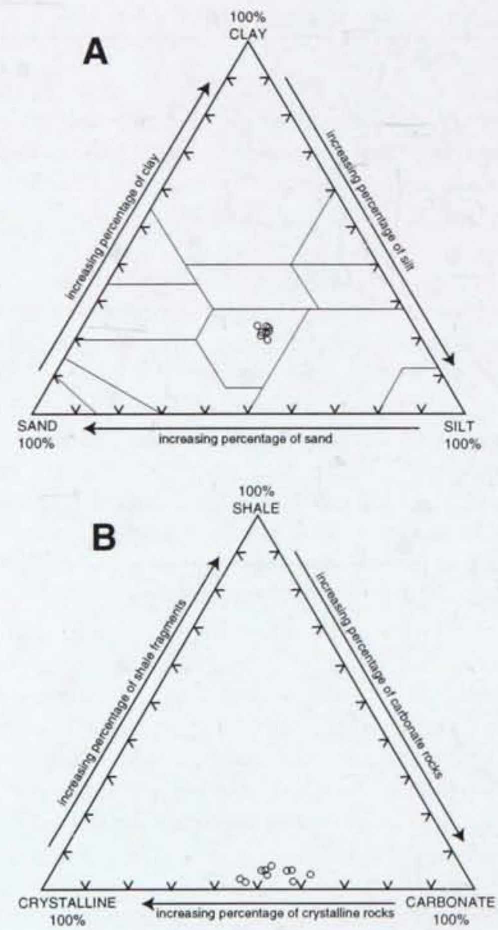

Figure 6. Ternary diagrams showing (**A**) matrix texture and (**B**) detrital grain composition of 1–2 mm sand fraction of samples in till unit 1 (n=12).
(**A**) Average sand:silt:clay = 35:43:22
(**B**) Average crystalline:carbonate:shale = 43:52:05

the Brandon Till. Lineburg (1993) correlates the Brandon Till with the upper unit of drift complex 3 found in the Coteau des Prairies, and Gilbertson (1990) correlates the Whetstone Till with drift complex 3. Despite some uncertainties, these units are all indicated to represent the same stratigraphic interval in Table 1.

Till Unit 2 - Description

Till unit 2 is best exposed on the lower, northern part of face B (Fig. 4). Till unit 2 has a sandy loam matrix, and is calcareous. It is massive and pebbly. It ranges in color from brownish yellow (10YR 6/6) to light olive brown (2.5Y 5/4), although it appears distinctly red in the exposed section. The red tint results from the presence of detrital grains of red sandstone. The texture and detrital-grain types for till unit 2 are shown in Figure 7 and Tables 2 and 4.

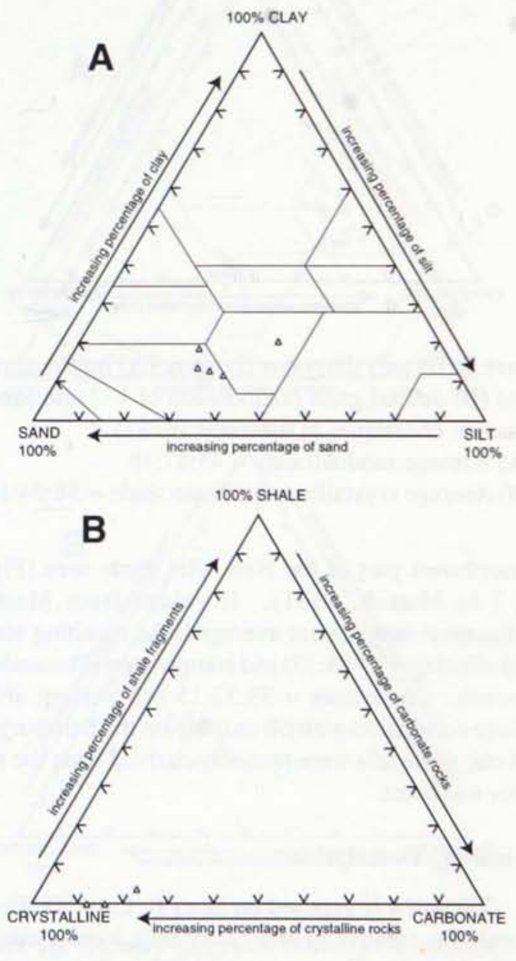

Figure 7. Ternary diagrams showing (**A**) matrix texture and (**B**) detrital grain composition of 1–2 mm sand fraction of samples in till unit 2 (n=5).
(**A**) Average sand:silt:clay = 51:33:16
(**B**) Average crystalline:carbonate:shale = 84:15:01

In face A, till unit 2 overlies till unit 1. The contact is marked by a thin zone of silt and coarse sand. In face B, till unit 2 is in unconformable stratigraphic contact with the overlying till unit 4. This contact is irregular and marked locally with a line of rounded cobbles. A thick sequence of stratified coarse sand and gravel grading into fine cross-bedded sand occurs within till unit 2. The entire sand unit is up to 3.6 m thick and is capped with a thin "shelf" of cemented sand. In face C till unit 4 is underlain by till unit 5, and till unit 2 is absent. The contact between till unit 2 and till unit 5 is not observed in the Salisbury Hill road cut.

Till Unit 2 - Interpretation

The texture and detrital-grain types within till unit 2 are consistent with ice transport from the Lake Superior basin in the northeast (Figs. 3 and 7 and Table 4). Red sandstone clasts are derived from the Lake Superior basin; rhyolitic, intrusive igneous and metamorphic clasts are probably derived from the northeast. The stratified sand and gravel unit contains a similar range of detrital-grain types and was probably derived from the same source area. The sand and gravel may represent subglacial deposits.

Till unit 2 correlates well with the Hawk Creek Till on the basis of composition and texture as described by Matsch (1971, 1972), who cites a location near Le Sueur, Minnesota (sec. 11, T 112 N., R. 34 W., about 5 mi south of Henderson; Fig. 1) as an exposure of Hawk Creek Till. Till unit 2 also correlates well, both compositionally and texturally (Table 4), with the Hawk Creek Till in South Dakota as described by Gilbertson (1990), and with a red till described from a Rotasonic drill core in Rice County, Minnesota (Patterson and Hobbs, 1995).

Till Unit 3 - Description

Till unit 3 is best exposed on faces C and D (Fig. 4); a minor amount of till unit 3 is present in the upper parts of face B. Till unit 3 is a calcareous sandy loam. It is olive yellow (2.5Y 6/6) to reddish brown (7.5YR 6/6), massive, and hard to break, and it contains abundant pebbles. Clast types include abundant igneous and metamorphic rocks, a moderate amount of carbonate clasts, and a minor amount of shale clasts. The texture and detrital-grain types for till unit 3 are shown in Figure 8 and Table 4.

Stratigraphic relations between till unit 3 and underlying till units 4 and 5 on face B are not clear. Till unit 3 overlies till unit 5 in the uppermost part of face B; till unit 3 also forms an isolated body of till extending down into till unit 4 in the upper part of face B. On face C, till unit 3 is the most voluminous. It overlies till unit 4 (which thins to the southeast). Where till unit 4 is absent, till unit 3 overlies till unit 5. Till unit 3 extends laterally

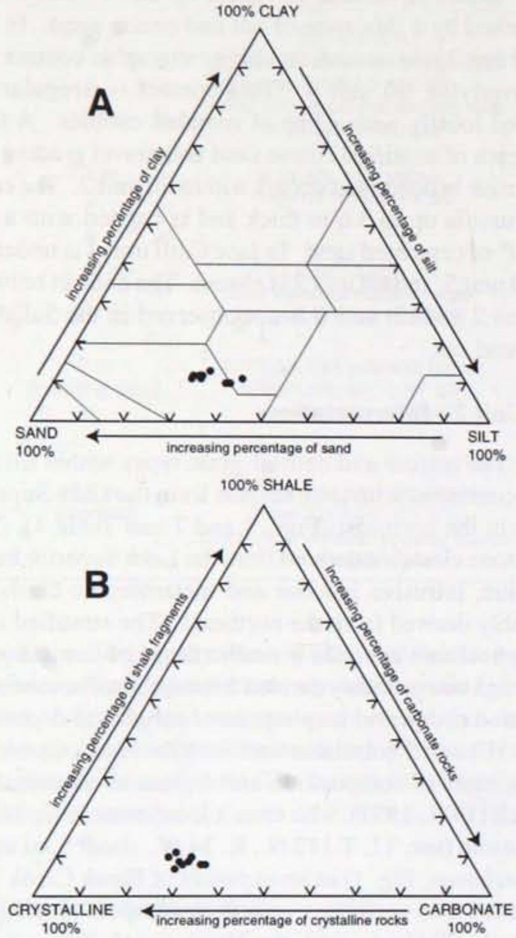

Figure 8. Ternary diagrams showing (**A**) matrix texture and (**B**) detrital grain composition of 1–2 mm sand fraction of samples in till unit 3 (n=10).
(**A**) Average sand:silt:clay = 56:33:11
(**B**) Average crystalline:carbonate:shale = 62:29:09

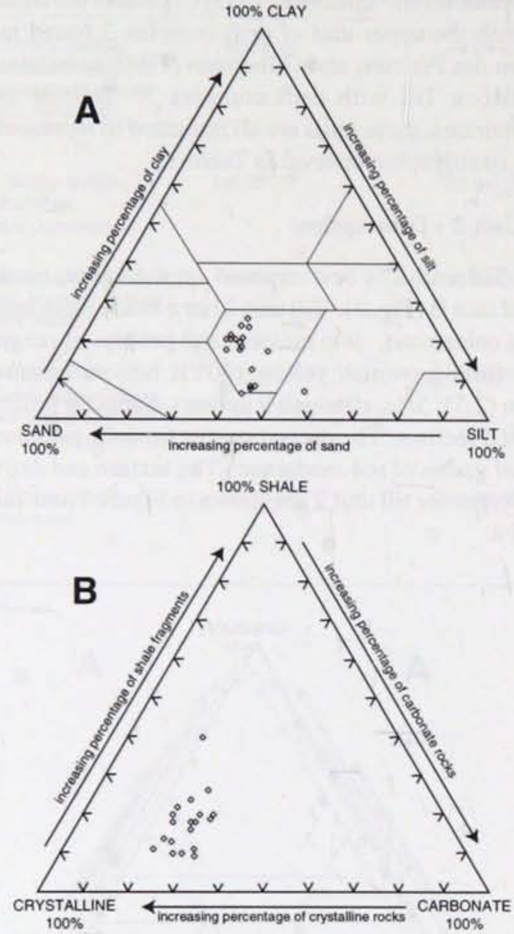

Figure 9. Ternary diagrams showing (**A**) matrix texture and (**B**) detrital grain composition of 1–2 mm sand fraction of samples in till unit 4 (n=21).
(**A**) Average sand:silt:clay = 45:37:18
(**B**) Average crystalline:carbonate:shale = 58:24:18

northeastward and is exposed on face D; here it contains a large (25 m long, 4 m thick) body composed of till units 4 and 5. This large inclusion is easily identified by the distinctive color of till units 4 and 5 compared to the lighter color of surrounding till unit 3.

Till Unit 3 - Interpretation

Till unit 3 correlates well with the Granite Falls Till. Till unit 3 is characterized by a relatively low percentage of both clay and shale (Tables 2 and 4, Fig. 8). The Granite Falls till as described by Matsch (1971) can be separated into two distinct groups, each with a slightly different texture and detrital-grain type. Granite Falls Till collected by Matsch from the southeastern part of the New Ulm study area is consistently sandier and contains a higher proportion of crystalline rock, compared with that from the northwest part of the New Ulm study area (Figs. 6 and 7 in Matsch, 1971). If values from Matsch's southeastern samples are averaged, the resulting texture (sand:silt:clay = 54:33:13) and composition (Precambrian: Paleozoic: Cretaceous = 53:32:15 [<5 percent shale]) indicate correlation with till unit 3 from the Salisbury Hill road cut; these tills were probably derived from the north and/or northeast.

Till unit 4 - Description

Till unit 4 is exposed on faces B, C and D (Fig. 4). Till unit 4 is an olive yellow (2.5Y 6/6), loamy, massive, and blocky unit. Clast types are dominantly igneous and metamorphic, and carbonate clasts are locally common; shale clasts range from common to rare. The texture and detrital-grain types for till unit 4 are shown in Figure 9 and Tables 2 and 4.

On face B, till unit 4 overlies till unit 2. To the south the nature of this contact is obscured. The upper contact of till unit 4 on face B is complex (Fig. 4); between 50–65 m till unit 4 is overlain by till unit 5, and the contact appears to be sheared. Laterally to the southwest, the upper contact of till unit 4 is highly sheared, and lenses of boudinaged and sheared silt, sand, and gravel are present. The sand forms lenses and boudin-like pods. Fingers or wedges of till from below intrude up into the sand in some locations. Wedges of till unit 5 are also sandwiched between layers of unit 4. In the uppermost part of face B, the sands and gravelly sands are overlain by till unit 4, and the lateral transition between till units 5 and 4 is obscured.

On face C till unit 4 overlies till unit 5 and underlies till unit 3, thinning to become absent in the southeast. The nature of both the upper and lower contacts of till unit 4 is unclear, although at 150 m till unit 5 and till unit 4 are interlayered. The nature of the contact between till units 4 and 3 is not readily apparent in the field. Five of the samples from till unit 4 (indicated with an asterisk in Table 2) were collected in the vicinity of the contact and contain slightly less clay than the rest of the 21 till unit 4 samples (Fig. 9A). These five till samples are texturally most similar to till unit 3 (Fig. 8A). Till unit 4 is more compositionally diverse (Fig. 9B) than till unit 3, but the same four samples that are texturally distinct from most of till unit 4 are also those that bear most compositional similarity to the more homogeneous till unit 3 (Fig. 8B). On face D till unit 4 forms an isolated lens or body wrapped by till unit 5, which itself is part of a lens or tongue that is wrapped by till unit 3.

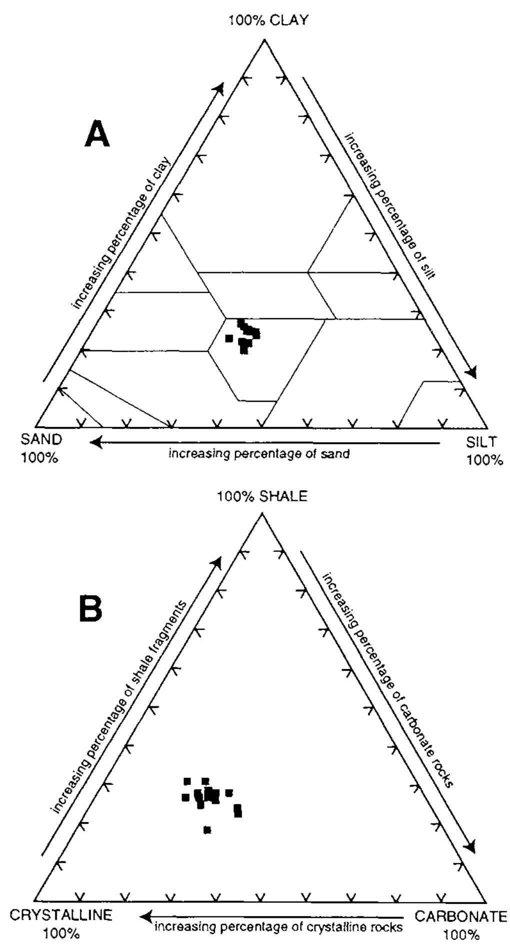

Figure 10. Ternary diagrams showing (**A**) matrix texture and (**B**) detrital grain composition of 1–2 mm sand fraction of samples in till unit 5 (n=15).
(**A**) Average sand:silt:clay = 42:34:24
(**B**) Average crystalline:carbonate:shale = 48:24:28

Till unit 4 - Interpretation

The moderate carbonate and shale content of till unit 4 suggests derivation from a source to the northwest. In southwestern Minnesota and eastern South Dakota, Patterson (1995), Gilbertson (1990), and Lineburg (1993) have identified tills containing similar rock types in the coarse-sand fraction (Table 1), which may correlate with Matsch's "extra morainic" till (Matsch, 1972). Till unit 4, however, does not correlate well texturally or compositionally with any of the locally described tills.

Till unit 4 may represent till of the earliest Late Wisconsinan advance dated at approximately 20,000–30,000 yrs. B.P. Till of this advance includes the Toronto Till (Gilbertson, 1990), the extra-morainic till (Matsch, 1972), and possible correlative tills listed in Table 1. Till of the earliest Late Wisconsinan advance is recognized in southwestern Minnesota and Iowa (Clayton and Moran, 1982). However, there is no record of other such tills across south-central Minnesota (Zumberge and Wright, 1956; Matsch, 1971, 1972). Without additional data from the local area, any correlation between till unit 4 and these southwestern tills is questionable.

Evidence from face B (50–65 m) linked to evidence from face C (125–160 m) and face D, suggests that the upper part of till unit 4 on face B, as well as till unit 4 on faces C and D may represent a zone of mixing between till units 3 and 5. This would also account for the observation that no local tills correlate with till unit 4.

Till unit 5 - Description

Till unit 5 is a loamy calcareous till that is olive yellow (2.5Y 6/6) to reddish yellow (7.5YR 6/6), although color does change laterally. It is generally massive and blocky, although small lenses and pods of fine sand and gravel, as well as thin layers of fine silt, are common. Clast types include abundant crystalline rocks, with carbonate and shale being present in about the same proportion. The texture and detrital-grain types for till unit 5 are shown in Figure 10 and Tables 2 and 4. This till unit is the most extensively exposed and is at least 30 m thick.

Till Unit 5 - Interpretation

The high shale content of till unit 5 indicates derivation from the northwest. It correlates well with the surface Des Moines-lobe till described throughout southern Minnesota (Table 1). Correlation of till unit 5 with this youngest regional Late Wisconsinan till, together with evidence of disturbed contacts between till unit 5 and adjacent till units suggests that a significant amount of deformation took place during or after deposition of till unit 5, particularly if the current position of till unit 5 beneath the older till units is considered.

CONCLUSIONS

The five till units exposed in the Salisbury Hill road cut are interpreted here as not being in their correct stratigraphic sequence. The current position of till units 3, 4, and 5 is interpreted to result from deformation during and/or after deposition of till unit 5. More recent landslides and slumping continue to obscure the already complex relations.

These interpretations are based on two lines of reasoning. Firstly, if tentative correlation of all but one of the five till units with tills described from southern Minnesota is valid, the current stratigraphic sequence of tills observed in the Salisbury Hill road cut does not match the sequence elsewhere in Minnesota. Secondly, comparison with the till sequence elsewhere in southern Minnesota indicates the current placement of clearly younger till units beneath clearly older till units. When coupled with field evidence for the folding and shearing of units it is clear that these units have been deformed.

Additional support for deformation can be gleaned from the compositional evidence that the most disturbed till unit (till unit 4) does not correlate with any locally known till units. The composition of till unit 4 seems to indicate that it is, in part at least, a mixture of till units 3 and 5. Alternatively, till unit 4 could be a separate till that reflects the easternmost extent of the 20,000–30,000 yrs B.P. ice-margin that, to date, has only been identified as extending into southwestern Minnesota. Regardless of the origin of till unit 4, deformation of till units 3, 4, and 5 is clearly established.

This deformation may have taken place either as post-glacial downhill slumping or as a result of glacial thrusting. The folding and the boudinaged and sheared nature of the lithologic contacts (faces C and D, Fig. 4) may reflect active thrusting associated with the movement of ice over a relatively soft substrate. Semi-consolidated till may have been overturned during transport and subsequently been re-deformed during deposition. The combination of features observed indicates that deformation could have occurred both by shearing and by compression and extension during ice advance, all of which are processes typical of subglacial deformation (Hart and Boulton, 1991). Assessment of at least two other sections in the vicinity of Henderson (Lusardi, 1994) provides evidence for deformation. More extensive detailed analysis of these sites would provide constraints on the timing and nature of deformation and the origin of till unit 4. Correlations and stratigraphic relations indicate that the till units were deposited and deformed as follows:

1. Deposition of till unit 1 followed by deposition of the silt and sand and gravel units which overlie till unit 1.
2. Erosion of some of till unit 1 and the silt, sand and gravel, followed by the deposition of till unit 2.
3. Localized erosion of till unit 2 and formation of a cobble layer that locally mantles the upper erosion surface.
4. Deposition of till unit 3.
5. Deposition of till unit 5. Deformation associated with ice advance across the soft substrate of till unit 3 resulted in the development of a mixed till unit (till unit 4), which locally mantles underlying till unit 2 in an apparent sedimentary contact (face B, 10 m). Deformation associated with deposition of till unit 5 probably took place in a series of stages, and accounts for the apparent complex relations observed between till units 3, 4 and 5, and their local stratigraphic inversion.

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THE "GASTROPOD SILTS" OF WESTERN MINNESOTA AND NORTHEASTERN SOUTH DAKOTA

Mary E. Pirkl[1], Carla L. Kuglin[2], and J.F.P. Cotter[2]

ABSTRACT

Pollen and beetle studies indicate that the informally named "gastropod silts" were deposited under subarctic conditions. This is in agreement with previous suggestions that the "gastropod silts" are glaciofluvial and glaciolacustrine in origin. These laminated to massive fossiliferous clays, silts, and sands are Late Illinoian in age. The environmental interpretations presented here for the "gastropod silts" are important for the reconstruction of pre-Wisconsinan glacial history of the Upper Midwest.

INTRODUCTION

The informally named "gastropod silts" are commonly recognized in drill cores and exposed in deep stream cuts (Fig. 1) at several localities in western Minnesota and eastern South Dakota (Gilbertson and Huber, 1989), however, the lateral extent of these deposits is unknown. They are laminated to massive fossiliferous clays, silts, and sands, which have been interpreted as glaciofluvial and glaciolacustrine in origin (Gilbertson and Huber, 1989; see also Table 1 of Lusardi, this volume). The depositional mechanisms, environment, and paleoclimate associated with this unit, as well as its postdepositional history, are poorly understood. Samples from two previously studied "gastropod silt" localities, together with samples from a newly identified "gastropod silts" locality were examined to assess and interpret their pollen and beetle content. The goals of this study were (1) to further constrain the age of the "gastropod silts"; (2) to determine whether the pollen and beetle data will allow more detailed correlation between localities, and (3) to interpret the paleoclimatic conditions during or immediately prior to deposition of the "gastropod silts."

The "gastropod silts" underlie the Early Wisconsinan Hawk Creek Till (Fig. 2). Gilbertson and Huber (1989) concluded on the basis of pollen and beetle analysis that the unit was deposited during a glacial rather than interglacial period. Amino-acid racemization measurements of two shells of the gastropod *Pupilla muscorum* provided a date of 140,000 ± 70,000 yrs B.P. (Gilbertson, 1990), which led Gilbertson and Lehr (1989) and Gilbertson (1990) to assign a Late Illinoian age and tentatively correlate the gastropod silts with the Gervais Formation (Harris and others, 1974) of the Red Lake River valley in northwestern Minnesota.

The gastropod silts typically consist of a basal inorganic layer of iron-rich sands, silts, and clays, which grades upward into a 0.5 m thick organic clayey silt that contains microfossils and gastropods. Five aquatic snails and eight land snails were identified (Hoganson and Cvancara, 1990), as well as small wood fragments and other organic material. The organic silts are overlain by a 0.4-m layer containing abundant wood fragments and dense organic material.

METHODS

The gastropod silts were described, sampled, and analyzed for pollen and beetle content at three localities (Fig. 1). The Nordick Farm locality contains one exposure in a drainage ditch leading to the North Fork of the Yellow Bank River in Lac Qui Parle County, Minnesota (SW1/4 NW1/4 NE1/4 NE1/4 sec. 20, T. 120 N., R. 46 W.). The

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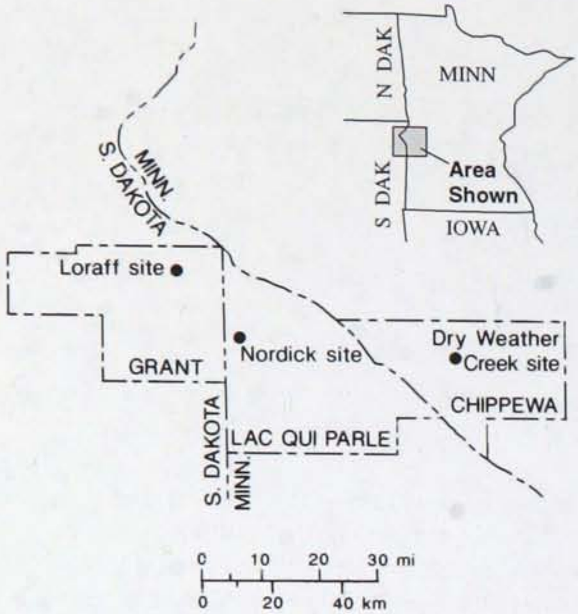

Figure 1. Localities sampled for pollen and beetle studies in western Minnesota and northeastern South Dakota

Dry Weather Creek locality is an exposure in a stream cutbank in Chippewa County, Minnesota (NW1/4NE1/4NE1/4 NE1/4 sec. 11, T. 118 N., R. 41 W.). The Loraff locality is an exposure in a stream cutbank in the North Fork of the Whetstone River in Grant County, South Dakota (SW1/4SW1/4NW1/4NE1/4 sec. 13, T. 121 N., R. 46 W.). The Nordick Farm and the Loraff site have both been analyzed previously for pollen (Gilbertson and Huber, 1989) and beetle content (Garry, 1992). The Dry Weather Creek locality has not been previously examined. At the Nordick Farm and the Dry Weather Creek localities ten samples were taken for pollen analysis and four for beetle analysis. At the Loraff site twelve samples were taken for pollen analysis and three for beetle analysis.

Sample processing and pollen analysis were conducted at the University of Minnesota in Morris. Prior to chemical treatment of samples a Lycopodium clavatum spike was added to each 1 cm^3 sample to document loss of pollen and to determine pollen concentrations. Chemical preparation of pollen samples included deflocculation with potassium hydroxide, leaching of silicates with hydrofluoric acid, and acetolyzation of organic matter with glacial acetic acid and a fresh mixture of acetic anhydride and concentrated sulphuric acid following the method of Faegri and Iverson (1975). Pollen concentrates with Lycopodium spike were then suspended in Permount, stained with crystal violet, and mounted on slides.

