QUATERNARY GEOLOGY ALONG THE EASTERN FLANK OF THE COTEAU DES PRAIRIES, GRANT COUNTY, SOUTH DAKOTA

A THESIS

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ABSTRACT

The Quaternary sediments and landforms of Grant County in northeastern South Dakota were evaluated in an effort to determine the lithostratigraphy, morphostratigraphy, and Late Cenozoic history of the area.

Nine lithologically distinct tills were identified from surface exposures, with five additional units, termed drift complexes, recognized in the subsurface of the Coteau des Prairies. Five of the tills (Whetstone, South Fork, Yellow Bank, Hawk Creek, and Granite Falls) and all of the drift complexes (1 through 5) are pre-Late Wisconsin in age, and some may date to the late Pliocene. Clast lithologies and orientations indicate that most of the pre-Late Wisconsin glaciers advanced into the area from the north and northwest, although the Hawk Creek Till was deposited by a glacier from the northeast.

Four Late Wisconsin-aged tills were recognized. The oldest unit, the Toronto Till, is exposed in the western third of the County and was deposited between 30,000 and 20,000 yrbp. The New Ulm Till and the till which comprises the Big Stone Moraine are found over the eastern two-thirds of the County and were deposited by the Des Moines Lobe between 14,000 and 11,700 yrbp. The till of the Dakota Moraine was deposited by the James Lobe about 14,000 to 13,500 yrbp.

Six distinct geomorphic zones are found in the area. Each can be associated with a specific phase of Late Wisconsin glacial activity or individual ice lobe. In Grant County, the eastern-most extent of the James Lobe is marked by a push moraine (the Dakota Moraine). The Toronto Till Plain is a well-dissected surface lacking constructional landforms. The Bemis Moraine and Altamont-Gary Moraine Complexes are made up of a variety of moderate- to high-relief ice-contact and ice-stagnation features and mark the eastern edge of the Coteau des Prairies. The Minnesota River Valley is an area of relatively low relief ground moraine that covers the eastern half of the County. The Big Stone Moraine is an arcuate belt of low-relief, hummocky topography in the northeastern part of the County and marks the final advance of Late Wisconsin ice in the area.

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INTRODUCTION

A complex history of glacial activity in northeastern South Dakota is recorded in the Quaternary sediments and landforms of the Coteau des Prairies and the adjacent Minnesota River Valley. In places, composite drift thicknesses in excess of 800 feet have been encountered by drilling. Numerous pre-Late Wisconsin drift units, some possibly as old as late Pliocene, are found throughout the area. Sediments of Late Wisconsin age were deposited during several phases of glacial activity, each with a characteristic suite of landforms marking the ice-marginal position of each advance.

Statement of Problem

While the major features of the Quaternary geology of northeastern South Dakota have long been established, no detailed investigation of the area has been conducted. The nature and extent of the numerous surface and subsurface units, particularly as they may relate to the origin of the Coteau des Prairies, are poorly understood. Likewise, the marked variation in landform assemblages associated with individual Late Wisconsin ice margins has not been adequately explained in terms of the glacier dynamics and depositional environments. This investigation was undertaken with the intent to provide both a lithostratigraphic and morphostratigraphic framework within which the glacial deposits and Quaternary history of northeastern South Dakota and adjacent areas may be more clearly understood.

This study is part of a larger investigation into the geology and water resources of Grant and Codington Counties conducted through the combined efforts of the South Dakota Geological Survey and the United States Geological Survey. Their cooperative efforts are designed primarily to locate and evaluate the mineral and water resources available in each of the counties.

Study Area

Grant County, located in northeastern South Dakota, was the principal area of investigation. It is bordered by Deuel, Codington, Day, and Roberts Counties in South

Dakota, and Big Stone and Lac Qui Parle Counties in Minnesota. The actual area of study was extended beyond the County borders to include critical exposures and to trace landscape boundaries. A total area of approximately 800 square miles was surveyed during this investigation (Figure 1).

Previous Investigations

The earliest known maps that show glacial features in northeastern South Dakota are those prepared by Warren Upham as part of his studies in western and southwestern Minnesota (in Winchell, 1880, 1881). They show a sequence of terminal moraines associated with the most recent period of glacial activity. Upham traced the moraines north and west from southwestern Minnesota into Dakota Territory where they curved around the northern end of the Coteau des Prairies.

Chamberlain (1883) compiled a comprehensive summary of the glacial drift border in the northern United States. He incorporated Upham's moraine positions in his maps of southwestern Minnesota and the eastern part of Dakota Territory. Chamberlain identified the moraines on either side of the Coteau des Prairies as being the products of two separate ice masses, the Minnesota (later Des Moines) Lobe on the east and the Dakota (James) Lobe to the west. He named the outermost moraine of the Minnesota lobe (Upham's First moraine) the Altamont. Upham's Second moraine became the Gary and the Third the Antelope.

Although Chamberlain (1883, p. 394) clearly referred to the outermost moraine of the western ice lobe as the Dakota Moraine, later references to this and younger moraines of the James Lobe used either names from the Des Moines Lobe (Todd, 1896, 1899, 1909; Rothrock, 1934; and Steece and others, 1960) or assigned new names (Rothrock, 1935; Leap, 1988).

Leverett (1922a) described a subtle, yet distinct, moraine outside of the Altamont Moraine in eastern South Dakota, southwestern Minnesota, and northern Iowa, which he called the Bemis Moraine and identified as the outermost terminal moraine of the Des Moines Lobe. Leverett considered all drift found within and behind the Bemis Moraine and the outer moraine of the James Lobe, the Dakota Moraine, to be the result of the

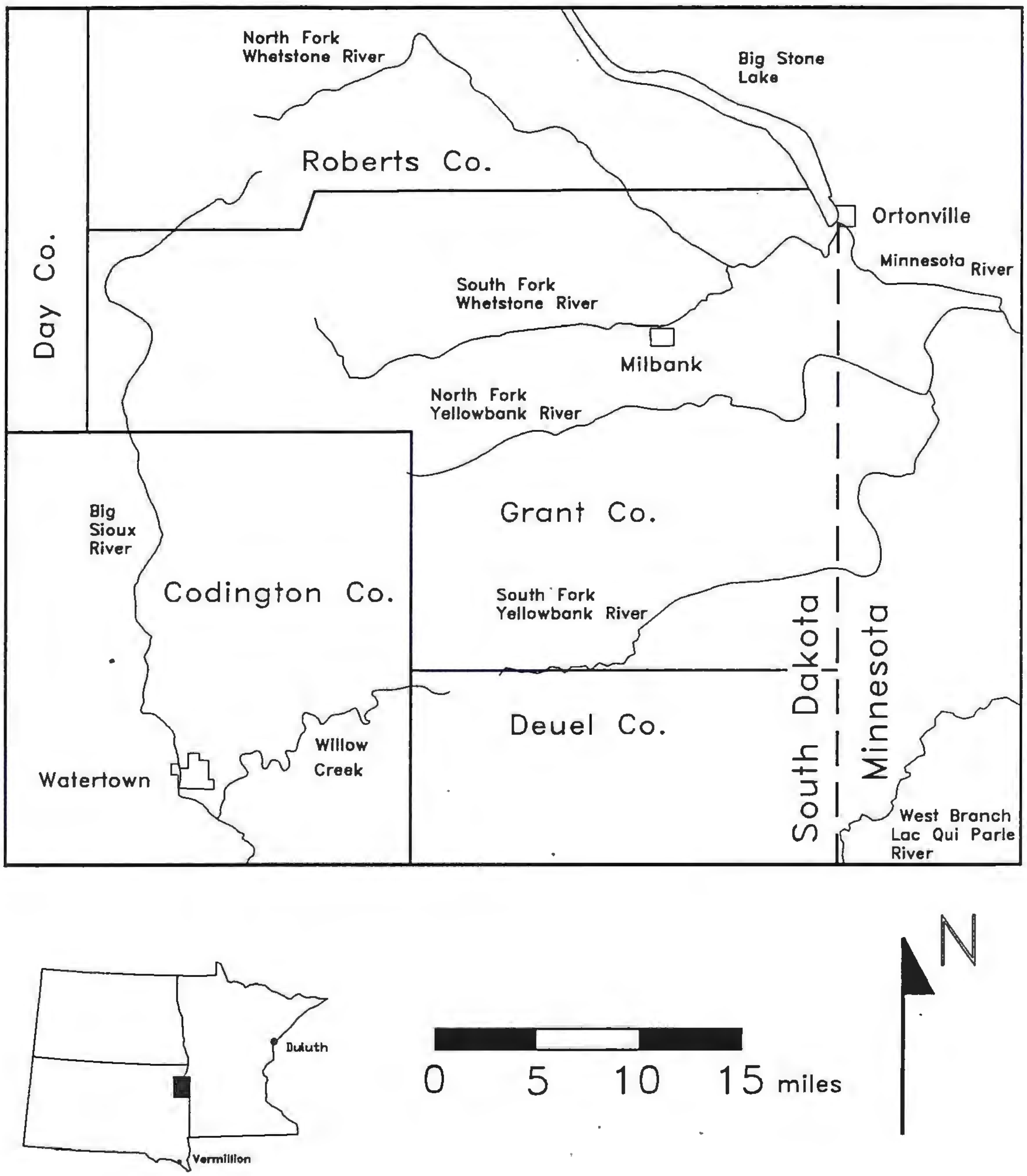


Figure 1. Location of study area.

most recent (Wisconsin) glaciation. The older drifts found in the interlobate area between these moraines he attributed to the progressively older Iowan and Kansan glaciations.

In a separate paper, Leverett (1922b) described the nature of the various glacial deposits that make up the Coteau des Prairies. He attributed the high relief of this topographic feature to a thick accumulation of drift, of which the surficial units (Wisconsin, Iowan, and Kansan) made up only a small part.

In 1932, Leverett published a more detailed description of the Quaternary geology of the eastern half of the Coteau des Prairies. It included descriptions of previously identified ice-marginal features, the Bemis, Altamont, Gary, and Antelope moraines, as well as several additional ice-marginal features, most notably the Big Stone Moraine. The drift boundaries and many of the moraine names used in his report are largely still in use today.

The first detailed geologic investigation within the study area was a brief report on the geology of Grant County (Rothrock, 1934). Rothrock followed the terminology of Leverett (1932), with the following exceptions: 1) he referred to the outer-most James Lobe moraine as the Altamont Moraine, 2) the Bemis Moraine was not recognized, and 3) he suggested that the Antelope Moraine may not be a separate feature, but instead might be associated with the Big Stone Moraine. Of note also was his recognition of distinctly older tills (Kansan) exposed in stream cuts along the flank of the Coteau des Prairies.

A summary of the Quaternary geology of eastern South Dakota was presented by Flint (1955) and remains the only comprehensive evaluation of the glacial deposits and Quaternary history of the State. In northeastern South Dakota, Flint's map, although more detailed, does not differ greatly from those of Leverett (1932) or Rothrock (1934) and he retained most of the names used by earlier workers.

In the interlobate area, Flint recognized the two separate drift areas that had been reported by earlier workers. Following the terminology of Ruhe (1950), Flint renamed the younger drift unit (Leverett's Iowan) the Tazewell, and the older drift (Leverett's Kansan) the Iowan. Both were considered to be part of the Wisconsin glaciation. The boundary between the two drifts he placed in a similar position to that of Leverett (1932), although Flint did not extend it quite as far to the north.

Surficial mapping in the northern part of the Big Sioux River basin by the South Dakota Geological Survey in the late 1950's produced a number of 15-minute quadrangle maps which included portions of the Grant County area (Steece, 1958a,b,c; Tipton 1958 a,b,c,d). As a result of these studies, and others conducted farther to the south, Steece and others (1960) and Lemke and others (1965) revised the glacial history of the area. Specifically, they considered all drift within the Des Moines Lobe Bemis Moraine and the James Lobe Dakota Moraine (their James Lobe Altamont Moraine) to be Late Wisconsin in age, deposited sometime between 22,000 and 10,000 years before present (yrbp). They did not recognize Flint's (1955) Tazewell and Iowan divisions in the drift outside of these moraines, and considered the glacial deposits of the whole area to be Early Wisconsin in age.

Investigations into the Quaternary geology of the upper Minnesota River Valley resulted in the recognition and description of a multiple-till stratigraphy in the Grant County area (Matsch, 1972; Rutford and Matsch, 1972; Matsch and others, 1972). The surface drift, associated with the Bemis Moraine and younger features, was defined as the New Ulm Till and is Late Wisconsin in age. Scattered exposures of progressively older tills, the Granite Falls and Hawk Creek, were found along the valley of the Minnesota River and its tributaries. The absolute age of these units could not be clearly defined, but they were believed to be the result of Early Wisconsin glaciations.

In Deuel and Hamlin Counties, immediately to the south of Grant County, Beissel and Gilbertson (1987) assigned a Late Wisconsin age to the drift beyond the border of the Bemis Moraine. Wood fragments collected from the base of the surface till in this area yielded radiocarbon ages that range between 22,000 and 27,000 yrbp. These ages, while notably older than that of the Bemis Moraine (14,000 yrbp, Ruhe, 1969), were still within what is considered Late Wisconsin time.

Additional modifications to the Quaternary geology of the area have been published as the result of ongoing investigations in Codington and Grant Counties (Gilbertson, in preparation) and in Brookings and Kingsbury Counties (Jarrett and others, in preparation). However, given the overlapping nature of these investigations with the current study, they will be discussed later in the text.

Methods of Investigation

The collection and evaluation of field data presented in this report began in the spring of 1984 and continued sporadically through the summer of 1989. Laboratory analyses of sediment samples were performed between October, 1989, and February, 1990.

Field Studies

Surficial geology was mapped primarily using 1:24,000 scale topographic maps and supplemented with 1:125,000 scale infra-red and 1:20,000 scale black & white aerial photographs. The U.S.D.A. Soil Survey of Grant County (Miller, 1979) also proved useful in tracing the areal distribution of units and landforms. The information was compiled on a base map with a scale of 1:100,000.

Subsurface information was derived from several hundred mud-rotary and auger test holes drilled by the South Dakota Geological Survey as part their overall study. A listing of test holes used in this study is presented in Appendix A. Records of pre-existing state, federal, and private test holes and wells were also analyzed. At several locations throughout the study area, continuous-core samples of unconsolidated sediments were taken to collect samples for stratigraphic studies (Appendix B). Additional subsurface information was derived from ground-water supply studies conducted for the towns of Milbank (Barari, 1976) and Big Stone City (Green & Gilbertson, 1987).

Representative samples of the various Quaternary sediments in the area were collected from natural and man-made exposures and prepared for laboratory analysis. At several localities, till fabric orientations were measured by noting the azimuth of elongate clasts. Descriptions of critical sections are presented in Appendix C. Hand-augers were used to collect samples in areas lacking surface exposures.

Laboratory Analyses

Grain-size analyses were performed on 299 drift samples in order to determine the relative matrix textures of the various stratigraphic units. A slightly modified version of the sieve and pipette method described by Folk (1974) was used. Wentworth (1922) clast size boundaries were used in this study.

The lithology of the very-coarse sand fraction (1-2 mm) was determined for all samples using a binocular microscope. Normally, between 150 and 250 sand grains were analyzed per sample. Numerous studies, starting with Matsch (1971), have demonstrated the usefulness of this parameter in both the recognition and characterization of tills in the region as well as determining the source and flow path(s) of the ice lobes which deposited them. Following Meyer (1986), the clasts were grouped by geologic age rather than by the more traditional lithologic divisions.

Textural analyses and very-coarse sand lithologies for all samples analyzed are given in Appendix D. A description of the analytical procedures is given in Appendix E.

REGIONAL SETTING

Glacial activity in the area, and hence the nature and distribution of glacial sediments and landforms, was strongly influenced by pre-existing topography and geology. Likewise, post-depositional circumstances have controlled the preservation and distribution of these features. For these reasons, an understanding of the general geology and physiography of the region is important in the interpretation of the Quaternary geology.

Physiography

The western half of Grant County is part of the Coteau des Prairies division of the Central Lowlands Physiographic Province (Fenneman, 1931). The Coteau des Prairies is a broad, flat-iron shaped highland composed of a thick sequence of glacial deposits. It rises as much as 1,300 feet above the Minnesota River Valley to the east and 700 feet above the James River Valley to the west (Figure 2). The Big Sioux River, with its headwaters in Grant County, drains the central portion of the Coteau.

In the study area, the surface of the Coteau des Prairies has two distinct forms. Adjacent to, and east of, the Big Sioux River is a relatively mature landscape. Broad, smooth interfluves separate numerous stream valleys that lead to the river. Closed depressions are almost entirely absent and local relief can reach 150 feet adjacent to major drainage ways. Bordering this central area, on the west and east, is knob and kettle topography typical of recently glaciated terrain. Drainage within these areas is mostly internal, with closed depressions flanked by rock-strewn ridges and low hills. Local relief rarely exceeds 100 feet west of the Big Sioux River, but may be slightly greater along the eastern side of the Coteau.

The eastern half of Grant County is in the Minnesota Valley division of the Central Lowlands Physiographic Province. The landscape is dominated by a series of northeast-trending, permanent and intermittent stream valleys which originate along the eastern edge of the Coteau des Prairies and eventually drain into the Minnesota River. A series of northwest-southeast trending channels, likely earlier courses of the Whetstone River, cross the northeast corner of the County and result in the lateral off-set of most

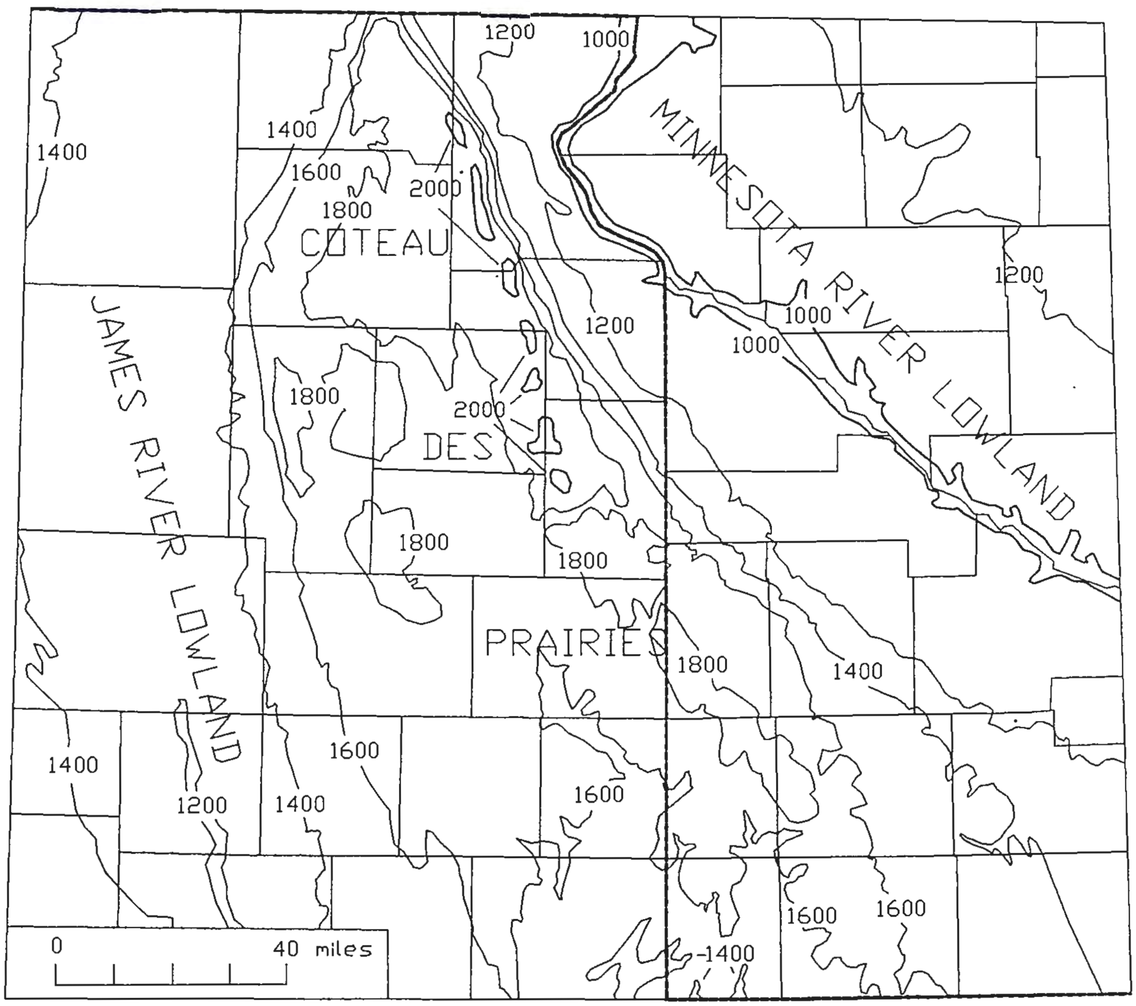


Figure 2. Generalized topography of the Coteau des Prairies and flanking lowlands, northeastern South Dakota and southwestern Minnesota. Contour interval = 200 feet. After Matsch and others, 1972.

streams. The interfluve areas are moderately-well drained, but some knob and kettle topography is present. Local relief rarely exceeds 30 feet, except along major drainages.

Bedrock Geology

A wide variety of bedrock lithologies is found throughout northeastern South Dakota, eastern North Dakota, and northern Minnesota. Distinctive assemblages of diverse rock types found in the tills of the area can be used to: 1) characterize individual units and determine their stratigraphic position and 2) establish the flow path(s) and provenance of the various ice lobes that deposited them.

Rocks of Precambrian age comprise the bedrock surface over much of central and northern Minnesota (Figure 3); however extensive outcrops of these rocks are limited to the northeastern part of the State and along major drainageways. Glacial sediments of varying thickness cover most of this surface.

The majority of Precambrian rocks in the area can be placed into two broad categories: 1) coarse crystalline units (granitic/granodioritic intrusives and gneisses), and 2) metasediments and metavolcanics. These units range in age from 3.8 to 1.8 billion years and record the complex early history of the region (Sims and Morey, 1972).

The only bedrock exposures in the study area are of rocks from this period. The Milbank granite (Petsch, 1948; Carlson, 1959) is exposed at several localities east of Milbank in Grant County. Goldich and others, (1970) assigned an age of about 2.7 billion years to these and related rocks found in the Minnesota River valley south of Ortonville.

In extreme northeastern and east-central Minnesota, a series of younger Precambrian rocks are found (Figure 3). These rocks are associated with the Midcontinent Rift System and consist of a series of mafic to felsic extrusives (the North Shore Volcanic Group) and mafic intrusives (the Duluth Complex) (Wold and Hinze, 1982), overlain by a variety of arkosic sedimentary rocks (Dickas, 1986).

Rocks of Paleozoic age, predominantly Ordovician limestones and dolomites, subcrop beneath the glacial sediments in extreme northwestern Minnesota, northeastern North Dakota, and southern Manitoba (Mossler, 1987). Comparable lithologies are also found in the Hudson Bay Lowlands of northern Ontario (Karrow and Geddes, 1987; Hicock and others, 1989).

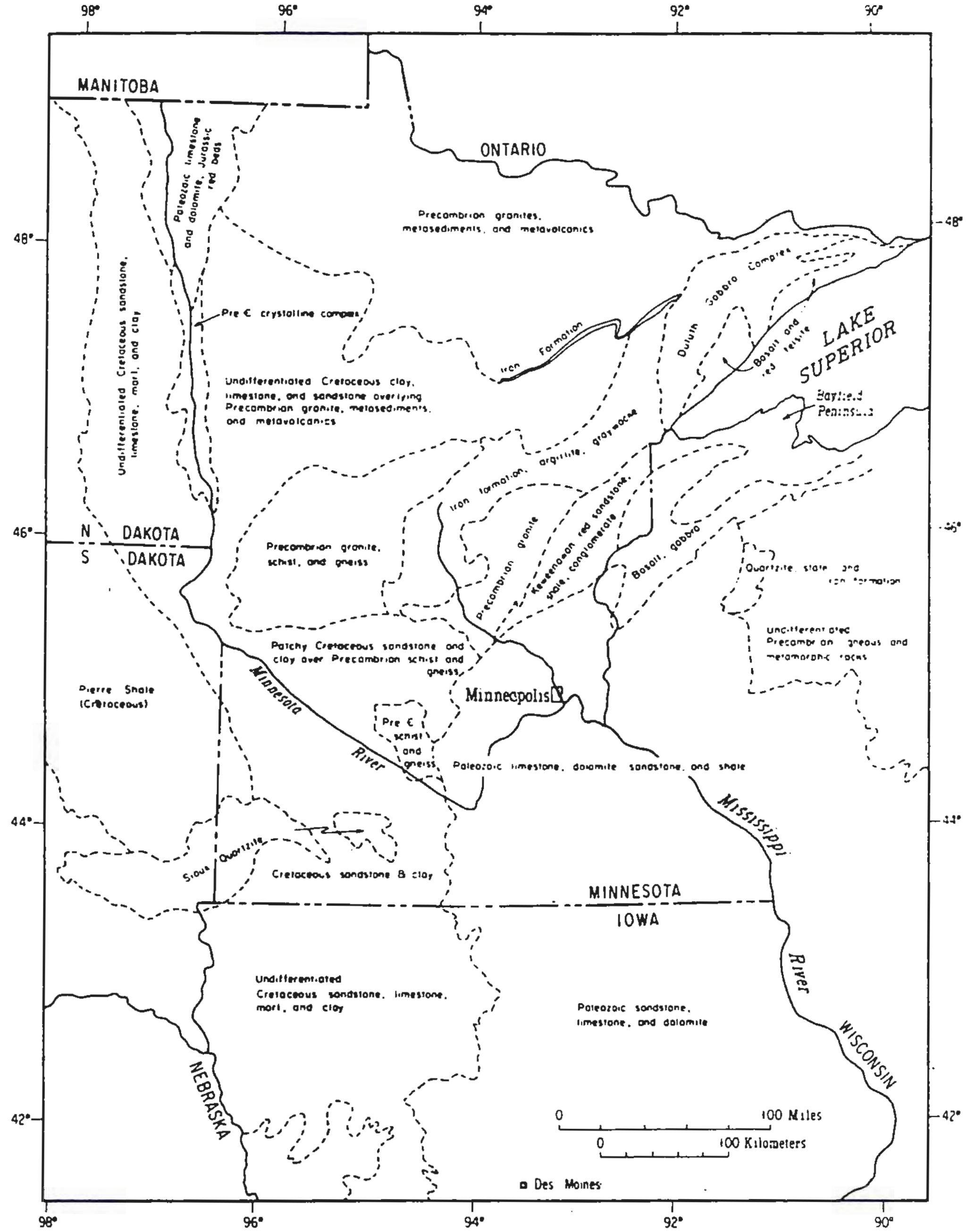


Figure 3. Generalized bedrock geology of Minnesota and adjacent areas. From Wright and others, 1973.

Cretaceous sediments constitute the youngest bedrock units in the region (Merewether, 1983; Witzke and others, 1983). A thick succession of Late Cretaceous age marine units, predominately the Pierre Shale, is found in eastern North and South Dakota. This sequence thins eastward, exposing early Late Cretaceous aged near-shore and non-marine shales, carbonates, and sandstones (Shurr and others, 1987). Post-Cretaceous erosion has greatly disrupted the lateral continuity of many of these units in Minnesota.

Bedrock Surface

Bedrock topography has had a strong influence on the Quaternary history of the area. Ice movement through the region tended to be concentrated along topographic lows, and as a result, glaciers became extremely lobate (Wright, 1972; Matsch and Schneider, 1986). Although each successive period of glaciation has likely altered the landscape, the general position of topographic high and low trends, which are controlled by the relative resistance of the bedrock, has probably not changed through the Quaternary Period.

Ice moving through the region followed one of two general paths: the northeast-southwest trending Lake Superior Lowland in northeastern Minnesota influenced ice movement from the north and east; glaciers advancing from the north and west have tended to follow a broad low now centered over the Red River valley along the Minnesota and North Dakota border. The higher ground flanking these two areas would have been ice covered only if the adjacent basins were occupied by a sufficient thickness of glacier ice. Figure 4 shows the general bedrock topography of the region.

Quaternary Geology

Northeastern South Dakota has been the site of repeated glaciations throughout the Pleistocene Epoch. Quaternary sediments and landforms of Late Wisconsin age are found through the area. Pre-Late Wisconsin glaciations are represented by sediments exposed along stream and river cutbanks and encountered in test hole borings.

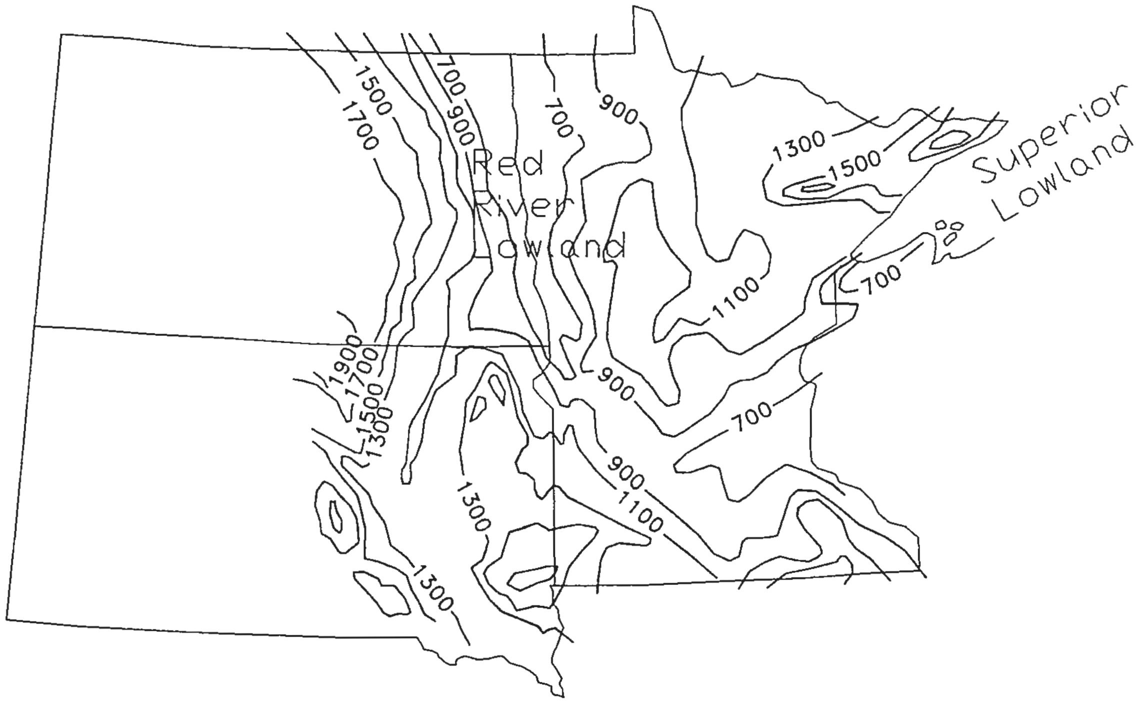


Figure 4. Generalized bedrock topography of Minnesota and eastern North and South Dakota. Contour interval = 200 feet.

In this report, the time scale and ages proposed by Richmond and Fullerton (1986) for the Late Cenozoic will be used (Table 1).

Pre-Late Wisconsin

Glaciers may first have covered the region as early as two to three million years ago. Gilbertson and Lehr (1989) reported the scattered occurrence of volcanic ash beds separating various pre-Late Wisconsin drift complexes in the subsurface of the Coteau des Prairies. They correlated the uppermost ash bed with the 610,000 year old Pearlette type-O ash exposed in southeastern South Dakota and western Iowa (Hallberg, 1986). This unit has a relatively high stratigraphic position in the overall drift sequence found on the Coteau, indicating that a considerable portion of the glacial sediments within the core of the Coteau are Middle to Early Pleistocene in age. The oldest glacial sediments may date to the Late Pliocene Epoch.

The oldest exposed glacial drift in the region is a gray, carbonate-rich, shale-poor till found beneath the Hawk Creek Till at a few localities in the upper Minnesota River Valley (Matsch, 1972; Rutford and Matsch, 1972). This till is believed to have been deposited by a pre-Wisconsin glacier that passed through southeastern Manitoba and western Minnesota. Gilbertson and Jensema (1987) identified a possibly correlative unit, the Whetstone Till, in the current study area. In a summary of the regional stratigraphy, Matsch and Schneider (1986) have assigned a pre-Illinoian age to this unit.

The Hawk Creek Till (Matsch, 1972) is the next youngest unit and is found in numerous exposures along the upper Minnesota River Valley. It is a reddish-brown, sandy till, with pebble lithologies and till fabrics that indicate it was deposited by ice advancing out of the Lake Superior lowlands. Matsch (1972) originally assigned an Early Wisconsin age to this till, but has recently revised its age to Pre-Illinoian (Matsch and Schneider, 1986).

The youngest of the pre-Late Wisconsin drifts exposed in the area is the Granite Falls Till (Matsch, 1972). It is a sandy, carbonate-rich till with a very-low percentage of Cretaceous lithologies. This till was deposited by an ice sheet that moved across northern Minnesota, but bypassed the area of Cretaceous sub-crop in western Minnesota and the

Table 1. Provisional ages assigned to informal time division boundaries in the United States. From Richmond and Fullerton, 1986.

Formal Geochronologic Units		Informal Time Divisions			Age (yr)
	Holocene		Post-Pleistocene		
					10,000[1]
				Late Wisconsin	
					35,000[2]
		Late Pleistocene	Wisconsin	Middle Wisconsin	
					65,000[2]
				Early Wisconsin	
					79,000[2]
				"Eowisconsin"	
					122,000[2]
Quaternary	Pleistocene		Sangamon		
					132,000[2]
		Late middle Pleistocene	Illinoian	Late Illinoian	
					198,000[2]
				Early Illinoian	
					302,000[2]
		Middle middle Pleistocene	Pre-Illinoian		
					610,000[3]
		Early middle Pleistocene			
					788,000[4]
		Early Pleistocene			
					1,650,000[5]
Tertiary	Pliocene	Pre-Pleistocene			

[1] Arbitrary age assigned to the Pleistocene–Holocene boundary (Hopkins, 1975).

[2] Estimated astronomical age of correlated marine oxygen isotope stage boundary, interpolated from Figs 4 and 6–10 in Johnson (1982).

[3] 'Best estimate' K–Ar age of Lava Creek Tuff and Pearlette "O" volcanic ash bed (Izett, 1981).

[4] Astronomical age of the Matuyama–Brunhes magnetic polarity reversal (Johnson, 1982).

[5] Provisional radiometric age of the proposed Pliocene–Pleistocene boundary at the Vrica section, southern Italy (Aguirre and Pasini, 1984).

eastern Dakotas. Matsch (1972) originally assigned an Early Wisconsin age to this till, but has recently assigned it to the Illinoian (Matsch and Schneider, 1986).

The absence of distinct marker beds, the discontinuous nature of the units, and the paucity of material suitable for age-dating have made the correlation of pre-Late Wisconsin glacial sediments in the Upper Midwest highly speculative. Although detailed local stratigraphic sequences have been developed for several parts of the region, e.g. the Red River Valley in northwestern Minnesota (Harris and others, 1974; Moran and others, 1976), the Todd County area in central Minnesota (Meyer, 1986; Goldstein, 1989), and the Minnesota River Valley (Matsch, 1972), individual units can rarely be conclusively correlated between areas (Matsch and Schneider, 1986). Regional correlation of the various pre-Late Wisconsin drifts found in the study area will be discussed in a later section.

Late Wisconsin

Glacial sediments of Late Wisconsin age are found at the surface throughout the study area. Using topographic expression and a limited number of radiocarbon ages, Beissel and Gilbertson (1987) identified two separate periods of Late Wisconsin glacial activity in northeastern South Dakota. Ice first covered the area between 30,000 and 20,000 years ago. A second period of activity began about 14,000 years ago and ended with the final retreat of active ice from the area about 12,000 years ago.

Early Late-Wisconsin drift, the Toronto Till of Gilbertson and Lehr (1989), is recognized at the surface in the interlobate area between the Des Moines Lobe Bemis Moraine and the James Lobe Dakota Moraine on the Coteau des Prairies. It is believed to have been deposited by an ice lobe that occupied the Minnesota River Valley. Gilbertson and Lehr (1989) have tentatively identified end moraine segments associated with this advance (the Still Lake Moraine) in Hamlin, Deuel, and Codington Counties, South Dakota.

The landscape developed on this drift is fairly mature, with few undrained depressions. This surface is correlative with that underlain by the Tazewell drift mapped and described by Flint (1955) in eastern South Dakota and with the area of extra-morainic shale-bearing till of Matsch (1972) in southwestern Minnesota.

