Quaternary Geology of the Southern Lake Agassiz Basin

Kenneth L. Harris, Mark R. Luther
and
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Editors

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F.O.P. 96
LAKE AGASSIZ

Guidebook and Miscellaneous Short Papers for:

Midwest Friends of the Pleistocene 43rd Annual Meeting
May 31-June 2, 1996
&
Post-Meeting Fieldtrip
June 2-3, 1996

NORTH DAKOTA GEOLOGICAL SURVEY MISCELLANEOUS SERIES 82

Meetings of the Midwest Friends of the Pleistocene

1	1950	Eastern Wisconsin	Sheldon Judson
2	1951	Southeastern Minnesota	H.E. Wright, Jr. & R.V. Ruhe
3	1952	Western Illinois & Eastern Iowa	P.R. Shaffer & W.H. Scholtes
(4)	1953	Northeastern Wisconsin	F.T. Thwaites
(5)	1954	Central Minnesota	H.E. Wright, Jr. & A.F. Schneider
6	1955	Southwestern Iowa	R.V. Ruhe
(7)	1956	Northwestern Lower Michigan	J.H. Zumberge & W.N. Melhorn
8	1957	South-central Indiana	W.D. Thornbury & W.J. Wayne
9	1958	Eastern North Dakota	W.M. Laird & Others
10	1959	Western Wisconsin	R.F. Black
11	1960	Eastern South Dakota	A.G. Agnew & Others
12	1961	Eastern Alberta	C.P. Gravenor & Others
13	1962	Eastern Ohio	R.P. Goldthwait
14	1963	Western Illinois	J.C. Frye & H.B. Willman
15	1964	Eastern Minnesota	H.E. Wright, Jr. & E.J. Cushing
16	1965	Northeastern Iowa	R.V. Ruhe & Others
17	1966	Eastern Nebraska	E.C. Reed & Others
18	1967	South-central North Dakota	Lee Clayton & T.F. Freers
19	1969	Cyprus Hills, Saskatchewan & Alberta	W.O. Kupsch
20	1971	Kansas-Missouri Border	C.K. Bayne & Others
21	1972	East-central Illinois	W.H. Johnson & Others
22	1973	West-central Michigan & East-central Wisconsin	E.B. Evenson & Others
23	1975	Western Missouri	W.H. Allen & Others
24	1976	Meade County, Kansas	C.K. Bayne & Others
25	1978	Southwestern Indiana	R.V. Ruhe & C.G. Olson
26	1979	Central Illinois	L.R. Follmer & Others
27	1980	Yarmouth, Iowa	G.R. Hallberg & Others
28	1981	Northeastern Lower Michigan	W.A. Burgis & D.F. Eschman
29	1982	Driftless Area, Wisconsin	J.C. Knox & Others
30	1983	Wabash Valley, Indiana	N.K. Bleuer & Others
31	1984	West-central Wisconsin	R.W. Baker
32	1985	North-central Illinois	R.C. Berg & Others
33	1986	Northeastern Kansas	W.C. Johnson & Others
34	1987	North-central Ohio	S.M. Totten & J.P. Szabo
35	1988	Southwestern Michigan	G.J. Larson & G.W. Monaghan
36	1989	Northeastern South Dakota	J.P. Gilbertson
37	1990	Southwestern Iowa	E.A. Bettis III & Others
38	1991	Mississippi Valley, Missouri & Illinois	E.R. Hajic & Others
39	1992	Northeastern Minnesota	J.D. Lehr & H.C. Hobbs
40	1993	Door Peninsula, Wisconsin	A.F. Schneider & Others
41	1994	Eastern Ohio & Western Indiana	T.V. Lowell & C.S. Brockman
42	1995	Southern Illinois & Southeast Missouri	S.P. Esling & M.D. Blum

- No meetings were held in 1968, 1970, 1974 and 1977.
- Meeting numbers in parentheses have been listed previously as "U" or unnumbered.
- The 1952 meeting that is commonly included in the list of Midwest FOP meetings as Southwestern Ohio was actually an Eastern FOP meeting in central Ohio - to which Midwest Friends were invited by Dick Goldthwait the previous week in Western Illinois.

Introduction

This publication was created specifically for the North Central cell of the Friends of the Pleistocene 43rd annual field conference. The informal format of the conference was established by the original organizers (who included Richard Foster Flint and Richard P. Goldthwait); they intended such conferences to be an opportunity for researchers and teachers of Quaternary history to gather to observe and discuss sites of controversy. The informal character of such conferences obviated the necessity of any officers. Today, there are seven cells of the Friends of the Pleistocene in North America; some of these have convened more regularly than others, but each field conference has been a valuable learning experience for all participants.

It is appropriate for the North Central cell to devote this 43rd field conference to the Glacial Lake Agassiz region, as numerous new revelations have been documented on the complexity and global significance of that former lake. This conference is an attempt to summarize what is known about the late- and post-glacial history of Minnesota and North Dakota in and adjacent to Glacial Lake Agassiz.

This publication includes a detailed road log of the conference, including the post-conference trip. In addition, several contributed papers, related to the Glacial Lake Agassiz region, have been included. Most of these include material never published before. We are pleased to provide this outlet for such research results.

This conference has been organized with significant help from the Minnesota Geological Survey, the North Dakota Geological Survey, and the Department of Geology and Geological Engineering at the University of North Dakota. Without their encouragement and assistance this conference would not be possible.

Kenneth L. Harris
Mark R. Luther
John R. Reid

Editors

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Field Guide

ROADLOG FOR NORTHEASTERN NORTH DAKOTA
Saturday, June 1, 1996

Mark Luther
North Dakota Geological Survey
Bismarck, North Dakota

John Reid
University of North Dakota
Grand Forks, North Dakota

The purpose of the first day of this field conference is to acquaint you with a variety of landforms within and adjacent to the Lake Agassiz Plain of northeastern North Dakota. The trip route will take us down the axis of the lake basin to a site of groundwater discharge, then across the plain, over beaches and strandlines into the glacial drift-covered area. We will spend the remainder of the day examining exposures of till and outwash as well as understanding the relationships between the end/lateral moraines (a very special esker) and the Elk Valley Delta.

Mile 0 *Grand Forks to Salt Lake*: Travel north on Interstate 29 to ND Hwy 17

Mile 23.6 Head west 4 miles; Turn north 3 miles to Salt Lake (*Figure 1*)

Mile 30.6 *Stop #1:* Salt Lake (SE 1/4 36, 158N, 51W)

Salt Lake is one of several saline lakes that occur in northeastern North Dakota within the Glacial Lake Agassiz Basin. These saline lakes, including Kelly's Slough, Lake Ardoch, Salt Lake, and North Salt Lake, occur along a north-south oriented linear trend eight (8) to ten (10) miles west of the modern north flowing Red River of the North (RRN). These lakes are highly saline and have a substantial impact on the receiving streams and rivers into which they flow. To understand how these lakes formed and why they contain such saline water, we must look at a much larger region (about 600 miles wide) and have an understanding of the pre-Tertiary bedrock stratigraphy and structure in the Northern Plains.

The dominant structural feature in the Northern Plains is the Williston Basin, which underlies North Dakota and portions of Montana, South Dakota, Saskatchewan, and Manitoba. The Basin reaches a depth of more than 16,000 feet in west-central North Dakota and contains rocks representing every geologic period in the Phanerozoic. Many of these rock formations consist of impermeable shales or salts, but a substantial portion consists of permeable sandstone, limestone, or dolostone, some of which stretch from one margin of the basin to the other.

Downey (1986) has separated these permeable formations into five major aquifers that constitute one of the largest confined aquifer systems in the United States. This aquifer system stretches more than 600 miles from its recharge area in the highlands of Montana, Wyoming, and South Dakota to the low-lying discharge areas in eastern North Dakota and southern Manitoba. Along this extended flow path, water that enters the aquifer 3,000-4,000 feet above sea level may flow to depths nearly 14,000 feet below sea level near the center of the Williston Basin before discharging at the surface at an elevation less than 1,000 feet above sea level in eastern North Dakota and southern Manitoba. During this long journey to the northeast, the flowing

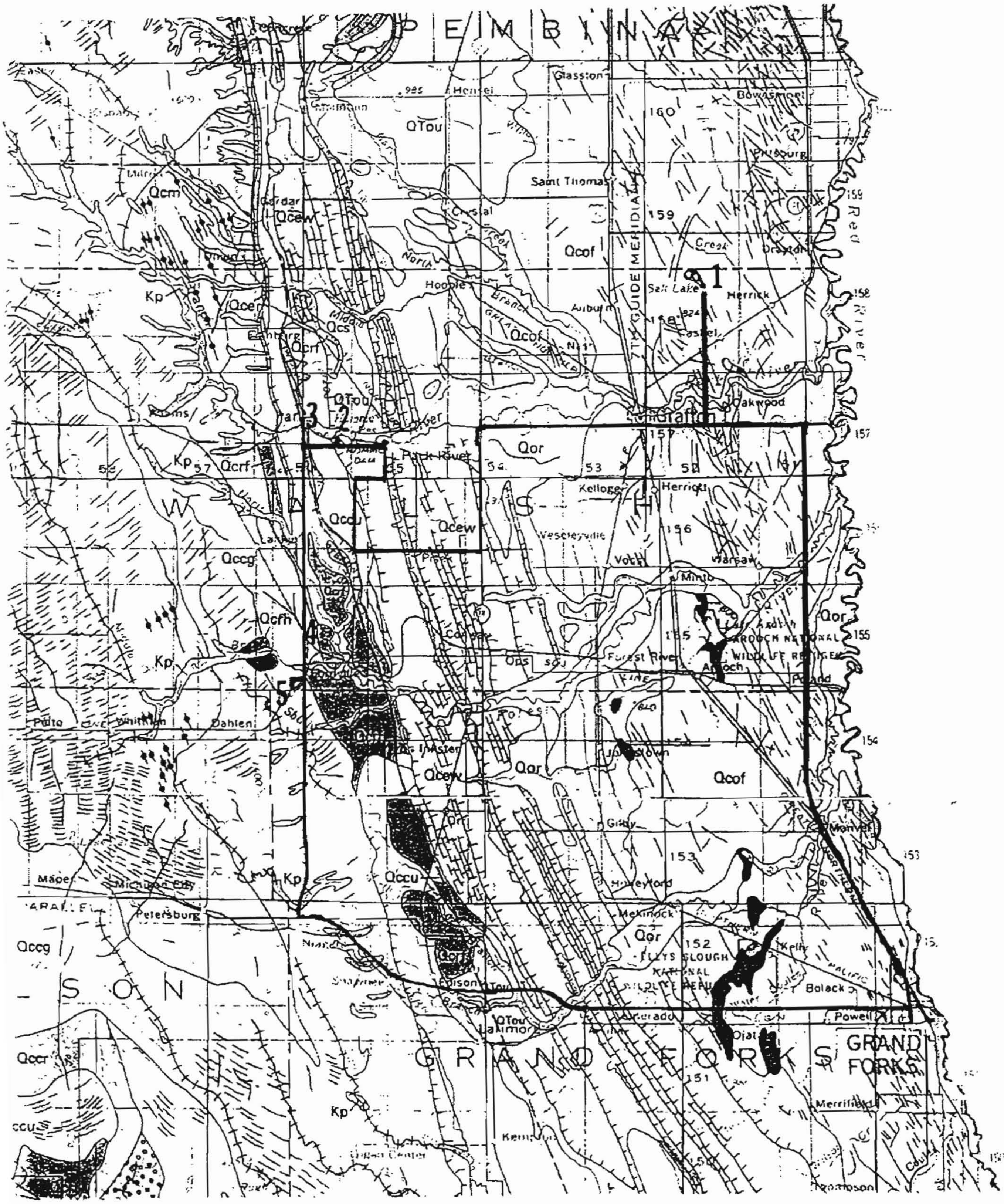

Figure 1. **Route Map for Saturday, June 1 (modified from <u>Geologic Map of North Dakota</u>, Clayton, 1980)**

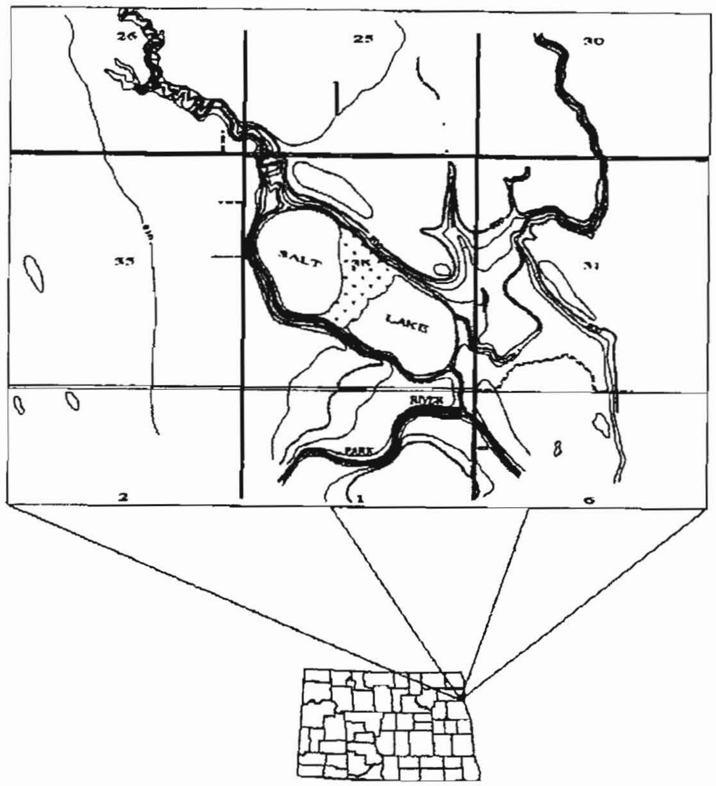

Figure 2

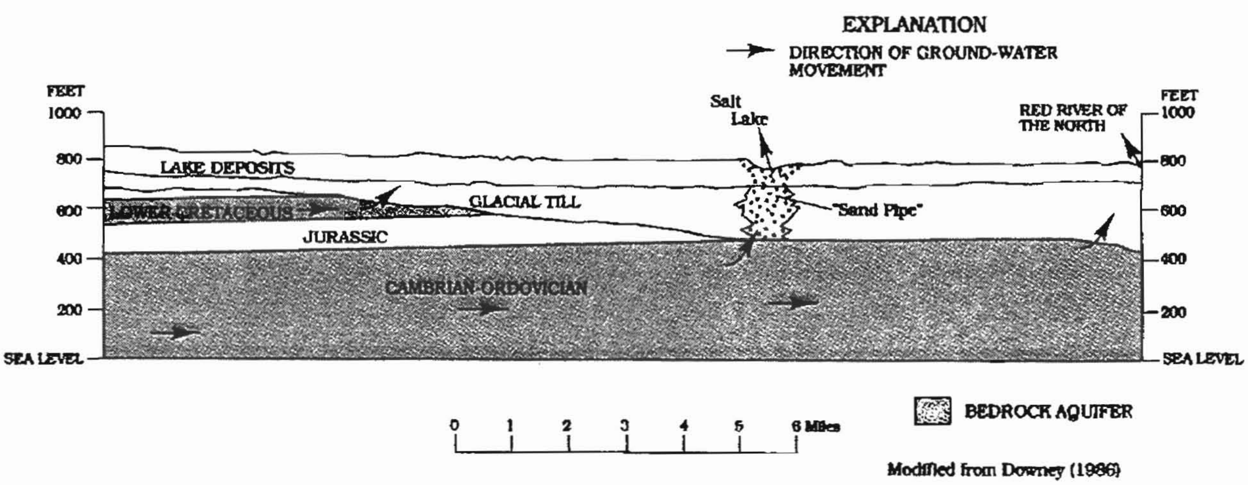

Figure 3

groundwater encounters saline brines and salt deposits that increase the salinity to that in discharge areas such as Salt Lake.

In the specific case of Salt Lake, it is a well defined lake *(Figure 2)* located in Township 158 North, Range 52 West, Section 36. Although the lake receives some surface runoff, it is predominantly a spring-fed lake, located in a spring pit formed within very low relief lake sediments deposited by glacial Lake Agassiz. Overflow from the lake goes into the nearby Park River, and then continues downstream into the RRN. Due to its highly saline nature, the water that flows from Salt Lake into the Park River greatly influences both the water quality and organisms found within the river, downstream from its confluence with the Salt Lake outlet, to its juncture with the RRN (Cvancara, 1983). During periods of low flow, such as during winter or during the drought of the late 1980's, the percentage of flow contributed by these saline springs/lakes is sufficient to cause fish kills and violations of water quality standards. It was during one of these periods of low flow (January 4, 1989, when water quality standards in the Park River had been exceeded) that Mike Ell (N.D. State Health Department) and I took some water samples from Salt Lake and its outlet to document that the violation of water quality standards was caused by natural processes. The results of analyses conducted on the water samples is shown below.

Total Dissolved Solids	17,200	mg/l
Sodium (Na)	5,700	mg/l
Calcium (Ca)	391	mg/l
Magnesium (Mg)	178	mg/l
Chloride (Cl)	8,970	mg/l
Sulfate (SO4)	1,420	mg/l
Bicarbonate (HCO3)	986	mg/l

The saline lakes in eastern North Dakota roughly correspond to the area where impermeable bedrock formations that overlie bedrock aquifers have been removed by erosion. These exposed aquifers were subsequently buried during the Pleistocene by unconsolidated till and lake sediments. It is along these subcropping bedrock aquifers that saline water discharges through the sediments to the surface, forming lakes/spring pits such as Salt Lake *(Figure 3)*.

Although these bedrock aquifers subcrop over quite a large area, visible flow to the surface occurs in only a few locations. Saline water flows to the surface at Salt Lake through a "sand pipe" that provides a permeable conduit between the bedrock aquifer (in this case probably the Ordovician Red River Formation) and the surface. Test drilling shows that this "sand pipe" cuts through more than 100 feet each of relatively impermeable till and lake sediments, and that it is areally restricted to the immediate vicinity of Salt Lake. Test holes within a mile of Salt Lake show that three (3) to five (5) layers of sand and/or gravel separated by till are present, but test holes a greater distance away (two (2) or more miles) reveal more than 100 feet of till overlain by more than 100 feet of lake sediment (clay and silt).

The groundwater flow system today was in place well before Pleistocene glaciation modified and deposited till in the valley of the RRN/Lake Agassiz Basin. While the valley was occupied by glacial ice it would have been unlikely that the bedrock aquifers could have discharged in such a high-pressure environment. In fact, Downey (1986) has hypothesized that water at the base of the glacier may have been of sufficient pressure to recharge the bedrock aquifers, thus reversing the flow of groundwater and overpressuring the aquifer. He further theorized that with the retreat of glacial ice, the highly pressurized aquifer would have once again discharged to the surface with enough force locally to "blow through" the relatively impermeable till and create or at least initiate the "sand pipe". Once initiated, the "sand pipe" would have preferentially reoccupied the same location during subsequent glacial retreats due to that being the path of least resistance. The fact that as many as five (5) sand/gravel layers, interbedded with till, occur a short distance away from the Salt Lake, "sand pipe" may be evidence for at least five (5) periods of very powerful discharge from the bedrock aquifer located there. No such sand layers have been found in the lake sediments.

Following the retreat of the last glacier, and during occupation of the valley of the RRN/Lake Agassiz Basin by Lake Agassiz, the saline spring at Salt Lake probably functioned much as it does today, flowing strongly enough to remove clay and other fine particles, but leave the sand. The lack of sands within the lake sediments indicate that high discharge of groundwater terminated before significant accumulation of lake sediments.

Salt Lake, therefore, is an unusual feature that owes its existence to processes that occurred during Pleistocene glaciation of the Lake Agassiz basin.

	Return (3) miles south to Highway 17; Go west through Grafton 10 miles
Mile 39.6	*Intersection of Highway 18* (both highways bending south): 7 miles south on Highway 18
Mile 54.6	The highway crosses the Emerado strandline of Glacial Lake Agassiz (about 9,600 BP)
Mile 56.6	Head west 4 miles to Pisek; Immediately west of town is a steep scarp marking the Campbell-McCauleyville levels of the lake (11,000 to 9,700 BP)
Mile 63.1	*Wave-eroded Proximal Side of the Edinburg Moraine:* Deposited during the Caledonia ice advance (Falconer Formation)
Mile 64.6	*Junction:* Turn north crossing along the moraine once again
Mile 68.6	Follow the road to east 2 miles; North 2 more miles to west edge of Park River, ND; Turn west
Mile 75.6	*East margin of Edinburg Moraine*: Turn north ¼ mile to Dobmeier farm (on left); West to spring discharge pit
Mile 75.9	*Stop #2*: Gerald Dobmeier Discharge Pit (SE 1/4 23, 157N, 56W)

According to Mr. Dobmeier, this pit began to form in 1954, about the time Homme Reservoir began to fill (northeast of here). "A loud noise was heard one night" and the next morning massive slumping was observed to have occurred. Discharge continues today. U.S.G.S. personnel measured 1.5 million gallons/day entering the Park River from this site. The stratigraphy is shown, below (*Figure 4*).

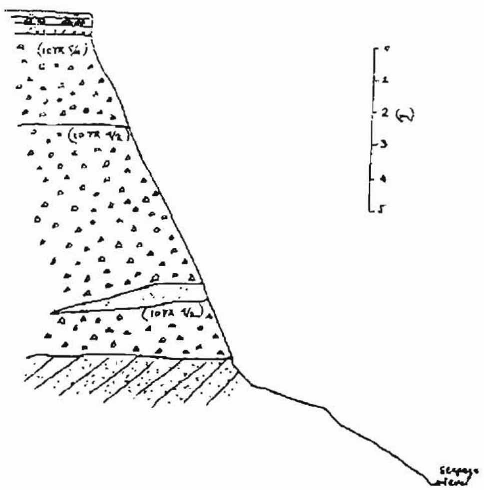

Figure 4. **Sketch of Dobmeier Pit, Park River, ND**

The lowest till is 33% sand, 49% silt, and 18% clay; the very coarse sand grains are 48% shale fragments, 33% carbonate, and 17% crystalline. Separating this till from the overlying one is a fine massive sand unit. The overlying till is 42% sand, 46% silt, and 12% clay; the very coarse sand grains are 39% shale, 34% carbonate, and 24% crystalline. Both till units are dark gray-brown (10YR 4/2). It is likely that both units are the same till, but have not been correlated outside this site, yet. The upper till is distinctly more yellow (10YR 5/4), with 22% sand, 37% silt, and 41% clay. The very coarse sand is 78% crystalline, 21% carbonate, and 5% shale (perhaps Upper Red Lake Falls till).

The cause of the sudden initiation of the discharge is still unknown, but it probably is from the northern limits of the Elk Valley Aquifer immediately to the west of the Edinburg Moraine.

Return to Highway 17; Turn west 2 miles to Highway 32; Turn north 1 1/4 miles to Park River Cut

Mile 79.3 *Stop #3*: Park River Cut (SW 1/4 15, 157N, 56W)

Two (2) tills are exposed by the Park River here. They are separated by a sand and gravel bed from which springs discharge. In places, the upper till has planed boulders in place. Striations and crescentic gouges indicate a north-northeasterly flow source for the glacier.

The lower pale brown till (10YR 6/3) is highly compacted and contains fewer inclusions of sand and gravel lenses than the upper one. The sand:silt:clay ratios average 50:37:13 and the very coarse sand grains average 46% shale, 29% crystalline, 18% carbonate, and 7% other. This appears to correlate best with the Dahlen Formation.

The upper brown till (10YR 5/3) is also highly compacted, but contains a greater percentage of sand lenses, probably a basal melt-out till. The sand:silt:clay ratios are 41:45:14 and the very coarse sand consists of 47% crystalline, 39% shale, and 15% carbonate (considerably less shale). Its stratigraphic position requires that it be Falconer till of the Caledonia advance, but its composition best fits Harris' Heiberg Till. Only when more tills are analyzed between here and the northern-most extent of Harris' studies will correlation be clarified.

> Head south on Hwy 32; 6 miles south (and 1 mile west) of the intersection of Hwy 17 is Lankin.

The "city" is built on a narrow lateral moraine of the Red River Lobe *(Figure 5).* The moraine crosses the highway two (2) miles farther south. Just before then is a new excavation, opened in summer 1995 to extract silt to mix with sand and gravel from a larger pit one (1) mile to the east of here. The excavation was frustrated by the large percentage of boulders at the surface (and some within the till). With a sudden demand for riprap to protect roads bordering Devils Lake that summer because of very high lake levels (ca 75 miles to the west), the boulders became a valuable resource. Two months were spent hauling boulders from this pit to Devils Lake.

Mile 87.8 *Brief Stop #4a: Figure 5*

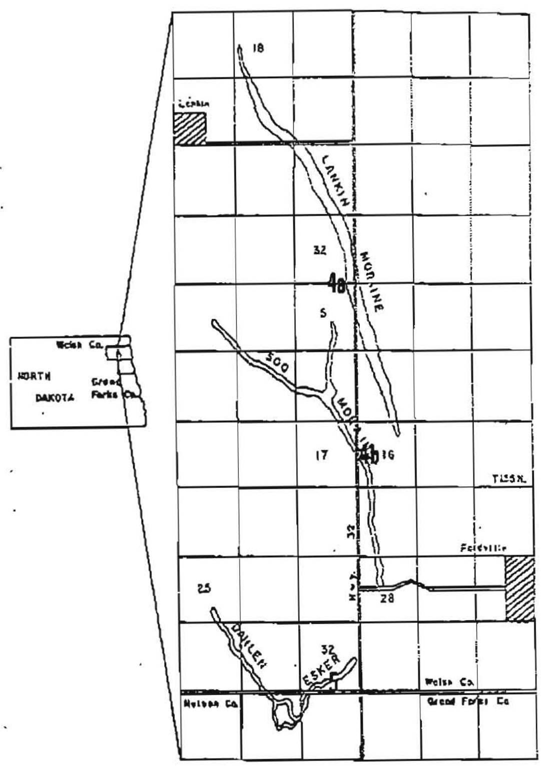

Figure 5. **Landforms along ND Highway 32, Walsh County (from Friestad, 1966).**

The till is yellowish-brown (10YR 5/4) and the sand:silt:clay ratios are 33:43:24. The very coarse sand lithology is 75% shale, 13% carbonates, and 12% crystalline. It correlates well with the upper till at the Dobmeier site.

The Lankin Moraine is unusual in that it is so small for a continental glacier lobe terminus. It is parallel to the Edinburg Moraine to the east and is composed of till.

Immediately to the east is the surface expression of the Elk Valley "delta" (one of three "deltas" identified in the early work of Upham,1896) along the western shore of Glacial Lake Agassiz. The associated aquifer here is the Fordville aquifer, a major source of water for this region (and a critical resource for cooling the electronic systems in the ill-fated ABM site approximately 35 miles north-northwest of here). The "delta" is bordered on the west by the Pembina escarpment (cut into Cretaceous marine shales) and on the east by the Edinburg moraine. It covers about 650 square km, ranging from less than one (1) meter thick along the western margin to about 15 meters near the moraine. The source of the sediments, mainly sand and gravel, were streams flowing off the Pembina escarpment and meltwater from the ice sheet to the east.

The deposit consists of two (2) units: 1) a lower shale sand and 2) an upper granitic sandy gravel (*Figure 6*). The lower unit continues beneath the Edinburg moraine.

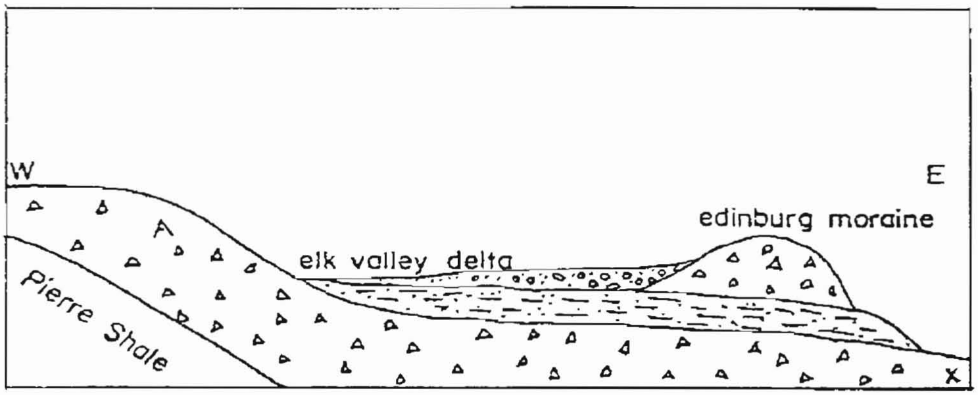

Figure 6. **Generalized cross section through the Edinburg Moraine and Elk Valley Delta, north of Fordville, Walsh County, ND.**

Continue south; Note another ridge to the west (this, the Soo Moraine, crosses the highway 2 1/2 miles farther south *[Figure 5]*)

Mile 91 *Brief Stop #4b*

Note that the crest is veneered with boulders (from the Canadian Shield). Also, note that there are two (2) branches to this landform, suggesting an esker origin. No glaciofluvial sediment has been found in this feature. If it is a till-veneered esker the sand and gravel are deep within its core. The roadcut exposed only till. Because it is composed of till, and it is parallel to both the Lankin and Edinburg moraines, it is interpreted to be either another lateral moraine, or a landform controlled by crevasses. The Prairie crocus (Pasqueflower) may still be in bloom - it is the State Flower of South Dakota!

Mile 92.8 *Minuteman Missile Site (to the west)*: As a result of the "realignment" of Grand Forks Air Force Base, all 150 missiles in eastern North Dakota are in the process of being moved to Malmstrom AFB, Montana (this will be completed by 1998)

Continue south 2 ½ miles; Directly to the southwest and far to the west is the Dahlen Esker; Turn west 1 mile; South 1 mile on section line roads We will park east of here as near to the base of the esker as appropriate.

Mile 95.6 *Stop #5*: Dahlen Esker (NW 1/4 5, 56W, 154N)

The Dahlen esker begins near the intersection of ND Highway 32 and the Soo Line Railroad, (where it is about 22m high). From there, it extends southwest into northeastern Grand Forks County (where a slightly earlier route was cut off) and northwest for about three (3) more km (*Figure 7*). This esker is unobscured, largely undisturbed by humans, and hosts an important assemblage of flora, many of which, because of the high permeability of the sediment, are characteristic of more arid species farther west. Few, if any, North Dakota sites have as diverse a flora in a comparable area as the Dahlen esker.

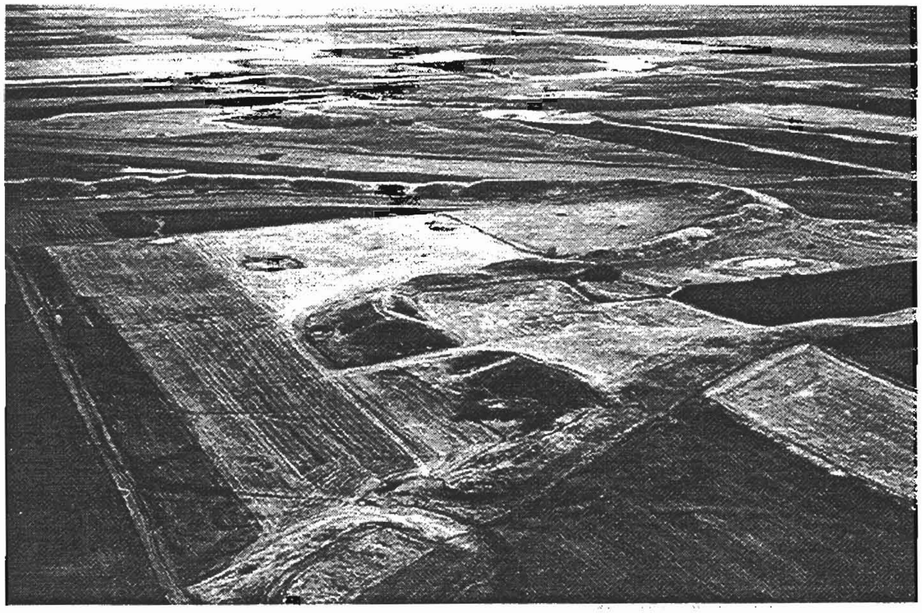

***Figure 7.* Aerial photograph of Dahlen Esker, looking southeast.**

Composition: The gravel content of this esker is typical of this part of North Dakota. It is loaded with Cretaceous shale clasts, making it of such poor quality for construction purposes that only a few borrow pits mar the otherwise undisturbed landform. The clasts are slightly coarser near the southern limits and fining to the northwest, where the esker is capped by a variable thickness of till.

Origin: Eskers normally form as a result of deposition of glaciofluvial sediments in tunnels in retreating glaciers, although some eskers may form in open channels in the ice. Eskers that form beneath the glacier, or in open channels extending to the base of the ice, tend to display undisturbed bedding except along the margins where the channels were in contact with ice. If the bedding is disturbed throughout, the probability is that the channel bottom was in ice. The Dahlen esker appears to have formed by a supraglacial stream, flowing along the surface of the rapidly thinning Red River (Winnipeg) Lobe approximately 11,300 C14 yrs B.P. (Clayton and Moran, 1972). The angular plan shape of the esker suggests that the stream was at first structurally controlled, flowing to the southwest along a crevasse remnant. An early channel was abandoned, either because of blockage of some kind or because of stream piracy. The new channel is about 400 m north of the older one. From here, the meltwaters flowed via a subglacial tunnel to the northwest. Complete ablation of the ice resulted in the partly till-veneered esker we see today.

Question: Why did the glacial stream discharge to the northwest? This presumes that the ice was thinner in that direction. But, the ice lobe was thickest toward the northeast, which would mean that it would have been thinner to the southwest, not the northwest! Also, consider that the land would have been depressed more to the northeast. Perhaps the combination of a subglacial gradient to the north and increased ablation along the western contact of the lobe, caused the stream to flow northwest.

Return to Hwy 32: Continue south

As we head south the drift becomes very thin. The rolling topography at first is constructional, but by mile 88 the surface reflects the underlying Cretaceous Niobrara shale topography. The exposure along the North Branch Turtle River near mile 95 (to east), shows shale almost at the surface (this highway passes along several Minuteman Missile silos - in the process of being dismantled and moved to Montana).

Mile 111.8 *Intersection of U.S. Hwy 2*: Head east

Mile 119.8 *Approximate position of the Herman Beach (*the highest traceable beach of Glacial Lake Agassiz)

Mile 111.9 *West edge of the Elk Valley Delta*

Mile 125.4 *Approximate location of the Edinburg moraine (missing here)*: A short distance farther, the surface is wave-planed till all the way to mile 131.2

Mile 131.2 *McCauleyville-Campbell Beach Complex (best-developed of the beaches this side of the former lake)*: 1 mile farther east; For the ensuing mile are the Blanchard beaches and the Hillsboro beach.

Mile 133.7 *Emerado Beach (used to extend along the west edge of Grand Forks Air Force Base)*

The base is presently undergoing "realignment", meaning that its missile wing is being deactivated and its mission as a tanker support base is being strengthened. Approximately 9,900 people live on base - and another 4,000 live off base - making the base the 9th largest city in North Dakota!

Mile 136.7-137.3 *Depression in the Lake Plain*

Underlain by saline soils (Ojata Association). Groundwater discharges from the glacially-truncated Inyan Kara Formation (Dakota Group). Salt Water Coulee and Kelly's Slough are further results of that saline water, as was Salt Lake *(Stop #1)*.

Mile 140.7 *Road north to Kelly's Slough (a Wildlife Preserve)*

Mile 201 *University of North Dakota*: End of this part of the trip

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ROADLOG
Sunday, June 2, 1996
Morning
Kenneth L. Harris
Minnesota Geological Survey - St. Paul, Minnesota

We will travel from Grand Forks, North Dakota (GF), through Crookston, Minnesota (C), Fertile, Minnesota (F) and Red Lake Falls, Minnesota (RLF). This route will take us across the Lake Agassiz plain, the Campbell beach, Campbell wave-cut scarp, interbeach complex, and wave-washed till. Plates I and II show geologic and lithostratigraphic maps of the Red Lake Falls area. You can follow our route to Red Lake Falls on these maps. We will visit one outcrop on the Red Lake River near Red Lake Falls, the Three Creeks Section, and an area of stabilized sand dunes on the Fertile delta, near Fertile. The busses will travel their routes in opposite directions, in order to minimize congestion at the stops.

BUS #1

Mile 0 (0.0)	*Grand Forks, ND*: East on US-2
Mile 25 (25.0)	*Crookston, MN*: East on US-2 to MN-102; Southeast on MN-102 to MN-32; South on MN-32 to Fertile
Mile 49 (24.0)	*Fertile, MN*: 1.5 miles south on MN-32 to unnamed county road (about 0.8 South of Sand Hill River); 0.5 mile west on unnamed county road
Mile 51 (2.0)	*Fertile dunes*: Return to Fertile
Mile 53 (2.0)	*Fertile, MN*: North on MN-32
Mile 78 (25.0)	*Red Lake Falls, MN*: 1.25 miles west on International Drive (south edge of town); 1 mile north (road is just west of settling ponds); 0.25 west at Red Lake River
Mile 80.5 (2.5)	*Three Creeks Section*: The cutbank is north of the farm house; Get permission to visit the outcrop before going any further; Return to Red Lake Falls
Mile 83 (2.5)	*Red Lake Falls, MN*: South on MN-32 to US-2; West on US-2 to Crookston
Mile 108 (25.0)	*Crookston, MN*: West on US-2 to Grand Forks
Mile 133 (25.0)	*Grand Forks, ND*

BUS #2

Mile 0 (0.0)	*Grand Forks, ND*: East on US-2 to Crookston
Mile 25 (25.0)	*Crookston, MN*: East on US-2 to MN-32; North on MN-32 to Red Lake Falls
Mile 50 (25.0)	*Red Lake Falls, MN*: 1.25 miles west on International Drive (south edge of town); 1 mile north (road is just west of settling ponds); 0.25 west at Red Lake River

Mile 52.5 (2.5)	*Three Creeks Section*: The cutback is north of the farm house; Get permission to visit the outcrop before going any further; Return to Red Lake Falls
Mile 55 (2.5)	*Red Lake Falls, MN*: MN-32 south to Fertile
Mile 80 (25.0)	*Fertile, MN*: North on MN-32 to unnamed county road (about 0.8 south of Sand Hill River); 0.5 mile west on unnamed county road
Mile 82 (2.0)	*Fertile dunes*: Return to Fertile
Mile 84 (2.0)	*Fertile, MN*: North on MN-32 to MN-102 (about 1 mile); MN-102 to US-2; US-2 to Crookston
Mile 108 (24.0)	*Crookston, MN*: US-2 west to Grand Forks
Mile 133 (25.0)	*Grand Forks, ND*

The surface geology of the Red Lake Falls, Minnesota area (Plate I), can be divided into three (3) categories based on the presence of similar landforms (Harris, 1975 *[Figure 8]*).

The Lake Agassiz Plain

The floor of Glacial Lake Agassiz consists of flat-bedded, laminated silts and clays and areas of eroded glacial sediment. The most common landforms presented on this level plain are very low relief ice-drag grooves (generally < 1 m) and compaction ridges.

The Shoreline Complex

The nearshore and shoreline area of glacial Lake Agassiz consists of flat-bedded and cross-bedded silt, sand, and gravel as well as areas of wave-eroded glacial sediment. The most common landforms are beach ridges, nearshore bars, spits, wave-planed areas, and wave-cut scarps.

The Glacial Upland

This is the glaciated area adjacent to the glacial lake plain that hasn't been modified by any lacustrine processes. The sediment here is generally pebbly, sandy, silty clay (till) or sand and gravel. The most common landforms on the glacial upland are meltwater channels, eskers, and undulating to hummocky topography, characterized by rolling hills and closed depressions containing bogs or lakes.

GEOLOGIC HISTORY

The geologic history of the area for about the last two million years, can be summarized as follows (approximate ages interpreted from Clayton and Moran, 1982; Harris and others, 1995):

1. An unknown number of glaciers advanced over and retreated from this area during the pre-Wisconsinan portion of the Pleistocene. These glaciations were punctuated by interglacial episodes with mild climates. There is no nearsurface evidence for these glaciations in the Red Lake Falls area (about 2 MA to about 100 KA [?]).