Beetle analyses were completed at the Quaternary Entomology Laboratory of North Dakota State University with the assistance of Dr. Donald Schwert. Chitonous remains of insects were isolated from sediments and prepared for identification and storage following the procedures of Ashworth (1979). The beetle remains are now stored for further study by C. Garry, University of Wisconsin at River Falls.

RESULTS

Pollen Analysis

Due to extensive oxidation and deformation, and the obscuring of pollen grains by large organic fragments, a total of only 153 pollen grains was counted from all three sites (109 at the Loraff locality, 23 at the Nordick locality and 21 at the Dry Weather Creek locality); the pollen percentages are presented in Figure 3. Unidentified grains are included in percentage calculations (Fig. 3) to indicate the extent of the poor preservation.

At each site *Picea* (spruce, 13–31 percent) and *Pinus* (pine, 3–8 percent) are represented in significant proportions. Pollen of other arboreal species were recognized and include *Quercus* (oak) and *Salix* (willow). Nonarboreal species include Rosaceae (rose), family Ericaceae (heaths), and Rubiaceae (madder) family. Also represented are Cyperaceae (sedges), *Sphagnum* , and Polypodiaceae. The variation in occurrence and percentages of different pollen species among the three sites is due to influence of local vegetation as well as poor

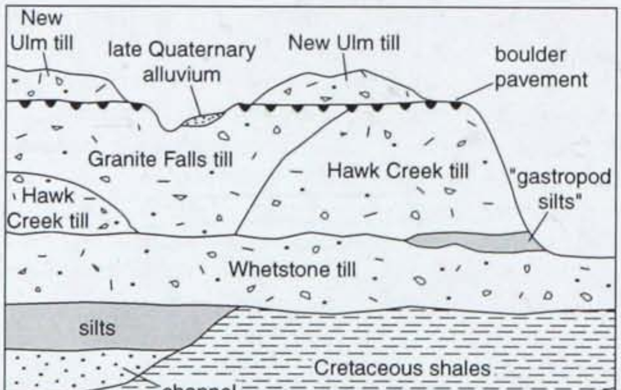

Figure 2. Generalized stratigraphic section showing the relative position of near-surface units in western Minnesota and northeastern South Dakota (redrawn from Gilbertson and Lehr, 1989)

preservation. Because of the poor preservation, only the "presence" of species is certain. The pollen percentages provide only an indication of species population.

Beetle Analysis

Approximately 37 pronota, elytra, and heads were recovered from bulk samples through a series of floatings in kerosene (Ashworth, 1979). The chitinous exoskeletons survived postdepositional weathering to such an extent that identification of species was possible in many cases. Analysis yielded members of the Carabidae, Staphylinidae, Byrrhidae, and Hydrophilidae families (Table 1). The best and most paleoenvironmentally significant species identified were those of *Diacheila polita* Faldermann, *Olophrum latum* Maklin, and *Helophorus arcticus* Brown.

Paleoenvironmental Interpretation

Previous studies (Gilbertson and Huber, 1989; Gilbertson, 1990; Garry, 1992) suggested that the gastropod silts were deposited in a laterally extensive, possibly proglacial lake during a cool interval in the Late Illinoian deglaciation. On the basis of gastropod analysis, Hoganson and Cvancara (1990) concluded that the sediments were deposited close to a wooded area. The results of this study are in agreement with these interpretations. Although poorly preserved, the pollen and beetle assemblages appear to indicate a subarctic climate with a mean July temperature of approximately 12°C.

Table 1. Cumulative species list for Arthropods (beetles) retrieved from the Nordick Farm, Loraff, and Dry Weather Creek Localities

[Compiled by D. Schwert, Sept. 19, 1991]

—Phylum: Arthropoda
—Class: Insecta
—Order: Coleoptera
—Family: Carabidae
—*Diacheila polita* Faldermann
—Family: Staphylinidae
—*Olophrum latum* Maklin
—*Bledius* sp.
—*Stenus* sp.
—*Eucnecosum* sp.
—*Tachinus* sp.
—Family: Byrrhidae
—*Simplocaria* sp.
—Family: Hydrophilidae
—*Helophorus arcticus* Brown

The pollen assemblage represents an environment characterized by ground mosses, shrubs, and sparse trees, typical of wet regions with cold temperatures. Sedge, Sphagnum, and Polypodiaceae are indicative of standing water. The presence of heath, rose, and madder, together with low percentages of willow and oak (perhaps as shrubs) indicate that relatively few trees other than conifers were in the area. The high amounts of pine (3–8 percent) and spruce (13–31 percent) pollen in the samples may be misleading, for the bladders of these pollen types make them conducive to wide airborne distribution. The

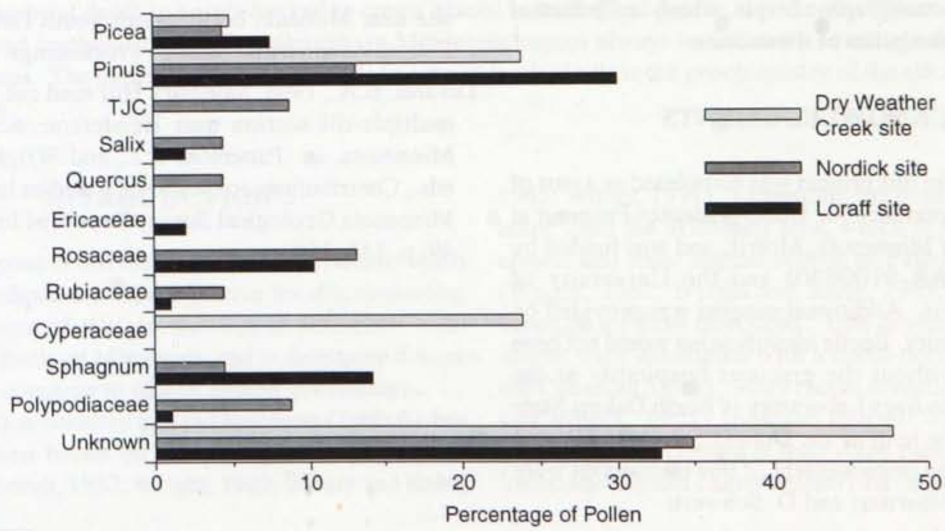

Figure 3. Pollen diagram for the Loraff, Nordic Farm and Dry Weather Creek localities. Pollen types are indicated on the vertical axis (TJC = Thuja, Chamaecypris, and juniperis); obscured, crumpled and unidentifiable grains were counted as 'unknown'. Percentage of Pollen axis represents the percentage of pollen at each individual site.

presence of pine and spruce in the pollen record is therefore believed to represent regional rather than local occurrence of these trees.

The beetle species identified at these sites are subarctic species adapted to harsh temperatures and a lack of ground cover. All taxa today occur in tundra and indicate a subarctic climate. Garry (1992) similarly concluded that the biotic community represented at both the Nordick Farm and the Loraff localities represents a forest-tundra environment.

Age and Correlation

The amino-acid age of 140,000 ± 70,000 yrs B.P. from gastropods (Gilbertson, 1990), together with the presence of subarctic flora and fauna, the absence of Sangamonian interstadial indicators (soils and temperate flora) as well as their stratigraphic position all support a Late Illinoian age for the "gastropod silts" as suggested by Gilbertson and Lehr (1989) and Gilbertson (1990). However, age assessments would be clarified if the stratigraphic relations between the gastropod silts and the Gervais Formation of the Red Lake lowlands in northwestern Minnesota could be determined.

The Gervais Formation (Harris and others, 1974) and the "gastropod silts" yield similar ages based on amino-acid analysis of wood (Gilbertson, 1990); they also share sedimentological characteristics and have a similar microfossil content. Both units consist of interbedded sand, silt, and clay with abundant wood fragments and mollusk shells. Both units contain 40–50 percent clay and silt, and range from dark gray (5Y 4/1) when wet to brown (7.5YR 5/2) when dry. Both the gastropod silts (in the south) and the Gervais Formation (in the north) occur at similar stratigraphic levels, which lends further support to the correlation of these units.

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METHODS OF TILL ANALYSIS FOR CORRELATION AND PROVENANCE STUDIES IN MINNESOTA

Angela S. Gowan

ABSTRACT

Many methods are used to describe tills. In order to determine which methods best discriminate between tills in Minnesota, this study compared the data from four commonly employed techniques (grain-size determination, matrix carbonate content, sand-grain composition, rock-magnetic properties) with that from matrix geochemistry on group of samples from six Minnesota tills. The six tills were chosen to include typical examples of both northeast- and northwest-sourced till, and one sample for which the provenance is disputed. The samples are from the Brainerd and Independence Tills (northeast provenance), the New Ulm, Granite Falls, and Browerville Tills (northwest provenance), and the Hewitt Till (disputed provenance).

Each till sample was described by a total of 68 variables, of which grain size accounted for 23, matrix carbonate content for 1, 1–2-mm sand-grain composition for 13, rock magnetic properties for 2, and matrix geochemistry for 29 of the variables. The data set was analyzed by traditional graphical methods as well as statistically using principal component analysis (PCA). The results of the PCA of the six tills were applied to till samples of uncertain origin collected from drillhole OB-402 northwest of Mille Lacs Lake in Minnesota. The resulting information was used to interpret the stratigraphy and glacial history for the area north of Mille Lacs Lake. This study shows that: (1) Each of the six tills is geochemically distinct and can be differentiated statistically. (2) The geochemistry statistics show a separation between northeast- and northwest-sourced tills; the disputed Hewitt Till is geochemically more similar to the northeast-sourced tills. (3) The New Ulm and Granite Falls Tills are geochemically similar. (4) The geochemistry of the silt and clay fractions of till samples can be used to map the stratigraphy at depth in boreholes and to create glacial histories for specific regions. (5) The commonly employed methods used to describe tills in Minnesota cannot always be utilized to distinguish among till groups. The parameter found to best define the individual tills is the geochemistry of the silt and clay fraction.

INTRODUCTION

The purpose of this investigation is to evaluate which method or methods are most effective for discriminating between groups of tills in the Upper Midwest, with particular emphasis on Minnesota, and to determine if there is a signature common to tills of similar provenance.

Distinction between tills in Minnesota (Table 1) has commonly been based on the presence or absence of limestone (Leverett, 1932; Wright, 1962; Wright and Ruhe, 1965; Winter, 1971). Limestone has been interpreted to come from the Winnipeg area, which is regarded as the closest and most logical source of Paleozoic limestone (Wright, 1962; Wright and Ruhe, 1965; Winter, 1971) based on ice-flow directions. Tills in which limestone is absent were associated with a north-northeast source in the Canadian Shield. More recent investigations (Martin and others, 1991) indicate that all of the northern Minnesota tills contain at least some carbonate, and thus limestone content cannot reliably be used as an indicator

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The geochemical signature of the till may reflect a mixture of provenance. The northeast-sourced tills contain limestone, possibly derived from the Hudson Bay-James Bay lowland, or Hudson Bay itself (Fig. 1). Therefore, previous stratigraphic works based on carbonate rock types are suspect (Martin and others, 1988, 1989; Buchheit and others, 1989).

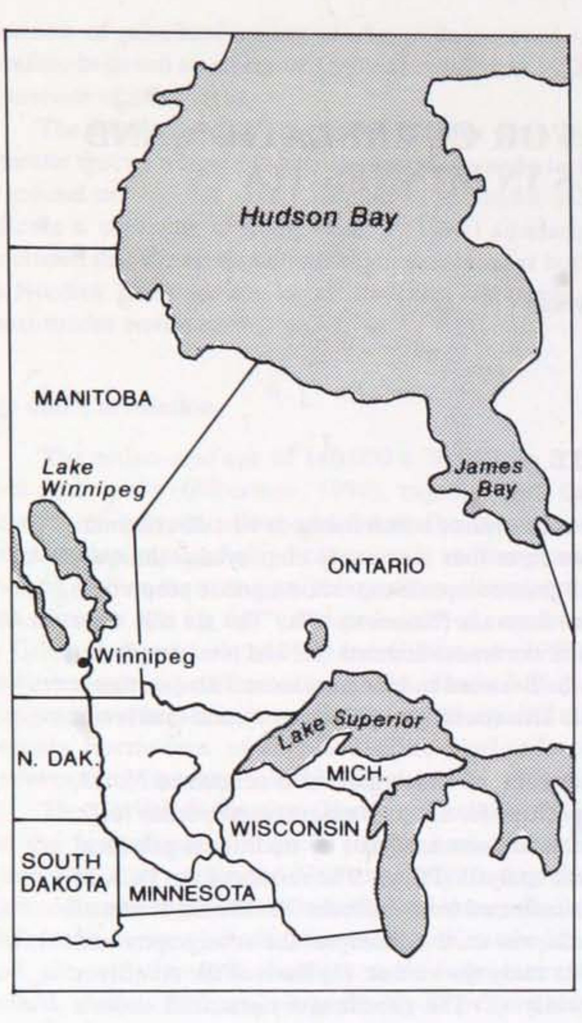


Figure 1. The Upper Midwest and Canada, showing location of places mentioned in text.

Mineral exploration in Minnesota has recently been extended to include glacial sediments. The technique of "drift prospecting" has been employed in Canada and Finland (Alley and Slatt, 1976; Kujansuu, 1976; Shilts, 1976; Drake, 1983; DiLabio and Coker, 1987), and strives to locate ore deposits that are buried under glacial sediments by tracing anomalously high geochemical signatures in the till up-glacier to the source. However, without knowing the provenance of the till, the usefulness of this technique is limited. Additionally, if the geochemical anomaly is assigned to the wrong body of ice because the glacial stratigraphy of the area is poorly understood, efforts to locate ore deposits are fruitless. Successful mineral exploration by drift-prospecting methods in Minnesota requires a better knowledge of the stratigraphy and provenance of glacial deposits.

To accomplish this, a "control" group of samples, representing areas of known till stratigraphy and provenance was assessed (Fig. 2 and Tables 1 and 2). Frequently used techniques, including grain size analysis, matrix carbonate content, sand-grain composition, and rock-magnetic properties (Dreimanis, 1971; Fenton and Dreimanis, 1976; Karrow, 1976; Raukas and others, 1978) were used to describe these tills. Geochemistry of the silt and clay fraction was also included, based on the assumption that the silt and clay fraction represents rock types incorporated farther up-glacier than the larger clasts or grains, providing an overall rather than a local signature, thus indicating the source region. The parameters used for the various methods of till description were assessed using descriptive statistics and principal components analysis (PCA). The results of the descriptive stratigraphy and PCA were then used to try to classify tills of unknown or uncertain provenance from drill core OB-402, obtained from north of Mille Lacs, in the South Range of the Cuyuna district.

REGIONAL GLACIAL GEOLOGY

The Laurentide glaciers that deposited sediments in Minnesota also traversed and/or deposited sediments across southern Manitoba, western Ontario south and east of Hudson and James Bays, eastern North Dakota and Wisconsin (Figs. 1 and 3). Most of this region is underlain by Precambrian rocks of the Superior Province of the Canadian Shield (Fig. 4). A much smaller area is underlain by Paleozoic platform deposits of the Hudson Bay lowland in the northeast, the Williston Basin in the northwest, and miscellaneous Phanerozoic deposits.

Previous Investigations

The history of interpretations of the source regions for the various Laurentide ice lobes that extended across Minnesota during the Pleistocene was summarized by Prest (1990). Dawson (1891) first recognized that there was more than one ice center. He identified the Laurentide ice center in the east and the Cordilleran ice center in the west. Chamberlin (1894) produced a map showing three ice centers, one on the west side of the Rocky Mountains, one centered over the district of Keewatin northwest of Hudson Bay, and one centered in Labrador. It was Tyrrell (1896, 1897, 1898) who finally named the Keewatin and Labradoran ice centers. A fourth center of outflow was proposed by Tyrrell (1913) in the area west of James Bay, which he named the Patrician glacier. The concept of ice dispersal centers is still under revision.

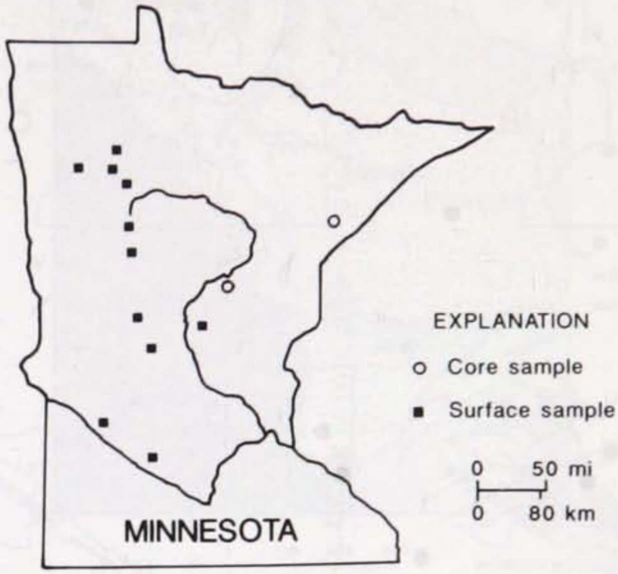


Figure 2. Location of sample sites for control group surface tills. Drill core localities OB-402 and CDC-33 are also shown. See Table 2 for additional data on control group till sample localities.

The earliest comprehensive studies of the glacial geology of Minnesota were made by Winchell and Upham, during the late 1800's (Winchell and Upham, 1884). The surficial geology was presented in map form; the whole state was described as drift-covered with the exception of the extreme southeastern and northeastern parts. He stated that the greater proportion of till is blue or grey in color except in the northeast and much of the east-central part of the state, where it is red or "has the color of non-hydrated iron-peroxide." He described the blue till as occupying the western two-thirds of the state, being clayey, with its upper 5–50 ft oxidized to a yellowish color; it contained up to 50 percent limestone, plus granite, syenite, schist, and quartzite clasts. The limestone clasts were interpreted to be derived from sources near Winnipeg on the basis of glacier-flow directions (Winchell and Upham, 1884). Winchell and Upham (1884) reported the northeast and east-central portions of Minnesota to be covered with "red drift," the color of which results from the incorporation of red sandstones, siltstones and volcanic rocks derived from near Lake Superior. Typical clasts include granite, gneiss, schist, gabbro, diabase, and, very rarely, limestone (Winchell and others, 1899).

In the early 1900's Leverett and Sardeson (1932) reconstructed the geologic history of Minnesota based on the surficial deposits. Leverett described the "glacial gathering grounds" that supplied ice to Minnesota during the Wisconsinan glaciation as Keewatin, Labrador and Patrician. He also described each of the pre-Wisconsinan

Table 1. Characteristics of surface tills of Minnesota discussed in this report.
[based on information supplied in the referenced material]

Till (lobe affiliation)	Carbonate Content	Color	Matrix Texture	Clast Composition	References
Alborn Till (St. Louis sublobe)	variable	5YR 4/4–2.5YR 4/3	silty-clay to silt	granite, minor calcareous shale and carbonate	Baker (1964)
Brianerd Till (Rainy lobe)	non-calcareous	7.5YR 4/4	3% granules; 70% sand; 18% silt; 9% clay	Precambrian rocks of northeastern Minnesota	Schneider (1956)
Browerville Till (uncertain)	highly calcareous	10YR 5/1	clay loam	Paleozoic carbonate; minor shale	Meyer (1986) Goldstein (1989)
Granite Falls Till (?Wadena lobe)	highly calcareous	2.5Y 8/4–2.5Y 8/6	sandy loam; loam; clay loam	≤50% carbonate; 30% granite 0-5% Cretaceous shale	Matsch (1972)
Hewitt Till (Wadena lobe)	strongly calcareous	10YR 5/4–10YR 5/6	sandy loam	approx. 40% carbonate NO Cretaceous shale	Wright and Ruhe (1965)
Independence Till (Rainy lobe)	non-calcareous	gray-brown	sand	gabbro some granite basalt	Wright and others (1970)
New Ulm Till (Des Moines lobe)	strongly calcareous	2.5Y 7/4–2.5Y 5/4	clay loam; loam	10-40% Paleozoic carbonate abundant Cretaceous shale granite	Matsch (1972)
Cromwell Formation (Superior lobe)	low carbonate content	5YR 4/4–5YR 4/3	3% granules; 60% sand; 25% silt; 11% clay	red sandstone and siltstone; basalt; Lake Superior agate	Wright and others (1970)

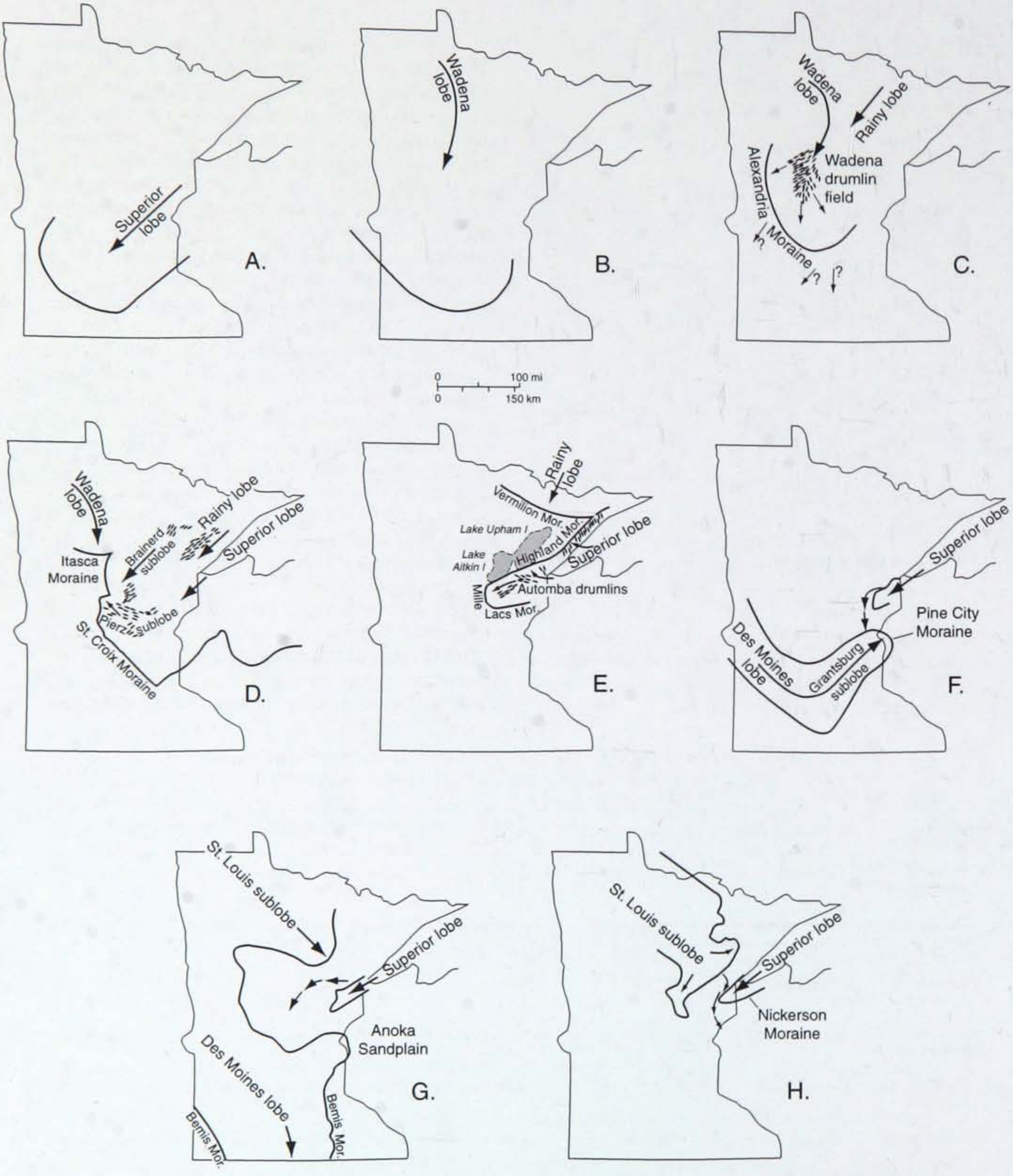


Figure 3. Sequence of glacial phases in Minnesota according to Wright (1972). (A) Deposition of Hawk Creek Till by the Superior lobe. (B) Deposition of the Granite Falls Till by the Wadena lobe. (C) Hewitt phase of the Wadena lobe. (D) St. Croix phase of the Superior, Rainy and Wadena lobes. (E) Automba phase of the Superior and Rainy lobes. (F) Split Rock-Pine City phase of the Grantsburg sublobe and the Superior lobe. (G) Bemis phase of the Des Moines lobe. (H) Nickerson-Alborn phase of the Superior lobe and the St. Louis sublobe. Modified from Wright (1972).

Late Wisconsinan glacial lobes (Fig. 3), the northeast-sourced Rainy and Superior lobes, and the northwest-sourced Wadena and Des Moines lobes. Other studies include those of Schneider (1961) who studied the Pleistocene geology of the Randall region and described the Brainerd and Pierz tills. Schneider (1961) also described the Superior-lobe and Wadena-lobe tills; he considered all tills except the Wadena-lobe till to be of northeast provenance.

Winter (1971) assessed the glacial history of the Mesabi and Vermilion iron ranges. Winter (1971) grouped glacial sediments of the region into 3 units. The first (or basal) unit represented the Early or pre-Wisconsinan ice advance of northwest-sourced ice, as inferred from the calcareous content of the till. The second unit was a noncalcareous till attributed to an advance of the northeast-sourced Rainy lobe. Winter (1971) divided the youngest glacial sediments, those of the St. Louis sublobe of the Des Moines lobe, into two types. Those of western and north-central Minnesota were characterized by a calcareous, gray or brown till; those of south-central Minnesota were less calcareous, forming a red to red-brown till. Matsch (1972) studied the Pleistocene stratigraphy of southwestern Minnesota. He defined 3 new tills: the New Ulm Till and Granite Falls Till of northwestern provenance, and the Hawk Creek Till of northeastern provenance. Meyer (1986) described the subsurface stratigraphy of the Todd County area, and identified a series of tills including the Browerville Till and the Pierz and Wadena-lobe tills. The Brainerd Till and the Pierz and Superior-lobe tills were assessed by Mooers (1988) who found the Pierz and Superior-lobe tills to be indistinguishable (Mooers, 1990). Goldstein (1989) described the subsurface Browerville and Hawk Creek Tills, and focused on the characteristics of the Wadena drumlin field (Goldstein, this volume).