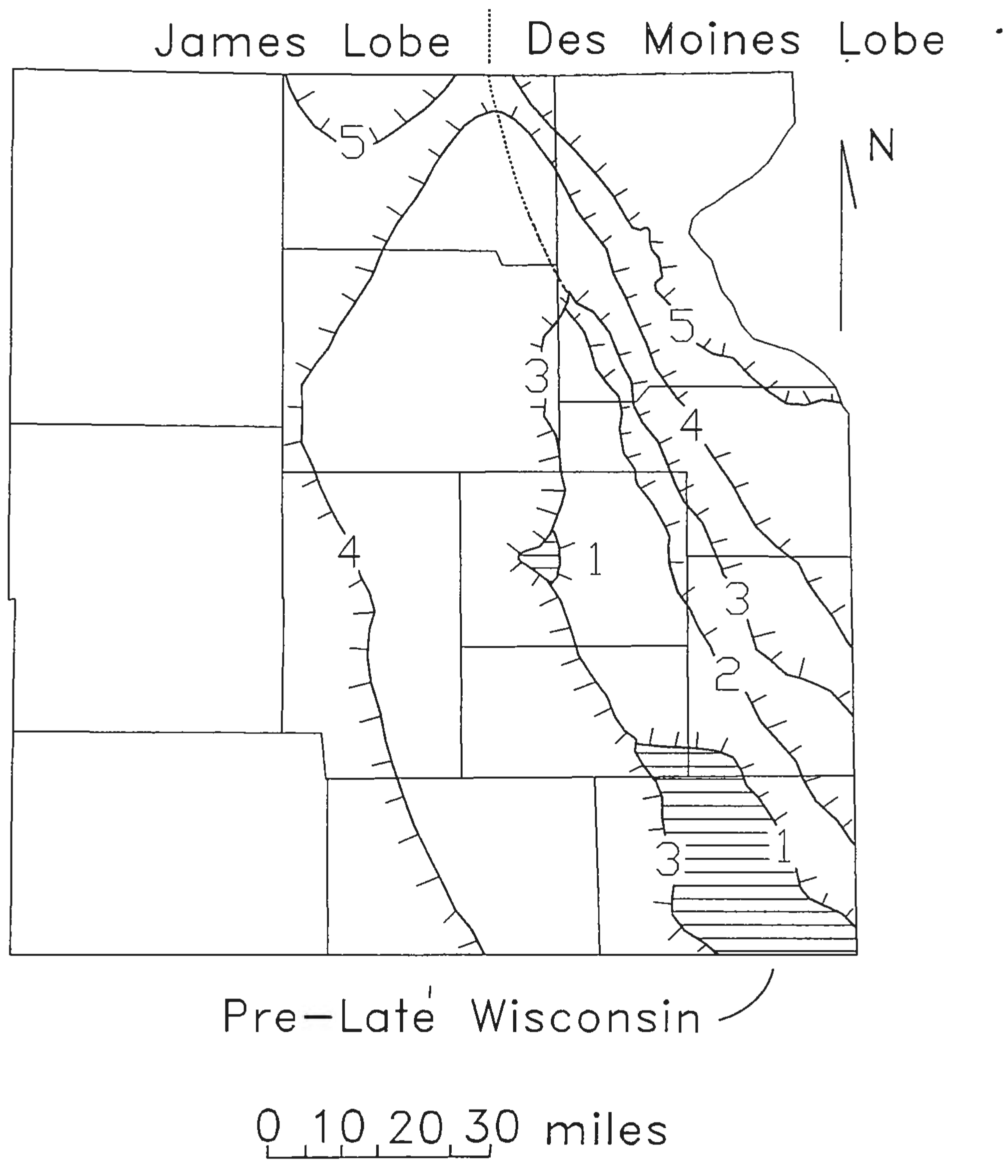
The second period of Late Wisconsin glaciation was marked by the well-defined lobation of the ice in the region. Ice moving south along the Red River lowland was split into two lobes that subsequently moved along either side of the Coteau des Prairies. The Des Moines Lobe occupied the Minnesota River Valley on the east and the James Lobe occupied what is now the James River Valley to the west. At their maximum extent, the two lobes had expanded onto the Coteau des Prairies; the ice margins coalesced at its northern end, but remained separate farther south.

A sequence of nested end moraines indicates that there were at least four distinct phases of glacial activity during Late Wisconsin time (Figure 5). Approximately 14,000 years ago the Des Moines Lobe reached its maximum extent and formed the Bemis Moraine (Matsch and others, 1972). The somewhat younger Dakota Moraine marks the farthest extent of the James Lobe. At the interlobate junction, the Dakota Moraine is confluent with the Altamont Moraine of the Des Moines Lobe, which is approximately 13,000 years old (Matsch and others, 1972). The Gary Moraine of the Des Moines Lobe and the DeSmet Moraine of the James Lobe form a continuous ridge around the outer edge of the Coteau. The Big Stone (Des Moines Lobe) and Oakes (James Lobe) Moraines were formed approximately 11,700 years ago (Fenton and others, 1983). They represent the last active glacial ice in the area.

Drift deposited by each lobe contains abundant Cretaceous shale fragments. Matsch (1972) designated the drift of the Des Moines Lobe in this area the New Ulm Till. The drift deposited by the James Lobe has not been formally described or named.

As the ice margins retreated from the area, meltwaters were repeatedly ponded between the ice front and generally higher ground to the south, resulting in the formation of a series of proglacial and ice-marginal lakes in the Minnesota River and James River Lowlands. Glacial Lake Dakota (Todd, 1894) and Lake Agassiz (Upham, 1895) are the most prominent examples, but smaller areas of glaciolacustrine sediments can be found over much of the area.

During the early phases of Glacial Lake Agassiz, an outlet channel was established in the Minnesota River Valley. Called Glacial River Warren (Upham, 1884), this spillway was active during the Cass and Lockhart phases of the lake (between 11,700 and 11,000 yrbp). The channel was abandoned temporarily when lower, more northerly



James Lobe	#	Des Moines Lobe
Oakes	5	Big Stone
DeSmet	4	Gary
Dakota	3	Altamont
	2	Bemis
	1	Still Lake

Figure 5. Approximate Late Wisconsin end moraine positions in northeastern South Dakota. From Gilbertson and Lehr, 1989.

outlets were exposed, but reoccupied during the Emerson high-water phase of the lake (9,900 to 9,500 yrbp) (Fenton and others, 1983).

Holocene

Following the retreat of active ice from the region and the demise of the large glacial lakes, sediment accumulation and landscape modification proceeded at a considerably slower pace. Alluvial materials accumulated in most of the major stream valleys as integrated drainage networks developed in the areas once covered by ice. Streams, originating on the Coteau des Prairies, cut deep gullies along the flanks of this highland. Sediments fans formed at the base of many of the steeper reaches of these streams (Jarrett, 1986). In areas as yet without external drainage, small-scale sediment transfer, slope wash, creep, etc., resulted in basin filling and a general reduction in local relief.

QUATERNARY STRATIGRAPHY

A number of glacial and non-glacial sedimentary units have been recognized in the study area (Table 2). They were identified on the basis of texture, clast lithology, color, stratigraphic position, weathering horizons, and topographic expression. Not all of these characteristics proved useful in identifying and correlating any given unit at all locations. All of the units are exposed at the surface except for the drift complexes that make up the core of the Coteau des Prairies.

Table 2. Quaternary stratigraphic units of the Grant County area.

	Coteau des Prairies	Minnesota River Valley
Late Wisconsin:		
		Till of the Big Stone Moraine
	Till of the Dakota Moraine	New Ulm Till
	Toronto Till	Lac Qui Parle Till[1]
Pre-Late Wisconsin:		
	Drift Complex 5	Granite Falls Till
		Hawk Creek Till
		Gastropod Silts
	Drift Complex 4	Yellow Bank Till
	Drift Complex 3	Whetstone & South Fork Tills
	Drift Complex 2	
	Drift Complex 1	

(1 - Bratrud, in preparation)

The Quaternary sediments in the area range in age from at least Early Pleistocene to Holocene. However, for most of the units, there is no method for absolute age determination. For this reason they have been separated into two groups, those within the range of radiocarbon dating (Late Wisconsin and Holocene) and older units (pre-Late Wisconsin).

Pre-Late Wisconsin Units

Pre-Late Wisconsin age sediments are found throughout the study area. The total pre-Late Wisconsin stratigraphic section ranges in thickness from less than 30 feet near bedrock knobs cropping out east of Milbank to over 700 feet in the western part of Grant County. Individual units have been described from cutbank exposures and cores in the northeastern part of the County. Over the remainder of the area a more general sequence of drift complexes has been described from test hole drilling.

Prairie Coteau Drift Complexes

Characterization of the thick sequence of pre-Late Wisconsin sediments that underlie the Coteau des Prairies is made solely on information supplied by rotary test hole logs. Individual units, termed drift complexes, are separated on the basis of certain gross characteristics, particularly the presence of extensive oxidized zones, outwash bodies, and geophysical log signals. At least five such drift complexes in a stratigraphic sequence over 700 feet thick are recognized beneath the late Wisconsin deposits in southern and western Grant County (Figure 6).

The tills that make up the individual drift complexes are typically gray to dark-gray, pebbly clay loams. Cretaceous lithologies are a common component of the greater-than-2mm size fraction, and the relative percentage of these rock types appears to increase with depth. Oxidized horizons appear finer textured, and range in color from pale-yellow to olive green to dark brown in color. Geophysical logs (single-point resistivity, spontaneous potential, and natural gamma) indicate that some contacts between individual units are sharp (erosional?) and others are more gradational.

The greatest number of drift complexes has been identified along the eastern edge of the Coteau des Prairies, where the pre-Late Wisconsin sequence is the thickest. Drift Complex 1, the oldest unit, is restricted to this area, with progressively younger units extending farther west (Figure 6).

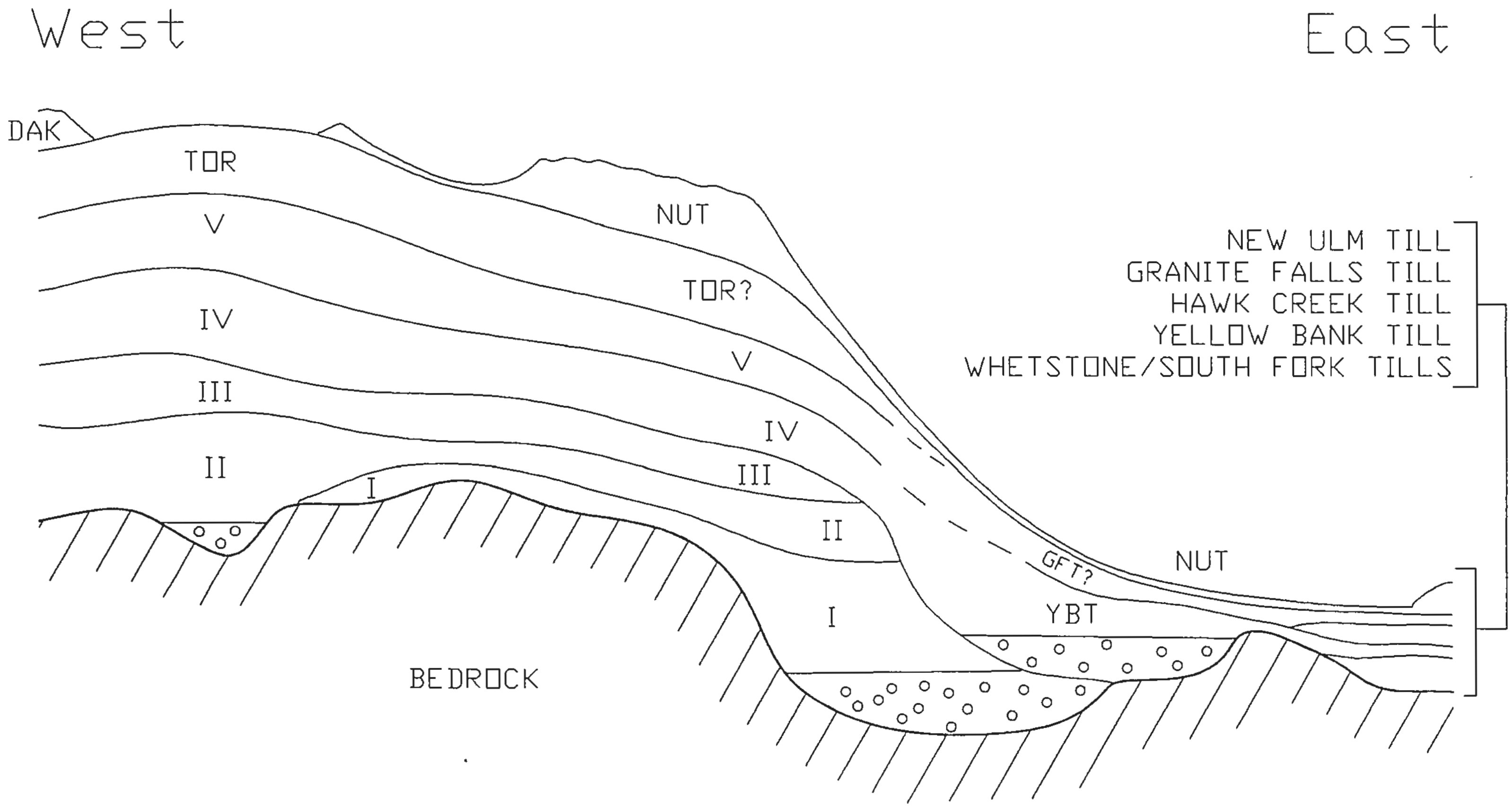


Figure 6. Generalized stratigraphic section of the Quaternary deposits in Grant County.

The ages of the various drift complexes are not well known because material suitable for age determination is uncommon.

The top of Drift Complex 3 is occasionally marked by material interpreted to be altered volcanic ash. This material might be remnants of the Pearlette "O" volcanic ash bed recognized in southeastern South Dakota and Iowa. If this is the case, Drift Complex 3 has a minimum age of 610,000 yrbp.

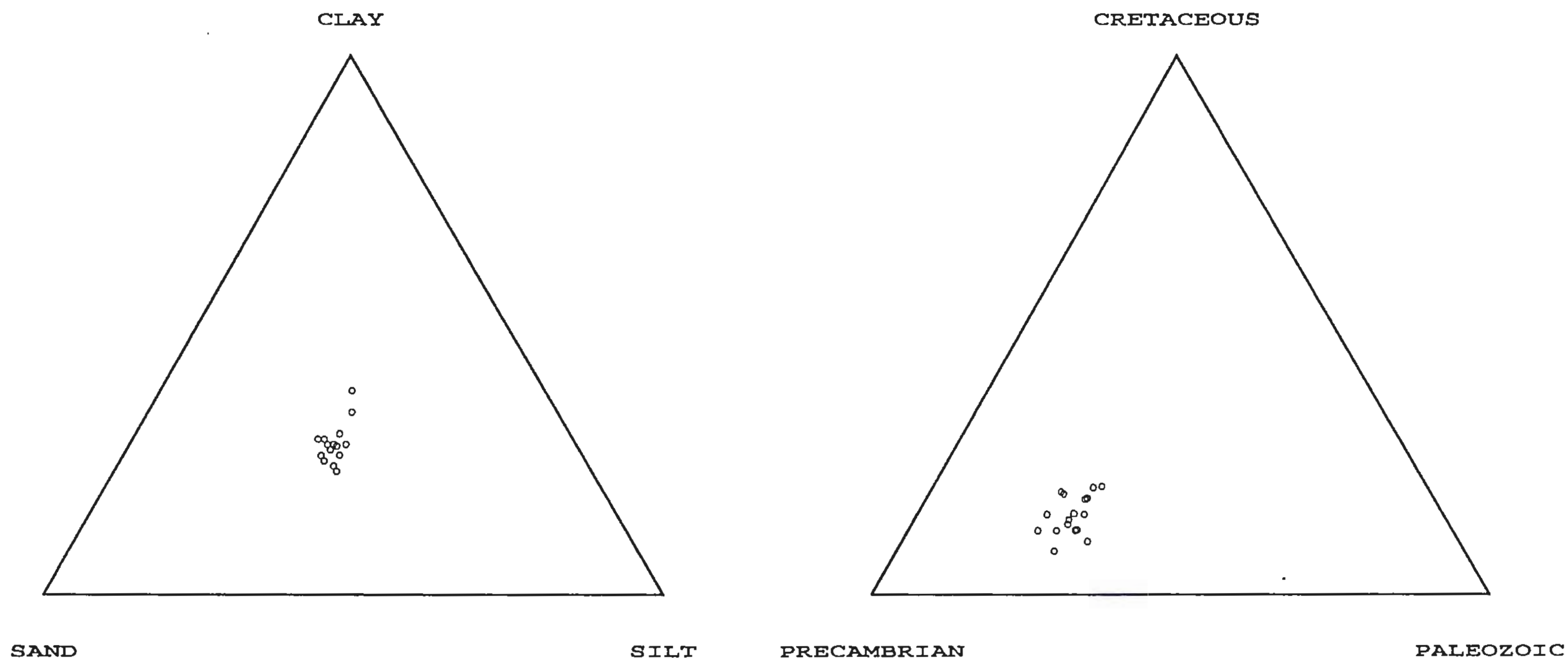
Additional, scattered ash beds have been recognized at stratigraphically lower positions within Drift Complexes 1, 2, and 3. If these deposits are correlative with other wide-spread ash beds recognized in the region (the 1.27 Ma Pearlette "S" and 2.01 Ma Pearlette "B", Hallberg, 1986), then portions of the drift within the Coteau des Prairies may date to the Late Pliocene.

Drift Complexes 4 and 5 are tentatively correlated with tills exposed in the Minnesota River Valley (the Yellow Bank and Granite Falls Tills, respectively) and are thought to be Illinoian in age.

Whetstone Till

The Whetstone Till (Gilbertson and Jensema, 1987) is the oldest glacial deposit exposed in the study area. It is a massive, calcareous, pebble-poor loam to clay-loam that is typically gray (10YR 5/1) when dry and dark gray (2.5Y 4/1) to very dark grayish brown (10YR 3/2) when wet. In outcrop, the till appears structureless to weakly jointed, and develops fairly steep slopes. No oxidized or leached horizons have been observed. The Whetstone Till is best exposed along the Whetstone River, about 1 mile WSW of Big Stone City (T 121 N, R 46 W, Section 18 NW¼ SE¼ SW¼ NE¼, Gaging Station Section, Appendix C).

The Whetstone Till contains very few pebbles and cobbles. Very few clasts with diameters in excess of about 5 cm were observed. The till matrix (less than 2mm fraction) contains from 31% to 42% sand, 30% to 36% silt, and 24% to 38% clay (Figure 7). The very-coarse sand fraction contains 52% to 67% Precambrian lithologies, 21% to 30% Paleozoic carbonates, and between 8% and 20% Cretaceous lithologies (Figure 7). Siliceous shale makes up only about 28% of the Cretaceous fraction.



(A) Matrix Texture

(B) V.C. Sand Lithologies

Figure 7. Matrix texture and very-coarse sand lithologies for the Whetstone Till. (17 samples)

A) Average Sand : Silt : Clay = 39 : 33 : 28, with standard deviations of 3 : 2 : 3.
B) Average PreC : Palz : Cret = 60 : 25 : 15, with standard deviations of 4 : 2 : 4.

In exposures, a sharp, irregular erosional contact separates the Whetstone Till from the overlying sands of the Gastropod Silts (Figure 8). Ground water seeps commonly mark this boundary. The lower contact is not exposed. When the Whetstone till has been identified in test holes, it is commonly bounded by sorted sediments, but the nature of the contacts is unclear.

Surface exposures of the Whetstone Till are limited to cutbanks along the lower reaches of the Whetstone River in northeastern Grant County and the Yellow Bank River in northwestern Lac Qui Parle County in Minnesota. Exposed thicknesses of the Whetstone Till range from 3 to 10 feet.

In the subsurface, it can be traced westward to the central part of the County where it is truncated by an erosional unconformity (Figure 6). The upper limit of Drift Complex 3 within the Coteau des Prairies is marked by the same unconformity and it is believed that the two drift units are correlative. Up to 35 feet of Whetstone Till has been encountered in test holes in eastern Grant County.

The Whetstone Till probably correlates with the Kandiyohi Till described by Giencke and others (1983/84) and Crum and Rust (1986) in Kandiyohi County and the Browerville Till (Meyer, 1986) in Todd County in west-central Minnesota, and the lower till exposed at North Mankato in the Minnesota River Valley (Meyer, 1986; unpublished data, J.R. Lucas, 1972). In southeastern North Dakota, Harris (unpublished data, 1988) has identified an as yet unnamed till with similar lithologic characteristics.

The age of the Whetstone Till is not known, but stratigraphic position suggests that it is at least Pre-Illinoian in age (>302,000 yrbp). If the till does in fact correlate with Drift Complex 3 on the Coteau des Prairies, then an Early Middle Pleistocene age (>610,000 yrbp) is likely (Gilbertson and Lehr, 1989).

The Whetstone Till was deposited by a glacier that advanced across northwestern Minnesota and into the study area. The relative abundance of Paleozoic and Cretaceous lithologies in the very-coarse sand precludes a northeastern origin, but the low percentage of Pierre Shale in the Cretaceous fraction indicates that the glacier had to have passed to the east of the Minnesota-North Dakota border. This trajectory is similar to that described for the Wadena Lobe (Wright, 1962). Orientations of elongate clasts in the till suggest that local ice movement was from the north-northeast (Figure 9). The general absence of depositional layering and interbedded sorted sediments, combined with the

Figure 8. Exposure of the Whetstone Till.

Top of Whetstone Till marked by ground-water seeps. Section is twenty feet high. Location: T121 N, R 46 W, Section 18 NW¼ SE¼ SW¼ NE¼, Grant County.

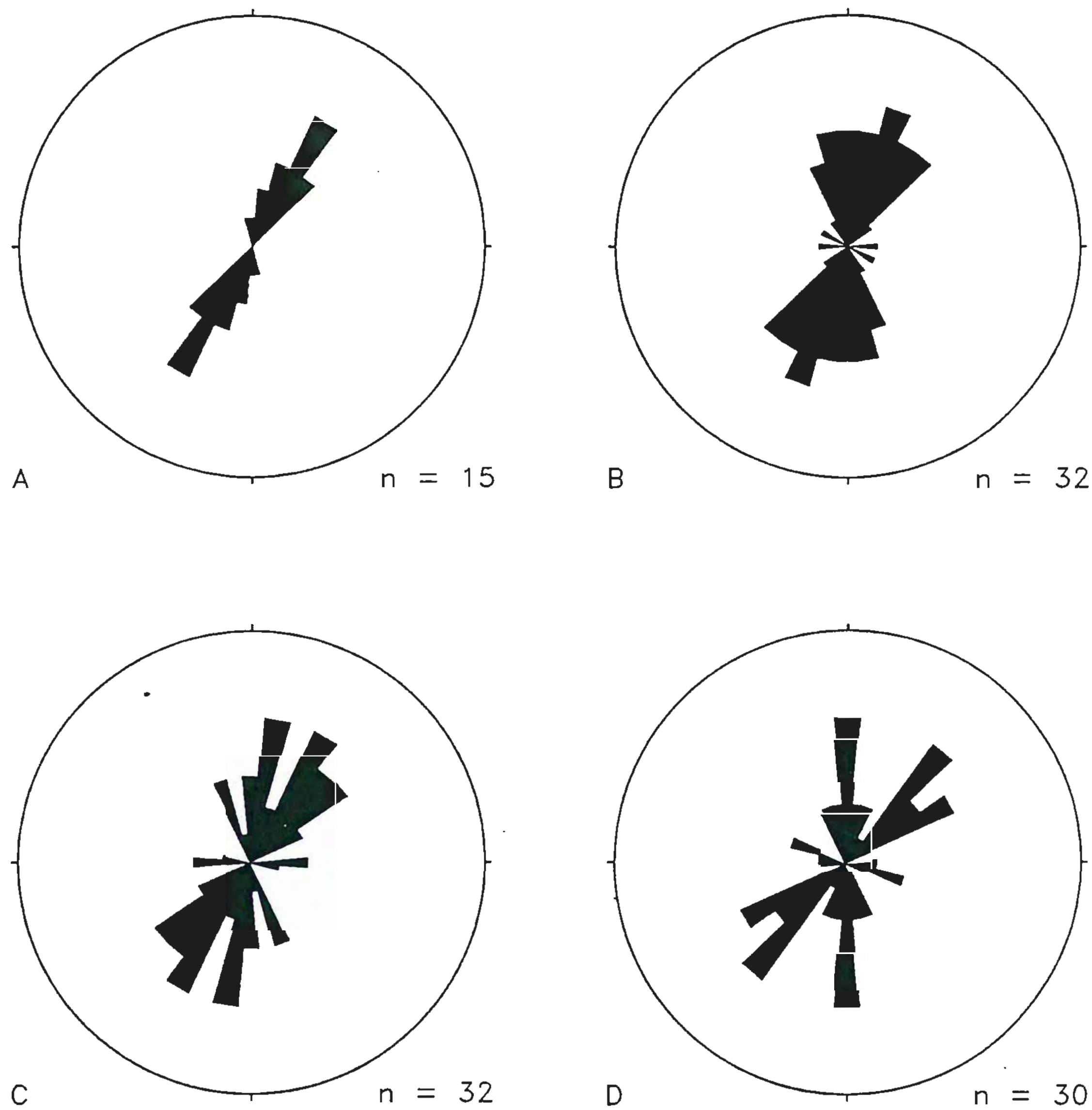


Figure 9. Orientation of elongate stones in the Whetstone Till.

A - Whetstone Bridge Section	(121-47-13ccdd)
B - Gaging Station Section, north end	(121-46-18bdca)
C - Gaging Station Section, south end	(121-46-18bdca)
D - Nordick Farm Section	(120-46-20aacb)

strong fabric and scattered bullet-shaped clasts indicate that the Whetstone Till was deposited in a sub-glacial environment, most likely as a lodgement till.

South Fork Till

A till in a similar stratigraphic position to that of the Whetstone Till has been identified in core from a test hole drilled along the South Fork of the Whetstone River near Milbank (T 120 N, R 48 W, Section 06 NE¼ SE¼ NE¼ SE¼, Core C862, Appendix B). Called the South Fork Till, it is a massive, calcareous, pebble-poor clay loam that is gray (10YR 5/1) when dry and dark brown (10YR 3/3) to very dark grayish brown (2.5Y 3/2) when wet.

Core samples of the South Fork Till contain about 10% pebbles. The till matrix contains between 29% and 37% sand, 30% to 32% silt, and 32% to 40% clay (Figure 10). The very-coarse sand fraction contains 50% to 63% Precambrian lithologies, 14% to 20% Paleozoic carbonates, and between 23% to 33% Cretaceous rocks (Figure 10). Pierre Shale makes up about 53% of the Cretaceous fraction.

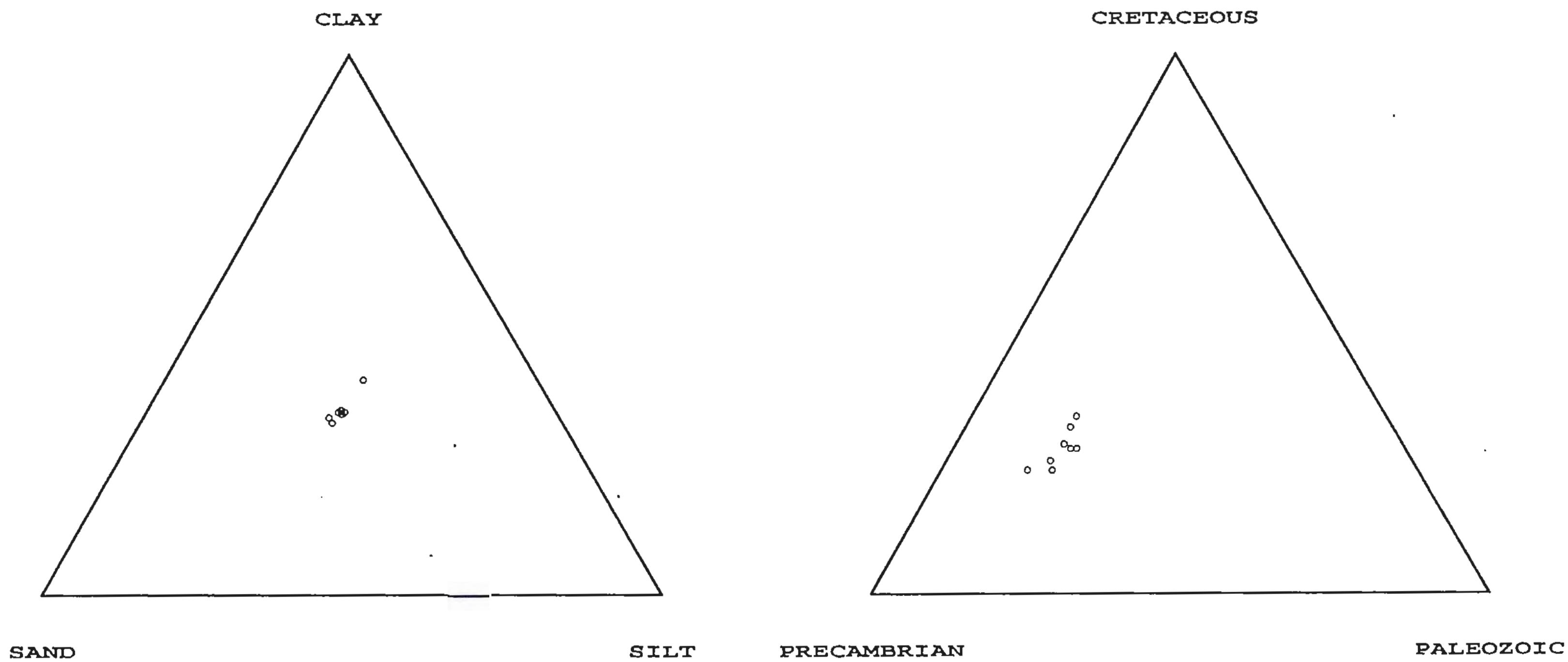
In the core, the South Fork Till is overlain by the Hawk Creek Till. The contact is sharp and apparently erosional. The base of the unit is marked by an abrupt transition to sands and fine gravel. The sorted sediments overlie Late Cretaceous shales.

No clear stratigraphic relationship between the South Fork and Whetstone Tills has been established. Separation of the two units was made solely on the basis of laboratory analyses of matrix texture, weight-percent-sand distribution, and very-coarse sand lithologies. Each till has distinctly different characteristics and can be readily identified. While it is possible that the South Fork Till may represent a local variation of the Whetstone Till, the absence of any pronounced overlap of characteristics suggests that it is a separate unit.

The South Fork Till has not been correlated with other Quaternary deposits in the region.

The age of the South Fork Till is not known, but stratigraphic position suggest that it is Pre-Illinoian in age.

The South Fork Till was deposited by an ice lobe with a similar trajectory to that which deposited the Whetstone Till. However, the increased percentage of Pierre Shale



(A) Matrix Texture

(B) V.C. Sand Lithologies

Figure 10. Matrix texture and very-coarse sand lithologies for the South Fork Till. (8 samples)

A) Average Sand : Silt : Clay = 34 : 31 : 35, with standard deviations of 3 : 1 : 2.
B) Average PreC : Palz : Cret = 55 : 17 : 27, with standard deviations of 4 : 2 : 3.

clasts suggests a more westerly track. No stone orientation data are available for the South Fork Till. A sub-glacial depositional environment is proposed for the South Fork Till, based on the general absence of related sorted sediments.

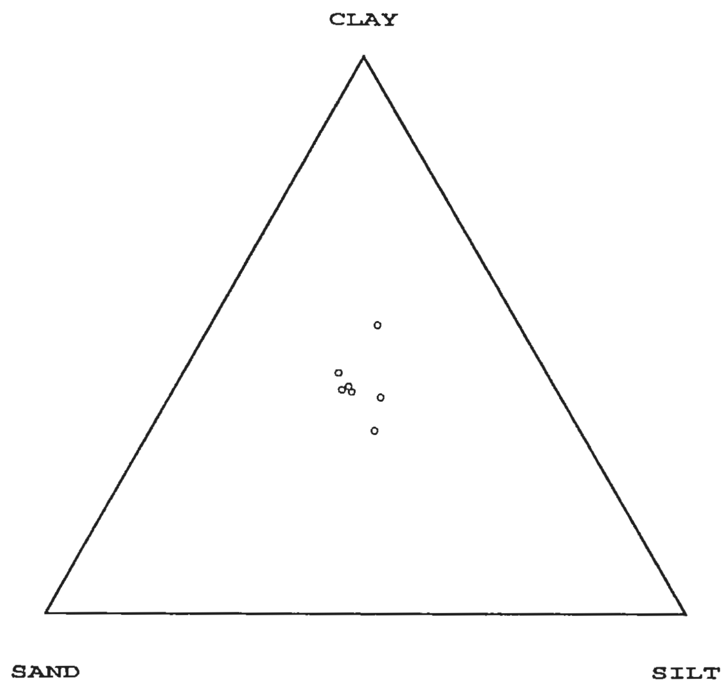
Yellow Bank Till

The youngest of the pre-Hawk Creek tills found in the area is the Yellow Bank Till. It is a calcareous, pebbly clay to clay loam. The till is gray (5Y 6/1) when dry and olive gray (5Y 4/2) to dark grayish brown (2.5Y 4/2) when wet. Weathered Yellow Bank Till is very pale yellow (10YR 7/3) to brownish yellow (10YR 6/6) if dry and light olive brown (2.5Y 5/4) to yellowish brown (10YR 5/4) when wet. The oxidized till is highly fractured, with secondary gypsum and iron staining common along joints. In outcrop, the Yellow Bank Till is quite crumbly and forms a moderate slope.

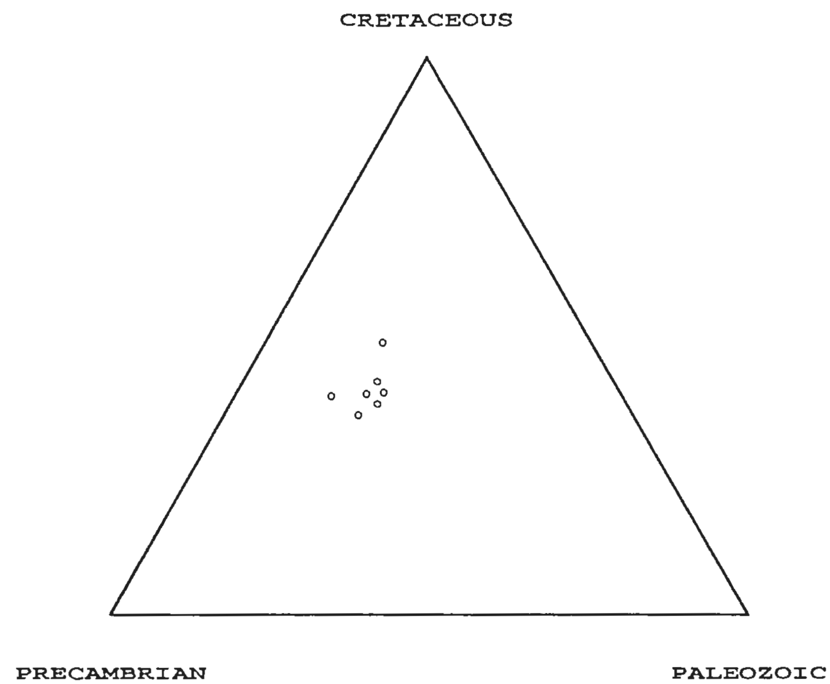
Shale and carbonate pebbles are abundant in the Yellow Bank Till. The till matrix contains 22% to 33% sand, 24% to 33% silt, and 39% to 52% clay (Figure 11). The very-coarse sand fraction contains 37% to 45% Precambrian lithologies, 15% to 23% Paleozoic carbonates, and 38% to 48% Cretaceous rock types (Figure 11). Siliceous shale (the Pierre Shale) makes up over 75% of the Cretaceous fraction.

The Yellow Bank Till is currently recognized at only a few localities in northeastern Grant and southeastern Roberts Counties. At the lone exposure of the Yellow Bank Till in the study area, along the south shore of Big Stone Lake, the upper and lower contacts of the till are obscured by slumps. It is overlain by the Hawk Creek Till at this site, but no older units are exposed. When the till was encountered during coring, the contacts were sharp, with sand and gravel commonly present. The Yellow Bank Till overlies a sequence of varved lacustrine sediments and outwash at a site south of Milbank. New Ulm Till overlies the Yellow Bank Till at this locality (T 120 N, R 49 W, Section 36 SE¼ SE¼ NE¼ NE¼, Core C861, Appendix B). At a second core site, the Yellow Bank was overlain by the Granite Falls Till, but the base of the unit was not reached. A maximum thickness of 17 feet has encountered during coring.

Yellow Bank Till is believed to be roughly correlative with the till of Drift Complex 4 found within the Coteau des Prairies (Figure 6). The Yellow Bank Till is



(A) Matrix Texture



(B) V.C. Sand Lithologies

Figure 11. Matrix texture and very-coarse sand lithologies for the Yellow Bank Till. (7 samples)

A) Average Sand : Silt : Clay = 30 : 29 : 41, with standard deviations of 4 : 4 : 5.
B) Average PreC : Palz : Cret = 39 : 20 : 40, with standard deviations of 4 : 3 : 4.

textually and lithologically similar to an unnamed, shale-rich till in southeastern North Dakota (Harris, 1988, unpublished data).

The age of the Yellow Bank Till is not known, but stratigraphic position suggests an Early Illinoian or Pre-Illinoian age. Amino acid analyses have been conducted on wood fragments recovered from lacustrine sediments found beneath the till. The results of these analyses will be discussed later in the text.

The Yellow Bank Till was deposited by an ice lobe that advanced out of Manitoba and moved south along the Minnesota/North Dakota border. The relatively high percentage of siliceous shale in the Cretaceous fraction indicates that the lobe overrode the Pierre Shale subcrops in eastern North Dakota. This course is similar to that of the Late Wisconsin Red River and Des Moines Lobes (Matsch and Schneider,1986). A sub-glacial depositional environment is proposed for the Yellow Bank Till.

Gastropod Silts

The next youngest stratigraphic unit recognized in the area is a suite of glaciofluvial and glaciolacustrine sediments referred to as the Gastropod Silts (Gilbertson and Huber, 1989). It is composed primarily of two distinct lithologies, a massive, gray (10YR 6/1) sandy silt and a bedded, medium- to coarse-grained, light-brown (7.5YR 6/4) pebbly sand. Although these two units are commonly interbedded, there is a general fining-upward trend to the overall package. The top of the sequence is commonly marked by a thin (15 cm) organic-rich horizon (Figure 12). Gastropod shells are found scattered throughout the sandy silts, along with a wide variety of other plant (pollen, algae, and seeds) and animal (clams, ostracodes, and microtine rodents) remains (Hoganson and Cvancara, 1990).

The base of the Gastropod Silts is marked by a sharp, irregular erosional contact with underlying materials, typically the Whetstone Till (Figure 8). In all exposures, the Gastropod Silts are overlain by the Hawk Creek Till. The contact is sharp and planar. In places, slickensides, oriented sub-parallel to Hawk Creek ice movement (~255°), can be observed at the contact.

Figure 12. Organic horizon at the top of the Gastropod Silts.

Location: T 121 N, R 47 W, Section 13 SW¼ SW¼ NW¼ NE¼, Grant County.

The Gastropod Silts are found in several cutbanks along the lower reaches of the Whetstone River in South Dakota and the Yellow Bank and Chippewa Rivers in Minnesota. In exposures where both upper and lower contacts are found, the thickness of the Gastropod Silts ranges from 1 to 15 feet. Where the Gastropod Silts have been identified in test holes, similar thicknesses are noted.

The Gastropod Silts are likely correlative with the Gervais Formation (Harris and others, 1974) found in the Red Lake River Valley in northwestern Minnesota.

The age of the Gastropod Silts can not be firmly established, but it is likely Late Illinoian in age. Analyses of amino acids from two *Pupilla muscorum* (snail) shells recovered from the sandy silts gave an age estimate of 140,000 ± 70,000 years B.P. (AGL-540), a range from Early Wisconsin to Late Illinoian. An Early Wisconsin age is tentatively rejected based on the absence of any clear evidence for glacial activity in the region at this time (Fullerton and Colton, 1986; Curry, 1989). Paleoecological evaluation of the organic remains recovered from the unit suggest a cool environment (Huber and Gilbertson, 1990; A.J. Smith, written communication, 1987), which would likely preclude the Sangamon Interglaciation.