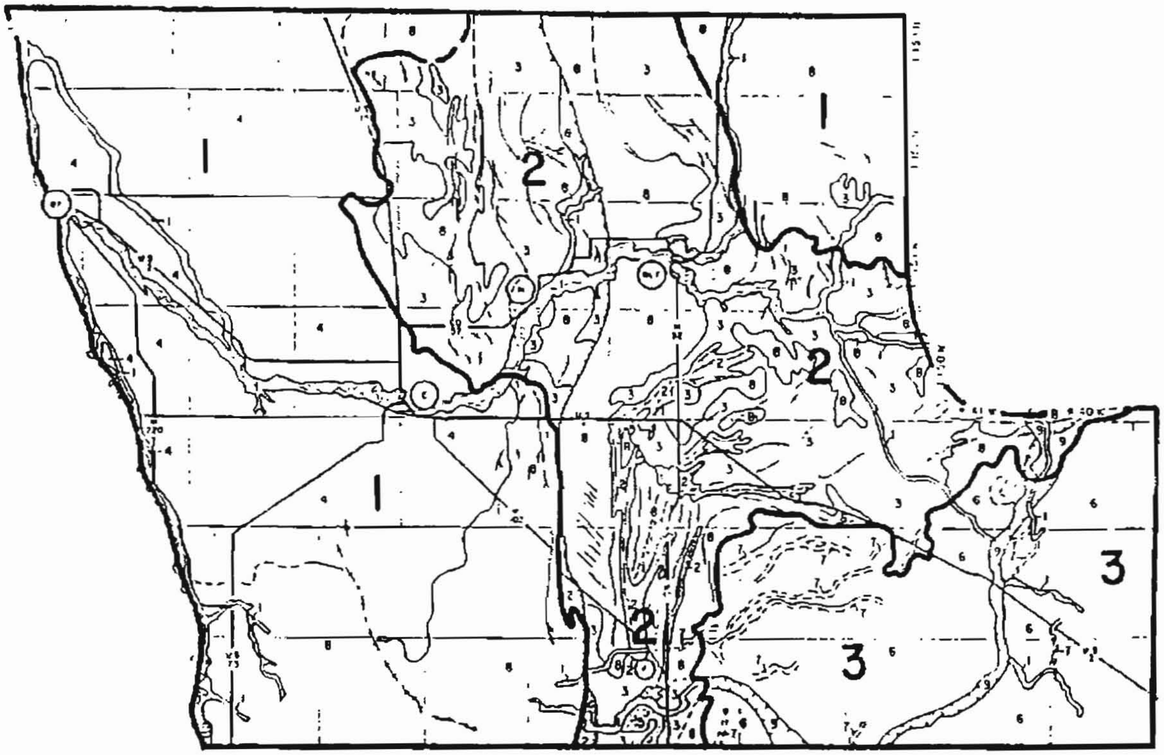


Figure 8. **Areas of similar landforms: 1) Lake Agassiz plain; 2) Shoreline complex; and 3) Glacial upland (from Harris, 1987).**

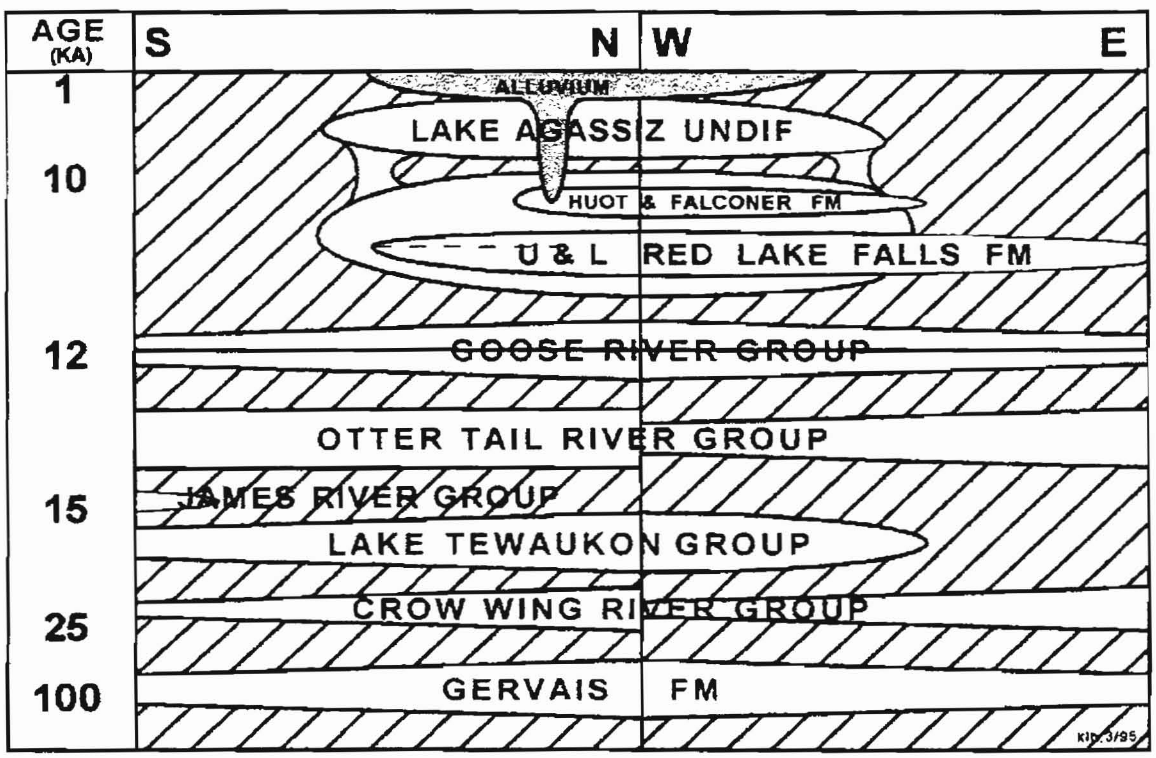


Figure 9. **Time distance diagram showing periods of deposition of formations in the southern Lake Agassiz basin (modified from Harris and others, 1995).**

2. The glaciers that deposited the Gervais Formation (Crow Wing River group, Lake Tewaukon group, Otter Tail River group, and Goose River group) advanced over the area and retreated (about 100 KA to 11.7 KA *[Figure 9]*). It is likely that proglacial lakes occupied the Lake Agassiz basin numerous times before and after these advances. Rotasonic drilling in the basin has recovered lake sediment associated with the Crow Wing River and Goose River groups.

3. The glacier that deposited the Red Lake Falls Formation advanced into the area and retreated. The lake basin was flooded by meltwater that ponded south of the advancing glacier. This was a pre-Cass (or early Cass) Phase of Lake Agassiz (about 11.7 to 11.5 KA *[Figure 9]*). Presumably, lake sediment was preserved beneath the advancing glacier, but none has been reported. The offshore lake sediment (Argusville Formation) was deposited in the lake basin south of the terminus, near Comstock, Minnesota.

4. Glacial ice readvanced into the "Red River Valley" as far south as the Caledonia, North Dakota area (Shelly, Minnesota). This advance deposited the glacial sediment of the Huot and Falconer Formations (about 11.4 to 11.3 KA *[Figure 9]*). Lake sediment was deposited in front of the advancing glacier (Wiley Formation) and continued to be deposited south of the terminus (Agrusville Formation).

5. Glacier ice retreated to the north. Lake sediment was again deposited in the lake basin (Brenna Formation - Lockhart Phase; about 11.3 to 10.5 KA *[Figure 9]*).

6. Glacier ice retreated sufficiently to open the eastern outlets of Lake Agassiz and the lake drained (Moorhead Phase; about 10.5 to 9.9 KA *[Figure 9]*). Vegetation was established on the lake plain and tributary streams and rivers flowed to a trunk stream (Poplar River Formation).

7. Glacier ice readvanced far enough to block the eastern outlets of the Lake Agassiz basin; Lake Agassiz reflooded (Emerson Phase; about 9.9 to 9 KA *[Figure 9]*). The sediment deposited in the lake basin is the Sherack Formation - the surface sediment over much of the "Red River Valley."

8. Glacier ice wanes, Lake Agassiz drains, mild weather prevails, complete with warm rains (about 9.0 KA to present *[Figure 9]*).

GEOLOGIC MAP

A generalized map of the surficial geology of the Red Lake Falls area is provided on Plate I (modified from: Harris, 1975, 1987; Harris and Luther, in prep.). This map shows the field trip route. A description of the map units and line symbols is provided in *Figures 10* and *11*. The interpreted relationship between sediment age, sediment origin, and map units is shown in *Figure 12*.

DESCRIPTION OF THE GEOLOGIC MAP UNITS

HOLOCENE

River Sediment

1

Overbank Sediment - clay, silt, sand, and disseminated organic debris; obscurely bedded; dark colored; often associated with sand and gravel of older, river-channel sediment; usually less than a metre (3 feet) thick; deposited on the flood plains of modern rivers.

Lake Sediment

2

Shoreline Sediment - sand and gravel; moderately to well sorted; plane bedded and cross bedded; as much as 5 metres (15 feet) thick; deposited along the shoreline of a lake, usually on eroded till; beach ridges are shown by line symbols.

3

Nearshore Sediment - silt and sand; moderately to well sorted; cross bedded to flat bedded; as much as 5 metres (15 feet) thick; deposited in shallow water near the shore of a lake, usually on eroded till; beach ridges are shown by line symbols.

4

Offshore Sediment - clay with thin silt laminae; flat bedded, usually laminated; as much as 60 metres (200 feet) thick; deposited in deep, quiet water of a lake; compaction ridges are shown by line symbols.

Windblown Sediment

5

Dune Sediment - sand; medium- to fine-grained: well sorted; obscurely bedded; associated with older lake and river deposits; dunes are as much as 10 metres (30 feet) high and generally stabilized by vegetation: active blowouts are common; windblown sediment with a hummocky, wind scoured surface.

PLEISTOCENE

Glacial Sediment

6

Glacial Sediment - sand, silt, and clay; pebbly; unsorted, unbedded; contains abundant cobbles and boulders; as much as 30 metres (100 feet) thick (multiple-event deposits as thick as 200 metres [600 feet]); the surface is flat or very hilly; deposed by glacial ice.

7

Glacial Sediment - Overlying Sand and Gravel - sand, silt, and clay, pebbly; unsorted; unbedded; 1 to 5 (?) metres (3 to 15) [?] feet) of glacial sediment overlying sand and gravel; glacial sediment deposited on older river sediments.

8

Wave-Eroded Glacial Sediment - sand, silt, and clay; pebbly, unsorted; unbedded; glacial sediment that has been eroded (washed) by the action of waves in a lake; the surface of the eroded glacial sediment is flat or undulating; a veneer of nearshore or shoreline sediment is commonly present.

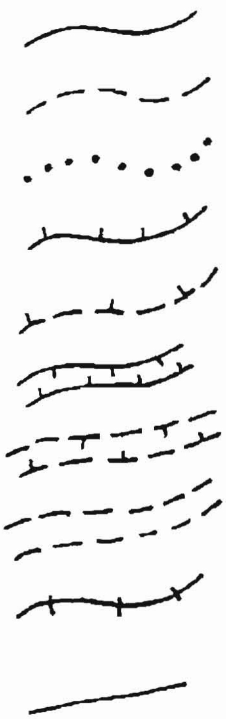
River Sediment

9

River Channel Sediment - sand and gravel; moderately to poorly sorted; cross bedded to flat bedded; as much as 30 metres (100 feet) thick; deposited by meltwater rivers.

Figure 10. **Description of surface geologic map units (modified from Harris, 1987).**

MAP LINE SYMBOLS



- confident contact
- approximate contact
- uncertain contact
- continuous scarp
- discontinuous scarp
- sharply defined fluvial channel
- obscure. partially buried fluvial channel
- obscure. mostly buried fluvial channel
- ridges apparent on airphotos; see description of map units for interpretation of origin
- any lineation apparent on airphoto

Figure 11. **Description of Plate I map line symbols.**

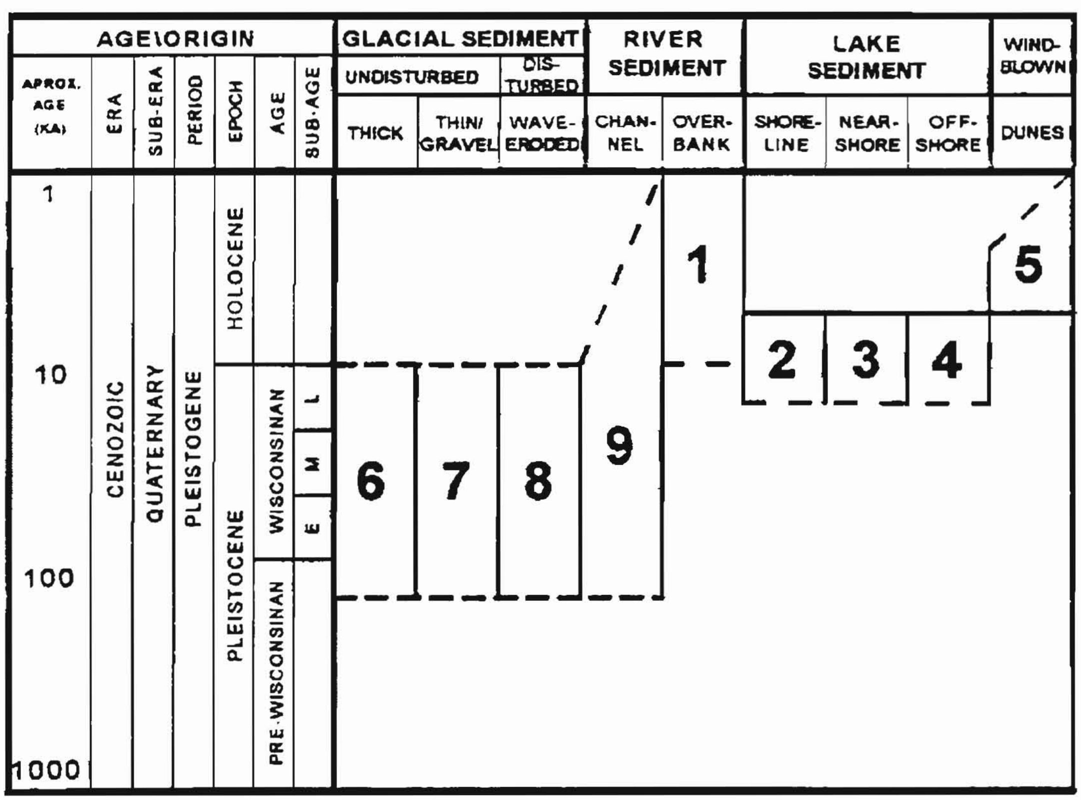


Figure 12. **Legend for Plate I.**

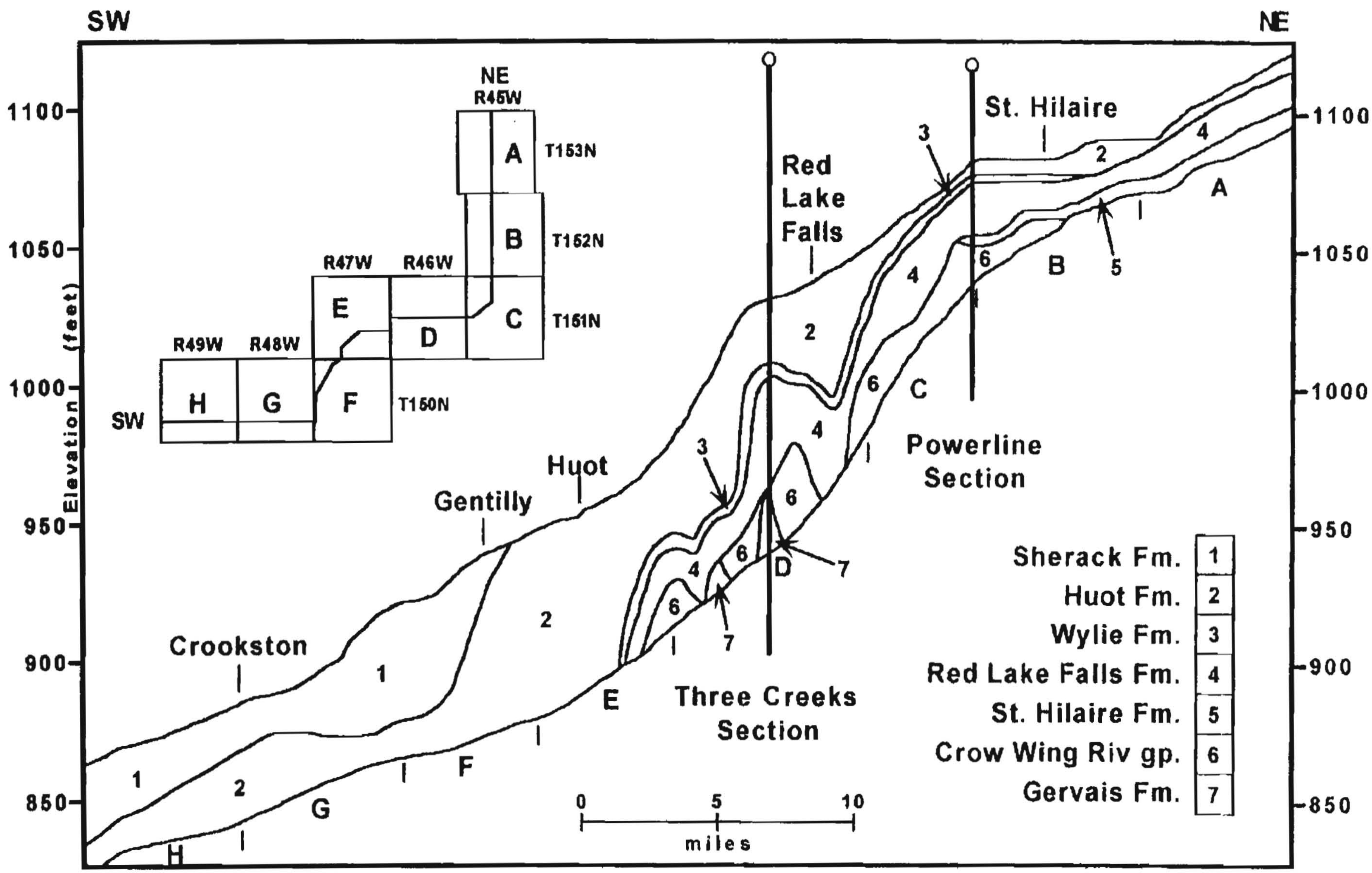


Figure 13. Generalized cross section along the Red Lake River in the Red Lake Falls, Minnesota area (modified from Harris and others, 1974).

STRATIGRAPHY

Stratigraphic units exposed in the Red Lake River trench include six (6) formations that are composed largely of glacial sediment and four (4) units composed of lacustrine or fluvial sediment (Harris and others, 1974). All are believed to be Wiconsinan or younger *(Figure 9)*. Stratigraphic units are referred to by formal or informal names and glacial tills by a label (RRVXX) used in the Southern Red River Valley Regional Assessment (SRRV-RHA; Harris and others, 1995). A detailed discussion of the lithostratigraphic units is included in *Appendix A*.

The stratigraphic framework presented here is based on field identifiable characteristics, and computer-assisted interpretation of natural associations of textural and course-sand (1-2 mm) lithologic correlation parameters (Harris, 1973; Harris and others, 1974; Harris and others, 1995). About 2,100 samples were used in this analysis (see *Computer-assisted Lithostratigraphy* - this volume).

The outcrop we will visit expose all but five (5) of the units shown in *Figure 9*. Those we won't see are: 1) the St. Hilaire Formation (Goose River group) - a shale rich glacial sediment deposited by the Red River lobe, very thin or absent in this area; 2) the Falconer Formation - glacial sediment that is the stratigraphic equivalent of the Huot Formation, but present only outside the Lake Agassiz basin; 3) the Brenna Formation - lake sediment deposited in the pre-last Lake Agassiz (Lockhart Phase); 4) the Poplar River Formation - river sediment deposited in the dry lake basin before Lake Agassiz flooded for the last time (Moorhead Phase); and 5) the Sherack Formation - lake sediment deposited during the last flooding of the Lake Agassiz basin (Emerson Phase) (Clayton and Moran, 1982).

The spacial relationship of these stratigraphic units and the location of the Three Creeks and Powerline Sections is shown in *Figure 13*. The Powerline section is located near the southeastern limit of occurrence (in the Red Lake River Valley) of the St. Hilaire Formation. The Three Creeks section is one of two known exposures of the Gervais Formation in the Red Lake River trench. Progressively younger sediments are exposed downstream *(Figure 13)*.

SURFACE EXPOSURE OF THE STRATIGRAPHIC UNITS

Plate II shows the areas where these stratigraphic units are exposed at the surface. A legend for Plate II is provided in *Figure 14*.

Three (3) lithostratigraphic units, with distinctly different textural and coarse-sand lithologic characteristics, are exposed at the surface in the Red Lake Falls area. The Huot Formation is exposed in a band extending from the Red River of the North (near Shelly, MN) northeastwardly through the Huot-Red Lake Falls, Minnesota area. The upper member of the Red Lake Falls Formation is exposed north and east of Red Lake Falls, MN, and the lower member is at the surface southeast of Red Lake Falls and in the adjacent glaciated uplands (see Harris and others, 1995; Plate II). These and other stratigraphic units exposed in the Red Lake River trench are discussed in detail in *Appendix A*.

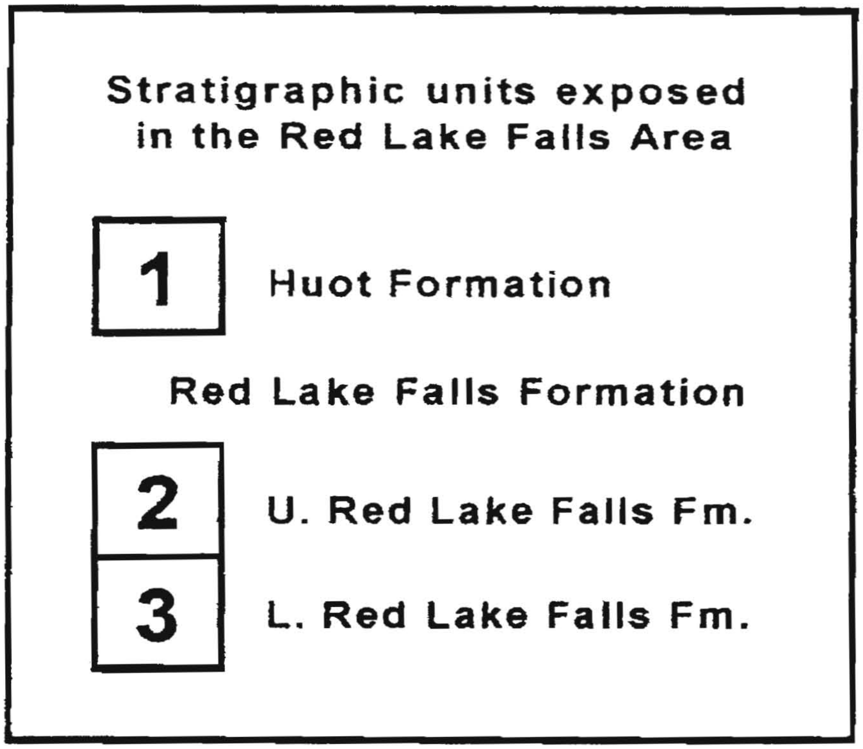


Figure 14. **Legend for Plate II, areas of surface exposure of stratigraphic units (modified from Harris, 1987).**

POWERLINE SECTION
SE/SE/NE SEC. 5, T. 151 N., R. 43 W.
Left bank of the Red Lake River

Section described by K. L. Harris, S. R. Moran, and Lee Clayton

DEPTH (ft)	ELEVATION (ft)	DESCRIPTION
Red Lake Falls Formation		
0-28	1082-1054	Pebble-loam, friable; light gray (5Y 6/1 dry); abundant sand lenses present; lower contact gradational; cobble, sand, and gravel concentrations occur at contact.
St. Hilaire Formation		
28-30	1054-1052	Pebble-loam; clayey; unbedded; friable; gray (5Y 5/1 dry); sharp lower contact.
Crow Wing River group (Marcoux Formation)		
30-47	1052-1035	Pebble-loam; sandy; unbedded; hard; light gray (2.5Y 6/2 dry); lower contact not exposed.

Figure 15. **Detailed section description of the Powerline Section; Red Lake County, Minnesota (modified from Harris and others, 1974).**

SD-SL-CY	XT-CO-SH	SD-NS-NX-SH
30-46-24	50-35-15	30-66-59-15
38-40-22	00-99-00	38-65-00-00
34-43-23	51-35-14	34-65-59-14
44-39-17	00-99-00	44-70-00-00
45-40-15	00-99-00	45-73-00-00
46-38-16	60-37-03	46-70-62-03
41-43-16	00-99-00	41-73-00-00
36-46-18	58-38-04	36-72-60-04
38-45-17	00-99-00	38-73-00-00
31-53-16	00-99-00	31-77-00-00
47-37-16	00-99-00	47-70-00-00
43-43-14	00-99-00	43-75-00-00
46-38-16	00-99-00	46-70-00-00
43-41-16	58-39-03	43-72-60-03
50-33-17	56-41-03	50-66-58-03
51-32-17	00- 99-00	51-65-00-00
30-38-32	38-28-34	30-54-58-34
37-37-26	44-36-20	37-59-55-20
45-45-10	60-31-09	45-82-66-09
40-39-21	59-32-09	40-65-65-09
58-32-10	85-12-03	58-76-88-03
52-22-26	78-15-07	52-46-84-07
52-35-13	77-15-08	52-73-84-08
57-17-26	79-14-07	57-40-85-07
51-40-09	85-15-00	51-82-85-00

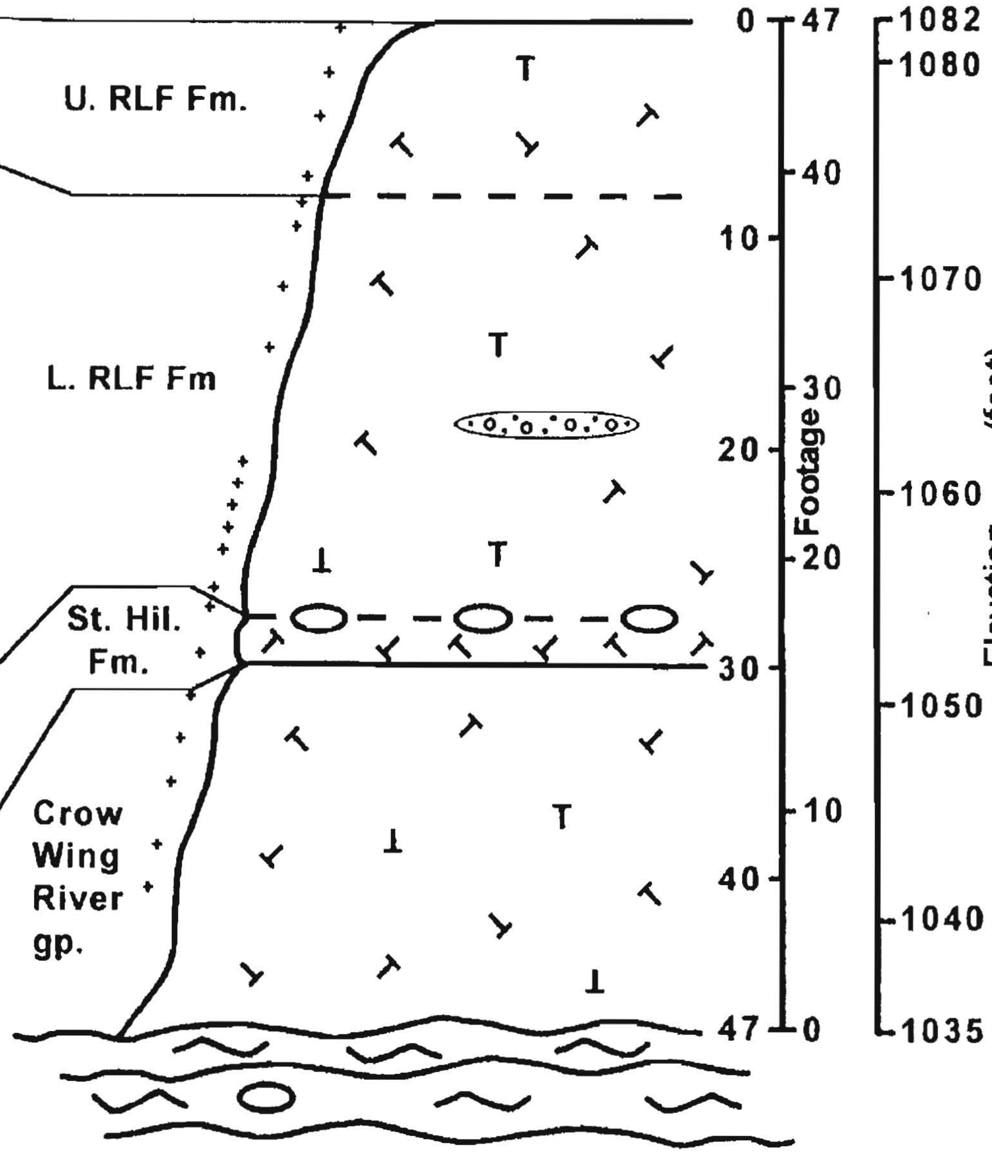


Figure 16. Outcrop sketch and data summary for Powerline Section; Red Lake County, Minnesota (modified from Harris, 1987).

THE OUTCROPS

Powerline Section

We won't be able to visit this exposure, but I will include the description since it is a good example of the stratigraphy exposed by the Red Lake River between Red Lake Falls and Thief River Falls. Generally, three (3) units are exposed in this area: 1) the Red Lake Falls Formation; 2) the St. Hilaire Formation; and 3) the Crow Wing River group. This surface has been wave-washed by the waters of Lake Agassiz. Consequently, the surface is level or undulating and the occurrence of the surface stratigraphic units is variable. Either the Huot Formation, Wylie Formation, or Red Lake Falls Formation may be exposed at the surface.

The Crow Wing River group and the St. Hilaire Formation have been eroded at this location. Only a thin remnant of the St. Hilaire Formation remains.

A detailed outcrop description is shown in *Figure 15* and a data summary and outcrop sketch is shown in *Figure 16*. Detailed descriptions of the stratigraphic units exposed are given in *Appendix A*.

Three Creeks Section

This section exposes all of the stratigraphic units present along the Red Lake River Valley except the St. Hilaire and Sherack Formations.

The Huot Formation is present in the uplands, above the vertical slopes. It is very slump-prone and does not stand up well in outcrops. The top of most of the outcrops in this area are irregular areas of slumped Huot Formation.

The Wylie Formation is a laminated clay that forms the boundary between the Huot and Red Lake Falls Formations.

The glacial sediment of the Crow Wing River group (Marcoux Formation) is almost gone here. It has been eroded and replaced by 20 foot thick sand bed.

The Gervais Formation is known to be present at only one other outcrop along the Red Lake River. This is one of the most unusual and oldest glacial sediments exposed in the Upper Midwest. It contains abundant disseminated organic debris including wood and fossil beetle fragments. The wood, including some six (6) inch (.15 m) diameter spruce logs, has been radiocarbon dated twice and found to be >39.9 KA (I-5317; Harris, Moran, and Clayton, 1974; Ashworth, 1980). This would indicate an early Wisconsinan or pre-Wisconsinan age for the Gervais Formation.

The fossil beetle assemblages present in the Gervais Formation were studied by Ashworth (1980). He suggests that the sedimentary environment indicated by the beetles was a small lake with open margins characterized by open areas and a spruce woodland. The climate was similar to that found today in the Lake Superior region or somewhat farther north near the tundra-forest transition zone.

A detailed outcrop description is shown in *Figure 17* and a data summary and outcrop sketch is shown in *Figure 18*.

The Fertile Dunes

The Fertile Dunes, or Fertile Sandhills, are medium- to high-relief sand dunes located on the Fertile delta. This delta formed when water flowing in the McIntosh channel discharged into Lake Agassiz (Plate I). The elevation of the floor of the McIntosh channel is at about 1,150 feet, well above the Campbell "beach" (Emerson phase; about 1,000 feet), so the channel would have been active during the earlier Cass and Lockhart phases of Lake Agassiz (about 11.4 KA).

The McIntosh channel was active most recently, when the Red River lobe stood at the Edinburg moraine. The channel carried meltwater flowing in response to the elevation difference between Lake Koochiching and Lake Agassiz (see Harris and others, 1995; Plate I, this volume). There are deltas on the west end (Fertile delta) and north end (Traill delta) of the McIntosh Channel. It seems that the direction of water flow in the channel changed in response to changes in the relative water levels between the two lakes (Moran and others, 1976).

The Sand Hill River was called "ga-papiqwutawangawi zibi" by the Ojibway people, or "the river of sand hills, scattered here and there in places." Early explorers and trappers also referred to the Sand Hill River as the "Riviere aux Buttes de Sable." During the early 1800's, a trader named William Henry had a post on the Sand Hill River and reported trading beaver, black bear, grizzly bear and numerous other smaller animals. That was the last grizzly bear reported in Minnesota. Buffalo and Elk were reported to be abundant (Agassiz Environmental Learning Center, 1992).

The Nature Conservancy manages a natural area in the Fertile Sandhills. We will stop there. The Sandhills are a popular recreation area and home of the Agassiz Environmental Learning Center.

THREE CREEKS SECTION

NE/NE/NW, SEC. 21, T. 151 N., R. 44 W.
Left bank of the Red Lake River

Section description by K. L. Harris

DEPTH (ft)	ELEVATION (ft)	DESCRIPTION
Huot Formation		
0-15	1023-1008	Clay; very slightly pebbly; unbedded; gray (5Y 5/1 dry); contains tan, pebble-sized, calcareous inclusions; highly slumped; gradational contact with Wylie Formation.
Wylie Formation		
15-19	1008-1004	Clay and silt; thinly laminated; clay is olive gray (5Y 5/2 dry); silt is light brownish gray (2.5Y 6/2 dry); laminae thicken upward; gradational contact with Red Lake Falls Formation.
Upper Red Lake Falls Formation		
19-25	1004-998	Pebble-loam; clayey; unbedded; friable; light brownish gray (2.5Y 6/2 dry); lower contact gradational; laminated clay at contact.
Lower Red Lake Falls Formation		
25-41	998-982	Pebble-loam; unbedded; friable; light brownish gray (2.5Y 6/2 dry); abundant sand inclusions; sharp contact with Marcoux Formation.
Crow Wing River group (Marcoux Formation)		
41-58.5	982-964.5	Sand; alternating fine- and medium-grained; flat bedded to ripple cross-bedded; jointed; limonitic stains; gradational lower contact.
58.5-59	964.5-964	Pebble-loam; sandy; unbedded; friable; light gray (5Y 6/1 dry); lower contact is sharp; cobbles are common at contact.
Gervais Formation		
59-85	964-938	Clay-loam; silty; very slightly pebbly; unbedded; friable; light olive-gray (5Y 6/2 dry); wood chips, twigs, and logs abundant near base; pebbles and sand lens inclusions increase upward; mollusk fragments and charcoal flakes present; lower contact not exposed.

Figure 17. **Detailed section description of the Three Creeks Section; Red Lake Falls County, Minnesota (modified from Harris and others, 1974).**

SD-SL-CY	XT-CO-SH	SD-NS-NX-SH
20-42-38	41-44-15	20-52-48-15
19-42-39	50-36-14	19-52-58-14
38-35-27	52-38-10	38-56-58-10
38-32-30	55-34-11	38-52-62-11
43-28-29	50-37-13	43-49-57-13
48-29-23	58-36-06	48-56-62-06
46-31-23	52-41-07	46-57-56-07
42-29-39	56-40-04	42-50-58-04
44-31-25	62-34-04	44-55-65-04
50-35-15	63-37-00	50-70-63-00
20-43-37	50-49-01	20-54-51-01
18-46-36	42-58-00	18-56-42-00
18-48-34	48-49-03	18-59-49-03
22-48-30	52-48-00	22-62-52-00
20-47-33	41-59-00	20-59-41-00
20-47-33	27-68-05	20-59-28-05
21-45-34	37-60-03	21-57-38-03
16-48-36	37-50-13	16-57-43-13

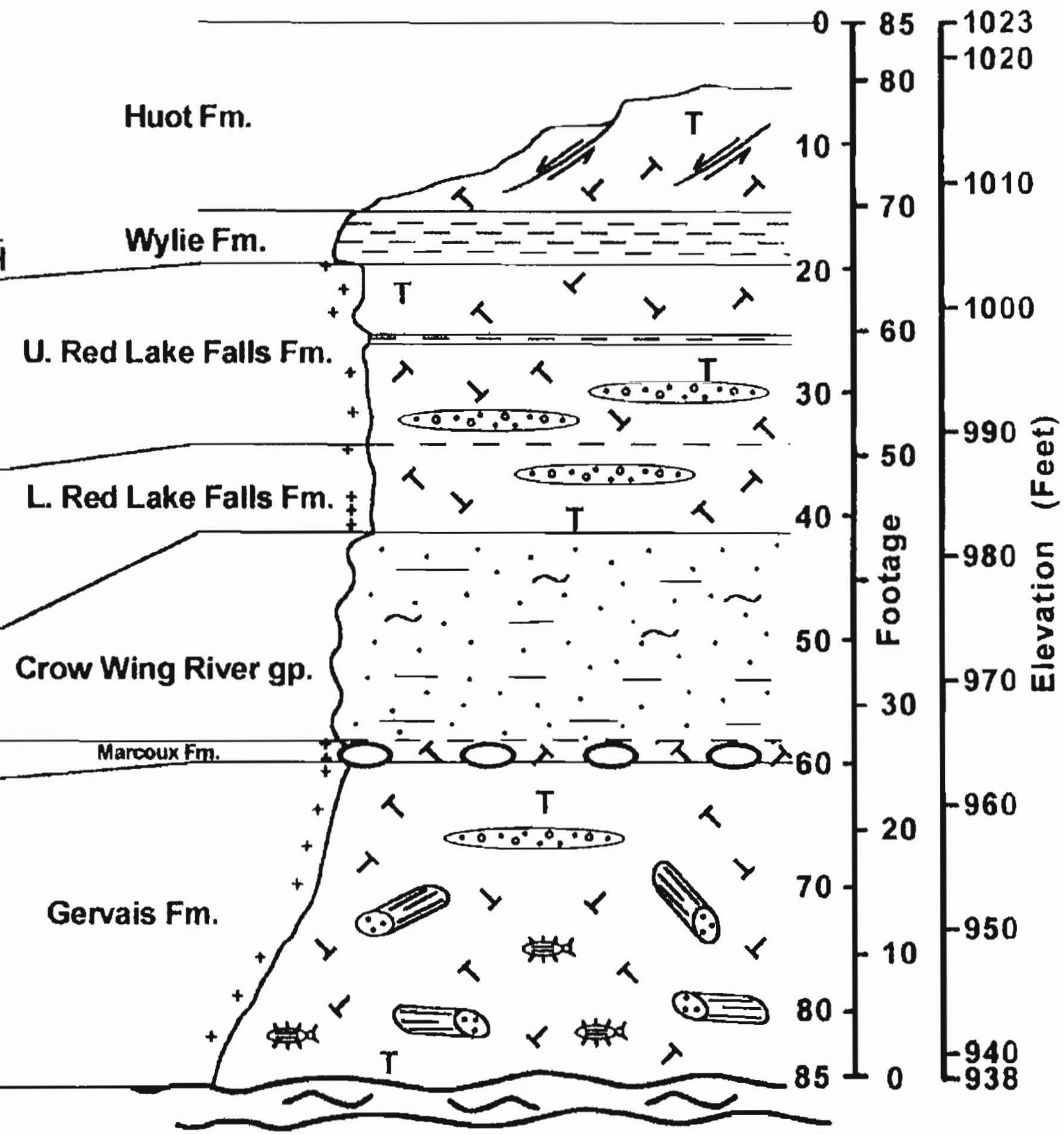


Figure 18. Outcrop sketch and data summary for Three Creeks Section; Red Lake County, Minnesota (modified from Harris, 1987).