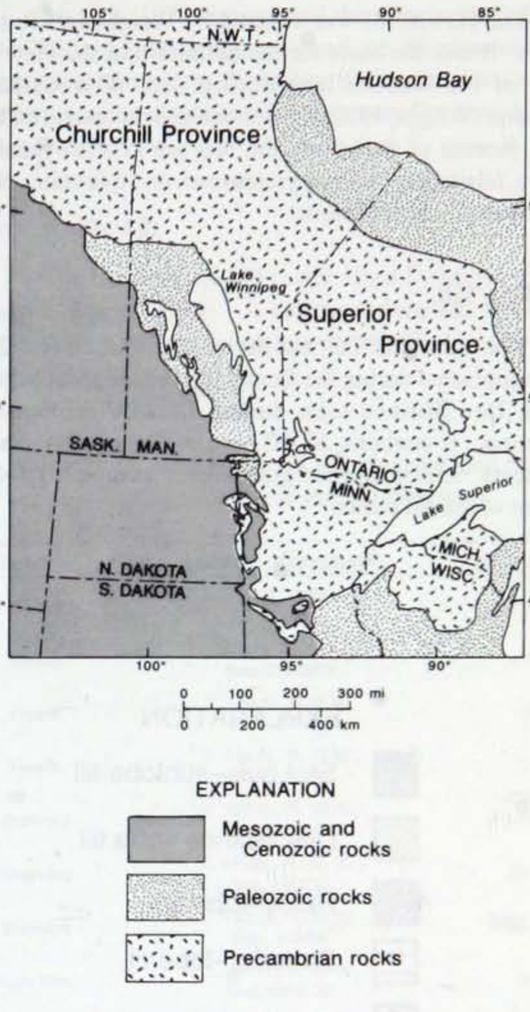


Figure 4. General bedrock geology of the Upper Midwest and Canada (modified from Teller and Bluemle, 1983)

(Nebraskan, Kansan, Illinoian, and Iowan) "drifts" and identified two "drifts" for the Wisconsinan; the "Wisconsin red drift" and the "Wisconsin gray drift." Leverett's "red drift" had its origin in the District of Patricia, Ontario. It was reddish in color, has a loose texture, and contained clasts derived from the west end of Lake Superior (Leverett and Sardeson, 1932). The "gray drift" which originated in the District of Keewatin, was yellow to gray, clayey, and its principal components were limestone and shale clasts. Wright (Wright, 1962, 1972; Wright and Ruhe, 1965; Wright and Watts, 1969; Wright and others, 1970, 1973) has made the greatest contributions to the understanding of the glacial history of Minnesota. With the use of local and regional studies, Wright developed the general framework for the glaciation of Minnesota (Wright and Ruhe, 1965), and defined or summarized many of the tills. Wright (1972) identified four major

STRATIGRAPHY

The stratigraphy of pre-Late Wisconsinan glacial sediments is not well known in Minnesota. Surface tills have been assigned to a time and parent lobe, except for those in southeastern part of the state which was unglaciated during the Wisconsinan Stage. Subsurface glacial sediments are poorly defined as to source region and age, with interpretations largely reflecting current models, and sometimes requiring the definition of new lobes (e.g. the Winnipeg and Old Rainy lobes of Meyer in Martin and others, 1989). Tills exposed at the surface, and some of those studied from the subsurface are summarized in Figure 5. This study is concerned with the physical characteristics of eight surface tills in Minnesota. Five of these tills (Brainerd, Browerville, Granite Falls, Hewitt, and New Ulm) were collected from surface exposures. Another group of 3 till samples was collected from Minnesota Geological Survey rotasonic drillhole CDC-33, which cored a Toimi drumlin, formed by the Late Wisconsinan Rainy lobe. Two additional surface tills (Cromwell Formation and Alborn till) are of interest because they have been documented in the region studied (Martin and others, 1991). The essential characteristics of these glacial sediments are summarized in Table 1, and discussed briefly in the text below.

Brainerd Till

The Brainerd Till (Schneider, 1956) was deposited in central Minnesota by the Rainy lobe during the Late Wisconsinan glaciation. Clasts are largely derived from the Precambrian rocks of northeastern Minnesota. Red sandstones and siltstones from the Lake Superior basin are present as a result of contamination from underlying glacial sediment.

Hewitt Till

The Hewitt till was defined by Wright and Ruhe (1965). It was the basis for the definition of the Hewitt phase of the Wadena lobe during Late Wisconsinan glaciation (Wright, 1972). Limestone and dolostone make up 40 percent of the clasts; the rest are granite, basalt, gabbro, felsite, graywacke, greenstone, and quartzite. No Cretaceous shale is present.

New Ulm Till

The New Ulm Till was defined by Matsch (1972). It was deposited during the Bemis and subsequent phases of the Des Moines lobe during Late Wisconsinan glaciation. It contains 20–50 percent Cretaceous shale fragments. Limestone and granite each compose 10–40 percent of the till clasts.

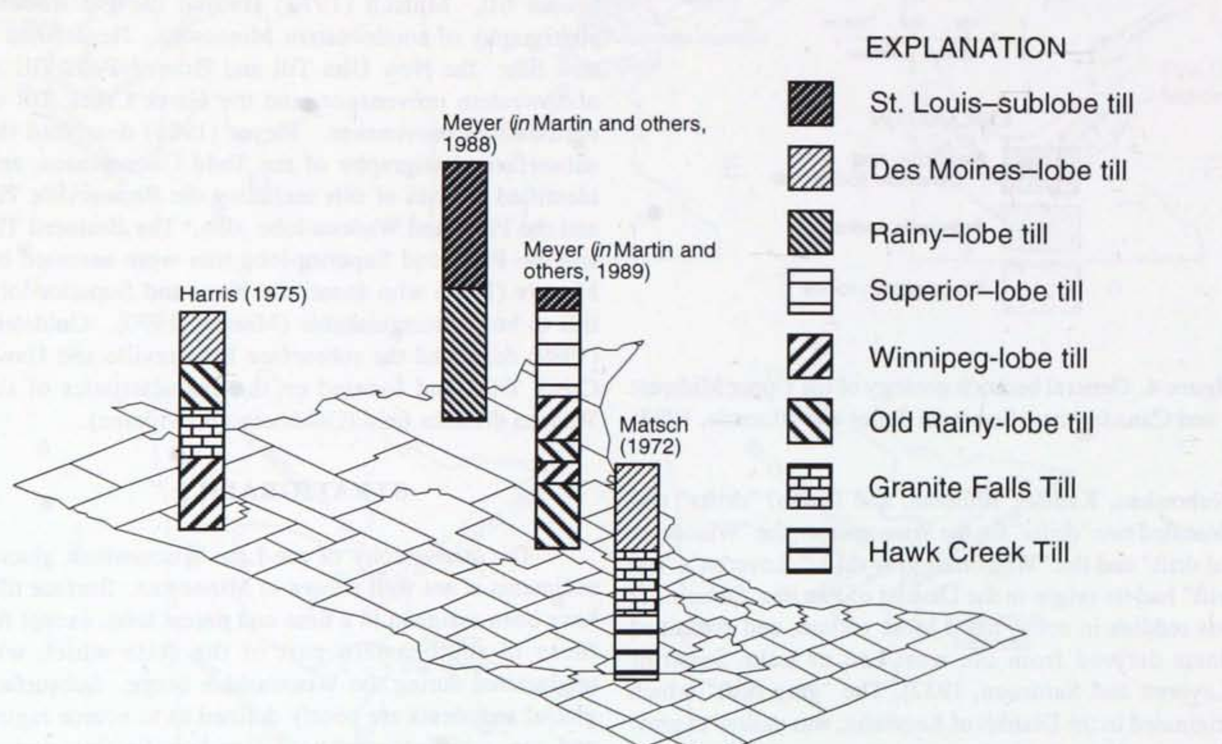


Figure 5. Glacial stratigraphy at four localities in Minnesota, showing lateral and vertical range in till type distribution. Stratigraphic columns are schematic; they are not drawn to scale and are not an accurate portrayal of the relative thickness of glacial sediments. The names used for the till units are those designated by the authors.Column (A) from Harris (1975).Column (B) from Meyer (in Martin and others, 1988).Column (C) from Meyer (in Martin and others, 1988).Column (D) from Matsch (1972).

Granite Falls Till

Matsch (1972) interpreted the Granite Falls Till to be a Wadena lobe deposit of pre-Late Wisconsinan age. It contains as much as 50 percent carbonate clasts and 30 percent granitic clasts, and 0 to 5 percent Cretaceous shale fragments.

Browerville Till

The Browerville Till is described by Meyer (1986) and Goldstein (1989). It contains abundant Paleozoic carbonate clasts and only a few percent Cretaceous shale fragments.

Table 2. Control group till samples and drill core OB-402. Details of sample location.

Till Name	Location* of sample site	sample number
Hewitt	T. 137 N., R 35 W., Sec. 27C	HT NoS
Hewitt	T. 143 N., R. 35 W., Sec. 27BBAD	L A
Hewitt	T. 143 N., R 36 W., Sec. 24AA	LS
Hewitt	T. 144 N., R. 37 W., Sec. 5DD	Z
Brainerd	T. 137 N., R. 35 W., Sec. 4AAA	HT SoM
Brainerd	T. 143 N., R. 30. W., Sec. 12CCD	92-1
Brainerd	T. 143 N., R. 30 W., Sec. 14ABA	92-2
New Ulm	T. 147 N., R. 42 W., Sec. 35BBCC	MI
New Ulm	T. 112 N., R. 34 W., Sec. 4BD	92-7
Granite Falls	T. 116 N., R. 39 W., Sec. 28DBBB	92-4
Granite Falls	T. 116 N., R. 39 W., Sec. 28DBBB	92-5
Browerville	T. 130 N., R. 33 W., Sec. 16DBC	92-8A
Browerville	T. 130 N., R. 33 W., Sec. 16DBC	92-8B
Browerville	T. 128 N., R. 32 W., Sec. 16CAC	92-9A
Browerville	T. 128 N., R. 32 W., Sec. 16CAC	92-9B
Toimi#	T. 57 W., R. 10 W., Sec. 21A	33 105-7
Toimi#	T. 57 W., R. 10 W., Sec. 21A	33 164
Toimi#	T. 57 W., R. 10 W., Sec. 21A	33 207

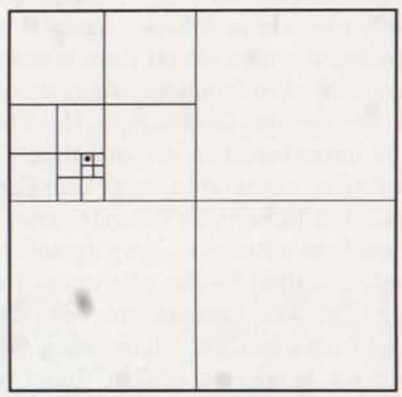
*locations are given using the abbreviated subsection system; see explanation adjacent to table.
#collected from Minnesota Geological Survey rotasonic drillhole CDC-33

Independence Till

The Independence Till (Wright and others, 1970) was deposited by the Rainy lobe during the Late Wisconsinan. It contains high percentages of gabbro, with lesser amounts of granite, basalt, felsite, slate, and graywacke. Red sandstone and carbonate clasts are rare.

Superior-Lobe Tills (Hawk Creek Till, Cromwell Formation, Barnum Till)

Three tills have been attributed to the Superior lobe in Minnesota: the Hawk Creek Till (Matsch, 1972), the Cromwell Formation (Wright and others, 1970), and the Barnum Till (Baker, 1964). In this study the Cromwell Formation was examined. It is characterized by a low but variable carbonate content, up to 50 percent red sandstone clasts, less than 15 percent siltstone clasts, less than 21 percent basalt clasts, up to 32 percent felsite clasts, up to 15 percent acidic intrusive clasts, up to 28 percent graywacke clasts, and up to 8 percent iron-formation clasts (Wright and others, 1970).



***** *Diagram to illustrate the process of locating a drill hole (bullet) within a section by means of the abbreviated subsection system***

The location of drill holes in Tables 1 and 2 is described by township number (T), range number (R), section number (Sec.), and subdivisions of sections by quarters. The system used by the Minnesota Geological Survey to subdivide a section (one square mile) assigns letters to the quarters of a section where A is the NE1/4, B is the NW1/4, C is the SW1/4, and D is the SE1/4. Each quarter is then subdivided into four more quarters using the letter system. In listing quarters the largest subdivision is given first and each quarter of a quarter is given in succession. In the example above the subdivisions of the section would read BCDAB.

Alborn Till

The Alborn Till (Baker, 1964) was deposited by the St. Louis sublobe of the Late Wisconsinan Des Moines lobe. Two tills were originally attributed to this advance: the Alborn Till is a red-brown (5YR 4/4 when wet) silty-clay to slightly stoney till containing clasts of granite (21 percent), carbonate (2 percent) and chert (1 percent). A slightly younger till is olive-brown (2.5YR 4/3), silty, and slightly stoney, and contains pebble-grade clasts of shale, carbonate, and granite (all of which are typical of the Des Moines lobe) was termed the Prairie Lake Till (Baker, 1964), although subsequent authors (Wright, 1972, Wright and others, 1973, Matsch and Schneider, 1986) have included both of Baker's (1964) units within the Alborn Till.

METHODS

Sample Collection

A total of 77 till samples was collected from the surface and subsurface at 13 locations around Minnesota, including drillhole OB-402 (Fig. 2). Each sample was approximately one liter in volume. Samples of surface tills were collected with a shovel from beneath the soil horizon; they were taken from areas where the occurrence of Brainerd, Browerville, Granite Falls, Hewitt, and New Ulm Tills is uncontested in the literature (Table 2). Samples of tills associated with the Rainy lobe (Independence Till, Browerville Till and Granite Falls Till) were retrieved from a Rotasonic core through one of the Toimi drumlins drilled by the Minnesota Geological Survey (core CDC-33). Because three separate till units were sampled from core CDC-33, including the surficial Independence till, an informal label of "Toimi" was given to this sample group.

Drillhole OB-402—Description

Drillhole OB-402 is located north of Mille Lacs Lake in the Moose Lake-Glen Township in the South Range of the Cuyuna district (Fig. 2). The local bedrock represents one of the structural panels of the Penokean orogen in Minnesota (Southwick and others, 1988), and consists of metasedimentary and metavolcanic rocks including graphitic schist and slate, mafic to intermediate flows and volcaniclastic rocks, and iron-formation. The core from drillhole OB-402 was described visually using Munsell color notation of wet samples when viewed under fluorescent light; and by qualitative textural analysis (rubbing between fingers), and by determination of relative carbonate content using degree of effervescence (none, low, medium, high) under the application of dilute hydrochloric acid. Distinctive clast types were also noted.

Analyses

Sample Preparation for Analytical Work

All 77 samples were split into two unequal portions. A subsample (approximately 50 g) of the smaller split was used for grain-size analysis. The 1–2-mm fraction obtained from the grain size analysis was used to determine grain composition by point-count methods (Gowan, 1993). The larger split was dry-sieved to retrieve one fraction that was 1 mm - 62 µm, and one that was less than 62 µm. The silt and clay fraction (less than 62 µm) obtained from the larger split was utilized in geochemical analyses and determination of rock-magnetic properties.

Analytical Techniques

The analytical techniques chosen for this study were picked on the basis of their widespread use by other workers (Dreimanis, 1971; Raukas and others, 1978). They are:

1. Grain-size analysis
2. Carbonate content
3. Rock magnetic properties
4. Clast and grain counts

Grain size analyses are used in many of the studies on till (Dreimanis and Vagners, 1971; Gross and Moran, 1971; Fenton and Dreimanis, 1976; Karrow, 1976; Boulton, 1978; Teller and Fenton, 1980). Carbonate content is in widespread use as a quantitative till descriptor in Minnesota, because it has been widely regarded as a provenance indicator (Winchell and others, 1899; Leverett and Sardeson, 1932; Winter, 1971; Matsch, 1972; Wright and others, 1973; Chernicoff, 1980, 1983; Teller and Fenton, 1980; Norton, 1983 and Goldstein, 1985). Two methods (loss on ignition and carbon coulometry) were used for determination of carbonate content for all samples in this study.

Rock-magnetic properties are a fairly recent addition to the suite of methods used to describe tills. Low frequency magnetic susceptibility measurements (χ) have largely taken the place of heavy mineral studies, because they measure the ferromagnetic mineral content (Gravenor and Stupavsky, 1974; King and others, 1982). Banerjee and others (1981) outlined the use of plots of anhysteretic remanent magnetization (ARM) versus magnetic susceptibility (χ) to show changes in the grain size of magnetite in sediments. Several studies have used one or both of these magnetic properties to characterize tills (Gravenor and Stupavsky, 1974; Chernicoff, 1983; Mooers, 1988, 1990; Goldstein, 1989 and this volume). Clast counts of the pebble (or coarser) fraction and grain counts of the sand-grade fraction are commonly used to determine what rock types are present and in what proportion (Hobbs, this volume). This information has been used for both classification and provenance purposes (Horberg and Potter, 1955; Arneman and Wright, 1959; Gross and Moran, 1971; Wright and others, 1973; Gwyn and Dreimanis, 1979; Teller and Fenton, 1980; Chernicoff, 1983; Norton, 1983; Goldstein, 1985, 1989; Mooers, 1988, 1990).

The fifth analytical method chosen for this study is till matrix geochemistry, which has not been widely used in glacial geology, although May and Dreimanis (1973) used a four-element suite for their till study of southern Ontario. Whole rock major and trace element analyses were included in this study because of their value in provenance determination, particularly in the context of highly prospective terrains mantled by glacial sediments. A 34-element geochemical analysis using Inductively Coupled Plasma-Atomic Emission Spectroscopy was performed by Bondar-Clegg & Company, Ltd., of Ottawa, Ontario on all 77 samples.

DESCRIPTIVE STATISTICS AND PRINCIPAL COMPONENTS ANALYSIS

Descriptive statistical techniques (mean grain size expressed in ϕ units, standard deviation, skewness, and kurtosis) were used to summarize the results of grain size analyses obtained for the control group. These statistical descriptors then became variables that were added to the data set, and were used as variables for the Principal Components Analysis (PCA). PCA is a statistically-based method used to determine which combination of information best differentiates between groups of samples (Davis, 1996). Each sample is characterized by a series of variables (e.g. grain size data, geochemistry, carbonate content, grain-type, clast type, magnetic data). PCA determines the eigen vectors (principal components) and eigen values for the correlation matrix of the input variables. Each input variable has a loading on each component which is simply its coefficient in the linear equation which the component (eigen vector) defines. "Loading" describes the importance of each variable in the component mathematically. The goal of PCA is not to group samples, but simply to statistically describe the variance among them. The clustering of like samples in discrete groups in a particular biaxial plot enables a description of the group based on component loadings.

RESULTS AND DISCUSSION

Till Samples

The ternary plot of the grain-size data for the control samples (Fig. 6A) shows clustering of the data points for groups of till samples. However, many of the groups

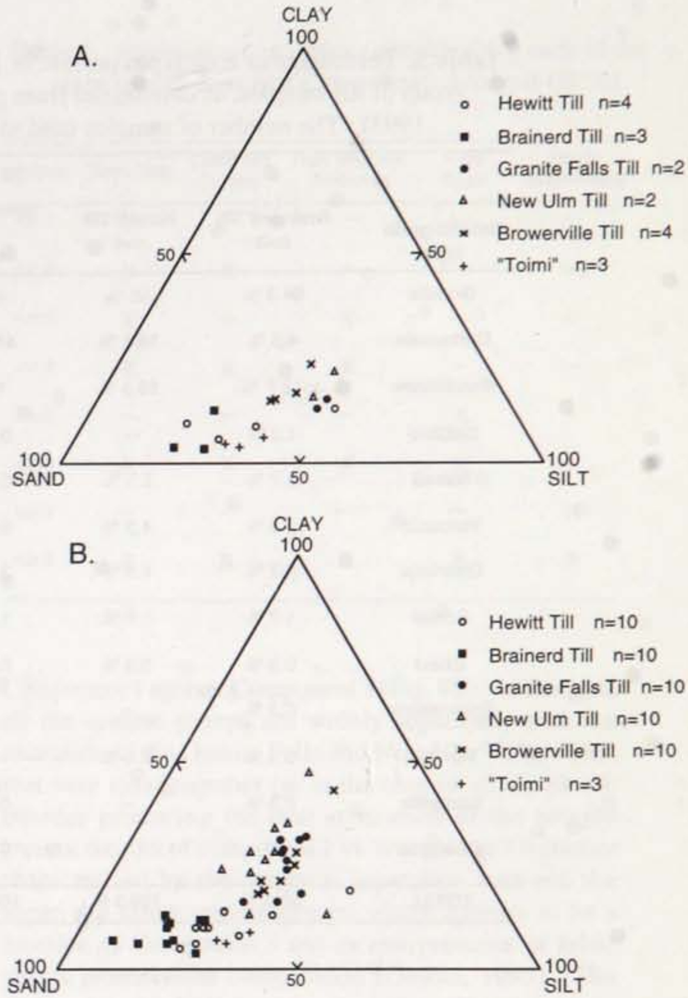


Figure 6. Matrix texture for control group of till samples including Hewitt Till, Brainerd Till, Granite Falls Till, New Ulm Till and Browerville Till. Patterned lines represent fields for each till unit. **A.** Fields for matrix texture based on data obtained in this study. **B.** Fields for matrix texture based on data obtained in this study together with data obtained from Mooers (1988) and Matsch (written comm., 1993).

overlap. The small number of sample points makes it difficult to state with any degree of confidence where the complete fields for these groups might lie. For the same reason it also precludes serious use of this plot to classify unknown samples. Owing to this difficulty, a larger number of data points is plotted in Figure 6B using data from previous investigations (Mooers, 1988; Matsch, written commun., 1993). When a greater number of points is used, the plot shows the same clustering and overlapping of groups observed with fewer data points, even though each group space is better defined. It would still be difficult to predict group membership of unknowns using this technique alone.

Table 3. Percentage of rock types present in 1–2-mm fraction of each till type in the control group of till samples, as determined from grain count data (following method of Gowan, 1993). The number of samples used to determine this average is indicated (n=3).

Detrital-grain type	Till Name Brainerd Till n=3	Hewitt Till n=4	Browerville Till n=4	Granite Falls Till n=2	New Ulm Till n=2	Toimi Samples n=3
Granite	64.3 %	55 %	41 %	27.5 %	44.5 %	16.7 %
Carbonate	4.3 %	16.3 %	41.8 %	55 %	41.5 %	1.0 %
Sandstone	12.7 %	15.3 %	11 %	15 %	9.5 %	33.3 %
Gabbro	1.0 %	–	0.5 %	0.5 %	–	23.3 %
Basalt	5.7 %	2.5 %	0.3 %	0.5 %	0.5 %	12.0 %
Volcanic	2.3 %	4.3 %	0.8 %	–	0.5 %	4.3 %
Quartzite	6.3 %	4.3 %	3.0 %	1.5 %	–	0.7 %
Schist	1.7 %	1.8 %	1.3 %	1.0 %	1.5 %	–
Chert	0.3 %	0.3 %	0.3 %	–	–	–
Greenstone	0.3 %	–	–	–	1.0 %	0.7 %
Perthite	0.3 %	0.5 %	–	–	–	5.3 %
Hematite	0.3 %	–	0.5 %	–	0.5 %	0.5 %
Opaques	–	–	0.3 %	–	–	1.0 %
TOTAL	99.5 %	100.3 %	100.8 %	101 %	99.5 %	98.8 %

Average grain count data for the 1–2-mm fraction (Table 3) within each of the till samples is a much better discriminator than the grain-size information. The Toimi samples are distinctly different than the other tills, having high percentages of sandstone, granite, basalt, and gabbro. The Brainerd and Hewitt Tills differ from each other mainly in the amount of carbonate present; if the carbonate in the Hewitt Till were reduced it would appear indistinguishable from the Brainerd Till. The three remaining tills, the Browerville, Granite Falls, and New Ulm Tills, have broadly similar proportions of granite, carbonate, and sandstone, which are their major constituents. The New Ulm and Browerville Tills closely resemble each other, possessing roughly equal amounts of granite and carbonate. The Granite Falls Till has approximately 15 percent more carbonate than either the Browerville or New Ulm Till, and has 15 percent less granite. The presence of shale in the New Ulm Till is not addressed, since shale was not distinguished from sandstone in the grain counts.

Magnetic properties and carbonate-content data (Fig. 7) allow easy recognition of the Toimi samples. The Toimi samples have high values for ARM and χ, whereas the other groups overlap (Fig. 7A). A better distinction is obtained by plotting ARM versus LOI, in which the Toimi, Brainerd, and Granite Falls samples can readily be distinguished (Fig. 7B).

Principal Components Analysis

Eight PCA runs were completed for the control group data. Each run included different combinations of variables (Table 4). Run 7 (geochemistry) allowed the best differentiation between samples of the control groups. Variance among the samples was determined to be largely a function of the geochemistry of the till matrix, in conjunction with carbonate content. The component score plots derived from the loadings for the four significant components from the analysis of matrix geochemistry are shown in Figure 8, with the component loadings shown in Figure 9. The placement of one of the Toimi samples relative to the other two for Component 1 (Figs. 8A, B, and C) is perplexing. This particular sample (33-207) has a high negative value for Component 1. The negative field for Component 1 is interpreted to reflect chemical signatures common to rocks of carbonate platforms, which have high calcium, magnesium, lead, and bismuth, compared to rocks typical of the Canadian Shield, for which the chemical signatures are more positive. A possible explanation for the placement of the Toimi sample is the location of sample 33-207 in core CDC-33. Sample 33-207 was collected from a depth of 207 ft, immediately above bedrock of the Duluth Complex, which is high in calcium plagioclase and magnesian olivine and pyroxene, thus giving it a high calcium and magnesium signature.