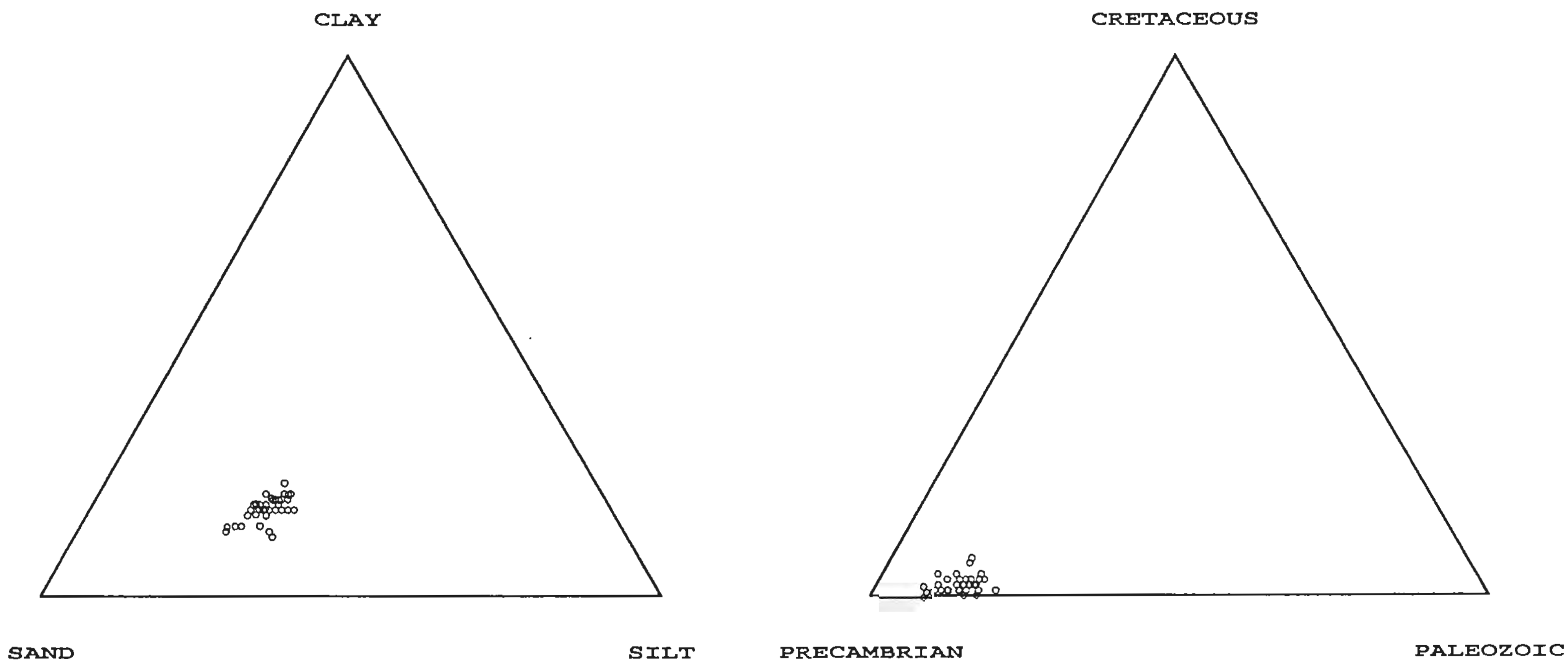
Hawk Creek Till

The Hawk Creek Till, first described in the area by Matsch (1972) and Rutford and Matsch (1972), is a massive, weakly-calcareous, pebbly sandy loam with a distinctive reddish color (Figure 13). Unoxidized Hawk Creek Till is commonly reddish gray (5YR 5/2) when dry to reddish brown (5YR 4/3) when wet. Oxidized till is pinkish gray (5YR 7/2) if dry to reddish yellow (5YR 6/6) when wet. The till is quite compact and forms steep slopes, although weak vertical and horizontal joints impart a blocky texture to weathered exposures. Joint surfaces are typically stained reddish yellow (7.5YR 6/6). The best exposure of the Hawk Creek Till in the area is found along the Whetstone River about 2 miles WSW of Big Stone City (T 121 N, R 47 W, Section 13 SW¼ SW¼ NW¼ NE¼, Loraff Farm Section, Appendix C).

The Hawk Creek Till contains abundant pebbles, cobbles, and boulders. The till matrix contains between 50% to 64% sand, 24% to 32% silt, and 11% to 21% clay (Figure 14). The very-coarse sand fraction contains 82% to 91% Precambrian lithologies,

Figure 13. Exposure of the Hawk Creek Till.

Section is approximately 40 feet high. Location: T 121 N, R 47 W, Section 13 SW¼ SW¼ NW¼ NE¼, Grant County.



(A) Matrix Texture

(B) V.C. Sand Lithologies

Figure 14. Matrix texture and very-coarse sand lithologies for the Hawk Creek Till. (45 samples)

A) Average Sand : Silt : Clay = 55 : 29 : 16, with standard deviations of 3 : 2 : 2.
B) Average PreC : Palz : Cret = 84 : 14 : 2, with standard deviations of 3 : 3 : 1.

8% to 20% Paleozoic rocks, and less than 5% Cretaceous lithologies (Figure 14). Precambrian rock types derived exclusively from the Lake Superior Lowland (typically red sandstones) are commonly found in the coarse-sand and larger fractions.

The lower contact of the Hawk Creek Till, where exposed, is sharp and planar (Figure 12). Immediately above the basal contact, there is commonly a thin (less than 1 foot) zone of interlaminated Hawk Creek Till and older gray diamicts. Individual layers range from 1/4 to 3/4 of an inch in thickness. Elongate and tabular stones within this zone are oriented parallel to the layering. The gray layers likely represent blocks or clasts of older till that have been incorporated into the Hawk Creek Till. Intense shearing at the base of the glacier resulted in the rapid homogenization and incorporation of the older drift. Similar features have been noted at the base of the till of the Late Wisconsin Grantsburg Sublobe in eastern Minnesota (Chernicoff, 1983).

The contact between the Hawk Creek Till and the next youngest unit, the Granite Falls Till, is rarely exposed. When found, the contact is sharp (Figure 15a) but commonly irregular. At most localities in the study area, the Hawk Creek Till is overlain by the Late Wisconsin New Ulm Till. The contact between these units is sharp and generally marked by a boulder pavement associated with the base of the New Ulm Till (Figure 15b). Where the pavement is absent, bedded sands and fine gravels are present.

Hawk Creek Till is found in cutbank exposures along the Whetstone and Yellow Bank Rivers in northeastern Grant County. It can be traced in the subsurface south and east for several miles but has not been recognized southwest of Milbank (Figure 16). Scattered exposures of the till can be found along the valley of the Minnesota River as far east as Franklin, Minnesota, approximately 100 miles southeast of Grant County (Matsch, 1971).

Thicknesses of the Hawk Creek Till range from 5 to 34 feet in exposures and 8 to 21 in test holes.

The Hawk Creek Till is readily differentiated from other units in the region because of its distinct color and lithologies. Red, sandy tills in similar stratigraphic positions have been described in central Minnesota by Meyer (1986), Goldstein (1987), and Mooers (1988). The Marcoux Formation of northwestern Minnesota (Harris and others, 1974) and the pre-Late Wisconsin River Falls Formation (Baker and others, 1983;

A

B

Figure 15. Exposures of the upper contact of the Hawk Creek Till.

A) Contact with the Granite Falls Till along Dryweather Creek, Chippewa County, Minnesota.

B) Contact with the New Ulm Till along the South Fork of the Yellow Bank River, Lac Qui Parle County, Minnesota.

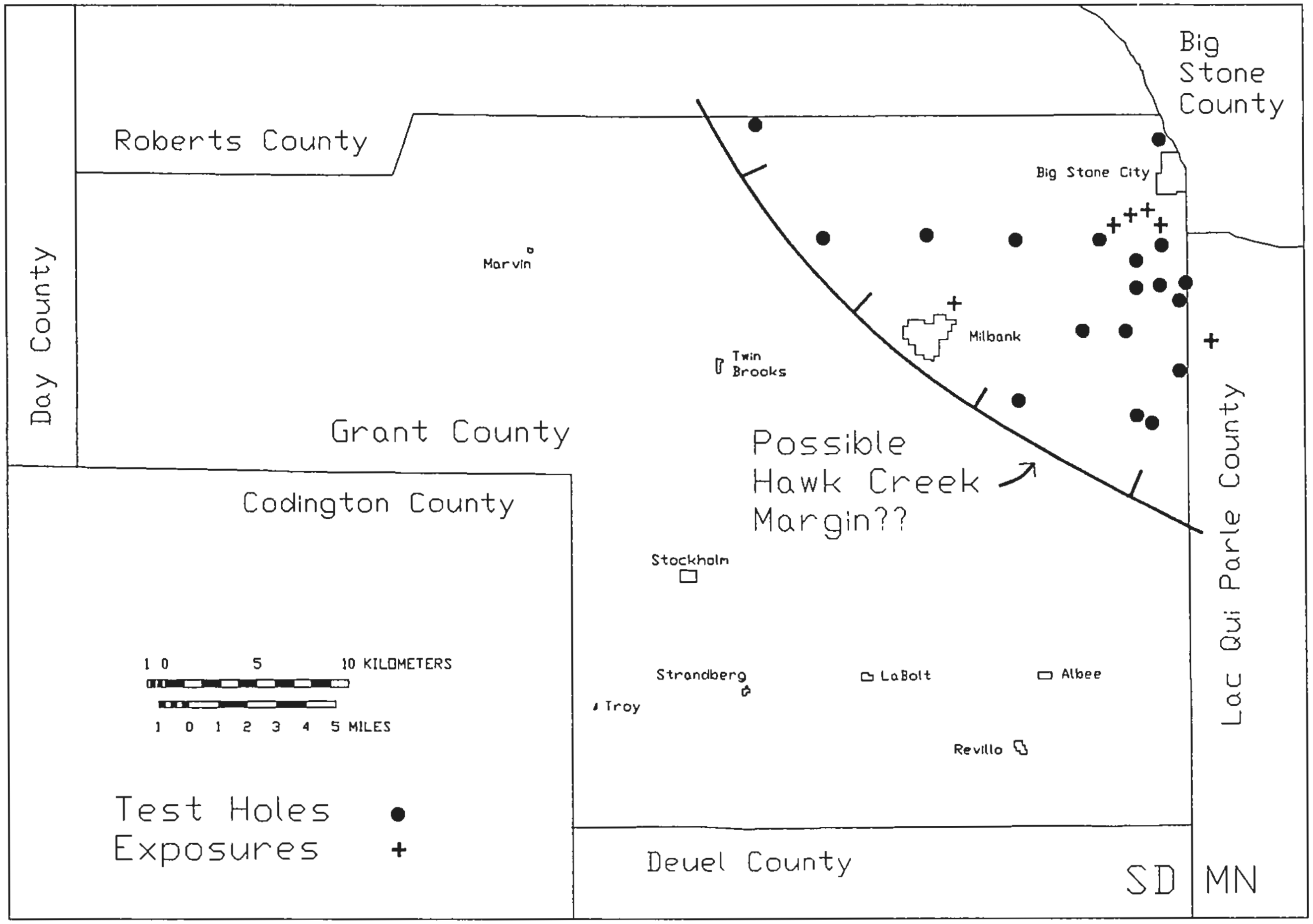


Figure 16. Known occurrences of the Hawk Creek Till in the study area.

Mickelson and others, 1984) in eastern Minnesota and western Wisconsin also have similar characteristics.

The age of the Hawk Creek Till cannot yet be clearly established, but stratigraphic position suggests that it is Late Illinoian in age. Radiocarbon analyses of wood recovered from the Hawk Creek Till have yielded infinite ages, >25,000 yrbp (GX-2734) and >32,000 yrbp (GX-13,775).

The Hawk Creek Till was deposited by an ice lobe that advanced out of the Lake Superior Lowland and moved into the area from the northeast. This trajectory is supported by the abundance of northeast source Precambrian rock types and the general paucity of any Cretaceous lithologies. Elongate clasts in the till are oriented roughly northeast-southwest (Figure 17). Also, slickensides and other deformational structures found in the underlying Gastropod Silts indicate ice movement in this direction.

The majority of the Hawk Creek Till observed at exposures and in cores appears to have been deposited as sub-glacial lodgement till. Sorted sediments are rarely found within the till. Clasts within the till show evidence of sub-glacial erosion and many are bullet shaped. The uniform texture and composition (Figure 14) and strong fabric (Figure 17) support this interpretation. A sequence of interbedded reddish-brown till and sand, interpreted to be supra-glacial Hawk Creek Till, was found in a core near Corona in north-central Grant County (T 121 N, R 48 W, Section 06 NE¼ NE¼ NE¼ NE¼, C865, Appendix C).

Granite Falls Till

The youngest of the pre-Late Wisconsin tills is the Granite Falls (Matsch, 1972). It is a massive, calcareous, pebbly loam (Figure 18). Unoxidized Granite Falls Till is light gray (10YR 7/1) to gray (10YR 6/10 and dark gray (2.5Y 4/1) when wet. The oxidized till is a very pale yellow (10YR 7/4) when dry and brownish yellow (10YR 6/6) if wet. Closely-spaced vertical and horizontal joints are commonly observed in weathered exposures of Granite Falls Till. Joint surfaces are typically stained reddish yellow (7.5YR 6/6). When dry the till is quite friable and forms moderate to gentle slopes. The Granite Falls Till is best exposed at a cutbank along a small stream about 5 miles north of

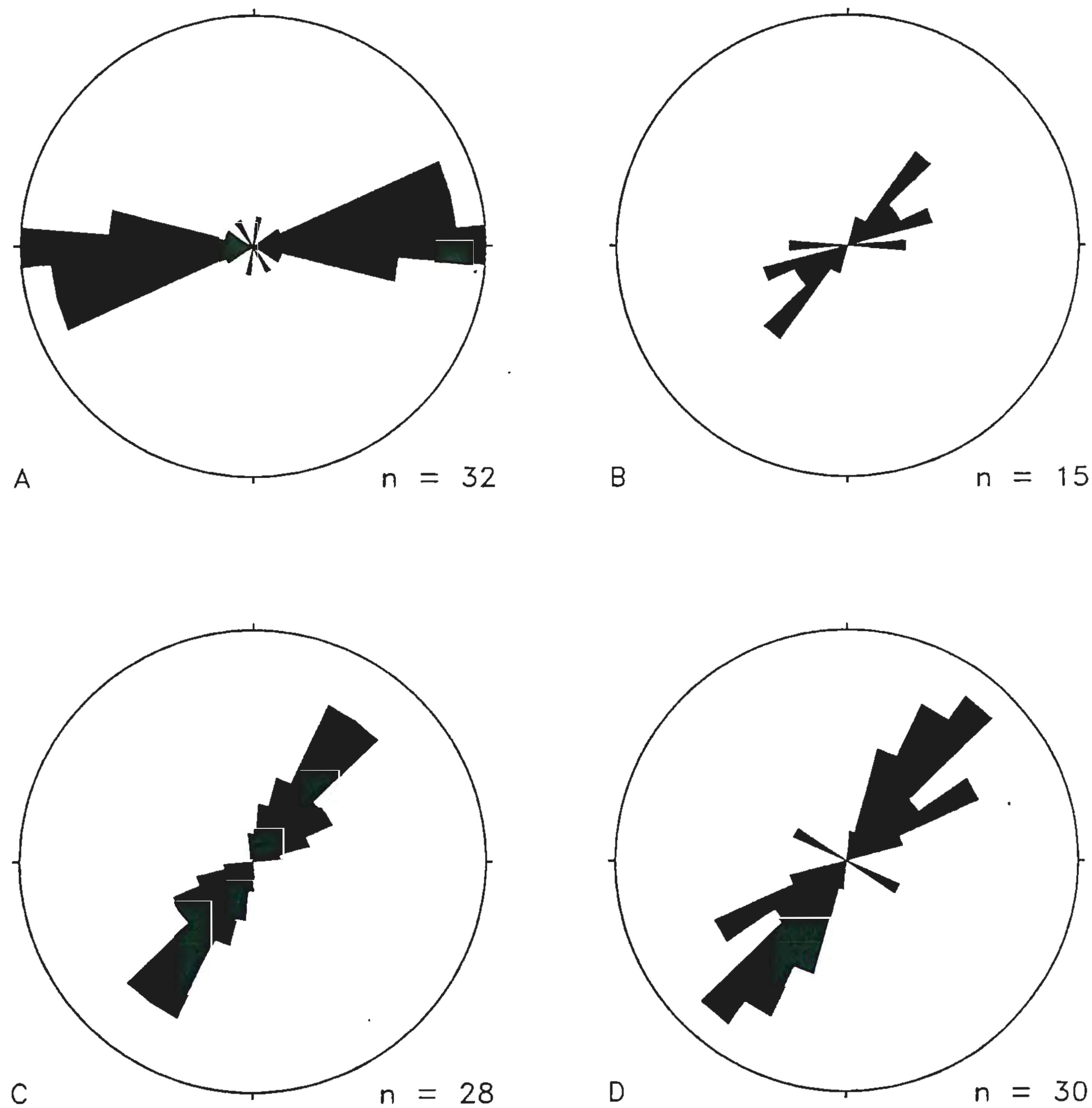


Figure 17. Orientation of elongate stones in the Hawk Creek Till.

A - Ditch northwest of Loraff Farm Section	(121-47-13ccba)
B - Whetstone Bridge Section	(121-47-13ccdd)
C - Gaging Station Section, north end	(121-46-18bdca)
D - Nordick Farm Section	(120-46-20aacb)

Figure 18. Exposure of the Granite Falls Till.

Shovel is 18 inches long. Location: T 121 N, R 48 W, Section 13 SW¼ NW¼ NW¼ NW¼, Grant County.

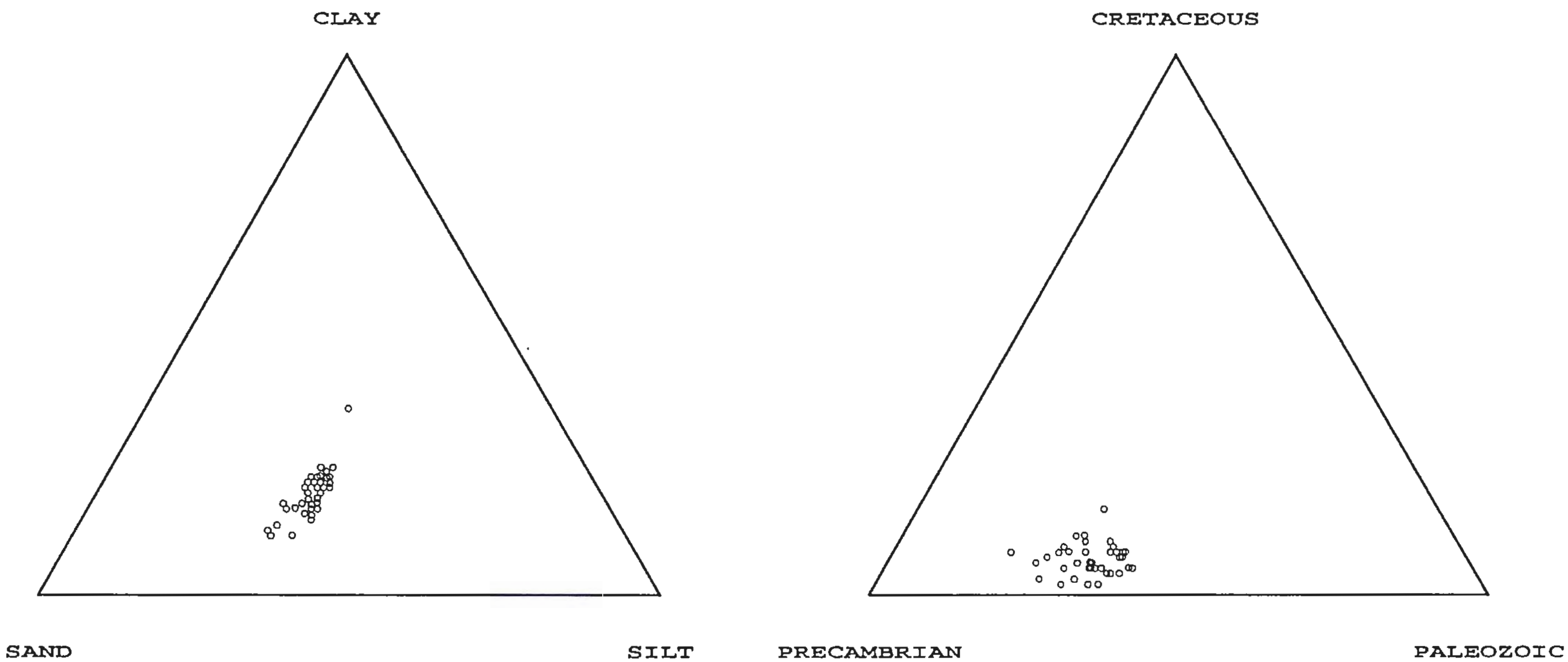
Milbank (T 121 N, R 48 W, Section 13 SW¼ SW¼ SW¼ NW¼, Rethke Farm Section, Appendix C).

The Granite Falls Till contains abundant pebbles and cobbles. While most of the stones are composed of Precambrian lithologies, Paleozoic carbonates make up a considerable percentage, a useful trait for field identification. The till matrix contains between 41% and 57% sand, 31% to 37% silt, and between 11% and 24% clay (Figure 19). The very-coarse sand fraction contains 54% to 73% Precambrian lithologies, 24% to 40% Paleozoic rock, and 2% to 16% Cretaceous lithologies (Figure 19). Siliceous shale makes up only about 35% of the Cretaceous fraction.

Where the base of the Granite Falls Till can be observed, it is marked by a sharp, but irregular, erosional contact with either the Hawk Creek Till (Figure 15a) or the Gastropod Silts. Where exposed, the contact between the Granite Falls Till and the overlying New Ulm Till is sharp and marked by the sub-New Ulm Till boulder pavement (Figure 20). Where the pavement is absent, bedded sands and fine gravels are present. When the Granite Falls Till has been identified in test holes, it is commonly bracketed by sorted sediments, but the nature of the upper or lower contacts is unclear.

Exposures of the Granite Falls Till are found mostly along the Whetstone and Yellow Bank Rivers and their tributaries, but isolated exposures can be found across the eastern half of Grant County. The western-most exposure of the till is in a cutbank along a minor tributary to the North Fork of the Yellow Bank River (T 119 N, R 49 W, Section 18 NE¼ NE¼ NE¼ NE¼, Glaciotectonic Section, Appendix C). In the subsurface, the Granite Falls Till has been identified over the eastern part of the County. Stratigraphic position and a limited number of lithologic and textural analyses suggest that the Granite Falls Till and Drift Complex 5 on the Coteau des Prairies are equivalent (Figure 6), but additional study would be needed to confirm this.

The Granite Falls Till in the study area correlates with the Granite Falls Till in southwestern Minnesota (Matsch, 1972) and in Kandiyohi County, in west-central Minnesota (Giencke and others, 1983/84; Crum and Rust, 1986). Outside of the Minnesota River Valley, the Granite Falls Till is correlated with the Wadena Till (Meyer, 1986; Goldstein, 1989) and the Wadena Formation (Mooers, 1988) in central Minnesota (the Hewitt till of Wright, 1962), the Lower Red Lake Falls Formation in northwestern Minnesota (Harris and others, 1974; Sackreiter, 1975), and the New York Mills



(A) Matrix Texture

(B) V.C. Sand Lithologies

Figure 19. Matrix texture and very-coarse sand lithologies for the Granite Falls Till. (37 samples)

A) Average Sand : Silt : Clay = 47 : 35 : 19, with standard deviations of 5 : 2 : 4.
B) Average PreC : Palz : Cret = 61 : 32 : 7, with standard deviations of 5 : 5 : 3.

Figure 20. Contact between the Granite Falls Till and the overlying New Ulm Till.

Boundary between the tills is marked by faceted boulder pavement. Location: T 122 N, R 48 W, Section 29 SE¼ SE¼ SE¼ NE¼, Roberts County.

Formation in west-central Minnesota (Anderson, 1976; Perkins, 1977). A similar carbonate-rich, shale-poor sandy till has also been identified in southeastern North Dakota (Harris, unpublished data, 1988).

The age of the Granite Falls Till has not been firmly established. Radiocarbon analyses of wood collected from sediments associated with the till near Redwood Falls, Minnesota, were inconclusive, producing ages of 34,000 ± 2,500 yrbp (GX-1309) and >39,900 yrbp (I-4932) (Matsch, 1971). Stratigraphic position indicates it is either Early Wisconsin or Late Illinoian in age.

The Granite Falls Till was deposited by ice that was moving from northeast to southwest across the study area, as indicated by the orientation of elongate clasts in the till (Figure 21). The very low percentage of Cretaceous lithologies suggests that the ice moved along a path that was to the east of the broad area of outcrop of these rocks in western Minnesota and the eastern Dakotas.

Most of the Granite Falls Till observed at exposures and in cores appears to have been deposited as sub-glacial lodgement till. Sorted sediments are rarely found within the till. Clasts within the till show evidence of sub-glacial erosion and many are bullet shaped. The uniform texture and composition (Figure 19) and strong fabric (Figure 21) support this interpretation.

Late Wisconsin Units

Glacial sediments of Late Wisconsin age make up the surficial deposits through the study area. The total Late Wisconsin section ranges in average thickness from only a few feet adjacent to the Whetstone River to approximately 200 feet in the vicinity of the Altamont Moraine in the central part of the County. Individual units have been described from analysis of drift collected from surface exposures and core, and by relation to major geomorphic boundaries.

Toronto Till

The Toronto Till is the oldest Late Wisconsin unit in the study area (Gilbertson and Lehr, 1989). It is a calcareous, pebbly clay loam. The till is typically massive, but thin

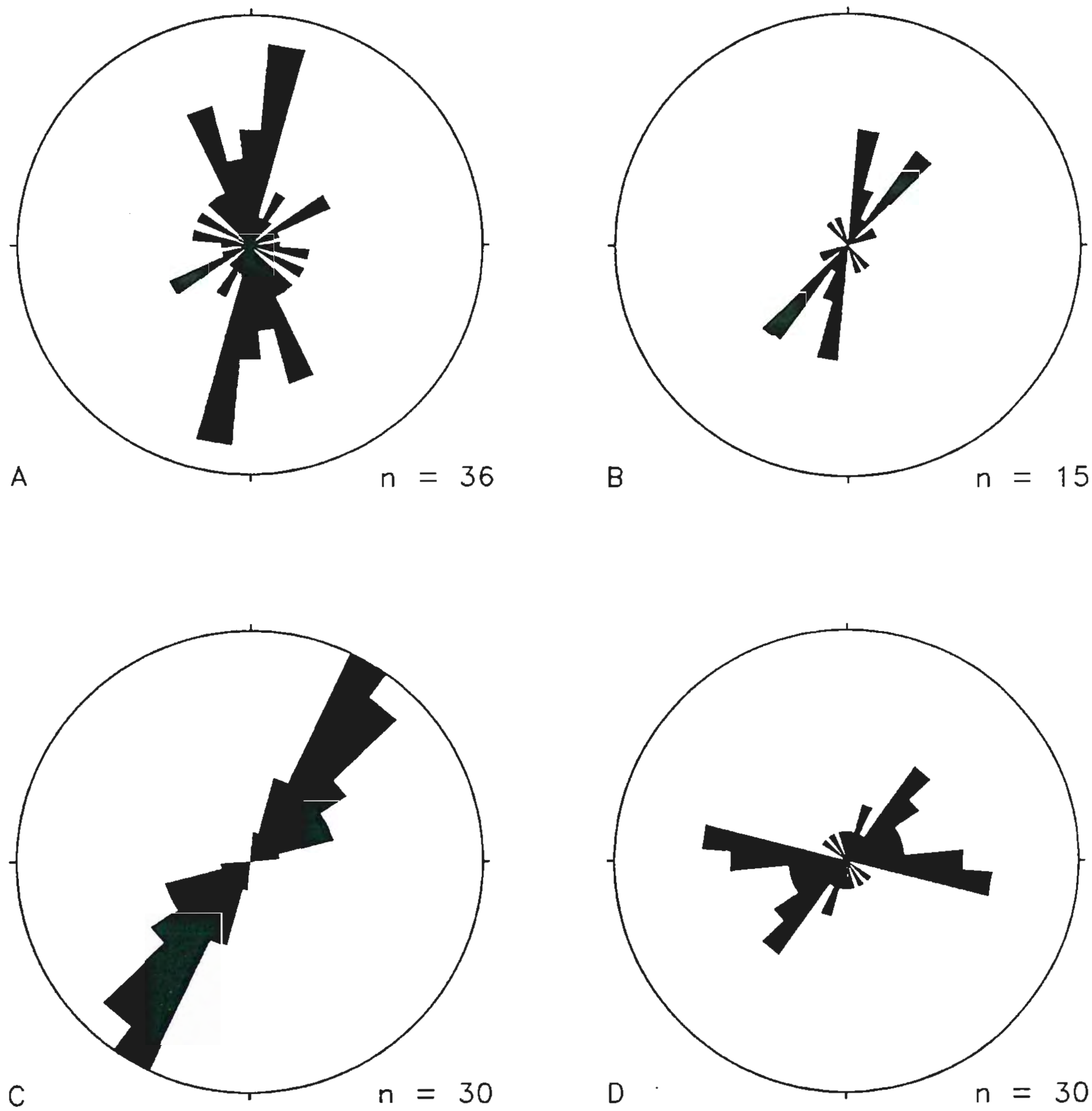


Figure 21. Orientation of elongate stones in the Granite Falls Till.

A - Rethke Farm Section	(121-47-13cbbb)
B - Exposure southeast of Dakota Rose Quarry	(120-47-20baab)
C - Nordick Farm Section, near falls	(120-46-20aacb)
D - Nordick Farm Section, midpoint	(120-46-20aacb)

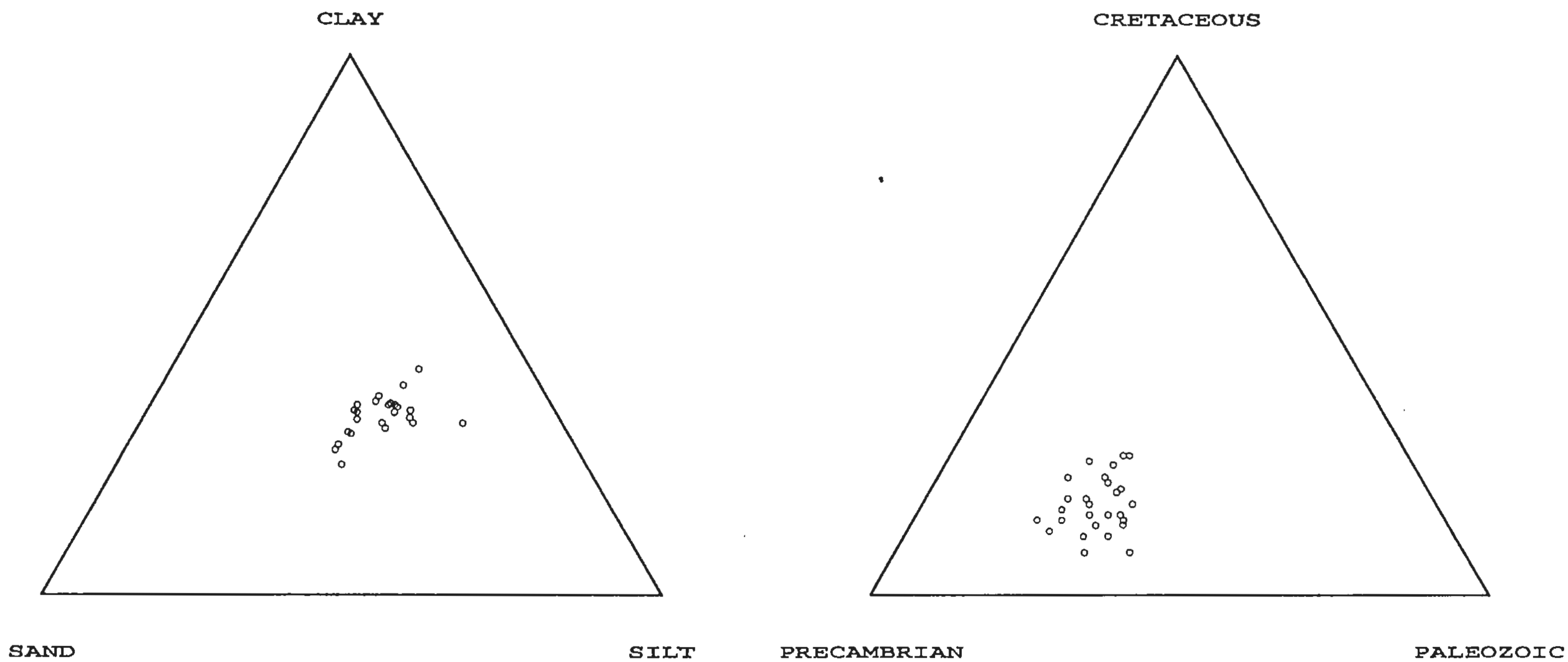
layers of interbedded sorted sediments are not uncommon. Unweathered Toronto Till is typically gray (10YR 5/1) if dry and dark olive gray (5Y 3/2) when wet. Oxidized till is pale yellow (2.5Y 7/4) when dry and light yellowish brown (10YR 6/4) if wet. Vertical joints are common, with joint surfaces stained reddish yellow (7.5YR 6/6) or yellowish red (5YR 5/8). Secondary carbonates and gypsum are found within the joints. In weathered exposures, the till is quite friable and does not support steep slopes. Surface exposures of the till are rare, and the till can best be characterized from material recovered from two cores taken in western Grant County (Cores C881 and C882, Appendix B).

The Toronto Till contains a moderate amount of pebbles and cobbles, and most are fairly well weathered. The till matrix contains from 16% to 39% sand, 34% to 52% silt, and 24% to 37% clay (Figure 22). The very-coarse sand fraction of the till is made up of 45% to 66% Precambrian lithologies, 24% to 38% Paleozoic rocks , and between 8% and 26% Cretaceous lithologies (Figure 22). Siliceous shale makes up approximately 70% of the Cretaceous fraction.

The base of the Toronto Till has not been identified in surface exposures. In test holes, this contact is readily identifiable by the rapid transition from unoxidized till to oxidized till or gravels associated with the underlying Drift Complex V. Core of this boundary shows a sharp contact with the subjacent material (Core C882).

In western Grant County, where the Toronto Till is at or near the surface, the upper contact is marked by a sharp transition to slightly younger Late Wisconsin loess or an erosional surface overlain by Holocene fluvial or colluvial sediments. Where the Toronto Till is overlain by the younger New Ulm Till or the till of the Dakota Moraine, the contact between the tills is difficult to identify. All three tills have similar matrix textures and very-coarse sand lithologies, and in the absence of distinct marker horizons, such as the sub-New Ulm boulder pavement or oxidized Toronto Till, the actual position of the contact cannot be determined.

The Toronto Till is found throughout the western half of Grant County and its distribution is roughly coincident with the Coteau des Prairies in the study area. No equivalent till is recognized in the eastern part of the County. The Toronto Till ranges in thickness from an average of 50 feet near the Day County Border to a maximum of about 120 feet underneath the Bemis Moraine. East of the Bemis moraine it is projected to thin to a feather edge near the eastern limit of the Coteau des Prairies (Figure 6).



(A) Matrix Texture

(B) V.C. Sand Lithologies

Figure 22. Matrix texture and very-coarse sand lithologies for the Toronto Till. (27 samples)

A) Average Sand : Silt : Clay = 28 : 38 : 33, with standard deviations of 6 : 5 : 4.
B) Average PreC : Palz : Cret = 55 : 28 : 17, with standard deviations of 5 : 4 : 5.

The Toronto Till is correlative with the Tazewell Till of northwestern Iowa (Ruhe, 1950; Kemmis and others, 1981), the shale-bearing extra-morainic till of Matsch (1972) in southwestern Minnesota, and the till of the Toronto Till Plain in eastern South Dakota (Lehr and Gilbertson, 1988). A possibly correlative unit, the Lac Qui Parle Till, has recently been recognized in isolated exposures in the Upper Minnesota River Valley, between Correll and Watson, Minnesota (Bratrud, in preparation).

Wood associated with the Toronto Till in South Dakota has yielded radiocarbon ages that span approximately 10,000 years. Wood collected from within the Toronto Till at an exposure in Grant County (Radiocarbon Section, Appendix C) had an age of 29,910 ± 1,100 yrbp (GX-14,675). Beissel and Gilbertson (1987) reported two samples recovered from the base of their Late Wisconsin I till (Toronto equivalent) in Hamlin County which yielded ages of 26,150 +3,000/-2,000 yrbp (GX-2864) and 22,900 ± 1,000 yrbp (GX-3439). Wood found beneath a glaciotectonically-disturbed block of Hawk Creek Till exposed near Big Stone City in Grant County produced an age of 20,670 +1,500/-1,000 yrbp (GX-2741) and was likely buried during this time (Clayton and Moran, 1982).

The Toronto Till was deposited by an ice lobe that advanced through western Minnesota, just east of or along the border with North and South Dakota. This trajectory is indicated by the relative abundance of Cretaceous lithologies, particularly the siliceous shales, in conjunction with Paleozoic carbonates. Sand and gravel is sometimes found interbedded with the Toronto Till in test holes in the area, suggesting a supra-glacial origin for at least some of this till. However, most of the till encountered in the test holes and in surface exposures is massive, indicating subglacial deposition.

New Ulm Till

The New Ulm Till (Matsch, 1972) is found at the surface over most of the eastern two-thirds of Grant County. It is a massive, calcareous pebbly clay loam. Unweathered New Ulm Till is gray (5Y 5/1) if dry and dark grayish brown (2.5Y 4/2) when wet. Weathered New Ulm Till is pale yellow (2.5Y 7/4) to pale olive (5Y 6/3) when dry and brownish yellow (10YR 6/6) to light olive brown (2.5Y 6/6) when wet. Vertical joints are common in exposures of the till. Joint surfaces are stained brownish yellow (10YR 6/8) and often host secondary minerals (carbonates and gypsum). The New Ulm

Till is hard and resistant in dry exposures and forms near vertical slopes (Figure 23). The thickest exposed sequence of New Ulm Till in the study area (38 feet) is in a drainage ditch adjacent to the North Fork of the Yellow Bank River, about 9 miles ESE of Milbank (T 120 N, R 46 W, Section 20 NE¼ NE¼ SW¼ NW¼, Nordick Farm Section, Appendix C).

Inclusions of massive to bedded sorted sediments are common. These may take the form of thin stringers, channel fillings, and deformed blocks. The sorted sediments are commonly found interbedded with layers of contorted till.