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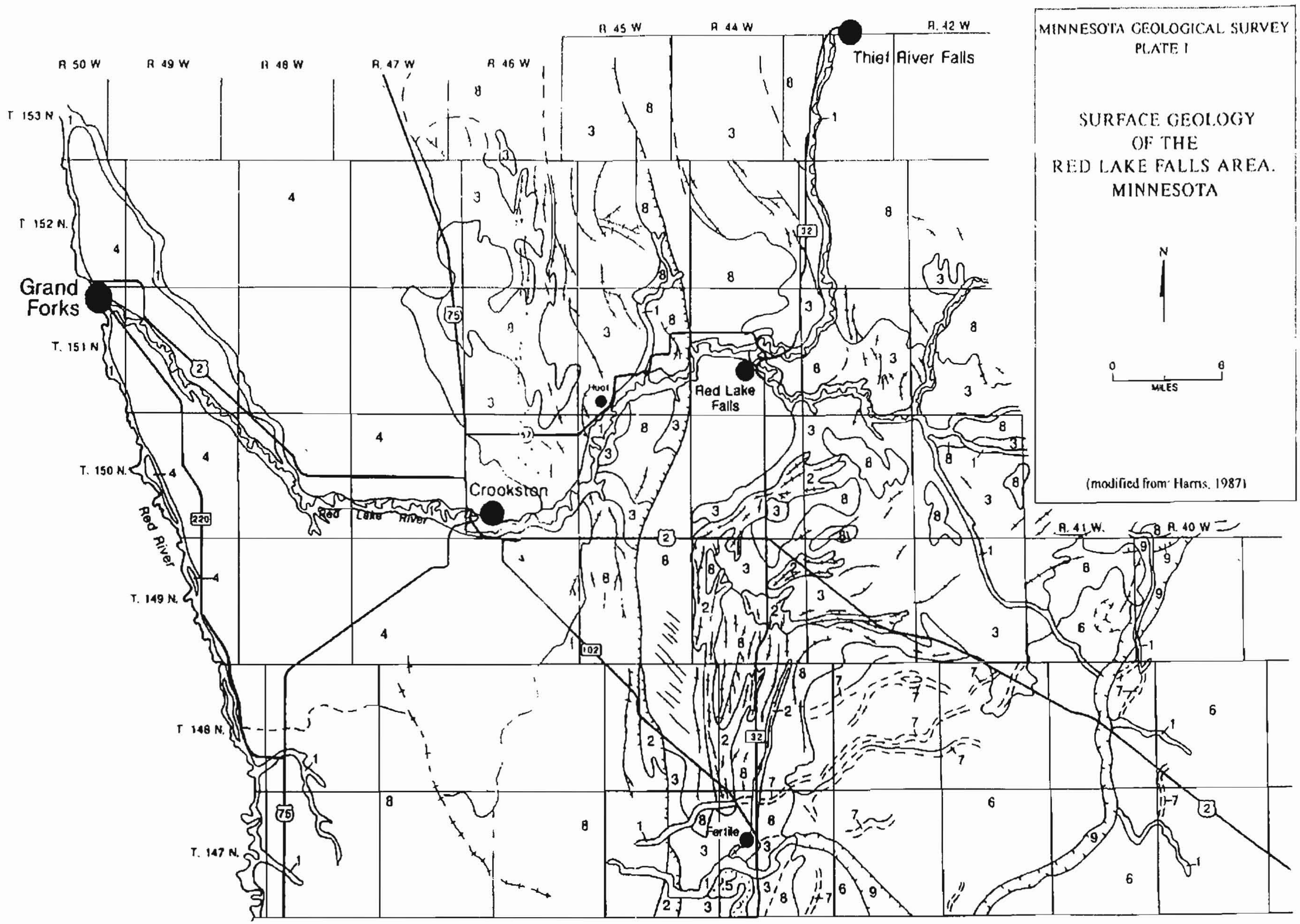
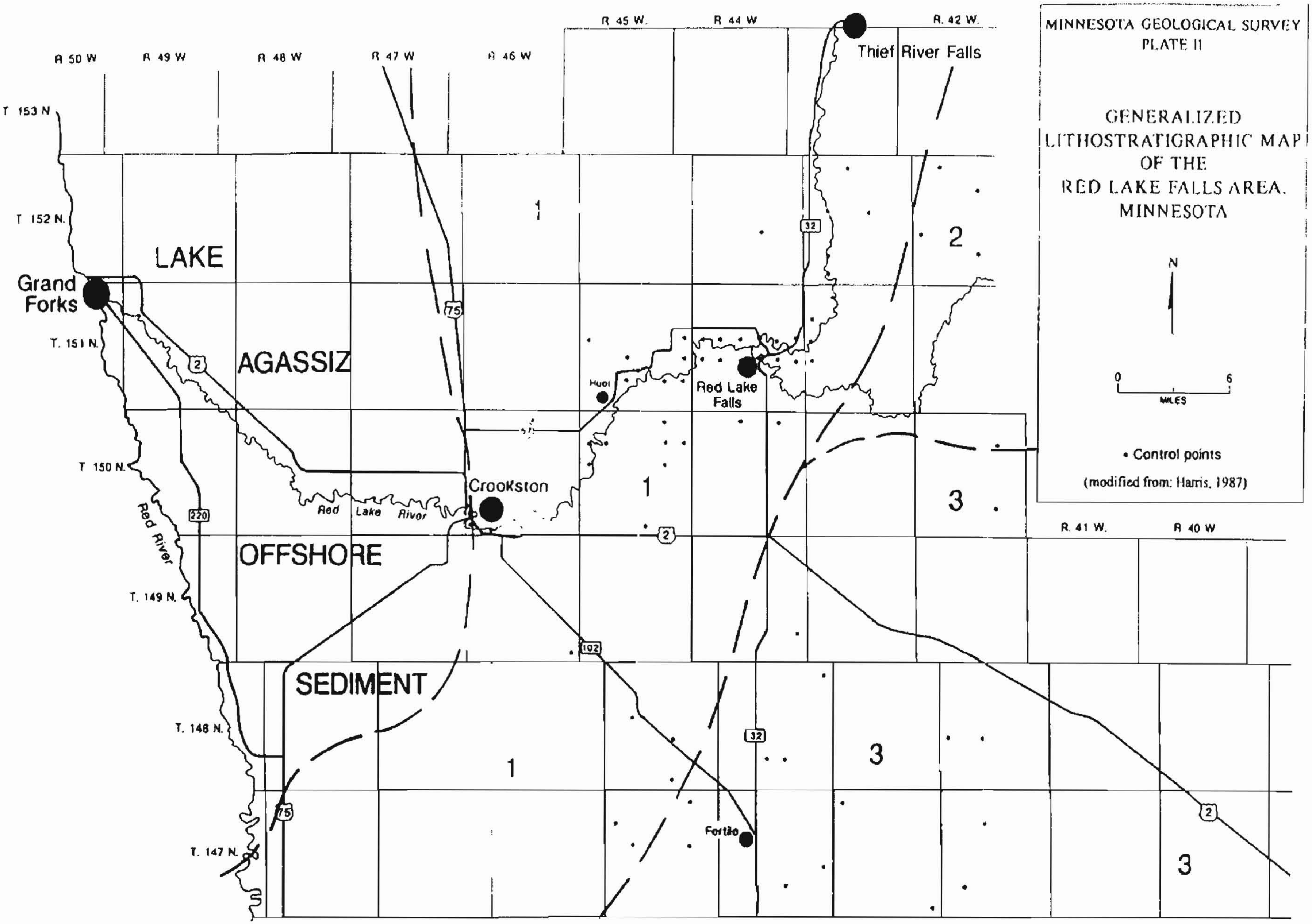

MINNESOTA GEOLOGICAL SURVEY
PLATE I
SURFACE GEOLOGY
OF THE
RED LAKE FALLS AREA,
MINNESOTA
N
0
8
MILES
(modified from: Harris, 1987)
R. 50 W
R. 49 W
R. 48 W
R. 47 W
R. 46 W
R. 45 W
R. 44 W
R. 42 W
R. 41 W.
R. 40 W
T. 153 N.
T. 152 N.
T. 151 N.
T. 150 N.
T. 149 N.
T. 148 N.
T. 147 N.
Grand Forks
Thief River Falls
Red Lake Falls
Huot
Crookston
Red Lake River
Red River
Fertile


MINNESOTA GEOLOGICAL SURVEY
PLATE II
GENERALIZED
LITHOSTRATIGRAPHIC MAP
OF THE
RED LAKE FALLS AREA,
MINNESOTA
N
0
6
MILES
• Control points
(modified from: Harris, 1987)
LAKE
AGASSIZ
OFFSHORE
SEDIMENT
1
2
3
Grand Forks
Thief River Falls
Red Lake Falls
Huot
Crookston
Fertile
Red Lake River
Red River
R 50 W
R 49 W
R 48 W
R 47 W
R 46 W
R 45 W.
R 44 W
R. 42 W.
R. 41 W.
R 40 W
T 153 N
T 152 N.
T. 151 N.
T 150 N.
T. 149 N.
T. 148 N.
T. 147 N.
2
75
32
220
102

ROADLOG
Sunday, June 2, 1996
Afternoon
Kenneth L. Harris
Minnesota Geological Survey - St. Paul, Minnesota

We will travel from Grand Forks, North Dakota to Dilworth, Minnesota. *Figure 19* shows a generalized surficial geologic map and a generalized lithostratigraphic map. The surface geology of the North Dakota part of this trip is shown in more detail on the Surface Gology of the Goose River Map Area (Harris and Luther, 1991). The surface geology of the Minnesota part of this trip is shown in more detail on Plate I of the Southern Red River Valley Regional Hydrogeologic Assessment (Harris and others, 1995, in pocket).

Mile 0 (0.0) *Grand Forks*: Drive south on I-29 to US-200

Edinburg Moraine (Mile 24 to 38): This is a verylow-relief moraine that crosses the Lake Agassiz basin. The till that forms the moraine (Huot Formation) was deposited in Lake Agassiz and is a pebble-poor, clay-rich flow till. It is very difficult to map the boundary between the lake sediment and till in this area (difficult to differentiate between stones and potatoes in the fields). In season, fresh road cuts (drainage ditches) expose the till. The moraine is a topographic high that separates the Elk Valley delta (estuary) from the main part of Lake Agassiz north of Grand Forks, ND. Numerous, parallel beach ridges formed on the moraine during the Lockhart and Emerson Phases of Lake Agassiz.

Mile 38.0 (38.0)	*Hillsboro, ND*
Mile 42.0 (4.0)	*I-29 & US-200*: West on US-200
Mile 45.0 (3.0)	*US-200 & Unnamed Traill County Road*: South on unnamed Traill County road
Mile 48.0 (3.0)	*Unnamed Traill County Road & Unnamed Traill County Road*: East on unnamed Traill County road
Mile 49.5 (1.5)	*Cross the Hillsboro Aquifer* (a compaction ridge)

Hillsboro Aquifer: This feature is expressed at the surface as a low-relief ridge on the Lake Agassiz plain. The ridge is oriented north-south, is at least 25 miles in length, and extends south from the Edinburg Moraine (Huot Formation) that crosses the Red River Valley here (Harris and Luther, 1991; Harris and others, 1995).

Lake Agassiz Compaction Ridges: These are discontinuous, low-relief, sinuous ridges present on the Lake Agassiz plain. They are visible on airphotos, but generally difficult to see on the ground. The ridges are thought to mark the location of buried fluvial channel sediment deposited by streams that flowed across the lake plain prior to the last flooding of the Lake Agassiz (Moorhead Phase). The channel deposits are expressed - at the surface - as subtle ridges because of differential compaction. Most of the modern tributaries of the Red River have "shadow" compaction ridges because the subtle topography of these ridges has influenced the course of modern streams (see *Running*, this volume).

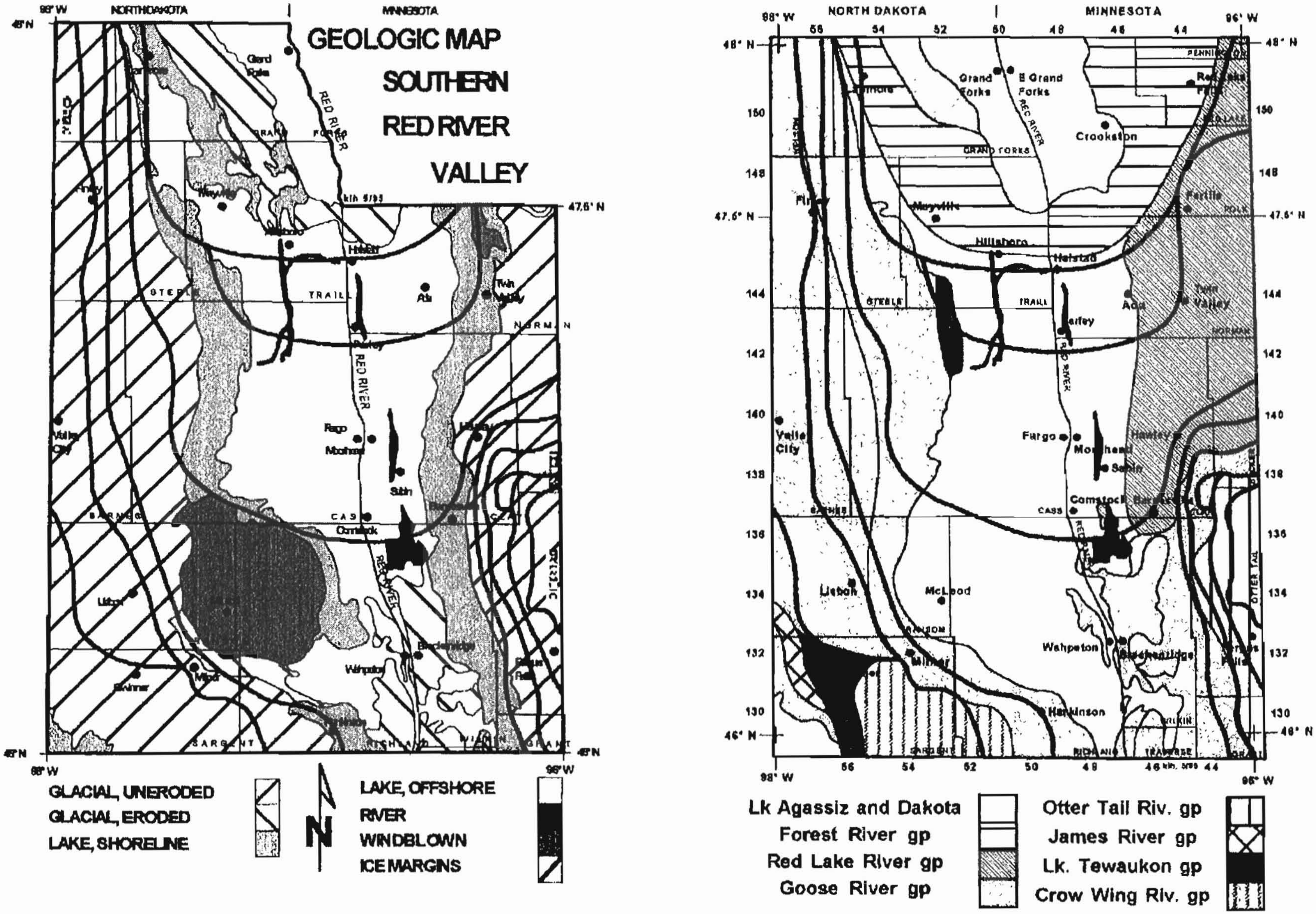


Figure 19. Maps showing generalized surficial geology (left) and lithostratigraphy (right) of the southern Lake Agassiz basin (compliled from Harris, 1987; Harris and Luther, 1991; Harris and others, 1995).

The Hillsboro aquifer has been interpreted as a beach ridge or a compaction ridge by various workers (Bluemle, 1967; Harris and Luther, 1991), but there are water wells in the ridge that penetrate more than 100 feet of sand and gravel. No comprehensive study of the aquifer has been done, so speculation on its origin continues.

A "network" of compaction ridges is associated with the Edinburg moraine and Perley and Comstock ice margins (Harris and Luther, 1991; Harris and others, 1995). The Hillsboro aquifer is "connected" by the Hillsboro-Halstad ridge (Kelso Ridge, see *Reid and Olson*, this volume) to an enlarged north-south oriented compaction ridge on the Minnesota side of the Red River. This ridge forms a "trunk" ridge that extends south to the Buffalo aquifer. The Hillsboro aquifer, part of this "network", appears to be a narrow channel incised into the lake plain filled with sand and gravel. Possibly it is a buried tunnel valley associated with the recession of the perley ice margin, similar to the Buffalo aquifer.

Mile 52.0 (2.5)	*Unnamed Traill County Road & US-81*: North on US-81
Mile 54.0 (2.0)	*US-81*: Cross the Halstad-Hillsboro ridge (a compaction ridge)

Hillsboro-Halstad Ridge: This feature is also a low-relief ridge on the Lake Agassiz plain. The ridge, as mapped by Harris and Luther (1991), is oriented east-west, is at least 12 miles in length, and is located just south of the Edinburg moraine (Huot Formation) that crosses the Red River Valley here. The ridge has been interpreted as a "compaction ridge". The location, proximal and parallel to the Edinburg moraine, suggests it may be related to meltwater associated with the Perley ice margin (Harris and others, 1995).

Mile 55.0 (1.0)	*US-81 & US-200*: East on US-200; The Hillsboro-Halstad ridge is about 3 to 2 mile north of US-200 here
Mile 55.6 (0.6)	*Cross the Hillsboro-Halstad Ridge* (a compaction ridge)
Mile 61.5 (5.9)	*Cross the Hillsboro-Halstad Ridge* (a compaction ridge)
Mile 65.0 (3.5)	*Halstad, MN (US-200 & US-75)*: South on US-200
Mile 69.0 (4.0)	*US-200 & US-75*: East on US-200
Mile 83.0 (14.0)	*Ada, MN*: East on US-200
Mile 94.0 (11.0)	*US-200 & MN-32*: South on MN-32
Mile 95.0 (1.0)	*Heiberg, MN*: The Heiberg section; Continue south on MN-32

Heiberg Section: This cutbank is usually difficult to get to because of high water in the Wild Rice River. The section exposes thin shoreline sand and gravel overlying three (3) tills (L. Red Lake Falls Formation, St. Hilaire Formation and the Heiberg till *[Figure 20]*). The L. Red Lake Falls Formation has a low- to moderate-shale content (northerly source; Red Lake River group). The St. Hilaire Formation and Heiberg till both are relatively high-shale units (northwesterly source; Goose River group; Harris and others, 1995).

Mile 96.9 (1.9)	*Twin Valley, MN (MN-32 & Norman County 29)*: East on Norman County 29
Mile 97.0 (0.1)	*Twin Valley, MN (Norman County 29 & Norman County 31)*: Southeast on Norman County 31

Mile 101.6 (4.6)	*Fossum, MN (Norman County 31 & Norman County 36)*: South on Norman County 36
Mile 104.6 (3.0)	*Frenchman's Bluff*: Continue south on Norman County 36

Frenchman's Bluff: This feature is interpreted to be a large overridden ice-contact deposit. Numerous sand and gravel mines operate in this area. Here, a thin till (L. Red Lake Falls Formation) overlies the sand and gravel core of the bluff. Saturation on basal cobbles show a northwest-southeast orientation.

Mile 105.6 (1.0)	*Norman County 36 & MN-113*: West on MN-113
Mile 109.6 (4.0)	*MN-113 & MN-32*: Continue west on MN-113
Mile 115.6 (6.0)	Campbell beach scarp and shoreline complex (elevation is about 100 feet)
Mile 121.1 (5.5)	*MN-113 & MN-9*: South on MN-9
Mile 123.1 (2.0)	*Enter Clay County*
Mile 128.1 (5.0)	*Felton, MN*: South on MN-9
Mile 130.1 (2.0)	*MN-9 & Clay County 108*: East on Clay County 108
Mile 133.6 (3.5)	*Ames Sand and Gravel (B-B Ranch)*: Return to MN-9

Ames Sand and Gravel Pit: Operators of gravel pits in this area use a slackline to mine gravel to a depth of 85 feet. This gravel contains abundant cobbles and boulders and no shale. The surface geology of the area is characterized by the presence of a wave-cut scarp and Lake Agassiz beach ridges (Campbell level; elevation about 100 feet). It seems likely that this sand and gravel was deposited by meltwater streams flowing along the east side of the Red River lobe, and that the meltwater deposits were later reworked by shoreline processes.

Mile 137.1 (3.5)	*MN-9 & Clay County 108*: South on MN-9
Mile 149.1 (12.0)	*MN-9 & US-10*: West on US-10
Mile 158.1 (9.0)	*Dilworth, MN*: Howard Johnson Motel

Dilworth: We will be staying overnight in the Dilworth Howard Johnson Motel. Rooms and dinner are included in your registration fee. Rooms are double occupancy so you need to pair up and check in. Dinner will be served in the conference room followed by an informal discussion led by Jim Teller. Posters can be displayed in the conference room.

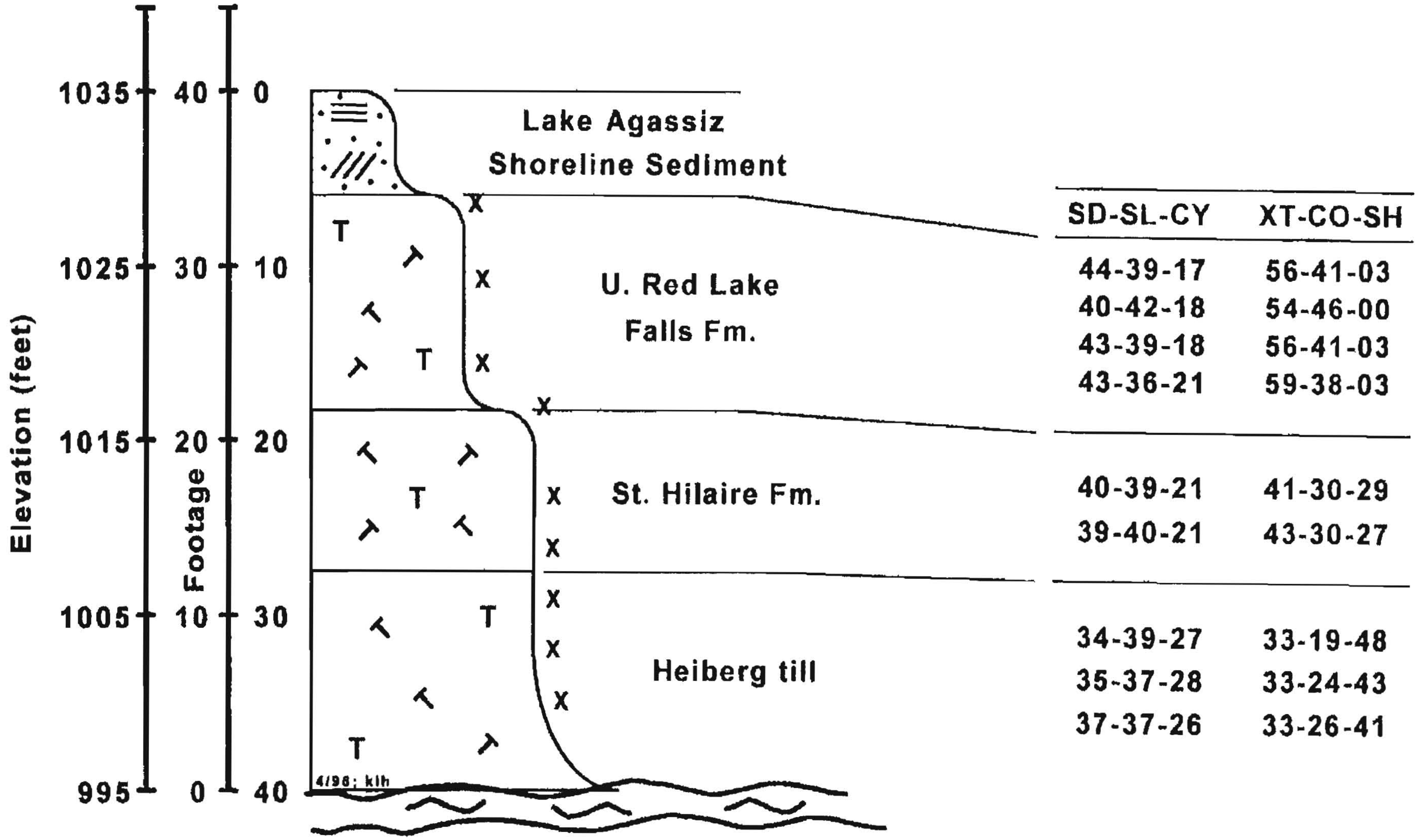


Figure 20. Outcrop sketch and data summary for the Heiberg Section, Norman County, Minnesota.

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ROADLOG
Monday, June 3, 1996
Morning
Kenneth L. Harris
Minnesota Geological Survey - St. Paul, Minnesota

We will travel from Dilworth, Minnesota, to Christine, North Dakota, this morning. *Figure 19* shows generalized surface geology and lithostratigraphy of the southern Lake Agassiz basin. The surface geology and Quaternary stratigraphy of this area is shown in more detail on Plates I and II of the Southern Red River Regional Hydrogeologic Assessment (Harris and others, 1995, in pocket).

Mile 0 (0.0)	*Dilworth, MN (Howard Johnson Motel)*: East on US-10
Mile 1.9 (1.9)	*US-10 & Clay County 11*: South on Clay County 11
Mile 2.8 (0.9)	*The abandoned gravel pits and Irrigated fields east of the road are located on the surface of the Buffalo aquifer*
Mile 3.9 (1.1)	*Clay County 11 & I-94*: Continue south
Mile 4.4 (0.5)	*Rehabilitated Truck Stop*: All contaminated surface materials have been removed and replaced with clean fill
Mile 6.9 (2.5)	*Clay County 11 & Clay County 12*: East on Clay County 12
Mile 7.9 (1.0)	*Clay County 12 & Unnamed County Road*: North on unnamed county road
Mile 8.9 (1.0)	*Unnamed County Road & Clay County 75*: West on Clay County 75
Mile 9.2 (0.3)	*Entrance to Northern Improvement Gravel Pit*
Mile 9.7 (.06)	*Visit Pit & Return to Entrance*: West to Clay County 11

Buffalo Aquifer: The Buffalo aquifer is interpreted to be a buried tunnel valley/tunnel falley fan complex (Harris and others, 1995; Plate II; Harris and others, 1996). Airphoto mapping shows a "broom stick" plan view where the "broom handle" is the tunnel valley and the "broom straw" is the tunnel valley fan. Lithologic cross sections show that the channel is about 17 miles long, about one (1) to two (2) miles wide, and as much as 243 feet deep. The cross sections show the channel deposits are stratigraphically complex and rise to the south. The fan deposits display a "broom straw" shape in plan view (apex north), about 12 miles long (north to south), and about nine (9) miles wide (east to west). Three-dimensional diagrams of water-well, sand and gravel deposits, and surface-resistivity data (Zody, 1979) in this area were created to help visualize the feature (see *Harris and others*, this volume). These three-dimensional diagrams support the surface and subsurface mapping in the area. Moorhead City water wells, active and remediated truck stops, crop irrigation, a drag strip, and active and inactive gravel pits are located in and on the Buffalo aquifer. Obviously some prioritization of the use of this resource will eventually be necessary.

The Northern Improvement Gravel Pit: The operator of this pit uses a slackline to mine gravel to a depth of 80 feet from the Buffalo aquifer. The sand and gravel recovered is said to be generally fine-grained; course material must be added for certain applications.

Hydrogeology of the Buffalo Aquifer: Recharge to the Buffalo aquifer occurs through unconfined windows in the aquifer as well as influx of regional water. The result is that the chemistry and flow within the aquifer is not as uniform as might be expected if the aquifer were more isolated. One interesting feature is that the aquifer has cut through older east-west deposits, effectively cutting off the recharge source for aquifers west of the Buffalo aquifer. This partly accounts for the significant drawdown in aquifers near Moorhead (Trojan, in prep.)

Mile 10.4 (0.7)	*Clay County 75 & Clay County 11*: North on Clay County 11
Mile 12.4 (2.0)	*Clay County 11 & I-94*: Continue North on Clay County 11
Mile 14.4 (2.0)	*Clay County 11 & US-10*: East on US-10
Mile 14.9 (0.5)	*Moorhead City water wells located north of the US-10 draw water from the Buffalo Aquifer*
Mile 21.8 (6.9)	*US-10 & MN-9*: South on MN-9
Mile 22.0 (0.2)	*Stockwood Site*

Stockwood Fill Site (Donald Schwert, NDSU Geosciences and Mark Peihl, Clay County Historical Society; see *Schwert*, this volume): Facing east from this position, one can view the abrupt change in topography that marks the eastern margin of the Lake Agassiz basin. Prior to 1906, eastbound traffic of the Northern Pacific Railroad faced a 1.5% grade over this margin, significant enough to require either a reduction in tonnage or the use of pusher engines. In March, 1906, construction began on the "Stockwood Fill", which would lower the grade to .3%. A pile and timber trestle 4.75 miles in length was constructed and then buried by five (5) million cubic yards of fill. This loading of saturated lake/deltaic sediment immediately caused localized subsidence of the fill, with up to eight (8) meters of sagging occurring. Compressional ridges associated with this process are still visible today, although evidently long inactive.

Mile 22.2 (0.2)	*US-10 & MN-9*: East MN-9
Mile 26.8 (4.6)	*US-10 & Clay County 23*: South on Clay County 23
Mile 29.8 (3.0)	*Clay County 23 & Clay County 12*: East on Clay County 12
Mile 29.8 (0.0)	*Gravel Pit*

Clay County Landfill Sites: These gravel pits are located near the Clay County landfill. A variable thickness of the L. Red Lake Falls Formation overlies the sand and gravel being mined here. We are located near the Comstock ice margin (ice margin #3), and the sand and gravel here is intensely folded and faulted. Surficial materials north and west of here have been eroded by fluvial and shoreline processes. In some places Red Lake Falls Formation and older Red River Lobe tills have been completely removed. A test hole, four (4) miles to the northwest, drilled 182 feet of Otter Tail River and Crow Wing River group tills and lacustrine sediment. The Alexandria moraine sediment is thinly buried in this area.

Mile 31.8 (2.0)	*Clay County 12 & Unnamed County Road*: South on unnamed county road
Mile 34.8 (3.0)	*Rushfieldt Lake*
Mile 37.1 (2.3)	*Unnamed County Road & Clay County 10*: East on Clay County 10
Mile 42.3 (5.2)	*Clay County 10 & MN-32*: South on MN-32
Mile 44.1 (1.8)	*Rollag, MN*: Continue south on MN-32

Rollag Area: We have driven up on the buried Alexandria moraine. Thin Red River lobe tills cover Wadena/Rainy lobe tills here, the buried Alexandria moraine. We are about one (1) mile west of the eastern edge of the Red River lobe tills (Harris and others, 1995).

Mile 45.6 (1.5)	*MN-32 & Clay County 6*: West on unnamed county road
Mile 48.6 (3.0)	*Big Slough*

Big Slough: This major meltwater channel is the Big Slough. It probably carried meltwater from the Winnipeg lobe (Red River lobe) at ice margin #4 (Harris and others, this volume). This ice margin marks the approximate boundary of the Goose River group (St. Hilaire Formation) (Harris and others, 1995).

Thrust Ridges: Subtle thrust ridges can be seen on airphotos in this area. They trend northeast-southwest and are thought to have been formed by the Winnipeg lobe (Red River lobe) during the deposition of the Goose River group (St. Hilaire Formation) (Harris and others, 1995).

Mile 49.6 (1.0)	*Unnamed County Road & Clay County 31*: South on Clay County 31

Drumlins: Subtle drumlnis can be seen on airphotos in this area. They trend northwest-southeast and are thought to have been formed by the Winnipeg lobe (Red River lobe) during the deposition of the Goose River group (St. Hilaire Formation) (Harris and others, 1995).

Mile 54.1 (4.5)	*Clay County 31 & MN-34*: West on MN-34
Mile 57.1 (3.0)	*MN-34 & I-94*: West on MN-34
Mile 58.3 (1.2)	*MN-34 & MN-9 (Barnesville MN)*: Turn south on MN-9

Barnesville Area: We have driven out of the glacial upland that was characterized by ice marginal features, drumlins, thrust ridges, high-relief collapsed topography, esker swarms, and fresh, collapsed & palimpsest outwash channels. We are now back in the Lake Agassiz basin and the landscape is characterized by beach ridges, poorly drained swales between beach ridges, and wave washed till (Harris and others, 1995; Plate I).

Mile 61.2 (2.9)	*Wilkin County Line*: Continue southwest on MN-9
Mile 66.3 (5.1)	*MN-9 & Wilkin County 30*: East on Wilkin County 30
Mile 69.3 (3.0)	*We are driving west onto the Buffalo aquifer tunnel valley fan*

Wolverton "Mountain": This is the Buffalo aquifer tunnel valley fan. It is an area of low-relief sand and gravel veneered by Lake Agassiz silt and clay. Several gravel pits (swimming holes) are located on the Lake Agassiz plain in this area. Irrigated fields are an indication that sand and gravel is not deeply buried (Harris and others, 1995).

Mile 76.3 (7.0)	*We are driving off the west edge of the Buffalo tunnel valley fan*
Mile 78.9 (2.6)	*Wilkin County 30 & US-75*: North on US-75
Mile 79.4 (0.5)	*Wolverton, MN*: Continue north on US-75
Mile 79.9 (0.5)	*Wilkin County 30 & US-75*: West on Wilkin County 30
Mile 80.7 (0.8)	*Red River Bridge*: Continue west to Christine, ND
Mile 83.4 (2.7)	*Christine, ND*

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ROADLOG FOR THE SHEYENNE DELTA
Monday, June 3, 1996
Late Morning/Early Afternoon
Garry Leonard Running IV
Field Trip Leader

This road log will guide you on a tour intended to provide an overview of geomorphology and archeology on the Sheyenne Delta (for route map, see *Figures 21a and 21b*). The Sheyenne Delta formed in the early stages of Glacial Lake Agassiz when the lake was at its highest level (Cass Phase; Herman strandline or higher [*Figure 22* and *Table 1*]). It covers an 840 square mile area. The Sheyenne Delta has been the scene of dynamic landscape evolution during the last 9,500 years. The route outlined in the road log is intended to emphasize post-Glacial Lake Agassiz landforms and to give the participant a road's eye view of the scale, complexity, chronostratigraphy, and variety of landforms present on the Sheyenne Delta.

There are two (2) stops planned on this part of the field trip. In order to conform to the local road system, distances in the road log are reported in miles. All other measurements are reported in metric units.

This roadlog begins at Christine, North Dakota.

1. *Return to I-29*: Head north 4 miles to Highway 46. Turn west 10 miles (just past Kindred [the last rest facility]) to Highway 3. Just before Kindred, we cross the Sheyenne River which meanders with a relatively narrow alley. The Sheyenne River Valley is composed of late-Holocene alluvium (4,000 BP to present) inset into Glacial Lake Agassiz offshore sediments. Note the abrupt escarpment 3 to 4 miles ahead (west) that angles off to the northwest. This is the Campbell wave-cut escarpment, etched into deltaic sediments during the Lockhart Phase and again during the Emerson Phase (Brophy, 1967; Brophy and Bluemle, 1983).

2. *Take a left (south) on Richland County 3.*

3. *Continue south on Richland County 3 (cross the Sheyenne River again)*: Note that the Campbell wave-cut escarpment is directly in front of you (south) as you cross the river. Some low-relief eolian dunes are visible higher on the landscape. Upstream from the bridge, the Sheyenne River is flowing in a valley inset into deltaic sediments (the Sheyenne River Trench [*Figure 24*]). Turn right (west) at the first section road south of the river (this turn is about 50 meters south of the bridge and is still in the valley). Continue westward about 300 meters, over a meander scar in the modern Sheyenne River Valley. The large excavation to the left (south) of the road is the Rustad Pit, in and around which the Rustad Quarry archeological site (32RI775) is located.

STOP 1: The Rustad Quarry Site (32RI775)

The Rustad Quarry Site is an extraordinarily rich archeological site. The site was discovered in 1992. Since then some 100 square meters have been excavated, during the 1992 through 1995

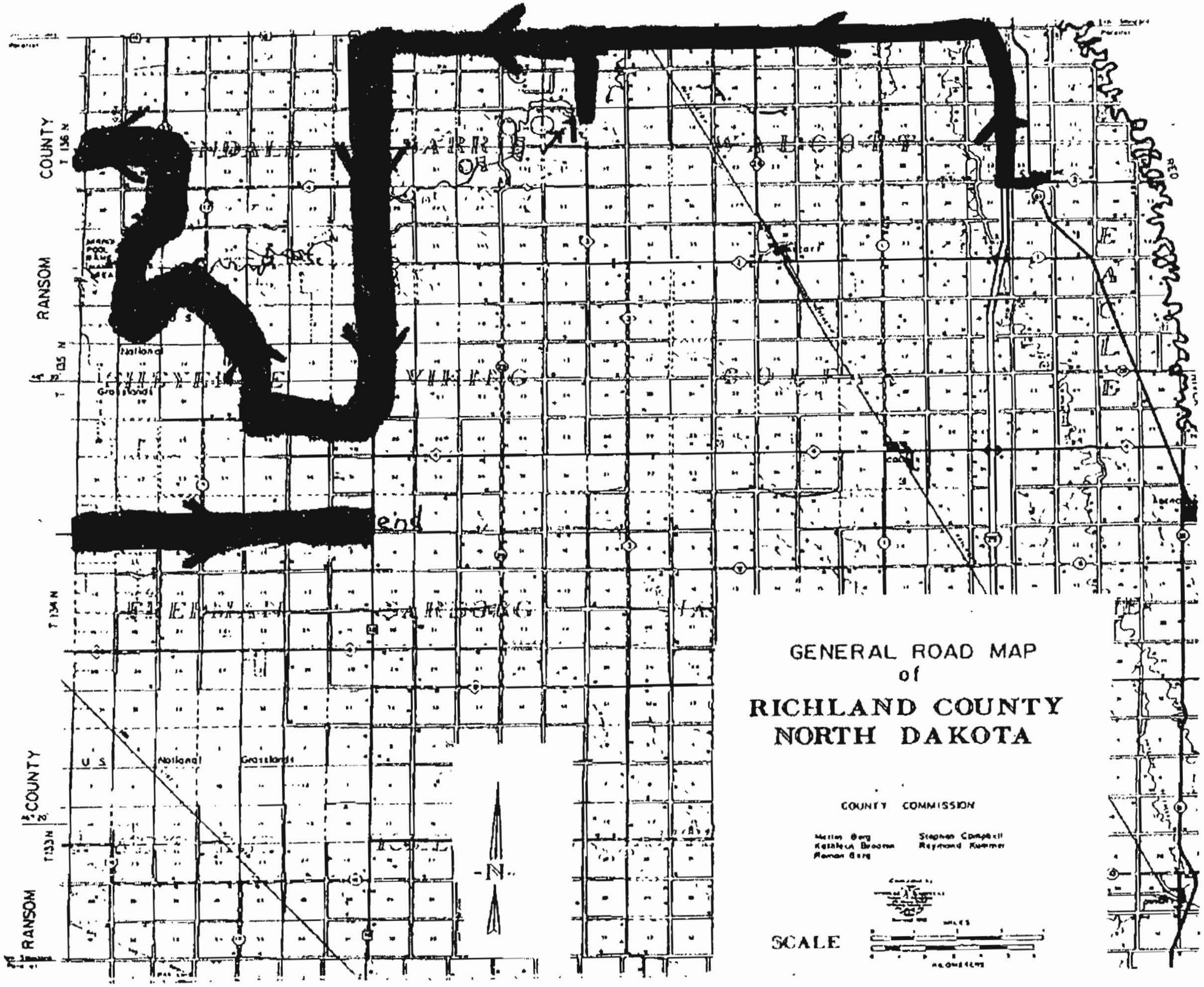

Figure 21a. The Sheyenne Delta field trip route in Richland County, North Dakota.