The best separation of the groups is accomplished by Component 1 (Fig. 8A, B, and C), as derived from run 7 which used geochemistry data alone (Table 4). Disregarding the Toimi outlier, the only overlap occurs between the Hewitt and Browerville samples. The problem of this overlap is eliminated by plotting

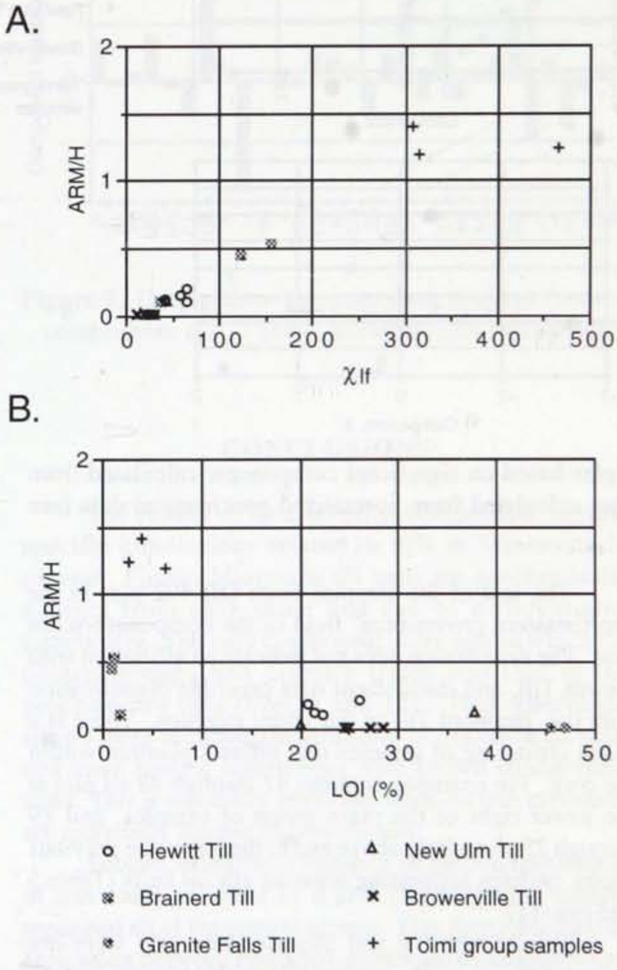


Figure 7. Rock magnetic properties and carbonate content of control group till samples. (**A**) Plot of ARM/H (ARM is anhysteretic remanent magnetization, measured in $m^3/kg \times 10^{-8}$; H is the magnetic field measured in amps/m) vs. χ lf (low frequency magnetic susceptibility, measured in $m^3/kg \times 10^{-8}$. (**B**) Plot of ARM/H vs. LOI (loss on ignition, given in percent; higher percentage indicates greater carbonate content).

Table 4. Summary of variables considered for each of the eight runs in Principal Components Analysis (PCA).

Analysis	Grain Size	Carbonate Content	Rock Magnetic Properties	Point Count	Matrix Geochemistry
run 1	X	–	–	–	–
run 2	X	X	–	–	–
run 3	X	–	X	–	–
run 4	X	X	X	–	–
run 5	–	–	–	X	–
run 6	X	X	X	X	–
run 7	–	–	–	–	X
run 8	X	X	X	X	X

Component 1 against Component 3 (Fig. 8B). In this plot, all the sample groups are widely separated, with the exception of the Granite Falls and New Ulm Tills, which plot very close together (as is the case in all six plots). Besides producing the best separation of the sample groups, the plot of component 1 vs. component 3 is further characterized by the diagonal separation between the upper and lower sample groups, which appears to be a function of Component 3 and its interpretation of felsic versus intermediate composition (Gowan, 1993). The three groups below this gap are all of widely acknowledged northwestern provenance, while the Brainerd Till and Toimi samples on the upper side of the gap are of undisputed northeastern provenance, leading to an interpretation that the gap separates the northwestern- and northeastern-provenance tills. Also located above the gap are the Hewitt Tills of disputed provenance.

Core OB-402 Stratigraphy

A stratigraphic column representing core OB-402, and the position of the samples collected from it is shown in Figure 10. To aid in evaluation of the general core stratigraphy, three sample parameters were plotted versus depth in the core (Fig. 11). The LOI data do not show much variation, with the exception of the large jump around 125 ft. The magnetics data show a little more detail, as does the grain-size information. If these three plots are read in conjunction, seven lithologic boundaries are defined, at approximately 10, 26, 45, 120, 136, 146, and 168 ft. The third boundary (45 ft) is not readily apparent from the stratigraphic column (Fig. 10), while the others concur fairly well with visible characteristics of the sediment.

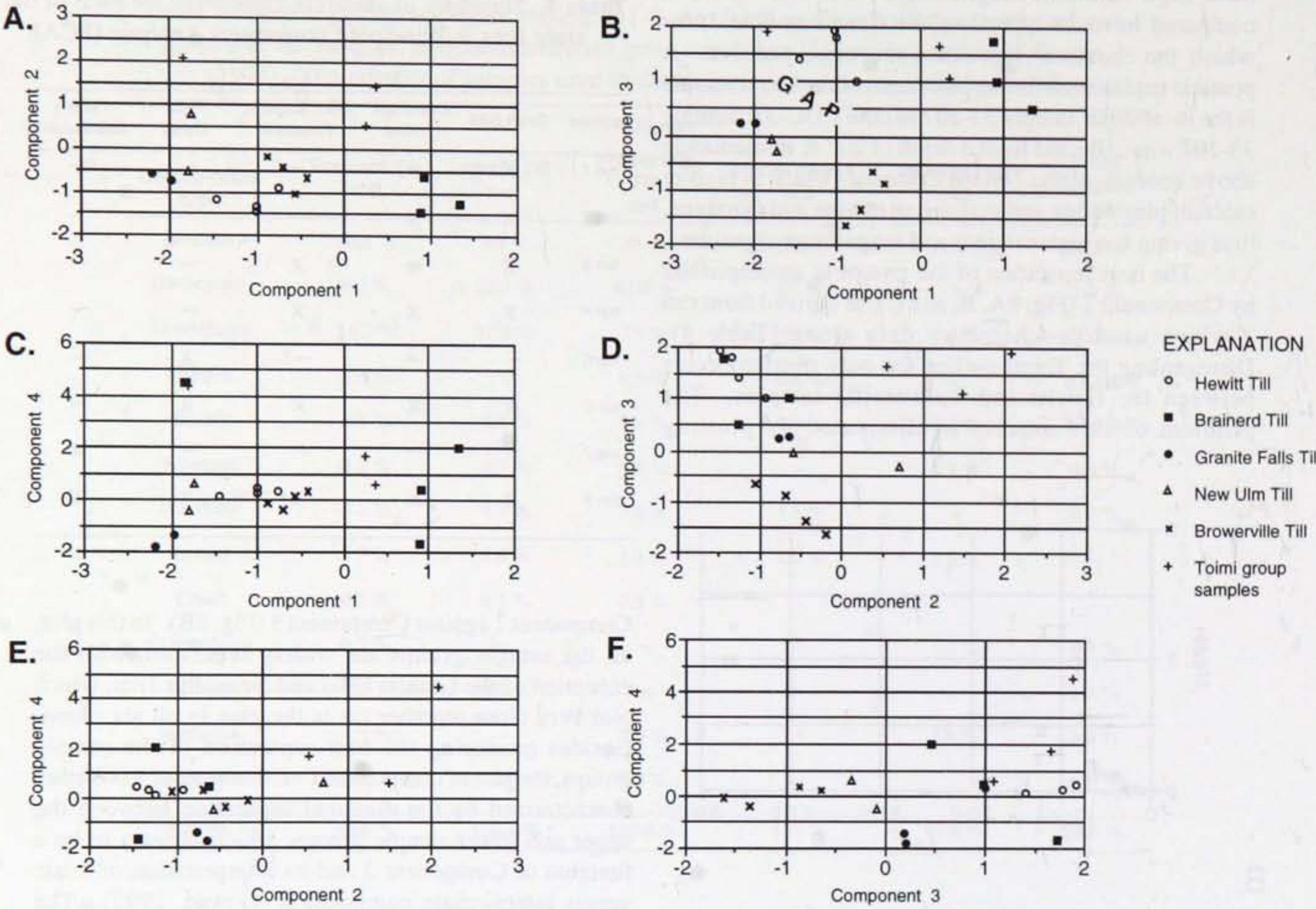


Figure 8. Component score plots for control-group till samples based on significant components calculated from geochemistry data (PCA run 7). Each axis represents values calculated from normalized geochemical data (see Figure 9).

Results of the PCA from the 6 known till groups or "control samples" were used to classify the eight stratigraphic units delineated in Figure 11. In the control samples, the plot of Component 1 versus 3 (from run 7, the geochemistry run) provided the best separation of northwestern versus northeastern provenance tills (Fig. 8). Based on the component score plot for the samples from the core (Fig. 12), there appear to be at the most 10, and more likely only 6, samples of northwestern provenance from core OB-402. Samples 31 through 34, as well as 38 and 39 are the samples of probable northwestern provenance, based on their position below the northeastern/northwestern gap on the component score plot. Samples 35, 36, 37, and 40 are of possible northwestern provenance, based on their position within the gap (Fig. 12) on the component-score plot. The position of all ten of these samples on the component score plot indicates that they do not belong to the three known groups of northwest-provenance till (Browerville, Granite Falls, New Ulm).

The rest of the samples from OB-402 plot in the "northeastern provenance" field of the component-score plot. The distribution does not indicate an affiliation with Hewitt Till, and insufficient data preclude classification with the Brainerd Till or the Toimi samples. There is a slight clustering of samples that reflects position within the core. For example, samples 41 through 48 all plot at the lower right of the main group of samples, and 19 through 25 plot a little above and to the left of the previous group, perhaps suggesting separate glacial units (Table 5 and Fig. 11).

The Alborn Till and Superior-lobe tills were not represented among the control tills analyzed in this study, but are chosen based on previous stratigraphic work done on this core (Martin and others, 1989), for which the subdivisions recognized correspond with those identified in this study. Further geochemical analyses should be completed to verify these conclusions, taking into account the anomalous placement of the Alborn Till samples (1, 2, and 5) within the northeastern field in Figure 12.

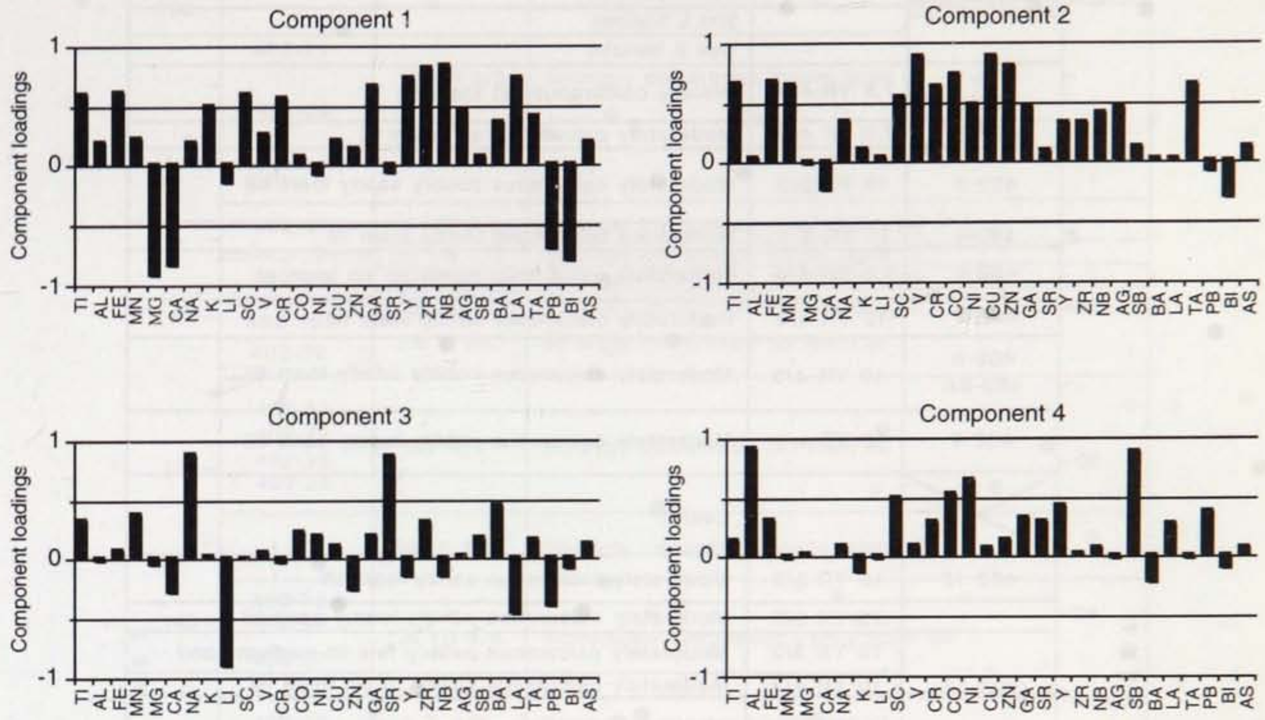


Figure 9. Graphs showing component loadings (vertical axes) computed for elements (horizontal axis) within PCA components 1, 2, 3 and 4, as determined from geochemical data used in this study.

CONCLUSIONS

The results of this investigation provide several specific conclusions related to tills in Minnesota in general. Firstly, Minnesota till units are geochemically distinct from each other and can be differentiated statistically. The only component score plot in which the control groups had discrete fields was that of the geochemistry data (Figs. 8 and 12). This observation allows more accurate identification of unknown till units and more precise correlations with known stratigraphic units. This is especially important when surface exposures are extremely limited or nonexistent.

Second, using these statistics on the control samples of this study resulted in a plot (Fig. 8B) that clearly separated all of the control groups. This figure also allows separation between northeast-provenance and northwest-provenance tills, although placement of the Hewitt samples nearer to the "northeastern-provenance" till field is problematic, since they have been interpreted in the past as of northwestern provenance. This may be an indication that the Hewitt Till was deposited by northeast-sourced ice (or was reworked from underlying northeast-sourced tills).

Table 5. Summary of stratigraphic interpretation of drillcore OB-402

Depth	Till Unit	Sample Numbers
0–10 ft	Alborn Till	402-1; 402-2; 402-5
10–26 ft	Mixed Alborn Till & Superior-lobe tills	402-3; 402-4; 402-5; 402-6; 402-7; 402-8; 402-8A
26–45 ft	Superior-lobe till and related deposits	402-9; 402-10
45–118 ft	Rainy-lobe till and related deposits	402-11; 402-19; 402-20 402-21; 402-22; 402-23 402-24; 402-25; 402-26 402-27; 402-28; 402-29
118–133 ft	pre-Late Wisconsinan northwestern-source till	402-29A; 402-30; 402-31; 402-32; 402-33; 402-34
133–146 ft	pre-Late Wisconsinan northwestern-source till	402-35; 402-36 402-37; 402-38
146–168 ft	pre-Late Wisconsinan northwestern-source till	402-39; 402-40
168–192 ft	pre-Late Wisconsinan northwestern-source till	402-41; 402-42; 402-43 402-44; 402-45; 402-46 402-47; 402-48

SAMPLE NUMBER	COLOR	DESCRIPTION
		Soil A horizon
		Soil E horizon
		Soil B horizon
402-1 402-2	7.5 YR 4/4	Weakly calcareous silt loam till
402-5	7.5 YR 4/4	Moderately calcareous silt loam till
402-3	10 YR 3/3	Moderately calcareous cobbly sandy loam till
402-4	10 YR 3/3	Moderately calcareous sandy loam till
402-6	7.5 YR 4/4	Moderately calcareous sandy to silt loam till
402-7	10 YR 4/3	Moderately calcareous sandy loam till
402-8 402-8A	10 YR 4/3	Moderately calcareous cobbly sandy loam till
402-9	10 YR 4/2	Moderately calcareous cobbly loamy sand till
		Lost
402-10	10 YR 3/3	Moderately calcareous sandy loam till
	10 YR 3/3	Moderately calcareous pebbly loamy sand till
	10 YR 3/3	Moderately calcareous pebbly fine to medium sand
402-11	10 YR 4/2	Moderately calcareous sandy to silt loam till
	10 YR	Weakly calcareous medium sand
	10 YR	Weakly calcareous pebbly coarse sand
	10 YR	Weakly calcareous pebbly very coarse sand
	10 YR 3/3	Weakly calcareous medium sand
	10 YR 3/3	Weakly calcareous coarse to very coarse sand
	10 YR	Weakly calcareous fine sand with darker more cohesive (silty?) sand blebs
	10 YR	Weakly calcareous medium sand
	10 YR	Weakly calcareous pebbly coarse to very coarse sand
402-19 402-20 402-21 402-22	10 YR 4/2	Strongly calcareous sandy loam till
402-23 402-24	10 YR 3/3	Strongly calcareous loamy sand till

DEPTH IN FEET (0–100)

Figure 10. Core OB-402. Numbers in column are sample numbers. Color was determined visually from wet samples in flourescent light, and is given in Munsell color notation. Brief descriptions were obtained by qualitative textural analysis and the use of dilute HCL.

DEPTH IN FEET	SAMPLE NUMBER	COLOR	DESCRIPTION
100	402-25 402-26	10 YR 3/3	Strongly calcareous loamy sand till
110			
	402-27	10 YR 3/3	Strongly calcareous sandy loam till
	402-28	10 YR 4/2	Strongly calcareous sandy loam till
	402-29	10 YR 3/3	Strongly calcareous mixed textures
		2.5 Y 5/2	Strongly calcareous sandy loam till
120	402-29A 402-30	2.5 Y 5/2	Strongly calcareous silt loam till
130	402-31 402-32 402-33 402-34	5 Y 4/1	Strongly calcareous silt loam till
		2.5 Y 5/2	Strongly calcareous sandy loam till
140	402-35 402-36 402-37	7.5 YR 4/4	Moderately calcareous sandy loam till
	402-38	5 Y 4/2	Strongly calcareous silt loam till
150–160			Lost
	402-39	5 Y 4/2	Strongly calcareous sandy loam till
	402-40	10 YR 3/3	Strongly calcareous sandy loam till
170	402-41	2.5 Y 4/2	Moderately calcareous silt loam till
		2.5 Y 4/2 & 2.5 YR 4/4	Moderately calcareous mixed till
	402-42 402-43	2.5 Y 4-3/2 layers	Moderately calcareous sandy loam to loamy sand till
180	402-44	2.5 Y 4/2	Moderately calcareous sandy loam - loamy sand till layers
	402-45	2.5 Y 3/2	Moderately calcareous sandy loam till
		2.5 Y 4/2	Moderately calcareous silty medium sand
	402-46 402-47	2.5 Y 3/2	Moderately calcareous loamy sand till
		10 YR 4/3	Moderately calcareous medium sand
190	402-48	2.5 Y 4/2	Moderately calcareous sandy loam till
200			Mixed cobbles
			Saprolite at 205.3'

Figure 10. Core OB-402 *continued.*

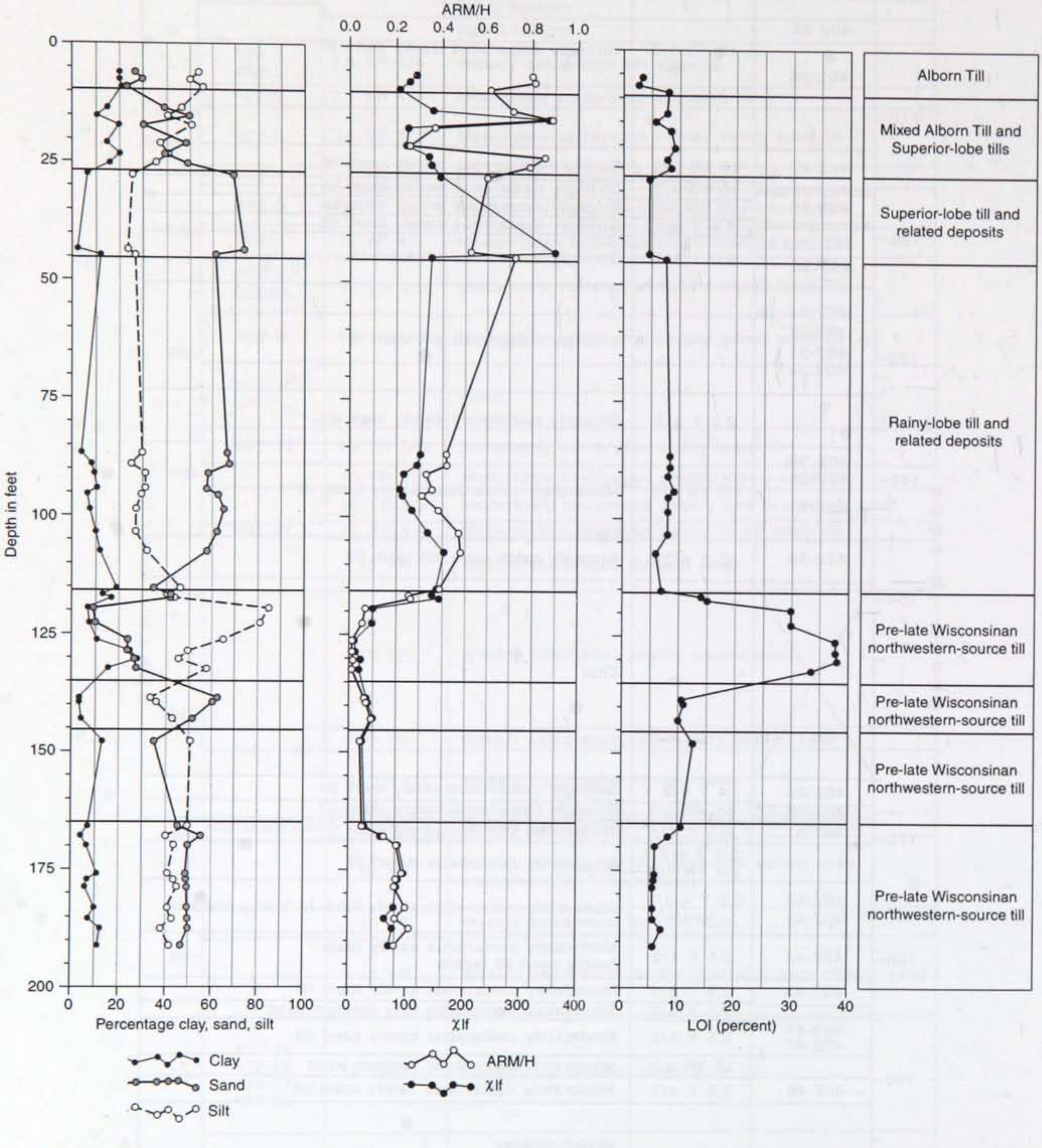


Figure 11. Characterization of till samples from core OB-402. Horizontal lines crossing all three plots indicate major breaks that allow subdivision into separate till units (see Table 5 and Figure 10). Vertical axis shows depth from surface. Horizontal axes are (left to right): Grain size, indicated as percentage of the clay, silt and sand fraction; anhysteretic remnant magnetization (ARM/H and χlf; see Figure 8); and carbonate content (LOI).

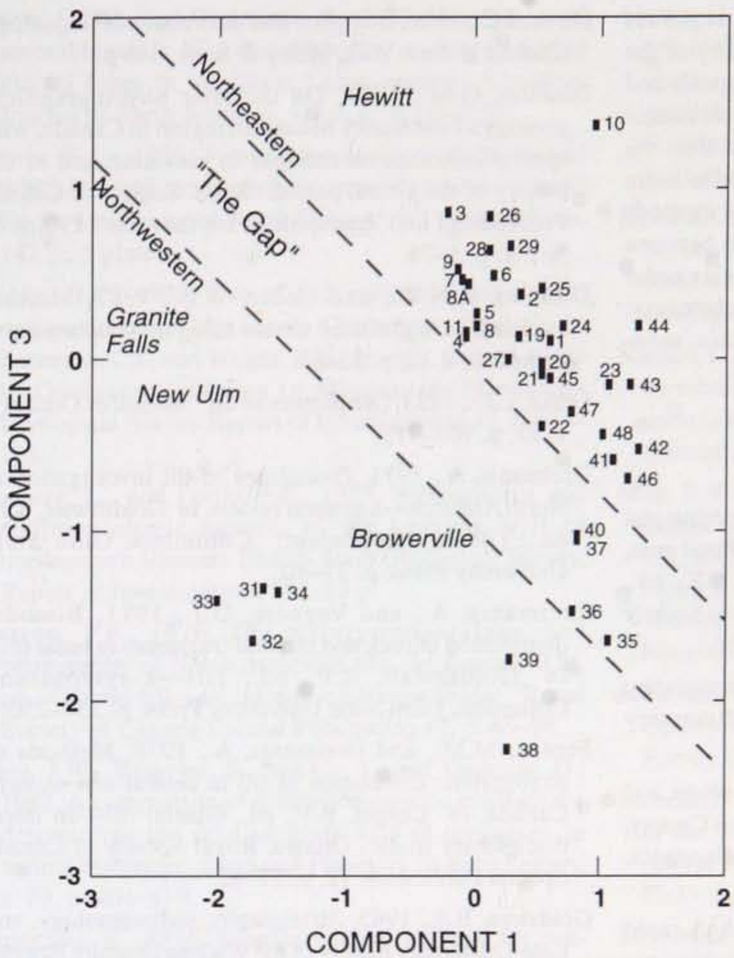


Figure 12. Component score plot for till samples from core OB-402. Sample numbers reflect position within core (see Fig. 10). General fields are for the Hewitt, New Ulm, Browerville, and Granite Falls Tills as determined from control group till samples. "The gap" between northeast- and northwest-provenance tills is indicated by two dashed lines. Component 1 and component 2 loadings are derived from PCA Run 7 (Table 4) on the control group till samples.

Thirdly, PCA analysis shows that the New Ulm and Granite Falls Tills are geochemically similar. Geochemical data show that it is possible that the New Ulm and Granite Falls Tills were deposited during separate glacial advances of ice from the same source region, because the silt and clay fraction of a till tend to represent material incorporated far up-glacier. However, the two tills are easily distinguished in the field based on shale clast content. Additional study is warranted before further conclusions can be drawn.

Fourthly, the glacial history of the region north of Mille Lacs Lake, as interpreted from the stratigraphy of core OB-402, shows a repeated alternation in advances of northeast-source and northwest-source ice, probably the pre-Late Wisconsinan "Old Rainy" and "Winnipeg" lobes of Meyer (in Martin and others, 1988, 1989). The first ice to occupy the area during the Late Wisconsinan was the northeast-sourced Rainy lobe. Upon withdrawal of the Rainy lobe, the northeast-sourced Superior lobe was able to spread into the region during the Automba phase (Wright, 1972; Mooers, 1988). The final glacial advance recorded is that of the St. Louis sublobe of the Des Moines lobe, represented by the Alborn Till.