The New Ulm Till is relatively pebble-poor, compared with the various older tills in the area. The till matrix texture is highly variable, containing between 14% and 50% sand, 24% to 42% silt, and between 15% and 59% clay (Figure 24). Lithologic composition of the very-coarse sand is also quite variable. This fraction contains from 21% to 77% Precambrian lithologies, 11% to 32% Paleozoic rocks, and 5% to 60% Cretaceous lithologies (Figure 24). Siliceous shale (Late Cretaceous Pierre Shale) typically comprises greater than 90% of the Cretaceous fraction.

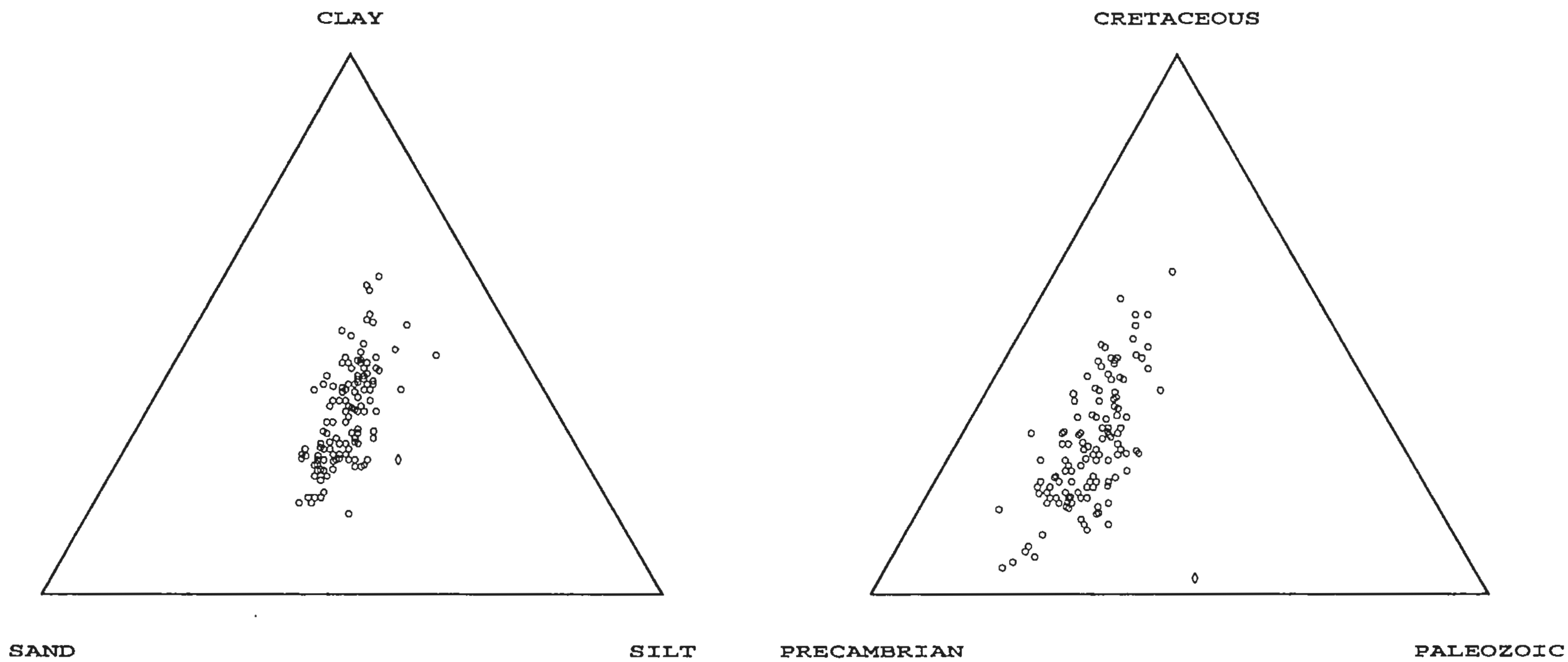
In his study of the New Ulm Till in the Minnesota River Valley, Matsch (1972) noted a systematic decrease in the Cretaceous shale content of the very-coarse sand fraction of the till away from the center of the Minnesota River Lowland (Figure 25). In general, this same pattern can be recognized in the New Ulm Till in the Grant County area (Figure 26), although local variability is more common than in southwestern Minnesota.

The New Ulm Till overlies a variety of older tills and Cretaceous bedrock in the study area. The contact with the underlying units is sharp and frequently marked by the presence of a one-stone-thick, faceted and striated boulder pavement (Figure 27). The pavement stones are made up of predominantly Precambrian crystalline rocks, but Paleozoic carbonates are not uncommon. Where the pavement is absent, a layer of shale-rich sand and gravel is commonly found. In places, subjacent materials show evidence of deformation related to the overriding of the Des Moines Lobe.

The New Ulm Till occurs at the surface in most eastern Grant County. In places however, the upper contact is marked by a sharp transition to younger Late Wisconsin and Holocene sorted sediments and/or colluvium.

Figure 23. Exposure of the New Ulm Till.

Total section is 60 feet high. Location: T 120 N, R 46 W, Section 20 NE¼ NE¼ SW¼ NW¼, Lac Qui Parle County.



(A) Matrix Texture

(B) V.C. Sand Lithologies

Figure 24. Matrix texture and very-coarse sand lithologies for the New Ulm Till. (131 samples)

A) Average Sand : Silt : Clay = 34 : 32 : 34, with standard deviations of 7 : 4 : 9.
B) Average PreC : Palz : Cret = 50 : 22 : 28, with standard deviations of 10 : 4 : 11.

Diamond marks the till of the Big Stone Moraine.

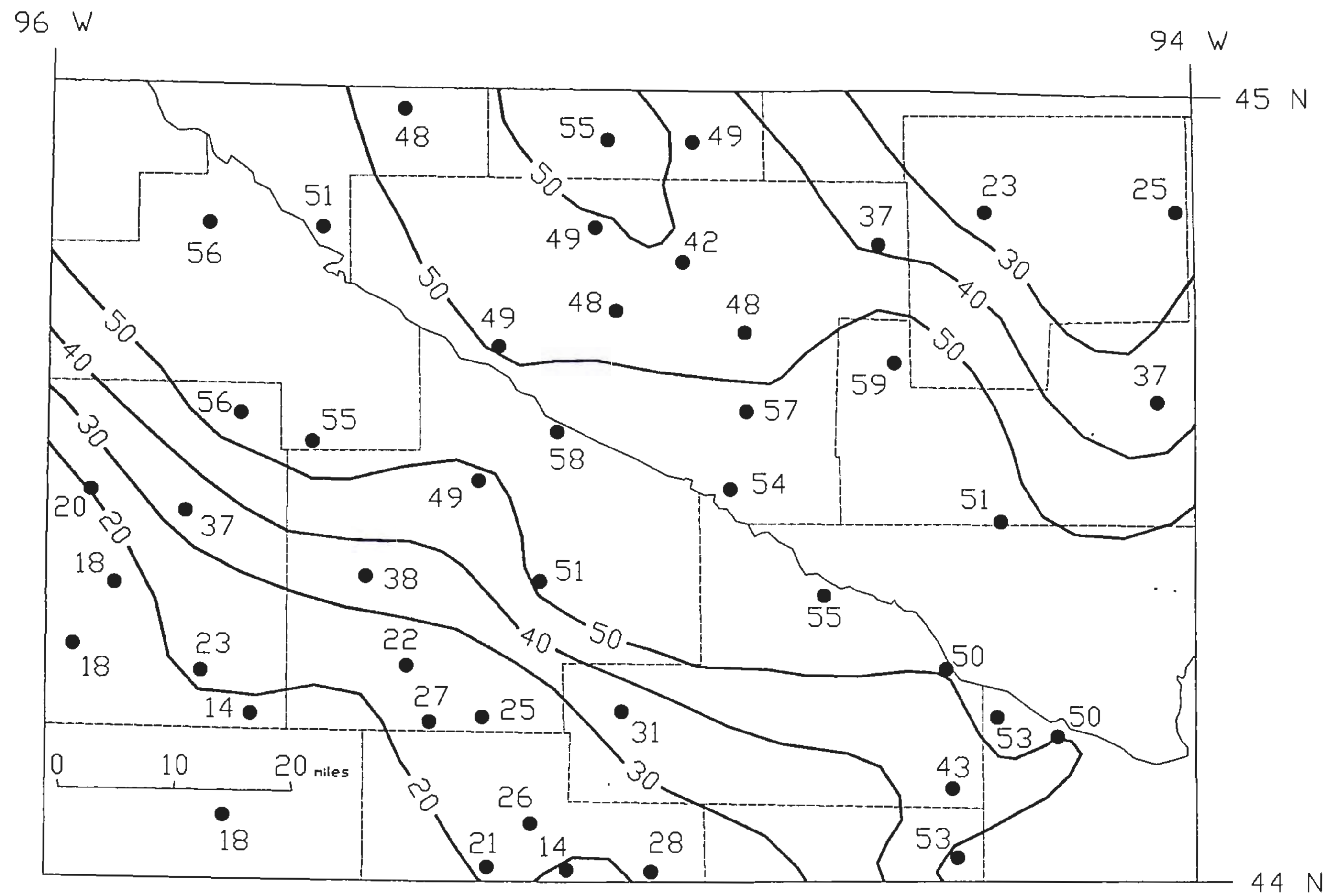


Figure 25. Distribution of shale (in percent) in the very-coarse sand fraction of the New Ulm Till in southwestern Minnesota. Contour interval = 10%. After Matsch, 1971.

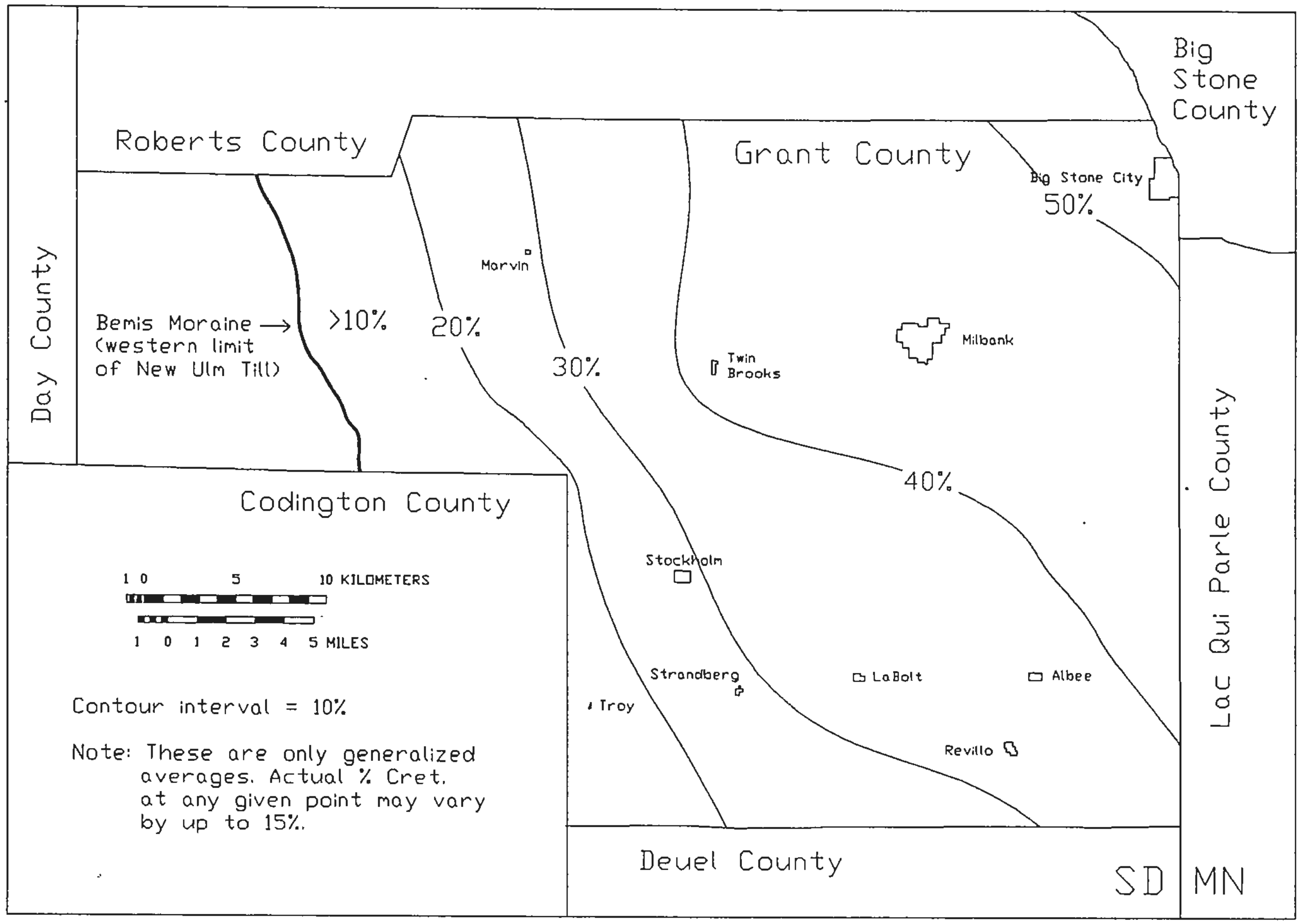


Figure 26. Distribution of Cretaceous lithologies in the very-coarse sand fraction of the New Ulm Till in the Grant County area.

A

B

Figure 27. Sub-New Ulm Till boulder pavement.

A) Distal view, New Ulm Till over older outwash.
B) Close-up view of single boulder, striae trend 156°.
Location: T 120 N, R 50 W, Section 04 NW¼ NW¼ NW¼ NW¼, Grant County.

The New Ulm Till rarely exceeds 20 feet in total thickness and in places has been totally removed by subsequent erosion. However, within the area bordered by the Altamont and Gary Moraines on the Coteau des Prairies, glaciotectonic stacking has resulted in accumulations of up to 100 feet of New Ulm Till.

The New Ulm Till found in the Grant County area and the Minnesota River Valley (Matsch, 1972) is correlated with other Late Wisconsin-aged, shale-rich tills throughout the area. Drift identified as the New Ulm Till has been recognized in Kandiyohi County in west-central Minnesota (Crum and Rust, 1986; Giencke and others, 1983/84) and in east-central Minnesota (Mooers, 1988). The New Ulm Till is correlative with the Dunvilla Formation of western Minnesota (Anderson, 1976; Perkins, 1977) and the Upper Red Lake Falls Formation in northwestern Minnesota (Harris and others, 1974). In Iowa, glacial sediments associated with the Des Moines Lobe are called the Dows Formation (Kemmis and others, 1981). The Dahlen Formation (Hobbs, 1975) and portions of the Cole Harbor Group (Clayton and others, 1980) in North Dakota also correlate with the New Ulm Till.

No material suitable for age determination has been recovered from the New Ulm Till in the Grant County area. However, radiocarbon analysis of wood found in association with similar tills in Minnesota and Iowa indicate that it was deposited between approximately 14,000 and 12,500 yrbp (Ruhe, 1969; Clayton and Moran, 1982).

The New Ulm Till was deposited by the Late Wisconsin Des Moines Lobe. The ice moved south along the Red River Lowland, then southeast down the Minnesota River Valley, incorporating significant quantities of Late Cretaceous lithologies, particularly the Pierre Shale. The high percentage of Pierre Shale in the New Ulm Till is the most diagnostic feature of this unit. Most exposures of the New Ulm Till show evidence of both sub-glacial and supra-glacial depositional environments.

The origin of the boulder pavement at the base of the New Ulm Till is not clearly understood. Matsch (1972) proposed a two-stage process of formation: (1) concentration of boulders by subareal erosion as a lag deposit on the older, relatively stony, Granite Falls Till; and (2) faceting and striating of the boulders by the later advance of the Des Moines Lobe. Ojakangas and Matsch (1982) attributed the pavement to the transport and lodgement of clasts in a soft, wet substrate (the Granite Falls Till), and then the subsequent overriding and erosion of the boulders, all by the Late Wisconsin Des Moines

Lobe. Stahman and Cotter (1985/86) identified elements of both modes of formation in a brief study of the boulder pavement in Grant and Roberts Counties, South Dakota. In all cases, the pavement was only recognized separating the New Ulm and Granite Falls Tills.

Several observations made during this investigation suggest that the dominant process of pavement formation was lodgement at the base of the Des Moines Lobe during deposition of the New Ulm Till. First, the boulder pavement marks only the base of the New Ulm Till. In the study area, it can be observed separating the New Ulm Till not only from the Granite Falls Till, but also the relatively stone-poor Hawk Creek (Figure 15b) and Whetstone Tills, as well as the Late Cretaceous Pierre Shale. Concentration of a sufficient number of boulders from these older units, particularly the Pierre Shale, is unlikely.

Second, the boulders that make up the pavement often show evidence of sub-glacial erosion prior to lodgement. The up-ice portions of elongate clasts are smooth and often striated, while down-ice ends are relatively ragged and plucked. They resemble bullet clasts commonly associated with lodgement till (Dreimanis, 1988).

Finally, directional indicators from pavement stones found along the flanks of the Coteau des Prairies record the progressive changes in the ice-flow directions of Des Moines Lobe (Figure 28). Along the sides of the Coteau des Prairies, elongate pavement stones are oriented toward the southwest. Faint striations and lunate fractures on the faceted surface of the stones indicate ice movement parallel to the long-axis orientation. This would indicate that the pavement stones were lodged and striated when the Des Moines Lobe first moved into the area. A second generation of striations, trending southeast, is superimposed over the older marks. These were likely produced when the Des Moines Lobe was at or near its maximum position (the Bemis Moraine?), and all ice movement within the Minnesota River Valley and along the flanks of the Coteau was to the southeast.

Till of the Dakota Moraine

In extreme western Grant County, deposits of the Late Wisconsin James Lobe are found in the form of the Dakota Moraine. Till contained within the moraine is a massive to weakly-bedded, calcareous, pebbly clay loam. It is pale yellow (2.5Y 7/4) if dry and

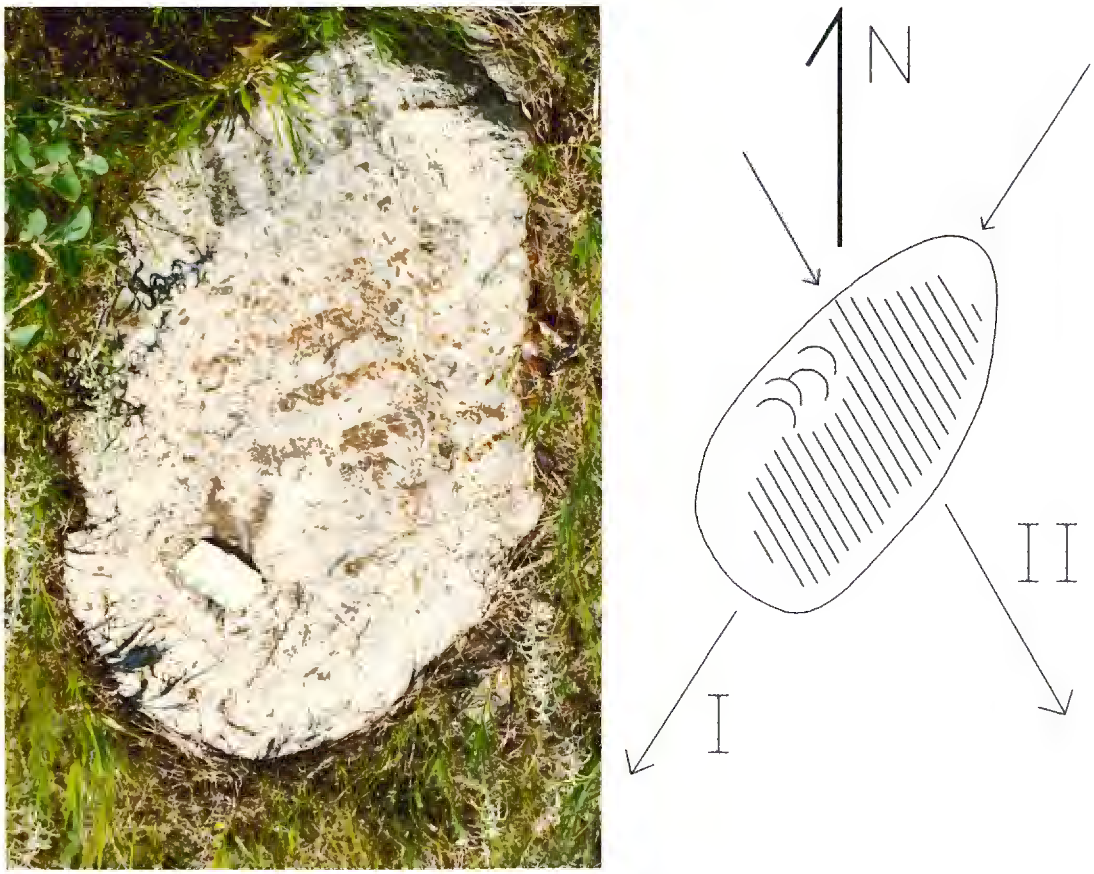


Figure 28. Pavement stone showing evidence of multiple ice flow directions.

Long axis of clast and lunate cracks indicate the initial direction of ice movement (I) was to the southwest, ~ 210°. Later movement to the southeast (II, ~ 150°) produced the abundant striations.

brownish yellow (10YR 6/6) when wet. It is found interbedded with sorted sediments. No unweathered till has been observed. It is best observed in a gravel pit in the moraine just west of the Day/Grant County line (T 121 N, R 53 W, Section 25 SE¼ NW¼ SE¼, Thurman Gravel Pit, Appendix C).

Cobbles and pebbles are common in the till of the Dakota Moraine. The till matrix contains on average 38% sand, 33% silt, and 29% clay (Figure 29). The very-coarse sand fraction has roughly 68% Precambrian clasts, 21% Paleozoic lithologies, and only 11% Cretaceous rock types (Figure 29). Siliceous shale makes up 65% of the Cretaceous fraction.

No exposed contact between this till and the underlying Toronto Till was found. In test holes, the contact is marked by sand and gravel layers and/or by a sharp transition to weathered Toronto Till. The till is at the surface over most of the Dakota Moraine area, although it may be covered by up to 18 inches of younger Late Wisconsin and Holocene loess and colluvium.

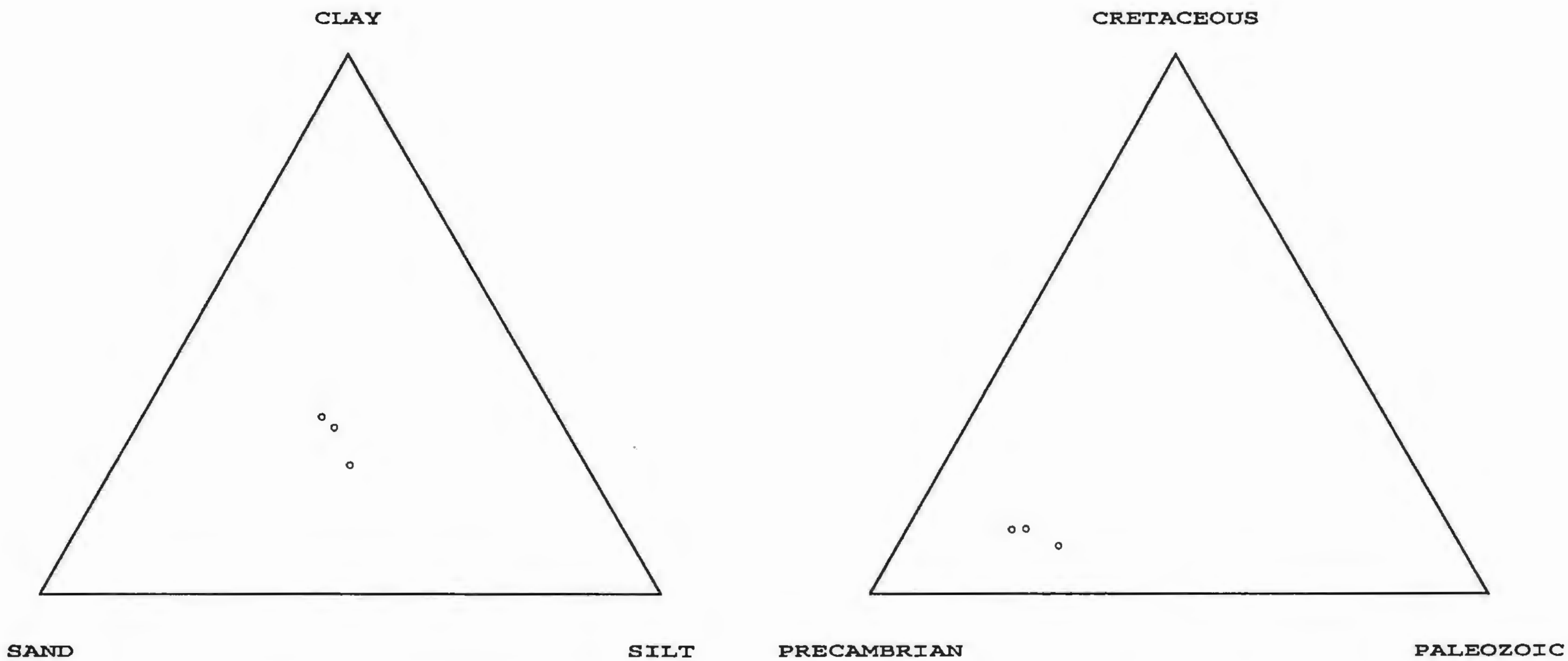
Till deposited by the Late Wisconsin James Lobe can be found at the surface over the western half of the Coteau des Prairies. Total thicknesses of over 150 feet have been encountered in Clark (Christensen, 1987) and Day (Leap, 1988) Counties, but test holes indicate only 15 to 20 feet of till occur in Grant County.

No formal stratigraphic descriptions of the glacial deposits of the James Lobe in South Dakota have been done. As only three samples of till were examined in this investigation, no correlation based on lithologic characteristics has been attempted.

The till within the Dakota Moraine was deposited during the maximum advance of the Late Wisconsin James Lobe (Leap, 1988; Steece and others, 1960), approximately 14,000 to 13,500 yrbp (Clayton and Moran, 1982). At the same time, the New Ulm Till was being deposited by the Des Moines Lobe on the eastern side of the Coteau des Prairies. In the study area, the till of the Dakota Moraine shows evidence of predominantly supra-glacial deposition.

Till of the Big Stone Moraine

The youngest till unit recognized in the study area is the till that makes up the Big Stone Moraine in extreme northeastern Grant County. It is a highly-calcareous,



(A) Matrix Texture

(B) V.C. Sand Lithologies

Figure 29. Matrix texture and very-coarse sand lithologies for the till of the Dakota Moraine. (3 samples)

A) Average Sand : Silt : Clay = 38 : 33 : 29, with standard deviations of 0 : 4 : 4.
B) Average PreC : Palz : Cret = 68 : 21 : 11, with standard deviations of 3 : 4 : 2.

pebbly silt loam that is light gray (2.5Y 7/2) if dry and very pale brown (10YR 7/3) when wet. Sorted sediments are frequently observed interbedded with the till. No substantial exposures (> 5 feet of exposed thickness) of the till are known in the area.

Pebbles are common in the till, with compositions split evenly between Paleozoic carbonates and Precambrian crystalline lithologies. The single sample analyzed had a matrix texture of 30% sand, 45% silt, and 25% clay (plotted with the data for the New Ulm Till, Figure 24). The relatively high silt content of this till is attributed to the incorporation of sediments deposited in a proglacial lake that existed prior to the advance to the Big Stone Moraine. The very-coarse sand fraction contained 46% Precambrian lithologies, 51% Paleozoic rocks, and only 3% Cretaceous lithologies (plotted with the data for the New Ulm Till, Figure 24). No siliceous shale was found in the Cretaceous fraction.

The base of the till is not exposed and has not yet been identified in rotary test holes. The nature of the contact with the underlying New Ulm Till is unknown. The till is presumed to be at the surface over most of the Big Stone Moraine, although in places it is covered by thin Late Wisconsin lacustrine sediments and Holocene colluvium.

The till of the Big Stone Moraine is correlated with the Barnesville Formation of west-central Minnesota (Anderson, 1976; Perkins, 1977). Both tills are characterized by a very-silty matrix and abundant carbonate in the very-coarse sand fraction.

The till of the Big Stone Moraine was deposited approximately 11,700 yrbp based on radiocarbon ages for wood associated with the Big Stone Moraine and related ice margins (Clayton and Moran, 1982; Mickelson and others, 1983).

The till that makes up the Big Stone Moraine was deposited by the Late Wisconsin Des Moines Lobe during the final period of glacial activity in the study area (Phase J of Clayton and Moran, 1982). Surface topography suggests that most of the till was deposited as superglacial sediments.

Glaciofluvial and Glaciolacustrine Sediments

Sorted sediments of Late Wisconsin age are found at the surface throughout the Grant County area as the result of various types of glaciofluvial and glaciolacustrine activity.

In Grant County, outwash deposits consist of massive to cross-bedded sands and gravels. Interlayered finer materials, mostly silt, are common. Quartz dominates the sand fraction, with Precambrian crystalline lithologies and Paleozoic carbonates making up the majority of the gravels. Clasts of Cretaceous rocks, mostly siliceous shale, are common and often concentrated in discreet layers within the sediments.

Outwash deposits range in thickness from less than 2 to over 80 feet. The base of the deposits is marked by a sharp to gradational boundary with subjacent units. In general, a fining-upward sequence can be recognized within any given section. The upper contact of most deposits is marked by a sharp to gradational boundary with overlying Holocene alluvium.

Most outwash deposits in the area formed as a result of the activities of the Des Moines Lobe as it was depositing the New Ulm Till and the till of the Big Stone Moraine. Meltwaters from the James Lobe during the construction of the Dakota Moraine also contributed sediments. As such, the bulk of the outwash in the area was deposited between 14,000 and 11,700 yrbp. Some older deposits, related to the Toronto Till, are found in the western part of the County.

Thin, discontinuous deposits of glaciolacustrine sediments are found over the Grant County area east of the Coteau des Prairies (Miller, 1979). The sediments are primarily silt and fine sand, with some coarser sand and fine gravel. Bedding is usually poorly developed, and no clear varves have been observed. The lacustrine sediments were deposited in a series of short-lived proglacial and ice-marginal lakes formed by meltwaters from the receding Des Moines Lobe.

Holocene Deposits

Sediments of Holocene age in the Grant County area consist of alluvium associated with modern stream valleys and colluvial sediments found along moderate to steep hillslopes.

Alluvium in the area is commonly a mixture of poorly- to well-sorted sand, silt, clay and organic material. Bedding is often visible, with sharp to gradational boundaries. The thickest deposits, up to 5 feet, occur along the Big Sioux and Whetstone Rivers, but over most of the area it rarely exceeds 2 feet in thickness. As such, alluvium is typically not a mappable unit in eastern South Dakota (Christensen, 1987).

Thin colluvial deposits can be recognized in areas with moderate to steep local relief, particularly along the eastern edge of the Coteau des Prairies. They are composed of unsorted to weakly-bedded, locally derived material and rarely exceed a few feet in thickness.

Relative Dating Using Amino Acids

Recent investigations have demonstrated the usefulness of amino acid analyses of wood, specifically aspartic acid D/L ratios, as a correlation tool in Quaternary sediments (Karrow and Rutter, 1988; Rutter and Crawford, 1984). It is particularly helpful when dealing with samples that are beyond the range of conventional radiocarbon dating, as meaningful amino acid racemization ratios can be obtained from material up to several million years in age (Bradley, 1985). A complete discussion of the principles behind amino acid dating techniques is beyond the scope of this report. Interested readers are referred to an excellent summary prepared by Bradley (1985).

A total of 18 samples of organic material, mostly wood, were submitted for amino acid analyses (Table 3). The analyses were conducted with two purposes in mind. First, to determine whether aspartic acid D/L ratios could be used in stratigraphic correlation and the relative age dating of Quaternary deposits in Grant County and adjacent areas. Second, to indirectly determine the age of older organic materials by extrapolating a curve of from known ^{14}C and aspartic acid D/L values to samples for which only aspartic acid values are known. Of particular interest in this case are aspartic acid D/L ratios from the organics found beneath the Yellow Bank Till.

To test the applicability of aspartic acid D/L ratios as a correlation tool, wood samples collected from the Gastropod Silts at three locations in the Minnesota River Valley and from the Gervais Formation in northwestern Minnesota. Both units are organic-rich lacustrine deposits that occur beneath very sandy, northeastern source tills. Like the Gastropod Silts in the study area, the Gervais Formation is thought to have been deposited either during Early Wisconsin or Late Illinoian time (Ashworth, 1980). Aspartic acid D/L ratios derived from the Gastropod Silts and the Gervais Formation

Table 3. Amino acid analyses - Aspartic acid D/L ratios.

Sample #	Location	D/L Ratio	Known age (yrbp)[1]	
Des Moines Lobe:				
B-7398	Iowa	0.2417	7,750 ± 70	(Beta-7398)
V-891	South Dakota	0.314	12,220 ± 120	(Beta-30,559)
W-1756	"	0.270	12,340 ± 300	(W-1756)
W-1757	"	0.230	12,680 ± 300	(W-1757)
IA-DF1	Iowa	0.234	approx. 14,000	
Toronto Advance:				
CG-88-W3	South Dakota	0.105	29,990 ± 1160	(GX-14,675)
Gastropod Silts:				
CG-86-W5	South Dakota	0.094	140,000 ± 7,000	(GL-540)
CG-88-W1	"	0.2488	"	
CG-88-W2	"	0.2285	"	
CG-88-W4	"	0.305	"	
CG-86-W3	Minnesota	0.3017	>56,000	(QL-4151,4152)
AA88-03	"	0.4382	?	
Gervais Formation:				
AA88-01	Minnesota	0.2436	>49,900	(Birm-522)[2]
AA88-02	"	0.2383	"	
Sub-Yellow Bank:				
CG-86-C1	South Dakota	0.538	?	
CG-86-C2	"	0.501	?	

(1 - radiocarbon age of sample submitted for aspartic acid analysis, except for GL-540, which is a finite date from amino acid analysis.
(2 - from Ashworth, 1980)

==

were quite similar, with most ranging between 0.23 and 0.31 (Table 3). These ratios are similar to those from comparably-aged deposits in the region (Nielsen and others, 1986). The two anomalous values (CG-86-W5 and AA88-03) were from samples collected as float, and were likely contaminated. It would appear that aspartic acid analysis of wood would be a useful correlation tool for sediments in the area.

In an effort to establish a curve by which approximate ages of older organics could be calculated, aspartic acid D/L ratios were determined for six samples of previously dated wood. The samples ranged in age from 7,750 to 29,910 yrbp. Four of the samples were collected at various points in eastern South Dakota and two were supplied by Art Bettis of the Iowa Geological Survey.

Unfortunately, all but the oldest sample (CG-88-W3) produced suspect results. Aspartic acid D/L ratios for Late Wisconsin to Early Holocene aged material are typically in the range of 0.05 to 0.10 (Rutter and Crawford, 1984). In this study, ratios typical of much older (Sangamon?) deposits were produced (Table 3). Similar, anomalous results were found for comparably aged material in southern Manitoba (E. Nielsen, 1989, written communication). No explanation for these results has yet been determined.

Figure 30 is an attempt to approximate the age of the sub-Yellow Bank organics based on the single 'good' Late Wisconsin sample and aspartic acid D/L ratios from the Gastropod Silts. As noted earlier in the text, the Gastropod Silts are thought to be Late Illinoian in age. An age of 135,000 yrbp was arbitrarily assigned to the unit and an average D/L ratio determined for the samples. There are now two points by through which a line can be drawn. Using a projection of this line, organics found beneath the Yellow Bank Till (aspartic acid D/L ratios of 0.501 and 0.538) were deposited about 300,000 yrbp during the Early Illinoian glaciation (Richmond and Fullerton, 1986).

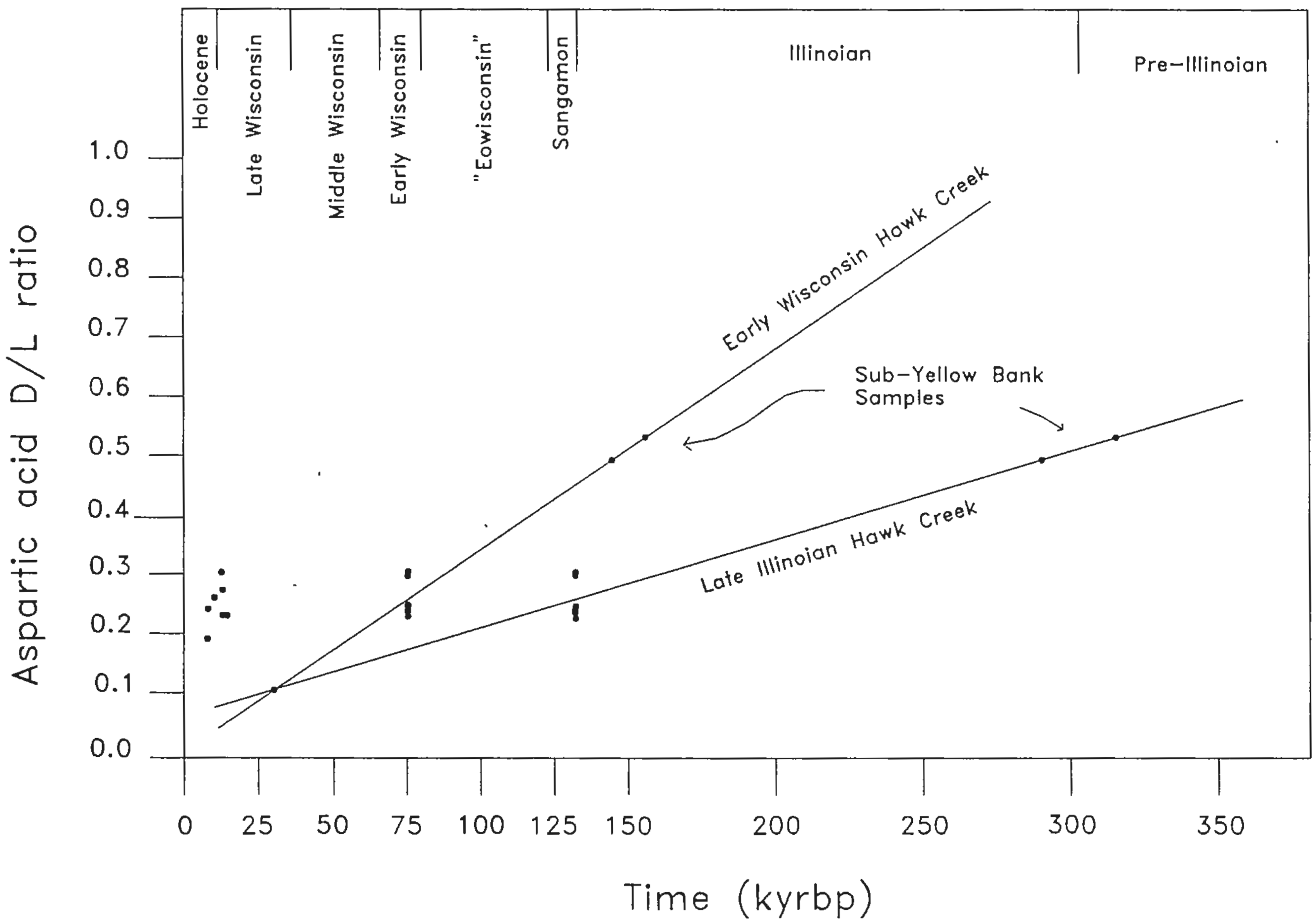


Figure 30. Plot of aspartic acid D/L ratios vs. known or inferred ages of wood from study area.