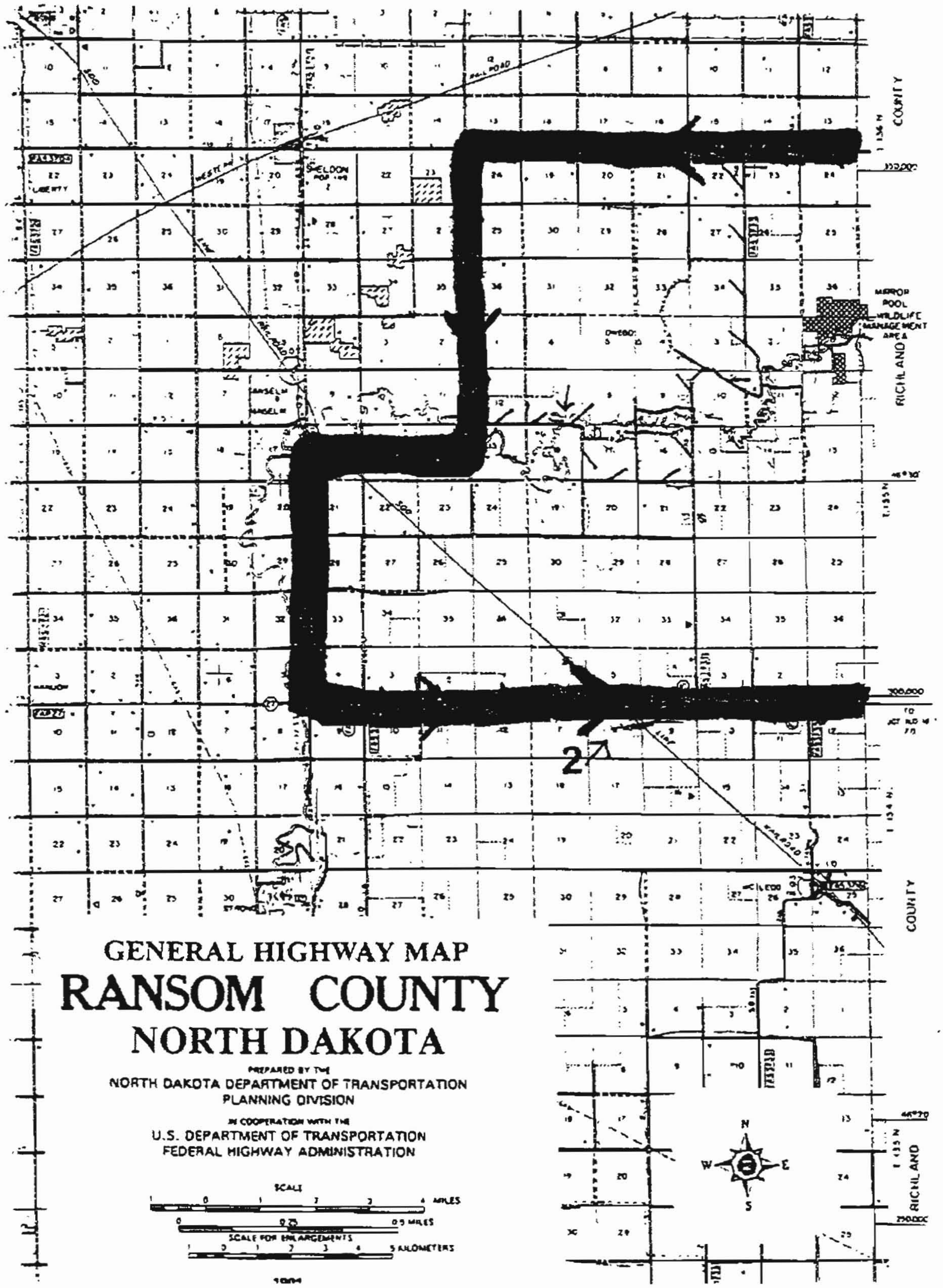

Figure 21b. **The Sheyenne Delta field trip route in Ransom County, North Dakota.**

Lake Phase/ Years BP	Strand-lines	Strandline Elevation (at south end/at Int'l Border, in ft)	Outlet(s)	Offshore sedi-ments	Actively Prograding Deltas
Nipigon 9,500-8,500	Gladstone Burnside Gimli	830/850 820/840 NA /about 830	eastern outlets, Hudson's Bay	Sherack, none	none
Emerson 9,900-9,500	Campbell II	990/1070	Glacial River Warren, NW outlets(?)	Sherack	none(?)
Moorhead 10,900-9,900	McCauley-ville Blanchard Hillsboro Emerado Ojata	970/1015 945/985 910/950 890/925 850/880	eastern outlets	Poplar River	Moorhead Delta, numerous lessor Deltas
Lockhart 11,600-10,900	Herman Norcross Tintah Campbell I	1080/1280 1050/1180 1020/1120 990/1070	Glacial River Warren	Brenna	Sheyenne, Elk Valley, Pembina, Assiniboine
Cass 12,300-11,600	none, Herman	>1080/ >1280	Milnor Channel, McIntosh/ Prairie spillways, Glacial River Warren	Wylie and Argusville	Sheyenne

Table 1. **Phases of Glacial Lake Agassiz history and associated features (after Fenton and others, 1983). Offshore sediment nomenclature after Arndt (1977).**

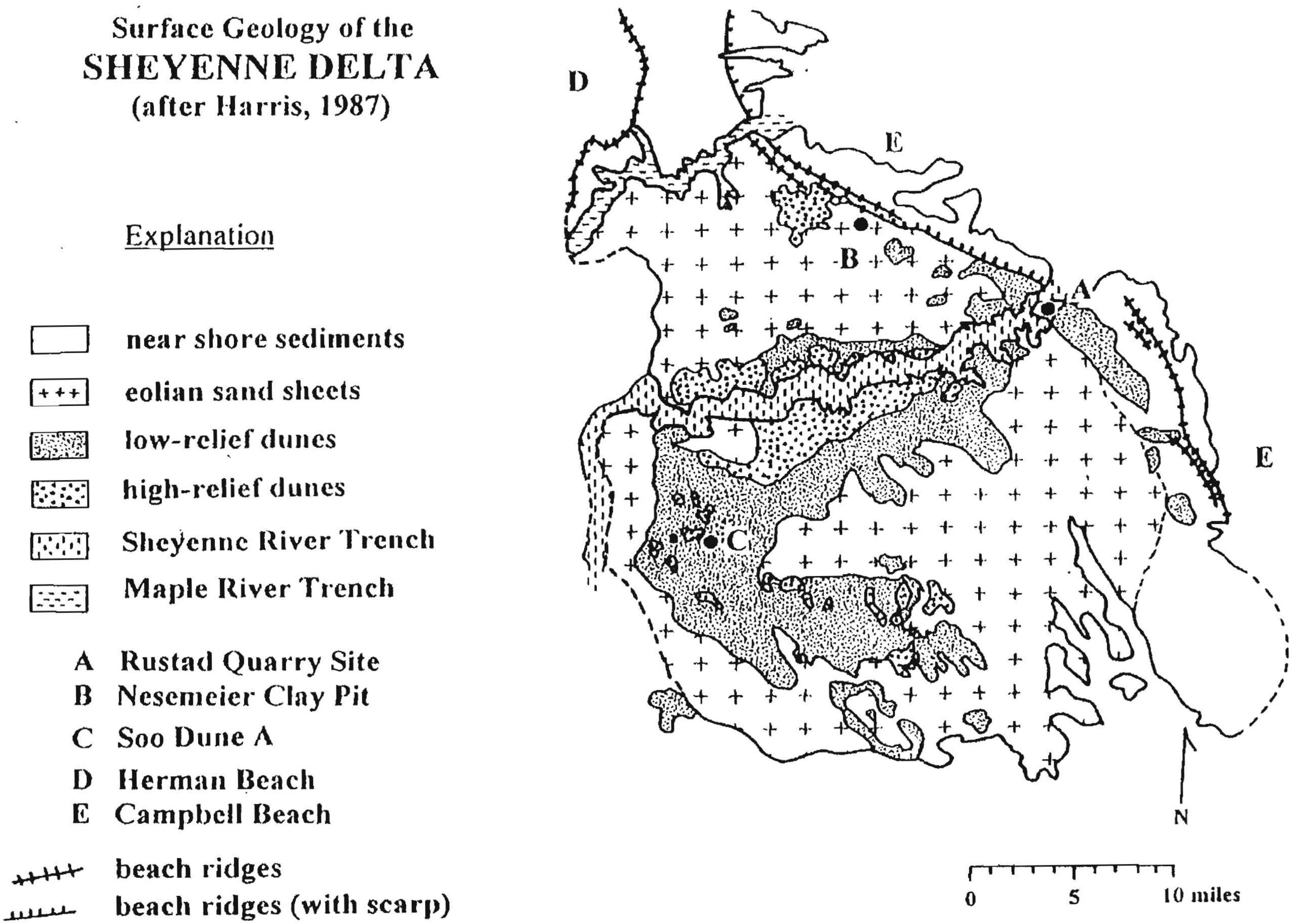

Figure 22. The Sheyenne Delta (after Harris, 1987), showing the location of the Rustad Quarry Site and the Soo Dune Site.

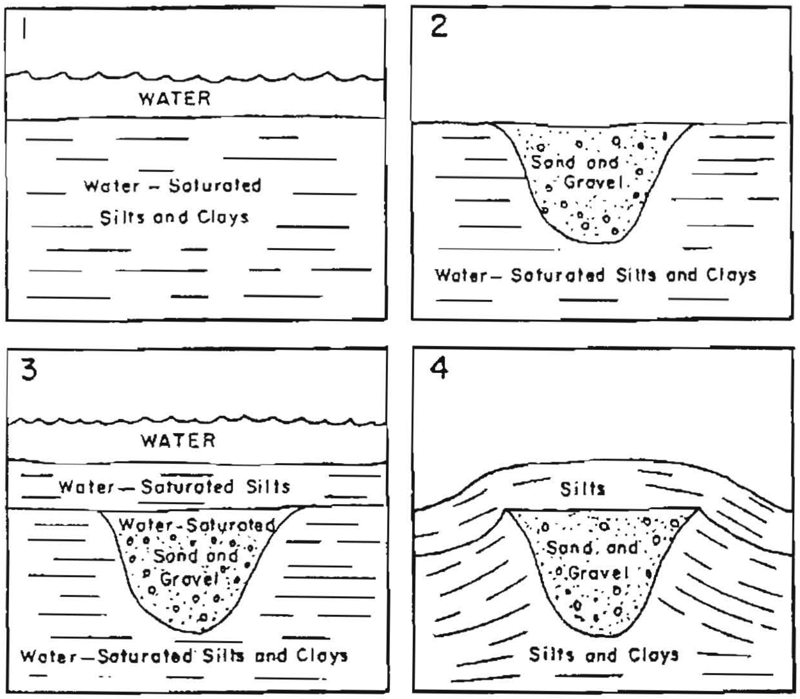

Figure 23. **Development of a compaction ridge (from Bluemle, 1988). 1) Lake Agassiz fine-grained offshore sediment deposited (Brenna Formation). 2) Fluvial channels cut and filled with coarse alluvium and channel lag during the Moorhead low Water Phase (Poplar River Formation). 3) Lake Agassiz fine-grained offshore sediment again deposited during the Emerson Phase (Sherack Formation). 4) Post-Glacial Lake Agassiz dewatering of fine-grained offshore sediments causes topographic reversal, leaving fluvial sediments as positive relief.**

field seasons, by Mike Michlovic and his crews (Moorhead State University, Department of Sociology and Anthropology). This brief summary of the cultural remains at the site is based on the work of Michlovic (1995) (also, see *Michlovic*, this publication, for a more detailed discussion of this site). The site appears to represent an Early Archaic camp and food-processing site. Few sites of this cultural period are known from the northern Great Plains (Artz, 1995). Campsites of this time period are fewer still. The site was occupied repeatedly by small groups from as early as 8,000 BP to as late as about 7,000 BP. A large number of stone artifacts have been recovered (5,000 flakes, 67 worked flakes, 53 bifaces, 42 points, 17 scrapers, 24 cores). Most of the lithic assemblage is made from Swan River chert (77%). Knife River flint is distinctively underrepresented in the lithic assemblage (only 3%). Many of the projectile points recovered are small (1-1.5 cm), thin, triangular, and side or corner-knotched. They are similar to those encountered at the Itasca Bison Kill site in west-central Minnesota (Shay, 1971). Were these points found in a surface scatter or isolated surface find, they would most likely be called "arrowheads" and assigned to a much younger cultural period.

Preservation of bone at the site is very good. Fifty-thousand (50,000) bone fragments have been recovered so far. The identifiable bone (670) is dominated by bison although the bones of bear, dog (tentative), beaver, bird, mollusk shell, and fish are also represented. Measurements of the bison bone suggest animals larger than modern bison, perhaps the extinct form *bison occidentalis*. Most of the bison bones recovered from the site are lower limb bones and/or bones associated with the meatier portions of the animals. The minimum number of individuals represented is eight (8) or nine (9), and the mixed herd composition that includes male, female, and juvenile members, along with the remains of aquatic animals, suggests a warm season kill or kills.

Cultural remains at the site are associated with some of the buried soils visible along the east wall

1 = eolian sand
2 = "Delta Soil"
3 = Sheyenne Delta
4 = wave-cut escarpment
5 = Rustad Quarry alluvial fan
6 = "Lacustrine Soil"
7 = Sherack Formation
8 = Moorhead Phase fluvial sediments
9 = cutoff meander
10 = Sheyenne River floodplain
11 = Lockhart Phase terraces
12 = Red River Valley
13 = Brenna Formation

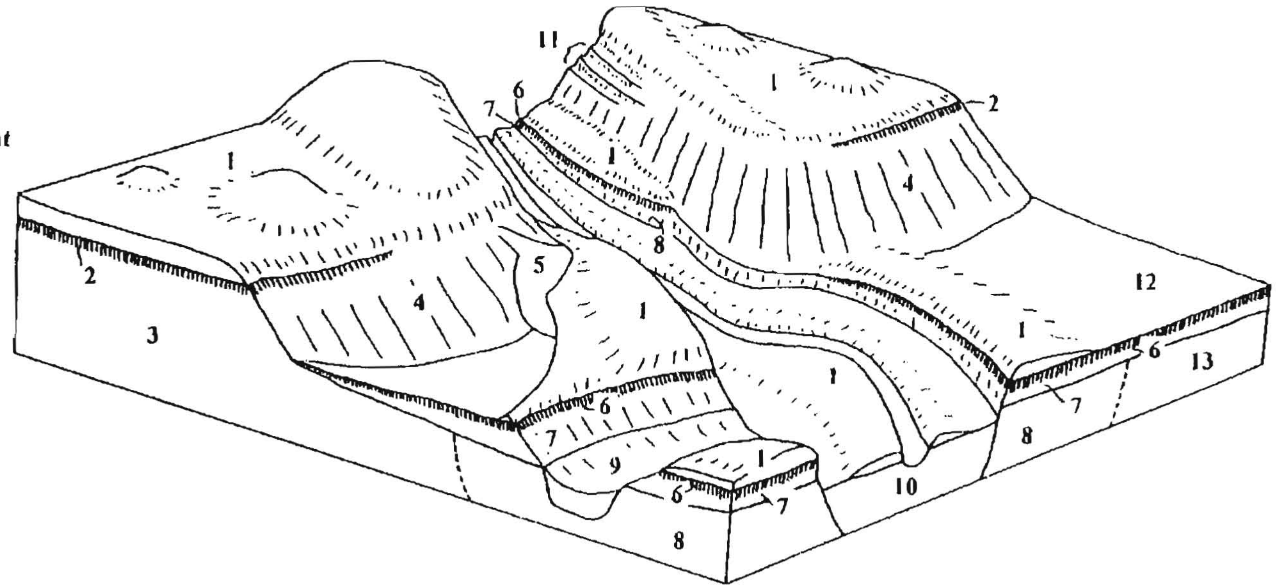

Figure 24. Block diagram of the Sheyenne Delta (from Running, 1995b). View to the west from Richland County 3. Not to scale.

of the excavation (*Ab2, Ab3, and Ab4* in *Figure 25*). The lowest buried soil, *Ab4* (the "Lacustrine Soil"), formed in sediments deposited during the Emerson Phase of Glacial Lake Agassiz. *Ab1* through *Ab3* formed in alluvial fan sediments (as mudflows). The alluvial fan formed from about 8,000 to 5,000 BP. Alluvial fan formation is one of the best indicators of mid-Holocene climatic warming/drying present on Sheyenne Delta. A more detailed discussion of the paleoenvironmental implications of Holocene landscape evolution recorded at the Rustad Quarry site is presented in Running (1995 and this publication). Alluvial fan sediments are buried by eolian sediments. Like most of the eolian deposits identified in the Sheyenne River Trench, this deposit is systematically thinner and finer-textured away from the Sheyenne River. Eolian deposits in the Sheyenne River Trench appear to be derived from sandy point-bar sediments exposed during low-flow and/or sandy overbank deposits.

4. *Return to the intersection of Richland County 3 and State Highway 46.* Turn left (west). You will be crossing the Campbell-age wave-cut escarpment in about 4 miles, after which you will be up onto the Sheyenne Delta proper (*Figure 26*). Large gullies cut into the escarpment are visible to the right (north) of the road. Alluvial fans have formed at the mouth of these gullies. The alluvial fans appear to have formed from catastrophic mudflows as a result of high magnitude, low-frequency precipitation events (Ashworth, 1978). They appear to be late-Holocene in age (Ashworth, 1978; Michlovic and others, 1988) and may be modern analog for mid-Holocene formation of the Rustad Quarry alluvial fan.

As you continue westward, note the flat to very gently rolling landscape. Here, silt-loam and loamy deltaic sediments are buried by an eolian sandsheet (.5-1 meter thick). The B-horizon of a truncated but well-developed buried soil, formed in deltaic sediments and buried by the sandsheet, is commonly encountered in core from State Highway 46 northward to the Campbell wave-cut escarpment. This buried soil, the "Delta Soil", is progressively less common to the south and has not been encountered south of the Sheyenne River Trench (see *Nesemeier Clay Pit data*, Running, 1995 and this publication). After 5 miles, turn left (south) at the intersection of State Highway 46 and State Highway 18 (a church is on the southeast corner).

5. *As you head south on State Highway 18, you will be traveling down a gradual slope.* The Highway follows the slope of the longest tributary to the Sheyenne River on the Delta (about 5 miles in length). This tributary valley is the only significant reentrant into the Sheyenne River Trench and presumably developed here because, locally, deltaic sediments are finer and have lower infiltration capacities (Downey and Paulson, 1974). The tributary valley is inset into deltaic sediments and does appear to have one or two wide, low terraces. However, due to access problems, I have no data on this tributary, its terraces, or its valley fill. Eolian sediments thicken as we move toward the Sheyenne River Trench. You will cross the Sheyenne River about 5 miles south of the State Highway 46/State Highway 18 intersection.

6. *As you cross the bridge over the Sheyenne River, look to the left (east) at the cutbank,* This exposure shows the Late-Holocene alluvial sequence typical in the modern Sheyenne River Valley. The alluvium is usually between two (2) and four (4) meters thick. The upper 2/3 is loamy-textured, fining upward sequences of overbank origin (vertical accretion). The lower 1/3 is composed of coarser, high-angle crossbeds and/or fining upward sequences of point-bar origin (lateral accretion). The moderately well-developed buried soil toward the top of the profile,

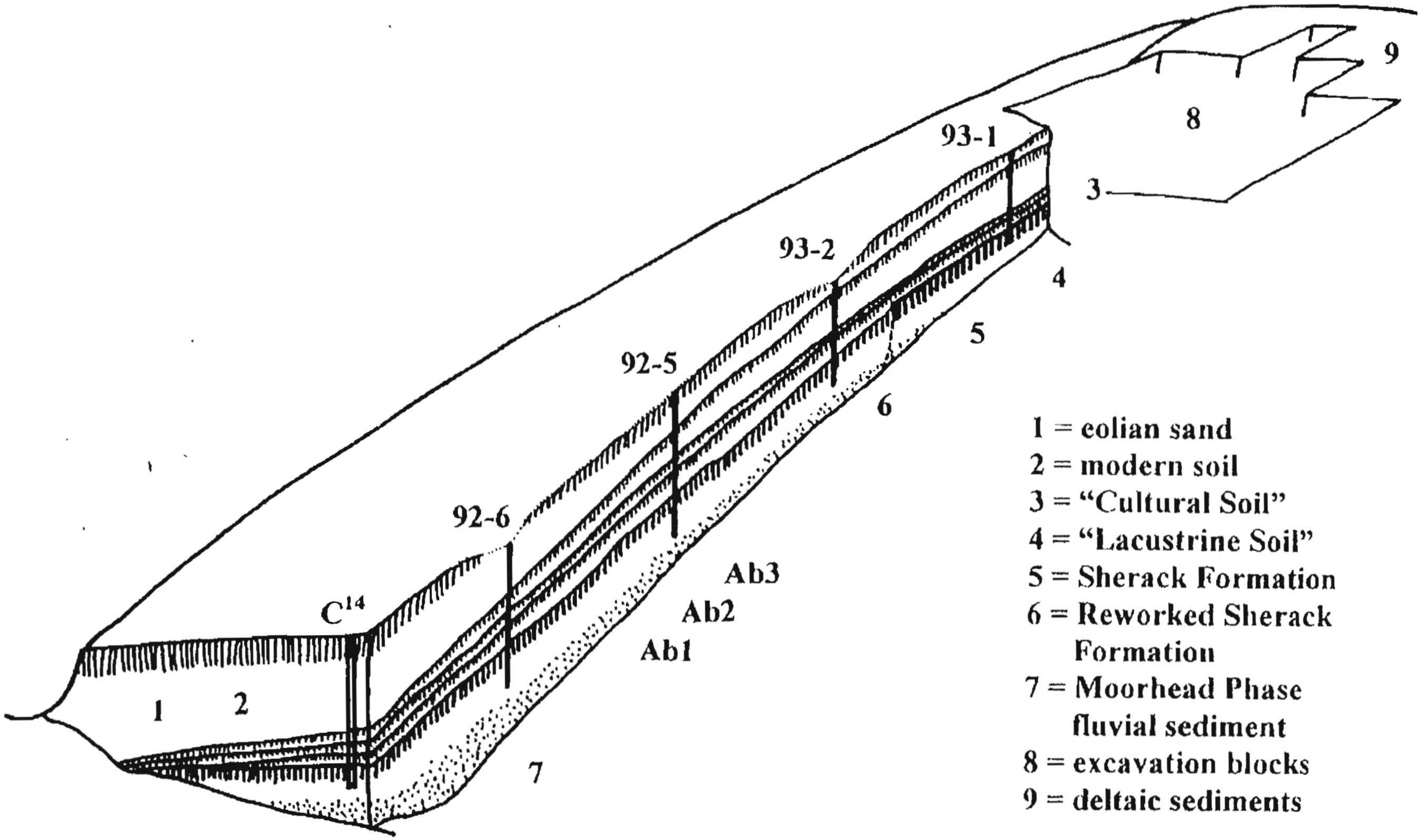

Figure 25. Schematic diagram of the east wall of the Rustad Quarry (from Running, 1995b).

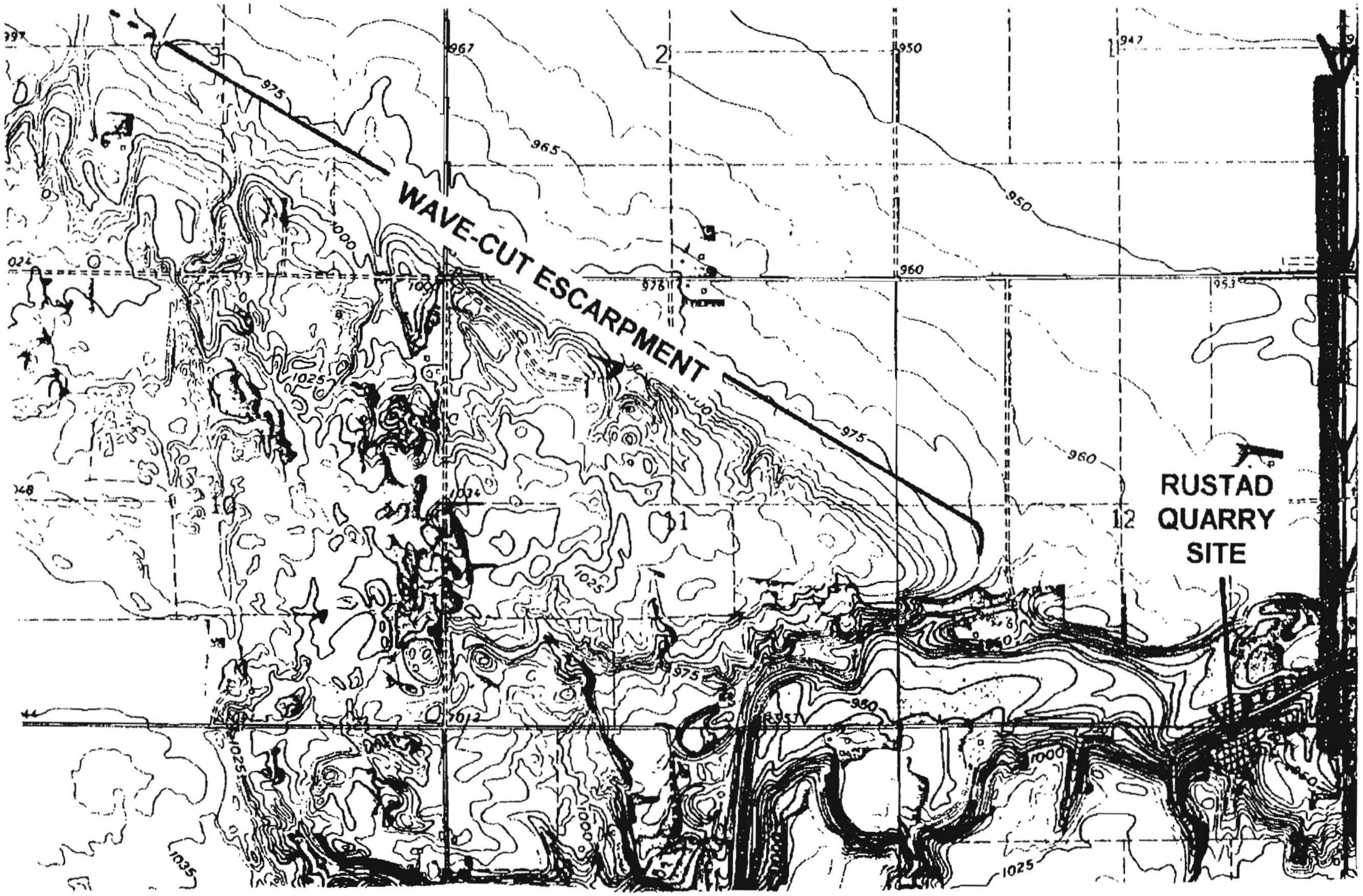

Figure 24. Block diagram of the Sheyenne Delta (from Running, 1995b). View to the west from Richland County 3. Not to scale.

formed in loam to sandy loam deposits, is widely encountered in cutbanks. It is informally referred to as the Iron Creek Paleosol (Hopkins and Arndt, 1991 [*Table 2*]). At least one sample of this soil has been analyzed for radiocarbon (235 BP +/- 90, I-2093 reported by Brophy, 1967; Moran and others, 1973). The Iron Creek Paleosol ("Pre-settlement Soil") formed on the Sheyenne River floodplain prior to extensive overbank deposition ("Post-settlement alluvium") initiated by European agricultural practices.

After you cross the Sheyenne River, note the abrupt, two (2) to three (3) meter high escarpment about 3 miles to the south of the river (to the west of State Highway 18 [*Figure 27*]). The terrace-scarp separates an older, higher terrace from the modern floodplain of the Sheyenne River. The remnant of the Moorhead Terrace visible here is composed of fluvial sediments graded to the Moorhead low-water Phase outlet of the Sheyenne River at West Fargo (Orate level). Fluvial sediments in the Moorhead Terrace are draped with about one (1) meter of silt-clay loam glaciolacustrine sediment. This sediment is the estuary equivalent of the Sherack Formation (after Arndt, 1977). A well-developed Aquoll-like soil (the stratigraphic equivalent of the "Lacustrine Soil" at the Rustad Quarry Site) formed in the thin lacustrine veneer and is commonly encountered on remnants of the Moorhead Terrace. The terrace is commonly buried, usually by eolian dunes and sometimes by alluvial fans. Continue south on State Highway 18.

7. *You will travel up out of the Sheyenne River Trench in about a mile onto a landscape dominated by eolian sandsheets and dunes.* Eolian landforms on the Sheyenne Delta have been divided into high-relief dunes, low-relief dunes, and sandsheets by Upham (1895) and Harris (1987). I follow that convention. There is an example of a high-relief dune just to the right (west) of the road about 1 mile south of the Sheyenne River Trench. High-relief dunes are generally restricted to within a mile of the trench and are generally oriented northwest-southeast or east-west. They are generally about 800 meters long, 450 meters wide, and between ten (10) and 20 meters high. The one visible here is about 730 meters long, 370 meters wide, and about 17 meters high. The age of high-relief dunes on the Sheyenne Delta is not known. However, it appears that they are composed of glaciofluvial sediments originally deposited in the later stages of delta formation (David, personal communication, 1995) that have since been reworked by wind. Low-relief eolian dunes are visible on both sides of State Highway 18, to the south of the high-relief dunes. These grade southward into an eolian sandsheet. Excellent examples of fence-row dunes are also visible. They are best developed south and east of plowed or formerly plowed fields. Continue an additional 4 miles south (5 miles from the bridge over the Sheyenne River). Turn right (west) at the intersection with Richland County 4.

8. *Follow Richland County 4 west for 3 miles.* You are crossing a flat to gently rolling landscape. Eolian sediments (sandsheet) are between one (1) and two (2) meters thick in this area. Buried soils are present in the sandsheet. Stratigraphy similar to that present at the Soo Dune site, which will be seen later on this trip, is found within these sandsheets and can also be seen in some blow-outs. Deltaic sediments are visible in the ditches along Richland County 4. Turn right (north) after 3 miles.

9. *This road winds its way northward through a landscape dominated by dunes.* Eolian sandsheets thicken and grade into dunes as you drive northward. The crests of eroded low-relief, parabolic dunes, about two (2) to three (3) meters high and about 50-300 meters in diameter, are

horizon	depth (in cm)	description
O	2.5 to 0	partly decomposed oak and grass leaves; clear abrupt boundary
A1	0 to 10	black (10YR2/1) fine sandy loam; moderate fine and medium granular structure; many fine and very fine and few medium roots; con-effervescent; clear smooth boundary
A2	10 to 28	black (10YR2/1) loamy fine sand; weak fine and medium subangular blocky structure; many fine and very fine and few medium roots; non-effervescent; clear smooth boundary
Bw	28 to 43	very dark gray (10YR3/1) light loamy fine sand; single grained; common fine and very fine roots; non-effervescent; clear smooth boundary
Bk	43 to 66	very dark grayish brown (10YR3/2) loamy fine sand; weak coarse and medium subangular blocky structure; common fine and very fine and few medium roots; strongly effervescent; clear wavy boundary
C	66 to 89	dark brown to dark yellowish brown (10YR3/3.5) fine sand; single-grained; common fine and very fine and a few medium roots; effervescent to strongly effervescent (with some areas non-effervescent); few fine (3mm dia.) pipestems present; many 10 to 13cm krotovina; clear abrupt boundary
Ab1	89 to 99	very dark grayish brown (10YR3/2) fine sandy loam; appears massive when dry, may have weak coarse prismatic structure; common very fine roots; hard consistence when dry; violently effervescent; clear smooth boundary
2Cb1	99 to 119	grayish brown (10YR5/2) unmixed, dark grayish brown (10YR4/2) rubbed; fine sand; common fine faint yellowish brown (10YR5/6) mottles; single-grained; few very fine roots; non-effervescent; lower 10cm of this horizon is hard when dry and is effervescent; abrupt smooth boundary
2A1b2	119 to 173	dark grayish brown (10YR4/2) dry, very dark gray (10YR3/1) moist; fine sandy loam; common brown (10YR3/2) dark brown (7.5YR4/4) and yellowish brown (10YR5/8) channel ferrans (most are 4mm dia.); massive; slightly hard consistence when dry; slightly effervescent; by 152cm the texture is loamy sands with an increase in medium sand; gradual smooth boundary
2A2b2	173+	dark brown (10YR3/3) fine sand; single-grained; non-effervescent

Table 2. A description of a soil profile in Maddock fine sandy loam (Hopkins and Arndt, 1991) that includes the Iron Creek Paleosol (2A1b2 [location = in modern Sheyenne River floodplains in a cutbank west side of Iron Springs Creek, SW 1/4, NW 1/4, Sec. 8, T135N, R52W]). The Iron Creek Paleosol is the informal name for the pre-settlement soil in the Sheyenne River Valley. According to Thompson and Joos (1975), the Iron Creek Paleosol is also routinely encountered in association with the Fairdale Series.

Figure 27. **Map view of a remnant of the Moorhead Phase Terrace (terrace scarp indicated by the arrow [T136N, R52W]). The north edge of this terrace remnant is buried by 2-3 meters of eolian sand derived from point-bar sediments exposed during periods of low-flow and/or sandy overbank deposits (contour interval = 5 feet).**

Figure 28. **Map view of a remnant of the Moorhead Phase Terrace at the Sohljem Site, (T135N, R52W) terrace scarp indicated by arrow (contour interval = 5 feeet).**

visible on both sides of the road. Like most of the low-relief dunes on the delta, these are oriented so their "horns" point to the northwest. They are similar in age, morphology, and origin to dunes on the Assiniboine Delta (David, 1971). They grade into low transverse ridges similar in morphology and orientation to high-relief dunes closer to the trench. You descend into the Sheyenne River Trench after about 4 miles. Turn to the left (west) onto the section-line road just before the bridge over the Sheyenne River.

10. *As you drive westward on the section-line road, look left (south).* You will note another short, steep escarpment (a church is on it east of Richland County 4, and the Sohljem farmstead is on it to the west of Richland County 4). This is another remnant of the Moorhead Terrace. Here, the "Lacustrine Soil" is buried by up to six (6) meters of eolian sand (*Figure 28*). If the soil moisture and lighting conditions are right, you will be able to make out a line of darker soil, near the top of the escarpment, where the "Lacustrine Soil" crops out. There is a fence-line extending west from the Sohljem farmstead that follows the escarpment. I have encountered Swan River chert flakes eroding out of the "Lacustrine Soil" just uphill from the gate near the west corner of that fence. These flakes are numerous and may identify another archeological site similar to the Rustad Quarry site (excavation units should be open at the time of the trip). The section-line road you are now on winds westward about 2 miles before turning north and crossing the Sheyenne River again. Excellent cutbank exposures are visible from the road and, depending on the stage, point-bar deposits from the 1993 floods may be visible in the channel. If you were to continue west another 2 miles, you would be on the remnant of the Moorhead Terrace from which McAndrews collected the mirror Pool pollen profile (McAndrews, 1967). Instead, turn north, cross the river and continue northward from the river about 2 miles.

11. *You are now north of the Sheyenne River Trench.* Turn right (east) at the first intersection with an east-west section-line road and go about 1 mile east. You will note another high-relief dune to the north of the road you are now on. It is about 640 meters long, 365 meters wide, and about 15 meters high. It is typical of the high-relief dunes north of the Trench. They are often eroded with blow-outs common on the north and west faces. One example, eroded into a large-scale yardang, has been misidentified as an "Indian Mound" (Floodman, personal communication, 1994 [were this correct, it would be the largest "Indian Mound" west of the Mississippi]). A buried soil is exposed in a blow-out about 2/3 of the way up this dune. It is about ten (10) cm thick, and is similar to *Ab1* at the Soo Dunes site. I believe it is late-Holocene in age (radiocarbon analysis is pending). Unlike most similar dunes, this one is oriented almost north-south. Note that it is actively migrating to the southeast. The trunks of cottonwoods on the downwind slope are being buried. It appears that this and some other high-relief transverse ridge dunes on the north side of the trench are being modified from an original north-south orientation to a northwest-southeast orientation (*Figure 29*). Take a left (north) at the section-line road intersection.

12. *Go north 2 miles (after 1 mile, you will be on blacktop - Richland County 2 and 23).* Turn left (west) on Richland County 23. Larger dunes and thicker eolian deposits are present to the left (south). Lower eolian dunes and eolian sandsheets are present to the right (north). Continue westward on Richland County 23 for 9 miles (you will be in Ransom County after the 2 mile mark). Turn left (south) at the section-line road intersection. You will drop down into the Sheyenne River Trench again in about 4.5 miles.

Figure 29. **Map view of the high-relief dune (SE 1/4, Sec. 2, T136N, R52W). Dotted line shows the outline of the dune prior to late-Holocene (?) reactivation. The apparent direction of migration indicated by arrow (countour interval = 5 feet).**

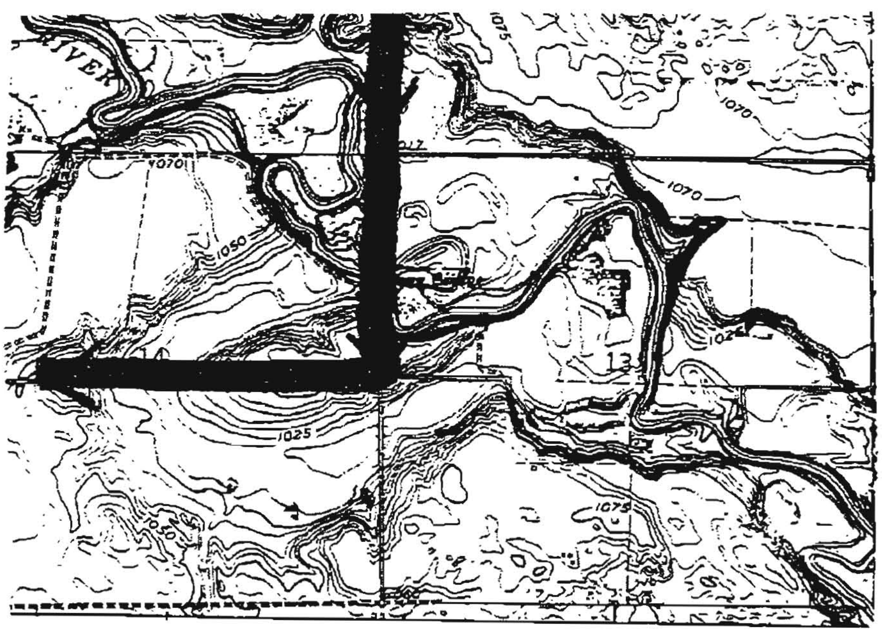

Figure 30. **Map view of a Lockhart Phase entrenched meander (Sec. 14, T135N, R54W).**

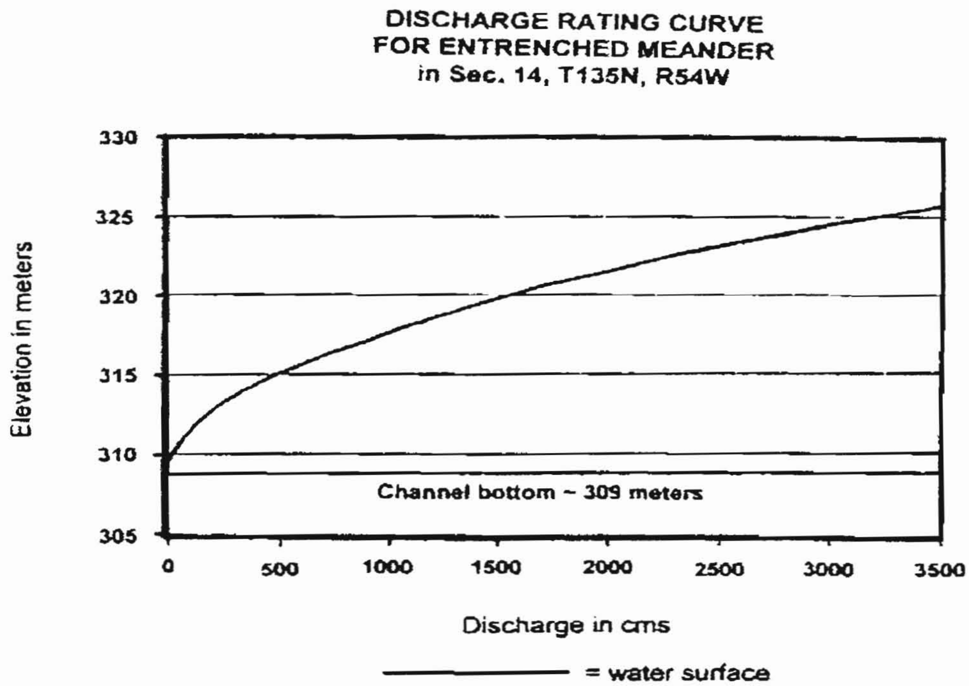

Figure 31. **Discharge Rating Curve for the entrenched meander.**

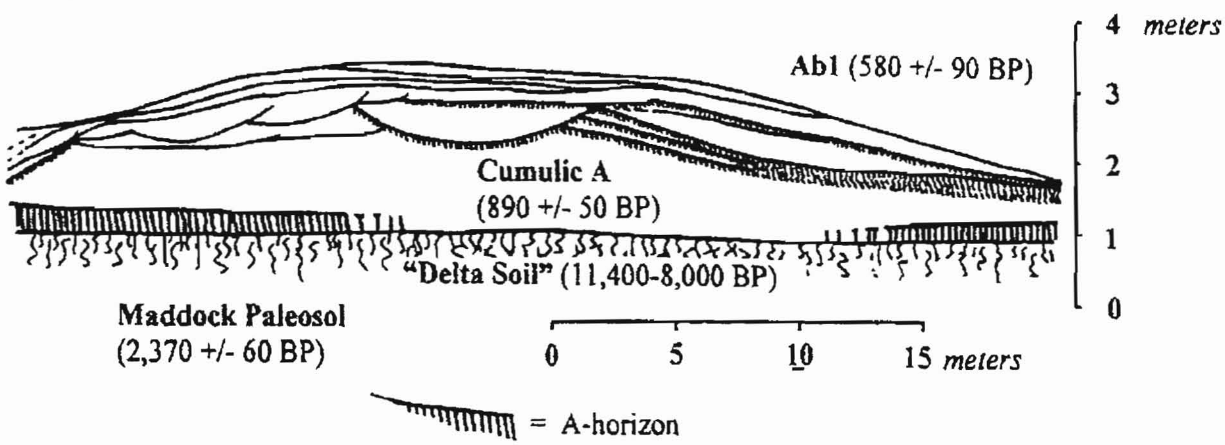

Figure 30. **Using the HEC-2 model (Becker, personal communication).**

13. *After crossing the Sheyenne River for the final time, you will quickly rise up out of the Sheyenne River Trench.* Continue south to the section-line road intersection about ¼ mile beyond the bridge and turn right (west). While facing east, south, or southwest, you will be looking downhill into one of three large-scale entrenched meanders found along the walls of the Sheyenne River Trench (*Figure 30*). This one appears to have a terrace inset in it (about 320 meters). The terrace is best observed on the west side. The other two, located on the other side of the Sheyenne River, appear to have two (2) terraces inset into them. This entrenched meander, the small of the three, is 425-430 meters wide and 12-17 meters deep. A discharge rating curve for this meander channel was generated using the HEC-2 model (Becker, personal communication, 1996). Using a bankfull stage elevation of 320 meters, the discharge through this channel appears to have been about 1,400 cms (.035 Manning's "n", and .000339 for the energy grade line [*Figure 31*]). The height of forset beds in the channel multiplied by five (5) to seven (7) provide another way to estimate water depth in the channel (Knox, personal communication, 1996). Channel forset beds from a similar setting nearby are between one (1) and two (2) meters in height yielding a minimum value of 700 cms.