Finally, this investigation shows that the methods commonly used for till description in Minnesota (grain-size analysis, carbonate content, sand-grain composition, and rock-magnetic properties) cannot be used to statistically distinguish between till groups. The parameter found to best define the individual tills is the geochemistry of the silt and clay fraction, which may also distinguish between northeast- and northwest-sourced tills.

The method(s) used to study provenance in glacial geological investigations should be tailored to the goals of the project and the tills to be investigated. For instance, studies into the regional variability within a particular till sheet might want to employ grain-size, carbonate content, sand-grain composition, and rock magnetic properties as variables with which to describe variation in the till. However, if the aim is to better define till stratigraphy for an area in which the general sequence is already known, the choice of analytical methods should depend on the expected units. Till assessment in an area where there are no northwest-sourced tills would not need to look at carbonate content; neither would rock magnetic properties need to be considered for northeast-sourced tills, unless a variation in magnetite grain-size is anticipated.

Results presented here show that regional stratigraphic studies should employ geochemistry of the silt and clay fractions in order to both distinguish and correlate till units. The silt and clay within the till matrix was incorporated over a much broader region than the sand and larger clasts, and is therefore regarded to more accurately represent the till as a whole. The other methods for describing tills were not able to distinguish between all six control tills used in this study. In decreasing order of distinguishing ability, and secondary to geochemistry, these other methods are rock-magnetic properties, sand-grain composition, and grain-size analysis.

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COMPUTER-ASSISTED LITHOSTRATIGRAPHY

Kenneth L. Harris

ABSTRACT

Computer-assisted interpretation of textural and lithologic (detrital-grain composition) data was used to assist in the identification and mapping of twenty lithostratigraphic units in a 38,000 square kilometer area in the Lake Agassiz basin in North Dakota and Minnesota. Seventeen of the units are placed in 6 groups. Each group represents a suite of tills that was deposited by glaciers that moved through the present Red River valley during the Wisconsinan.

INTRODUCTION

Previous Quaternary stratigraphic studies within the Lake Agassiz basin of North Dakota and Minnesota have been very local in scope (see next section). Sedimentary units have in the past been correlated without the assistance of a quantitative database. In this paper an interpretation of the quantitative textural and compositional data for tills of the Lake Agassiz basin is presented. The database (QBASE) is derived from a digital file of nearsurface stratigraphic data compiled by the North Dakota Geological Survey, termed N-FILE (North Dakota Geological Survey, 1995). The database also includes new data generated by the Minnesota Geological Survey (e.g. Harris and others, 1995). The computer-assisted lithostratigraphic techniques help to (1) identify natural tendencies in the data (clusters or tills), (2) interpret stratigraphic relations, and (3) correlate lithostratigraphic units.

Computer-assisted techniques permit the integration of databases containing data derived from outcrops, surface exposures, cores and well logs or boreholes. The integration of data from surface and subsurface sources facilitates the rapid development of regional lithologic maps, and stratigraphic interpretations. The technique has evolved over the past twenty years in an attempt to identify, interpret, and correlate tills in northwestern Minnesota and northeastern North Dakota.

This work was done in conjunction with a joint Minnesota Geological Survey and Minnesota Department of Natural Resources, Division of Waters mapping project in the southern Red River valley. The southern Red River valley study area is located in northwestern Minnesota and eastern North Dakota (Fig. 1). It extends from latitude 46°N to 48°N and from longitude 96°W to 98°W. The area straddles the North Dakota—Minnesota border and includes the southern part of the Lake Agassiz basin and adjacent areas of glacial upland. The Southern Red River Valley Regional Hydrogeologic Assessment (SRRV-RHA) describes the surface geology of the Minnesota part of the southern Red River valley and the Quaternary stratigraphy of the southern Red River valley region (Harris and others, 1995). The North Dakota Geological Survey has published maps (Harris, 1987a; Harris, 1987b, and Harris and Luther, 1991) that describe the surface geology of the North Dakota part of the southern Red River Valley region.

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p. 179–192 *in* Patterson, C.J., and Wright, H.E., Jr., eds., Contributions to Quaternary studies in Minnesota: Minnesota Geological Survey Report of Investigations 49 (1998)

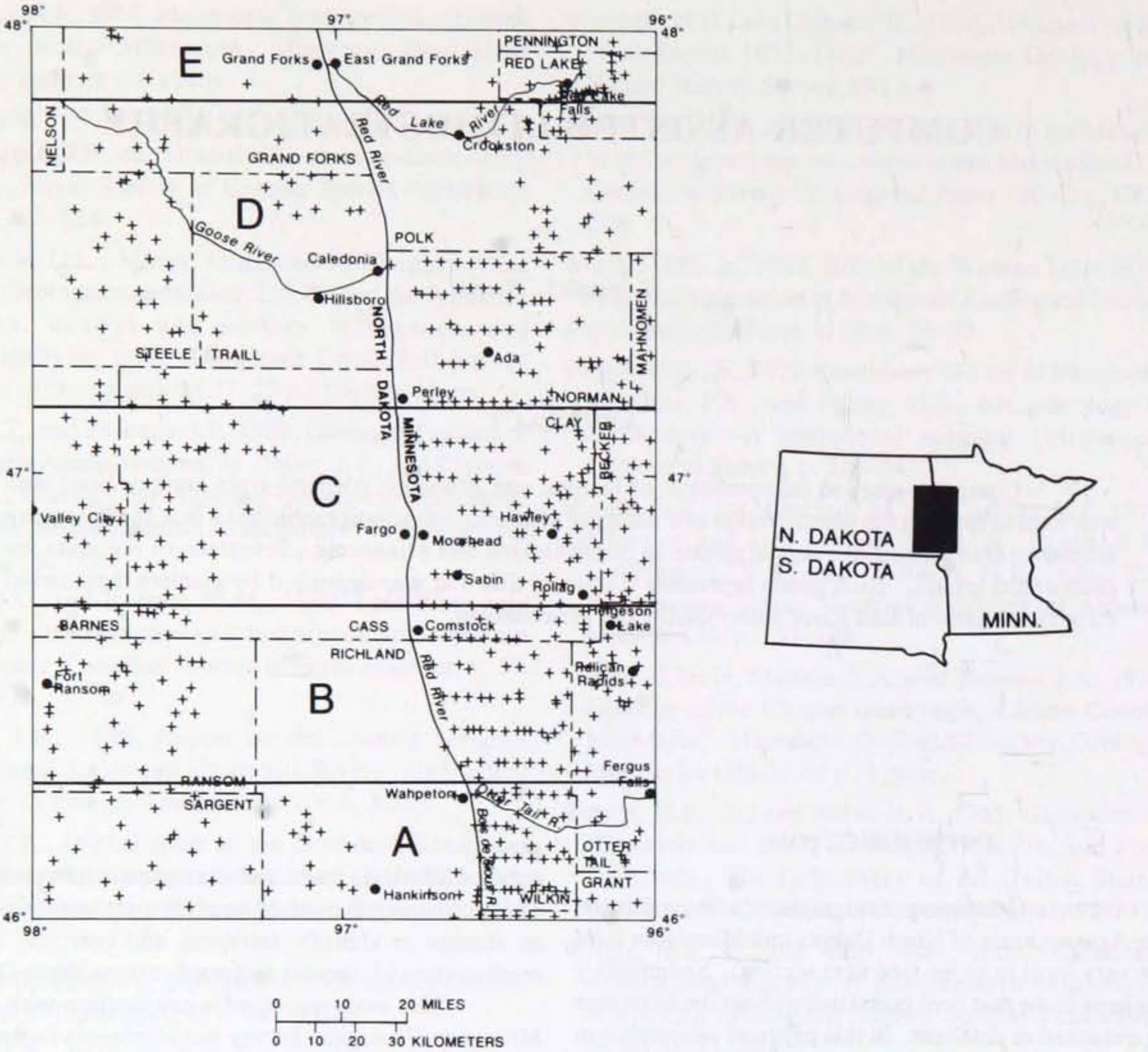

Figure 1. Map of SRRV-RHA study area. Location of data subsets A through E indicated. + indicates sample site.

PREVIOUS WORK

The Quaternary stratigraphy of the Glacial Lake Agassiz area is best observed in the incised valley through which the Red Lake River currently flows. The glacial stratigraphy was first investigated in the early 1970's by Moran and others (1971, 1973) and Harris (1973). Ten formations, including glacial and lacustrine sediments were formally defined for the region on the basis of both detailed work and extensive regional reconnaissance fieldwork. Subsequent studies have resulted in the definition of additional stratigraphic units for the Red River valley region (Harris, 1975; Sackreiter, 1975; Anderson, 1976; Perkins, 1977). A stratigraphic framework for Quaternary glacial sediments has also been developed for northeastern North Dakota (Salomon, 1975; Hobbs, 1975) and eastern North Dakota (Camara, 1977). Moran and others (1976) synthesized all the work on Quaternary stratigraphy conducted by the North Dakota Geological Survey, and by researchers at the University of North Dakota. Arndt (1977) recognized fourteen formations comprising lacustrine and glacial sediments in the Lake Agassiz basin.

Regional stratigraphic work, together with a chronology of the Lake Agassiz basin were used to develop further stratigraphic interpretations for the Upper Midwest (Clayton and Moran, 1982; Clayton, 1983), and for Manitoba and Ontario (Fenton and others, 1983). The surficial geology of the southern Red River valley has been mapped in North Dakota by Clayton and others (1980), Harris (1987b), and Harris and Luther (1991). In Minnesota the surficial geology has been mapped by Hobbs and Goebel (1982), Harris (1987a), and Harris and others (1995). The surficial geology of the southern Red

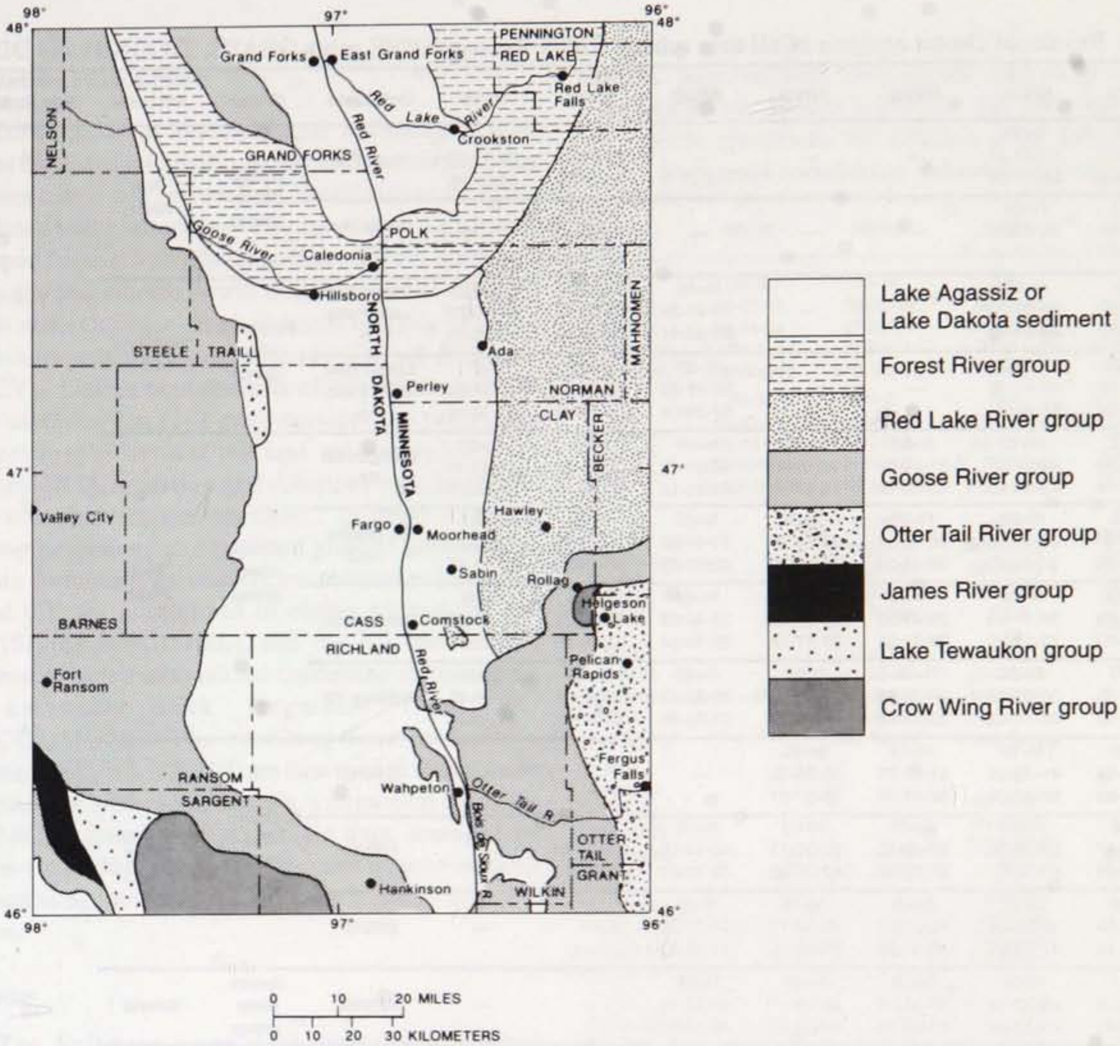

Figure 2. Lithostratigraphic map of SRRV-RHA study area showing interpreted distribution of lithostratigraphic units as defined by computer-assisted techniques.

River valley can be summarized (Fig. 2) as consisting of proglacial lake sediment and reworked tills in the central part of the lake basin, with collapsed glacial sediments and meltwater deposits flanking the lake basin.

THE DATABASE

Background

The database maintained by the North Dakota Geological Survey for nearsurface stratigraphic data (N-FILE) contains about 9000 entries (North Dakota Geological Survey, 1995). Data contained in N-FILE were generated by North Dakota Geological Survey and University of North Dakota geologists working in North Dakota and adjacent states, and represent a variety of surface and subsurface data collected from outcrops, hand-auger borings, soil-probe holes, and power-auger holes. N-FILE is available from the North Dakota Geological Survey.

The Minnesota Geological Survey (MGS) database (QBASE) contains data relevant to Quaternary studies in Minnesota. QBASE contains the Red River valley-RHA database (RRVOA), which consists of relevant data from the N-FILE database (Harris, 1973; Harris and others, 1974; Harris, 1975; Salomon, 1975; Hobbs, 1975; Sackreiter, 1975; Camara, 1977; Anderson, 1976; Perkins, 1977; Harris, 1987b; Harris and Luther, 1991), and includes additional data generated by the Minnesota Geological Survey for the SRRV-RHA (Harris and others, 1995). RRVOA consists of information on about 2100 samples, 700 of which were collected and analyzed during 1992-93 as part of the SRRV-RHA, including data from 4 continuous Rotasonic cores. Information stored in QBASE includes sample site location, sample elevation, geologist's name, project name, sample texture and coarse-sand composition. QBASE is available from the Minnesota Geological Survey.

Table 1. Results of cluster analysis of till data subsets RRVA through RRVE using QBASE, TILSRCH and DISCORT.

RRVOA	BHOA	RRVA	RRVB	RRVC	RRVD	RRVE	Unit Name	Group	Ice Lobe	Age (ka)
N=35 07-22-71 45-50-05	N=33 07-22-71 42-52-06	—	—	—	N=12 07-21-72 50-42-08	N=25 07-22-71 43-52-05	Huot Fm.	Forest River group	Red River	11
N=10 12-39-49 38-38-24	N=08 36-43-21 31-22-47	—	—	—	N=10 12-39-49 38-38-24	—	Falconer Fm.			
N=54 37-40-23 53-34-13	N=56 38-42-20 54-34-12	—	—	N=15 31-40-29 56-33-11	N=04 39-43-18 53-36-11	N=48 37-40-23 53-33-14	Upper Red Lake Falls Fm.	Red Lake River group	Wadena / Rainy	11.5
N=116 39-41-20 57-39-04	N=117 41-41-18 58-40-02	—	—	N=27 36-41-23 57-39-04	N=62 38-43-19 54-43-03	N=39 43-37-20 56-38-06	Lower Red Lake Falls Fm.			
N=32 19-42-39 45-41-14	N=18 20-41-39 48-44-08	N=09 21-45-34 43-40-17	N=07 20-39-41 48-39-13	N=09 16-41-43 46-40-14	N=04 20-45-35 40-48-12	N=03 18-41-41 39-48-13	Barnesville till	Goose River group	Red River	12
N=80 27-42-31 43-32-25	N=09 29-42-29 50-29-21	N=38 26-40-34 35-31-34	N=25 26-44-30 44-36-20	N=25 31-41-28 46-31-23	N=09 38-39-23 46-28-26	N=07 27-42-31 44-32-24	St. Hilaire Fm.			
N=174 30-41-29 27-18-55	N=22 34-41-25 23-18-59	N=58 26-41-33 26-21-53	N=43 27-41-32 27-17-56	N=48 33-44-23 28-18-54	N=34 36-39-25 24-16-60	N=09 37-40-23 28-17-55	Dahlen Fm.			
N=75 36-39-25 35-23-42	N=26 36-28-26 34-24-42	N=04 39-38-23 35-28-37	N=22 31-39-30 31-29-40	N=20 38-39-23 37-23-40	N=30 37-39-24 34-21-45	N=09 35-39-26 35-22-43	Heiberg till			
N=32 38-38-24 54-43-03	N=18 41-33-26 55-36-09	N=19 41-39-20 52-47-01	N=15 33-35-32 56-37-07	—	—	—	RRV10	Otter Tail River group	Rainy	14
N=38 44-39-17 66-33-01	N=28 53-32-15 63-35-02	N=06 56-29-15 64-32-04	N=03 52-35-13 67-31-02	N=18 40-44-16 68-31-01	N=17 46-35-19 65-34-01	—	RRV11			
N=26 46-35-19 50-31-19	N=32 38-38-24 47-28-25	N=08 42-37-21 46-31-23	N=16 49-34-17 54-30-16	N=02 41-37-22 45-33-22	—	—	RRV12			
N=11 47-35-18 44-23-33	N=04 49-32-19 45-27-28	N=06 47-34-19 45-23-32	N=03 45-38-17 42-23-35	N=02 49-33-18 46-24-30	—	—	RRV05	James River group	Souris	15
N=55 30-43-27 16-11-73	N=10 35-44-21 17-12-71	N=11 26-45-29 13-12-75	N=18 30-43-27 19-11-70	N=13 29-45-26 17-10-73	N=16 32-42-26 14-11-75	—	Gardar Fm.	Lake Tewaukon group	Red River	
N=27 20-42-38 14-12-74	—	N=16 22-41-37 14-12-74	N=09 16-48-36 13-12-75	N=03 15-50-35 11-12-77	N=02 24-42-34 11-15-74	—	facies RRV14			
N=23 32-35-33 61-36-03	N=26 33-35-32 64-33-03	N=24 32-35-33 62-35-03	—	—	—	—	RRV15	Crow Wing River group	Rainy/ Superior	25
N=11 56-34-10 86-13-01	N=84 50-35-15 76-24-00	—	N=03 61-21-18 96-04-00	—	N=03 68-21-11 86-14-00	N=10 55-36-09 86-13-01	RRV16			
N=26 57-29-14 74-25-01	N=12 51-34-15 84-16-00	—	N=03 56-26-18 75-22-03	N=13 59-27-14 72-27-01	N=05 58-30-12 77-22-01	N=05 53-33-14 76-23-01	Marcoux Fm.			
N=17 30-39-31 49-36-15	N=11 31-39-30 49-37-14	N=17 30-38-32 49-36-15	—	—	—	—	RRV18			
N=27 27-45-28 49-46-05	N=12 26-45-29 48-50-02	—	N=02 28-40-32 43-54-03	N=12 25-46-29 49-42-09	N=09 28-45-27 49-49-02	N=15 25-46-29 51-45-04	Gervais Fm.	—	Red River	100
N=12 68-20-12 93-07-00	N=19 65-26-09 97-03-00	—	N=12 68-20-12 93-07-00	—	—	—	Sebaka till	—	Superipr	strat. position uncertain

Till units are placed in their interpreted stratigraphic order. Column RRVOA is the average of all subset values for a given till unit. Column BHOA provides the average results compiled from regional borehole data. Unit Name indicates the existing stratigraphic unit with which the till cluster probably correlates; where no such stratigraphic unit already exists the Unit Name corresponds to the till cluster number. Notation for each till unit is as follows: N = number of samples; 1st line = percentage sand-silt-clay; 2nd line = percentage crystalline/metamorphic-limestone-dolostone/shale detrital grains; — indicates that no correlatable till clusters are identified for that area

Correlation Parameters

Differentiation among glacial sedimentary units requires the use of internally consistent characteristics that vary from unit to unit and are field identifiable or are easily determined in the laboratory. The correlation parameters developed for use with glacial sediments from northwest Minnesota and eastern North Dakota are derived from textural and lithologic data. Textural analysis provides the percentage composition of sand (SD), silt (SL), and clay (CY). Grain-count analysis of the lithology of the coarse-sand fraction (1–2 mm) provides the percentage composition of crystalline and metamorphic rock fragments (XT), limestone and dolostone rock fragments (CO), and shale fragments (SH). In order to speed computer processing and facilitate graphic presentation, these six correlation parameters are reduced to four. The SL and CY are normalized to obtain normalized silt (NS=((SL/(SL+CY))*100)), and the XT and CO are combined to obtain normalized crystalline-metamorphic and carbonate rock fragments (NX=((XT/(XT+CO))*100)). The resulting four correlation parameters (SD, NS, NX, SH) are then used to characterize tills within the study area. Finally, a sequential dataset is assembled; it consists of all sample data, arranged by location (township, range, section, and quarter section) and decreasing elevation at each sample site or borehole location.

Table 2. Residual units from cluster analysis of till data subsets RRVA through RRVE (i.e. till units that could not be classified). Till notation as for Table 1. Suggested correlations indicated in italics.

RRVA	RRVB	RRVC	RRVD	RRVE
N=8 37-41-22 25-19-56 *(Dahlen Fm. sandy facies)*	N=3 20-62-18 32-14-54 *(Dahlen Fm. silty facies)*	N=14 26-55-19 67-32-01 *(RRV11 silty facies)*	N=2 32-37-01 61-34-05 *(L. Red Lake Falls Fm.)*	N=7 51-36-13 55-43-02 *(L. Red Lake Falls Fm.)*
N=5 42-39-19 55-40-05 *(RRV10)*	N=5 45-40-15 24-15-61 *(Dahlen Fm. Sandy facies)*	N=2 35-42-23 89-11-00 *(RRV16 silty facies)*	N=4 23-55-22 58-35-07 *(L. Red Lake Falls Fm.)*	N=5 52-33-15 73-16-11 *(uncertain)*
N=4 23-34-43 61-28-11 *(RRV15)*	—	N=17 49-39-12 72-28-00 *(Marcoux Fm. silty facies)*	N=8 39-38-23 56-26-18 *(St. Hilaire Fm.)*	N=7 30-38-32 50-36-14 *(clayey U. Red Lake Falls Fm.)*
N=6 19-25-56 69-28-03 *(RRV15 clayey facies)*	—	N=15 47-33-20 70-29-01 *(Marcoux F. silty facies)*	N=4 53-28-19 28-16-56 *(Dahlen Fm. sandy facies)*	—
N=2 33-28-39 92-08-00 *(Sebeka till, clayey facies)*	—	—	N=2 45-34-21 90-10-00 *(uncertain)*	—
N=7 34-33-33 74-23-03 *(Marcoux Fm. clayey facies)*	—	—	N=08 19-48-33 56-41-03 *(uncertain)*	—
N=6 21-31-48 43-41-16 *(uncertain)*	—	—	—	—

Software

The software used with computer-assisted stratigraphy is designed to duplicate the procedures a geologist would use to evaluate textural and lithologic data, and develop interpretations and correlations (Harris, 1987c). Two programs are used in the identification, verification, and correlation of tills in a dataset. They are a cluster-analysis program (TILSRCH) and a display-correlate program (DISCORT). The programs are written in Microsoft QBASIC and require a DOS computer. Programs read comma-delimited files, and will handle about 450 samples per run. Consequently, study area data from RRVOA was divided into 5 data subsets termed RRVA, RRVB, RRVC, RRVD and RRVE (Fig. 1; Table 1) for the Red River valley region. These programs and other data-handling and graphic-display programs have been installed in a menu-driven environment designed for working with the till data.

TILSRCH

The cluster analysis program allows naturally occurring modal groups (clusters or tills) in a dataset to be identified and isolated; member samples within each cluster can then be labeled. Clusters are initially identified by generating cross plots of the dataset using the four correlation parameters. An external graphics program or the cross-plot display in TILSRCH can be used. In either case, coordinates of clusters can be determined. The coordinates are then used as keyboard input to TILSRCH to generate trial clusters. The cross plots generated for each of the five data subsets are: (1) sand vs. shale (SD-SH); (2) sand vs. normalized silt (SD-NS) and (3) shale vs. normalized crystalline (SH-NX). These are shown in Figures 3, 4 and 5. The most useful cross plot for identifying trial clusters is SD-SH since it displays data for both texture and detrital grain composition.

The initial definition of a modal group is refined interactively. This iterative process involves retrieving a target cluster of samples from the database with estimated mean values of the four correlation parameters and a "gate width" of +/- 2 standard deviations. TILSRCH will then retrieve all samples in the database that fit the definition of the target cluster. The mean and standard deviation of the returned samples are calculated (for each of the four correlation parameters) and compared to the input values.