GEOMORPHOLOGY

The Grant County area can be divided into six distinct geomorphic sectors, each associated with a specific phase of Late Wisconsin glacial activity or ice lobe (Figure 31). From west to east they are the Dakota Moraine, the Toronto Till Plain, the Bemis Moraine Complex, the Altamont-Gary Moraine Complex, the Minnesota River Valley, and the Big Stone Moraine.

Dakota Moraine

The Dakota Moraine represents the eastern-most extent of the Late Wisconsin James Lobe. It is found only along the western edge of the study area. In Grant County, it covers about three square miles (Figure 31) and has an average elevation of over 1900 feet.

The terminal position of the James Lobe is marked by a single, sharp, nearly-continuous, asymmetric morainic ridge roughly 1/2 mile wide (Figures 32 & 33). The distal, or east-facing, segment of the moraine is relatively steep, whereas the proximal slope is more gentle. The crest of the moraine stands about 50 feet above the Toronto Till Plain to the east. Behind the moraine is a broad area of kame-and-kettle topography, which extends to the edge of the Coteau des Prairies, approximately 35 miles to the west (Leap, 1988). In several locations the moraine is breached by meltwater channels that lead to the Big Sioux River.

Sediments exposed in a gravel pit in the distal face of the Dakota Moraine record the advance of the James Lobe to this position (Figure 34). At the base of the section are a series of bedded, gravelly sands (Unit I), deposited when the ice was still some distance to the west. These sediments grade upward into coarser sands and gravels (Unit II), indicative of a more proximal source. Overlying these sediments are interbedded cobble gravels and pebbly tills (Unit III) interpreted as debris flows off an adjacent ice front. Maximum ice advance is marked by a discontinuous layer of massive till (Unit IV) deposited as the ice overrode the earlier sediments. A boulder lag (Unit V) was likely developed by meltwater winnowing of older units as the ice stagnated. A thin layer of loess (Unit VI) caps the section.

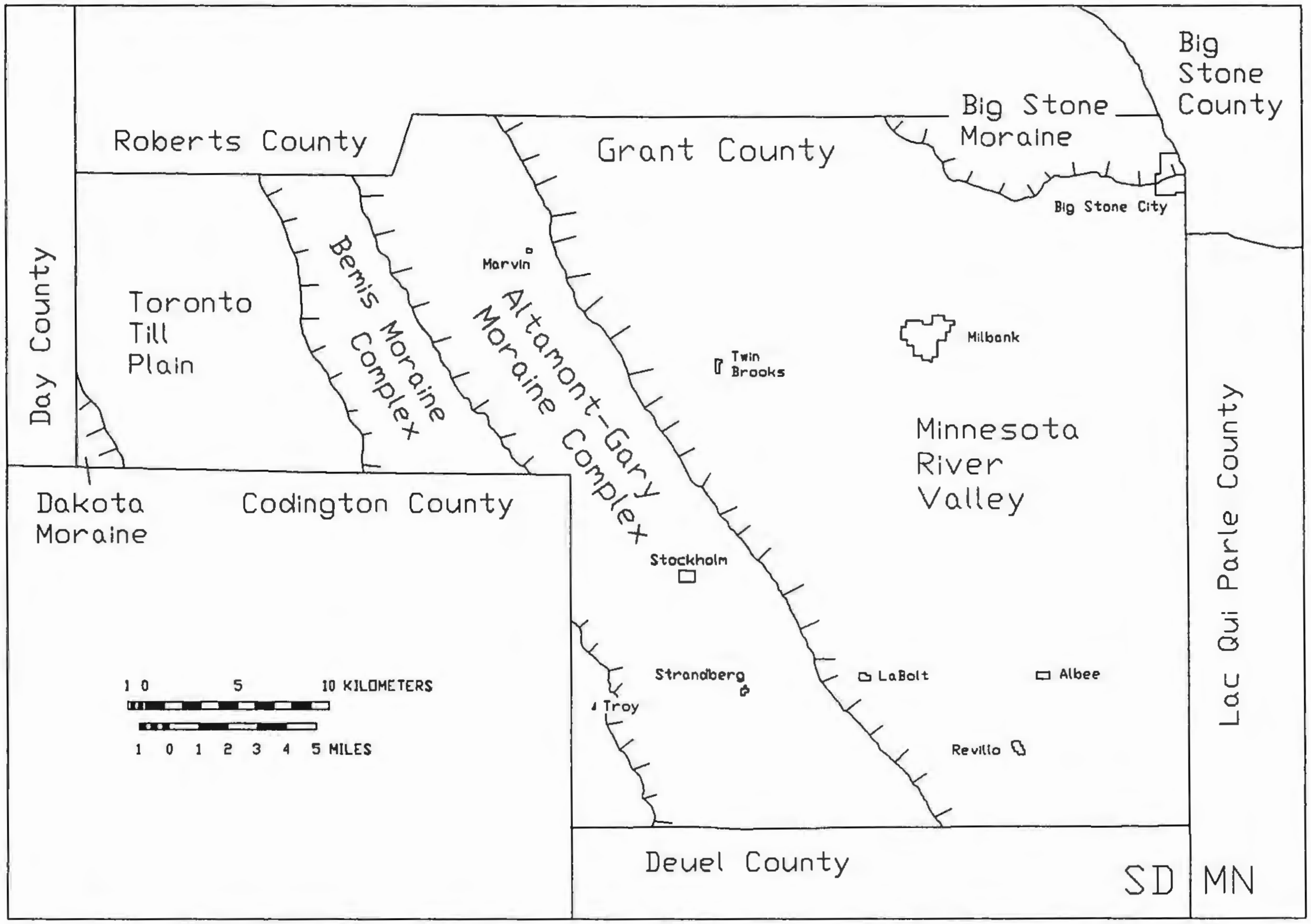


Figure 31. Major geomorphic divisions of Grant County.

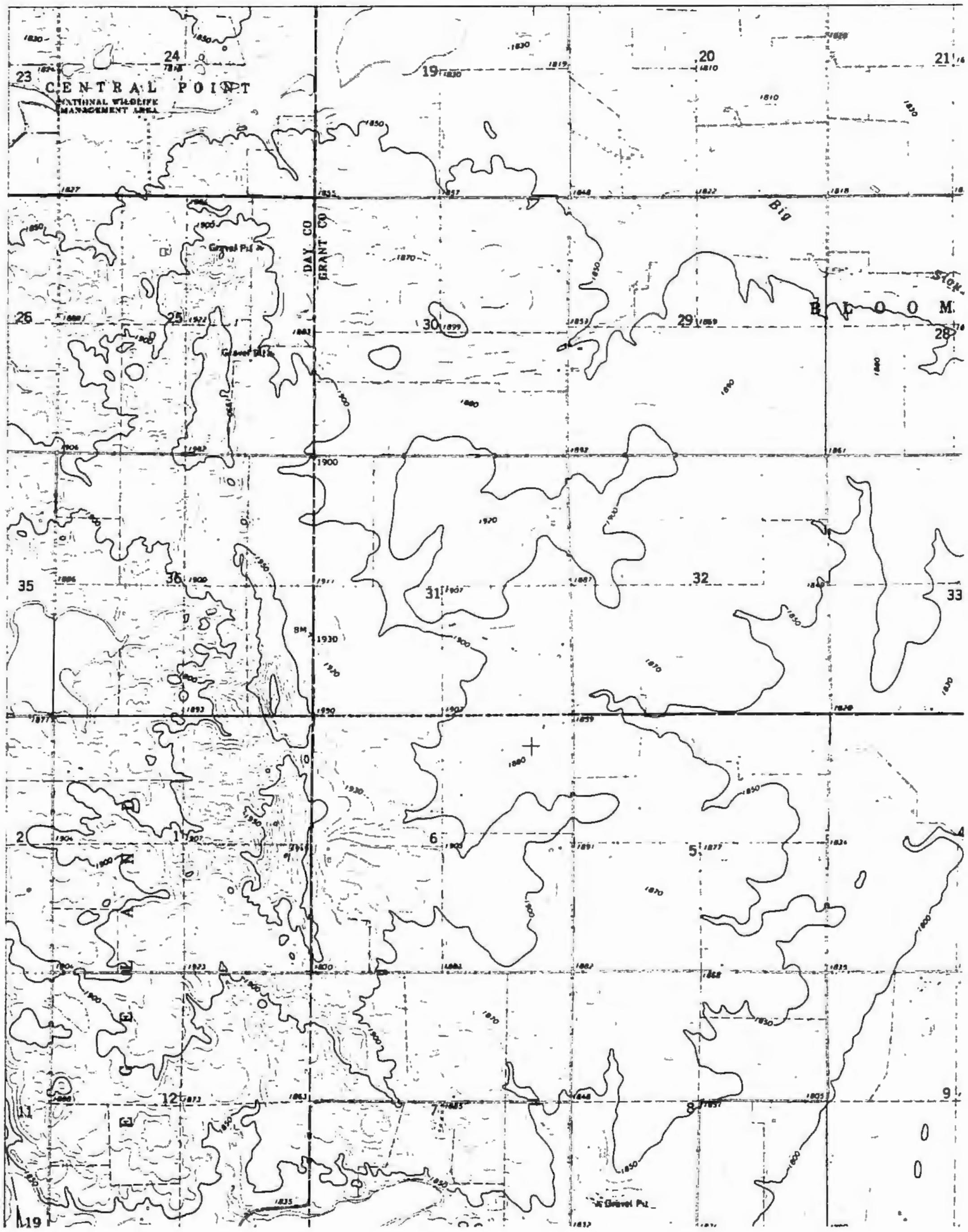


Figure 32. Topographic expression of the Dakota Moraine.

Part of the Lonesome Lake 7½-minute topographic quadrangle, Grant and Day Counties.

Figure 33. Ground-level view of the Dakota Moraine.

View is to the south. Note the smooth surface of the Toronto Till Plain in the upper-left corner of photograph. Location: T 121 N, R 53 W, Section 25 SE¼ NE¼ Res., Day County.

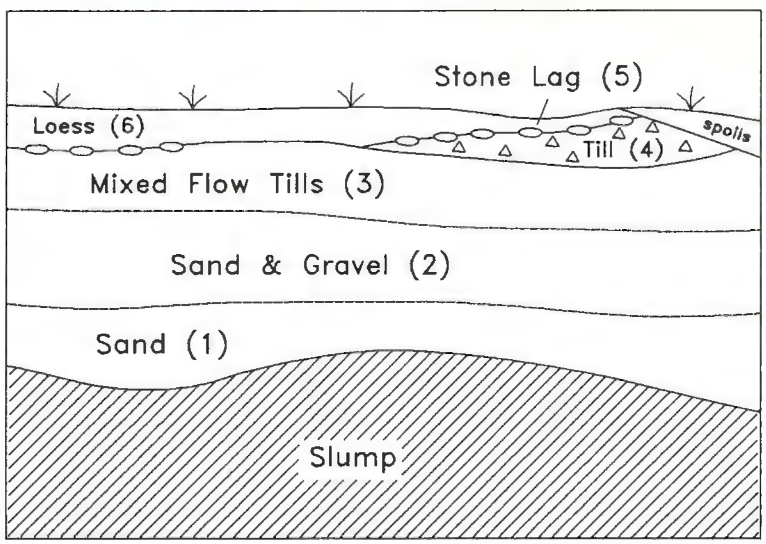


Figure 34. Exposure of the distal portion of the Dakota Moraine.

Units described in text. Location: T 121 N, R 53 W, Section 25 SE¼ NE¼ Res., Day County.

Further evidence of glacial activity can be seen in a dugout on the proximal slope of the moraine. Here, in a section oriented parallel to ice flow, a series of low-angle reverse faults (thrusts) can be observed in the till of the Dakota Moraine.

The asymmetric profile of the moraine, the evidence of intense shearing on the proximal slope, and the overriding of the distal margin suggest that the Dakota Moraine originated as a push moraine (Andrews, 1975; Goldthwait, 1988).

Toronto Till Plain

The Toronto Till Plain (Lehr and Gilbertson, 1988) is the oldest geomorphic surface in the area. In Grant County, it covers an area of approximately 76 square miles. It is bounded on the west by the Dakota Moraine and on the east by the Bemis Moraine (Figure 31). This surface is underlain for the most part by the Toronto Till. Total relief over the area is about 250 feet (1800 to 2050 feet in elevation), although local relief rarely exceeds 100 feet.

The surface of the Toronto Till Plain is best characterized by its well-developed drainage network and a general absence of any constructional landforms (Figure 35). The Big Sioux River provides the local base level for numerous permanent and intermittent streams that cut across the landscape. Several large stream valleys can be traced back to the margins of moraines of later ice advances. These drainages served as conduits for meltwaters when ice was at those positions, but they now contain underfit streams. Broad interfluves separate the drainages.

Loess can be found immediately overlying the Toronto Till throughout the area. Up to 5 feet of loess is preserved near the crests of the interfluves along the Big Sioux River, but it thins to less than a foot near the Bemis Moraine.

The topographic expression of the Toronto Till Plain is the result of extensive subareal erosion subsequent to the deposition of the Toronto Till between 30,000 and 20,000 yrbp. Beissel and Gilbertson (1987) attribute the advanced state of drainage development on this surface to the close proximity to the local master stream (the Big Sioux River) and the numerous meltwater channels that cross the surface. No point on the till plain is more than a few miles from one of these drainageways, and it is not unreasonable to assume that a well integrated stream network would develop rapidly in

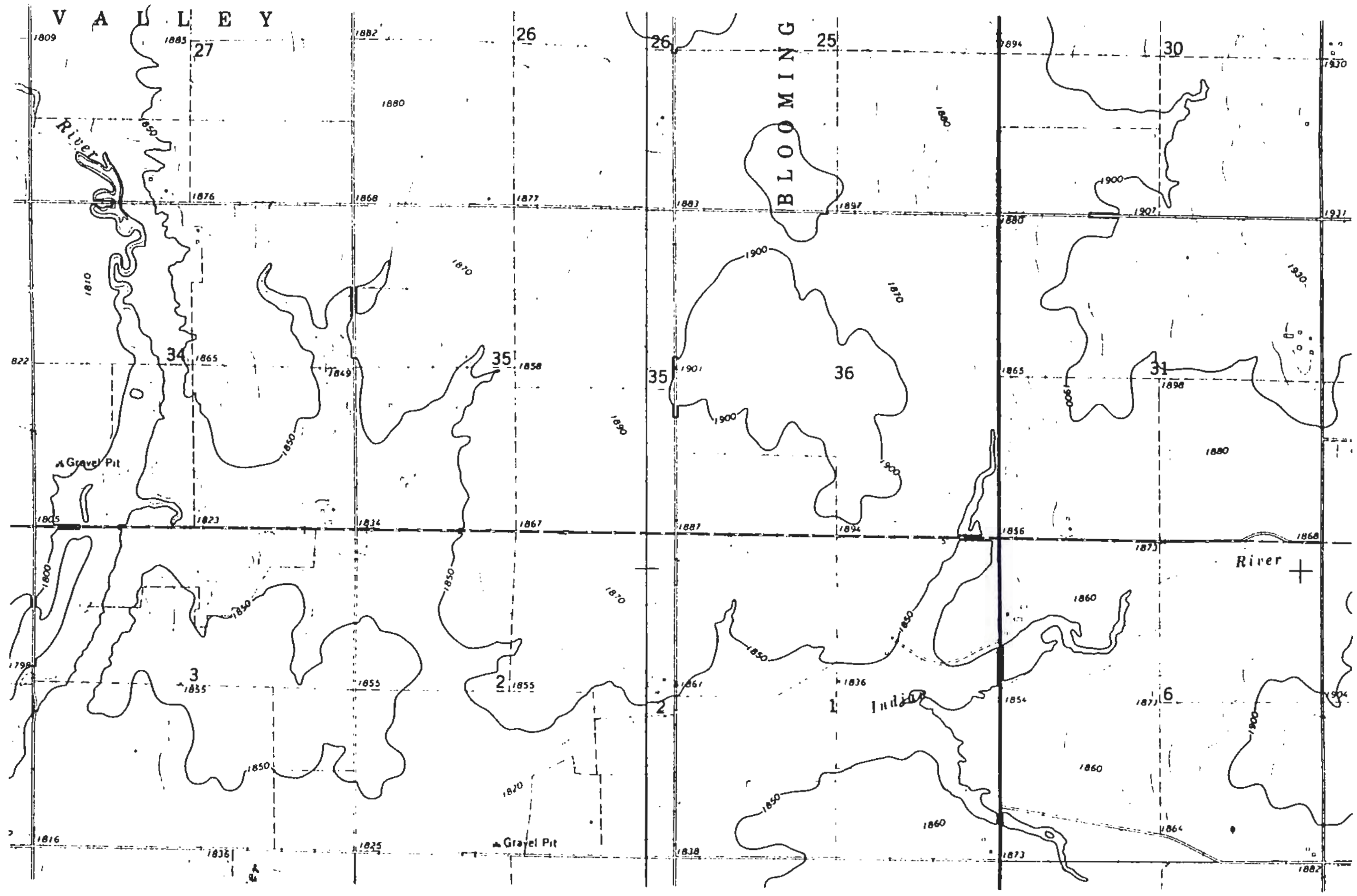


Figure 35. Topographic expression of the Toronto Till Plain.

Composite of parts of the Lonesome Lake and Still Lake NE 7½-minute topographic quadrangles, Grant County.

this area. By comparison, drainage development has proceeded much more slowly in the areas covered by the somewhat younger Des Moines Lobe and James Lobe sediments, where similar drainageways do not exist.

Bemis Moraine Complex

The Bemis Moraine Complex is composed of two elements. A narrow ridge (the Bemis Moraine) that marks the oldest and western-most advance of the Des Moines Lobe. To the east of this ridge is a belt of related ground moraine. The Bemis Moraine Complex is bounded on the west by the Toronto Till Plain and on the east by the Altamont-Gary Moraine Complex (Figure 31). It covers about 33 square miles in Grant County. Elevations within the complex range between 1950 and 2060 feet, making this the highest ground in the study area.

The Bemis Moraine in Grant County is a narrow (less than ¼ mile wide), discontinuous, morainic ridge composed of predominantly ice-contact stratified sands and gravels (Figures 36). The crest of the moraine rarely rises more than thirty feet above the surrounding landscape and is commonly covered with large cobbles and boulders. Where a well-defined ridge is absent, the position of the ice margin is marked by a lag concentration of boulders on the surface (Figure 37).

Numerous small drainages head at the distal edge of the Bemis Moraine. These originated as meltwater conduits when the ice was at this position. Most start out as ice-marginal channels, and then turn to flow to the southwest across the Toronto Till Plain, where they connect with the Big Sioux River. Thin (less than 5 feet thick) outwash deposits are commonly associated with these drainageways. Broad outwash aprons are found fronting the moraine where it crosses upland surfaces on the Toronto Till Plain (Figure 36).

Behind the moraine is an area of low-relief, irregular hummocky topography (Figure 36). On average, relief rarely exceeds 20 feet. This surface is composed of a layer of New Ulm Till and related sorted sediments mantling the Toronto Till Plain. These deposits are believed to be quite thin (less than 15 feet) as they only rarely mask the older topography. A fairly well-integrated drainage network has developed over most of this surface, which in most cases merges to the west with that of the Toronto Till Plain.

Figure 36. Topographic expression of the Bemis Moraine Complex.

Part of the Bemis 7½-minute topographic quadrangle, Deuel County.

Figure 37. Ground-level view of typical Bemis Moraine in the Grant County area.

Position of the moraine marked by discontinuous concentration of boulders. Location: T 121 N, R 51 W, Section 07 SE¼ NE¼ Res., Grant County.

The Bemis Moraine was formed when the Des Moines Lobe advanced to its maximum position in Iowa about 14,000 years ago (Ruhe, 1969). The Bemis Moraine was produced by the accumulation of supraglacial sediments along the margin of the ice and could be classified as a dump moraine (Andrews, 1975; Embleton and King, 1975). The scattered areas of kame-and-kettle topography found behind the Bemis moraine are the result of the stagnation of debris-rich supraglacial ice.

Altamont-Gary Moraine Complex

The Altamont-Gary Moraine Complex is a broad belt of predominantly high-relief, hummocky topography that occurs along the eastern edge of the Coteau des Prairies (Figure 31). Its western limit is marked by the contact between the low-relief stagnation moraine of the Bemis Moraine Complex and a series of coalescing outwash fans that head at the Altamont Moraine. The eastern limit of this zone is coincident with the eastern edge of the Coteau des Prairies and is marked by an abrupt transition to the lower elevations and low relief topography of the Minnesota River Valley. This assemblage of landforms covers about 180 square miles in Grant County.

Elevations within the complex decrease from west to east, dropping from an average of 2000 feet along the crest of the Altamont Moraine to approximately 1500 feet at the Gary Moraine. Within the complex, local relief often exceeds 75 to 80 feet. The New Ulm Till comprises the bulk of the surface sediment within the complex, with test holes typically encountering over 100 feet of drift throughout the area.

In this study, the term Altamont Moraine is applied only to western-most portion of this complex. In this segment, individual morainic ridges and ice-contact slopes are oriented roughly northwest-southeast, parallel to the inferred margin of the Des Moines Lobe (Figures 38 & 39). An extensive apron of collapsed outwash comprises the distal portion of the moraine.

To the east of the Altamont Moraine is a three- to four-mile-wide band of high-relief hummocky topography. Irregularly shaped hills and kettle holes abound, along with linear ridges that are typically randomly oriented (Figures 40 & 41). Numerous deeply-incised streams traverse this area but, in general, drainage is poorly developed. Ice-walled lake plains are common (Figure 42).

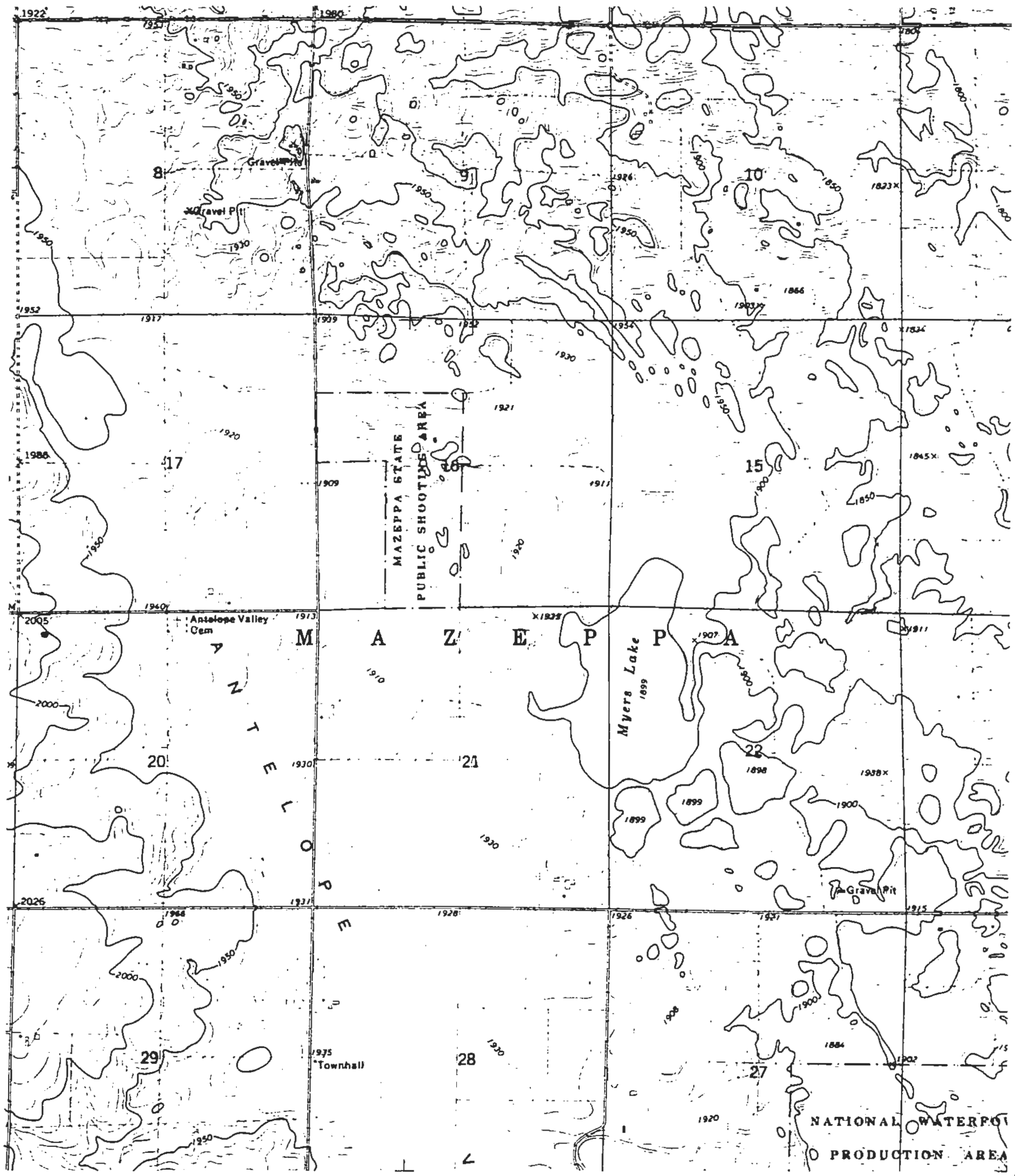


Figure 38. Topographic expression of the Altamont Moraine.

Part of the Antelope Valley 7½-minute topographic quadrangle, Grant County.

Figure 39. Areal view of the linear ridges that comprise the Altamont Moraine.

View is to the southwest. Note the subdued Bemis Moraine Complex surface in the distance.

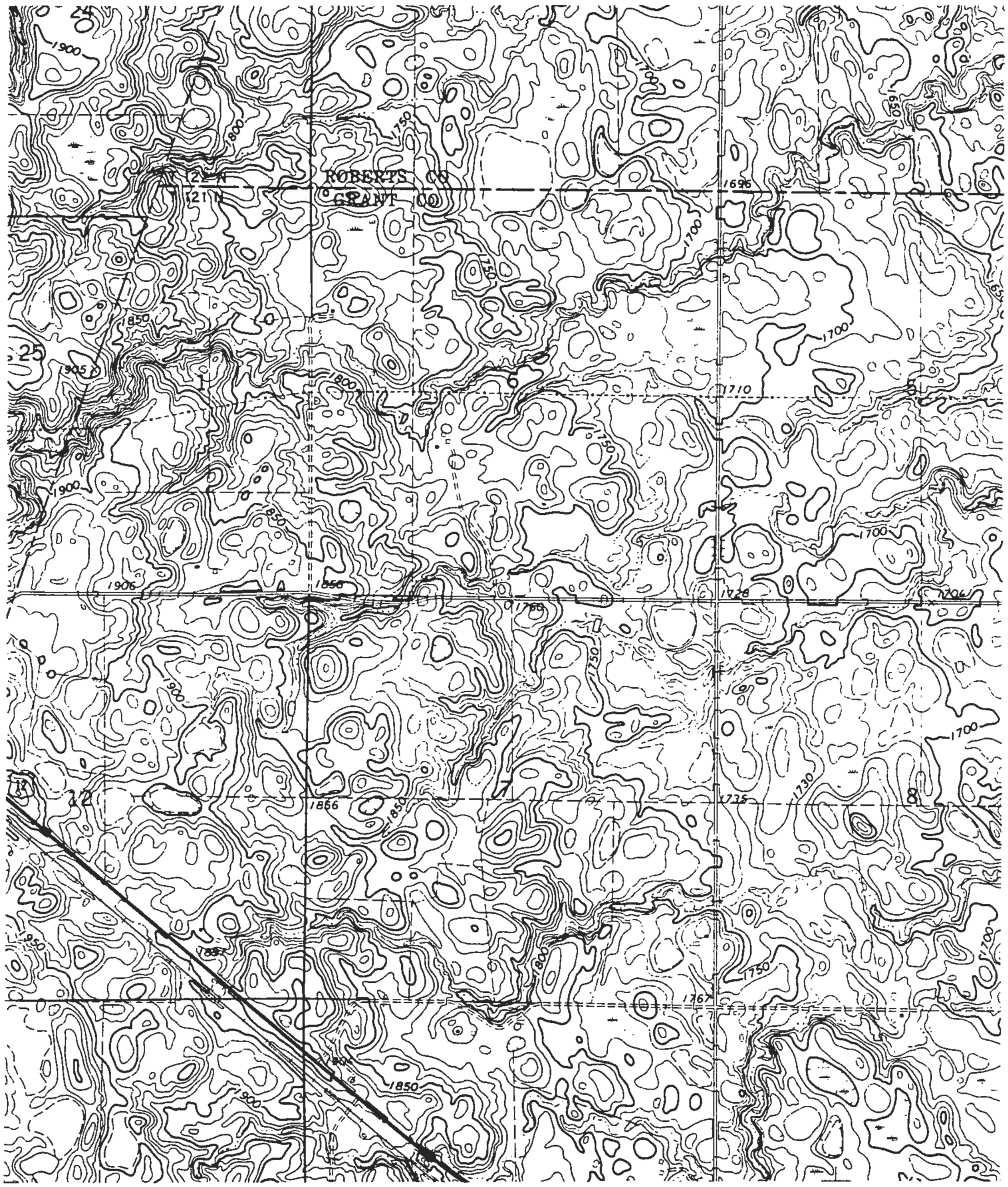


Figure 40. Topographic expression of the stagnation moraine within the Altamont-Gary Moraine Complex.

Part of the Marvin 7½-minute topographic quadrangle, Grant County.

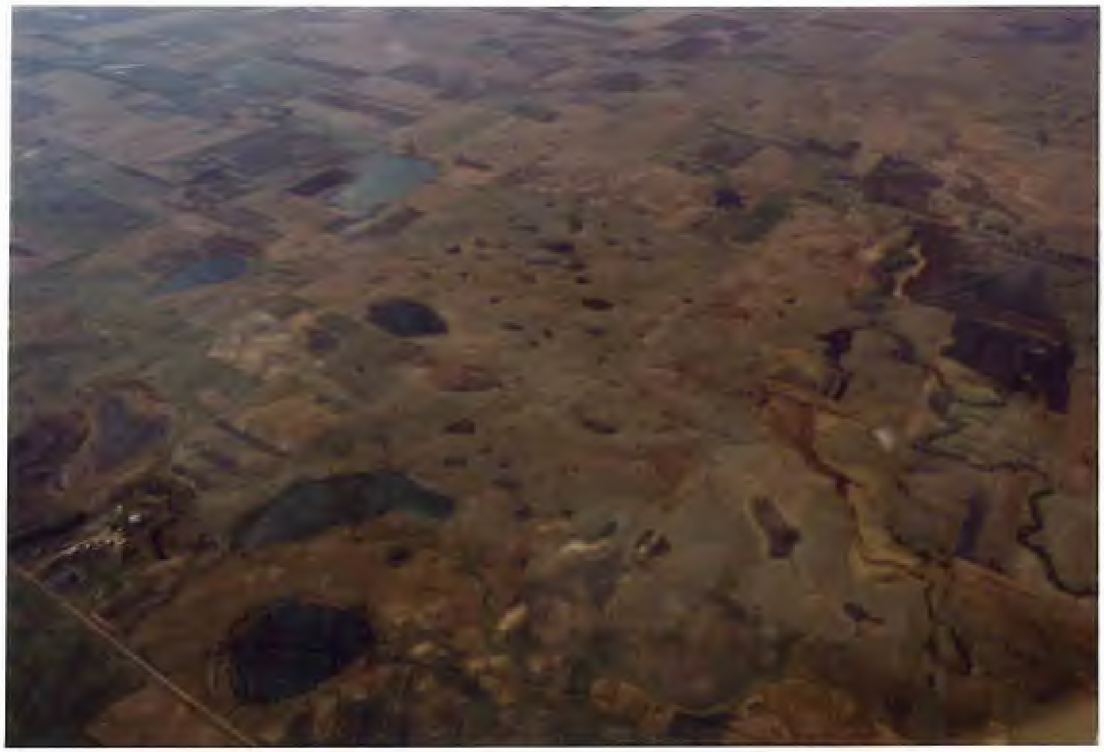


Figure 41. Areal view of stagnation moraine within the Altamont-Gary Moraine Complex. View is to the northwest.

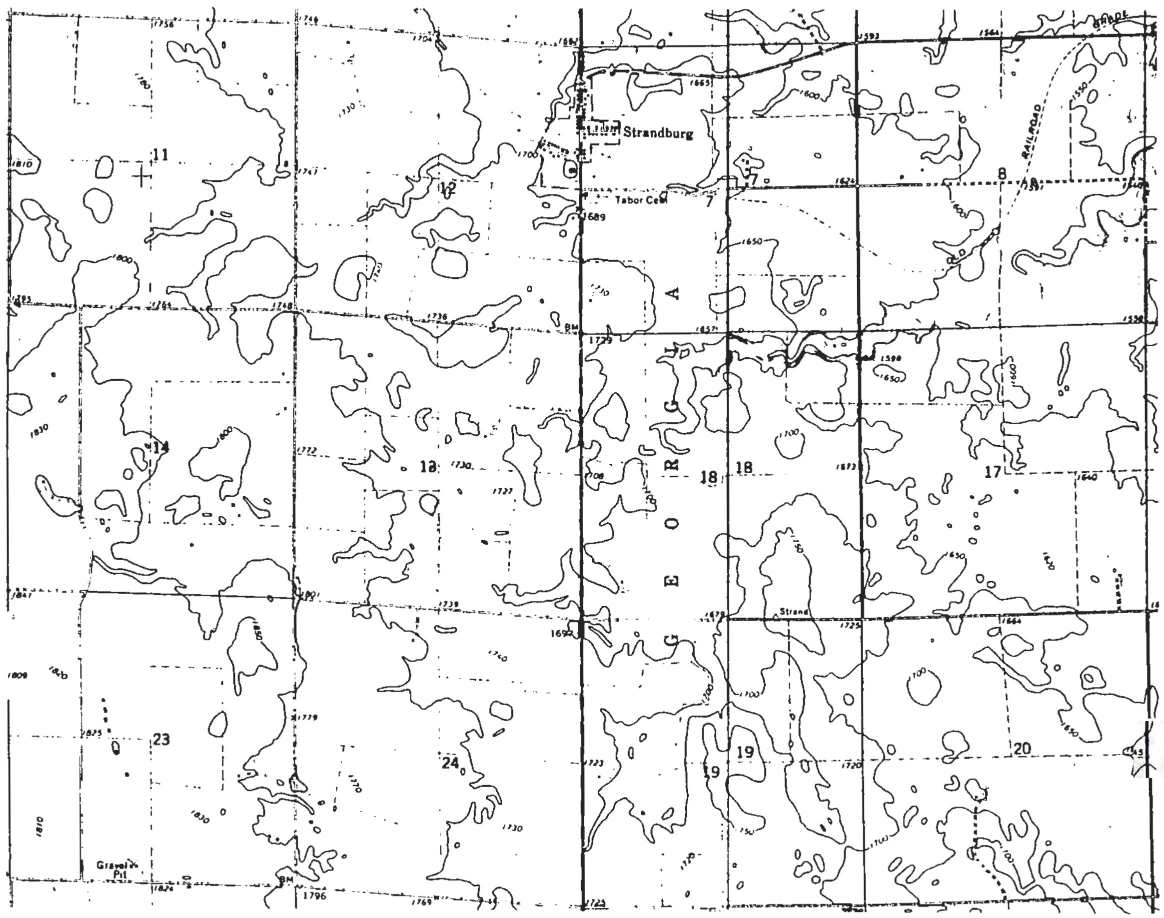


Figure 42. Topographic expression of ice-walled lake plains within the Altamont-Gary Moraine Complex.

Composite of parts of the Stockholm and LaBolt 7½-minute topographic quadrangles, Grant County.

The Gary Moraine marks the eastern edge of this complex, and comprises a narrow, discontinuous band of morainic ridges trending to the northwest, parallel to the edge of the Coteau des Prairies and the Altamont Moraine (Figure 43).

The sediments that underlie the Altamont-Gary Moraine Complex were deposited as a result of an advance of the Des Moines Lobe to the position of the Altamont Moraine about 13,000 yrbp. As the ice overrode the eastern edge of the Coteau des Prairies, increased compressive stress in the lobe resulted in elevated rates of erosion at its base and the incorporation of the subjacent material (the Toronto Till and older deposits). As the process continued, relatively debris-rich ice accumulated in the zone between the ice margin and the eastern edge of the Coteau. As a result of this process, thicknesses of New Ulm Till found in the Altamont-Gary Moraine Complex often exceed 100 feet. Over the rest of the study area, the New Ulm Till rarely exceeds 20 feet in thickness.

Evidence of the basal conditions of the Des Moines at this time can be observed in a cutbank exposure along a small stream, about 3 miles northeast of Stockholm (Figure 44). In this cut, New Ulm Till overlies Granite Falls Till, and both show evidence of glaciotectonic deformation. The contact between the two tills is sharp and marked by a thin, sheared layer of sand and gravel; it is fairly planar and dips to the northeast. Beneath the contact, the Granite Falls Till is interbedded with numerous small, irregularly-shaped, deformed sand bodies. The till is cut by thin fractures, less than ¼ inch thick, that are filled with fine sand.

The base of the overlying New Ulm Till also shows evidence of shearing. A large, folded sand and gravel layer occurs within the till. The fold axis trends to the northwest and the limbs are vertical. Several planar boulders can be observed within the till, and most are oriented parallel to the base of the till. Thin sand lenses with similar orientations have also been noted. Randomly-oriented, vertical fractures (joints) are common within the base of the New Ulm Till.