14. *Continue westward 3 miles and turn left (south).* Follow this road south for 4.5 miles until you reach the intersection with State Highway 27. Note a remnant of the Lockhart Phase Terrace visible to the right (west) and that the Sheyenne River Trench is narrow here. It is similarly narrow from the entrenched meanders you just left, upstream about 14 river miles, to the Milnor Channel outflow (see *Baker*, 1966/1967). Presumably, lateral movement of the Sheyenne river during the Holocene has been constrained in this reach by coarse glaciofluvial and deltaic sediments. Only a very narrow, low Holocene fluvial deposit is recognized in this change, and storage of fluvial sediments, are restricted to the Sheyenne River Trench downstream from the entrenched meanders. Turn left (east on State Highway 27).

15. *Continue east on State Highway 27 for 5.5 miles.* You are now traveling across a landscape draped with one (1) to three (3) meters of eolian sandsheet. Numerous low-relief dunes, similar to those seen on the Richland County 4 part of the trip, are visible. Turn right (south) at the access just west of the Soo Line Railroad/State Highway 27 intersection. Open the gate and follow the winding trail south about .5 mile (close the gate).

Warning: This trail is not improved. A four-wheel drive vehicle is not necessary under normal circumstances but **drive with caution**. This area is grazing land leased from the Forest Service. To minimize our impact on carrying the capacity and wildlife, please **stay on the trail as much as possible.**

Several blow-outs are visible from this trail. Note the buried soils visible in these exposures. The profile you see in these blow-outs is typical of blow-out exposures in low-relief blow-out dunes and sandsheets across the Sheyenne Delta. Stop prior to the gate (avoid bare sand or low-spots) and walk 25 meters to the east.

STOP 2: The Soo Dune Site

The Soo Dune site is a group of related low-relief blow-out dunes on the Sheyenne Delta. These dunes, like most of the low-relief dunes on the Sheyenne Delta, are parabolic forms (David, personal communications, 1995). The Soo Dunes, and other blow-out dunes on the delta surface, share a similar profile of buried soils suggesting that they formed at the same time and under similar conditions (*Figure 32*). The Soo Dunes are late-Holocene in age (see data, *Running*, this publication). They appear to be a younger generation of parabolic dunes formed from a larger and older set of parabolic dunes. The eroded remnant of these larger dunes, the Durler dunes, are visible to the north and west. Other larger low-relief dunes are visible to the southwest of the Soo Dunes. This *en echelon* pattern of parabolic dunes within parabolic dunes is seen elsewhere on the Sheyenne Delta (David, personal communication, 1995). A detailed discussion of the radiocarbon age, mobility index, stable carbon isotope signal, and paleoenvironmental implication of the Soo Dunes is presented in Running (1995a, 1995b, and this publication).

16. *Return to State Highway 27 (close the gate) and turn right (east).* The intersection with State Highway 18 is 11.5 miles east. Turn right (south) 12 miles to Wyndmere. Turn left on State Highway 13 in Wyndmere (an Amoco station and cafe is located at the State Highway 18/State Highway 13 intersection). Head east about 20 miles to I-29. Turn south. the South Dakota border is about 22 miles. Continue south for another 7 miles, or so, to exit 246. Turn east, following State Highway 127 to Rosholt, continuing east toward the White Rock Dam Road. Here, we drop onto the western arm of the channel of Glacial River Warren, which is about 3 miles wide and 120 feet deep at this location (see *Milbank AMS 1x2 topographic map sheet*). Continue east for 2.5 miles to White Rock Dam (on the Bois De Sioux River). We are now on the eastern edge of the Glacial River Warren channel. The southern outlet of Glacial Lake Agassiz will be seen and discussed here, as time permits.

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ROADLOG FOR LAKE AGASSIZ SOUTHERN OUTLET
Monday, June 3, 1996
Afternoon

William M. Becker
University of Wisconsin - Madison, Wisconsin

The southern outlet of Glacial Lake Agassiz consists of a number of channels. The rest area for the White Rock Dam is located in the lowest outlet channel. This channel was active during the latter part of the Lockhart phase, and possibly during the Emerson phase, whenever Glacial Lake Agassiz stood at or above the Campbell standline (299 m a.s.l.). To the east of this site is the remnants of an earlier channel associated with the Tintah strandline (311 m a.s.l.). To the west is the Cottonwood Slough, which was an active outlet whenever the lake stood above the Tintah strandline.

The Campbell stage outlet channel is approximately 4,500 m wide at the White Rock Dam site. The floor of the channel is covered here by a boulder layer. This layer is interpreted to be the remnants of a channel armor layer that inhibited further downcutting of the outlet. From this site, the outlet channel extends off to the southwest for approximately 24 kilometers before passing through the Big Stone Moraine near Browns Valley, MN. The channel reaches a minimum width of 1,200 m as it passes through the moraine. Turning southeast, the outlet channel joins with the Minnesota River Valley. The slope of the Campbell stage outlet channel is estimated to be less than 0.2 m/km. Lake Traverse currently fills the outlet channel from the White Rock Dam site down to the village of Browns Valley.

Computer simulations with an HEC-2 water profile modeling program for the lowest southern outlet channel suggest that the discharge of Glacial Lake Agassiz was less than 5,000 cms while it is stood at the Campbell strandline (Becker, 1995). Simulations for the channel associated with the Tintah strandline suggest a discharge for the lake of 24,000 cms (Becker, 1995). The maximum discharge capacity of the outlet is estimated at 290,000 cms.

Contributions

study area (Figure 1a) and the Quaternary stratigraphy of the entire study area (Harris and others, 1995). A surface map of the entire study area is being prepared (Harris and Luther, in preparation) using the SRRV RHA surface map, North Dakota Geological Survey published maps (Harris, 1987a; Harris, 1987c, and Harris and Luther, 1991), and the North Dakota Geological Survey geographical information system to compile a final product.

PREVIOUS WORK

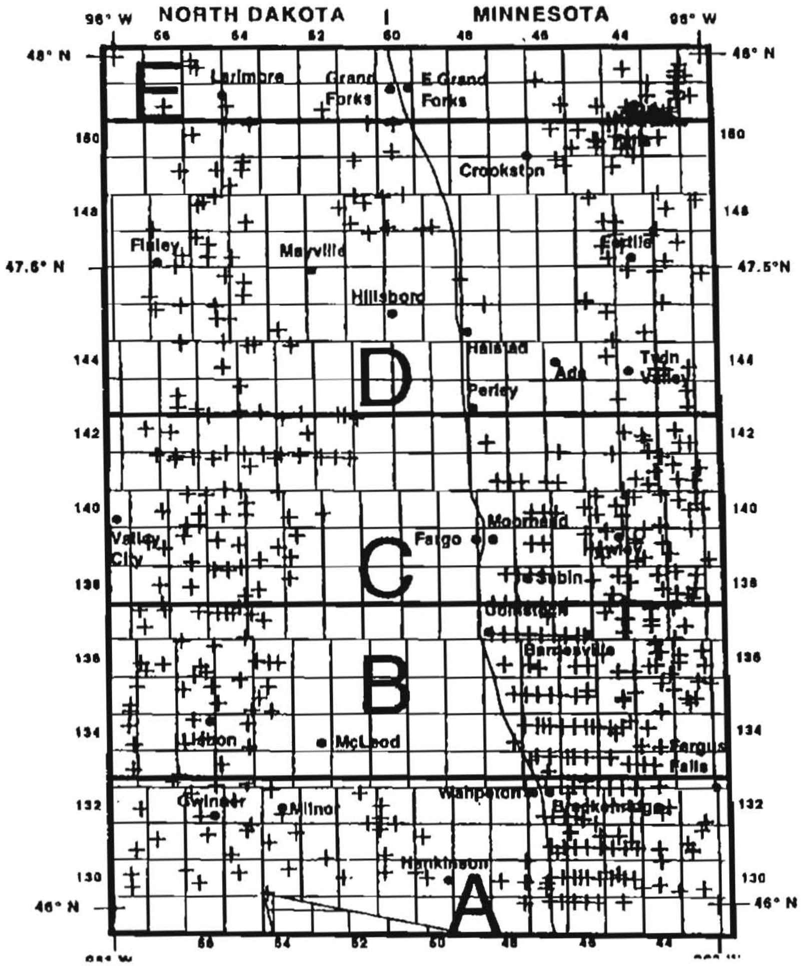
The glacial stratigraphy exposed in the Red Lake River trench was investigated in the early 1970's (Moran and others, 1971, Moran and others, 1973, Harris, 1973). The Red Lake River stratigraphy was combined with extensive regional reconnaissance fieldwork to develop formal definitions of ten formations composed of till and lacustrine sediment (Harris and others, 1974). Subsequently other studies in the region investigated the glacial stratigraphy, developed definitions of stratigraphic units, and interpreted stratigraphic sequences. The Red Lake River stratigraphy was expanded and extended in northwestern Minnesota by several workers (Harris, 1975; Sackreiter, 1975; Anderson, 1976; Perkins, 1977). Stratigraphic frameworks were developed in northeastern North Dakota (Salomon, 1975; Hobbs, 1975) and eastern North Dakota (Camara, 1977). A summary paper (Moran and others, 1976) synthesizes all North Dakota Geological Survey and University of North Dakota faculty and student work in Quaternary stratigraphy.

Lake Agassiz lithostratigraphy, event stratigraphy, and chronostratigraphy of offshore lake sediment and glacial sediment within the Lake Agassiz basin can be divided into fourteen formations composed of till and lacustrine sediment based on engineering, lithologic, and stratigraphic characteristics (Arndt, 1977). Regional stratigraphic interpretations were combined with the chronology in the Lake Agassiz basin and expanded to include other work in the upper Midwest (Clayton and Moran, 1982; Clayton, 1983) and Manitoba and Ontario (Fenton and others, 1983).

The surficial geology of the southern Red River Valley has been mapped in North Dakota (Clayton and others, 1980; Harris, 1987c; Harris and Luther, 1991) and Minnesota (Hobbs and Goebel, 1982; Harris, 1987a, and Harris and others, 1995). It can be characterized as consisting of proglacial lake sediment and eroded glacial sediment in the central part of the lake basin; and collapsed glacial and meltwater sediment flanking the lake basin.

STUDY AREA

The study area (Figure 1a) is located in northwestern Minnesota and eastern North Dakota. It is bounded by 46°N and 48°N latitude and by 96°W and 98°W longitude. The area straddles the North Dakota-Minnesota border and includes the southern part of the



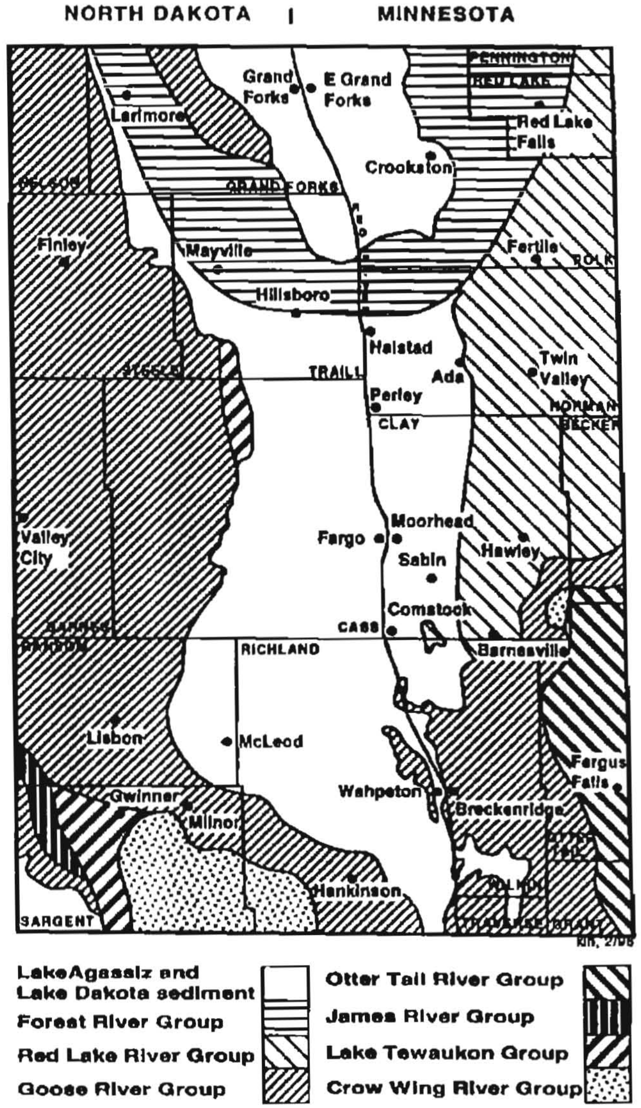


Figure 1 - (a; left) SRRV-RHA stratigraphic study area. Areas "A" through "E" show the location of data subsets RRVA through RRVE; "+" indicates a sample site, **(b; right)** Lithostratigraphic map of the SRRV-RHA study area.

Lake Agassiz basin and adjacent areas of glacial upland.

THE DATABASE

"N-FILE" is a database for nearsurface stratigraphic data that contains about 9000 entries and is maintained by the North Dakota Geological Survey (Moran, unpublished; North Dakota Geological Survey, 1995). Data contained in N-FILE were generated by North Dakota Geological Survey and University of North Dakota geologists working in North Dakota and adjacent states and represent a variety of surface and subsurface deposits collected from outcrops, hand-auger borings, soil-probe holes, and power-auger holes.

QBASE (Minnesota Geological Survey, 1995) contains all relevant data from the N-FILE (Moran, unpublished; Harris, 1973; Harris and others, 1974; Harris, 1975; Salomon, 1975; Hobbs, 1975; Sackreiter, 1975; Camara, 1977; Anderson, 1976; and Perkins, 1977; Harris, 1987c; Harris and Luther, 1991) plus additional data generated by the Minnesota Geological Survey for the SRRV RHA (Harris and others, 1995). QBASE consists of information on about 2100 samples, 700 of which were collected and analyzed during 1992-93 as part of the SRRV RHA, including data from 4 continuous rotasonic cores. Information in storage includes sample site location, sample elevation, geologist's name, project name, sample texture, coarse-sand lithology, and other data. N-FILE is available from the North Dakota Geological Survey. QBASE is available from the Minnesota Geological Survey.

METHOD

Internally consistent characteristics that vary from unit to unit and are field identifiable are needed to differentiate glacial units. Correlation parameters derived from textural and lithologic analysis of sediment samples are useful for correlating glacial sediment in this area. Textural analysis provides percentage composition of sand (SD), silt (SL), and clay (CY), and lithologic analysis of the coarse-sand fraction (1-2 mm) provides percentage composition of crystalline and metamorphic rock fragments (XT), limestone and dolostone rock fragments (CO), and shale fragments (SH). In order to speed computer processing and facilitate graphic presentation, the six correlation parameters are reduced to four. The SL and CY are normalized to obtain normalized silt (NS=((SL/(SL+CL))*100)), and the XT and CO are combined to obtain normalized crystalline-metamorphic and carbonate rock fragments (NX=((XT/(XT+CO))*100)). The resulting four correlation parameters (SD, NS, NX, SH) can be used to characterize the tills present in the dataset. A sequential dataset is then assembled consisting of all sample data arranged by location (township, range, section, and quarter section) and decreasing elevation at each sample site or borehole location.

THE SOFTWARE

The software is designed to duplicate the procedure a geologist would use to evaluate textural and coarse-sand lithologic data and develop interpretations and correlations (Harris, 1987b). Two programs allow the identification, verification, and correlation of tills in a dataset. They are a cluster-analysis program (TILSRCH) and a display-correlate program (DISCORT). These programs and other data-handling and graphic-display programs have been installed in a menu-driven environment designed for working with the till data.

Programs are written in Microsoft QBASIC and require a DOS computer. Programs read comma-delimited files and will handle about 450 samples per run. Consequently, QBASE was divide into 5 data subsets (RRVA, RRVB, RRVC, RRVD, and RRVE; Figure 1a) for analysis.

TILSRCH

Naturally occurring modal groups (clusters) in a dataset can be identified and isolated, and member samples can be labeled with TILSRCH. Clusters are initially identified by generating cross plots of the dataset using the four correlation parameters. An external graphics program or the cross-plot display in TILSRCH can be used. In either case, coordinates of clusters can be determined. The coordinates are then used as input for TILSRCH.

Figures 2 and 3 shows cross plots of the five data subsets (rows). Three graphs, SD vs SH, SD vs NS (texture), and SH vs NX (coarse-sand lithology), are shown for each data subset (columns). The most useful cross plot for identifying trial clusters is SD vs SH.

The initial definition of a modal group is refined interactively. This involves retrieving a target cluster of samples from the database with estimated mean values of the four correlation parameters and a "gate width" of +/- 2 standard deviations. TILSRCH will then retrieve all samples in the database that fit the definition of the target cluster. The mean and standard deviation of the returned samples are calculated (for each of the four correlation parameters) and compared to the input values. New input values are entered with the mean +/- 2 standard deviations for each of the four correlation parameters, and the process is repeated until the returned values match the input values for all four correlation parameters. When the input and output match, a stable cluster has been identified. The cluster is inspected with the program graphics, and if acceptable all member samples are labeled and removed from the working dataset. The values of the correlation parameters that define this cluster are then recorded. This procedure is repeated until all modal groups in the dataset have been identified and defined and the member samples labeled. The output of the program is provided in three forms:

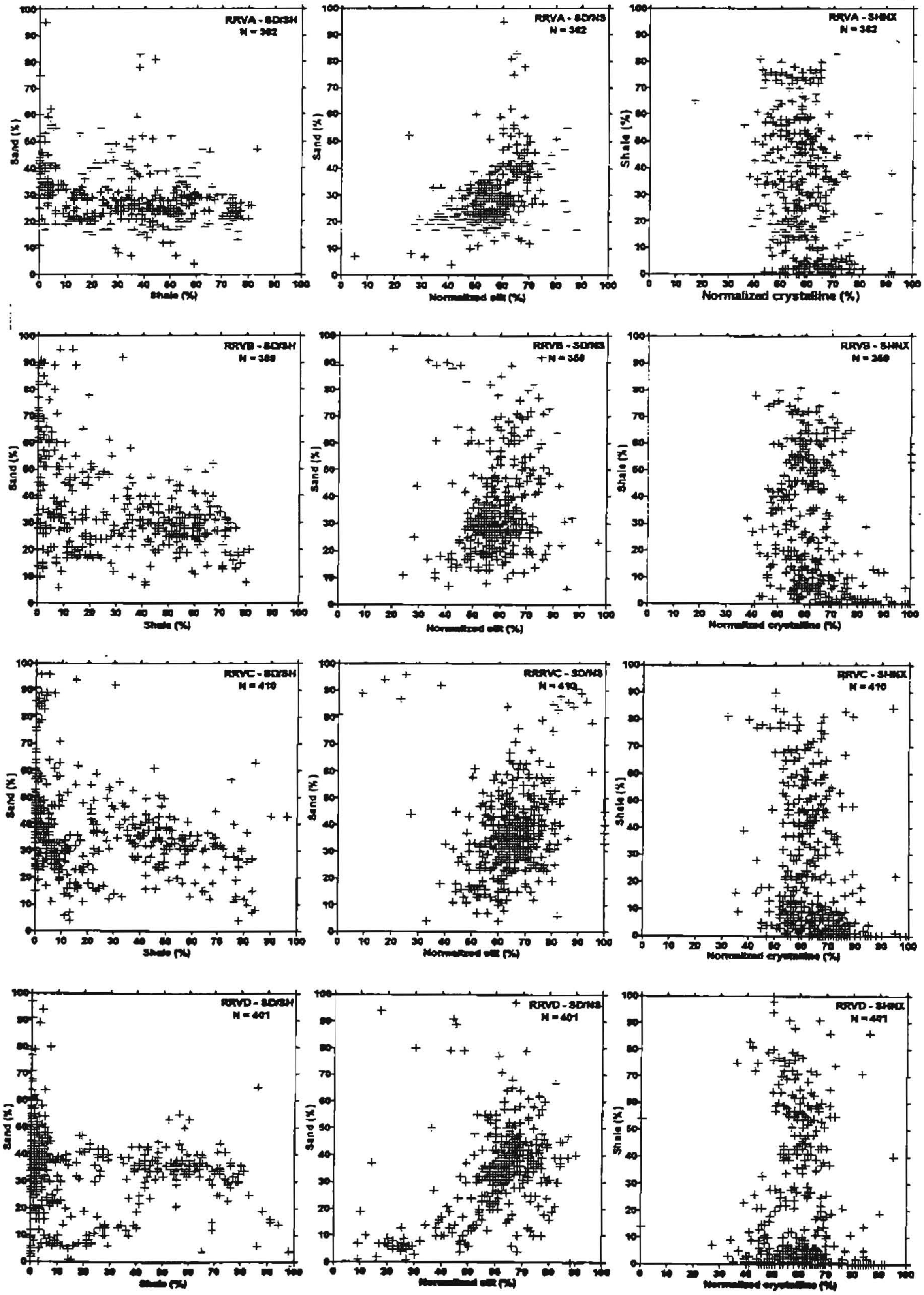


Figure 2 - Cross plots of the data subsets RRVA, RRVB, RRVC, and RRVD

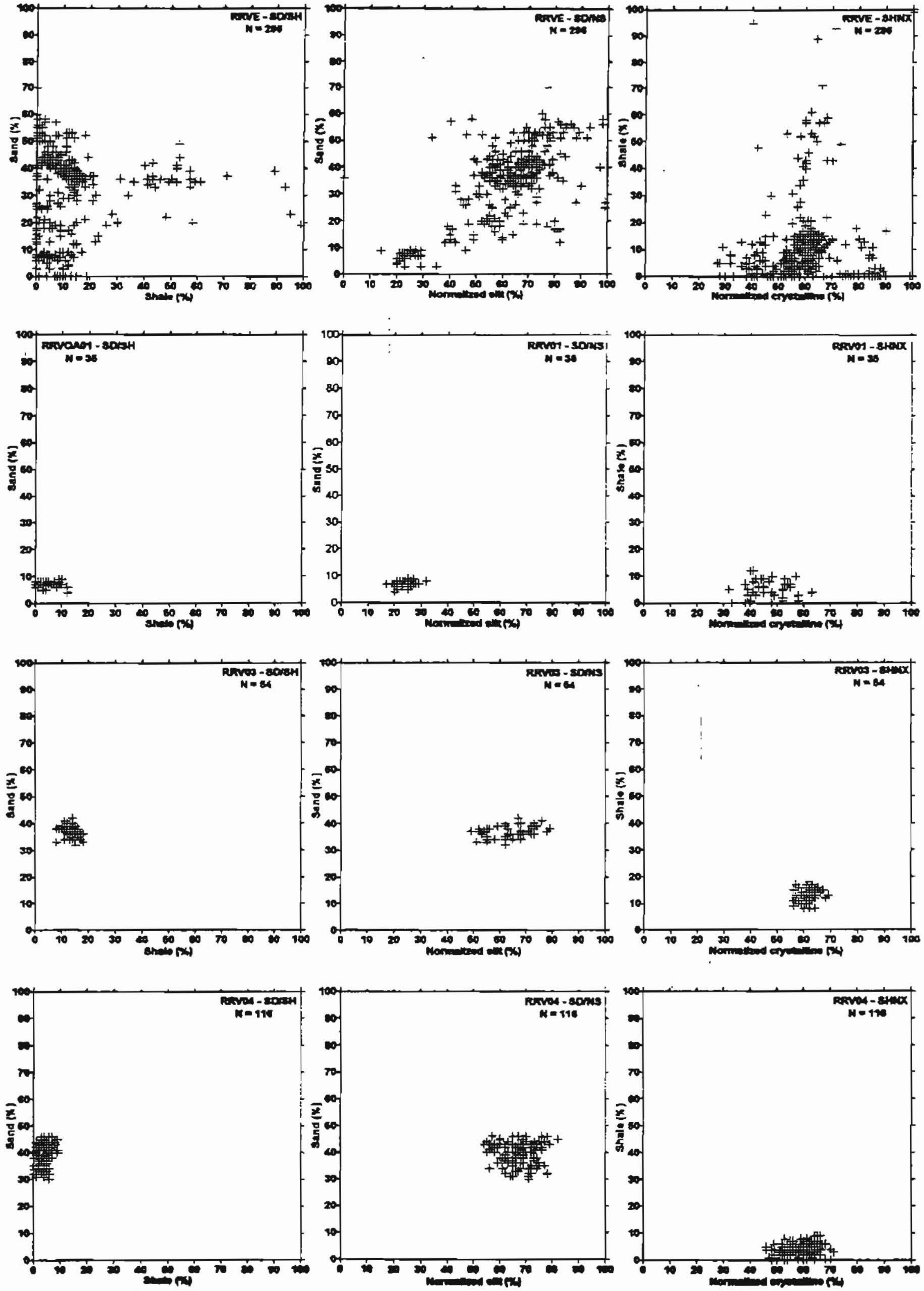


Figure 3 - Cross plots of the data subset RRVE and tills RRV01, RRV03, and RRV04.

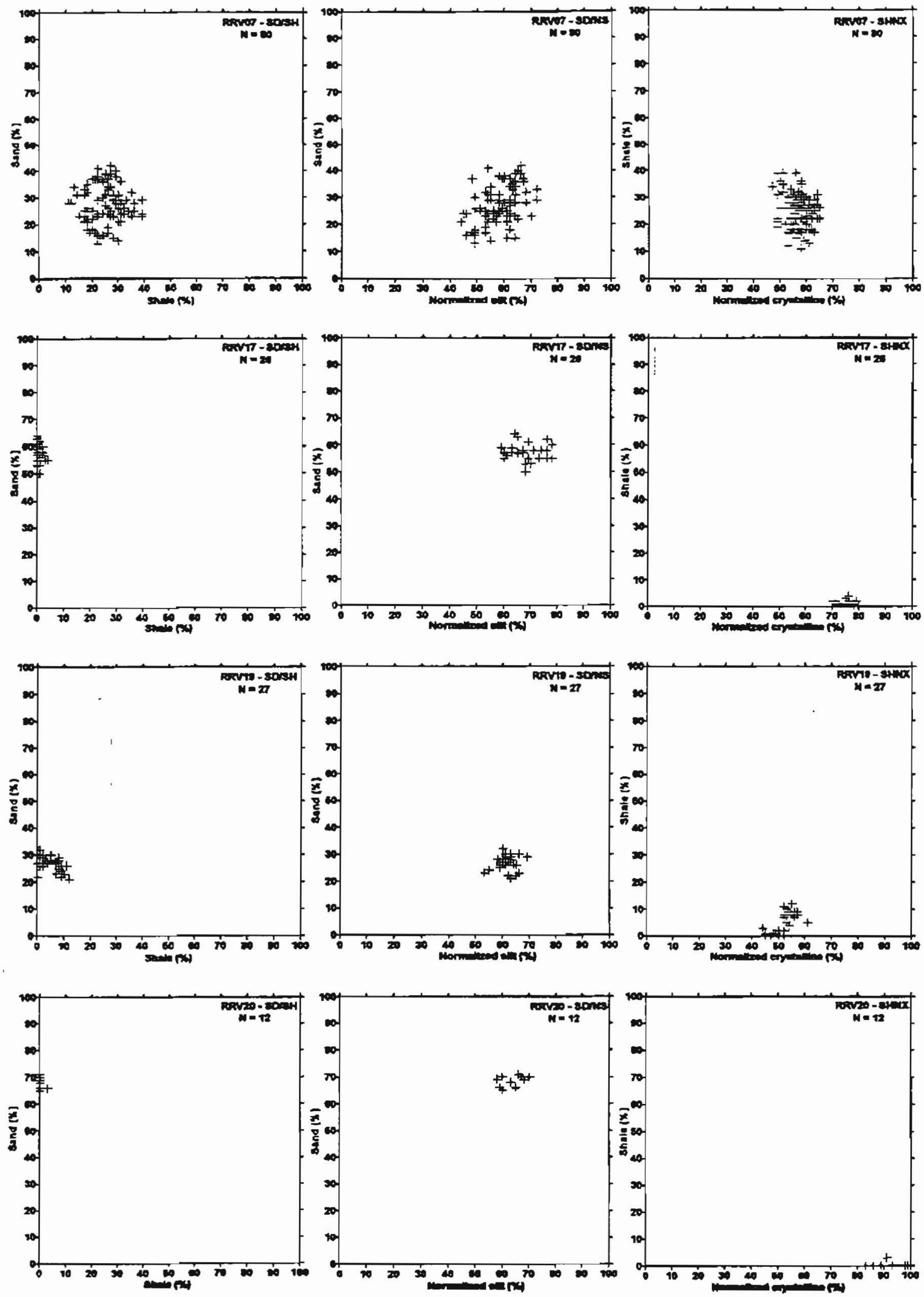


Figure 4 - Cross plots of tills RRV07, RRV17, RRV19, and RRV20.

- **The Till Dataset:** The till dataset consists of all member samples of a specific modal group (a cluster or a till).
- **The Correlated Dataset:** The correlated dataset is a sequential file that contains all labeled and unlabeled samples. All member samples of identified clusters are labeled in the data set. The sequential dataset is sorted by file number (sample site), decreasing elevation or increasing sample depth, section, quarter-quarter-quarter, township, and range. This provides a mappable summary of the correlated data, which can then be interpreted stratigraphically.
- **The Residual Dataset:** The residual dataset consists of all samples that do not meet the definition of any of the modal groups, the left overs.

DISCORT

DISCORT graphically displays the definitions developed in TILSRCH and checks for overlap between the definitions. The input required is a comma-delimited file consisting of the number of samples and the mean values of SD, NS, NX, and SH for each cluster (till) in the interpreted dataset. This program can be used in at least three ways.

- **Display:** It displays the correlation parameters of the "tills"as bar-charts.
- **Verification:** The quality of the definitions developed in a dataset can be tested. Each definition can be checked against each other definition to determine the degree of overlap that exists. Good-quality definitions should not overlap.
- **Correlation:** Definitions from one dataset can be compared with definitions from another dataset. Good-quality correlations should overlap.

RESULTS

LITHOSTRATIGRAPHIC UNITS

Table 1 shows the results of the cluster analysis of QBASE. The five data subsets (RRVA, RRVB, RRVC, RRVD, and RRVE) are shown in individual columns.

A lithostratigraphic unit is defined on the basis of both lithology (correlation parameters) and stratigraphic position. The clusters in each of the subsets were placed in stratigraphic sequence using the correlated datasets and field observations. Since good vertical control is scarce in this area, we were fortunate to have four rotasonic cores up to 300 feet long to use for stratigraphic control. Another data subset (BHOA) was established to provide stratigraphic reference; it consisted of all "deep" boring and outcrop data available in northwestern Minnesota and eastern North Dakota (both in and outside the study area). BHOA was interpreted with TILSRCH and DISCORT (Table 1). With the BHOA file and the RRV* subsets a reasonable stratigraphic interpretation was reached.

	RRVOA 05/12/94	BHOA 05/12/94	RRVA 04/26/93	RRVB 12/16/93	RRVC 04/27/94	RRVD 12/16/93	RRVE 04/12/93	Gp/Fm/till	Lobe	aprox age
A	(01), N=35 07-22-71 45-50-05 (KH-HUOT)	(01), N=33 07-22-71 42-52-06 (KH-HUOT)				(10), N=12 07-21-72 50-42-08 (KH-HUOT)	(05), N=25 07-22-71 43-52-05 KH-HUOT)	Forest River Group	Red River	11
B	(02), N=10 12-39-49 38-38-24 (KH-FALCONER)	(02), N=08 36-43-21 31-22-47 (KH-FALCONER)				(14), N=10 12-39-49 38-38-24 (KH-FALCONER)				
C	(03), N=54 37-40-23 53-34-13 (KH-U.RLF)	(03), N=56 38-42-20 54-34-12 (KH-U RLF)			(09), N=15 31-40-29 56-33-11 (KH-U RLF)	(11), N=04 39-43-18 53-36-11 (KH-U.RLF)	(09), N=48 37-40-23 53-33-14 (KH-U RLF)	Red Lake River Group	Wadena/ Rainy	11.5
D	(04), N=116 39-41-20 57-39-04 (KH-L.RLF)	(04), N=117 41-41-18 58-40-02 (KH-L.RLF)			(07), N=27 36-41-23 57-39-04 (KH-L RLF)	(06), N=62 38-43-19 54-43-03 (KH-L.RLF)	(06), N=39 43-37-20 56-38-06 (KH-L.RLF)			
E	(06), N=32 19-42-39 45-41-14 (A&P-B'VILLE)	(06), N=18 20-41-39 48-44-08 (A&P-B'VILLE)	(11), N=09 21-45-34 43-40-17 (A&P-B'VILLE)	(07), N=07 20-39-41 48-39-13 (A&P-B'VILLE)	(10), N=09 16-41-43 46-40-14 (A&P-B'VILLE)	(12), N=04 20-45-35 40-48-12 (A&P-B'VILLE)	(08), N=03 18-41-41 39-48-13 (A&P-B'VILLE)	Goose River Group	Red River	12
F	(07), N=80 27-42-31 43-32-25 (KH-ST.HILAIRE)	(07), N=09 29-42-29 50-29-21 (KH-ST.HIL)	(14), N=38 26-40-34 35-31-34 (KH-ST.HILAIRE)	(09), N=25 26-44-30 44-36-20 (KH-ST.HILAIRE)	(12), N=25 31-41-28 46-31-23 (KH-ST.HILAIRE)	(15), N=09 38-39-23 46-28-26 (KH-ST.HILAIRE)	(11), N=07 27-42-31 44-32-24 (KH-ST.HILAIRE)			
G	(08), N=174 30-41-29 27-18-55 (HH-DAHLEN)	(08), N=22 34-41-25 23-18-59 (HH-DAHLEN)	(16), N=58 26-41-33 26-21-53 (HH-DAHLEN)	(13), N=43 27-41-32 27-17-56 (HH-DAHLEN)	(15), N=48 33-44-23 28-18-54 (HH-DAHLEN)	(18), N=34 36-39-25 24-16-60 (HH-DAHLEN)	(13), N=09 37-40-23 28-17-55 (HH-DAHLEN)			
H	(09), N=75 36-39-25 35-23-42 (H&L-HEIBERG)	(09), N=26 36-38-26 34-24-42 (H&L-HEIBERG)	(15), N=04 39-38-23 35-28-37 (H&L-HEIBERG)	(11), N=22 31-39-30 31-29-40 (H&L-HEIBERG)	(14), N=20 38-39-23 37-23-40 (H&L-HEIBERG)	(16), N=30 37-39-24 34-21-45 (H&L-HEIBERG)	(12), N=09 35-39-26 35-22-43 (H&L-HEIBERG)			14
I	(10), N=32 38-38-24 54-43-03 (OTR GP)	(10), N=18 41-33-26 55-36-09 (OTR GP)	(02), N=19 41-39-20 52-47-01 (OTR GP)	(06), N=15 33-35-32 56-37-07 (OTR GP)				Otter Tail River Group	Rainy	
J	(11) N=38 44-39-17 66-33-01 (OTR GP)	(11), N=28 53-32-15 63-35-02 (OTR GP)	(06), N=06 56-29-15 64-32-04 (OTR GP)	(03), N=03 52-35-13 67-31-02 (OTR GP)	(05), N=18 40-44-16 68-31-01 (OTR GP)	(04), N=17 46-35-19 65-34-01 (OTR GP)				
K	(12), N=26 46-35-19 50-31-19 (OTR GP)	(12), N=32 38-38-24 47-28-25 (OTR GP)	(12), N=08 42-37-21 46-31-23 (OTR GP)	(08), N=16 49-34-17 54-30-16 (OTR GP)	(11), N=02 41-37-22 45-33-22 (OTR GP)					
L	(05), N=11 47-35-18 44-23-33 (JMS R GP)	(05), N=04 49-32-19 45-27-28 (JMS R GP)	(13), N=06 47-34-19 45-23-32 (JMS R GP)	(10), N=03 45-38-17 42-23-35 (JMS R GP)	(13), N=02 49-33-18 46-24-30 (JMS R GP)			James River Group	Souris	15
M	(13), N=55 30-43-27 16-11-73 (HH-GARDAR)	(13), N=10 35-44-21 17-12-71 (HH-GARDAR)	(19), N=11 26-45-29 13-12-75 (HH-GARDAR)	(15), N=18 30-43-27 19-11-70 (HH-GARDAR)	(16), N=13 29-45-26 17-10-73 (HH-GARDAR)	(20), N=16 32-42-26 14-11-75 (HH-GARDAR)		Lake Tewaukon Group	Red River	
N	(14), N=27 20-42-38 14-12-74 (CLAYEY FCS)		(18), N=16 22-41-37 14-12-74 (CLAYEY FCS)	(16), N=09 16-48-36 13-12-75 (CLAYEY FCS)	(17), N=03 15-50-35 11-12-77 (CLAYEY FCS)	(19), N=02 24-42-34 11-15-74 (CLAYEY FCS)				
O	(15), N=23 32-35-33 61-36-03 (CWR GP)	(15), N=26 33-35-32 64-33-03 (CWR GP)	(04), N=24 32-35-33 62-35-03 (CWR GP)					Crow Wing River Group	Rainy/ Superior	25
P	(16), N=11 56-34-10 86-13-01 (CWR GP)	(16), N=84 50-35-15 84-16-00 (X)		(01), N=03 61-21-18 96-04-00 (CWR GP)		(01), N=03 68-21-11 86-14-00 (CWR GP)	(01), N=10 55-36-09 86-13-01 (CWR GP)			
Q	(17), N=26 57-29-14 74-25-01 (KH-MARCOUX)	(17), N=12 51-34-15 76-24-00 (KH-MARCOUX)		(04), N=03 56-26-18 75-22-03 (KH-MARCOUX)	(03), N=13 59-27-14 72-27-01 (KH-MARCOUX)	(03), N=05 58-30-12 77-22-01 (KH-MARCOUX)	(02), N=05 53-33-14 76-23-01 (KH-MARCOUX)			
R	(18), N=17 30-39-31 49-36-15 (CWR GP)	(18), N=11 31-39-30 49-37-14 (CWR GP)	(09), N=17 30-38-32 49-36-15 (CWR GP)							
S	(19), N=27 27-45-28 49-46-05 (KH-GERVAIS)	(19), N=12 26-45-29 48-50-02 (KH-GERVAIS)		(05), N=02 28-40-32 43-54-03 (KH-GERVAIS)	(08), N=12 25-46-29 49-42-09 (KH-GERVAIS)	(05), N=09 28-45-27 49-49-02 (KH-GERVAIS)	(04), N=15 25-46-29 51-45-04 (KH-GERVAIS)	Gervais Formation	Red River	100
T	(20), N=12 68-20-12 93-07-00 (A&P-SEBEKA)	(20), N=19 65-26-09 97-03-00 (A&P-SEBEKA		(02), N=12 68-20-12 93-07-00 (A&P-SEBEKA)			kh, 1996	Sebeka till	Superior	Not in strati-graphic order

Table 1- The results of the cluster analysis of data subsets RRVA, RRVB, RRVC, RRVD, and RRVE and their interpreted stratigraphic sequence. RRVOA is the average of all subset values for each till. BHOA shows the results of an analysis of all regional borehole data. Explanation of till notation: (x)= till number, N = Number of samples, XX-XX-XX (top) = SD-SL-CY; XX-XX-XX (bottom) = XT-CO-SH; and (worker-unit name or comment).

	RRVOA 05/12/94	BHOA 06/12/94	RRVA 04/26/93	RRVB 12/16/93	RRVC 04/27/94	RRVD 12/16/93	RRVE 04/12/93
a			(17), N=08 37-41-22 25-19-56 (G)	(12), N=03 20-62-18 32-14-54 (G SILTY FCS)	(06), N=14 26-55-19 67-32-01 (J SILTY FCS)	(08), N=02 32-37-31 61-34-05 (D)	(03), N=07 51-36-13 55-43-02 (X)
b			(07), N=05 42-39-19 55-40-05 (I)	(14), N=05 45-40-15 24-15-61 (G SDY FCS)	(01), N=02 35-42-23 89-11-00 (P SILTY FCS)	(09), N=04 23-55-22 58-35-07 (D)	(07), N=05 52-33-15 73-16-11 (X)
c			(08), N=04 23-34-43 61-28-11 (O)		(02), N=17 49-39-12 72-28-00 (Q SILTY FCS)	(13), N=08 39-38-23 56-26-18 (F)	(10), N=07 30-38-32 50-36-14 (X)
d			(05), N=06 19-25-56 69-28-03 (O CLAYEY FCS)		(04), N=15 47-33-20 70-29-01 (Q SILTY-CLY)	(17), N=04 53-28-19 28-16-56 (G)	
e			(01), N=02 33-28-39 92-08-00 (P CLAYEY FCS)			(02), N=02 45-34-21 90-10-00 (?)	
f			(03), N=07 34-33-33 74-23-03 (Q CLAYEY FCS)			(07), N=08 19-48-33 56-41-03 (?)	
g			(10), N=06 21-31-48 43-41-16 (?)				klh, 1996

Table 2 - Residual units from the cluster analysis of data subsets RRVA, RRVB, RRVC, RRVD, and RRVE. Explanation of till notation: (x)= till number; N = Number of samples; XX-XX-XX (top) = SD-SL-CY; XX-XX-XX (bottom) = XT-CO-SH; and (comment).