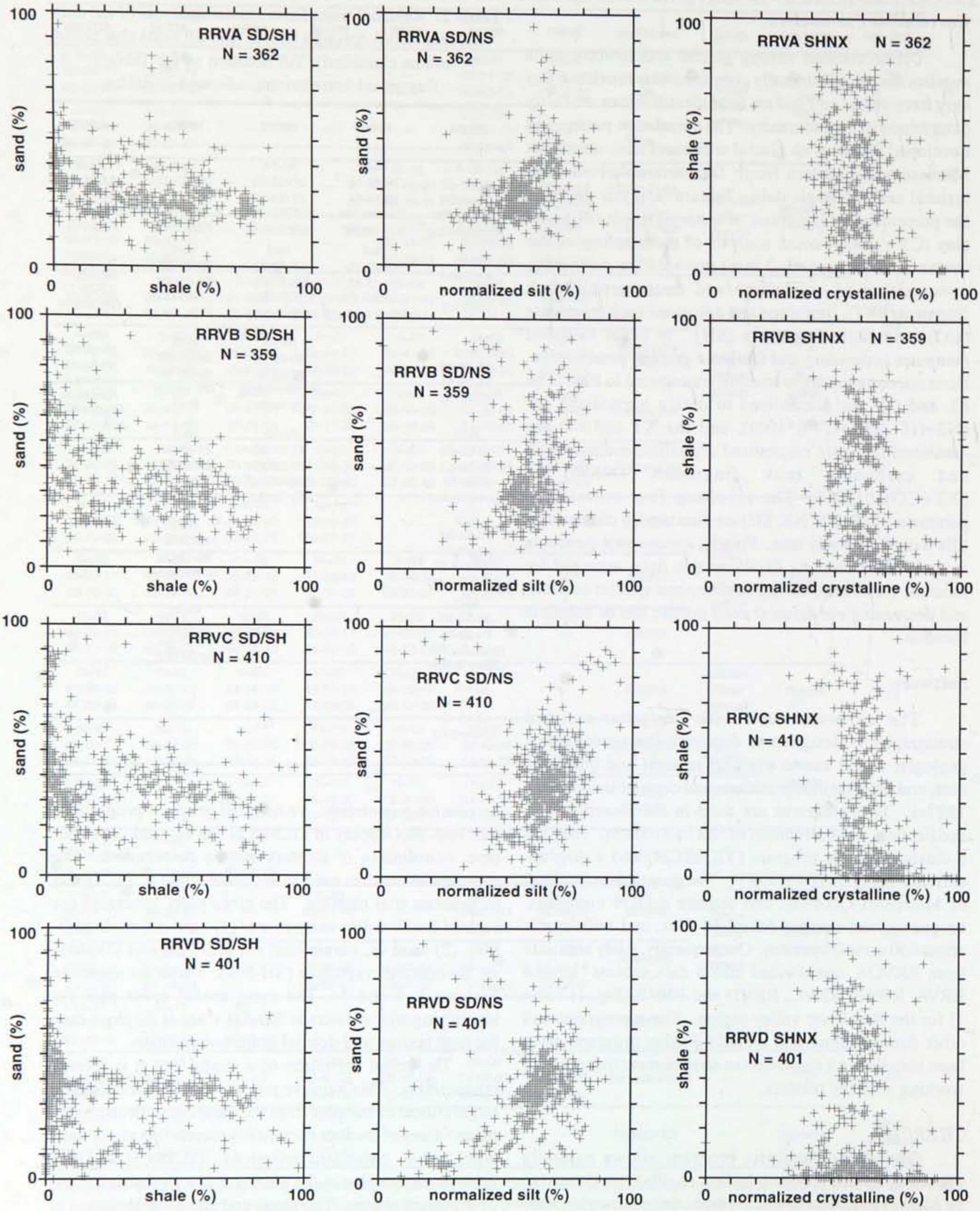

Figure 3. Cross plots of sand vs. shale (SD/SH); sand vs. normalized silt (SD/NS), and shale vs. normalized crystalline components (SHNX) for data subsets RRVA, RRVB. RRVC and RRVD.

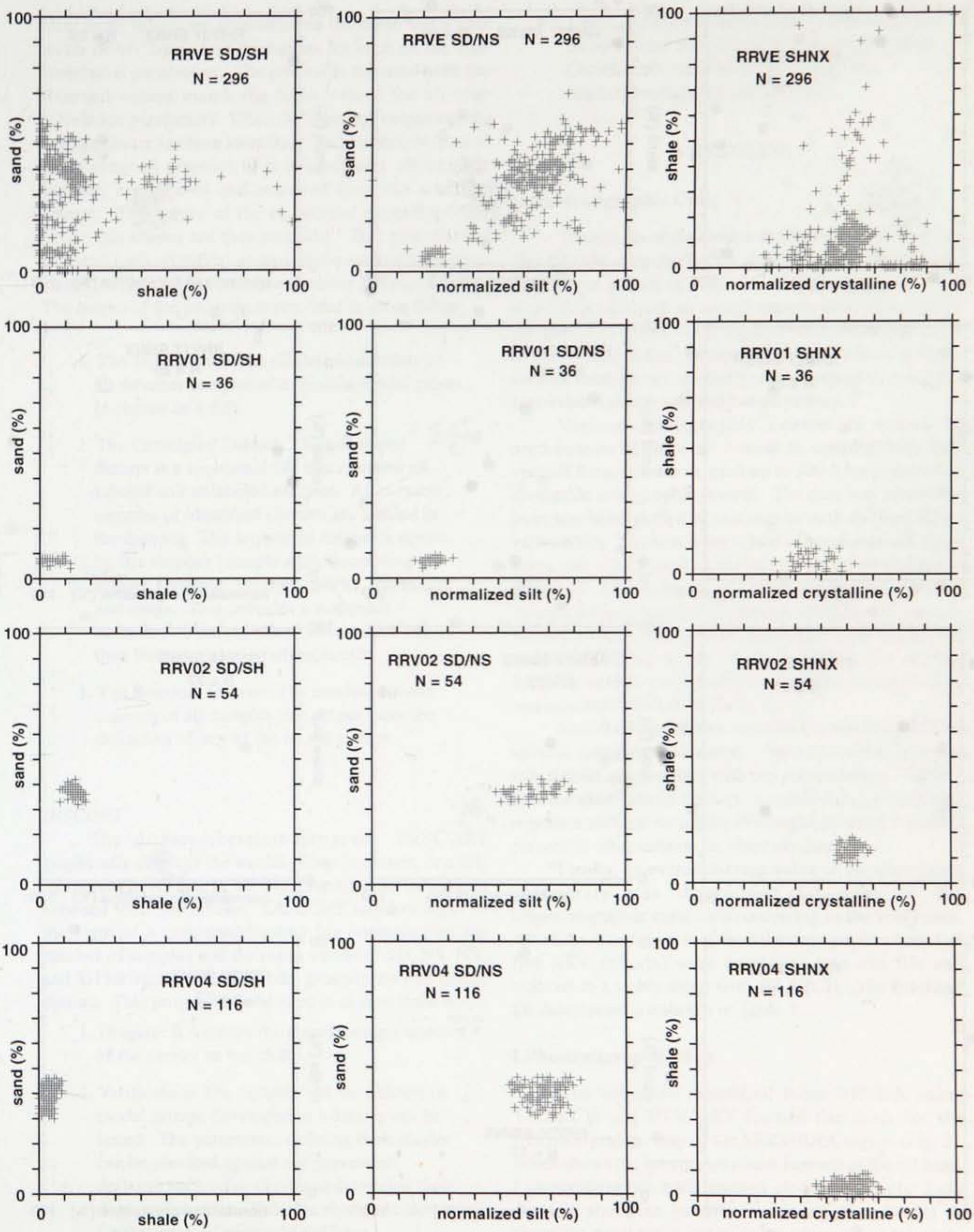

Figure 4. Cross plots of sand vs. shale (SD/SH); sand vs. normalized silt (SD/NS), and shale vs. normalized crystalline components (SHNX) for data subset RRVE and tills RRV01, RRV02, and RRV04.

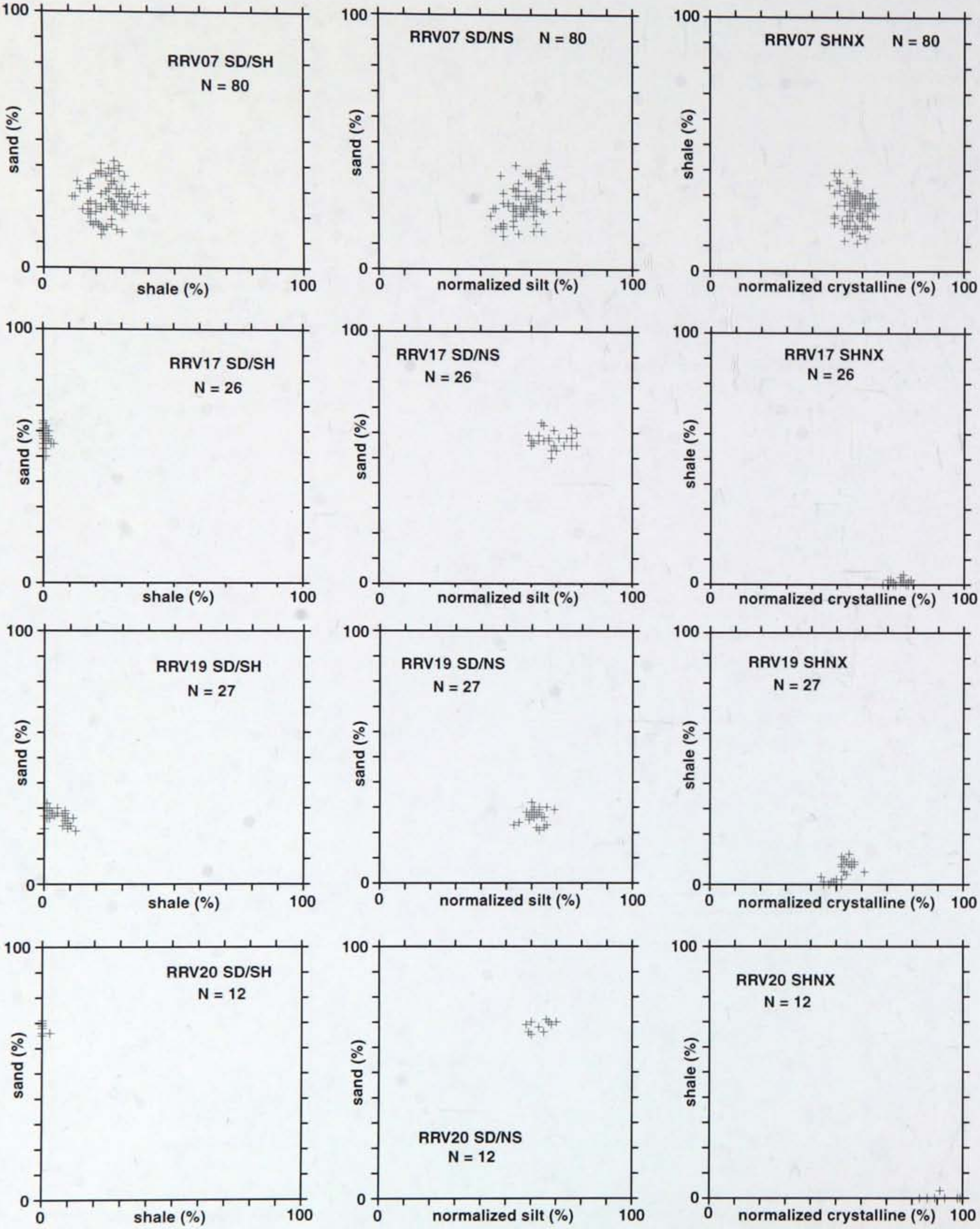

Figure 5. Cross plots of sand vs. shale (SD/SH); sand vs. normalized silt (SD/NS), and shale vs. normalized crystalline components (SHNX) for tills RRV07, RRV17, RRV19 and RRV20.

New input values are entered using the mean and a gate width of +/- 2 standard deviations for each of the four correlation parameters. The process is repeated until the returned values match the input values for all four correlation parameters. When the input and output match, a stable cluster has been identified. The cluster is inspected using program graphics; if it is acceptable all member samples are labeled and removed from the working dataset. The values of the correlation parameters that define this cluster are then recorded. This procedure is repeated until all modal groups in the dataset have been identified and defined and their member samples labeled. The output of the program is provided in three forms:

1. The Till Dataset: The till dataset consists of all member samples of a specific modal group (a cluster or a till).
2. The Correlated Dataset: The correlated dataset is a sequential file that contains all labeled and unlabeled samples. All member samples of identified clusters are labeled in the data set. The sequential dataset is sorted by file number (sample site), decreasing sample elevation, section, quarter, township, and range. This provides a mappable summary of the correlated data, which can then be interpreted stratigraphically.
3. The Residual Dataset: The residual dataset consists of all samples that do not meet the definition of any of the modal groups.

DISCORT

The display-correlate program DISCORT graphically displays the modal group (a cluster, or a till) definitions developed in TILSRCH and checks for overlap between their definitions. DISCORT requires input in the form of a comma-delimited file consisting of the number of samples and the mean values of SD, NS, NX, and SH for each cluster or modal group in the interpreted dataset. This program can be used in at least three ways:

1. Display: It displays the correlation parameters of the cluster as bar charts.
2. Verification: The "quality" of the clusters or modal groups developed in a dataset can be tested. The parameters defining each cluster can be checked against the parameters defining each other cluster to determine their degree of overlap. Reliable cluster definitions (in this case, tills) should not have overlapping definitions.
3. Correlation: Definitions from one dataset can be compared with those from another dataset. Correlatable clusters (tills) should have similar, overlapping definitions.

RESULTS

Lithostratigraphic Units

The results of the cluster analysis performed on the five RRVOA subsets (RRVA, RRVB, RRVC, RRVD and RRVE) are shown in Table 1. Lithostratigraphic units were defined based on modal groups determined using TILSRCH and DISCORT, together with prior knowledge of their stratigraphic position. The clusters in each of the subsets were placed in stratigraphic sequence using the correlated datasets and field observations.

Vertical stratigraphic control is scarce in northwestern Minnesota. Access to samples from four vertical Rotasonic cores, each up to 300 ft long, provided invaluable stratigraphic control. The core was recovered from test holes drilled in association with the Red River valley RHA. The data subset (BHOA) derived from these cores was established to provide essential stratigraphic reference. It consists of all "deep" boring and outcrop data available from northwestern Minnesota and eastern North Dakota. BHOA was interpreted with TILSRCH and DISCORT (Table 1). With the BHOA file and the five RRV subsets a reasonable stratigraphic interpretation was reached (RRVOA in Table 1).

Not all of the clusters identified in the five RRVOA subsets could be correlated. Some clusters in some subsets, did not correlate with any other clusters. Table 2 lists the uncorrelated clusters (residual data), which may represent textural variations of recognized units, units not present in other subsets, or aberrant data.

Finally, an overall average value of the correlation parameters was determined for each of the lithostratigraphic units (tills) occurring in the study area. All of the data for each of the lithostratigraphic units (all five RRV subsets) were combined into one file and reduced to a stable mean with TILSRCH. The resulting till descriptors are shown in Table 1.

Lithostratigraphic Map

The till units identified from RRVOA using TILSRCH and DISCORT formed the basis for the lithostratigraphic map of the SRRV-RHA region (Fig. 2), which shows the interpreted extent for each of the till units. Lithostratigraphic units present along the Glacial Lake Agassiz shoreline have been thinned or removed by shoreline erosion, in some cases exposing older units.

Table 3. Correlation of till units identified in this study of the SRRV-RHA with till units identified by other workers in North Dakota and Minnesota. Till notation as for Table 1.

WEST CENTRAL MINNESOTA Harris and others (this study)	NORTHEAST NORTH DAKOTA Salomon (1975)	NORTHEAST NORTH DAKOTA Moran and others (1976)	NORTHEAST NORTH DAKOTA Hobbs (1975)	SOUTHEAST NORTH DAKOTA Moran and others (1976)	SOUTHEAST NORTH DAKOTA Camara (1977)	NORTHWEST MINNESOTA Moran and others (1976)	WEST CENTRAL MINNESOTA Anderson (1976)	WEST CENTRAL MINNESOTA Perkins (1977)	Unit Name	Group	Ice Lobe	Age (ka)
N=35 07-22-71 45-50-05	—	—	—	—	—	06-22-72 41-53-06 *(Huot)*	—	—	Huot Fm.	Forest River group	Red River	11
N=10 12-39-49 38-38-24	31-45-24 38-31-31 *(Falconer)*	29-33-38 42-34-24 *(Falconer)*	29-33-38 42-34-24 *(Falconer)*	—	—	—	—	—	Falconer Fm.			
N=54 37-40-23 53-34-13	—	—	—	—	—	37-42-21 54-33-13 *(U. Red Lake Falls Fm.)*	—	—	Upper Red Lake Falls Fm.	Red Lake River group	Wadena / Rainy	11.5
N=116 39-41-20 57-39-04	43-39-18 44-54-02 *(L. Red Lake Falls Fm.)*	—	—	—	—	46-38-16 55-42-03 *(L. Red Lake Falls Fm.)*	—	—	Lower Red Lake Falls Fm.			
N=32 19-42-39 45-41-14	—	—	—	—	—	—	21-41-38 42-45-13 *(Barnesville)*	16-45-39 43-41-16 *(Barnesville)*	Barnesville till			
N=80 27-42-31 43-32-25	—	—	28-38-34 50-27-23 *(Hansboro)*	24-46-30 39-29-32 *(LF10)*	29-41-30 40-30-30 *(unit C)*	33-39-28 41-31-28 *(St. Hilaire)*	—	—	St. Hilaire Fm.	Goose River group	Red River	12
N=174 30-41-29 27-18-55	36-28-36 26-20-54 *(unit B)*	29-44-27 26-19-55 *(Dahlen)*	27-44-27 26-19-55 *(Dahlen)*	24-45-31 27-19-54 *(LF20)*	37-42-21 29-23-48 *(unit B)*	—	—	—	Dahlen Fm.			
N=75 36-39-25 35-23-42	35-45-20 32-21-47 *(Dahlen)*	34-35-31 40-25-35 *(Vang)*	34-35-31 40-25-35 *(Vang)*	28-40-32 38-27-35 *(LF60)*	30-43-27 31-25-44 *(Dahlen)*	—	40-35-25 40-25-35 *(Dunvilla)*	36-39-25 41-24-35 *(Dunvilla)*	Heiberg till			14
N=32 38-38-24 54-43-03	—	—	—	—	—	—	—	34-42-24 53-42-05 *(Hawley)*	RRV10	Otter Tail River group	Rainy	
N=38 44-39-17 66-33-01	—	—	—	—	—	—	50-30-20 65-31-04 *(NY Mills)*	50-32-18 71-27-02 *(NY Mills)*	RRV11			
N=26 46-35-19 50-31-19	—	—	—	—	—	—	—	—	RRV12			
N=11 47-35-18 44-23-33	—	—	—	46-31-23 40-30-30 *(LF40)*	—	—	—	—	RRV05	—	Souris	15
N=55 30-43-27 16-11-73	34-42-24 13-10-77 *(Gardar)*	32-42-26 10-08-82 *(Gardar)*	32-42-26 10-08-82 *(Gardar)*	—	22-49-29 19-16-65 *(Gardar)*	—	—	—	Gardar Fm.	Lake Tewaukon group	Red River	
N=27 20-42-38 14-12-74	—	—	—	18-48-34 15-15-70 *(LF30)*	—	—	—	—	facies RRV14			
N=23 32-35-33 61-36-03	—	—	—	—	—	39-33-28 70-29-01 *(unnamed-2)*	—	—	RRV15			
N=11 56-34-10 86-13-01	—	—	—	—	—	—	—	—	RRV16	Crow Wing River group	Rainy/ Superior	25
N=26 57-29-14 74-25-01	—	—	—	—	—	54-35-11 78-21-01 *(Marcoux)*	—	61-26-13 80-20-00 *(Sebeka)*	Marcoux Fm.			
N=17 30-39-31 49-36-15	—	—	—	—	33-40-27 52-29-19 *(Unit D)*	—	—		RRV18			
N=27 27-45-28 49-46-05	—	—	—	—	—	19-50-31 44-55-01 *(Gervais)*	—	—	Gervais Fm.	—	Red River	100
N=12 68-20-12 93-07-00	—	—	—	—	—	—	66-21-13 93-07-00 *(Sebeka)*	—	Sebaka till	—	Superior	strat. position uncertain

Table 4. Summary of "residual" till units identified by other authors in North Dakota and Minnesota. These till units could not be correlated with till units defined for the SRRV-RHA using QBASE, TILSRCH and DISCORT. The number of samples is not indicated. The stratigraphic nomenclature used by each author is indicated in italics. Till notation as for Table 1.

WEST-CENTRAL MINNESOTA	NE NORTH DAKOTA	NE NORTH DAKOTA	NE NORTH DAKOTA	SE NORTH DAKOTA	SE NORTH DAKOTA
Harris and others, this study	Salomon, 1975	Moran and others, 1976	Hobbs, 1975	Moran and others, 1976	Camara, 1977
	29-54-17 33-65-02 *(unit 1)*	27-38-35 21-28-51 *(Tiber)*	27-38-35 21-28-51 *(Tiber)*	33-44-23 26-22-52 *(LF50)*	34-43-23 67-23-10 *(unit E)*
All till units assigned (see column 1 in Table 3)	35-36-29 21-17-62 *(unitA)*	35-41-24 25-16-59 *(Cando)*	35-41-24 25-16-59 *(Cando)*	—	29-43-28 38-26-36 *(unit A)*
	30-27-43 30-28-42 *(unit C)*	—	—	—	—
	35-29-36 37-48-15 *(unit D)*	—	—	—	—

Lithostratigraphic units associated with Glacial Lake Agassiz and Glacial Lake Dakota are shown as a single map unit on Figure 2, and are not discussed in this paper.

LITHOSTRATIGRAPHIC CORRELATIONS

Lithostratigraphic correlations between stratigraphic units identified for the SRRV-RHA and lithostratigraphic units developed by other workers in the area are shown in Table 3. The texture and detrital grain composition of the units described by other workers were honored in the correlations, but stratigraphic position was determined by correlation with SRRV-RHA units. Table 4 lists those stratigraphic units that did not correlate with any of the SRRV-RHA units. Most of the units that did not correlate are in the northeastern North Dakota, where there are numerous stratigraphic units documented that are not present in the southern Red River Valley.

SUMMARY

Wisconsinan glaciers advanced into the Red River valley from the northwest (Keewatin provenance) and the north (Winnipeg provenance) as well as from the northeast and east (Labrador provenance) (Meyer and Knaeble, 1996). Glacial sediment deposited during each advance has a textural and detrital-grain composition that reflects its source area. The cross plots of the correlation parameters show the characteristics of tills associated with each of the source areas. The Huot (RRV01; Red River lobe) and Gervais Formations (RRV19; Red River lobe) are interpreted to be Winnipeg-provenance tills, and the St. Hilaire Formation (RRV07; Red River lobe) as a Keewatin-provenance till. The Upper and Lower Red Lake Falls Formation (RRV03 and RRV04; Wadena/Rainy lobe) are Keewatin- to Labrador- provenance tills, and the Marcoux Formation (RRV17; Rainy/Superior lobe) and Sebeka till (RRV20; Superior lobe) are Labrador-provenance tills.

The computer-assisted lithostratigraphy assumes that the rate of compositional change (with horizontal or vertical position) in a stratigraphic unit is small compared to the absolute difference in the correlation parameters between units. This seems to be the case in the study area. Interpretations of regional stratigraphic history depend on good lateral and vertical control. For nearsurface units, mapping the surface distribution of the units usually provides enough information to interpret stratigraphic relations. For subsurface units, drilling is necessary, and coring is preferred. The interpretations presented here are most robust for the younger units and weakest for oldest units.

CONCLUSIONS

Computer-assisted techniques have provided a new perspective to the problems of defining and correlating nearsurface glacial-lithostratigraphic units in northwest Minnesota and eastern North Dakota. Previously, progress in developing a sense of regional cohesiveness in glacial stratigraphy was very slow. Regional databases (N-FILE and QBASE) and computer-assisted interpretive techniques (TILSRCH and DISCORT) have provided us with a means of rapidly developing regional lithostratigraphic interpretations. This gives our Quaternary stratigraphy a new, broad-based perspective, which should provide valuable baseline stratigraphic information for a wide range of applications within hydrogeology, regional correlation, and glacial history as well as for the modeling of ice-flow dynamics and the further development of regional stratigraphic models.

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USE OF 1–2-MILLIMETER SAND-GRAIN COMPOSITION IN MINNESOTA QUATERNARY STUDIES

Howard C. Hobbs

ABSTRACT

The composition of the 1–2-mm (very coarse sand) fraction of glacial sediments provides critical information on sediment provenance and thus is useful for distinguishing among till units and for determination of ice-flow directions. Analysis of the 1–2-mm fraction has been used in Quaternary studies in Minnesota since the 1970's, and a considerable data base has been developed at the Minnesota Geological Survey (MGS). Very coarse sand grains may be grouped as crystalline, carbonate, shale, or as Precambrian, Paleozoic, Cretaceous. In the method described here, the latter groups are used; they are commonly subdivided into grain classes and individual grain types. Recognition criteria for these groups, classes, and grain types are provided here. The sand-grain composition data are routinely used to help reconstruct glacial history in Minnesota.

INTRODUCTION

Several different components of Quaternary sediments have been studied in Minnesota, in order to define and correlate stratigraphic units. Grain-size analysis and Munsell color description are recorded for virtually all samples collected. Grains are grouped into types as described below and are counted. These grain counts are undertaken for selected samples.

Bulk geochemistry and/or clay mineralogy are determined for selected samples where possible. The heavy-mineral component of the very fine sand fraction, and the clast type of the pebble fraction have also been used to define and correlate stratigraphic units in the past. These methods all provide evidence for the source and transport direction of the ice. This paper is written as a practical guide, to assist people studying and interpreting the very coarse sand (1–2 mm) fraction of Quaternary sediments; it concentrates on techniques currently in use at the Minnesota Geological Survey (MGS).

Grain-size analyses are quick and simple to do, but do not provide provenance-specific information, i.e. the gravel, sand, silt and clay particles have many potential sources. A given grain-size distribution (e.g. loam) can be represented in numerous stratigraphic units, which may be sourced in widely differing regions. Color is also an easy attribute to describe, but many stratigraphic units share an identical unoxidized color, and most units exhibit a range of oxidized and gleyed colors that is related to the post-depositional history of the unit.

Mineralogy and geochemistry of the silt and clay fraction of the till matrix have also been used to assist in distinction among till units. Clay minerals are divided into three groups: expandable clays (e.g. montmorillonite), illite, and kaolinite+chlorite. The relative proportions of these three clay groups can be determined by X-ray diffraction (Hallberg and others, 1978). This method is presented as semiquantitative and thus cannot be used in isolation for till-unit identification. However, it can complement other data and assist in dividing a sequence into stratigraphic units. Clay mineralogy can be also be determined for samples that lack a coarse fraction and could not otherwise be studied, such as lake clays and overbank alluvium. Matrix geochemistry shows promise in distinguishing provenance of tills (Gowan, this volume), although the total number of samples studied so far is small.