Minnesota River Lowland

The Minnesota River Lowland is the largest geomorphic unit in the study area (Figure 31). It includes all of the study area east of the Coteau des Prairies, with the

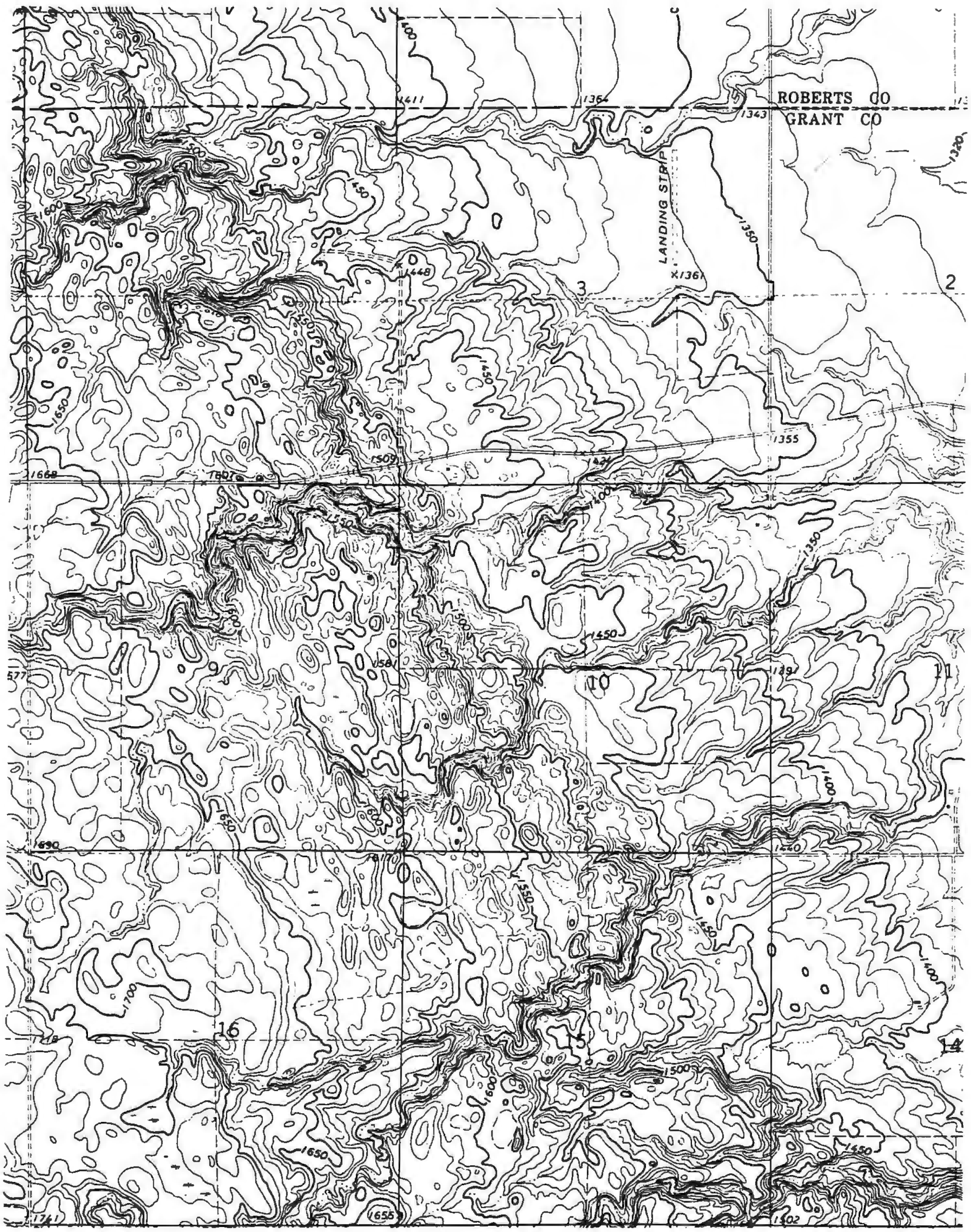


Figure 43. Topographic expression of the Gary Moraine.

Part of the Marvin 7½-minute topographic quadrangle, Grant County.

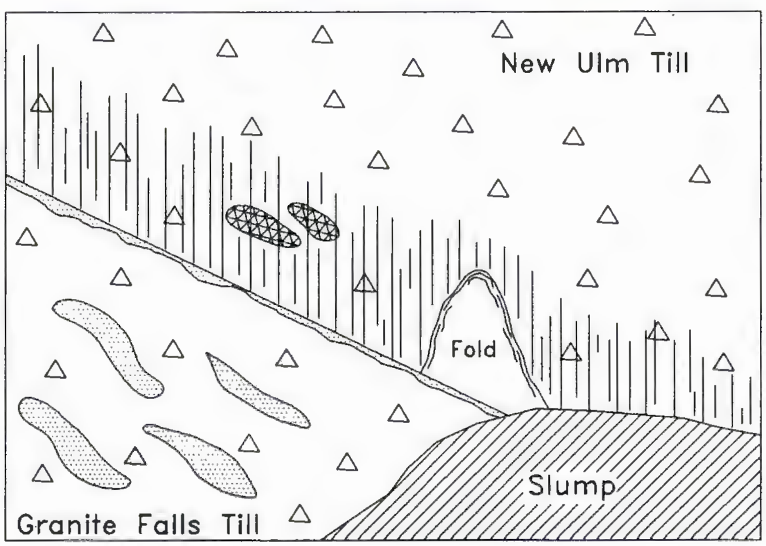


Figure 44. Base of the New Ulm Till showing evidence of glaciotectonic deformation. Location: T 119 N, R 49 W, Section 18 NE¼ NE¼ NE¼, Grant County.

exception of the Big Stone Moraine, and encompasses an area of about 377 square miles. The land surface slopes gently to the northeast, dropping from an elevation of about 1500 feet along the edge of the Coteau des Prairies to under 1000 feet in the northeast corner of the study area.

With the exception of the features noted below, the surface of the Minnesota River Lowland is quite subdued. It consists of a swell and swale topography interpreted to be ground moraine deposited by the Des Moines Lobe (Flint, 1955). In many areas, local relief has been further reduced by the presence of lacustrine sediments filling the broad, low swales. Stream networks are fairly well developed, but there are still many undrained areas. Test hole drilling and a limited number of surface exposures suggest that the underlying New Ulm Till rarely exceeds 20 feet in total thickness over most of the area. Local relief is typically less than 10 feet, although downcutting along several streams and rivers crossing the area may exceed 50 feet (Figure 45).

Minor Moraines

Several low morainic ridges traverse the area from the northwest to southeast. They are composed of a mixture of New Ulm Till and sorted sediments and are interpreted to be minor recessional moraines deposited as the Des Moines Lobe retreated across the area. Flint (1955) correlated many of the these minor moraines with similar moraines in the James River Valley.

Antelope Hills

Near the eastern edge of Grant County, there is a series of northwest-southeast trending ridges, locally referred to as the Antelope Hills (Figure 46). They rise as much as 90 feet above the surrounding landscape and can be traced for several miles. They are the most prominent topographic features in the area. Test holes drilled on and around these features indicate they are composed almost entirely of sand and gravel (Jarrett, 1986). The sediments range from thin beds of coarse silt to thick (>10 feet) layers of bouldery gravels.

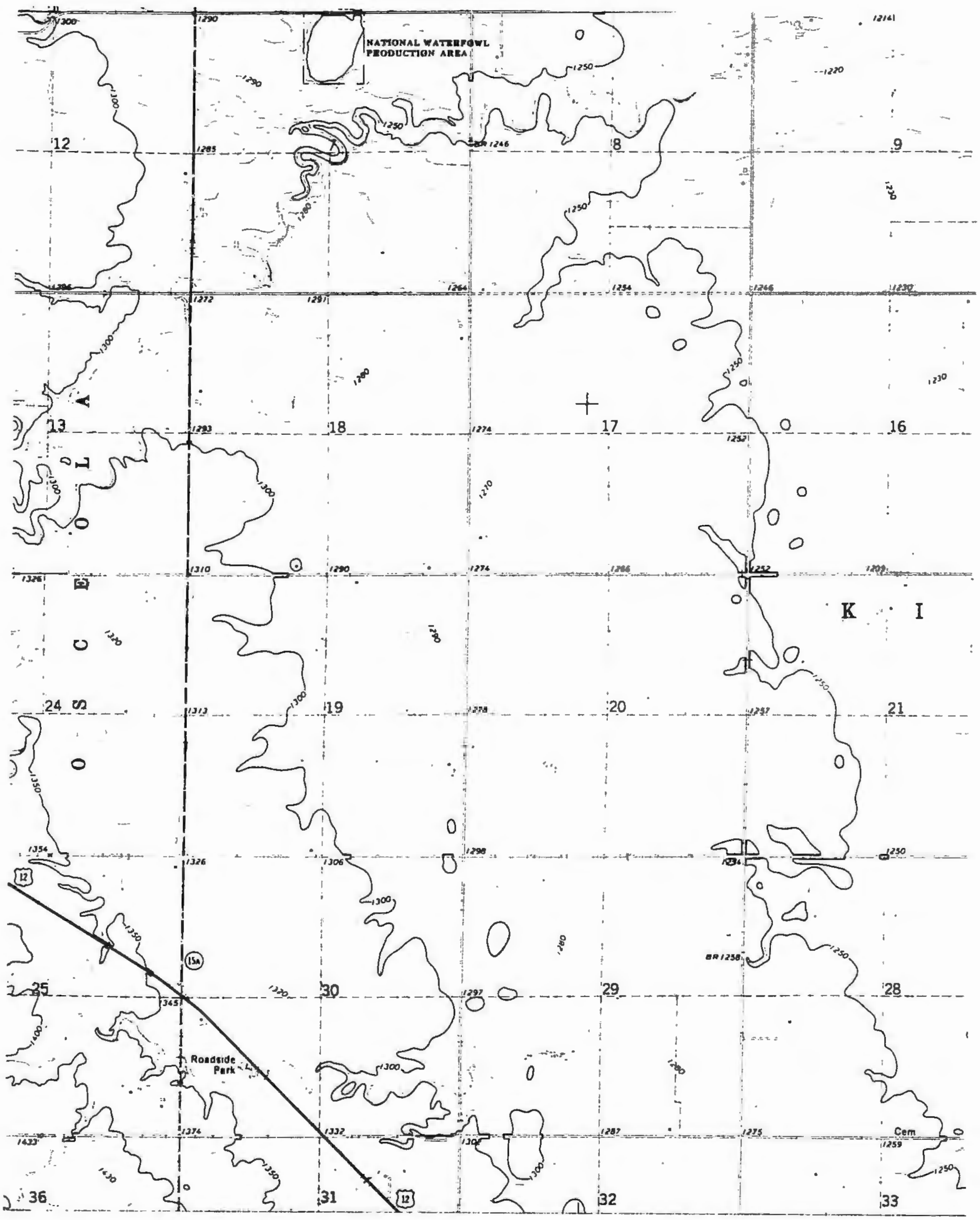


Figure 45. Topographic expression of Minnesota River Valley landscape.

Part of the Corona 7½-minute topographic quadrangle, Grant County.

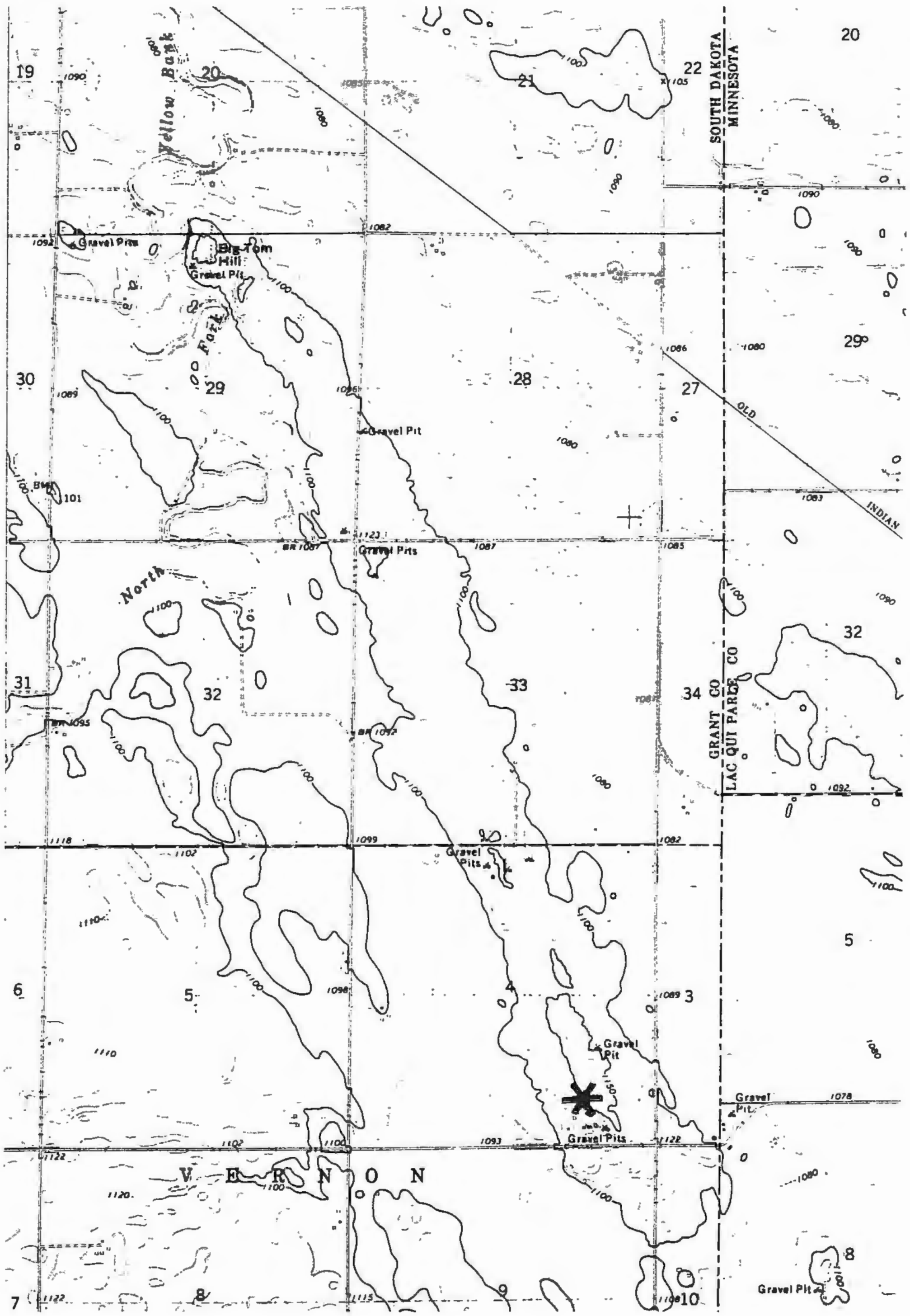


Figure 46. Topographic expression of the Antelope Hills crevasse filling.

Star marks location of exposure shown in Figure 47. Part of the Rosen, Minnesota-South Dakota, 7½-minute topographic quadrangle.

Although originally thought to be end moraines (the Antelope Moraine of Leverett (1932) and Rothrock (1934)), Matsch and others (1972) interpreted the ridges to have formed as longitudinal crevasse fillings in the stagnating Des Moines Lobe ice. The ridges are oriented parallel to the direction of ice movement (northwest to southeast). Steep ice-contact slopes are found on both sides of the ridges. Sand and gravel beds throughout the ridges typically display large-scale cross-stratification, with foreset beds indicating flow to the southeast (Figure 47).

Meltwater Channels

In the area north and east of Milbank, numerous abandoned river channels have been identified. The channels range in depth from 15 to 30 feet and may be up to 1/2 mile wide. In most cases the cutbanks of these channels are well preserved, although some have been obliterated by subsequent erosion. Segments of most of the modern streams and rivers that cross this area occupy parts of the channels, often resulting in a pronounced offset of the stream course (e.g., the lower reaches of the South Fork of the Whetstone River).

The channels are believed to have originated as meltwater conduits that developed when the Des Moines Lobe was at the Big Stone Moraine.

Big Stone Moraine

The Big Stone Moraine is an arcuate belt of fairly low-relief, hummocky topography in the northeastern part of Grant County (Figure 31), covering about 20 square miles. The moraine is bounded by the valley of the North Fork of the Whetstone River on the southwest and the Whetstone River on the southeast. Most of the moraine is composed of a silty till (described earlier), but outwash and glaciolacustrine deposits are also common.

The surface of the moraine is a series of low, closely-spaced, linear ridges, all oriented roughly parallel to the margin of the moraine (Figure 48). Within the moraine, local relief rarely exceeds 15 feet, although discontinuous individual ridge crests can be

Figure 47. Fore-set beds in the Antelope Hills crevasse filling.

View is to the northeast. Location: T 119 N, R 47 W, Section 04 SE¼ NE¼, Grant County (marked on figure 46).

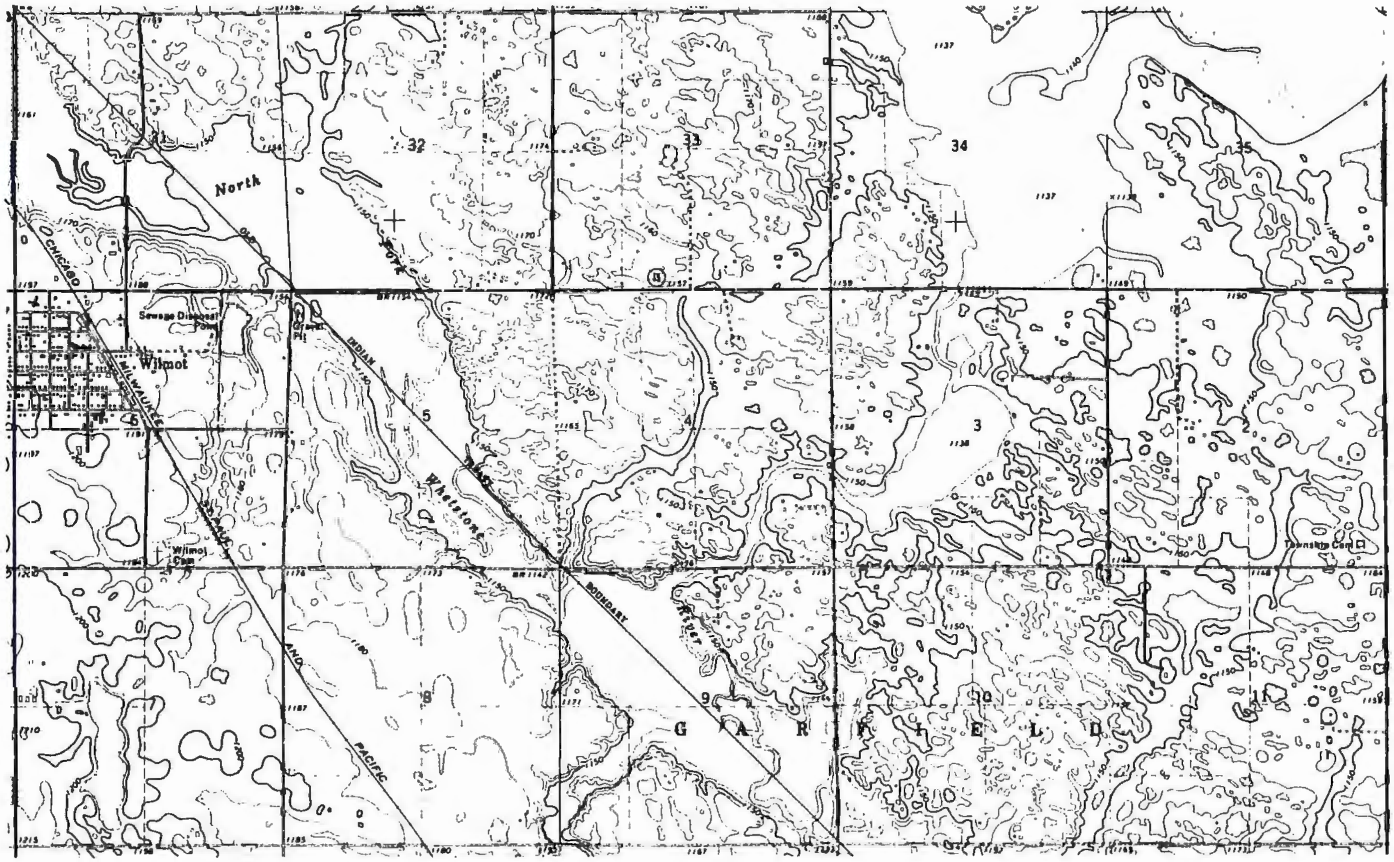


Figure 48. Topographic expression of the Big Stone Moraine.

Note the contrast with the Minnesota River Valley surface to the southwest. Part of the Wilmot 7½-minute topographic quadrangle, Roberts County.

traced laterally for several miles. Numerous, irregularly shaped swales are found throughout the moraine.

The Big Stone Moraine was formed by the last advance of the Late Wisconsin Des Moines Lobe into the study area. Ice-marginal drainages formed along the edge of the ice, in channels now occupied by the Whetstone River. Individual morainic ridges within the Big Stone Moraine are believed to be the result of the concentration of subglacial sediment at the base of the ice by shearing. Similar features have been identified in North Dakota (Clayton and others, 1980) and in west-central Minnesota (Sackreiter, 1975; Norton, 1982).

GLACIAL HISTORY

Northeastern South Dakota was glaciated many times during the Quaternary Period, but only the deposits of the most recent episode of glaciation, the Late Wisconsin, are well exposed. Sediments deposited by pre-Late Wisconsin glaciations are found only in the subsurface or in scattered exposures along river valleys. As such, our understanding of these earlier events is limited. This discussion of the Quaternary history of the Grant County area is divided into two sections: the pre-Late Wisconsin glaciations, and Late Wisconsin glaciations.

Pre-Late Wisconsin Glaciations

The Coteau des Prairies began to form during the earliest glacial activity in the area. Reconstructions of the subglacial bedrock surface (Duchossois, 1985; Gilbertson, 1985) suggest that the pre-glacial surface sloped to the east and northeast (Figure 49). It is postulated that as individual glaciers advanced against this regional slope, increased compressive stress within the ice resulted in the accumulation, by glaciotectonic stacking, of thick drift sequences near the margin, eroded from the substrate immediately up ice. The net result is that each successive ice advance would gradually increased the relative relief between the Coteau des Prairies and adjacent lowlands.

The earliest glacial advances into the region resulted in the deposition of the sediments that comprise Drift Complexes 1, 2, and 3 found in the subsurface of the Coteau des Prairies and the Whetstone and South Fork Tills in the Minnesota River Valley. An ash layer found at the top of Drift Complex 3 indicates that these sediments were deposited prior to about 610,000 yrbp. The original extent of these glacial advances is unknown; however numerous units of similar age are recognized in Iowa and adjacent states, indicating that many of the advances were widespread.The presence of significant amounts of Cretaceous and Paleozoic lithologies in the coarse sand fractions of these tills indicates the these glaciers advanced into the area from the north and northwest (Figure 50).

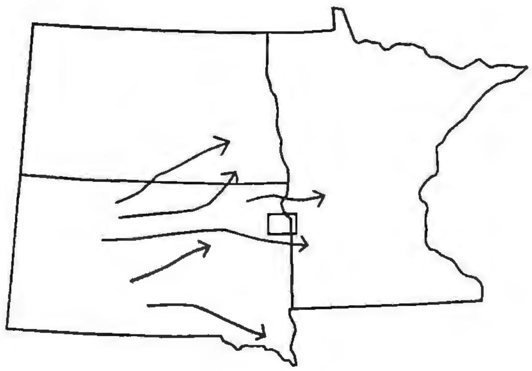


Figure 49. Pre-glacial drainage in eastern South Dakota and adjacent areas.

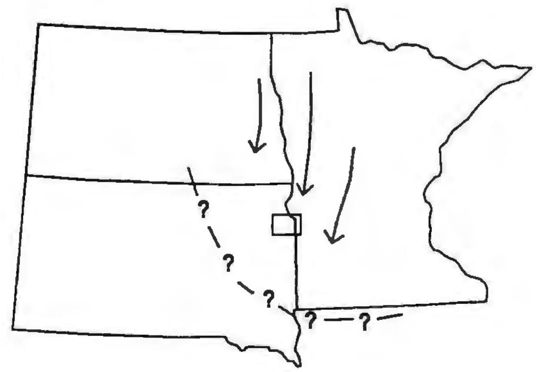


Figure 50. Earliest pre-Late Wisconsin ice advances. Deposition of the Whetstone and South Fork Tills and Drift Complexes 1, 2, and 3.

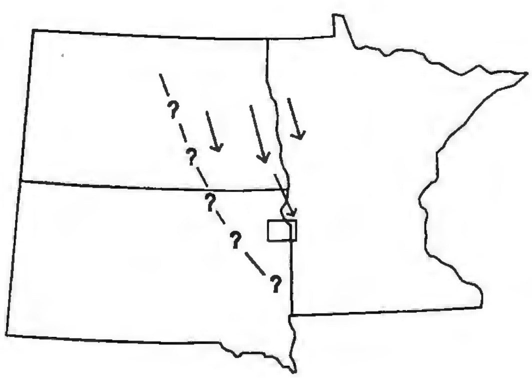


Figure 51. Early Illinoian(?) ice advance from the northwest. Deposition of the Yellow Bank Till and Drift Complex 4.

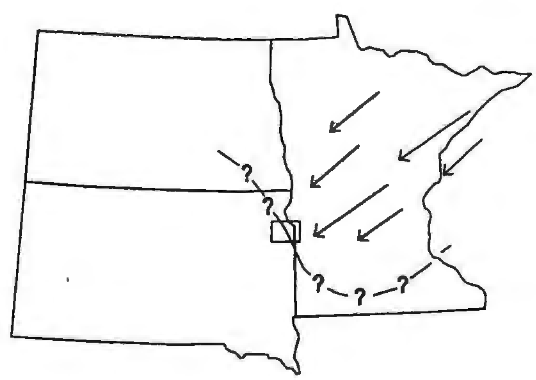


Figure 52. Late Illinoian advance of ice from the northeast. Deposition of the Hawk Creek Till.

An advance of ice from the northwest in the Early Illinoian(?) resulted in the deposition of Drift Complex 4 on the Coteau and the Yellow Bank Till (Figure 51). This advance overrode a thick sequence of lacustrine sediments in central Grant County.

The next glacial advance into the area, during the Late Illinoian, resulted in the deposition of the Hawk Creek Till. Clast lithologies, supported by fabric studies, indicate that the ice originated in the Lake Superior Lowland in northeastern Minnesota (Figure 52). The Hawk Creek Till has not been identified within the Coteau des Prairies. A southwest limit for this ice advance is probably in central Grant County (Figure 16).

At several places in the upper Minnesota River Valley, this advance overrode the fluvial and lacustrine sediments of the Gastropod Silts. Paleoenvironmental indicators within these beds indicate that cool, tundra conditions existed at the time of the Hawk Creek advance.

The final pre-Late Wisconsin ice advance into the area deposited the Granite Falls Till and Drift Complex 5 on the Coteau des Prairies. The timing of this advance is poorly constrained and may be either Late Illinoian, like the advance which resulted in the Hawk Creek Till, or Early Wisconsin as originally suggested by Matsch (1972). Clast lithologies indicate that the ice advanced into the area from the north, although fabric analyses show that local movement was from the northeast to southwest (Figure 53).

Late Wisconsin Glaciations

The first Late Wisconsin ice advance into the area occurred between 20,000 and 30,000 years ago and resulted in the deposition of the Toronto Till (Figure 54). Clast lithologies indicate that the glacial ice moved into the area from the north. The southwestern limit of this advance is marked by the Still Lake Moraine that traverses the Coteau des Prairies (Figure 5). Following retreat of the ice, well-developed drainage networks developed on the recently deglaciated areas and produced the characteristic landscape of the Toronto Till Plain.

By about 14,000 yrbp, ice of the Late Wisconsin Des Moines Lobe had reached the position of the Bemis Moraine (Figure 55). The ice did not remain at this position very long, as evident by the thin and discontinuous nature of the moraine and its attendant deposits.

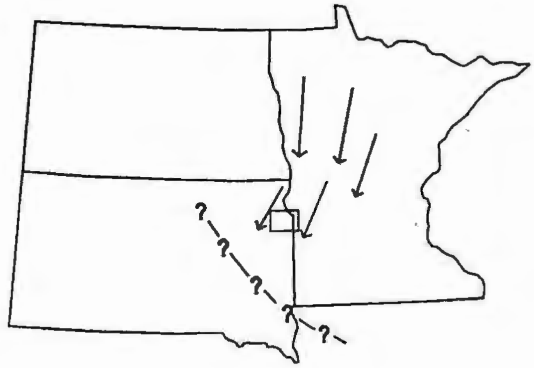


Figure 53. Late Illinoian (or Early Wisconsin?) advance of ice from the north. Deposition of the Granite Falls Till and Drift Complex 5.

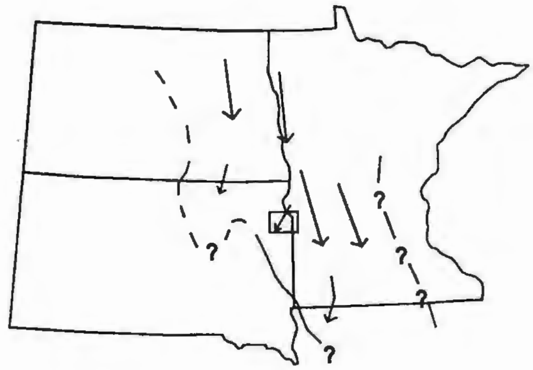


Figure 54. Earliest Late Wisconsin ice advance, between 30,000 and 20,000 yrbp. Deposition of the Toronto Till.

Figure 55. Late Wisconsin advance of the Des Moines Lobe to the Bemis Moraine. Initial deposition of the New Ulm Till.

Figure 56. Late Wisconsin Des Moines Lobe at the Altamont Moraine and the James Lobe at the Dakota Moraine.

By about 13,400 yrbp, the Des Moines Lobe was established at the position of the Altamont Moraine (Figure 56). It is unclear as to whether this marks a recessional position from the Bemis Moraine, or a full readvance of the ice back onto the Coteau des Prairies. While the ice margin stood at this position a considerable thickness of the New Ulm Till accumulated along the eastern edge of the Coteau des Prairies. At the same time, ice of the James Lobe had advanced to the Dakota Moraine.

The broad belts of uncontrolled stagnation topography behind the Altamont and Dakota Moraines indicate that the retreat of the Des Moines and James Lobes from these margins was quite rapid. It is suggested that the debris-rich ice on the Coteau des Prairies was abandoned catastrophically when the individual lobes in the valleys were no longer able to support active ice at the higher elevations on the Coteau des Prairies.

The next glacial advance into the area took place about 12,500 yrbp (Figure 57). The Des Moines and James Lobes were largely restricted to the Minnesota River and James River lowlands, respectively. The Gary Moraine in Grant County was formed at this time.

As the Des Moines Lobe margin retreated from the Gary Moraine, a series of small, temporary proglacial lakes formed between the ice margin and the higher ground to the south. Continued retreat of the ice margin into North Dakota resulted in the formation of a proglacial lake in the Agassiz basin (Figure 58).

The final advance of Des Moines Lobe ice into the area took place about 11,700 yrbp (Figure 59). The previously deposited lacustrine sediments were overridden and incorporated by this advance, producing the characteristically silty till of the Big Stone Moraine.

With the final retreat of active ice from the area, a large proglacial lake (Glacial Lake Agassiz, Upham, 1895) formed to the north of the Big Stone Moraine (Figure 60). During the early phases of the lake's existence, it developed an outlet (Glacial River Warren) that breached the moraine and drained down what is now the Minnesota River Valley.

Subaerial erosion and deposition have dominated the geological activities following the retreat of active ice from the area and the demise of the glacial lakes.

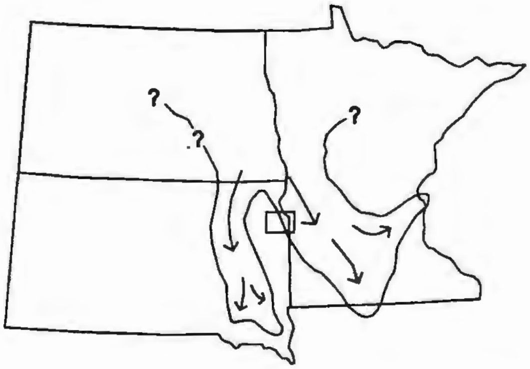


Figure 57. Late Wisconsin Des Moines Lobe at the Gary Moraine and the James Lobe at the DeSmet Moraine. Deposition of the New Ulm Till.

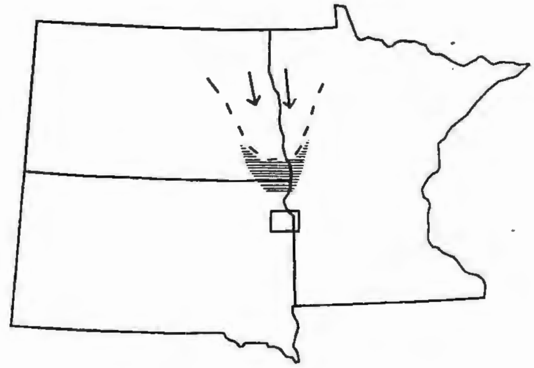


Figure 58. Early phase (?) of Lake Agassiz, prior to 11,700 yrbp.

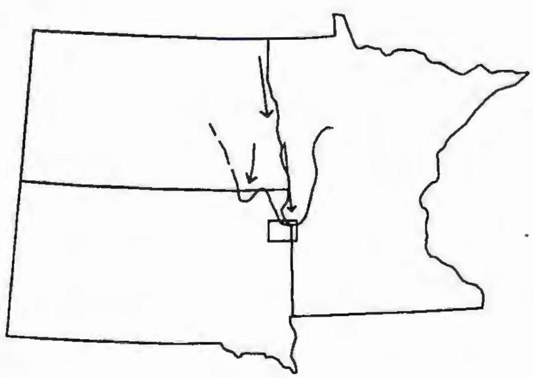


Figure 59. Final advance of the Late Wisconsin Des Moines Lobe to the position of the Big Stone Moraine.

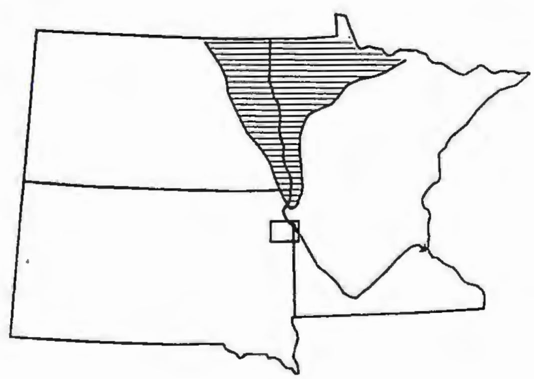


Figure 60. Development of Lake Agassiz, between 11,700 and 9,500 yrbp.

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APPENDIX A

Location of Test Holes Drilled for this Investigation

The following list contains the location, drilling method, and total depth of the rotary test holes drilled for this investigation. Complete descriptive logs for all test holes (rotary and auger) are on file with the South Dakota Geological Survey in Vermillion, South Dakota.

COUNTY: County in which the test hole was drilled. Codington, Day, Grant, and Roberts Counties are in South Dakota, Lac Qui Parle (L Q Parle) County is in Minnesota.

LOCATION: The location is listed by the smallest township number, then the smallest range number, the smallest section number and then by quarter section: NE (A), NW (B), SW (C), SE (D). Numbers following the smallest quarter section are used to separate multiuple test holes at a given location. An R following the location indicates a site within the boundaries of the Lake Traverse Indian Reservation.

DRILLING METHOD: Direct rotary rigs (ROTARY) were used to drill test holes for deep stratigraphic tests and to establish bedrock lithologies.

DEPTH: Depth of test hole, in feet below land surface.