	WC MN Harris et.al. this study	NE ND Salomon 1975	NE ND Moran et.al. 1976	NE ND Hobbs 1975	SE ND Moran et.al. 1976	SE ND Camara 1977	NW MN Moran et.al. 1976	WC MN Anderson 1976	WC MN Perkins 1977
a		(05), N=XX 29-54-17 33-65-02 (NS-UNIT 1)	(05), N=XX 27-38-35 21-28-51 (SM-TIBER)	(06), N=XX 27-38-35 21-28-51 (HH-TIBER)	(05), N=XX 33-44-23 26-22-52 (SM-LF50)	(01), N=XX 34-43-23 67-23-10 (MC-UNIT E)	(08), N=XX 20-46-34 62-38-00 (SM-UNNAM. 1)		
b		(06), N=XX 35-36-29 21-17-62 (NS-UNIT A)	(06), N=XX 35-41-24 25-16-59 (SM-CANDO)	(07), N=XX 35-41-24 25-16-59 (HH-CANDO)		(07), N=XX 29-43-28 38-26-36 (MC-UNIT A)			
c		(08), N=XX 30-27-43 30-28-42 (NS-UNIT C)							
d		(09), N=XX 35-29-36 37-48-15 (NS-UNIT D)							
e									KLH, 1996

Table 4 - Residual units from the correlation of SRRV-RHA (WC MN) units with stratigraphic units developed by other workers in the region. Explanation of till notation: (x)= till number; N = Number of samples; XX-XX-XX (top) = SD-SL-CY; XX-XX-XX (bottom) = XT-CO-SH; and (worker-unit name).

	WC MN Harris et.al. this study	NE ND Salomon 1975	NE ND Moran et.al. 1976	NE ND Hobbs 1975	SE ND Moran et.al. 1976	SE ND Camara 1977	NW MN Moran et.al. 1976	WC MN Anderson 1976	WC MN Perkins 1977	Group / Fm. / till	Lobe	approx. Age (KA)
A	(01), N=35 07-22-71 45-50-05 (KH-HUOT)						(01), N=XX 08-22-72 41-53-06 (SM-HUOT)			Forest River Group	Red River Lobe	11
B	(02), N=10 12-39-49 38-38-24 (KH-FALC.)	(01), N=XX 31-45-24 38-31-31 (NS FALC.)	(01), N=XX 29-33-38 42-34-24 (SM-FALC.)	(01), N=XX 29-33-38 42-34-24 (HH-FALC.)								
C	(03), N=54 37-40-23 53-34-13 (KH-U.RLF)						(02), N=XX 37-42-21 54-33-13 (SM-U.RLF)			Red Lake River Group	Wadena / Rainy Lobe	11.5
D	(04), N=116 39-41-20 57-39-04 (KH-L.RLF)	(04), N=XX 43-39-18 44-54-02 (NS-L.RLF)					(03), N=XX 46-38-16 55-42-03 (SM-L.RLF)					
E	(06), N=32 19-42-39 44-42-14 (A&P-BVILLE)							(01), N=XX 21-41-38 42-45-13 (A-BVILLE)	(02), N=XX 16-45-39 43-41-16 (P-BVILLE)	Goose River Group	Red River Lobe	12
F	(07), N=80 27-42-31 43-32-25 (KH-ST.HIL)			(02), N=XX 28-38-34 50-27-23 (H-HANSBORO)	(01), N=XX 24-46-30 39-29-32 (SM-LF10)	(05), N=XX 29-41-30 40-30-30 (MC-UNIT C)	(04), N=XX 33-39-28 41-31-28 (SM-ST HILAIRE)					
G	(08), N=174 30-41-29 27-18-55 (KH-DAHLEN)	(07), N=XX 36-38-26 28-20-54 (NS-UNIT B)	(02), N=XX 29-44-27 28-19-55 (SM-DAHLEN)	(03), N=XX 27-44-27 28-19-56 (HH-DAHLEN)	(02), N=XX 24-45-31 27-19-54 (SM-LF20)	(06), N=XX 37-42-21 29-23-48 (MC-UNIT B)						
H	(09), N=75 36-39-25 35-23-42 (KH-HERBERG)	(02), N=XX 35-45-20 32-21-47 (NS-DAHLEN)	(04), N=XX 34-35-31 40-25-35 (SM-VANG)	(05), N=XX 34-35-31 40-25-35 (HH VANG)	(08), N=XX 28-40-32 38-27-35 (SM-LF60)	(03), N=XX 30-43-27 31-25-44 (MC-DAHLEN)		(02), N=XX 40-35-25 40-25-35 (A-DUNVILLA)	(03), N=XX 36-39-25 41-24-35 (P-DUNVILLA)			14
I	(10), N=32 38-38-24 54-43-03 (P-HAWLEY)								(01), N=XX 34-42-24 53-42-05 (P-HAWLEY)	Otter Tail River Group	Rainy Lobe	
J	(11), N=38 44-39-17 66-33-01 (A&P-NY MILLS)							(03), N=XX 50-30-20 65-31-04 (A-NY MILLS)	(04), N=XX 50-32-18 71-27-02 (P-NY MILLS)			
K	(12), N=28 46-35-19 50-31-19 (RRV12)											
L	(05), N=11 47-35-18 44-23-33 (JAMES RIV GP)				(04), N=XX 46-31-23 40-30-30 (SM-LF40)					James River Gp.	Souris Lobe	15
M	(13), N=55 30-43-27 16-11-73 (KH-GARDAR)	(03), N=XX 34-42-24 13-10-77 (NS-GARDAR)	(03), N=XX 32-42-26 10-08-82 (SM-GARDAR)	(04), N=XX 32-42-26 10-08-82 (HH-GARDAR)		(04), N=XX 22-49-29 19-16-65 (MC-GARDAR)				Lake Tewaukon Group	Red River Lobe	
N	(14), N=27 20-42-38 14-12-74 (GARDAR-A)				(03), N=XX 16-48-34 15-15-70 (SM-LF30)							
O	(15), N=23 32-35-33 61-36-03 (RRV13)						(07), N=XX 39-33-28 70-29-01 (SM-UNNAM. 2)			Crow Wing River Group	Rainy / Superior Lobe	25
P	(16), N=11 56-34-10 86-13-01 (RRV16)											
Q	(17), N=28 57-29-14 74-25-01 (KH-MARCOUX)						(05), N=XX 54-35-11 78-21-01 (SM-MARCOUX)		(05), N=XX 61-26-13 80-20-00 (P-SEBEKA)			
R	(18), N=17 30-39-31 49-36-15 (RRV18)					(02), N=XX 33-40-27 52-29-19 (MC-UNIT D)						
S	(19), N=27 27-45-28 49-46-05 (KH-GERVAIS)						(06), N=XX 19-50-31 44-55-01 (SM-GERVAIS)			Gervais Fm.	Red River Lobe	100
T	(20), N=12 66-20-12 93-07-00 (A&P-SEBEKA)							(04), N=XX 66-21-13 93-07-00 (A-SEBEKA)	KLH, 1998	Sebeka till	Superior Lobe	Not in stratigraphic position

Table 3 - Correlations of SRRV-RHA stratigraphic units (WC MN) with stratigraphic units developed by other workers in the region. Explanation of till notation (x)= till number; N = Number of samples; XX-XX-XX (top) = SD-SL-CY; XX-XX-XX (bottom) = XT-CO-SH; and worker-unit name.

Some of the clusters in the subsets did not correlate with any of the other units. These are listed in Table 2. They may be textural variations of recognized units, units not occurring in any other subset, or an aberration in the data.

Finally, an overall average value of the correlation parameters was determined for each of the lithostratigraphic units occurring in the study area. All data for each of the stratigraphic units (RRV* subsets) were combined into one file and reduced to a stable mean with TILSRCH. The results (RRVOA) are shown in Table 1.

LITHOSTRATIGRAPHIC MAP

The lithostratigraphic map (Figure 1b) shows the surface exposure of lithostratigraphic units interpreted to be present at the surface in the map area. Lake Agassiz lithostratigraphic units are not defined on this map; they are all shown as a single map unit. Lithostratigraphic units present along the Lake Agassiz shoreline have been thinned or removed by shoreline erosion, in some cases exposing older map units.

LITHOSTRATIGRAPHIC CORRELATIONS

Table 3 shows correlations between SRRV RHA stratigraphic units (RRVOA) and lithostratigraphic units developed by other workers in the area. The lithologic aspect (texture and mineralogy) of their units were honored in the correlations, but stratigraphic position was determined by correlations with SRRV RHA units. Table 4 lists those stratigraphic units that did not correlate with the SRRV RHA units. Most are in the northeastern North Dakota, where there are no doubt many stratigraphic units present that are not found in the southern Red River Valley. Moran's and Camara's units from southeastern North Dakota that did not correlate were probably variants of known tills (Moran's (1976) #5 and RRVOA #8; Camara's (1977) #1 and RRVOA #11; and Camera's (1977) #7 and RRVOA #5). In Northwestern Minnesota Moran's (1976) # 8 is also thought to be a textural variant of RRVOA #11. All of Anderson's (1976) and Perkin's (1977) units were found, but the stratigraphic order is interpreted differently.

DISCUSSION

Figures 3 and 4 show crossplots of some identified tills. Late Wisconsin glaciers advanced into this area from the northwest (Keewatin provenance), north (Winnipeg provenance), and northeast and east (Labrador provenance); each advance left behind glacial sediment that has a textural and mineralogic composition characteristic of its source area. The cross plots show the characteristics of tills associated with each of the source areas. The Huot (RRV01; Red River lobe) and Gervais Formations (RRV19; Red River lobe) are interpreted to be Winnipeg provenance tills; the St. Hilaire Formation (RRV07; Red River Lobe) a Keewatin provenance till; the Upper and Lower Red Lake

Falls Formation (RRV03 and RRV04; Wadena/Rainy Lobe) Keewatin to Labradoran provenance tills; and Marcoux Formation (RRV17; Rainy/Superior Lobe) and Sebeka till (RRV20; Superior Lobe) Labradoran provenance tills.

This method of lithostratigraphy assumes that the rate of compositional change (with distance or position) in a stratigraphic unit is small compared to the absolute difference in the correlation parameters between units. This seems to be the case in the study area.

Stratigraphic interpretations are only as good as the vertical control. For near-surface units, mapping the surface distribution of the units usually provides enough information to interpret stratigraphic relationships. For subsurface units, drilling is necessary, and coring is preferred. The interpretations presented here are therefore strongest for the younger units and weakest for oldest units.

CONCLUSIONS

Computer-assisted techniques and desk-top computers have provided a new perspective to the problems of defining and correlating nearsurface stratigraphic units. Previously, progress in developing a sense of regional cohesiveness in glacial stratigraphy was very slow. The use of these programs and a large nearsurface database has provided us with a means of rapidly developing regional lithostratigraphic interpretations. This gives our Quaternary stratigraphy a new, broad-based perspective, which should provide valuable baseline stratigraphic information for a number of applications.

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FOREST RIVER EXPOSURE

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General

The exposure along the Forest River is in section 10AAC, T154N, R55W, in the northwest corner of Grand Forks County, ND, near the east edge of the Edinburg Moraine. The 30m high exposure is along the outer bank of a meander on the Forest River. The section consists of many units of questionable origin. Because of the limited space and steepness of this exposure, an earlier plan to include it as one of the stops has been abandoned. A summary of this exposure is included to provide information to those who may wish to visit it at a later date.

Lithology

Basal unit: The base of this exposure is usually buried beneath a thick cover of colluvium, but an early excavation, when fresh undercutting by the river had removed most of the cover, revealed thinly laminated lake clays at the base (Fig.1). No attempt has been made to study this unit to date, but it may correlate with the Argusville Formation, deposited during the deep water Cass Phase of Lake Agassiz around 11,600 yrs B.P. (Fenton, et al., 1983), or an earlier lake stage.

Till: The overlying till unit here has an average texture of about 38% sand, 44% silt, and 17% clay, with a very coarse sand lithology of 35% crystalline, 20% carbonate, and 42% shale. According to Harris' classification, this till best meets the description of the Heiberg till (ca. 20,000 yrs B.P.)(Harris, 1995). If this is correct, the underlying lacustrine sediment must be older than Argusville (Arndt, 1977). However, because the ice of the Caledonia Advance extended across this site, this till is the only candidate for that advance, which would make it the Falconer till (ca. 11,300 C14 years B.P.)(Harris et al., 1974).

Sands: The sediments directly overlying this till are moderately to well-sorted shaley sands displaying prominent small-scale rippled crossbedding. In several places the underlying till has been injected into the sands, causing faulting and folding of the beds. This probably resulted from the top-loading of the still saturated till.

Farther up the section (depending on the year) deltaic foreset (alpha) beds are exposed in a coarser, cleaner sand. Dip of the beds indicates a source from the west-northwest. Both of these sand units are interpreted to be part of the Fordville Aquifer, deposited by ice-marginal streams, confined between the retreating ice of the Caledonia advance on the east and the Edinburg Moraine

and the Pembina escarpment to the west. It is likely that the streams were subaerial at times and beneath the rising waters of Lake Agassiz at others. The "delta" is interpreted to have formed during the Lockhart Phase of Lake Agassiz.

The next higher unit consists of a 2.7m-thick poorly sorted-medium sand displaying large-scale trough cross-bedding. Numerous clasts of finer aggregates are present in the upper half of this unit. A thin sand unit overlies this sand.

Sandy silt: The next unit is most puzzling; it is a very well sorted sandy silt exhibiting contorted, convoluted structures (Fig. 2). A number of possible explanations has been proposed, including cryoturbation, penecontemporaneous deformation (mudflows), or disturbance by a nearby ice terminus. If the latter explanation is correct, it may have been the Caledonia advance, meaning that the till at this site is older than Falconer, perhaps Heiberg! If the till actually is of Heiberg origin, the question remains as to the location of the intervening till units that ought to be here. The easiest explanation is that they were eroded by the streams that deposited the Fordville Aquifer sands. If true, there should be a lag concentration of coarse clasts at the contact with the Heiberg till and the delta sands; there is none.

Figure 2. Contact between planar-bedded sand and convoluted unit. Forest River, ND.

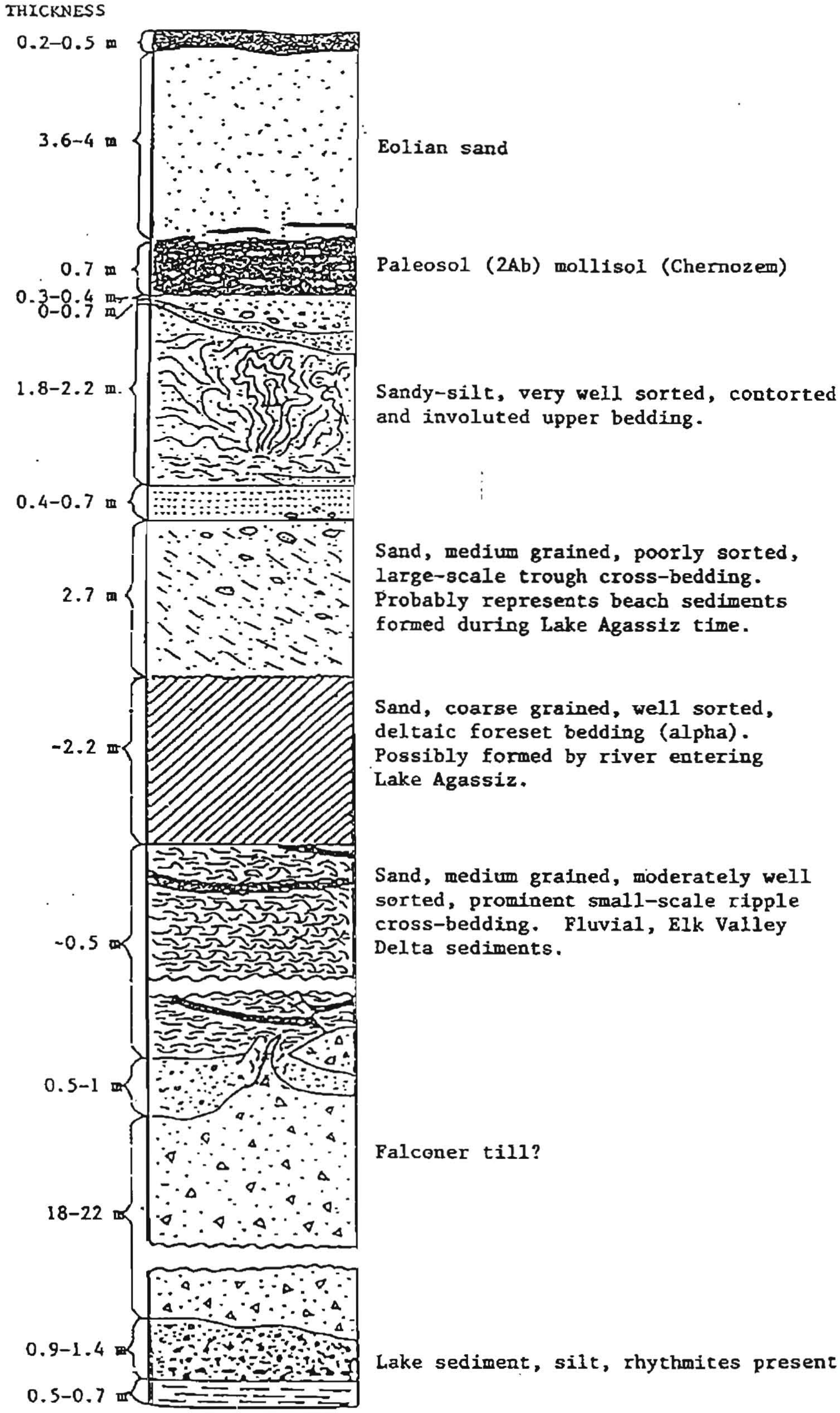

Figure 1. Columnar Section of Forest River exposure, T154N, R55W, Grand Forks County, ND.

Paleosol: A well-developed mollisol formed in the sediments overlying the disturbed sandy silt unit. No dates have been attempted, but the A-horizon presumably formed between the draining of Lake Agassiz and the Altithermal (ca. 9,500 and 7,500 yrs B.P.). During the Altithermal xeric conditions dominated the Great Plains (Ashworth and Cvancara, 1983). The eolian sands would have buried the soil then. An alternative interpretation is that the mollisol formed more or less continuously from the time of the draining of the lake up to the 1930's when drought and poor farming methods allowed erosion of the lands, burying the soil here. The present soil is considerably thinner than the paleosol. But how much time is necessary to form an A-horizon the thickness of the paleosol?

Discussion

The interpretation of the sequence of sediments at this site rests with the age of the till and the origin of the convoluted unit near the top of the section. The convoluted sediments are not the result of cryoturbation; sandy sediments are not susceptible to such deformation by frost action (Bryan, 1946). Penecontemporaneous deformation requires flowage to account for the structures that are present, but such flowage is more likely to be the result of compressional forces. A brief readvance of the Caledonia ice is a promising candidate to explain this unit. No corresponding tills have been found, though. Because the extent of this unit is unknown, it may be limited just to this site, in which case it could have been deformed by the icebergs that drifted across Glacial Lake Agassiz, creating the draglines that are so evident even today closer to the axis of the lake plain.

The simplest explanation, therefore, is that the till at this site is Falconer and the sands were deposited upon retreat of the Caledonia ice. Glacial Lake Agassiz subsequently inundated the site, depositing dirtier sand offshore. Icebergs, forced toward the shores by easterly winds, plowed into these sediments, deforming them accordingly.

Upon drainage of the lake a prairie soil (mollisol) developed, only to be interrupted by the Forest River cutting into this site, allowing for sand to be carried up from the floodplain (and the exposed face) onto the top of the bank. Sand dunes now exist there. Because eolian activity still exists, the present mollisol is poorly developed. Exactly when the eolian sand began to accumulate is not known. The age of the paleosol could reveal this, if radiocarbon dates on organic matter in soil were reliable, and if there weren't Paleocene lignite fragments in the sediment!

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GEOMORPHOLOGY/STRATIGRAPHY
of the
HALSTAD, MN, SITE

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INTRODUCTION

During the winter of 1994 a series of split-spoon, hollow-stem auger cores, 9-12m deep, was taken by the Minnesota Department of Transportation to evaluate the archaeological significance of a proposed bridge relocation across the Red River of the North near Halstad, MN (Fig. 1). The cores provided a detailed picture of the Late Wisconsinan and Holocene history of this area. The following is a summary of the geological observations.

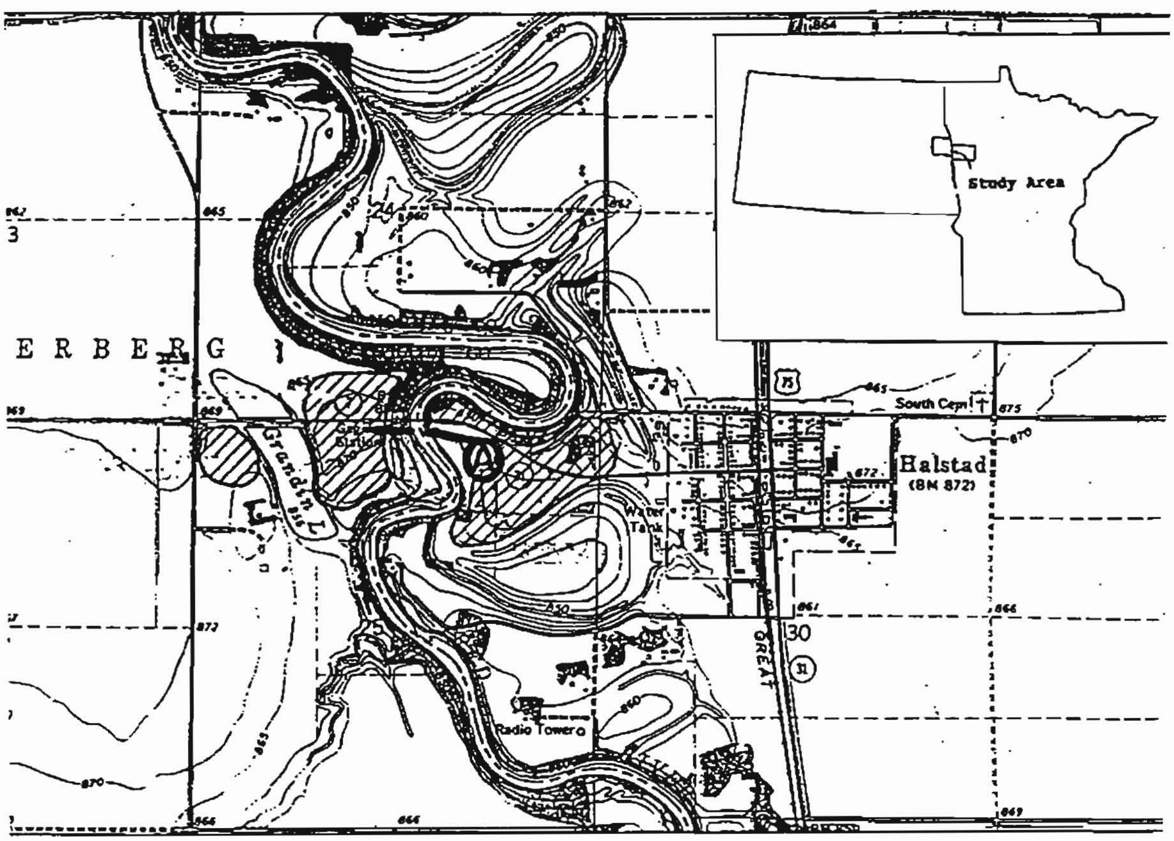

Figure 1. Map of Halstad, MN area. The Red River of the North flows northward, separating Minnesota (right) from North Dakota (left). Circled "A" in center, marks east end of coring transect.

The upland plain that overlooks the river valley is the former floor of glacial Lake Agassiz, with a gradient of only 0.50 to 1.75 m/km. An important local exception to this is Kelso Ridge, an east-west trending compaction ridge that marks an ancestral channel of the Elm River (Bluemle 1967). Although the ridge is only 2 to 3 m higher than the surrounding plain, this small elevational difference is sufficient to protect part of the site from flooding.

Abandoned floodplains (terraces) are few and far between along the river. If they are true terraces, they are non-paired, caused by lateral migration of meanders. But, because meander migration is inhibited by the erosion-resistant lake clays, most of these surfaces are more likely to be remnants of slump blocks. Surface morphology of the two types of landforms is similar, especially after infilling of the back zone of the slump blocks.

In contrast, paired terraces form as a result of stream incision into a floodplain as the gradient is increased or as the energy of the stream is increased by other means. Paired terraces would not be expected along the Red River because the gradient has been decreasing over time due to differential isostatic rebound which has raised the north end of the valley relative to the southern end (Johnston 1946).

We don't know how many times glaciers advanced over this area, but a continuing analysis of glacial sediments reveals about 20 separate units (Harris et al. 1995). Each time the glaciers advanced into what is now the Red River Valley, northward drainage was blocked and a proglacial lake formed south of the glacial front. Each successive advance scoured the pre-existing lacustrine sediments and incorporated them into compacted till at the base of the glacier. As the ice subsequently began to retreat, a proglacial lake again formed. In addition, each time the ice advanced, the Earth's crust was depressed in response to the weight of the overlying ice. A recent study (Brevik 1994) has determined that the maximum depression in the Grand Forks, ND, area was up to 350 m for the last major Wisconsinan glaciation which extended to Des Moines, Iowa. When the ice (as thick as 1040 m in the Grand Forks area) began to thin and retreat, the crust rebounded. The rebound was rapid at first, decreasing over time. The calculation of the maximum depression and rate of rebound is complicated by the fact that the more massive ice was replaced by proglacial Lake Agassiz water and its sediments, smaller in volume but denser than the ice. A second complicating factor is that the rebound did not occur uniformly along the north-south axis of the Red River Valley.

STRATIGRAPHY

The interpreted history of Glacial Lake Agassiz has been summarized by Fenton, et al. (1983). It is not my intent to repeat or evaluate that summary but, instead, to describe the related sediments from the Halstad, MN, site and to interpret how these tie into the Lake Agassiz sequence. The sediments are considered to belong to four formations: Brenna, Poplar River, Sherack, and Oahe (Fig. 2).

Brenna Formation

The lowest unit in the cores at the Halstad site belongs to the Brenna Formation, originally defined by Harris et al. (1974) as an obscurely laminated to unbedded dark gray (2.5Y3/0) to black (2.5Y2/0) clay that "...contains small, white, silty calcareous fragments that range in size from 1mm to 30mm." Although the Brenna Formation is defined as having accumulated during the Lockhart Phase of Lake Agassiz immediately following the retreat from the Caledonia Advance position (Edinburg moraine) (Fenton, et al. 1983), earlier deposition continued without interruption south of that moraine. There seems to be little reason, therefore, to define a separate formation (Argusville) for the earlier Cass Phase and another for the Lockhart Phase. Because the Halstad site is only 10-14km south of the Edinburg moraine position (Harris and Luther 1991) lacustrine sedimentation was continuous here through both of these phases of Lake Agassiz.

Another characteristic of the Brenna Formation are iceberg dropstones which occur throughout the unit, but are not common. The Brenna Formation is also noted as being highly plastic; slickensided surfaces are common in the core samples. The shear strength is reported to be typically less than 500 psf (Moran 1972) and the sediment has a high liquid limit and water content (Rominger and Rutledge 1952). The formation at the site is 24m thick (from one deep core taken earlier) (Michlovic, n.d.).

The lake was probably typical of most proglacial lakes in that the water was turbid (milky) from suspended clays and silts. The ultimate source of the sediment was the exposed clay-rich Cretaceous shales to the northwest, especially the Pierre Shale. Rivers flowing across the Pembina Escarpment in western Grand Forks, Walsh, and Pembina counties transported weathered shale into the lake. In addition, river and wave erosion of glacial sediments containing an abundance of shale also contributed to the Brenna Formation. The lake was also probably relatively sterile and devoid of biota.

The dark color of the Brenna Formation is the primary characteristic that distinguishes it from the clayey facies of the younger Sherack Formation. The two are nearly identical in terms of clay content. Where the two units are in direct contact the disconformity is generally diffuse, with sharp contacts occurring only along shear planes. (See accompanying paper, this publication)

Poplar River Formation

As a consequence of extensive retreat from the Edinburg moraine position, lower outlets were uncovered allowing Lake Agassiz to drain (catastrophically).

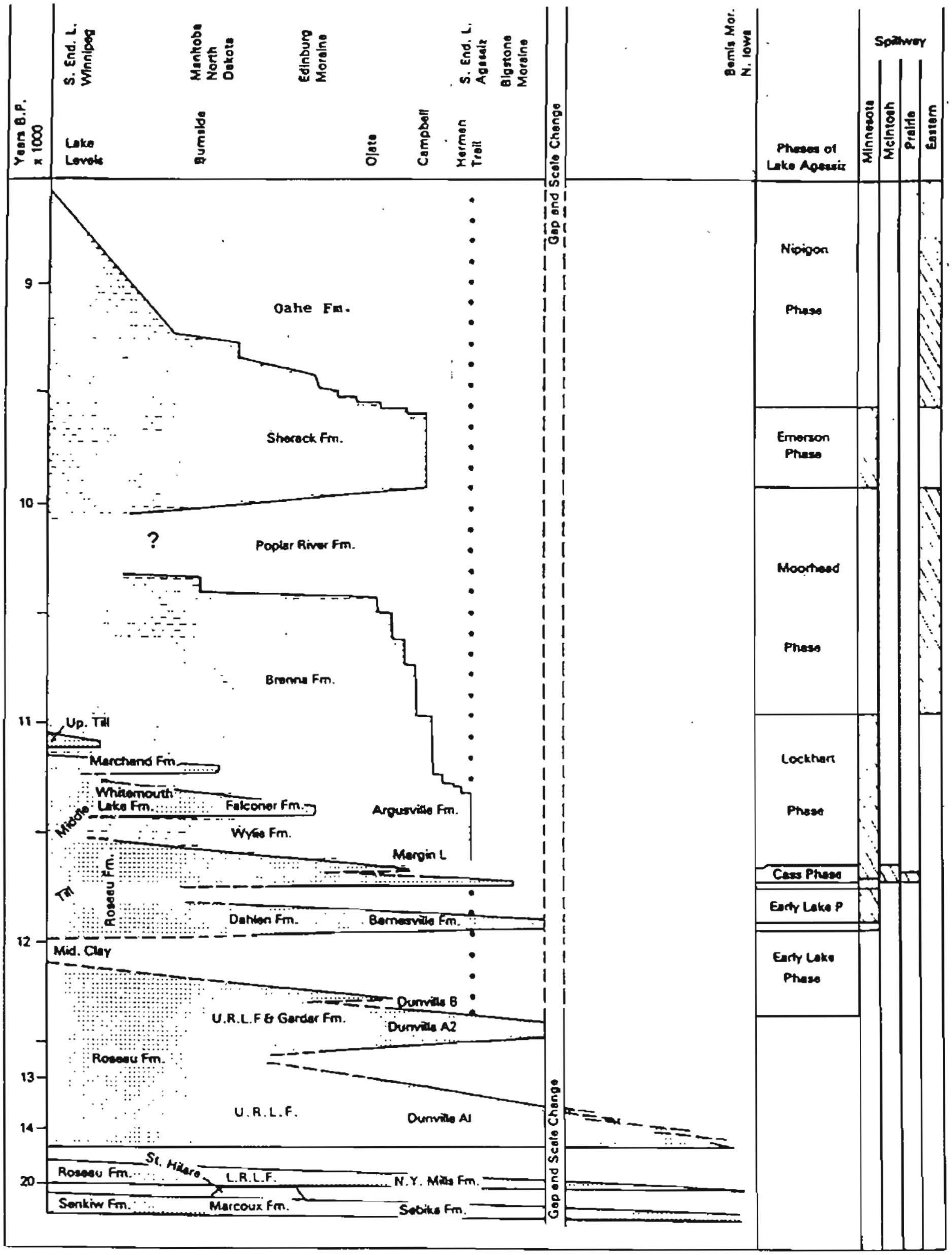

Figure 2. Time-distance diagram for the Late Wisconsinan in the southern part of Lake Agassiz, showing extent and sequence of depositional units (from Fenton, et al., 1983).

This, the Moorhead Phase of the lake, lasted from about 10,900 to 10,000 B.P. The lake floor, exposed perhaps as far north as the Winnipeg area, was desiccated, compacted, and exposed to pedochemical weathering and soil development. Rivers flowing across the plain cut channels into the lake clays, leaving deposits of fluvial sands and gravels (West Fargo Member of the Poplar River Formation)(Fenton et al. 1983). Where the rivers overflowed their banks, floodplain sediments accumulated (Harwood Member). The West Fargo Member is represented by Kelso Ridge. When the subsequent overlying water-saturated lake sediments (Sherack Formation) drained and settled, they became draped over the Kelso Ridge because the fluvial sands and gravels of the Poplar River Formation were more resistant to compaction than adjacent lake clays (Bluemle 1967). A broad ridge now marks the surface expression of this buried channel which extends from 17 km west of the study area and delineates the course of the ancestral Elm River (Bluemle 1967, Harris and Luther 1991). The ridge extends eastward across the modern Red River, ultimately joining a major, north-trending compaction ridge (Harris et al. 1974).

Iron oxide stains on bedding planes in the Halstad cores suggest periodic subaerial exposure. On the other hand, the lack of such stains, a higher sand fraction, and a loose consistency of the sandy facies is typical of the channel deposition.

The unit in the Halstad area is represented by the sand and gravel in Kelso Ridge. The contact between the Poplar River and Sherack Formations appears to be gradational, a region-wide characteristic noted by Harris et al. (1974).

The total thickness of the Poplar River Formation at the site is 17.7 m, much thicker than depicted by Smith (1985). Its base is also lower, incised 7.2 m into the Brenna Formation and 9.7 m deeper than the Red River channel. Deep entrenchment occurred because at ca. 10,900 B.P. the north end of the Lake Agassiz plain, while rising because of isostatic rebound, was still considerably lower than now (Brevik 1994). This elevational difference created a steeper northward gradient. By ca. 10,000 B.P. the rate of differential rebound had significantly decreased, probably causing aggradation within Poplar River Formation channels. This infilling may be represented by the shift from the deeper sandy facies to the silty facies in a deeper core from this site. Alternately, the silty facies may be a floodplain sediment.

Sherack Formation

The Sherack Formation is a silty lacustrine clay (55-70% clay) either overlying the Poplar River sediments or directly overlying the Brenna Formation. It is differentiated from the Brenna Formation primarily by its lighter color (2.5Y4/2 to 2.5Y6/2).

At the site, the formation consists of two facies, one clayey and one silty. The silty facies is restricted to elevations above ca. 264 m on Kelso Ridge where it is draped over the thick Poplar River Formation deposit. The clayey facies is restricted to elevations below ca. 257 m east of this ridge. The silty facies of the Sherack Formation was deposited in glacial Lake Agassiz as a relatively shallow water glaciolacustrine unit during the Emerson Phase, beginning about 9,900 B.P. The presence of ferric oxide iron stains on bedding planes here suggests either occasional subaerial exposure or secondary pedogenic deposition of ferric oxides. At the Kelso Ridge, the laminar bedding and high clay content of the silty facies of the Sherack Formation distinguishes it from the overlying Oahe Formation sediments.

The clayey facies of the Sherack Formation was deposited in glacial Lake Agassiz as a deeper water, glaciolacustrine unit. The high clay content and massive structure of the clayey facies of the Sherack Formation distinguishes it from overlying Oahe Formation sediments. Its lighter color differentiates it from underlying Brenna Formation clays.

The major source for Sherack Formation sediments appears to have been the surface of the Brenna Formation which was exposed to subaerial weathering throughout the Moorhead low-water phase. Streams also delivered carbonate-rich sediments from the glaciated surfaces north and west of the lake margin. Reflecting these sources, the Sherack formation is usually as clayey as the underlying Brenna Formation but is consistently lighter in color.

In the Halstad area, subsequent entrenchment and lateral erosion by the Red River removed most of the Sherack Formation, leaving only a remnant of the basal part of the unit. If the top of the unit was level with the Sherack Formation on Kelso Ridge, about 9 m of Sherack sediment originally covered the surface to the east.

Oahe Formation

General: All post-glacial sediments in North Dakota that have not been assigned to a previously recognized formation belong to the Oahe Formation. Some of the members are from slough environments, some from dunes and other eolian settings, and some are from fluvial environments. It is the last environment that is relevant to the study area. The Oahe Formation was the principal focus of geomorphological investigations at the Halstad site.

Halstad Area: The Oahe Formation sediments at the site range in thickness from 4.45 m to over 12 m (closest to the river). By far, the majority of these sediments are of a vertical accretion origin; seasonal overbank flooding apparently has been the primary source of sediment since drainage of Lake Agassiz. In contradiction to the interpretation by Smith (1985) who concluded that Oahe Formation sediments deeper than about 3 m below the surface were lateral accretion deposits, study of the cores revealed no sediments that could be identified as having a lateral accretion origin. The absence of these is significant. It means that the river has not migrated. This conclusion is supported by the paucity of abandoned meanders along the present channel and is largely due the resistance of the clay-rich bank sediment to erosion.

The floodplain sediments contain zones that are thinly-bedded, separated by more massive deposits that, at best, have poorly-defined bedding. Thin bedding is evidenced by calcareous laminations and by organic and/or charcoal-rich layers. The lack of visible bedding in the more massive sediments is attributable to the uniform characteristics of the silt and clay that were deposited at the site -- there was little variation in the texture and color of these sediments from one flood episode to the next. The upper 3 m of the Oahe Formation has alternating layers of lighter and darker sediment. The dark layers are buried organic layers -- thin cumulic A-horizons that formed during periods when there was a decreased rate of sediment aggradation. The lighter layers are carbonate-rich (marls).

Incorporated in the Oahe Formation are pelecypod shells (pill clams and mussels) and gastropod shells (primarily pulmonate snails). Charcoal flecks and fragments are common. There are also isolated occurrences of bone fragments, mostly from small mammals, birds, and fish.

The Oahe Formation consists primarily of reworked lacustrine sediments (Sherack and Brenna Formations). At the site it is distinguished from the directly underlying Sherack Formation by being distinctly laminated, by the presence of charcoal and shells, and by a consistently siltier texture.

A variety of scenarios can be advanced to interpret this sequence. The best guess is that all of these layers represent short-term, perhaps purely local events, that occurred during the transition from a lacustrine to a fluvial environment as Lake Agassiz drained. The most difficult layer to interpret is a basal sandy clay loam because two seemingly contradictory characteristics have to be accounted for: first, the loam has a texture that matches channel deposits of the Poplar River Formation (Kelso Ridge) and is much coarser than any of the lake sediments; but, second, it must have been deposited in a relatively fluid (soupy) state to allow for penetration by an observed dropstone. Neither the dropstone nor the fluidity of the sediments are characteristic of channel deposits. An hypothetical setting that meets these two conditions and provides a framework for interpreting the overlying layers is the speculation that coarse sediments slumped from Kelso Ridge and were deposited in a remnant of Lake Agassiz, perhaps via turbidity flows. This presupposes that either a valley was present at the close of Sherack time or that the early Red River was temporarily dammed, perhaps by a compaction ridge or by the Edinburg moraine, directly to the north. As the water level dropped, there was a progressive shift in the depositional environment from a lake to a marsh and finally to a river channel.

It should be apparent from the above that a series of events occurred in the study area at ca. 9,000 B.P. as Lake Agassiz drained for the last time. Initial entrenchment of the modern Red River along the north-south axis of the lake plain must have been rapid because the lake clay (Sherack Formation) was still dewatering and was both readily erodible and susceptible to slumping and flow. The Kelso compaction ridge which crosses the current course of the river must have been breached at this time, too.

The basal gravelly layer is believed to be a channel deposit that formed shortly after ca. 9,000 B.P. The age estimate is based on two considerations. First, although the modern river has the competence to transport coarse sediments, particularly during flood stages, none of the overlying, younger Oahe Formation sediments contains pebbles or sand layers. These sizes appear to have been available only for a limited time and to have been derived from sources that were no longer significant after the river ceased downcutting. Early post-lake sources included the Sherack Formation, several meters of which were flushed from the valley. Isolated coarse clasts within the formation (dropstones and other iceberg-rafted sediments) would tend to be concentrated in lag deposits as the lacustrine sediments were eroded. Other possible sources include breached Poplar River Formation channels and coarse sediments fed into the Red River by its tributaries. Secondly, calculations by Brevik (1994) indicate that both basin-wide isostatic rebound and differential rebound of the north end of the Lake Agassiz plain were ongoing processes during Poplar River times but were essentially completed by 9,000 B.P. Two predictions follow from this: (1) Poplar River Formation channels should be more deeply entrenched and should have a steeper gradient than Oahe Formation channels. (2) Large differences between the maximum depths of early and later Oahe channels should exist. Both predictions are met by channel characteristics in the study area. As previously noted, the Poplar River Formation beneath Kelso Ridge is entrenched at least 9.7 m below the modern river, whereas the gravelly Oahe sediment is, at most, 0.3 m lower than the base level of the modern river. Paleoenvironmental studies summarized in Wright (1983) and by Ashworth and Cvancara (1983) indicate that an open spruce forest was established in North Dakota and Minnesota following the retreat of the Late Wisconsinan Des Moines ice lobe. By ca. 8,500 B.P. this boreal forest was succeeded by prairie and by deciduous woodlands in moister environments. Wood fragments were found in a gravel layer in one of the Halstad cores and charcoal flecks from forest fires in two other cores. These indicate the river valley was forested shortly after its formation.