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For correlation purposes, clasts within tills can be identified; correlation or comparison between stratigraphic units must be based on clasts of the same size range, e.g. 4–8 mm (pebbles), 1–2 mm (very coarse sand), 0.125–0.250 mm (fine sand), etc. This is necessary because clast or grain composition within a unit varies with size fraction. Which clast or grain size is best to use for correlational purposes? The boulder and cobble fraction does not provide a quantitative measure of the range in clast types, because of the difficulties inherent in obtaining a representative sample. Clast counts conducted on the pebble fraction are potentially more useful than those conducted for the boulder component, because pebbles can be removed from a till sample and counted in the laboratory. However, statistically valid clast counts on pebble-grade material may require more than 1 kg of sample, depending on how pebbly the till is, and the size range of the pebbles. By comparison, samples routinely collected for textural analysis average 200 g, of which 50 g is consumed for textural analysis, and the remainder held as a reserve, in case additional analyses are needed. The MGS archive of drill cuttings contains samples weighing 20–50 g for each 5–10 ft of depth, rendering the drill cuttings impractical to use as a source of pebble-grade clasts. Most 50-gram till samples, however, contain at least several hundred 1–2-mm (very coarse sand) grains, so that grain counts can be done on samples already collected and processed.

The fine-sand fraction contains more grains per gram, but finer fractions are increasingly dominated by quartz, offering less potential for contrast between units. Identification of grain types under a low-power microscope is much more difficult for the fine-sand fraction than for the very coarse sand fraction. The heavy-mineral fraction of fine sand has been used as a correlation tool (Arneman and Wright, 1959; Hobbs, 1973), but both the separation and the counting are labor intensive. The 1–2-mm (very coarse sand) fraction is thus the most convenient and informative sample to use for quantitative analyses to assist in comparison and correlation of till units.

PREVIOUS USE OF CLAST AND DETRITAL-GRAIN COUNTS FOR GLACIAL SEDIMENTS OF THE UPPER MIDWEST

Anderson (1957) counted one-half to one-inch pebbles and coarse sand grains in an attempt to distinguish sediments deposited by the different glacial lobes of the central lowland of the southern Laurentide Ice Sheet during the Wisconsinan. He found that the relative proportion of different rock-fragment types provided a reliable indicator of ice lobe. However, no single rock type could be used as an indicator. The sand fraction provided results roughly similar to those produced with the pebble-count method, which was standard at that time.

Matsch (1971) was the first to use the 1–2-mm (very coarse sand) fraction for provenance studies in glacial sediments of the Upper Midwest. He divided grains into three categories: crystalline, carbonate, and shale. Regional bedrock mapping in the upper Midwest (Fig. 1) shows that shale grains are derived from eastern North and South Dakota and adjacent Manitoba. Carbonate grains are derived from the northern Red River valley and southeastern Minnesota, and crystalline grains from the Canadian Shield (see caption to Fig. 1). Matsch (1971) defined the New Ulm Till and the Granite Falls Till of southwest Minnesota; he discovered that the upper till (New Ulm Till) was richer in shale than the otherwise similar underlying Granite Falls Till. He also established that the shale content of the New Ulm Till was higher along the Minnesota River valley (the axis of the Des Moines lobe) and decreased away from the Minnesota River valley toward the inferred lobe margin. Matsch interpreted this pattern to indicate dilution of the initially shale-rich New Ulm Till by incorporation of clasts from the underlying Granite Falls Till.

Matsch's (1971) 1–2-mm grain-counting technique was adopted by University of North Dakota students for studies of tills in eastern North Dakota and Minnesota (Harris, 1973, 1975; Hobbs, 1975; Salomon, 1975; Sackreiter, 1975; Anderson, 1976; Camara, 1977; Perkins, 1977). The same technique has been used by students in Iowa (Van Zant, 1973; Lucas, 1977; Lucas and others, 1978), South Dakota (Schroeder, 1979; Gilbertson, 1990), and Manitoba (Fenton, 1974; Keatinge, 1975). Harris and others (1974) summarized stratigraphic work carried out in the Red River valley and characterized tills using both textural analysis and counts of the 1–2-mm (very coarse sand) fraction. Moran and others (1976) attempted to correlate stratigraphic units over a broader area.

Since the 1970's, numerous studies of glacial geology in North Dakota (Hobbs and Bluemle, 1987, Bluemle, 1985, Harris, 1987, Harris and Luther, 1991) and Minnesota (Harris and others, 1995, Harris, 1996, Hobbs, 1984, 1988, 1995, 1998; Hobbs and others, 1995; Lusardi, 1997a, 1997b, this volume; Meyer, 1986, 1997; Meyer and Knaeble, 1996; Moran and others, 1976; Mossler, 1998; Patterson, 1995a, 1995b) have used 1–2-mm grain counts to assist as an aid to Quaternary mapping and development of the stratigraphy. These data are typically presented as summaries, or selected data are reported. The original grain-count data are kept on file at MGS and the North Dakota Geological Survey (NDGS).

The classification of very coarse sand grains into crystalline, carbonate, and shale is simple and gives reliable results for the area in which it was first practiced (western Minnesota and eastern North and South Dakota).

A modified classification in which the main groups are Precambrian, Paleozoic, and Cretaceous is now used by some researchers at the MGS for glacial sediments in central and eastern Minnesota. Each of these groups is further subdivided (Fig. 2) into grain classes and types. The two systems give virtually the same results for glacial sediments of the eastern Dakotas and western Minnesota. The advantage of the modified classification system is: (1) it allows non-shale Cretaceous fragments (such as limestone) to be grouped with Cretaceous shale, instead of with Paleozoic limestone, which would give misleading results; (2) it provides a category for Precambrian sedimentary rock fragments, and subdivides Precambrian in a way that is useful for provenance studies in this region. Figure 1 shows the general distribution of source bedrock types in Minnesota and nearby areas, keyed to the modified classification system. The rest of this paper concentrates on the modified system developed by the author.

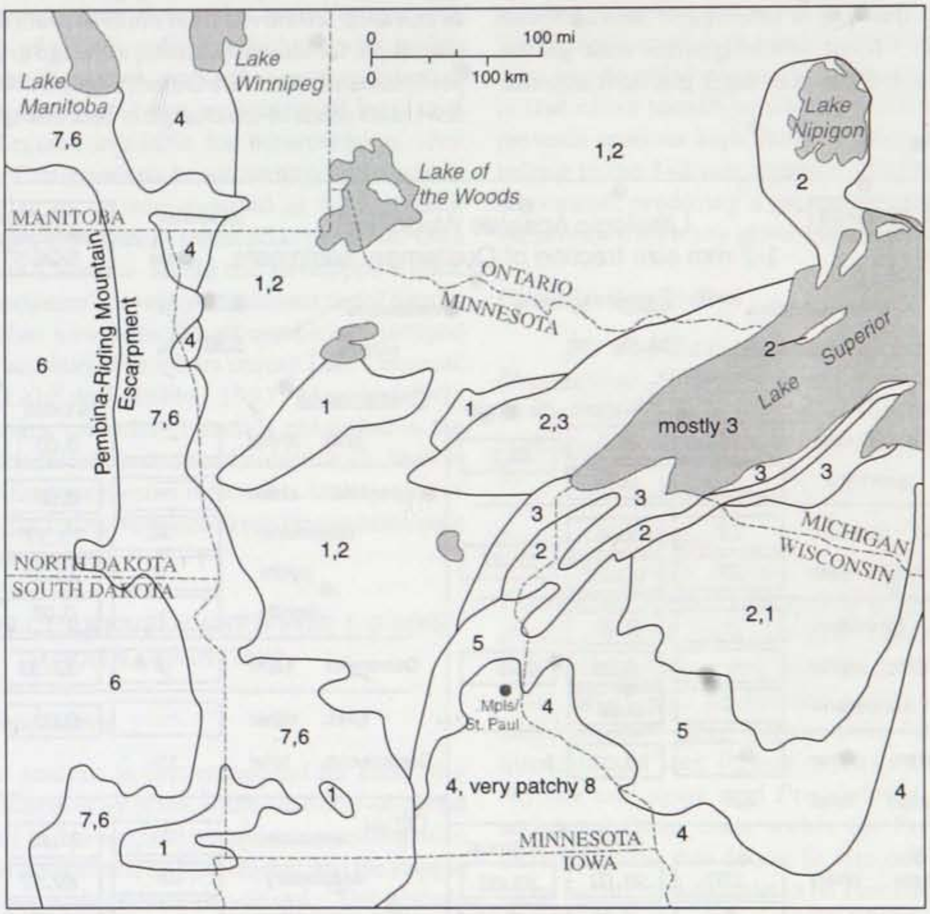

Figure 1. Simplified distribution of bedrock source regions in Minnesota and adjacent regions. Bedrock types are distinguished so that they correspond with grain categories used in detrital grain counts.
(1) Precambrian granite, gneiss, and quartzite;
(2) Precambrian mafic igneous and other metamorphic rocks;
(3) Precambrian iron formation, rhyolite, agate, and sandstone;
(4) Paleozoic carbonate, chert, and shale; (5) Paleozoic sandstone; (6) Cretaceous gray shale;
(7) Cretaceous speckled shale and limestone;* (8) Cretaceous Windrow Formation.
Where more than one rock type is present in an area, the dominant bedrock type is listed as the first number.
Bedrock geology is generalized from Bluemle (1983), Hedges and others (1982), Manitoba Mineral Resources Division (1979), Morey (1994), Morey and others (1982), Mudrey and others (1982), Ontario Geological Survey (1991), Osmani (1991) and Tester (1937).
* includes Jurassic sedimentary rocks in northwest Minnesota and southern Manitoba, which are mostly carbonates, shales and evaporites; these grain categories have not been recognized in grain counts.

Provenance studies are complicated by the reworking or recycling of material from older glacial deposits. Flowlines for Late Wisconsinan ice can be determined from geomorphic features, whereas the flowlines for pre- Late Wisconsinan ice must be inferred from till composition. Recycling is recognized where samples from a given till unit contain grains that cannot be derived from bedrock up-ice. For example, Des Moines-lobe tills contain large amounts of granite and other igneous rocks in all size fractions, but the nearest substantial subcrop of igneous rock along the presumed Des Moines lobe flowline is in northern Saskatchewan (Patterson, 1998). Most of the igneous rock grains, therefore, must be derived from older glacial sediments.

Where a single till directly overlies bedrock on a regional scale, clast composition tracks bedrock composition fairly closely; clasts of rock types that do not crop out up-ice are rare. For example, Everson (1977) compared a detailed bedrock map of the Long Island Lake 7.5-minute quadrangle in northeastern Minnesota to drift composition of five size fractions, ranging from 1–2 mm to more than 1 m in diameter. The northern part of the quadrangle is underlain by granite, the central by metamorphic rocks and the southern by intrusive rocks of the Duluth Complex, chiefly gabbro and related rocks. In this area, ice moved from north to south during the last glaciation; for all size fractions, a change to grains derived predominantly from the Duluth Complex was recorded a few miles south of the change in bedrock type. Boulders

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

sample	BE 3894-18	Scientist	Hobbs 2
split	no	Date	6/26/97
Precambrian	61.39 %	Cretaceous	4.02 %
Paleozoic	34.58 %	others	5.81 %

Precambrian		count	% class	% group
LIGHT	granite gneiss	188	82.1	82.1
	quartzite	–	0.00	
DARK	mafic igneous	12	5.24	17.47
	other meta	28	12.23	
RED	iron formation	–	0.00	0.44
	rhyolite agate	–	0.00	
	Precambrian sandstone	1	0.44	
	Precambrian other	–	0.00	
	Precambrian total	229		

Paleozoic	count	% class	% group
carbonate chert	120	93.02	93.02
Paleozoic sandstone	9	6.98	6.98
Paleozoic shale	–	0.00	0.00
Paleozoic other	–	0.00	
Paleozoic total	129		

Cretaceous	count	% class	% group
gray shale	–	0.00	0.00
speckled shale	–	0.00	
limestone	11	73.33	86.67
pyrite	2	13.33	
lignite	–	0.00	
Ostrander sand	2	13.33	13.33
Cret. other	–	0.00	
Cretaceous total	15		

Other	count	% class
unknown	7	30.43
secondary	16	69.57
other	–	0.00
other total		
grand total	396	
bulk total	373	

notes

Secondary carbonate grains here.
Strange... unless this is another till.
No sign of an oxidized zone, though.
Lower-middle till, unoxidized, unleached

Figure 2. Worksheet used for counting grain types in the 1-2 mm coarse sand fraction of Quaternary sediments Worksheet shows calculations for till sample BE 3894-18 from Goodhue County (see Figs. 4 and 5).

greater than one meter in diameter were of the same lithology as the underlying bedrock almost everywhere. Lehr and Hobbs (1992) noticed the same phenomenon in the area of the western Giants Range in northeastern Minnesota.

Provenance studies are also complicated by the temporal and geographic non-uniformity of the glacial erosion and depositional processes, which results in a great deal of variability in clast composition within single stratigraphic units. In addition, glacial erosion and deposition have changed the availability of different bedrock sources over time. In areas with thick accumulations of glacial sediment, bedrock was unable to act as a source during advances subsequent to its burial. In other areas, new rock types were exposed by glacial erosion and became available for incorporation. For example, older Cretaceous rocks and underlying Paleozoic and Precambrian rocks were exposed as the Pembina-Riding Mountain Escarpment retreated to the west. On a larger scale, the Canadian Shield had developed a thick saprolite or "residuum" cover by Cretaceous time (Austin, 1972), which has now been almost completely stripped off in places, and buried in others during Late Cenozoic glaciations (Lehr and Hobbs, 1992; Meyer, 1996). Saprolite contains secondary minerals not found in the fresh rock and lacks minerals found in fresh rock, such as feldspars and ferromagnesian minerals. At the onset of late Cenozoic glaciation, very little fresh Precambrian rock may have been exposed.

METHODS CURRENTLY USED FOR 1–2-MM GRAIN COUNTING

Analytical Procedures

Textural analysis is first completed for each 50-g sample. The sample is weighed, soaked in a clay-dispersal solution, mixed with water, and poured into a settling tube. Clay content is determined by hydrometer, and the sample is then wet-sieved, dried, and dry-sieved. The granule and pebble fraction, the very coarse sand fraction, and the remaining fine-to-coarse sand fraction are weighed separately and stored in envelopes. At this point the grains are clean, except for coatings that are resistant to normal washing and clay dispersal. Generally 1 g of 1–2-mm sand is adequate for grain-count analysis; it will contain about 300 grains. When the sample is greater than 2 g, it is split in a sample splitter. A 4-g sample is split twice, etc. A 300-grain sample is considered adequate as a rule. Where smaller sample size is unavoidable, for example due to low content of 1–2-mm sand in the original sample, it still is counted, but an asterisk is placed by the data in the data base; the small samples generally show the same general trends as the larger samples.

Grains are counted under a low-power binocular microscope (10x magnification). For identification of problematic grains, it may be necessary to use a higher magnification. Grains are separated into piles of each major group, manipulating them with a small drafting knife under the microscope. Alternatively, a tiny brush with a moistened tip may be used to move the grains around. Once the grains are separated into major groups, they may be separated into subgroups for counting.

Occasionally, one will notice a flood of identical grains; these are generally angular fragments from a weathered pebble such as biotite granite or gabbro. These identical grains are kept separate from other grains of their type, and recorded as a single grain (or not at all). A note to that effect should be added to that data sheet. This prevents spurious high numbers from grains that do not belong in the 1–2-mm fraction. Alternatively, they can be counted, producing a greater apparent compositional variability within any given till unit.

Classification System

The classification system uses four major groups (Precambrian, Paleozoic, Cretaceous and Other). Each of these groups is further subdivided into three classes; each class is composed of two or more grain types (Fig. 2).

Precambrian Group

Three main classes are recognized within the Precambrian group based largely on grain color. These classes are Light, Dark, and Red. These three classes are further divided into a total of seven grain types. The grain types are: (Light) *granite and gneiss*, *quartzite*; (Dark) *mafic igneous*, *other metamorphic* (other than gneiss, quartzite and iron formation); (Red) *iron formation*, *rhyolite and agate*, and *Precambrian sandstone*. The additional Other class within the Precambrian group includes grains that do not fit into one of the preceding types but are still thought to be Precambrian.

Light Grains The grain type *granite and gneiss* includes all coarse-grained felsic igneous and metamorphic rock fragments. Pink feldspar grains are counted in this type, rather than under Red. Coarse-grained schist is included in this type if each grain consists of only a few crystals. While some schists and migmatites break down into coarse-grained fragments counted in this type, they also contribute finer-grained fragments counted as *other metamorphic* in the Dark grain class; the number of such grains is small. Sometimes a subtype of *monomineralic quartz* is counted. This gives an indication of how much of the sample is derived from saprolite. Some monomineralic quartz grains are derived from unweathered granite, but most granite-derived quartz grains contain inclusions of feldspar or dark minerals.

The grain type *quartzite* includes clean metamorphic quartzite and solidly quartz-cemented sandstone (orthoquartzite). The latter is of minor importance in Paleozoic sandstones and nonexistent in local Cretaceous sandstones. Very few grains in this type have been counted within tills from eastern Minnesota; it is included because of its importance in recording Sioux Quartzite grains in southwestern Minnesota.

Dark Grains The Dark grain class includes the *mafic igneous* type and the *other metamorphic* type. These two types are difficult to separate from each other, as must be done to fill in the data sheet; for most purposes they are grouped together.

Mafic igneous grain types include basalt, gabbro, and low-grade (sub-amphibolite grade) metavolcanics ("greenstone"). It also includes intermediate rocks that lack quartz, such as diorite. These grains are gray, green, or black, and are not foliated. The grain type *other metamorphic* includes metagraywacke, slate, argillite, phyllite, and fine-grained schist. Foliated grains of the *other metamorphic* type are relatively easy to distinguish from *mafic igneous* grains. Non-foliated metamorphic grains are more difficult to distinguish and classify. Graywacke grains can be distinguished by their sedimentary texture, although detrital components may be masked by alteration and metamorphism of the matrix. Weathered graywacke grains and clasts are common in older tills; the grains look more like quartzite under the microscope, because much of the dark matrix has weathered away. Thus, for many grain counts done in the mid-1980's, before the relation to weathering and alteration was noted and understood, many grains of weathered graywacke were counted as quartzite (with an annotation on the counting sheet denoting "subgraywacke"). Such grains are currently counted as *other metamorphic.*

Red Grains *Iron-formation*, *rhyolite and agate*, and *Precambrian sandstone* constitute the Red class of the Precambrian grain group.

The *iron formation* grain type includes the various Precambrian iron formations of the Lake Superior region, as well as jasper. Grains derived from banded-iron formation can be easily distinguished, but it can be difficult for the non-specialist to identify all the different grains derived from non-banded iron formation. Some *iron formation* grains, such as the black ones, may be counted as Precambrian Other.

The grain type *rhyolite and agate* includes red nonclastic grains inferred to be derived from the Lake Superior basin, and includes felsite, red granophyre and red-stained basalt. These grains are typically darker and redder than the pink feldspars grains counted in the Light class. Some of these grains are dull reddish gray or reddish black, and could easily be counted as *mafic igneous* grains. Many grains falling in this class are difficult to categorize, and may not be immediately recognized as belonging to this class by an inexperienced counter. A rule of thumb is that when the number of definite Red-class grains is large, it is more likely that a reddish grain belongs in the Red class.

The *Precambrian sandstone* grains are derived from the Hinckley and Fond du Lac Sandstones now exposed to the southwest of Lake Superior, and other Precambrian sedimentary units which subcrop in the lake basin. Many of the grains are red arkoses, but some are quartzose sandstones and some are brown or buff sandstones. The brown sandstone grains are difficult to distinguish from grains in the Paleozoic Sandstone class; the latter are typically more mature, but some grains are of uncertain origin. If the amount of red sandstone in a sample is greater than the amount of Paleozoic Sandstone grains, the brown sandstone grains are more likely to be *Precambrian Sandstone.* The *Precambrian sandstone* grain type also includes a relatively minor percentage of red siltstone and shale grains derived from the Superior basin, as well as grains derived from red sediments interbedded with the North Shore volcanics. The discussion above makes it clear that the Red class is interpretive, rather than purely descriptive; some reddish-colored grains do not belong, like pink feldspar and pink Sioux Quartzite. Conversely, some grains within the Red class are not red, but brown or reddish-black.

Precambrian Other The class Precambrian Other includes grains that display characteristics of the Precambrian group but cannot be confidently assigned to one of the three main Precambrian classes. The number of grains assigned to the Precambrian Other class is usually low (normally less than 5 percent), because the main classes include almost all the Precambrian rocks of the area. However, secondary minerals derived from the saprolite belong in the Precambrian Other class. The mineral grains derived from the saprolite are spherical to botryoidal grains, range from clear to brown to pinkish-gray in color, and typically form microcrystalline to fine-grained aggregates of grains. Some spherical aggregates of clear euhedral crystals have been counted in this category. The spherical shape of these secondary minerals is similar to that of sand grains derived from Paleozoic sediments, but the Paleozoic grains are monocrystalline quartz. These grains inferred to be saprolite-derived are common in tills that also contain other evidence for saprolite incorporation, such as inclusions of pastel- and gley-colored clay, although their saprolitic source is as yet unproven. Some grain counts have included these grains in the undifferentiated Other group, but based on field and hand-sample observations, they are likely derived from the same region as the Precambrian group, and are thus classified as Precambrian Other.

Paleozoic Group

Three main classes are recognized within the Paleozoic group: Carbonate and Chert; Paleozoic Sandstone, and Paleozoic Shale. There is also a Paleozoic Other class.

Paleozoic Carbonate and Chert The Paleozoic Carbonate and Chert class includes limestone, dolomite, and chert grains, which are mostly gray to ivory colored. The carbonate grains typically have smooth surfaces. Angular, rough-surfaced carbonate grains are noted in areas with carbonate bedrock and are interpreted as locally derived. Ivory-colored dolomite grains resemble feldspar grains, from which they can be distinguished on the basis of their reaction with acid. The quickest method for distinguishing between dolomite and feldspar under the binocular microscope is to use the point of a dissecting knife; it will scratch the dolomite, but slide off the feldspar. Highly siliceous dolomite and chert are difficult to distinguish from feldspar, although feldspar grains may display obvious cleavage. Chert grains are characterized by conchoidal fractures on broken surfaces, and porous surfaces on weathered grains. Another method for distinguishing between carbonate grains and other light grains is to stain the sample prior to counting (Lucas and others, 1978), although this is not routinely done at the MGS. The distinction between Paleozoic Carbonate grains and grains derived from Cretaceous limestone is discussed in the Cretaceous section.

Paleozoic Sandstone The Paleozoic Sandstone category includes sandstone fragments as well as single grains of quartz derived from Paleozoic sandstone. The latter are easy to recognize if they are spherical and frosted; less spherical, unfrosted quartz grains are hard to distinguish from granite fragments or from sand grains derived from Cretaceous sediments (see Cretaceous group). Paleozoic Sandstone grains are generally soft and easy to disaggregate with the dissecting knife, because cement does not fill their pores, but instead forms "spot welds" on the grain boundaries. Sandstone grains that contain green glauconite are classified as Paleozoic Sandstone, whereas sandstone fragments strongly cemented by limonite are typical of the Cretaceous Ostrander Member of the Windrow Formation of southeast Minnesota. Experience shows that counts of the 1–2-mm fraction grossly under-represent the contribution ot Paleozoic sandstones to tills, because the Paleozoic sandstones tend to break down into their individual component grains, which are generally smaller than 1 mm.

Paleozoic Shale The Paleozoic Shale class contains soft to very soft, blue-gray to greenish-gray noncalcareous grains of shale. Cretaceous shale grains are typically a neutral gray. Paleozoic Shale grains are easily abraded and are extremely rare in tills, except when tills rest directly on Paleozoic shale or interbedded shale and limestone. Even where a large amount of Paleozoic Decorah Shale has been incorporated, the 1–2-mm fraction is typically dominated by fragments of fossil hash from thin limestone beds in the shale, rather than shale itself. The fossil hash is counted as Paleozoic Carbonate and Chert.

Paleozoic Other The Paleozoic Other class includes grains derived from Paleozoic rocks that do not fit into the above classes. This class is especially useful for the insoluble residuum left by weathering of carbonate rocks—drusy quartz rinds (former vug linings), goethite pseudomorphs after marcasite, and irregularly shaped grains of "siliceous trash."

Cretaceous Group

The Cretaceous group is informally divided into three classes, the Western, Intermediate, and Eastern classes, based on the location of the inferred source rocks (Fig. 1). The Western class is made up of *gray shale*. The Intermediate class includes four grain types: *speckled shale*, *limestone*, *pyrite*, and *lignite*. The Eastern class is made up of sand grains derived from the Ostrander Member, termed the *Ostrander sand* type. There is also a Cretaceous Other class.

The *gray shale* category includes grains derived from the Pierre Shale and other gray noncalcareous shales such as the Carlile Shale. The *gray shale* fragments are distinctive; the main identification problems are distinguishing them from Precambrian slate and Paleozoic shale grains. In addition to being harder than shale, Precambrian slate has a slight sheen on cleavage surfaces, whereas shales are dull. Paleozoic shale is very soft, and typically blue-gray or greenish-gray, rather than the neutral-gray color of most Cretaceous shale. Most Cretaceous shale in Minnesota is so soft that its fragments rarely survive transport as clasts (Dale Setterholm, oral. commun., 1998). The comminuted shale is typically incorporated into the till matrix. Most of the *gray shale* grains are derived from west of the Pembina-Riding Mountain Escarpment, which marks the eastern extent of the Pierre Shale.

Speckled shale grains are calcareous shale grains, that are speckled white and dark. The white speckles are calcite, and the dark speckles are probably organic matter and pyrite. These grains are derived from the Niobrara and Greenhorn Formations, which underlie the Pierre Shale and extend eastward into Minnesota. Some of these grains look like fine-grained schist, but they are much softer and they effervesce under dilute hydrochloric acid. Grains in the *speckled shale* category are not seen in leached tills and are uncommon in oxidized tills. Oxidation apparently releases sulfuric acid from small pyrite crystals in the grains, which then dissolves the carbonate, causing the grain to disintegrate.

The Cretaceous *limestone* category contains clear to translucent calcite grains that are gray in color and are not completely fused together. Cretaceous limestone grains react rapidly with hydrochloric acid, and leave behind a dirty residue of silt, fish scales, and other organic debris. These grains are easily distinguished from grains in the Paleozoic Carbonate class.