COUNTY	LOCATION	METHOD	DEPTH
GRANT	118N-47W-16DDDD	ROTARY	461.0
GRANT	118N-47W-31CCCC	ROTARY	375.0
GRANT	118N-47W-34CCCC	ROTARY	380.0
GRANT	118N-48W-15CCCC 1	ROTARY	455.0
GRANT	118N-48W-15CCCC 2	ROTARY	80.0
GRANT	118N-48W-18CCBC	ROTARY	485.0
GRANT	118N-48W-33DDDD	ROTARY	617.0
GRANT	118N-49W-01AAAA 1	ROTARY	308.0
GRANT	118N-49W-01AAAA 2	ROTARY	82.0
GRANT	118N-49W-04AAAA	ROTARY	115.0
GRANT	118N-49W-21AAAA	ROTARY	680.0
GRANT	118N-49W-36DDDD	ROTARY	594.0
GRANT	118N-50W-07CBCB	ROTARY	94.0
GRANT	118N-50W-16DCCC	ROTARY	881.0
GRANT	118N-50W-19BBBB	ROTARY	595.0
GRANT	118N-50W-29CCCC	ROTARY	186.0
GRANT	118N-50W-36DDAA	ROTARY	797.0
GRANT	119N-47W-06BBBA 1	ROTARY	217.0
GRANT	119N-47W-06BBBA 2	ROTARY	220.0
GRANT	119N-47W-16DDDD	ROTARY	256.0
GRANT	119N-47W-33DDDD	ROTARY	406.0
GRANT	119N-48W-13DDDD	ROTARY	291.0
GRANT	119N-48W-18CCCB	ROTARY	238.0
GRANT	119N-48W-21AAAB	ROTARY	280.0
GRANT	119N-48W-33DDDA	ROTARY	354.0
GRANT	119N-48W-36DDDD	ROTARY	282.0
GRANT	119N-49W-15CCCC	ROTARY	519.0
GRANT	119N-49W-18CCCC	ROTARY	620.0
GRANT	119N-49W-31CCCC 1	ROTARY	620.0
GRANT	119N-49W-31CCCC 2	ROTARY	740.0
GRANT	119N-49W-34CCCC	ROTARY	75.0
GRANT	119N-50W-01AAAD	ROTARY	470.0
GRANT	119N-50W-04BBBC	ROTARY	750.0
GRANT	119N-50W-16DDDB	ROTARY	480.0
GRANT	119N-50W-18CCCC	ROTARY	560.0
GRANT	119N-50W-31CCCC 1	ROTARY	575.0
GRANT	119N-50W-31CCCC 2	ROTARY	50.0
CODINGTON	119N-52W-01CCCC R	ROTARY	485.0
CODINGTON	119N-53W-06BBBB	ROTARY	590.0
L Q PARLE	120N-46W-05CCCC	ROTARY	56.0
L Q PARLE	120N-46W-10BBBC	ROTARY	45.0
L Q PARLE	120N-46W-20AACC	ROTARY	161.0
L Q PARLE	120N-46W-21ADAD	ROTARY	89.0
GRANT	120N-47W-03BBBB	ROTARY	115.0
GRANT	120N-47W-05BBBB	ROTARY	119.0
GRANT	120N-47W-06DDDD	ROTARY	85.0
GRANT	120N-47W-07BBBB	ROTARY	164.0
GRANT	120N-47W-09BBBB	ROTARY	45.0

COUNTY	LOCATION	METHOD	DEPTH
GRANT	120N-47W-10CCCD	ROTARY	155.0
GRANT	120N-47W-16DDDD	ROTARY	150.0
GRANT	120N-47W-17CCDC	ROTARY	26.0
GRANT	120N-47W-18CCCC	ROTARY	73.0
GRANT	120N-47W-20CCCC	ROTARY	94.0
GRANT	120N-47W-21BBAA	ROTARY	92.0
GRANT	120N-47W-22CCBC	ROTARY	191.0
GRANT	120N-47W-29AAAA	ROTARY	175.0
GRANT	120N-47W-33DDDC	ROTARY	195.0
GRANT	120N-48W-01BBBA 1	ROTARY	225.0
GRANT	120N-48W-01BBBA 2	ROTARY	60.0
GRANT	120N-48W-02CCCC	ROTARY	209.0
GRANT	120N-48W-02DDDA	ROTARY	135.0
GRANT	120N-48W-14AAAD	ROTARY	65.0
GRANT	120N-48W-19BBBB	ROTARY	329.0
GRANT	120N-48W-21AAAA	ROTARY	208.0
GRANT	120N-48W-23AAAA	ROTARY	115.0
GRANT	120N-48W-24CCCC	ROTARY	226.0
GRANT	120N-48W-34CCDD	ROTARY	254.0
GRANT	120N-49W-15CCCC	ROTARY	503.0
GRANT	120N-49W-34CCCD	ROTARY	75.0
GRANT	120N-49W-36DDAA 1	ROTARY	337.0
GRANT	120N-49W-36DDAA 2	ROTARY	270.0
GRANT	120N-50W-16DDDD	ROTARY	650.0
GRANT	120N-51W-09BBBC R	ROTARY	652.0
GRANT	120N-51W-17DDDD	ROTARY	745.0
GRANT	120N-51W-23AAAA	ROTARY	95.0
GRANT	120N-51W-23CCCA	ROTARY	120.0
GRANT	120N-51W-27BBBB 1	ROTARY	45.0
GRANT	120N-51W-27BBBB 2	ROTARY	143.0
GRANT	120N-51W-35ACCC 1	ROTARY	45.0
GRANT	120N-51W-35ACCC 2	ROTARY	35.0
GRANT	120N-51W-35CDAA	ROTARY	35.0
GRANT	120N-52W-08AAAB R	ROTARY	516.0
GRANT	120N-52W-11AAAA R	ROTARY	527.0
GRANT	120N-52W-20CCCC 2R	ROTARY	156.0
CODINGTON	120N-52W-25BBBB R	ROTARY	172.0
CODINGTON	120N-52W-26AAAA 1R	ROTARY	330.0
CODINGTON	120N-52W-26AAAA 2R	ROTARY	30.0
CODINGTON	120N-52W-26AAAA 3R	ROTARY	171.0
CODINGTON	120N-52W-26AAAA 4R	ROTARY	635.0
GRANT	120N-52W-36DDDD 1	ROTARY	425.0
GRANT	120N-52W-36DDDD 2	ROTARY	755.0
GRANT	121N-46W-29CCCC	ROTARY	162.0
L Q PARLE	121N-46W-33BBBB	ROTARY	150.0
GRANT	121N-47W-04AAAA	ROTARY	270.0
GRANT	121N-47W-14DDAD	ROTARY	149.0
GRANT	121N-47W-16CBBC	ROTARY	292.0

COUNTY	LOCATION	METHOD	DEPTH
GRANT	121N-47W-16CCBB	ROTARY	182.0
GRANT	121N-47W-21BBCC	ROTARY	20.0
GRANT	121N-47W-32DDDC	ROTARY	216.0
GRANT	121N-47W-35DDDD	ROTARY	190.0
GRANT	121N-47W-36AAAA	ROTARY	196.0
GRANT	121N-48W-03BBCC	ROTARY	319.0
GRANT	121N-48W-06AAAA 1	ROTARY	360.0
GRANT	121N-48W-13CCCC	ROTARY	260.0
GRANT	121N-48W-20AAAA	ROTARY	260.0
GRANT	121N-48W-33CCCC	ROTARY	395.0
GRANT	121N-48W-35DDDD 1	ROTARY	166.0
GRANT	121N-48W-35DDDD 2	ROTARY	394.0
GRANT	121N-49W-13CCCC	ROTARY	198.0
GRANT	121N-49W-35DDDD	ROTARY	350.0
GRANT	121N-50W-01BBBB	ROTARY	500.0
GRANT	121N-50W-05BBBB	ROTARY	785.0
GRANT	121N-50W-17DDDD	ROTARY	740.0
GRANT	121N-50W-25CCCC 1	ROTARY	545.0
GRANT	121N-50W-25CCCC 2	ROTARY	35.0
GRANT	121N-50W-35ADDD 1	ROTARY	65.0
GRANT	121N-50W-35ADDD 2	ROTARY	110.0
GRANT	121N-50W-35ADDD 3	ROTARY	100.0
GRANT	121N-51W-14DADB	ROTARY	585.0
GRANT	121N-51W-17AAAA R	ROTARY	758.0
GRANT	121N-51W-35CDDD	ROTARY	860.0
GRANT	121N-52W-01BBBB R	ROTARY	195.0
GRANT	121N-52W-02AAAA R	ROTARY	560.0
GRANT	121N-52W-02BBBA R	ROTARY	153.0
GRANT	121N-52W-09CDDD R	ROTARY	510.0
GRANT	121N-52W-13DDDD R	ROTARY	227.0
GRANT	121N-52W-15AAAA R	ROTARY	187.0
GRANT	121N-52W-15BBAA R	ROTARY	200.0
GRANT	121N-52W-21AAAA 1R	ROTARY	117.0
GRANT	121N-52W-25BBBB R	ROTARY	725.0
DAY	121N-53W-01AAAA R	ROTARY	545.0
DAY	121N-53W-24DDDD R	ROTARY	515.0
ROBERTS	122N-47W-35DDCD	ROTARY	200.0
ROBERTS	122N-48W-35DDDD 1	ROTARY	290.0
ROBERTS	122N-48W-35DDDD 2	ROTARY	49.0
ROBERTS	122N-49W-33CCCB	ROTARY	458.0
ROBERTS	122N-49W-35DDDD	ROTARY	372.0

APPENDIX B

Description of Hollow-Stem Auger Cores

CORE NUMBER: Unique identification number assigned to each core.

COUNTY: County in which the test hole was drilled. Grant and Roberts Counties are in South Dakota.

LOCATION: The location is listed by the smallest township number, then the smallest range number, the smallest section number and then by quarter section: NE, NW, SW, and SE. An R following the location indicates a site within the boundaries of the Lake Traverse Indian Reservation.

ELEVATION: Land-surface elevation determined from U. S. Geological Survey 7½-minute topographic maps.

DEPTH: Depth of test hole, in feet below land surface.

INTERVAL: Segment of core described, in feet below land surface.

DESCRIPTION: Field description of core.

CORE #:	C861
COUNTY:	Grant
LOCATION:	T 120 N, R 49 W, Section 36 SE¼ SE¼ NE¼ NE¼
ELEVATION:	1175'
DEPTH:	90'
<u>Interval</u>	<u>Description</u>
0.0 - 0.5'	Black topsoil.
0.5 - 7.5'	Olive-brown (oxidized), silty till (New Ulm Till). Light gray and tan mottling. Fractures/joints with secondary iron staining and gypsum. Gradational lower contact.
7.5 - 9.5'	Yellow-brown (oxidized), silty till (New Ulm Till). Gray mottling. Fractures/joints with secondary iron staining and gypsum. Gradational lower contact.
9.5 - 14.5'	Gray (unoxidized), silty till (New Ulm Till). Yellow-brown and tan mottling. Fractures/joints with secondary iron staining and gypsum. Sharp lower contact.
14.5 - 20.0'	Tan (unoxidized), silty till (Yellow Bank Till). Minor gray mottling. Fractures/joints with secondary iron staining and gypsum.
20.0 - 25.0'	Tan (unoxidized), silty till (Yellow Bank Till). Poor recovery.
25.0 - 32.5'	Gray (unoxidized), silty till (Yellow Bank Till). Sand layer between 30.5 and 30.8 feet. Sharp lower contact.
32.5 - 43.0'	Gray, fine- to medium-grained sand.
43.0 - 55.0'	No core.
55.0 - 57.8'	Gray, fine-grained lacustrine sediments. Light and dark couplets (varves?). Scattered, small (<0.1" diameter) pyrite concretions. Gradational lower contact.
57.8 - 59.0'	Gray silts and fine sands. Massive to weakly bedded. Coarsening upward sequence. Sharp lower contact.
59.0 - 60.0'	Mixed pebbles, sand, and dark gray clay. Possible turbidite deposit. Sharp lower contact.
60.0 - 63.5'	Gray silts and fine sands. Massive to weakly bedded. Coarsening upward sequence. Sharp lower contact.

CORE #:	C861 (cont.)
Interval	Description
63.5 - 64.0'	Gray, silty sand (lacustrine sediments?). Abundant organic material, twigs and plant fragments. Aspartic acid sample CG-86-C1. Gradational lower contact.
64.0 - 69.0'	Gray silts and fine sands. Massive to weakly bedded. Coarsening upward sequence. Gradational lower contact.
69.0 - 75.5'	Gray silts and clays (lacustrine sediments). Light and dark couplets (varves?). Scattered, small (<0.1" diameter) pyrite concretions. Sharp lower contact.
75.5 - 76.0'	Gray, silty sand (lacustrine sediments?). Abundant organic material, twigs and plant fragments. Aspartic acid sample CG-86-C2. Gradational lower contact.
76.0 - 84.0'	Gray silts and clays (lacustrine sediments). Light and dark couplets (varves?). Scattered, small (<0.1" diameter) pyrite concretions. Sharp lower contact.
84.0 - 85.5'	Mixed gray silts and bedrock(?) clasts. Clasts of marl (Niobrara Marl?). Sharp, irregular lower contact.
85.5 - 90.0'	Dark bluish-gray, claystone (Blue Hill Member - Carlile Shale).

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CORE #:	C862
COUNTY:	Grant
LOCATION:	T 120 N, R 48 W, Section 06 NE¼ SE¼ NE¼ SE¼
ELEVATION:	1125'
DEPTH:	70'
Interval	Description
0.0 - 0.5'	Black, sandy topsoil.
0.5 - 14.0'	Yellow-brown (oxidized), silty till (New Ulm Till). Secondary carbonate nodules. Abundant intermixed silt and fine sand layers. Sharp lower contact.
14.0'	Sub-New Ulm boulder pavement.

CORE #:	C862 (cont.)
Interval	Description
14.0 - 27.0'	Reddish-brown, sandy till (Hawk Creek Till). Massive. Sharp lower contact.
27.0 - 34.0'	Reddish-brown to reddish-gray sands and gravel. Thin (less than 3") clay (till?) stringers. Sharp (erosional?) lower contact.
34.0 - 39.0'	Reddish-brown, sandy till (Hawk Creek Till). Massive. Sharp lower contact.
39.0 - 42.5'	Reddish-brown to reddish-gray sands and gravel. Sharp (erosional?) lower contact.
42.5 - 45.2'	Reddish-brown, sandy till (Hawk Creek Till). Massive.Sharp lower contact.
45.2 - 63.0'	Gray (unoxidized), pebbly till (South Fork Till). Sharp lower contact.
63.0 - 64.5'	Sand and gravel. Gradational lower contact.
64.5 - 70.0'	Fine sand (and silt?) with intermixed sand and gravel layers.

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CORE #:	C863
COUNTY:	Roberts
LOCATION:	T 122 N, R 48 W, Section 29 SE¼ SE¼ SE¼ SE¼
ELEVATION:	1150'
DEPTH:	21'
Interval	Description
0.0 - 0.5'	Black, sandy topsoil.
0.5 - 2.5'	Tan to light yellow-brown silt and fine sand (loess). Diffuse lower contact.
2.5 - 21.0'	Yellow-brown (oxidized), silty till (New Ulm Till). Rust-colored mottling above 13', gray below 17'. Abundant shale pebbles. Fractures/joints are common, with secondary iron stains and gypsum. Intermixed sorted sediments, mostly as lenses of silt and fine sand. Sharp lower contact.

CORE #:	C862 (cont.)
Interval	Description
21.0'	Sub-New Ulm boulder pavement. Coring terminated.

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CORE #:	C864
COUNTY:	Roberts
LOCATION:	T 122 N, R 48 W, Section 33 NW¼ NW¼ NW¼ NE¼
ELEVATION:	1130'
DEPTH:	53'
Interval	Description
0.0'	Sub-New Ulm boulder pavement.
0.0 - 22.75'	Yellow-brown to brown (oxidized), sandy till (Granite Falls Till). Fractures/joints with secondary iron staining and gypsum throughout. Fine sand and silts from 9' to 9.75' and 12' to 13.5'. Gradational lower contact.
22.75 - 23.5'	Mixed yellow-brown and gray, sandy till (Granite Falls Till). Fractures/joints with secondary iron staining and gypsum. Gradational lower contact.
23.5 - 37.5'	Gray (unoxidized), sandy, pebbly till (Granite Falls Till). Massive. Gradational lower contact.
37.5 - 47.0'	Gray (unoxidized), sandy, pebbly till (Granite Falls Till). Intermixed sand and gravel layers throughout. Sharp lower contact.
47.0 - 47.25'	Gray silts. Diffuse lower contact.
47.25 - 51.5'	Gray (unoxidized), silty till (Yellow Bank Till). Massive. Sharp lower contact.
51.5 - 53.0'	Gravel. Poor recovery. Lower contact not encountered.

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CORE #:	C865
COUNTY:	Grant
LOCATION:	T 121 N, R 48 W, Section 06 NE¼ NE¼ NE¼ NE¼

CORE #:	C865 (cont.)
ELEVATION:	1145'
DEPTH:	32.5'
Interval	Description
0.0 - 0.25'	Black, sandy topsoil.
0.25 - 7.5'	Yellow-brown (oxidized), silty till (New Ulm Till). Tan and rust colored mottling. Shale and carbonate pebbles. Fractures/joints with secondary iron stains and gypsum. Gradational lower contact.
7. - 7.75'	Mottled brown and gray till (New Ulm Till). Gradational lower contact.
7.75 - 11.5'	Gray (unoxidized) till (New Ulm Till). Massive. Sharp lower contact.
11.5 - 32.5'	Reddish-brown, sandy till (Hawk Creek Till). Large red sandstone clast at 12'. Intermixed reddish-brown sands below 17' resulted in poor recovery.

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CORE #:	C881
COUNTY:	Grant
LOCATION:	T 120 N, R 51 W, Section 09 NW¼ NW¼ NW¼ SW¼ R
ELEVATION:	1935'
DEPTH:	47.5'
Interval	Description
0.0 - 0.25'	Black, silty topsoil.
0.25 - 3.0'	Yellow-brown to brownish-gray silt (loess). Sharp lower contact.
3.0 - 19.0'	Yellow-brown (oxidized), silty, pebbly till (Toronto Till). Massive. Fractures/joints common, surfaces coated with iron oxide and gypsum. Gradational lower contact.
19.0 - 47.5'	Gray (unoxidized), silty, pebbly till (Toronto Till). Some fractures/joints. Massive. Lower contact not encountered.

CORE #:	C882
COUNTY:	Grant
LOCATION:	T 120 N, R 52 W, Section 08 NE¼ NE¼ NE¼ SE¼ R
ELEVATION:	1840'
DEPTH:	50'
<u>Interval</u>	<u>Description</u>
0.0 - 0.25'	Black, silty topsoil.
0.25 - 2.0'	Yellow-brown to tan silt (loess).
2.0 - 17.5'	Yellow-brown (oxidized), silty, pebbly till (Toronto Till). Massive. Fractures/joints common, surfaces coated with iron oxide and gypsum. Gradational lower contact.
17.5 - 34.9'	Gray (unoxidized), silty, pebbly till (Toronto Till). Some fractures/joints. Massive. Sharp lower contact.
34.9 - 35.1'	Dark-brown to black silts. Organics.
35.1 - 45.0'	Tan to brown silts (loess?).
45.0 - 50.0'	Yellow-brown (oxidized), sandy, pebbly till (Drift Complex 5). Massive. Fractures/joints common, surfaces coated with iron oxide and gypsum. Lower contact not encountered.

APPENDIX C

Description of Stratigraphic Sections

COUNTY: County in which the section is located. Day, Grant, and Roberts Counties are in South Dakota, Lac Qui Parle County is in Minnesota.

LOCATION: Descriptive and legal locations. The legal location is listed by the smallest township number, then the smallest range number, the smallest section number and then by quarter section: NE, NW, SW, and SE. An R following the location indicates a site within the boundaries of the Lake Traverse Indian Reservation.

ELEVATION: Elevation of the top of the section as determined from U. S. Geological Survey 7½-minute topographic maps.

INTERVAL: Segment of section described, in feet below land surface.

DESCRIPTION: Field description of section.

Gaging Station Section

COUNTY:	Grant
LOCATION:	East Bank of the Whetstone River
	T 121 N, R 46 W, Section 18 NW¼ SE¼ SW¼ NE¼
ELEVATION:	1030'
Interval	Description
0.0 - 0.5'	Black topsoil.
0.5 - 4.0'	Light yellow-brown (oxidized), sandy, pebbly till(?). Abundant medium to coarse sand. Shale pebbles common. Sharp lower contact. (Colluvium? derived from New Ulm Till)
4.0'	Stone lag.
4.0 - 14.5'	Reddish-brown (oxidized), sandy till (Hawk Creek Till). Calcareous. Massive. Fractures/joints common, surfaces stained by iron oxides. Sharp (erosional?) lower contact.
14.5 - 14.75'	Gray, laminated clay (varved lacustrine sediments). Sharp, conformable lower contact.
14.75 - 19.0'	Tan silty fine sand to fine sand. Thinly laminated. Some medium sand layers. Top of sequence contains some disseminated organic material. Leisengange banding. Sharp, planar lower contact.
19.0 - 23.0'	Yellow-brown to tan coarse sand to pebbly, coarse sand. Tabular- and cross-bedding. Coarsening upward. Sharp, erosional lower contact.
23.0 - 34.5'	Dark gray (unoxidized), pebbly, silty till (Whetstone Till). Massive. Calcareous. Lower contact not visible.
34.5'	River level.

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Glaciotectonic Section

COUNTY:	Grant
LOCATION:	North bank of small stream.
	T 119 N, R 49 W, Section 18 NE¼ NE¼ NE¼ NE¼
ELEVATION:	1315'

Glaciotectonic Section (cont.)

Interval	Description
0.0 - 0.5'	Black topsoil.
0.5 - 10.0'	Yellow-brown to olive-brown (oxidized), silty, pebbly till (New Ulm Till). Massive. Blocky fracture pattern. Calcareous. Gradational lower contact.
10.0 - 17.0'	Gray to brownish-gray, pebbly till (New Ulm Till). Calcareous. Very hard. Columnar joints, with secondary carbonate on surfaces. Some deformed sand bodies. Large folded gravel body within segment, fold axis trending 340°, dipping at 20° to the northwest. Axial plane of folddips northeast at about 80°. Lower contact sharp and planar, dipping to the northeast.
17.0 - 17.2'	Sand and gravel.
17.2 - 25.0'	Gray (unoxidized), sandy, pebbly till (Granite Falls Till). many deformed, planar coarse sand and gravel bodies, striking northwest-southeast and dipping to the northeast. Lower contact not visible.
25.0'	Stream level.

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Loraff Farm Section

COUNTY: Grant

LOCATION: West bank of the Whetstone River.
T 121 N, R 47 W, Section 13 SW¼ SW¼ NW¼ NE¼

ELEVATION: 1050'

Interval	Description
0.0 - 0.5'	Black, sandy topsoil.
0.5 - 2.0'	Light-brown (oxidized), sandy, pebbly colluvium. Shale pebbles are common. Calcareous. Sharp lower contact.
2.0'	Sub-New Ulm boulder pavement.
2.0 - 22.0'	Light reddish-brown (oxidized), sandy till (Hawk Creek Till). Calcareous. Fractures/joints stained with iron oxides. Transitional lower contact.

Loraff Farm Section (cont.)

Interval	Description
22.0 - 35.8'	Dark reddish-brown to reddish-gray (unoxidized), sandy till (Hawk Creek Till). Calcareous. Fractures/joints stained with iron oxides. Transitional lower contact.
35.8 - 36.0'	Interlayered reddish-brown till (Hawk Creek Till) and gray, pebbly clay. Sharp, erosional lower contact.
36.0 - 36.2'	Alternating light and dark clays (varved? lacustrine sediments). Thin beds, less than ¼" thick. Scattered organic material and leaf imprints. Sharp lower contact.
36.2 - 36.5'	Dark grayish-brown to black, sandy silts (Gastropod Silts). Abundant organic material (finely disseminated plant matter, plant macrofossils, and mollusks). Transitional lower contact.
36.5 - 40.0'	Gray, sandy silts (Gastropod Silts). Massive. Some interbedded coarse sand and gravel, heavily oxidized. Abundant organic material (plant macrofossils and mollusks). Lower contact not visible.
40.0'	River level.

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Nordick Farm Section

COUNTY: Lac Qui Parle

LOCATION: Drainage ditch leading to the North Fork of the Yellow Bank River.
T 120 N, R 46 W, Section 20 NE¼ NE¼ SW¼ NW¼

ELEVATION: 1090'

Interval	Description
0.0 - 36.0'	Yellow-brown (oxidized), silty till (New Ulm Till). Shale clasts abundant. Lenses of sorted sand and gravel common. Gradational lower contact.
36.0 - 38.0'	Interbedded sand and gravel. Shale clasts common. Minor shale-rich till. Sharp lower contact.

Nordick Farm Section (cont.)

Interval	Description
38.0'	Sub-New Ulm boulder pavement.
38.0 - 50.0'	Intermixed dark gray, sandy till (Granite Falls Till) and reddish-brown, sandy till (Hawk Creek Till). Sharp lower contact.
50.0 - 51.0'	Dark-brown, silty sand (Gastropod Silts). Disseminated organic matter and some plant macrofossils. Sharp lower contact.
51.0 - 60.0'	Dark gray (unoxidized), pebbly till (Whetstone Till). Massive. Lower contact not visible.
60.0'	Base of ditch.

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Radiocarbon Section

COUNTY: Grant

LOCATION: North bank of the North Fork of the Yellow Bank River.
T 119 N, R 50 W, Section 09 SW¼ SW¼ NW¼ SW¼

ELEVATION: 1727'

Interval	Description
0.0 - 10.0'	Dark brown, silty, pebbly till (New Ulm Till). Shale pebbles common. Sharp lower contact, inclined at about 40° to the northeast.
10.0 - 15.0'	Interbedded fine sands and silt and tan, silty till (New Ulm Till). Possible flow tills. Beds inclined as in overlying unit. Gradational lower contact.
15.0 - 18.0'	Coarse sand and gravel. Very little shale. Beds inclined as in overlying unit. Sharp lower contact.
18.0 - 28.0'	Brown to grayish-brown, silty, pebbly till (Toronto Till?). Wood (sample #CG-88-W3) from interval dated at 29,910 ± 1160 yrbp (GX-14675). Beds inclined as in overlying unit. Lower contact not visible.
28.0'	Stream level.

Readers Digest Section

COUNTY:	Lac Qui Parle
LOCATION:	South bank of the South Fork of the Yellow Bank River. T 119 N, R 46 W, Section 11 SE¼ SE¼ NE¼ NE¼
ELEVATION:	1050'
Interval	Description
0.0 - 0.5'	Black topsoil
0.5 - 12.0'	Interbedded, oxidized silts and sand and gravel. Possible overbank deposits (or loess?). Sharp, erosional lower contact. Upper segment slumped.
12.0 - 16.0'	Pale brown (oxidized), pebbly, silty till (New Ulm Till). Abundant shale clasts. Calcareous. Sharp lower contact.
16.0 - 16.5'	Sand and gravel, oxidized. Abundant shale clasts. Sharp, erosional lower contact.
16.5'	Sub-New Ulm boulder pavement.
16.5 - 18.5'	Light reddish-brown (oxidized), sandy till (Hawk Creek Till). Calcareous. Gradational lower contact.
18.5 - 22.5'	Reddish-brown (unoxidized), sandy till (Hawk Creek Till). Calcareous.
22.5 - 24.5'	Dark-grayish-brown (unoxidized), silty till (Whetstone Till). Calcareous. Lower contact not visible.
24.5'	Water level.

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Rethke Farm Section

COUNTY:	Grant
LOCATION:	South bank of a small stream. T 121 N, R 48 W, Section 13 SW¼ NW¼ NW¼ NW¼
ELEVATION:	1112'
Interval	Description
0.0 - 2.0'	Light-brown (oxidized), sandy, silty till (New Ulm Till). Calcareous. Sharp lower contact.

Rethke Farm Section (cont.)

Interval	Description
2.0'	Sub-New Ulm boulder pavement.
2.0 - 19.0'	Yellow-brown (oxidized), sandy, pebbly till (Granite Falls Till). Calcareous. Fractures/joints with secondary iron stains and minor gypsum. Gradational lower contact.
19.0 - 25.0'	Dark gray (unoxidized), sandy, pebbly till (Granite Falls Till). Calcareous. Some fractures/joints. Lower contact not visible.
25.0'	Water level.

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Thurman Gravel Pit

COUNTY: Day

LOCATION: Gravel pit on distal face of Dakota Moraine.
T 121 N, R 53 W, Section 25 SE¼ NW¼ SE¼

ELEVATION: 1950'

Interval	Description
0.0 - 0.5'	Black, silty topsoil.
0.5 - 2.0'	Dark grayish-brown to light-brown silt (loess). Calcareous. Scattered large stones. Sharp, erosional(?) contact.
2.0'	Stone lag.
2.0 - 4.0'	Light grayish-brown, sandy till (till of the Dakota Moraine). Scattered large stone. Sharp lower contact.
4.0 - 8.5'	Brown to grayish-brown, sandy till (flow till). Poorly-bedded and poorly-sorted coarse sand to coarse gravel layers. Minor fine sand and silt layers. Gradational lower contact.
8.5 - 14.0'	Brown to tan, sand and fine pebbles. Planar bedding. Scattered clast up to 10" in diameter. Lower contact gradational.
14.0 - 20.0'	Brown to tan fine to medium sands and silts. Well-bedded. Scattered coarser layers, with some clasts to 5" diameter. Lower contact not visible.
20.0'	Base of section.

Whetstone Bridge Section

COUNTY:	Grant
LOCATION:	Exposure on east bank of Whetstone River, just north of bridge over river.
	T 121 N, R 47 W, Section 13 SW¼ SW¼ NE¼ NE¼
ELEVATION:	1050'

Interval	Description
0.0 - 5.0'	Covered.
5.0 - 15.0'	Yellow-brown (oxidized), coarse sand to coarse gravel. Sharp, erosional lower contact.
15.0 - 22.0'	Reddish-brown (oxidized), sandy till (Hawk Creek Till). Lower contact covered.
22.0 - 25.5'	Covered.
25.5 - 27.0'	Reddish-brown (oxidized?) sand and gravel. Sharp lower contact.
27.0 - 34.0'	Gray (unoxidized), pebbly till (Whetstone Till). Lower contact not visible.
34.0'	River level.

APPENDIX D

Textural and lithologic data.

LOCATION: The location is listed by the smallest township number, then the smallest range number, the smallest section number and then by quarter section: NE (A), NW (B), SW (C), SE (D). Numbers following the smallest quarter section are used to separate multiuple test holes at a given location. An R following the location indicates a site within the boundaries of the Lake Traverse Indian Reservation.

Sample #: Unique identification number assigned to each sample collected in the field or from core. Samples marked with an asterik (*) were not included in statistical analyses.

Munsell Color: Munsell Soil Color notation assigned to the silt and clay fraction in suspension, taken during the grain-size analysis.

TEXTURAL DATA

Weight % sand (phi): Relative percentage of the total sand fraction contained within whole phi intervals. Heading number is lower limit of interval. For eample, the 0 column is percent of total sand in the very coarse sand catergory (-1 to 0 phi or 2.0 mm to 1.0 mm).

Matrix Texture: Relative percentages of sand, silt, and clay in the matrix fraction (less than 2 mm) of sample.

VERY-COARSE SAND LITHOLOGIES

% Total: Relative percentages of Cretaceous, Paleozoic, and Precambrian lithologies in the very-coarse sand fraction of the sample. See Appendix E for an description of the various lithologic groups.

Kp/Kt: Ratio of number of Pierre Shale clasts to the total Cretaceous clasts in the very-coarse sand fraction.

LSI: Number of Lake Superior indicator clasts recognised in the very-coarse sand fraction of the sample.

Location	Sample #	Munsell Color	TEXTURAL DATA Weight % sand (phi) 0	1	2	3	4	Matrix Texture % Sd	% Sl	% Cl	V.C. SAND LITHOLOGIES % Total Ku	Pz	pC	Kp/Kt	LSI
BIG STONE MORAINE TILL															
121-47-04addd	TS89-103	10YR 7/3	11	12	18	34	26	30	45	25	3	51	46	0.00	0
DAKOTA MORAINE TILL															
120-54-01cccc	TS87-27	10YR 6/6	9	16	28	27	20	38	38	24	12	19	68	0.68	0
121-53-26cdcdR	TS87-26	10YR 6/6	7	13	21	30	28	38	29	33	9	26	65	0.56	0
121-53-35aaaaR	TS85-14*	10YR 5/4	6	19	29	29	18	48	25	27	0	0	100	0.00	0
121-53-36bbccR	TS87-25	10YR 6/6	9	15	26	29	21	37	32	31	12	17	71	0.71	1
DRIFT COMPLEX 5 TILL															
120-52-08aaadR	C882-07	10YR 6/6	17	16	23	26	17	49	28	24	7	26	67	0.67	0
GRANITE FALLS TILL															
118-47-18cbcd	CG84-02	10YR 6/6	9	16	25	28	21	57	31	12	5	40	55	0.15	2
119-49-08cbcc	CG88-08	10YR 6/4	6	12	26	34	22	43	34	24	2	30	68	0.33	0
119-49-18aaaa	CG88-02	2.5Y 4/2	7	13	22	31	27	42	35	23	7	25	67	0.35	0
119-49-18aaaa	TS89-04	10YR 4/2	8	15	23	31	24	33	33	35	8	28	63	0.43	0
119-49-18aaaa	TS89-38	10YR 5/3	8	12	21	30	29	49	34	17	8	19	73	0.73	0
120-46-20aacb	CG86-14a*	10YR 4/2	5	12	28	33	22	35	44	20	2	14	83	0.00	0
120-46-20aacb	CG86-20*	2.5Y 4/2	7	14	29	31	20	47	35	17	2	23	75	0.20	0
120-46-20aacb	TS89-23*	10YR 4/3	5	13	28	33	22	35	43	22	5	22	73	0.30	0
120-46-20aacb	TS89-24*	10YR 4/3	6	13	27	32	22	35	41	24	3	24	73	0.60	1
120-46-20aacb	TS89-25*	10YR 4/3	5	13	29	32	22	35	43	22	5	17	79	0.50	0
120-47-18cbcd	TS89-94	10YR 6/6	10	18	26	26	19	52	31	17	5	34	61	0.61	0
120-47-20baab	CG84-03*	10YR 6/6	6	14	29	31	20	52	32	16	2	23	75	0.00	1
120-47-20baab	TS89-31*	7.5YR 6/6	5	13	29	32	20	50	33	17	4	17	79	0.11	0
121-47-22cbbb	CG86-22*	10YR 7/6	10	15	23	26	25	43	36	22	4	36	59	0.08	0
121-47-23cccb	CG86-19	10YR 5/3	10	16	23	27	25	43	37	21	5	35	60	0.09	0
121-47-29bbcb	CG84-12	10YR 6/6	9	18	25	27	22	47	33	20	8	36	56	0.67	0
121-48-11bbbc	CG84-08	10YR 6/6	9	17	24	26	24	55	32	13	4	37	59	0.20	0
121-48-13cbbb	CG84-04	10YR 6/6	12	19	24	24	20	50	33	16	2	36	62	0.43	0
121-48-13cbbb	CG84-05	10YR 4/2	12	18	25	25	20	48	36	17	8	37	54	0.20	0
121-48-13cbbb	TS88-183	10YR 5/1	13	18	24	25	21	49	37	15	6	32	60	0.45	0
121-48-13cbbb	TS88-184	10YR 5/1	11	17	25	25	22	49	37	14	7	37	55	0.40	0
121-48-13cbbb	TS88-185	7.5YR 4/2	11	18	25	25	21	47	37	16	8	35	57	0.58	0

Location	Sample #	Munsell Color	TEXTURAL DATA Weight % sand (phi) 0	1	2	3	4	Matrix Texture % Sd	% Sl	% Cl	V.C. SAND LITHOLOGIES % Total Ku	Pz	pC	Kp/Kt	LSI
GRANITE FALLS TILL (cont.)															
121-48-13cbbb	TS88-186	10YR 6/6	13	19	26	25	17	48	36	16	8	31	61	0.33	0
121-48-13cbbb	TS88-187	10YR 6/4	12	17	26	25	20	46	36	17	4	38	57	0.36	0
121-48-13cbbb	TS88-188a	7.5YR 5/4	12	18	24	25	21	62	33	6	2	38	59	0.40	0
121-48-13cbbb	TS88-188b	10YR 6/4	10	14	22	31	23	40	35	24	16	35	49	0.80	0
122-48-02dcaa	CG86-09	2.5Y 6/6	10	18	25	26	21	45	33	22	11	29	59	0.56	0
122-48-29ddda	CG84-11	10YR 6/4	9	16	24	28	24	47	34	19	3	32	66	0.00	0
122-48-29ddda	TS88-168	10YR 6/4	9	16	25	27	22	45	34	21	5	33	61	0.60	0
122-48-29ddda	TS88-169	10YR 6/4	11	17	24	26	22	44	36	20	2	34	63	0.62	0
122-48-29ddda	TS88-170	10YR 6/4	10	16	24	26	24	44	35	21	6	31	64	0.35	0
122-48-29ddda	TS88-171	10YR 6/4	11	16	23	26	23	46	33	21	5	33	62	0.47	0
122-48-33bbba	C864-01	10YR 6/6	10	16	24	27	24	45	35	20	3	26	71	0.13	0
122-48-33bbba	C864-02	10YR 6/6	9	16	24	27	24	45	36	19	8	27	66	0.20	0
122-48-33bbba	C864-03	10YR 6/6	11	17	24	25	23	48	35	18	5	29	66	0.25	0
122-48-33bbba	C864-04	10YR 6/6	10	17	25	26	23	43	34	22	6	33	61	0.33	0
122-48-33bbba	C864-05	10YR 6/6	11	16	24	26	23	42	36	22	5	39	55	0.33	0
122-48-33bbba	C864-06	10YR 6/6	10	16	25	26	23	44	34	22	6	24	70	0.39	0
122-48-33bbba	C864-07	10YR 4/2	10	16	25	27	23	41	36	24	11	28	61	0.31	0
122-48-33bbba	C864-08	10YR 4/2	11	16	23	26	23	43	37	20	16	30	54	0.33	0
122-48-33bbba	C864-09	10YR 4/2	11	17	24	25	24	53	35	11	10	30	60	0.20	0
122-48-33bbba	C864-10	10YR 4/2	11	18	24	25	22	47	34	19	9	27	64	0.21	0
122-48-33bbba	C864-11	10YR 4/2	10	18	25	25	22	46	36	18	10	34	56	0.21	0
122-48-33bbba	C864-12	10YR 4/2	10	17	24	26	23	52	32	16	7	37	56	0.21	0
122-48-33bbba	C864-13	10YR 4/2	10	16	24	26	23	49	35	15	9	35	56	0.30	0
122-48-33bbba	C864-14	10YR 5/2	9	13	31	28	20	57	32	11	8	37	55	0.65	0
HAWK CREEK TILL															
119-46-11ddaa	CG86-26a	7.5YR 5/4	6	14	30	31	18	51	31	18	1	17	82	0.00	0
119-46-11ddaa	CG86-26b	7.5YR 5/4	6	13	31	31	19	55	29	16	2	15	83	0.00	0
119-46-11ddaa	CG86-27	5YR 5/6	7	13	30	31	19	61	26	13	1	15	84	0.00	0
120-46-20aacb	CG86-13	7.5YR 4/4	4	11	32	33	19	57	31	12	4	9	87	0.00	1
120-46-20aacb	CG86-14b*	5YR 4/4	5	13	32	32	18	63	25	12	12	36	52	0.00	2
120-46-20aacb	TS89-20	5YR 6/6	5	13	32	32	18	58	26	16	2	14	84	0.40	7
120-46-20aacb	TS89-21*	10YR 5/3	6	13	29	33	19	41	38	21	2	13	85	0.20	3
120-46-20aacb	TS89-22	5YR 5/4	5	13	32	32	18	64	24	12	2	8	90	0.00	11
120-46-20aacb	TS89-30	5YR 6/6	5	13	31	32	19	57	26	17	2	14	84	0.00	9
120-48-06adad	C862-04	5YR 4/3	6	13	30	32	20	54	29	18	4	12	84	0.25	0