Altithermal B-Horizons: Reddish, iron-stained horizons were found in three cores from the Halstad site. Organic nuclei (roots and flecks of organic matter) are surrounded by grey, chelated mottles and by sinuous tracks that often have thin ferric iron stains around their edges. Strong brown (7.5YR5/6) to yellowish-red (5YR5/6) colors are superimposed as overtones on the colors of the pre-existing sediments. Elsewhere, iron stains tend to be dark yellowish-brown (10YR4/4-4/6). The horizons range from about 0.5 m to 0.8 m thick and are interpreted to be weakly-developed B-horizons. It is important to note that nowhere else in the cores or in excavations conducted at the site were other B-horizons encountered. This is due in part to relatively continuous overbank deposition which has limited the duration that surfaces were exposed, and to a high water table. Requirements for B-horizon formation at the site include a surface exposed to prolonged subaerial weathering (and, hence little or no overbank deposition) and conditions drier than present. Given the paleoclimatic history of the region (cf. Wendland 1978), the most likely period for B-horizon formation was during the Altithermal (the Atlantic climatic episode in Wendland's terminology) when xeric conditions dominated the Great Plains (ca. 5,000-7,500 B.P.). This is consistent with the age estimates for other Oahe sediments at the site (ca. 9,000 B.P. for the basal gravelly layer and a minimum of ca. 3,400 B.P. for an overlying buried organic layers (Smith 1985).

In a summary of responses of Midwestern tall-grass prairie river systems to Holocene climatic changes, Knox (1983) concluded that
river valley erosion "tends to be associated with vegetational changes that imply shifts to cooler and moister conditions, and alluviation tends to be associated with vegetational changes that imply shifts to warmer and drier conditions." During the Altithermal the Red River must have had a significantly reduced discharge; meander migration and overbank deposition either ceased or were minimal, and the channel itself probably aggraded. Supporting this relationship is the fact that early post-glacial channel sediments are preserved in locations where they probably would have been eroded if the Altithermal channel was as deep as the modern depth. The rejuvenated post-Altithermal river cut through the aggraded alluvium, and some of the silts and clays from this riverine source were redeposited, perhaps quite rapidly, as massive strata.

HOLOCENE SUMMARY

Cores of the Oahe Formation at the Halstad, MN, site preserve a sequence of sediments that date to as early as 9,000 B.P. Unfortunately, none of the sediments from the cores has been directly radiocarbon-dated and age estimates are extrapolated from the known chronology of Lake Agassiz and from dated strata identified in previous excavations at the site (Michlovic 1985, Smith 1985).

After Lake Agassiz drained at ca. 9,000 B.P., the Red River entrenched the lake plain, leaving a gravelly channel lag deposit. Covering the gravelly alluvium are massive vertical accretion deposits up to 10 m thick which contain marly laminae deposited in ephemeral, backwater puddles and ponds. Aggradation was probably relatively rapid once post-glacial rebound in the area had ceased, but there was a hiatus during the Altithermal, ca. 7,500-5,000 B.P., when weak B-horizons formed on terrace surfaces. Buried organic layers that cap massive alluvium and gleyed sediments west of the site are believed to be at least partly contemporaneous and to have formed prior to ca. 3,400 B.P. During this time, one or more forest fires swept the site, leaving fire-oxidized soils at higher elevations and charcoal in channel deposits. Lastly, a cumlic A-horizon has formed within the last thousand years.

The oldest documented Oahe channel deposits occur at a depth close to that of the modern river channel. Subsequently, channel depth fluctuated above and below this level. During the Altithermal the channel was probably shallower, but when the next unit was deposited, the channel may have been deeper than at present. These fluctuations were responses of the river system to arid and moist climatic regimes, respectively.

The rate of channel migration was most rapid in early post-lake times when 125 m of lateral movement has been documented from the cores on the east side of the present channel. At this time, the lacustrine clays into which the river was entrenched were probably soft and susceptible to erosion and collapse. Thereafter, channel migration was extremely slow due to a shallow gradient and confinement of the river by erosion-resistant bank sediments. The preserved subsurface landforms east of the modern river -- possible terraces associated with the Altithermal B-horizons and the slopes approximating modern cutbanks on the west side of these buried terraces -- require no more than a single westward and downstream shift of one meander.

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FRACTURES IN THE HALSTAD, MN, CORES

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General

Among the most conspicuous structures encountered in the Halstad, MN, cores (Reid and Olson, this volume) are inclined and vertical fractures. The fractures occur in the glacial Lake Agassiz clays, the Brenna and Sherack Formations, and in the vertical accretion deposits comprising the Holocene Oahe Formation. Characteristics of these fractures and possible causes are as follows:

Inclined Fractures

The most common fracture in the cores is the result of shearing. The defining characteristics of these are inclined, slickensided surfaces with striations running parallel to the direction of slippage (Fig. 1). Such fractures have orientations ranging from zero to 74 degrees with a mean orientation of 42.4 degrees and a very pronounced modal orientation of 45-48 degrees from the horizontal. Figure 2 illustrates the angular distribution of the 101 shear planes recorded in the core samples. This distribution should be used with caution because there may be a systemic bias towards low angle shear planes. The probability of intersecting a given shear plane is a function of its length and angle. If low angle and high angle shear planes have comparable lengths, low angle planes are more likely to be intersected during coring because of their greater horizontal component.

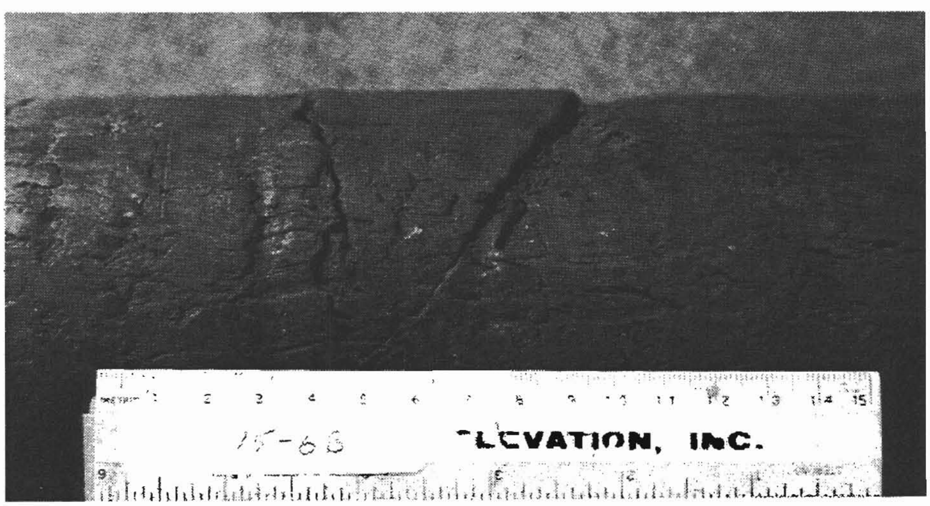

Figure 1. Shear fracture in Oahe Formation sediments (8m below surface) Halstad, MN.

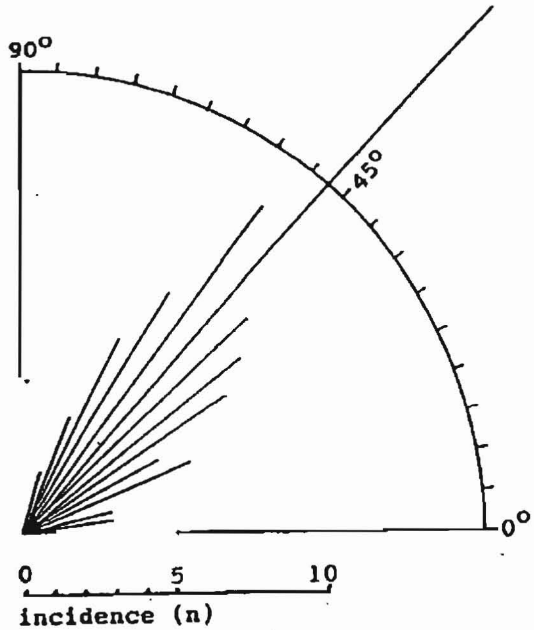

Figure 2. The distribution of shear plane orientations by 5° intervals in the Halstad cores.

Seven of the 101 inclined planes had a secondary precipitate of gypsum, two had a calcite precipitate, and one had iron oxide stains. Fifteen of the planes had a thin (1-2 mm) border of gray colored, chelated sediment resulting from ground water seeping along the fracture. Most, however, lacked precipitates or chelated borders, indicating that the planes were tightly sealed due to formation under compressive forces and most had not served as conduits for ground water. Those with mineralization or alteration, as well as those that truncated strata, are significant in that they demonstrate that the planes are not an artifact of coring.

Shearing is typically the result of compressional stress release. The only logical source of compression is the weight of the overlying sediments. This is evidenced by the vertical distribution of the planes: 92 percent occurred at depths greater than 7 m below the modern surface. It is also evidenced by the distribution of shear planes. Of the 101 planes, 23 were in the Oahe Formation, 55 in the Sherack Formation, 17 in the Brenna Formation, and six in sediments of uncertain identification or extended across the contact of two formations. The relatively low incidence of cracks in the Brenna Formation is due to limited sampling of the formation -- the maximum core depth was only 11.8 m and penetrated at most only the upper 2 m of the Brenna Formation. Field logs of deeper coring by the North Dakota Department of Transportation (1990, 1992) and by the U. S. Army Corps of Engineers (1980) in the Halstad area consistently cite slickensided surfaces throughout the entire thickness of the Brenna Formation.

Soil texture also plays a significant role in shear plane formation. The frequency of shear planes occurring 7-9 m below the modern surface in the Oahe Formation (40-60% clay) is 0.42 planes per meter of core length. The frequency for the same depth range for the Sherack Formation (>75% clay) is 1.67 planes per meter of core length, a four-fold increase attributable to the susceptibility of clay-rich sediments to shear failure. Likewise, of those fractures that occur at depths shallower than 7 m below the modern surface, all but one are in the Sherack Formation. The shallowest recorded fracture was only 4.25 m below the surface.

Shear planes also tend to occur in clusters; 34% of the planes occur within 5 cm of another plane and 53% occur within 10 cm of another plane. This clustering suggests that the planes define zones of structural weakness that are separated by zones of sediment with greater structural integrity. In the majority of cases, the planes within a cluster tend to have at least subparallel orientations but there are two instances in which one shear plane was truncated by second, almost orthogonal to it. These represent multiple episodes of shearing.

Vertical Fractures

Nine nearly vertical fractures (>85 degrees), ranging up to 1.15 m long were observed. Although the incidence of vertical fractures in the core samples is far lower than that of shear planes, it is probable that this is a sampling bias due to the orientation of fractures. Near-vertical fractures are likely a common phenomenon. Two of the nine fractures were in Oahe sediments, seven in the Sherack Formation, and two in the Brenna Formation.

The surfaces of these fractures are generally planar, but include some sinuous and irregular examples. None of the fracture faces was slickensided. Secondary precipitates of white powdery gypsum occurred in 30% of the fractures and off-white calcite in one fracture. Gray-colored chelated zones extended 0.5 to 1.0 cm to either side of the fractures. The relatively thick chelated borders and the heavy mineralization of the fractures indicates that these fractures have served as paths for ground water flow at some point in their history (cf. Taylor 1994). The fractures are also a preferential route for root penetration -- webs of root hairs commonly followed fracture surfaces.

As noted, shear planes tend to occur in clusters separated by zones of sediment with few shear planes. It is within these zones that vertical fractures occur. It is inferred from this distribution that atleast some of the vertical fractures were created by tensional stresses due to sediments being dislocated along shear planes. Two additional observations are relevant here. First, the steepest shear plane was only 72 degrees from the horizontal. It is suspected that at angles greater than this the clay fails along near-vertical fractures. Some steep shear planes with orientations greater than 60 degrees from the horizontal have a stepped configuration, supporting this idea. Such planes consist of short, slickensided surfaces oriented about 45 degrees from the horizontal that alternate with short, near-vertical faces without slickensides. The stepped planes therefore appear to be composites of shear planes and near-vertical fractures.

Secondly, four of the near-vertical fractures terminated (either at their upper or lower ends) at shear planes that had a low mean angle (30 degrees from the horizontal; range, 7-45 degrees). Although the sample is small, it suggests that vertical fractures are associated with sediment movements that have large horizontal components. There are no cases where strata or features such as shear planes are offset by vertical fractures. This, plus the absence of slickensided faces, also suggests that the sediment movements creating vertical fractures primarily involve lateral displacements.

As with the shear planes, the near-vertical fractures provide evidence of multiple episodes of failure. Although the near-vertical fractures never offset shear fractures, the reverse does occur. In these cases shearing must have occurred after the vertical fracture formed. In contrast, other shear planes cross vertical fractures without being offset and these represent shear planes that existed prior to vertical fracturing.

DISCUSSION

In addition to lateral movement during shearing, other processes cause vertical fracturing. Because of their high clay content, the Oahe, Sherack, and Brenna Formations shrink as they dry from subaerial exposure. Such shrinkage could be reflected by near-vertical desiccation cracks. Examples were found in excavations at archaeology site 32TR402, located on Kelso Ridge directly west of the coring locations (Olson 1994). Here, numerous cracks were encountered that are roughly 10 cm wide at the A/AB-horizon contact and diminish to cracks that are a centimeter or less in width at depths of 50-60 cm. In plan, these cracks form polygonal patterns 20 to 50 cm in diameter.

Desiccation fractures may occur either in the modern surface or in older subaerial surfaces that are now buried. Those on Kelso Ridge were conspicuous because they were filled with dark A-horizon soil. Although the fractures could not be traced upward through the A-horizon, this is because the fill and the enclosing material are the same dark color. The fact that the cracks contain A-horizon sediment implies that they formed when at least some A- horizon material was present.

Likewise, deeper in the Halstad cores, desiccation cracks could have formed at the upper contact of the Brenna Formation which was exposed to subaerial weathering during the Moorhead Phase of Lake Agassiz, at the upper contact of the Sherack Formation, exposed after the final emptying of the lake, or at any of numerous levels in the vertical accretion deposits comprising the Oahe Formation.

The two vertical fractures within the Oahe Formation may be desiccation cracks, but those in the Sherack Formation cannot be. Not one of the seven recorded vertical fractures in that formation extend to its upper contact. All were internal to it and, hence, unlikely to represent cracking due to desiccation.

Thermal (frost) contraction can also create vertical fractures. Again, examples were visible in the 32TR402 excavations (Olson 1994). Contrasting with the small polygons produced by desiccation, these consist of 15-25 cm-wide zones of dark sediment that appear to be the borders of polygons 1.5-2 m in diameter. In vertical section, the zones are visible as well-defined columns of dark sediment. Most columns terminate at the Oahe-Sherack contact, suggesting their depth is texturally controlled. This type of vertical fracture is believed to be the result of thermal contraction, frost cracking, that occurs when temperatures drop rapidly below -22 degrees Celsius (Lachenbruch 1962).

Like desiccation cracking, frost cracking could originate at modern or older surfaces that were exposed. But, as in the case of desiccation cracking, the distribution of the nearly vertical fractures in the Halstad cores does not match this expectation.

A third mechanism that may have created vertical cracks is isostatic rebound. Rebound characteristically produces horizontal sheeting failures but tensional forces are also part of rebound. According to calculations by Brevick (1994), isostatic rebound in the Halstad area should have largely been completed by Sherack time and, thus, is unlikely to have caused post-depositional fracturing of the Sherack and Oahe sediments.

In summary, although desiccation cracking, frost cracking, and isostatic rebound are plausible mechanisms that can fracture sediments vertically, the distribution of these fractures in the cores and the inferred environment at the time of their formation suggest that these cannot explain many of the observed vertical fractures in the Halstad cores. More likely are two other processes, bank failure and dewatering, disussed below.

A requirement for compressional shearing and tensional fracturing is that there must be a space into which the sediments can be displaced. Bank failures, common along the Red River, provide one such setting. There appear to be at least two types of such failures. Leer and Bell (1970) described landslides (slumps) at the Thompson and Hendrum bridge sites a short distance north of the Halstad area. These slides involved large blocks of sediment, 70 to 140 m in width. Failure was attributed to loading caused by bridge footings and occurred during low water levels after floods had saturated and weakened the bank sediments. In the Halstad area, two terrace-like landforms on the west bank of the Red River directly opposite the coring location likely represent this type of failure. Both have an arcuate plan form and have 25 to 85 m-wide treads that slope slightly back into the hillside. Here, loading could have oeen caused by

Kelso Ridge, immediately to the west.

The second type involves smaller-scale undercut bank edge collapse. An example is one about 12 m beyond the east end of the Halstad core line, where a 15 m-wide block of land has failed and slid partly into the river.

Each of these bank failures can produce both shear planes and vertical fractures. Leer and Bell (1970) were able to interpolate the cross-section of the Hendrum slide from data provided by inclinometers placed in bore holes. That slide involved a rotational failure that sheared along an arc with an orientation ranging from zero to about 60 degrees from the horizontal (in other words, a true rotational slump failure). The base of the slide, where low angle shearing occurred, was 17.5 below the modern ground surface. Inspection of the larger Halstad bank failure, noted above, suggests that the upper part of the block failed along a surface steeper than 60 degrees and most likely is a rotational slump block.

Although rotational failures vary with loading, two relationships can be expected. First, shear angles should vary along the plane of failure, with no single preferred orientation. Secondly, angles should decrease with increasing depth. Neither of these relationships is reflected by shear planes in the Halstad cores; shear angles have a pronounced modal distribution (Figure 2) and angles tend to <u>increase</u> with depth (Figure 3).

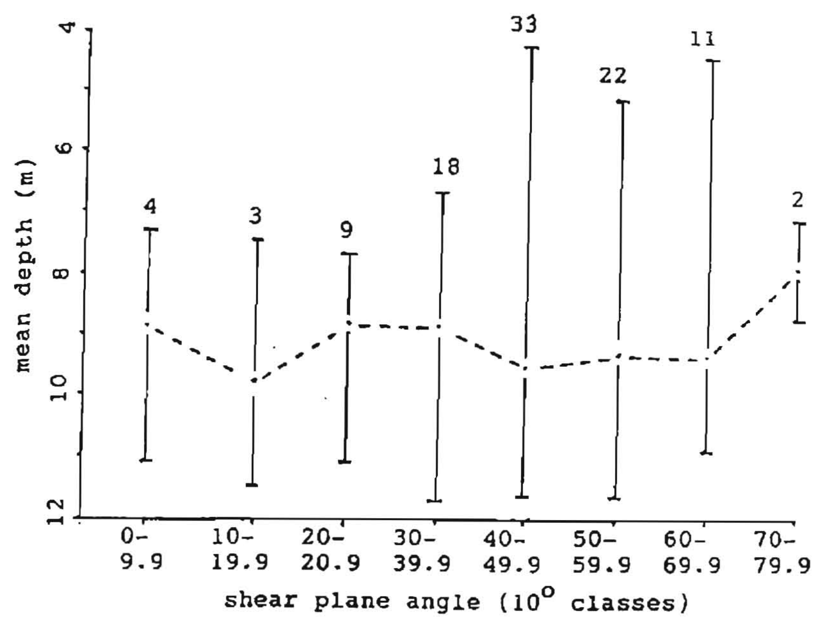

Figure 3. Shear plane orientations plotted as a function of mean depth in the 11 m deep Halstad cores. Numbers designate the number of planes per class and bars represent the range per class.

Despite this, there is independent evidence that bank failures have occurred repeatedly at the Halstad site. Certain contacts and strata can be traced from core to core. These include the Brenna/Sherack contact, the Sherack/Oahe contact, a gravel layer, and a horizon strongly stained by iron oxide within the Oahe Formation. Vertical extensional offsets of these markers by 80-100 cm between adjacent cores suggest that at least five episodes of small-scale slumping have occurred. The direction of extension, toward the present river, is supported by surface landforms originally interpreted as non-paired terraces (Reid and Olson 1994). However, because the Brenna/Sherack contact predates the modern river and because the ancestral Red River was east of the study location during the Moorhead phase (Arndt 1977), offsets of this contact cannot be due to small-scale bank collapse and must represent slump phenomena. By extension, the same is believed to be true of displacements along the Oahe/Shearck contact and those internal to the Oahe Formation. (This slumping must have occurred prior to 3400 C-14 years B.P., the age of a zone of buried cumulic A-horizons (Michlovic 1985) which are not offset).

All of the recorded vertical fractures occur where one or more extensional offsets are documented. The conclusion drawn, therefore, is that most or all of the vertical fractures are due to slumping of sediments towards the river. The same does not hold true for compressional shear planes. Other processes must be responsible for the modal distribution of the shear plane angles in the cores. The most likely candidate is dewatering.

Some shearing, deep in the Brenna Formation, clearly cannot be attributed to bank failure. In such sediments the necessary space required for shearing was provided by dewatering of the saturated lake clay. Unlike bank failures which entailed significant lateral movements, dewatering resulted primarily in vertical compression due to thick sediment accumulation. It is suggested here that the compressive forces were released along short shear planes preferentially oriented at 45 degrees. The same is believed to apply to the Sherack Formation, roughly six to twelve meters of which have been removed in the study area by lateral migration of the modern Red River. Evidence suggesting this are shear planes that existed prior to vertical fracturing and the shallow depth of some shear planes in the formation. The latter include those noted above at a depth of 4.25 m below the modern surface. Because the cumulic A-horizons covering them are not offset, the shear planes must have formed when no more than a three-meter thickness of Oahe sediments had accumulated. Other depth data suggest this thickness is insufficient to cause shearing. More likely, the shearing occurred prior to the deposition of the Oahe Formation and prior to the erosion of about six meters of Sherack sediments.

In summary, vertical fracturing in the Halstad cores is attributed to slumping of sediments towards the Red River channel. Most shear planes, however, are attributed to dewatering on the basis of distributional data that do not match that expected for slumping.

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THE BUFFALO AQUIFER, A BURIED TUNNEL VALLEY

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FROM: Harris, Kenneth L., West, Susan A., Tipping, Robert G., in preparation, The Buffalo aquifer, buried tunnel valley: *in* Patterson, C.P. (ed.) Shorter contributions to the Quaternary of Minnesota: Minnesota Geological Survey, St. Paul, Report of Investigation 49.

ABSTRACT

The Buffalo Aquifer was investigated as part of the Southern Red River Valley Regional Hydrogeologic Assessment (RRV RHA; Harris and others, 1995). The aquifer, although exposed at the surface (known locally as the Sabin Ridge or the Kings Trail), has little surface expression, and in most places is difficult to see on the low-relief surface of the Lake Agassiz plain.

The aquifer is a narrow channel oriented north-south and filled with sand and gravel. It is incised into Lake Agassiz sediment, underlying glacial sediment, and bedrock and has a fan-shaped surficial deposit of sand an gravel located immediately south of the channel. Both the channel and fan were partially buried by sediment deposited during a later phase of Lake Agassiz.

Data from water wells, test wells, and a surface-resistivity survey were interpreted to develop maps, cross sections, and computer images. They show that the internal channel stratigraphy is complex, suggesting that more than one discharge event occurred. They also show that the channel rises in elevation to the south and seems to undulate vertically as well as meander horizontally.

The Buffalo aquifer is interpreted as sediment deposited in a tunnel valley, similar to the exposed features discussed for eastern Minnesota by Wright (1973), by the discharge of basal meltwater under the margin of the Red River lobe as it stood in the Red River Valley. The tunnel valley discharged water and sediment, episodically and under great hydraulic pressure, to the south into a ice-marginal lake.

INTRODUCTION

REGIONAL GEOLOGIC SETTING

Surficial geologic, airphoto, and lithostratigraphic mapping in the Red River Valley (Figure 1) have identified eight ice margins (Harris, 1987; Harris and Luther, 1991; Harris and others, 1995), three of which cross the Red River Valley between Breckenridge, Minnesota and Grand Forks, North Dakota (Figure 2). They are interpreted as recessional ice-marginal positions of the Red River lobe.

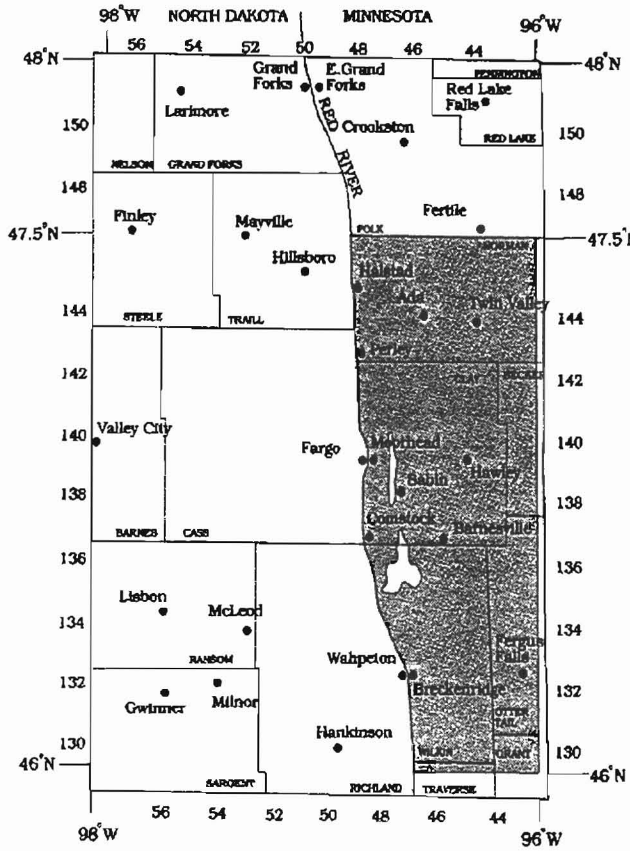


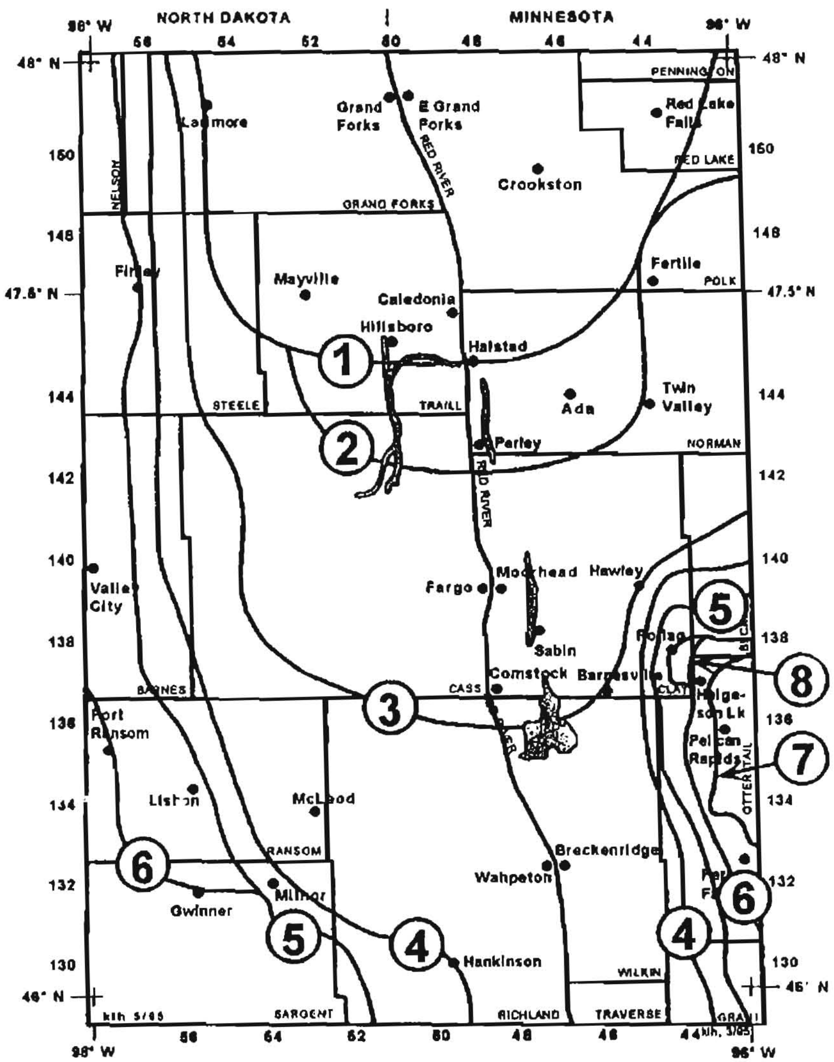
Figure 1 - RRV RHA Quaternary stratigraphy study area. Gray area is the surface mapping study area. Irregular white area is the Buffalo aquifer.

Arcuate or linear areas of hummocky, high-relief moranic topography typically characterize the ice margins of the Red River lobe. However, ice margins that cross the Red River Valley have been wave-washed (smoothed) and covered by lake sediment; they are very subtle, low-relief features that are difficult to see on the ground.

The best example of a wave-washed moraine is the Edinburg moraine which marks a stable position of the Red River lobe near Halstad, Minnesota (Figure 2, margin 1; Harris and others, 1974; Arndt, 1977; Clayton and Moran, 1982; Harris and Luther, 1991; Harris and others, 1995). The Edinburg moraine marks the southern limit of the Huot Formations in the Red River Valley (Figure 2 and 3). It crosses the Lake Agassiz basin at the north end of the SRRV RHA map area, but the lake plain has no collapse topography. A change in the character of the surface sediments, from clayey lake sediment to clayey glacial sediment, is the only indication of its location. Careful field work and test borings are necessary to map this ice-marginal position. Outside the lake plain (and the map area), in Grand Forks and Walsh Counties of North Dakota, the Edinburg Moraine exhibits collapse topography, more characteristic of a lateral moraine.

Two other ice-marginal positions are believed to be present in the southern Red River Valley. They cross the valley near Perley, Norman County, Minnesota, and near Comstock, Clay County, Minnesota (Figure 2, margins 2 & 3). They represent two stable positions of the retreating Red River lobe and mark the southern boundaries of the Upper Red Lake Falls Formation (Perley ice-marginal position) and the Lower Red Lake Falls Formation (Comstock ice-marginal position).

The Comstock ice-marginal position is marked by the presence of glacial sediment of the Red Lake Falls Formation in the lake plain and by the Buffalo aquifer.



Ice Margin	Associated Group	Associated Formation	Associated Ice Advance
1	Forest River group	Huot and Falconer Formations (RRV01 & 02)	Caledonia advance of the Red River lobe
2	Red Lake River group	U. Red Lake Falls Formation (RRV03)	Perley advance of the Wadena/Rainy lobe
3	Red Lake River group	L. Red Lake Falls Formation (RRV04)	Comstock advance of the Wadena/Rainy lobe
4	Goose River group	St. Hilaire Formation (RRV06 & 07)	Hankinson ice-marginal position of the Red River lobe
5	Goose River group	Dahlen Formation and Heiberg till (RRV08 & 09)	Rollag ice-marginal position of the Red River lobe
6	Lake Tewaukon group	Gardar Formation (RRV13 & 14)	Fort Ransom ice-marginal position of the Red River lobe
7	Otter Tail River group	RRV10, 11, & 12	Pelican Rapids ice-marginal position of the Rainy lobe
8	Crow Wing River group	RRV15, 16, 17 (Marcoux Fm.), & 18	Helgeson Lake ice-marginal position of the Rainy/Superior lobes

Figure 2 - Ice margins and associated units and events (Modified from: Harris and others, 1995)

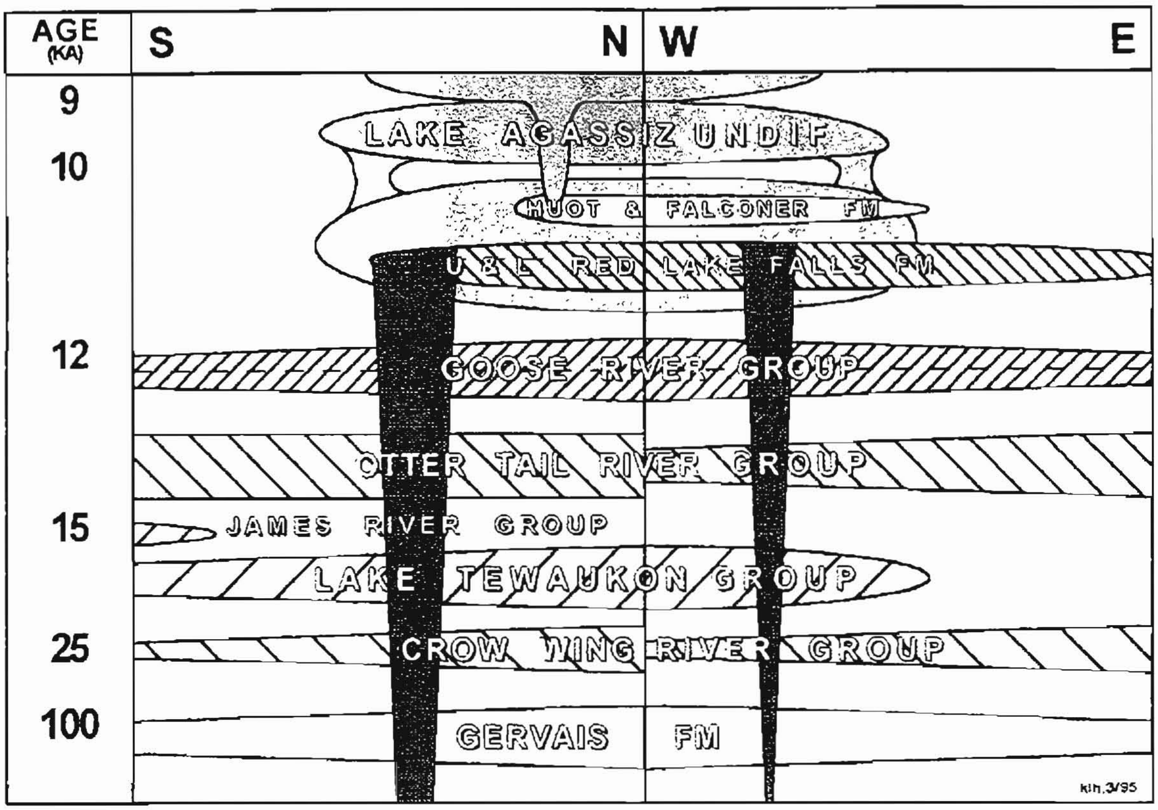


Figure 3 – Time-distance diagram showing lithostratigraphic units in space and time in the RRV RHA area. Dark gray vertical unit is the Buffalo aquifer. Modified from: Harris and others, 1995

The Perley ice-marginal position is less well documented. The lithostratigraphic sequence dictates a recession of the Red River Lobe from the Comstock ice-marginal position to the Perley ice-marginal position. The Perley ice-marginal position crosses the Lake Agassiz plain just south of an enlarged section of a "compaction ridge" (interpreted to be buried sand-and-gravel channel fill). The ridge is about a mile (1.6 km) wide and 14 miles (22 km) long. A similar feature in a similar location, the Hillsboro aquifer, has been mapped in Traill County, North Dakota (Bluemle, 1967; Clayton and others, 1980; Harris and Luther, 1991).

These ice margins are recognized by morainic topography, airphoto mapping, and lithostratigraphic boundaries and are coincident with discrete aquifers (the Buffalo, "enlarged compaction ridge" and the Hillsboro aquifer). It is this association that led us to the hypothesis that the aquifers represent the deposits of subglacial streams discharging at an ice margin.

Each of the ice lobes that occupied the Red River Valley blocked the pre-existing northerly drainage system and caused the flooding of the valley. The ice lobes also diverted pre-existing tributary systems that drained into the valley as ice-marginal streams. They were diverted the south into Lake Agassiz. In this way, Lake Agassiz and the Glacial River

Warren captured all the drainage from Manitoba and Saskatchewan east to the Red River Valley.

PREVIOUS WORK

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

METHODS

The surficial geology of the Buffalo aquifer (Figure 4) was studied on aerial photographs and soil maps and from shallow borings as part of the RRV RHA. Lithologic cross sections were constructed with data from 272 water wells in the Minnesota Geological Survey's (MGS) County Well Index (CWI) and 60 USGS test wells. Logs of these wells were used to construct a sand-and-gravel isopach map, a north-south cross section, and six east-west cross sections (Figures 5 and 6).

Computer-generated images were constructed using indicator kriging techniques. Data from CWI, USGS test wells, and USGS resistivity surveys were used to examine the shape of the aquifer by estimating the distribution of the buried sand and gravel. This technique provided an objective view of the geometry of the Buffalo aquifer. Because these images are based on estimates, they do not show the exact location of aquifer deposits. Figure 7 and 8 provide a qualitative look at the shape of the aquifer.

RESULTS

The surficial geologic map of the Buffalo aquifer (Figure 4) shows the north-south orientation of the sand-and-gravel channel and the fan-shaped sand-and-gravel deposit at its southern end. The sand-and-gravel deposits are expressed as a subtle topographic high that

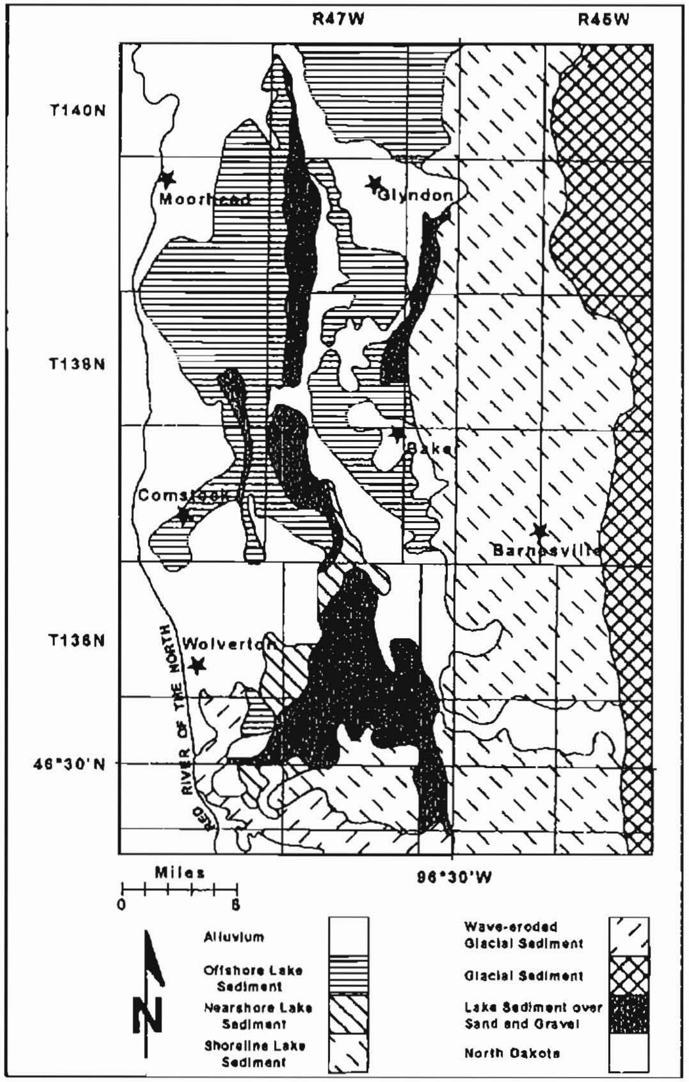


Figure 4 - Surficial geologic map of the Buffalo aquifer. Modified from Harris and others, 1995.

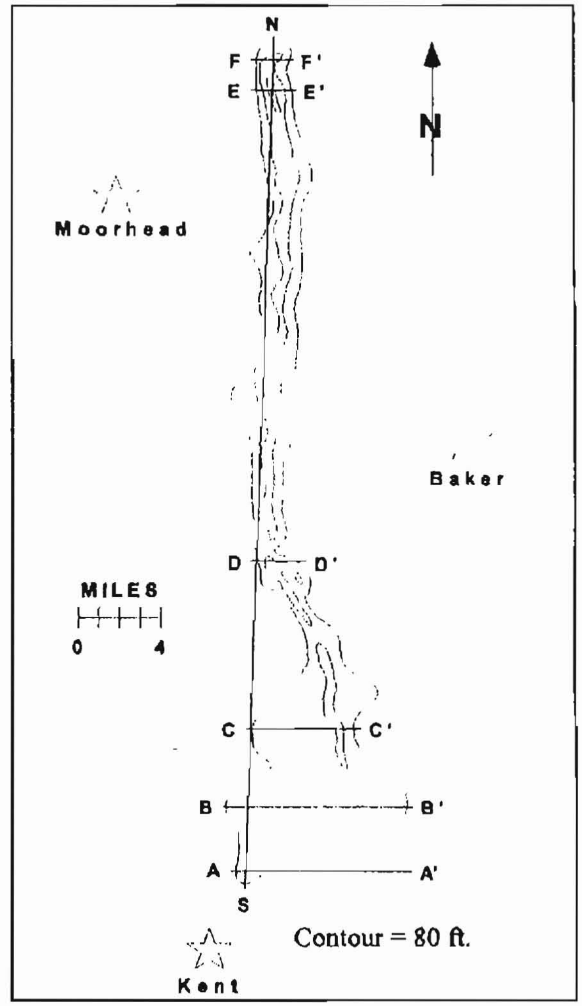


Figure 5 Isopach map of the Buffalo Aquifer. Labeled lines show approximate location of lithologic cross sections. Mofified from Harris and others, 1995

is surrounded by river, lake, and eroded glacial sediment.