Grains in the *pyrite* category are identified as Cretaceous-derived when they are fine grained and have a hackly surface. Precambrian-sourced pyrite is generally coarsely crystalline, and Paleozoic iron sulfides generally have the crystal form of marcasite rather than pyrite (though there are exceptions). Pyrite is not common enough in Paleozoic or Precambrian rocks to warrant a separate category in those groups.

The Cretaceous *lignite* category includes grains that are soft and black and range from shiny to dull in luster. These grains are light in weight and break easily. The *lignite* grains are classified as Cretaceous, although some lignite grains in Minnesota could be derived from Paleocene rocks of central to western North Dakota (Lerud, 1982; Bergstrom and Morey, 1985). The typical association of lignite grains with Cretaceous shale grains suggests a shared provenance.

The grain category *Ostrander sand* contains grains derived from the Ostrander Member of the Windrow Formation (Andrews, 1958). Sloan (1964) discusses the age and correlation of the Ostrander Member. Although the evidence for its Cretaceous age is not overwhelming, it is accepted for the purpose of this paper. These grains are single grains of quartz, chert, and black iron formation or aggregates of such grains cemented by iron oxides. The grains are typically polished and somewhat rounded but are not spherical. The rounding and polishing is best developed in the 2–20-mm (granule to pebble) clasts and diminishes progressively with size. Ostrander Member-derived sand grains in the 1–2-mm fraction display a range of polish from dull to an almost liquid sheen. The former are difficult to distinguish from glacially rounded quartz grain of the *granite-gneiss* grain type of the Precambrian group and from poorly rounded grains of the Paleozoic Sandstone class. A few grains have been noted that were both spherical and highly polished. These are interpreted as Paleozoic quartz grains incorporated into the Ostrander Member and are counted with the latter. Grain counts completed for in-place Ostrander sands and gravels indicate that only about half of the detrital grains in the 1–2-mm fraction display enough distinguishing characteristics to allow them to be distinguished from grains derived elsewhere. It is worthwhile, however, to have a category in which to put grains clearly derived from the Ostrander Member. A large number of these grains indicates incorporation of locally derived material, because the source area is not extensive (Fig. 1).

The class Cretaceous Other includes grains interpreted to be derived from Cretaceous rocks that do not clearly fit into one of the Cretaceous types listed above. Angular iron oxide fragments are the most common grain of this type and are interpreted as broken concretions derived from Cretaceous marine sediments, or as fragments of the Iron Hill Member of the Windrow Formation of southeast Minnesota. Shark teeth also fit into this category, although they are rare.

Other Group

Grains that are placed in the Other group cannot be identified as Precambrian, Paleozoic, or Cretaceous. Three classes are recognized within this group: Unknown, Secondary, and Other. This group is not included when compiling triangular diagrams, and in general is not very helpful in provenance determination, although the presence of distinctive grain types should be noted because they may yet prove to be useful. Data from this group are included in calculations, and are shown in brackets when the numbers are presented as a ratio.

Unknown The class Unknown includes grains that are fine-grained and lack diagnostic features. Many of these grains are either weathered or are partly coated with secondary minerals; where they are completely coated with secondary minerals, they should be counted in the Secondary class. The number of grains within this class should be low, although it is better to count a grain of unknown origin as Unknown rather than to count it incorrectly.

Secondary The class Secondary includes secondary carbonate, gypsum, and iron and manganese oxides that formed post-glacially in the till. To be counted as Secondary, the grains must be authigenic, i.e. they formed by precipitation *in situ* in a till, and were not transported to the site as grains. The following criteria are useful for determination of their secondary origin: fragile, porous grains almost certainly formed in place, because they would be destroyed during transport. Secondary carbonate grains can easily be distinguished from limestone; they are chalky white and porous and effervesce violently in dilute HCl. Euhedral grains of soft minerals like gypsum most likely formed in place. If samples are collected from various levels in the weathering profile developed in a till, the proportion of grains in the Secondary class will vary regularly with depth, whereas the proportion of reworked secondary grains show little or no correlation with depth. Iron oxide grains are the most problematic grain type, because they are included in all four major groups (Precambrian, Paleozoic, Cretaceous, and Other), and because secondary iron oxide may be resistant enough to be recycled into new tills. Secondary iron oxide forms *in situ* mainly as a coating on other grains, rather than as individual mineral grains. When samples contain large numbers of unidentifiable grains cemented with iron oxides, the aggregates should be counted in the Secondary class. These grains typically break up as they are counted, but each aggregate should be counted only once.

Other The class Other is used for grains that can be identified (thus they are not Unknown), but are not Secondary, and cannot be assigned to one of the major groups. Wood or modern shells fall into this class, as does any material that drillers put down the borehole to stabilize the hole, such as cottonseed hulls, bentonite or shredded money.

Calculating and Grouping

The grain-count data are tabulated on a recording sheet (Fig. 2). The number of grains in the Precambrian, Paleozoic, and Cretaceous groups are totalled ("bulk total") for each sample, and the percentage of each group is calculated on the basis of this bulk total. The total for the Other group is then added to the bulk total to create the "grand total" and the percentage of the Other group is calculated from the grand total and is put in parentheses after the other three. The percentages of grain types in each class and the percentage of each class within a group can also be calculated.

This grain-count system is very similar to the crystalline-carbonate-shale system used by Matsch (1971) for Minnesota tills, which produces similar results. The results from both methods can be plotted on a triangular diagram, which provides a visual impression of the variability within and between stratigraphic units. The results can also be integrated with computer-assisted stratigraphy, as has been done by Harris (1987, and this volume), who used Matsch's crystalline, carbonate, and shale system.

The purpose of subdividing each class into grain types is to identify tills that contain distinctive grain populations. For example, the deposits of the Rainy and Superior lobes are dominated by Precambrian grains (with some notable exceptions). Unless the Precambrian grains are subdivided, the distinguishing characteristics of the till units are not apparent. Subdivision of the Cretaceous group is mainly useful in southern Minnesota, where it enables distinction between deposits of the Late Wisconsinan Des Moines lobe and older tills of Keewatin provenance, as well as distinction among the older Keewatin-provenance tills.

It is essential to make the most detailed subdivision of grains as possible when counting, because it may prove to be significant later. The subdivisions used should be appropriate for the stratigraphic or correlational problem in a given area; the basic data, however, should be kept on file, for use by others. If another person's grain-count data are used, it is important to look at the original data sheets, rather than just using the summary calculations. This is because there may be notes about the grains placed in the Other or Unknown classes of the Other group, that, with increased knowledge about provenance, would lead one to classify the grains differently from that done in the original grain count.

APPLICATIONS

Lobes and Provenance

Deposits associated with different ice lobes have been recognized for many years in Minnesota. By the early 1970's four lobes and several sublobes were hypothesized to account for glacial deposits in Minnesota (Wright, 1972). This recognition preceded the advent of widespread 1–2-mm sand-grain counting; it was based on geomorphology and inferred ice-flow direction, supplemented by till color and clast content, generally of the pebble fraction. Arneman and Wright (1959) compared deposits of the lobes in many aspects: color, grain size, counts of granules (2–4 mm) and pebbles (4–64 mm), heavy-mineral content, clay mineralogy, and total potassium content. The clast classification scheme was slightly different from that presented here for 1–2-mm grains but the overall results were comparable. The clast content of sedimentary deposits associated with specific ice lobes as defined by Arneman and Wright (1959) is as follows:

1. Des Moines-lobe deposits—these are the only deposits in which Cretaceous shale is reported, although the number of shale grains may be quite small. Limestone and dolomite are common to abundant in all samples. Rock types associated with the North Shore of Lake Superior are present as clasts in all samples. The largest number of pebbles is in the category basalt-gabbro-diabase, which could be sourced in areas other than the

Superior basin. Red sandstone and iron formation clasts are very minor components. Pebbles are mostly granitic and metamorphic, neither of which are provenance-diagnostic.

2. Wadena-lobe deposits—these deposits are essentially similar to those of the Des Moines lobe, except that Wadena-lobe deposits lack shale.
3. Rainy-lobe deposits—deposits inferred to be associated with the Rainy lobe were assessed at three locations; in the Toimi area northeast of Lake Superior and in the Pierz and Brainerd areas in central Minnesota. Till from all three areas lacked limestone and dolomite clasts. All the tills are rich in North Shore-derived rock types; red sandstone is a minor clast type, although it is present in almost all samples.
4. Superior-lobe deposits—sediments deposited by the Superior lobe contain a similar range in clast types to the Rainy lobe, except that the proportion of red sandstone is higher, especially where the sample overlies red sandstone.

The results of Arneman and Wright (1959) showed that the deposits of different ice lobes could be distinguished in a general way by clast content, but that clast composition varied considerably from area to area and sample to sample. It is not possible to identify the ice lobe associated with a till on the basis of the clasts in one single sample.

An essential attribute of lobe definition is the inferred ice-flow direction, determined by geomorphology, principally the alignment of drumlins and moraines, as well as by clast content. Subsequent work with 1–2-mm grain-counts (and other methods) has confirmed the broad outlines of the Arneman and Wright synthesis, but has added many details, and has redefined the Wadena lobe as a distinct element of the Rainy lobe. The Wadena controversy is discussed by Goldstein (this volume), Carney and Mooers (this volume), Gowan (this volume), and Wright (this volume).

All the ice lobes mentioned above were associated with the most recent (Late Wisconsinan) glaciation. Lobe terminology is not as useful for pre-Wisconsinan glacial deposits, because the geomorphic clues are largely absent. This difficulty can be overcome by defining provenance regions (Meyer and Knaeble, 1996, Meyer, 1997) for the subsurface till units. The provenance method of defining ice-lobe affiliations has been extended to surface tills. The term Riding Mountain provenance was defined for tills containing gray Cretaceous shale, because at least one component of these tills came from west of the Pembina-

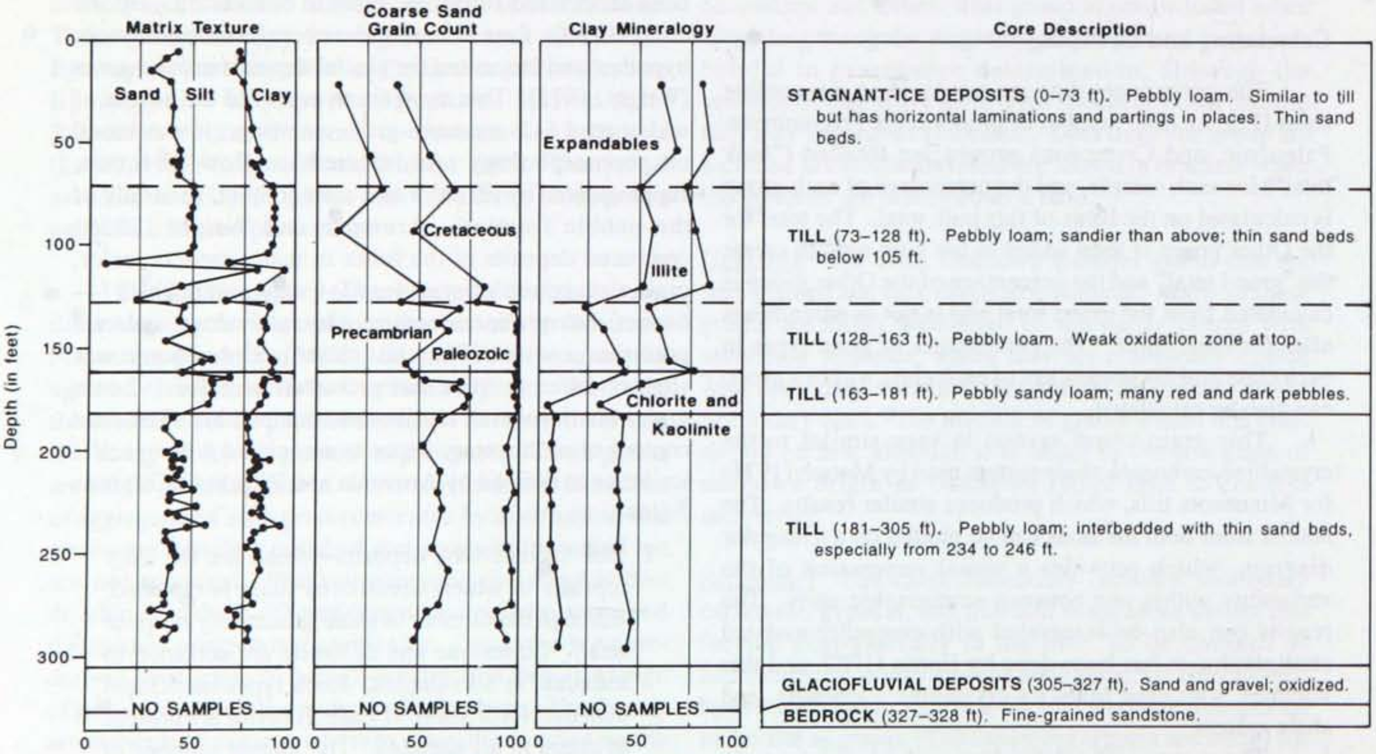

Figure 3. Stratigraphic column of sediments penetrated by Rotasonic boring 3, Rice County. (From Figure 2 of Hobbs and others, 1995).

Riding Mountain escarpment. The term Winnipeg provenance was defined for tills containing considerable Paleozoic carbonate but little or no shale, similar to the composition of the old Wadena lobe. Rainy-provenance till contains roughly the same grain assemblage as the Rainy-lobe tills; the grains are predominantly Precambrian, but only a few of them Red; Cretaceous shale is absent, and Paleozoic carbonate is low. Superior-provenance till contains roughly the same assemblage as Superior-lobe tills, with a high proportion of Dark and Red grains in the Precambrian fraction. Mixed or borderline provenances can be specified by using both descriptors, e.g. Rainy-Superior. However, provenance is typically mixed to some extent, and it is not necessary to use two descriptors for every case in which the assemblage does not fit the ideal.

Examples

The 1–2-mm sand-grain counts can be used with other data, to subdivide sequences of Quaternary sediments examined in exposures or from cores One example is a Rotasonic core obtained in Rice County, Minnesota (Fig. 3). The upper two units are of Riding Mountain provenance, which is indicated by their high content of Cretaceous grains, which are mostly gray shale. These two units also contain large amounts of expandable clays, due to their high Cretaceous-shale component. Some of the shale fragments have already been ground into clay.

The third unit down contains practically no Cretaceous fragments in the 1–2-mm fraction, and a lesser amount of expandable clay, but more expandable clay than the lower units. The matrix texture of the third unit is similar to that of the Riding Mountain units. It clearly has a Winnipeg provenance, but does not correlate with other tills in the region. This third unit may have been deposited by ice that moved across Cretaceous sediment, but must have incorporated it as clay rather than as fragments or detrital grains, based on the clay mineralogy and matrix texture data.

The next (fourth) unit down also contains practically no Cretaceous fragments, and is very rich in Precambrian grains. Many of the Precambrian grains are Dark and Red. This till can be classified as having a Superior provenance, despite the presence of Paleozoic carbonate, which is derived from the reworking of older calcareous tills or the underlying carbonate bedrock, or both. The matrix is rich in sand, another characteristic of Superior-lobe tills. Clay mineralogy of this fourth unit is intermediate between the third unit and the basal till unit.

The basal till unit is thick (greater than 100 ft), but the data do not present any basis for its subdivision. Grain-count data show this till to contain less than 10 percent Cretaceous grains—most of which are speckled shale and limestone. The percentage of Precambrian grains is high, but Red grains are rare. Paleozoic carbonate is common. This is a Winnipeg provenance till, but it differs from the third unit down. The high percentage of kaolinite in the clay fraction of the basal till implies that the Canadian Shield was still largely covered with saprolite at the time that ice associated with this till unit advanced across it. Although this till is believed to be pre-Illinoian, its age has not been determined. Many pre-Illinoian tills have been identified in Minnesota, but at this site most of the pre-Illinoian section has been eroded.

A point to note in this example is that the samples for grain counts and the samples for clay mineralogy are subsets of the samples run for texture. Texture in glacial sediments is generally variable, and texture analysis is fairly rapid and routine; for both these reasons, texture samples are collected at close intervals. The acquisition of grain-count data and clay-mineralogy data requires more specialized training, thus they are typically acquired for selected samples only, at greater intervals.

A second example is from a rotasonic core obtained in Goodhue County (Fig. 4). All four till units in this core are pre-Illinoian in age and have essentially the same (Winnipeg) provenance. All the tills have low percentages of both Cretaceous grains and Precambrian Red grains but contain appreciable amounts of Paleozoic carbonate. However, they can be distinguished from each other by subtle differences in texture and grain lithology. The upper till contains the highest number of Precambrian grains and also the highest proportion of Red grains, and the lowest proportion of Paleozoic grains. The proportion of Paleozoic grains increases downsection from till to till.

The upper-middle till combines the highest proportion of Cretaceous grains and the lowest proportion of Red grains, of any of these four tills. The distinction between the upper-middle and the lower-middle till is the most subtle of contacts, not marked by any outwash or interglacial material, but there is a slight increase in the percentage of Paleozoic grains and a decrease in the percentage of clay downsection. There is also a concentration of secondary carbonate grains in the uppermost sample of the lower-middle till, indicating a period of soil formation.

The basal till is represented by only two samples over a depth interval of 7 ft (the boring did not extend to bedrock); these samples both indicate that the till is richer in clay and in Paleozoic grains than the overlying tills. Many of the grains are fossil hash from the Decorah Shale, but most of the shale was evidently incorporated as clay rather than as fragments.

The stratigraphy of the Goodhue Rotasonic borehole was used as a model with which to correlate till samples collected from shallow soil borings at various elevations elsewhere in Goodhue County. The grain-count data from

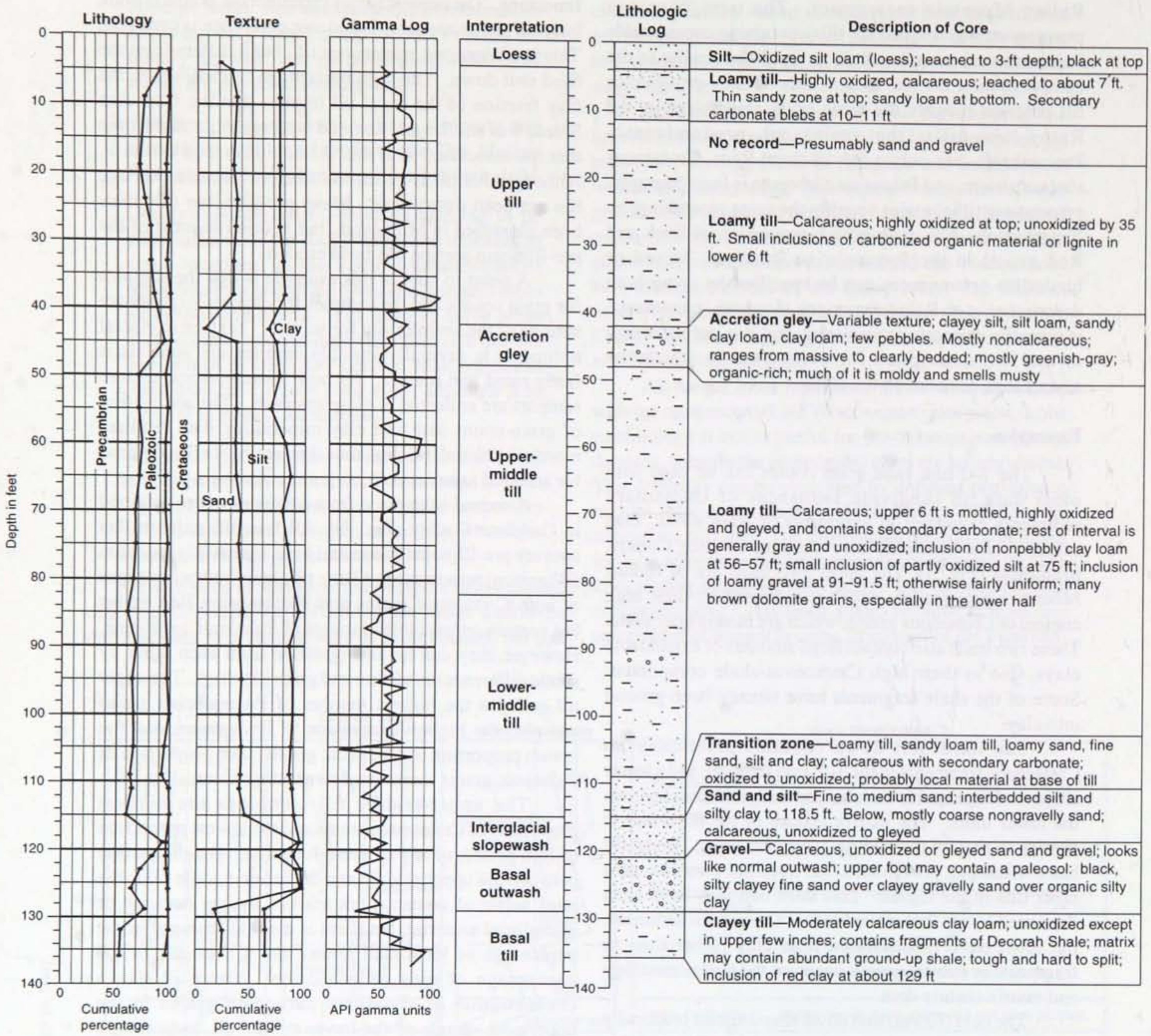

Figure 4. Stratigraphic column of Quaternary sediments from Rotasonic boring 1, Goodhue County (from Hobbs, 1998)

the Rotasonic core and the soil borings are presented in a triangular diagram (Fig. 5). This plot provides visual representation of the variation within and between units and can be used to assist in till correlation.

Glacial Stratigraphy

The first use of very coarse (1–2 mm) sand-grain composition and provenance studies was to assist interpretations of glacial stratigraphy (Matsch, 1971), and that is still one of its main uses. Sand-grain composition has also been used in preparing surficial maps and Quaternary cross sections for MGS county geologic atlases (references in section on "Previous use of Clast Counting"). In some instances the samples were "scanned" rather than "counted" under the microscope, with a brief note being made of the predominant grain types or the presence or absence of a particular grain type. In cases where samples were scanned, counts were

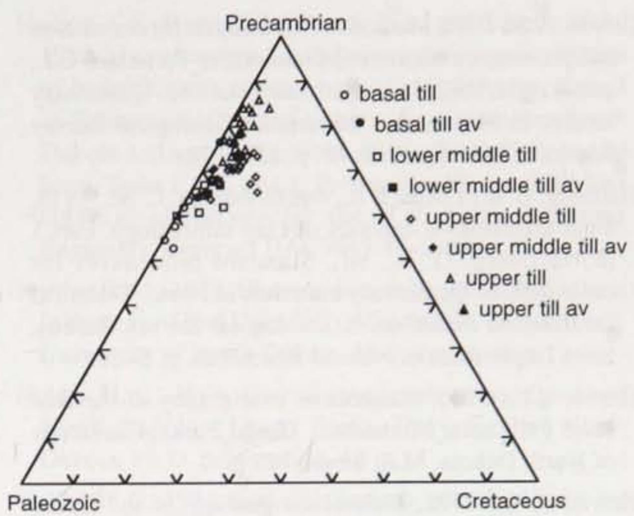

Figure 5. Triangular plot of grain-count data from tills in Goodhue County (previously unpublished).

unnecessary because other characteristics of the sediments (color, texture, gross pebble lithology) were diagnostic. Grain counts have been instrumental in helping establish the till stratigraphy of central Minnesota (Meyer, 1986; Meyer and Knaeble, 1995), and north-central Minnesota, where Meyer (1997) recently completed a study using undisturbed samples from nearsurface cores and from deeper cores that extended down to bedrock.

The glacial stratigraphy of the southern Red River valley is based on a combination of texture and 1–2-mm grain counts, in which grains were classified as crystalline, carbonate, or shale (Harris and others, 1995; Harris, this volume). A considerable data base called NFILE (North Dakota Geological Survey, 1996) was developed for eastern North Dakota and northwestern Minnesota in the early 1970's by S.R. Moran of the North Dakota Geological Survey. The database has been augmented over the years by NDGS workers, University of North Dakota students, and other workers in the region.

Sand-grain composition has been used mainly for establishing till stratigraphy and correlating till units. It can also be used to relate glaciofluvial sediments to correlative tills. In such cases, the glaciofluvial percentages may not match those of their respective tills well because of sorting and abrasion associated with stream processes, as well as incorporation of material from stream banks, which may modify the composition. For example, shale in outwash from the Des Moines lobe decreases rapidly away from the ice margin. Thus a few shale grains in an eastern Minnesota outwash deposit indicates a connection to the Des Moines lobe, because no other till in the area contains more than a trace of gray shale.

Ice-flow Direction

Drift prospecting is a procedure whereby glacial sediments are sampled for minerals indicative of ore zones; the knowledge of ice movement directions is then used to trace the glacial sediments to locate mineralized zones in the bedrock (Kujansuu and Saarnisto, 1990). The Minnesota Department of Natural Resources, Division of Minerals, has sponsored several drilling projects to assist minerals exploration in Minnesota (Martin and others, 1988; 1989; 1991). These reports cover the location, quantity, and type of indicator minerals, using grain counts for the 1–2-mm fraction. The reports describe the glacial stratigraphy and the ice-flow directions inferred for till units. Recognition of an indicator train requires comparison of many samples from the same stratigraphic unit, preferably the basal till.

Other Applications

Once the fundamental glacial stratigraphy is established for a region, it is then possible to use sand-grain composition to address issues such as conditions at the glacier bed. For example, Chernicoff (1980) examined the compositional variability within Grantsburg-sublobe tills, using texture, total carbonate, and magnetic susceptibility. These measurements provided quantitative data for the modeling of sediment transport at the base of the ice. Composition of the 1–2-mm fraction can be used in the same way, either alone or in concert with other methods.

The study of sand-grain composition can provide critical information about the transport and depositional mechanisms associated with different till units. In addition, sand-grain composition allows one to model the mixing of till units derived from multiple source regions, and the role of reworking by fluvial processes. In the more distant future, it should be possible to reconstruct the landscape of the very earliest continental glaciations, based on the sand-grain composition and other characteristics of the oldest tills.

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