Location	Sample #	Munsell Color	TEXTURAL DATA Weight % sand (phi) 0	1	2	3	4	Matrix Texture % Sd	% Sl	% Cl	V.C. SAND LITHOLOGIES % Total Ku	Pz	pC	Kp/Kt	LSI
HAWK CREEK TILL (cont.)															
120-48-06adad	C862-05	5YR 4/3	5	13	31	31	19	53	28	18	3	11	86	0.00	0
120-48-06adad	C862-06	5YR 4/3	6	13	30	32	20	53	29	18	3	16	80	0.00	0
120-48-06adad	C862-07	5YR 4/3	5	12	31	32	20	54	30	16	4	16	80	0.25	0
120-48-06adad	C862-08	5YR 4/3	5	13	31	31	20	52	30	18	2	15	82	0.67	0
120-48-06adad	C862-09	5YR 4/3	5	13	31	31	19	56	26	17	3	13	84	0.00	4
120-48-06adad	C862-10	5YR 4/3	5	14	30	31	20	55	28	17	3	14	83	0.17	5
120-48-06adad	C862-11	5YR 4/3	5	13	30	31	20	54	27	19	6	13	80	0.09	3
120-48-06adad	CG86-08	7.5YR 6/6	7	15	29	31	19	56	29	15	0	15	84	0.00	0
121-46-18bdca	CG87-08	2.5YR 5/8	6	13	31	31	20	64	24	13	1	12	87	0.33	9
121-46-18bdca	CG87-09	5YR 5/6	6	15	31	29	19	56	27	17	2	16	83	0.00	10
121-46-18bdca	TS88-194	7.5YR 6/4	6	13	29	30	22	53	31	16	1	20	80	0.50	0
121-46-18bdca	TS88-195	10YR 6/4	7	15	28	30	20	52	30	18	3	17	80	0.43	0
121-46-18bdca	TS88-196	5YR 5/6	5	12	31	32	20	62	25	13	2	10	88	0.20	6
121-46-18bdca	TS88-197	10YR 6/4	3	8	20	36	33	51	31	18	3	17	80	0.33	3
121-46-18ddbd	CG86-01	5YR 6/6	5	13	30	31	20	51	30	19	1	15	84	0.00	4
121-47-13acba	CG87-16	5YR 5/6	7	15	31	29	18	55	28	16	0	9	91	0.00	3
121-47-13accb	CG87-17	5YR 5/6	5	12	31	32	20	52	30	18	1	14	85	0.50	1
121-47-13bdcc	CG87-19	5YR 5/6	4	12	31	33	21	53	30	17	2	10	88	0.00	0
121-47-13bdcc	CG87-20	7.5YR 5/6	5	13	31	31	20	56	28	16	1	15	84	0.33	8
121-47-13caad	CG87-22	5YR 5/6	6	14	30	31	19	55	29	16	1	9	90	0.00	5
121-47-13cacd	CG87-23	5YR 4/4	5	14	30	31	21	52	30	18	2	8	90	0.50	7
121-47-13cbbb	TS89-12	5YR 4/4	5	14	30	32	19	56	27	16	1	11	88	0.00	7
121-47-13ccba	TS89-95	7.5YR 4/2	6	13	29	30	21	51	31	18	7	13	80	0.17	8
121-47-13ccba	TS89-97	7.5YR 4/2	7	10	30	32	21	51	31	19	2	13	85	0.50	5
121-47-13ccba	TS89-98	7.5YR 4/2	6	13	29	31	21	50	31	19	2	16	82	0.17	5
121-47-13ccba	TS89-99	7.5Y 4/6	7	14	29	31	19	52	32	16	1	14	85	0.00	6
121-47-13ccba	TS89-100	7.5YR 6/6	6	15	29	31	20	53	30	17	0	17	82	1.00	5
121-47-13ccba	TS89-101	5YR 6/6	6	13	29	30	22	57	27	15	1	12	86	0.33	10
121-47-13ccba	TS89-102	7.5YR 6/6	6	14	29	31	20	53	30	18	1	14	86	0.00	5
121-47-13ccdd	CG86-18	7.5YR 6/4	10	15	28	28	19	56	28	16	1	15	84	0.00	0
121-47-13ccdd	TS89-15	7.5YR 6/4	7	10	31	33	19	54	30	16	2	16	83	0.67	0
121-47-14daab	TS89-11	2.5Y 6/4	7	11	18	33	31	36	34	30	8	24	69	0.07	0
121-48-06aaaa	C865-08	7.5YR 4/2	6	15	32	29	17	58	29	13	2	14	83	0.25	0
121-48-06aaaa	C865-09	7.5YR 4/2	12	22	35	21	10	55	28	17	2	15	82	0.29	7
121-48-06aaaa	C865-10	7.5YR 4/2	6	15	30	32	18	51	33	16	3	15	83	0.00	2
121-48-06aaaa	C865-11	7.5YR 4/2	4	12	33	31	20	57	32	11	2	16	81	0.00	3
121-48-06aaaa	C865-12	7.5YR 4/2	5	13	30	33	19	50	29	21	1	12	87	0.33	8

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HAWK CREEK TILL (cont.)																
122-48-02dcaa	CG86-10	5YR 5/6	5	14	31	31	20	59	26	15	1	10	89	0.00	0
LOESS FROM TORONTO TILL PLAIN																
120-51-09bbbcR	C881-01	2.5Y 7/6	2	3	7	13	74	3	85	12	0	0	0	0.00	0
NEW ULM TILL																
118-47-06cdcd	TS89-75	2.5Y 5/4	9	13	21	31	26	32	29	38	30	11	59	0.81	0
118-47-10bbbc	TS89-76	10YR 6/6	7	13	20	32	28	40	34	26	30	16	53	0.93	0
118-48-13cbcc	TS89-74	10YR 6/6	6	12	20	33	29	26	26	48	9	21	70	0.80	0
118-48-27ccbc	TS89-73	10YR 6/6	10	15	24	29	23	28	32	40	16	13	72	0.73	0
118-48-30cddc	TS89-72	10YR 6/6	9	14	23	29	25	32	30	38	18	23	59	0.87	0
118-49-01bbaa	TS89-37	2.5Y 6/4	5	10	22	37	26	20	34	45	44	22	34	0.93	0
118-49-02cbbc	TS89-32	2.5Y 5/6	8	14	27	29	22	34	32	34	20	17	63	0.77	0
118-49-05dddd	TS89-33	2.5Y 5/6	8	15	28	30	19	27	29	43	22	25	53	0.90	0
118-49-07bbbb	TS89-34	2.5Y 5/4	10	16	24	29	20	29	31	41	30	25	45	0.81	0
118-49-30ddcc	TS89-70	10YR 6/6	9	13	22	30	26	45	29	25	25	15	60	1.00	0
118-49-34aabb	TS89-71	7.5YR 6/6	9	15	24	28	23	33	33	35	19	24	57	0.86	0
118-50-09dccd	TS89-36	10YR 6/4	15	19	24	25	17	44	29	27	5	19	77	0.60	1
118-50-11bbbb	TS89-35	2.5Y 5/4	8	15	24	31	22	27	31	42	28	26	46	0.80	0
118-50-24cccc	TS85-03*	2.5Y 6/4	6	27	25	23	19	41	31	28	18	21	61	0.93	0
118-50-31cccc	TS89-68	2.5Y 6/6	10	17	25	27	21	31	33	37	30	19	51	0.71	0
118-50-36cdbc	TS89-69	2.5Y 6/6	10	15	22	28	24	41	31	27	21	20	59	0.95	0
118-51-25	TS85-02*	10YR 6/4	10	17	23	28	22	37	30	33	4	33	64	0.75	0
119-46-01aaba	CG86-31	10YR 4/6	8	13	20	31	28	43	35	22	60	19	21	0.99	0
119-46-11ddaa	CG86-28	2.5Y 5/4	7	11	19	33	30	45	36	19	44	18	38	1.00	0
119-47-08dddd	TS89-77	10YR 6/4	7	10	19	34	30	44	32	24	41	15	45	0.99	0
119-47-18bbbc	TS89-78	10YR 5/4	8	13	23	32	24	33	30	38	24	20	56	0.82	0
119-48-21cccc	TS89-79	2.5Y 6/4	8	14	26	31	21	30	27	43	30	24	47	0.85	0
119-49-07ddaa	TS89-05	2.5Y 6/4	10	17	29	32	12	28	32	41	25	19	56	0.96	0
119-49-08cbcc	CG88-07	10YR 5/4	5	15	25	30	24	25	34	42	27	21	50	0.93	0
119-49-17bbbb	CG88-06	10YR 5/4	7	15	26	30	22	28	32	40	16	23	59	0.90	0
119-49-17ccdc	TS89-01	10YR 6/4	7	13	25	31	24	27	32	41	28	18	54	0.78	0
119-49-18aaaa	CG88-04	10YR 4/3	8	15	26	29	21	31	34	35	19	19	62	0.60	0
119-49-18aaaa	CG88-05	10YR 5/4	7	14	25	30	24	25	33	42	23	20	57	0.95	0
119-49-18aaaa	TS89-02	10YR 6/4	7	15	25	32	22	29	31	40	18	25	57	0.74	0

Location	Sample #	Munsell Color	TEXTURAL DATA Weight % sand (phi) 0	1	2	3	4	Matrix Texture % Sd	% Sl	% Cl	V.C. SAND LITHOLOGIES % Total Ku	Pz	pC	Kp/Kt	LSI
NEW ULM TILL (cont.)															
119-49-18aaaa	TS89-03	10YR 6/6	6	14	23	31	26	33	31	36	16	24	60	0.54	0
119-49-18aaaa	TS89-39	10YR 4/3	11	16	24	27	22	32	34	34	23	21	56	0.69	0
119-49-18aaaa	TS89-40	10YR 6/4	8	15	25	30	22	30	31	39	22	19	59	0.91	0
119-50-06aaaa	TS89-44	10YR 6/6	7	13	20	33	27	35	40	25	20	28	51	0.71	0
119-50-09cbcc	CG88-13	10YR 5/3	8	17	25	28	22	28	34	38	21	22	57	0.54	0
119-50-09cbcc	CG88-14	10YR 4/4	9	13	20	29	28	31	35	34	35	23	43	0.84	0
119-50-09cbcc	TS89-42	10YR 5/3	9	16	26	29	20	31	32	38	19	18	64	0.79	0
119-50-09cbcc	TS89-43	10YR 5/4	8	12	21	32	28	23	39	38	27	21	52	0.86	0
119-50-15cccc	TS89-41	7.5YR 5/6	6	13	23	31	28	14	41	44	36	21	42	0.84	0
119-50-20cddd	TS85-04*	10YR 5/4	5	11	25	33	26	44	26	31	2	1	98	0.67	0
119-51-13dddc	TS89-06	10YR 6/8	10	16	24	28	22	42	33	25	21	20	59	0.93	0
120-46-20aacb	CG86-15	2.5Y 4/4	7	13	20	32	28	43	32	24	52	19	29	0.97	0
120-46-20aacb	CG87-04	10YR 5/6	9	13	19	31	28	43	33	23	46	15	39	0.98	0
120-46-20aacb	CG87-05	10YR 5/4	10	13	19	32	27	42	33	25	55	13	32	0.97	0
120-46-20aacb	TS89-26	10YR 5/6	7	12	18	32	30	44	33	23	46	22	32	0.98	1
120-46-20aacb	TS89-27	2.5Y 4/2	9	12	21	31	28	43	34	23	45	21	35	0.93	0
120-46-20aacb	TS89-28	2.5Y 5/6	9	13	19	31	28	44	34	21	42	24	34	0.99	1
120-46-20aacb	TS89-29	2.5Y 5/6	9	12	19	33	27	41	35	25	50	18	32	0.97	1
120-48-06adad	C862-01	10YR 6/4	5	11	21	34	29	33	31	36	43	18	39	0.78	0
120-48-06adad	C862-02	2.5Y 6/6	7	12	21	31	29	43	32	25	33	25	42	0.88	0
120-48-06adad	C862-03	10YR 5/6	6	10	19	33	31	45	33	22	26	27	47	0.89	0
120-48-06adad	CG86-07	10YR 5/4	9	13	20	31	27	40	35	25	52	17	31	0.95	0
120-48-10daaa	TS89-80	10YR 6/6	5	10	18	34	32	50	33	17	28	18	54	0.90	0
120-48-11bbbb	TS89-92	2.5Y 6/6	7	11	19	33	30	43	32	26	38	18	44	0.91	0
120-49-04dddd	TS87-01	2.5Y 5/6	7	13	21	31	27	34	30	36	33	20	47	0.95	0
120-49-06dddd	TS89-48	2.5Y 5/4	5	17	25	30	23	27	24	49	46	14	39	0.96	0
120-49-07bbbb	TS87-02	2.5Y 5/6	7	12	22	33	27	19	25	57	44	18	39	1.00	0
120-49-29aaaa	TS89-81	2.5Y 6/4	5	12	20	34	29	22	27	51	30	16	54	0.83	0
120-49-36ddaa	C861-01	2.5Y 5/6	7	13	23	31	26	29	28	43	38	28	34	0.91	0
120-49-36ddaa	C861-02	2.5Y 5/6	8	11	19	32	30	29	28	43	30	23	46	0.96	0
120-49-36ddaa	C861-03	2.5Y 5/6	7	12	21	32	29	29	27	44	40	19	41	0.89	0
120-49-36ddaa	C861-04	5Y 4/3	9	20	23	26	22	37	25	38	42	16	41	0.87	0
120-49-36ddaa	C861-05	5Y 4/3	12	20	19	26	23	35	26	39	41	18	41	0.95	0
120-50-03dddd	TS87-03	2.5Y 6/4	9	15	21	28	27	21	27	52	33	17	50	1.00	1
120-50-04bbbb	TS89-47	2.5Y 5/4	6	10	21	31	32	16	34	50	29	24	46	0.83	0
120-50-04cccb	TS87-04	2.5Y 5/6	8	14	27	28	23	24	32	44	43	15	41	0.96	0
120-50-05cccc	TS87-05*	2.5Y 5/6	1	3	11	27	58	7	40	53	0	0	100	0.00	0

Location	Sample #	Munsell Color	TEXTURAL DATA Weight % sand (phi) 0	1	2	3	4	Matrix Texture % Sd	% Sl	% Cl	V.C. SAND LITHOLOGIES % Total Ku	Pz	pC	Kp/Kt	LSI
NEW ULM TILL (cont.)															
120-50-05dddd	TS89-50	2.5Y 6/6	6	14	25	30	26	28	33	39	22	19	60	0.85	0
120-50-08bbbb	TS89-51	2.5Y 6/6	10	17	26	26	21	35	29	36	22	29	50	0.90	0
120-50-08cdca	CG88-11	10YR 6/6	8	13	20	30	28	38	37	25	21	28	51	0.91	1
120-50-08cddd	CG88-10	10YR 4/3	7	13	20	30	29	37	40	24	27	30	44	0.83	0
120-50-08cddd	TS89-46	10YR 4/3	7	13	20	31	29	38	39	24	25	24	51	0.76	0
120-50-11aaaa	TS89-49	10YR 6/6	12	15	21	28	23	19	24	58	33	22	46	1.00	0
120-50-17baaa	CG88-09	10YR 4/3	9	14	21	29	27	37	36	27	27	23	50	0.83	0
120-50-17bcbb	CG88-12	10YR 6/6	7	13	20	31	28	38	34	28	23	30	47	0.82	0
120-50-17bcbb	TS89-45	10YR 6/6	9	13	20	30	27	37	35	28	21	26	53	0.85	0
120-50-34bbaa	TS89-82	10YR 6/4	9	16	25	29	21	34	33	33	20	19	61	0.73	0
120-51-01cbbb	TS87-07	2.5Y 5/6	9	15	24	27	24	31	30	39	21	17	62	0.83	0
120-51-01cbcb	TS88-176	7.5YR 5/2	11	14	24	28	23	27	30	44	30	19	51	0.93	0
120-51-01cbcb	TS88-177	7.5YR 4/2	10	14	24	29	24	24	32	44	30	19	52	0.83	0
120-51-01cbcb	TS88-178	10YR 4/2	8	15	24	29	24	27	32	41	25	22	52	0.77	0
120-51-01cbcb	TS88-179	5YR 4/2	10	14	23	28	24	26	31	43	31	25	44	0.88	0
120-51-01cbcb	TS88-180	7.5YR 5/4	10	15	23	28	23	27	30	43	24	22	54	0.93	0
120-51-01cbcb	TS88-181	10YR 5/4	9	16	26	26	24	25	29	47	31	23	46	0.91	0
120-51-01cbcb	TS88-182	10YR 6/4	9	16	28	27	19	29	31	39	25	26	49	0.95	0
120-51-01daad	TS87-06	2.5Y 5/6	7	15	27	29	23	32	33	34	14	27	59	0.78	0
120-51-03ccdd	TS89-53	10YR 6/4	9	15	26	28	22	33	32	35	17	23	59	0.89	0
120-51-03dddb	TS87-08	10YR 5/4	9	14	22	28	26	45	30	26	18	26	56	0.89	0
120-51-04cbcb	TS89-55	2.5Y 5/4	7	13	24	33	23	27	34	40	18	23	58	0.64	0
120-51-04cdba	TS87-10	10YR 5/6	7	12	19	30	32	29	37	34	26	24	50	0.95	0
120-51-05dddd	TS85-08	10YR 6/4	10	15	24	28	23	38	30	32	8	21	71	0.67	0
120-51-09baaa	TS89-54	10YR 6/6	7	12	21	33	27	32	39	29	27	23	50	0.79	0
120-51-09cccc	TS89-61	10YR 5/6	7	15	24	31	22	35	33	32	11	22	66	0.70	0
120-51-10bbbb	TS87-09	10YR 5/6	7	12	19	31	30	35	36	29	27	27	46	0.97	0
120-51-11baaa	TS89-52	2.5Y 6/4	8	15	25	31	21	27	34	39	17	22	61	0.84	0
120-51-12bbbb	TS85-09*	10YR 4/4	9	18	29	28	16	31	48	21	1	2	97	1.00	0
120-51-20cccc	TS89-62	10YR 6/6	7	19	29	25	19	34	32	34	6	20	74	0.50	0
120-51-24cddb	TS89-83	2.5Y 6/4	10	15	22	30	24	41	32	27	19	24	57	0.88	0
120-51-32bbbb	TS89-63	10YR 6/6	10	16	25	27	22	34	28	39	12	29	59	0.70	1
120-52-01cbcc	TS87-13	10YR 6/6	8	17	27	28	20	36	29	35	15	29	56	0.85	0
120-52-01ddad	TS87-12	10YR 5/6	9	15	25	29	22	48	34	18	15	29	55	0.83	0
120-52-14bcbc	TS87-14	10YR 6/6	9	15	23	28	25	34	36	31	17	30	53	0.79	0
120-52-24aaaa	TS89-64	10YR 6/6	10	16	23	29	23	39	31	30	7	23	70	0.59	0
121-47-13bdcc	CG87-21	10YR 5/6	10	15	21	30	24	46	36	18	44	17	39	0.95	1

NEW ULM TILL (cont.)

Location	Sample #	Munsell Color	TEXTURAL DATA Weight % sand (phi) 0	1	2	3	4	Matrix Texture % Sd	% Sl	% Cl	V.C. SAND LITHOLOGIES % Total Ku	Pz	pC	Kp/Kt	LSI
121-47-13cbdb	TS89-13	10YR 6/6	8	13	21	33	25	47	35	18	48	19	34	0.93	0
121-47-14daab	TS89-10	10YR 6/6	9	14	21	33	23	48	35	17	38	21	42	0.96	0
121-48-03bbba	CG84-09	10YR 6/4	11	16	22	26	25	38	33	29	16	28	54	0.80	0
121-48-06aaaa	C865-01	2.5Y 6/6	8	15	27	30	21	35	37	28	35	22	43	0.87	0
121-48-06aaaa	C865-02	2.5Y 6/6	8	17	24	28	23	37	31	32	19	22	59	0.89	0
121-48-06aaaa	C865-03	2.5Y 6/6	9	16	26	29	20	38	34	28	28	20	51	0.89	0
121-48-06aaaa	C865-04	2.5Y 4/2	10	17	23	25	25	39	35	25	33	19	47	0.74	0
121-48-06aaaa	C865-05	2.5Y 4/2	9	16	28	26	21	35	36	28	26	28	45	0.74	0
121-48-06aaaa	C865-06	2.5Y 4/2	8	16	24	26	26	39	35	26	26	30	43	0.74	1
121-48-06aaaa	C865-07	2.5Y 4/2	10	16	28	25	20	38	36	26	20	26	54	0.69	0
121-48-11bbbc	CG84-07	2.5Y 6/6	10	13	16	27	34	43	42	15	29	23	48	0.96	0
121-48-13bccd	CG84-06	2.5Y 6/6	8	12	19	32	29	41	35	23	46	22	32	0.92	0
121-48-19aaaa	TS89-91	2.5Y 6/6	9	15	22	30	24	34	26	41	38	17	44	0.95	0
121-49-03bbbb	TS89-90a	2.5Y 6/4	7	12	22	32	27	29	29	42	21	25	54	0.91	0
121-49-21aaaa	TS89-90b	10YR 6/3	5	10	21	35	29	21	28	50	31	22	47	0.89	0
121-50-01aaaa	TS89-89	10YR 5/4	5	11	19	30	35	16	25	59	28	17	55	0.67	0
121-50-09baaa	TS89-88	2.5Y 6/6	9	14	24	29	24	31	33	37	17	24	59	0.90	0
121-50-19cddc	TS89-60	10YR 5/4	9	14	25	28	23	26	29	45	18	20	62	0.86	0
121-50-35baaa	TS89-07	10YR 5/4	7	14	24	29	25	29	33	38	20	25	55	0.92	0
121-51-01dddd	TS89-87	2.5Y 6/4	7	11	19	31	32	39	31	30	36	19	45	0.90	0
121-51-04adddR	TS89-59	10YR 5/6	11	16	28	26	19	31	38	30	17	20	63	0.77	0
121-51-08aadaR	TS89-58	10YR 6/6	10	16	24	28	23	29	35	36	13	32	55	0.76	0
121-51-10ccccR	TS89-57	10YR 6/6	9	15	24	29	23	34	36	30	13	28	59	0.67	0
121-51-14dbdd	TS89-08	10YR 5/4	7	12	20	33	28	45	29	26	26	23	51	0.95	0
122-48-29ddda	CG84-10	10YR 5/4	9	11	17	31	31	36	40	24	40	21	39	1.00	0
122-48-29ddda	TS88-172	2.5Y 6/4	8	13	20	32	27	35	35	30	40	20	39	0.99	0
122-48-29ddda	TS88-173	10YR 6/4	7	9	19	32	33	37	38	25	33	23	43	1.00	0
122-48-29ddda	TS88-174	2.5Y 6/4	10	12	18	34	26	39	32	28	44	18	38	0.99	0
122-48-29ddda	TS88-175	2.5Y 6/4	9	10	14	35	33	35	35	30	36	21	41	1.00	0
122-48-29dddd	C863-01	10YR 5/6	3	7	23	38	28	46	34	20	17	62	21	0.90	0
122-48-29dddd	C863-02	10YR 5/6	4	7	15	37	36	38	37	25	46	15	39	1.00	0
122-48-29dddd	C863-03	10YR 5/6	4	8	19	39	30	39	30	30	37	14	48	0.94	0
122-48-29dddd	C863-04	10YR 5/6	8	12	18	34	28	40	33	27	36	15	49	1.00	0

Location	Sample #	Munsell Color	TEXTURAL DATA Weight % sand (phi) 0	1	2	3	4	Matrix Texture % Sd	% Sl	% Cl	V.C. SAND LITHOLOGIES % Total Ku	Pz	pC	Kp/Kt	LSI
SOUTH FORK TILL															
120-46-20aacb	TS89-17	5Y 3/2	12	18	24	26	22	28	32	40	33	17	50	0.48	0
120-48-06adad	C862-12	10YR 3/3	11	18	26	26	19	37	30	33	27	19	54	0.53	0
120-48-06adad	C862-13	10YR 3/3	10	18	26	27	19	35	31	34	23	14	63	0.58	0
120-48-06adad	C862-14	2.5Y 3/2	10	16	26	27	21	34	31	34	27	17	53	0.58	0
120-48-06adad	C862-15	2.5Y 3/2	10	16	26	27	21	34	32	34	23	18	59	0.56	0
120-48-06adad	C862-16	2.5Y 3/2	9	17	26	27	21	35	32	34	31	17	52	0.54	0
120-48-06adad	C862-17	2.5Y 3/2	12	16	25	26	20	37	31	32	25	17	59	0.46	0
120-48-06adad	C862-18	2.5Y 3/2	9	16	26	28	21	34	32	34	27	20	53	0.53	0
TORONTO TILL															
117-52-24cccc	CG84-01	2.5Y 6/4	8	15	22	28	27	35	34	30	17	34	49	0.60	0
120-51-04bcbcR	TS87-15	2.5Y 6/6	7	13	23	31	26	38	34	28	18	26	56	0.81	0
120-51-09bbbcR	C881-02	2.5Y 6/4	12	17	26	24	20	32	34	34	26	28	46	0.81	0
120-51-09bbbcR	C881-03	2.5Y 6/4	11	17	23	26	23	32	33	34	26	29	45	0.75	0
120-51-09bbbcR	C881-04	5Y 4/3	12	17	27	24	19	32	33	34	25	23	52	0.71	0
120-51-09bbbcR	C881-05	5Y 4/3	10	17	23	27	24	26	40	34	19	30	50	0.69	0
120-51-09bbbcR	C881-06	5Y 4/3	9	16	26	25	23	24	44	32	24	27	48	0.61	1
120-51-18abbbR	TS89-66	2.5Y 6/6	11	17	25	26	22	32	34	34	18	23	59	0.75	0
120-52-08aaadR	C882-01	2.5Y 6/4	10	16	24	27	23	25	39	35	13	34	52	0.73	0
120-52-08aaadR	C882-02	2.5Y 6/4	9	17	25	27	22	29	39	32	12	23	65	0.71	0
120-52-08aaadR	C882-03	2.5Y 6/4	9	14	27	28	21	23	42	34	17	27	56	0.81	0
120-52-08aaadR	C882-04	2.5Y 5/4	5	11	21	31	32	16	52	32	11	29	60	0.75	0
120-52-08aaadR	C882-05	2.5Y 5/4	6	14	25	28	26	16	52	32	13	30	57	0.50	0
120-52-11ddddR	TS89-67	10YR 6/6	11	16	25	27	21	27	36	37	16	23	61	0.86	0
120-52-26abba	TS89-65	2.5Y 6/6	9	15	23	28	25	35	35	30	15	33	52	0.82	0
121-51-04aaaaR	TS89-85	10YR 6/4	11	16	25	25	24	18	40	42	21	28	51	0.55	0
121-51-06bcccR	TS89-84	10YR 6/4	10	15	24	27	25	24	43	33	20	31	50	0.70	0
121-51-29bbbbR	TS87-16	10YR 6/6	7	13	22	31	27	39	34	27	8	31	62	0.47	1
121-52-21daddR	TS87-20	10YR 6/4	9	16	26	27	22	39	36	24	8	38	54	0.54	0
121-52-25aaddR	TS87-17	2.5Y 6/6	9	17	26	26	22	31	33	35	22	21	57	0.85	0
121-52-25bbbbR	TS87-18	2.5Y 6/6	10	16	25	27	22	28	36	36	22	27	51	0.72	0
121-52-27aaaaR	TS87-19	2.5Y 5/6	9	17	26	27	21	33	35	33	14	20	66	0.68	0
121-52-27cdcdR	TS89-56	2.5Y 6/4	9	15	26	27	22	25	40	35	15	28	57	0.57	0
121-52-29cdccR	TS87-22	10YR 7/6	10	16	26	27	21	26	38	35	15	31	54	0.65	0
121-52-30dccdR	TS87-23	10YR 6/6	7	16	26	27	23	29	40	31	14	24	62	0.87	0
121-52-32aaaaR	TS85-13*	10YR 3/2	8	23	33	23	14	18	51	31	0	5	95	0.00	0

Location	Sample #	Munsell Color	TEXTURAL DATA Weight % sand (phi) 0	1	2	3	4	Matrix Texture % Sd	% Sl	% Cl	V.C. SAND LITHOLOGIES % Total Ku	Pz	pC	Kp/Kt	LSI
TORONTO TILL (cont.)															
121-52-33baabR	TS87-21	10YR 7/6	11	15	24	26	24	26	39	36	14	34	52	0.88	1
121-52-36bbbbR	TS85-12*	10YR 3/2	3	10	27	37	24	12	56	33	3	0	97	0.00	0
122-52-31ccccR	TS89-86	10YR 6/4	9	15	22	28	26	22	39	39	11	33	56	0.69	0
WHETSTONE TILL															
119-46-01aaba	CG86-30	10YR 4/2	7	11	23	33	26	41	36	23	12	21	67	0.21	0
119-46-11ddaa	CG86-25	10YR 4/3	7	13	26	31	23	42	32	26	14	25	61	0.38	0
120-46-20aacb	CG86-16	10YR 3/3	6	12	24	33	25	39	34	28	13	25	61	0.29	0
120-46-20aacb	CG87-03	10YR 4/3	6	13	24	32	25	40	31	29	8	25	65	0.23	1
120-46-20aacb	TS89-18	5Y 3/2	7	13	25	33	21	40	32	28	12	24	64	0.28	0
120-47-18cbcd	TS89-93	10YR 4/2	7	14	25	31	23	37	33	30	15	27	58	0.30	0
121-46-18bdca	CG87-06	2.5Y 3/2	7	13	24	32	24	40	33	27	18	26	57	0.33	0
121-46-18bdca	CG87-07	2.5Y 3/2	7	12	24	32	25	41	35	24	15	21	64	0.25	0
121-46-18bdca	CG87-10	2.5Y 4/2	4	9	21	38	28	42	33	25	12	27	60	0.38	0
121-46-18bdca	TS88-189	10YR 4/1	7	12	23	31	28	37	33	30	20	27	52	0.30	0
121-46-18bdca	TS88-190	10YR 4/1	7	13	24	32	24	40	31	29	15	25	59	0.23	0
121-46-18bdca	TS88-191	10YR 5/1	6	12	24	32	25	39	33	28	19	21	59	0.19	0
121-46-18bdca	TS88-192	10YR 4/2	7	12	25	32	24	39	35	26	18	26	56	0.35	0
121-46-18bdca	TS88-193	7.5YR 4/2	8	13	23	32	23	41	30	29	10	30	60	0.20	0
121-47-13bdca	CG87-18	10YR 3/3	6	12	23	32	28	37	35	28	12	27	61	0.21	0
121-47-13ccdd	CG86-17	10YR 3/3	7	12	23	31	27	33	33	34	19	22	60	0.24	0
121-47-13ccdd	TS89-16	2.5Y 4/2	7	13	25	33	22	31	31	38	20	26	54	0.45	0
YELLOW BANK TILL															
120-49-36ddaa	C861-06	2.5Y 5/4	9	14	20	30	26	32	27	41	38	23	39	0.77	0
120-49-36ddaa	C861-07	2.5Y 5/4	15	15	18	27	25	33	26	40	42	21	37	0.95	0
120-49-36ddaa	C861-08	10YR 5/4	8	13	20	31	29	32	28	40	36	21	43	0.95	0
120-49-36ddaa	C861-09	5Y 4/2	8	13	19	30	30	28	33	39	48	18	32	0.80	0
120-49-36ddaa	C861-10	5Y 4/2	10	16	21	28	24	22	26	52	39	15	45	0.62	0
120-49-36ddaa	C861-11	5Y 4/2	8	18	26	28	20	32	24	43	39	20	39	0.54	0
122-48-02dcaa	CG86-11*	2.5Y 5/4	10	18	23	25	23	26	32	42	15	18	68	0.56	0
122-48-33bbba	C864-15	2.5Y 4/2	10	15	23	27	24	32	35	33	40	23	37	0.67	0

APPENDIX E

Description of laboratory procedures.

Grain-size analysis procedure

The grain-size analysis procedure outlined here is adapted mainly from that of Folk (1974) and consists of three steps: wet sieving, dry sieving, and pipette analysis.

1) Randomly select about 30 grams of air-dried sediment and place in a labeled 250 ml beaker. Enter beaker number on data sheet.

2) Add approximately 150 ml distilled water to the beaker. Carefully measure exactly 20 ml of dispersant solution and add to beaker. Record the weight of dispersant solution on data sheet. Allow sample to soak for 12 hours.

3) Wet both sides of a 0.0625 mm sieve and place loosely onto a funnel draining into a labeled 1000 ml graduated cylinder. Record cylinder number on data sheet. After the sample has completely disaggregated, stir the contents of the beaker thoroughly and wait a few seconds for the larger particles to settle out. Carefully decant the muddy water onto the sieve. Add more distilled water to the beaker, stir and decant.

4) Repeat the process until only sand remains in the beaker. Wash the sieve with distilled water to remove all less than 0.0625 mm particles. Note: Care should be taken so that the total amount of water and fine sediment in the cylinder does not exceed 1000 ml. Cover cylinder and set aside.

5) After the wet sieving, a small amount of sand may remain on the sieve. Carefully wash this sediment back into the 250 ml beaker. Decant any excess water from the 250 ml beaker containing the greater than 0.0625 mm material. Place the beaker into a drying oven set at 95° Celsius. Sample should dry in approximately 6 hours.

6) When the coarse fraction is dry, place it in a stack of clean sieves, consisting of whole phi sieves from -1 to 4 (2.0 mm, 1.0 mm, 0.5 mm, 0.25 mm, 0.125 mm, 0.0625 mm)

and a pan. Place the stack of sieves into a ATM Sonic Sifter and shake for 7 minutes.

7) Discard any pebbles caught in the 2.0 mm sieve. Weigh the sand caught on each of the sieves to the nearest 0.01 grams and record weight on the data sheets. Retain the very-coarse sand fraction (1.0 mm sieve) for lithologic analysis. The remaining sand fraction can be retained for future study or discarded. Discard any material in the pan.

8) Fill the graduated cylinder to the 1000 ml level with room temperature distilled water. Agitate the contents of the cylinder thoroughly with a plunger and allow to stand. If flocculation occurs, add additional dispersant and reagitate. Continue until there is no flocculation. Record the weight of any additional dispersant.

9) Reagitate the cylinder thoroughly, beginning at the bottom with short, quick strokes, and ending with long, uniform strokes from top to bottom. Make certain that all sediment from the bottom of the cylinder is in suspension. When all material is in suspension, stop agitation and record the time on the data sheet.

10) Insert a 20 ml pipette to a depth of 20 cm. After 20 seconds has elapsed, withdraw 20 ml of the sediment suspension. This withdrawal contains only material less than 0.0625 mm in diameter (silt and clay only). Empty the contents into a pre-weighed (to nearest 0.0001 gram) 50 ml beaker. Rinse pipette once into the beaker with distilled water. Record beaker number on data sheet. Set beaker aside.

11) Reagitate the material in the cylinder. When all the sediment is once again in suspension, stop agitation and record time on data sheet.

12) Insert a 20 ml pipette to a depth of 20 cm. After 20 seconds has elapsed, withdraw 20 ml of the sediment suspension. Empty the contents into a pre-weighed (to nearest 0.0001 gram) 50 ml beaker. Rinse pipette once into the beaker with distilled water. Record beaker number on data sheet. Set beaker aside.

13) Record the temperature in a cylinder containing distilled water and 20 ml of dispersant on the data sheet. From the table below, determine the time for the less than 3.9 micron (0.0039 mm) extraction. Record this time on the data sheet.

Temperature, °C	Withdrawal depth (cm)	Withdrawal time
20	10 cm	2 hr 2 min
21	10 cm	1 hr 59 min
22	10 cm	1 hr 56 min
23	10 cm	1 hr 53 min
24	10 cm	1 hr 51 min
25	10 cm	1 hr 48 min
26	10 cm	1 hr 46 min
27	10 cm	1 hr 44 min

14) At the appropriate time, insert a 20 ml pipette to a depth of 10 cm and withdraw 20 ml of suspension. Empty the contents of the pipette into a pre-weighed 50 ml beaker. Wash pipette once into the beaker with distilled water. Record the beaker number on the data sheet.

15) Place the labeled beakers into the drying oven set at 95° Celsius overnight.

16) When all moisture has evaporated from the beakers, remove from the oven and allow them to equilibrate to ambient room temperature and humidity. Weigh the beakers to the nearest 0.0001 gram and record the weights on the data sheet.

Computation of results:

17) Total the individual weights of the various sand-fraction separates.

18) Subtract the tare weight and dispersant weight from the gross weight of all three beakers. Determine the average of the two less than 0.0625 mm extractions. Multiply the value by 50 to determine the total weight of silt and clay in the sample. Multiply the weight of the less than 0.0039 mm withdrawal by 50 to get the total weight of clay in the sample. The total weight of silt is the difference between these two numbers.

19) Add the total weight of the silt and clay to that of the sand. This is the total weight of the till matrix in the sample. Relative percentages of sand, silt, and clay are determined by dividing the fraction weight by the total weight.

20) Within the sand fraction of each sample, relative weight percents are determined by dividing the fraction weight by the total weight of sand.

Preparation of dispersant solution

Heat approximately 1 liter of distilled water to near boiling on a hot plate. To the water add about 100 grams of sodium hexametaphosphate and about 10 grams of sodium bicarbonate. Stir until the solutes are completely dissolved. Remove from heat and allow to cool completely. Transfer the dispersant solution to a clean Nalgene bottle.

Pipette exactly 20 ml of the solution into a pre-weighted 50 ml beaker. Rinse the pipette into the beaker with distilled water. Repeat with a second beaker. Place both beakers into a drying oven set at 95° Celsius. After all moisture has evaporated, remove beakers from the oven and allow them to equilibrate to ambient room temperature and humidity. Weigh the beakers to the nearest 0.0001 gram.

Subtract the tare weight from the final weight of each beaker. Average the two values. Divide this number by 50 and write this number on the outside of the Nalgene bottle. This is the approximate weight of dispersant in each of the 20 ml sediment solution extractions taken during the grain-size analyses.

Analysis of very-coarse sand lithologies.

The following procedure was used in the analysis of the very-coarse sand fraction of the samples.

1) Place the very-coarse sand fraction collected during grain-size analysis in a 50 ml beaker. Add about 10 ml of alizarin red dye solution (0.1 gram alizarine red dye in 100 ml 0.2% hydrochloric acid). Let stand for 1 minute.

2) Pour off the dye and place beaker into a drying oven set at 95° C. Drying takes about 1 hour.

3) Split sample once to get about 200 grains for counting. Examine the sand split with a binocular microscope set at 10x. This is sufficient magnification for most identifications. The sand grains were separated into 10 catergories, listed below as Lithologic Subdivisions, based on lithology and inferred age (Table E-1).

4) Relative percentages of the major age groups (Cretaceous, Paleozoic, and Precambrian) are determined by dividing the total number of clasts in the group by the total number of identifiable grains. Secondary minerals and clasts and unidentifiable grains are not included.

Table E-1. Very-coarse sand lithologic divisions.

Major Grouping	Lithologic Subdivision	Typical Clast Lithologies
Cretaceous	Shale	Siliceous shale
	Carbonate	Calcareous shale Limestone
	Other	*Inoceramid* fragments Shark/fish teeth
Paleozoic	Carbonate	Limestone Dolostone Chert
Precambrian	NE Indicators	Agates Red sandstones Vesicular & amydaloidal volcanics
	Crystalline	Coarse-grained igneous & metamorphic rocks Quartz Biotite
	Aphanitic	Basalt Slate
	Other	Quartzite Chert Graywacke
Misc.	Secondary	Gypsum Fe-cemented aggregates
	Unknowns	