East-west lithologic cross sections D-D', E-E', and F-F' (Figure 6) were constructed in the "broomstick" part of the aquifer. They show a sand-and-gravel-filled channel incised into older Lake Agassiz sediment and the underlying glacial sediment. These cross sections show that the channel varies in depth and width over its length.

East-west lithologic cross sections A-A', B-B', and C-C' (Figure 6) were constructed in the "broom straw" part of the aquifer. They show a relatively thin, near-surface sand and gravel body, underlain by glacial or lake sediment, that becomes thinner and wider to the south. The surface of the fan is overlain by a variable thickness of lake and river sediment.

The north-south lithologic cross section (Figure 6) shows that the channel rises and thins to the south, and consists of a complex mixture of sand and gravel, glacial till, and lake sediment. The complex stratigraphy suggests multiple episodes of cut and fill.

Figure 7 shows a view of the sand and gravel in the Buffalo aquifer based on the occurrence of sand and gravel reported in water wells. The data source was the MGS CWI, which contains driller's descriptions and interpreted lithology for field-located wells. The interpreted lithology was used to estimate probable distribution of sand and gravel at discrete horizons (elevations) above sea level. The results were then stacked to produce the image shown. They clearly show a channel and fan oriented north-south.

Figure 8 shows a view of the sand and gravel in the Buffalo aquifer based on interpreted resistivity data. The USGS published a surface resistivity survey of the Buffalo aquifer in 1979 (Zohdy and Bisdorf). Their interpretations of the resistivity data (Zohdy, personal communication) displayed a striking similarity to the airphoto geologic map we had developed of the Buffalo aquifer. Arrangements were made to obtain the USGS resistivity data and interpretation software. The resistivity data was processed, and a resistivity value determined that corresponded to the lithologic break between sand and gravel and till or clay (40 ohm-meters). Slice maps were constructed of the resistivity data for a range of elevations, and the occurrence of sand and gravel was displayed by stacking these maps. The images produced clearly shows the Buffalo aquifer, the aggrading sand deposits in the fan (Figure 9-C), and the sinuous shape of the north-south channel.

DISCUSSION

Lithologically the Buffalo aquifer is an anomalous deposit of sand and gravel that is incised into lake sediment, glacial till, and bedrock . It is a discrete deposit that is completely surrounded by fine-grained sediment. Both the channel and fan sediment are overlain by a veneer of lake and river-overbank sediment.

The east-west cross sections (Figure 6) and computer images (Figures 7 & 8) show that the

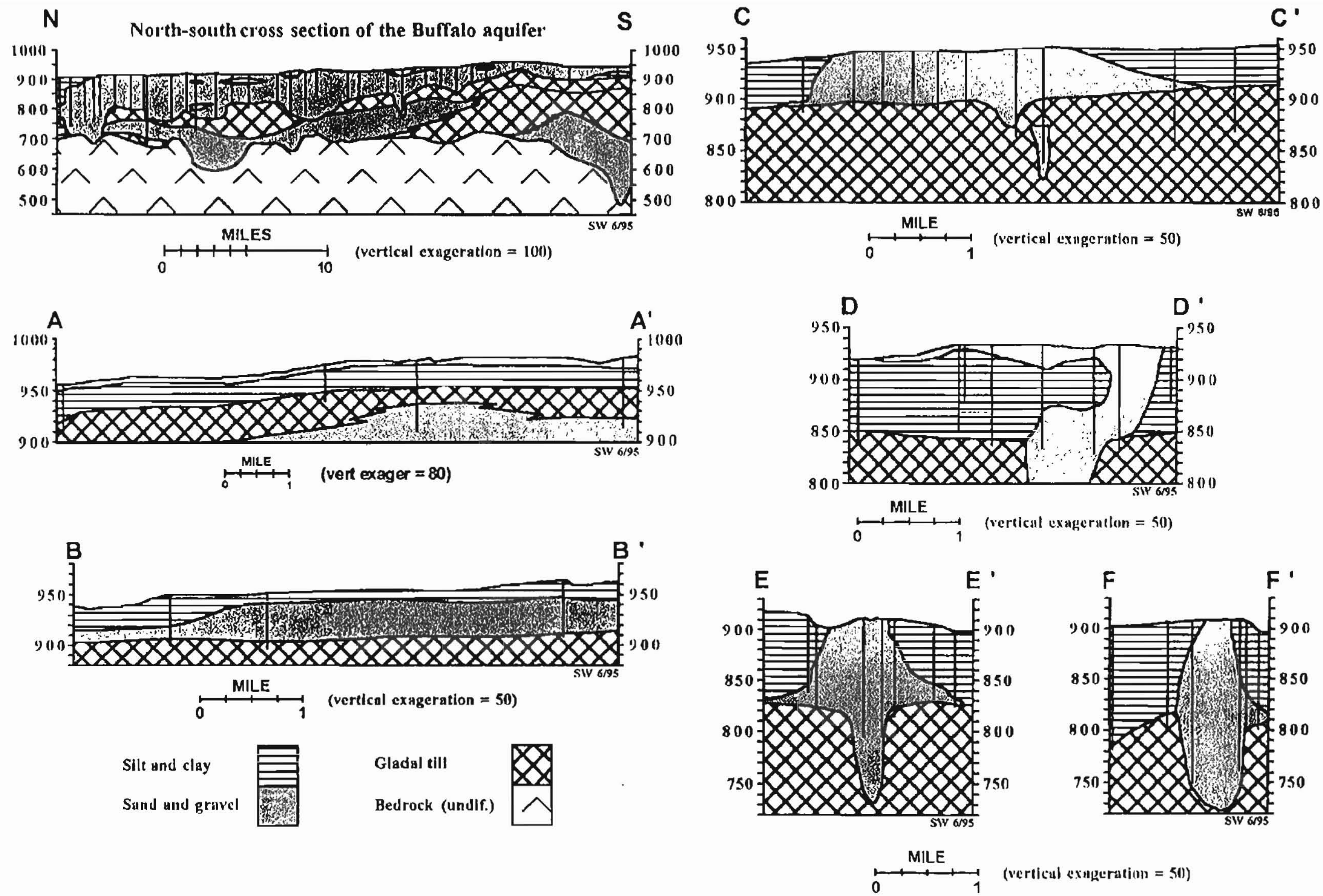


Figure 6 - Lithologic cross sections of the Buffalo aquifer (Modified from: Harris and others, 1995)

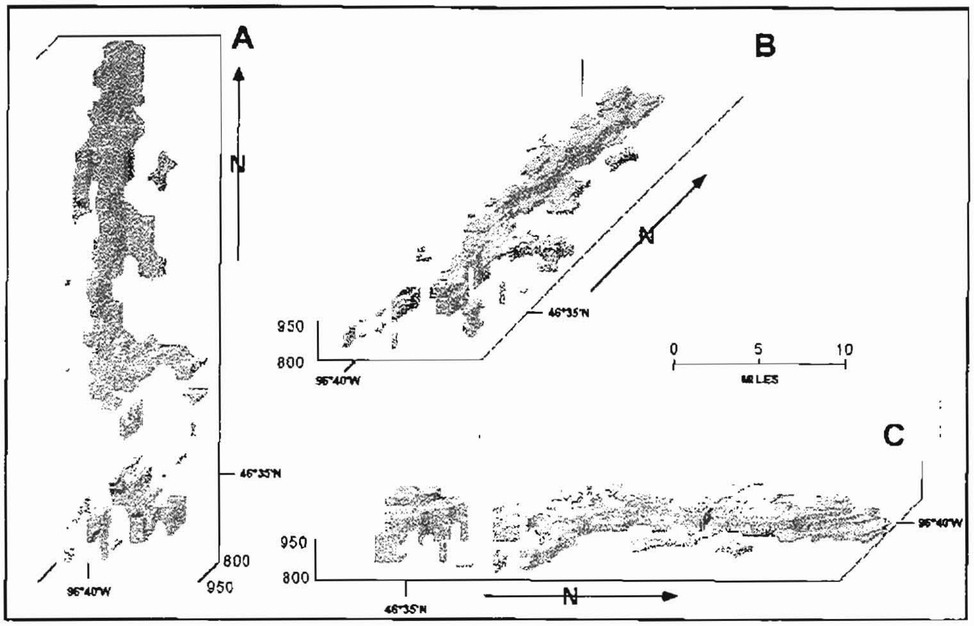


Figure 7 - Computer generated images of the occurrence of sand and gravel in the Buffalo aquifer. Images based on water well records in the MGS CWI.

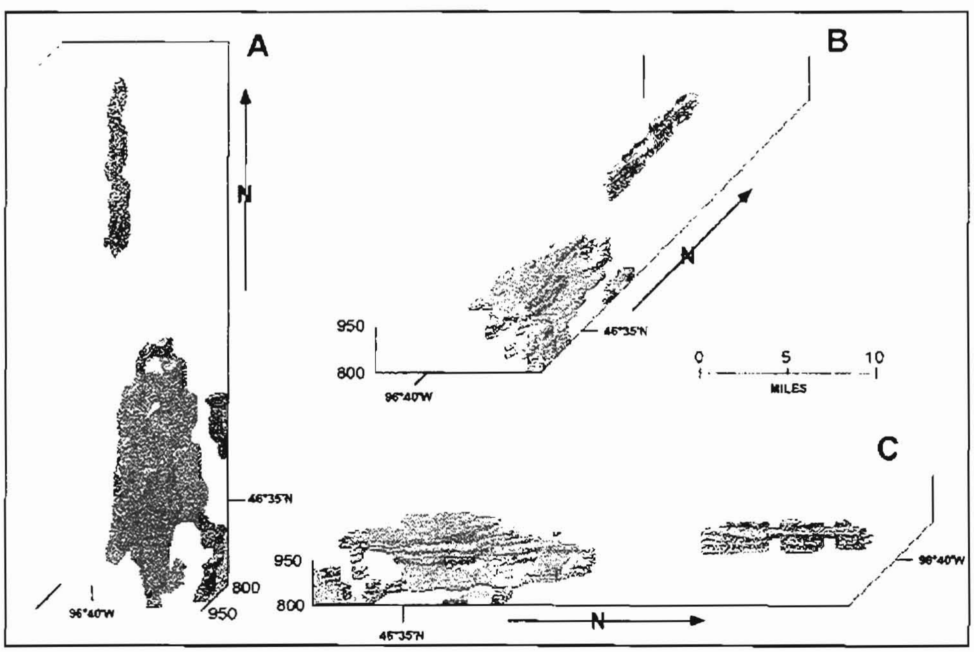


Figure 8 - Computer generated images of the occurrence of sand and gravel in the Buffalo aquifer. Images based on USGS surficial resistivity surveys (Zohdy and Bisdorf, 1979). From: Harris and others, 1995

gravel-filled channel is sharply incised into surrounding sediments. The north-south cross section (Figure 6, N-S cross section) shows that the channel rises to the south and is stratigraphically complex. It suggests that the deposit is the result of multiple episodes of cut and fill.

The presence of the fan suggests that there was a source of sediment to the north, that the sediment was transported by water, and deposited, probably subaqueously, on the floor of a lake as the discharged water lost its ability to transport the sand and gravel.

The geometry of the sand-and-gravel deposit is shown in the lithologic cross sections and the computer images. They work together to reinforce the "broom" model for the shape of the Buffalo aquifer. The overall length of the channel and fan is 32 miles (51 km). The channel portion is about 24 miles (38 km) long, and Figure 6 shows that the channel rises in elevation toward the south. The maximum thickness of sand and gravel recorded in the well available data was 243 feet (74 m). The channel width varies, but ranges between a fraction of a mile to about 2 miles (3 km). All but the highest parts of the channel are overlain by thin lacustrine and fluvial overbank sediment.

The fan measures about 8 miles (13 km) from north to south and about 7 miles (11 km) in width (east to west). It is a shallow, relatively thin, sand-and-gravel deposit that, like the channel portion, is veneered with lake and river overbank sediment.

The geomorphology of the Buffalo aquifer is unusual. It is oriented north-south, perpendicular to and astride the Comstock ice-marginal position (Figure 2). The channel portion of the feature extends north of the Comstock ice margin, and the fan extends south of that ice margin.

Stratigraphically the sand-and-gravel deposits of the Buffalo aquifer are interpreted as part of the Lower Red Lake Falls Formation (Figure 3). The sediment is thought to have been deposited beneath and in front of the snout of the glacier that deposited the Red Lake Falls Formation while it stood at the Comstock ice-marginal position. The Comstock ice margin does not mark the maximum extent of this advance, but rather it seems to mark a stable ice position that generally corresponds to the occurrence of Lower Red Lake Falls glacial sediment (Harris and others, 1995).

The Perley ice margin to the north is thought to mark a stable ice margin of the glacier that deposited the till of the Upper Red Lake Falls Formation which overlies the Lower Red Lake Falls Formation; so, the only sediment that would have been deposited on the topographically high sand and gravel of the Buffalo aquifer would have been lake sediment associated with the subsequent phases of Lake Agassiz (Clayton, 1983) and post-Lake Agassiz river sediment (Figure 3). The sediment cover on the Buffalo aquifer is quite thin along the axis of the feature and thickens laterally, toward the edges of the deposit.

The tunnel-valley channel appears to have been eroded by water discharging under the toe of the glacier. A high-pressure source of water would be required to incise a channel of this size and shape. Because it appears that several generations of cut and fill are present in the channel fill, the discharges were probably episodic and of limited volume.

The source of the water was either surface or basal meltwater. Presumably, the surface meltwater would have flowed to the base of the glacier through a system of fractures and tunnels in the ice. Surface fractures could exist only in brittle ice, near the surface of the glacier. We would not expect them to extend very far into the deeper, more plastic ice. Surface meltwater may be a source for discharge beneath thin, stagnant ice, but probably not for discharge beneath an active ice margin.

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

Because of the unique lithology, geometry, geomorphology, stratigraphy, and hydrology we suggest that the Buffalo Aquifer consists of sand and gravel deposited in a tunnel valley excavated under the snout of the glacier that deposited the Lower Red Lake Formation as it stood at the Comstock ice-marginal position. We further suggest that the shallow, broad sand and gravel deposit to the south is a tunnel-valley fan deposited in front of the glacier. It is likely that the "enlarged compaction ridge" and the Hillsboro aquifer also are buried tunnel valleys that developed at the Perley ice-marginal position, analogous to the Buffalo aquifer.

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Toils Induced by Weak Soils: Geo-Historic Perspectives on Northern Pacific Railway's Construction of the Stockwood Fill, Clay County, Minnesota

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Introduction

"The flatness of the surface that uniformly prevails throughout the valley may be regarded as a defect in its character that cannot be easily remedied."
(William H. Keating, geologist for the Long Expedition of the Red River Valley, 1823)

Underlying the flat surface of the Red River Valley of Minnesota and North Dakota are soils that induce some of the world's greatest agricultural productivity, as well some of its most challenging geotechnical conditions. The twin cities of Moorhead and Fargo rest on ≈ 32 m of smectitic clays and silty-clays, derived predominantly from late-glacial erosion and reworking of Pierre Shale (Cretaceous), and dispersed as suspended sediments into glacial Lake Agassiz. Beneath these cities, concrete caissons and steel pilings, emplaced generally to depths >32 m, support nearly all bridges, water towers, and high-rise structures. At the site of the Fargo water treatment plant (1989-91 data, Midwest Testing Laboratory), typical soil engineering values for the Sherack Fm (depth: ≈ 1 - 6 m) are: PL = 30, LL = 85, N = 12, and Qu = 3000. For the uppermost Brenna Fm (depth: ≈ 8 m), typical values are PL = 31, LL = 113, N = 6, and Qu = 1370. Where the lake sediments are unconfined, their high plasticity leads to slope instability; examples are prevalent along the valley walls and channel margins of the Red River and its tributaries. The high shrink-swell properties of these clays likewise cause foundation shifting, pavement failure, and utility line rupture.

Although Moorhead and Fargo, positioned near the axis of the basin, rest on some of the thickest accumulations of Lake Agassiz sediments, the stratigraphy underlying these cities is at least somewhat predictable. Approximately 6 m of the tan-buff, laminated silty-clays of the Sherack Fm are underlain by ≈ 26 m of the gray, slickensided, fat clays of the Brenna/Argusville Fms, a monotony broken only by the occasional dropstone (albeit sometimes "house-sized") or a sand-cored compaction ridge. Toward the margins of the basin, however, the stratigraphy becomes much more problematic. Here, slope-wash, beach, spit, bar, submarine fan, and deltaic deposits often complexly interfinger the clay-rich lacustrine sediments.

Our report focuses on one such region: N½ of Secs. 7, 8 and 9, T.139N., R.46W., Downer and Glyndon South 7.5' quadrangles, Clay County, Minnesota. During the time of Lake Agassiz, this region received both fine-grained lacustrine sediments and coarser-grained deltaic/fan sediments, delivered by the Buffalo River from glacial uplands to the east. Waters of the Buffalo River today flow across the east and north of the region, producing frequent and occasionally severe flooding and deposition of backwater sediments. Although the study region lies on the floor of the Lake Agassiz basin, the Campbell strand and its associated shore and near-shore deposits lie within 2 - 3 km to the east. The eastward rise in topography from the study region is relatively striking; southeastward from the Minnesota Highway 9 underpass (Fig. 1) at the Burlington-Northern (formerly Northern Pacific, or N.P.) tracks, the land rises up to 64 m (≈ 210 ft) over distances of ≈ 10 km (≈ 6 mi). Aquifers are numerous, generally local, often shallow, and frequently confined, with the regional slope inducing an artesian-pressure surface in many.

Thus, the sediments underlying the study region have a complex depositional history involving interactions among lacustrine, glacial, coastal, and fluvial processes. Except for the lighter-colored, sandier nature of the soils and subtle changes in the associated prairie vegetation, however, the flat land surface here appears deceptively like that elsewhere within the Red River Valley. Therefore, just after the turn of the 20th century, engineers designing a grade change for the N.P. line anticipated few problems in accomplishing their task.

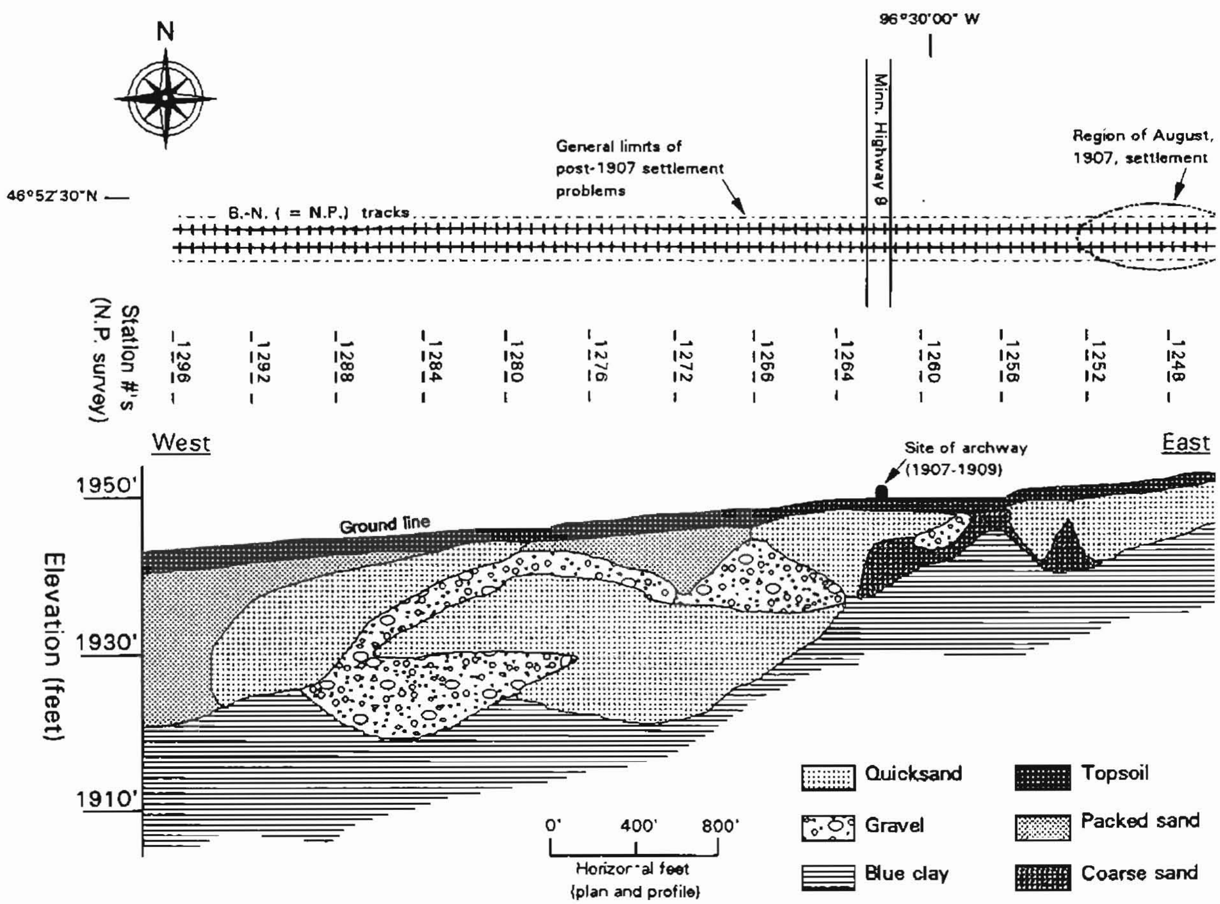

Figure 1. Plan view and geologic cross-section of Stockwood Fill in the region of the present-day Minnesota Highway 9 underpass. Cross-section is re-sketched from soundings profile of S.A. McCoy (November 1, 1909).

The Stockwood Fill

"The problem of raising from the Red River Valley eastward is . . . of particular importance as that will be the limiting grade on about 550 miles of main line."
(Letter from N.P. Chief Engineer E.J. Pearson to N.P. President H. Elliot, April 11, 1905)[1]

In 1870, the Northern Pacific began construction of a transcontinental rail line extending westward from Duluth, Minnesota. Tracks reached the Red River by 1872 and Puget Sound by 1883. Initial construction closely followed topography, resulting in many steep grades which slowed traffic and often forced uphill assistance by pusher engines. A grade reduction program for the eastern end of the line was initiated in 1897. By 1900, a dramatic increase in traffic made revision of all remaining steep grades imperative.

Among the problem grades was a 3.5 mile long, 0.75% eastbound grade rising from the Lake Agassiz plain up over the strands. This grade began just to the east of Stockwood, a tiny village that used to occupy the region about the Highway 9 underpass. At Stockwood, the N.P. maintained pusher engines to assist eastbound rail traffic. In February, 1906, the N.P. authorized its engineering department to reduce this and all regional grades to 0.3%. A decision was made to construct a huge earthen embankment (the "Stockwood Fill") rising eastward from Glyndon over a distance of 7.3 mi. Crews would raise and fill track on the ends of the embankment. In between, construction would involve building and filling a wooden, pile-supported trestle 4.75 mi long (Fig. 2), using ballast plows and side-opening dump cars. The trestle would require over 2 million board feet of lumber and would rise up to 50 ft in places. Wooden piles supporting the trestle would be driven to 15 ft in depth. The fill would primarily come from gravel and sands derived from railroad grade cuts in the glacial uplands to the east. Local road access through the fill would be via a 125 ft long, 16 ft high concrete archway (Fig. 3) resting on wooden piles driven to 30 ft deep. Railroad survey crews marked "stations" every 100 ft along the N.P. line, with the station numbers increasing from east to west (Fig. 1). The N.P. engineering division placed S.A. McCoy in charge, with an overall project budget of $2,133,000 and an expectation that the embankment would be completed within two years. In April, 1906, pile driving began.

A Failing Grade for the Northern Pacific

"For some thirteen hundred feet, it seemed to break through the prairie and sank a maximum of about thirty feet."
(Letter from N.P. President H. Elliott to S. Rea, V. President, Pennsylvania Railroad, November 30, 1907).

Except for persistent labor problems, construction of the Stockwood Fill progressed satisfactorily until about August 1, 1907. At that time, settlement of up to 2 ft was noted

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[1] Letters are from the archives of the Northern Pacific Railway Company, Minnesota Historical Society. We have maintained the use of English units of measurement when applying data recorded in historical documents. In our inclusion of direct quotations, we have maintained the grammar and spelling utilized in the original documents.

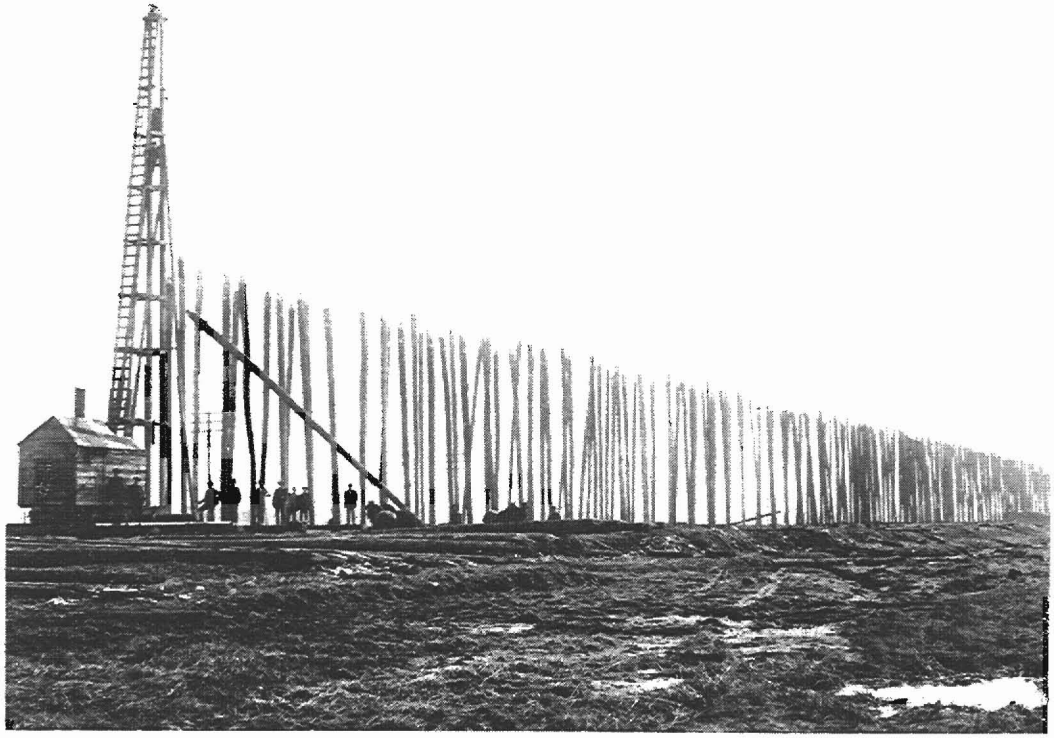

Figure 2. Driving piles for the Stockwood Fill, *ca.* spring, 1906. (S.P. Wange photo, Clay County Historical Society).

in the fill between stations #1244 and 1251 (Fig. 1, part), with the ground to either side of the embankment rising by about an equal amount. By August 4th, settlement had increased to 8 ft, and the adjacent ground had risen 7 ft. Over the next week, the embankment settled rapidly (Fig. 4). On August 13th, McCoy wrote, *"The bank was practically complete to grade on the 1st, and between August 1st and 8th we unloaded within the 600 feet . . . a total of 71680 cubic yards, endeavoring to keep our track to grade; since August 8th to date, we have unloaded in the same hole 43540 cubic yards, and the condition is growing worse daily. . . . The incline has become so steep that it is almost impossible to unload trains in the hole with the present equipment"* (letter to W.L. Darling, N.P. Chief Engineer).

On August 8th, McCoy initiated an investigation of substrate conditions extending westward from station #1240. These consisted of a series of *"test pits," "holes," "boarings"* and *"soundings"* (we have been unable to determine exactly how the soundings were accomplished, although it was apparently commonplace for railroads to test penetration resistance by using their pile driver to vertically drive piling or pieces of old rail). Sometime between August 13th and 20th, a "drilling machine" was finally delivered. Borings were taken to depths of up to 75 ft, and McCoy continued to report the progress of these investigations daily by telegram to St. Paul. By early November, several stratigraphic profiles of soil conditions had been completed from stations #1240 to 1328 (Fig. 1, part).

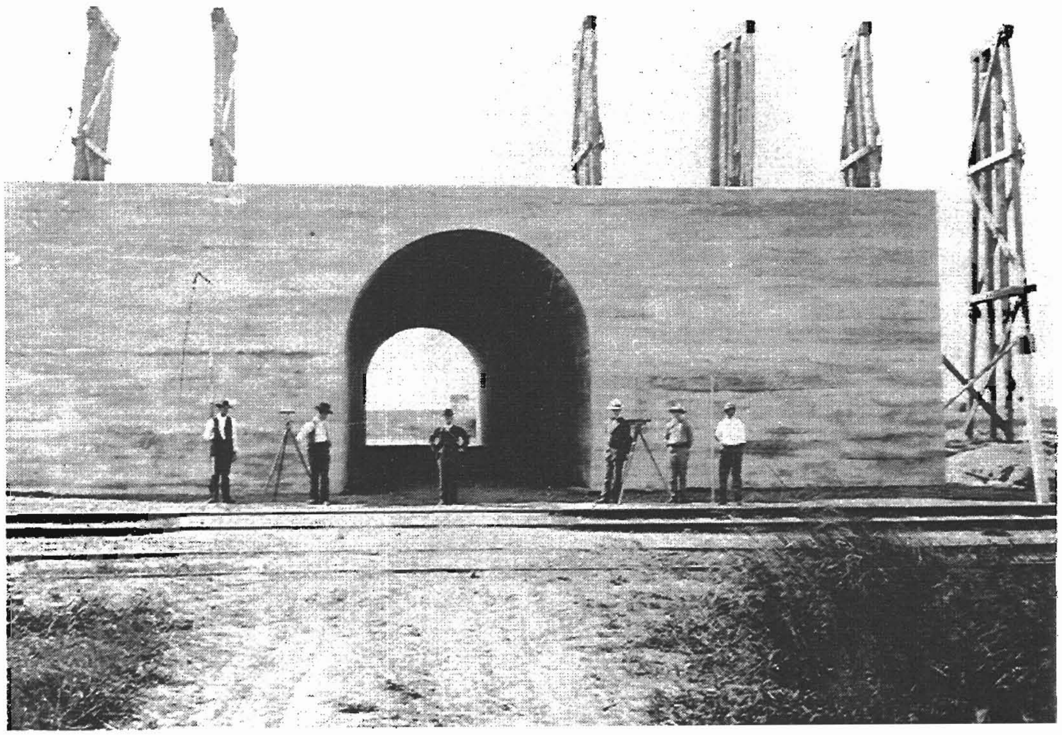

Figure 3. View facing to the south of the concrete archway near station #1262, Stockwood Fill, *ca.* fall, 1906. The gentleman at the center is probably S.A. McCoy. (S.P. Wange photo, Clay County Historical Society).

These profiles reveal a complex package of interfingered sands, gravels, and clays of variable thickness and extent, resting on *"blue clay"* (apparently Brenna Fm.). McCoy repeatedly dismissed any problems induced by the quick nature of the sands that were encountered: *"While the above soundings indicate that there is quicksand throughout the*

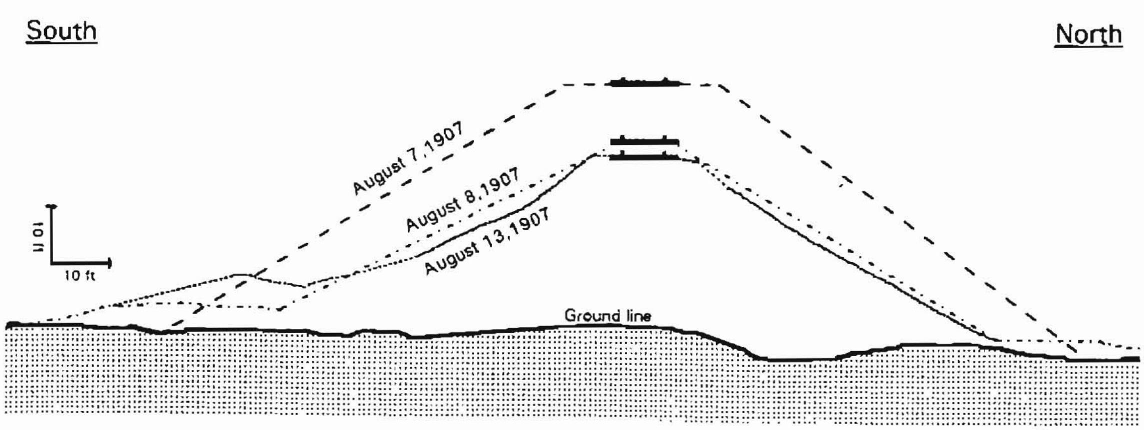

Figure 4. Profile changes at station #1245, Stockwood Fill, August 7 - 13, 1907. (Re-sketched from an N.P. profile, probably dating to August 13, 1907).

entire Stockwood country, I do not think that we need fear any serious results therefrom" (letter to W.L. Darling, August 24, 1907).

Soon, however, the tracks on either end of the sag became too steep for the work trains (Fig. 5). McCoy built and filled a second trestle over the problem region, but that also sank within days. McCoy ignored suggestions to simply build a strong trestle over the problem area and to then leave the sink alone until filling of the trestle to the west was completed. Instead, he doggedly continued to dump fill on the sink, only to watch it disappear.

Figure 5. Attempting to fill the Stockwood Fill sink, *ca.* fall, 1907. View is to the southwest. Note the concrete archway (≈ at station #1262) at the right and the settling embankment at the left, forcing the tracks and trestle downward. (S.P. Wange photo, Clay County Historical Society).

By December, the embankment was no more complete than it was in August. McCoy sought employment elsewhere, and the N.P. placed its construction superintendent, F.L. Birdsall, in charge. In the spring and summer of 1908, Birdsall had a 3000 ft long, permanent bridge constructed over the sink, extending westward over the archway (station #1262). Construction of this bridge allowed dump trains to access the west end of the embankment via Glyndon and to progress eastward from there in burying the trestle. Work progressed rapidly, but in May a second zone of settlement developed near station #1340 and in July a third zone of settlement between stations #1323 and 1331. Eight hundred feet of track sank 5 to 8 ft per day for a week. Birdsall extended the width of the fill outside of the slope of the trestle, hoping that a wider "mattress" would help support the embankment.

The strategy seemed to work, at least for a while. Birdsall reported no settling through early October, and it appeared that the N.P. might complete the embankment by November 1st. However, on October 10th, a fourth zone of settlement developed between stations #1272 and 1279. Cracks opened on either side of the embankment from stations #1272 to 1330, and Birdsall reported that *"indications are now that the entire fill for this distance will go down as we widen it out"* (letter to W.C. Smith, N.P. Chief Maintenance-of-Way Engineer, October 25, 1908). Then on October 31st, Birdsall wrote Smith: *"Had to stop work this P.M. on account of the permanent bridge opposite the Stockwood Depot settling so badly that we were not able to get over it."*

The Archway

"The arch has not shown any settlement lately . . . but it is just hanging on a balance."

(Letter from F.L. Birdsall to W.C. Smith, November 1, 1908)

Smith and other N.P. officials were horrified to read this latest news from Birdsall, for just to the southwest of Stockwood Depot (region of station #1261) was their $11,000

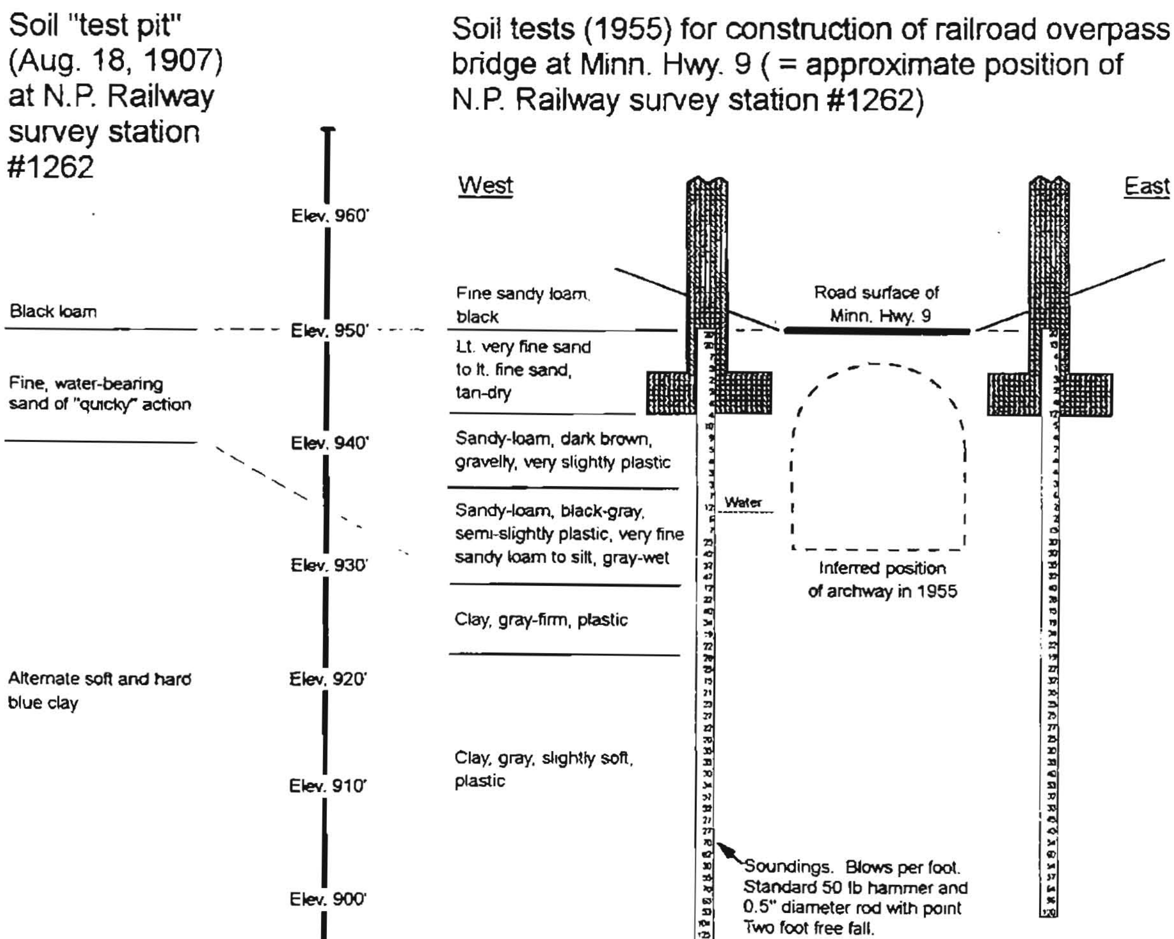

Figure 6. Comparison of soil test profiles in the region of Stockwood Fill station #1262 (data from S.A. McCoy, 1907, and Minnesota Dept. of Highways, 1955).

archway (≈ station #1262) (Figs. 1, 3). A "test pit" set at station #1262 on August 18, 1907, had shown 10 ft of quicksand overlying the 63 ft of blue clay (Fig. 6). Birdsall's superiors reluctantly agreed to let him fill in the permanent bridge, but they ordered him to keep the fill away from the archway until a wide "mattress" could be completed around the concrete structure. The photograph in Figure 7 dates from this time. The view is from the north facing toward the southwest, with the concrete archway barely visible

Figure 7. Filling trestle near concrete archway, *ca.* June, 1909. View is to the southwest. (A.F. Rusten photo, Clay County Historical Society).

below and to the right of a sharp hump in the railroad tracks. The hump itself coincides with the only remaining stretch of unburied trestle, and the elevation of its peak is the last artifact of the intended (design) grade. The embankment to the east and west of this point shows significant settlement to elevations many feet below design grade. The zone of broken ground in the foreground represents a compressional ridge forced upward by recent fill settlement.

As filling progressed toward the region of the archway, the ground cracked in advance of dumping. Despite the decision to withhold filling of the archway, the stresses of embankment settling nonetheless reached this structure. By 1908, small cracks had begun to develop in the concrete, and these increased in size during the spring of 1909. In July, 1909, as fill loading of the archway's trestle was nearly completed, the embankment at station #1262 underwent severe settlement. The archway, stressed at its center by the downward pressures of embankment settlement and at its openings by the upward pressures of rising compression ridges, sheared across its center (Fig. 8). The embankment settlement and flanking compressional ridge are visible in this photograph,

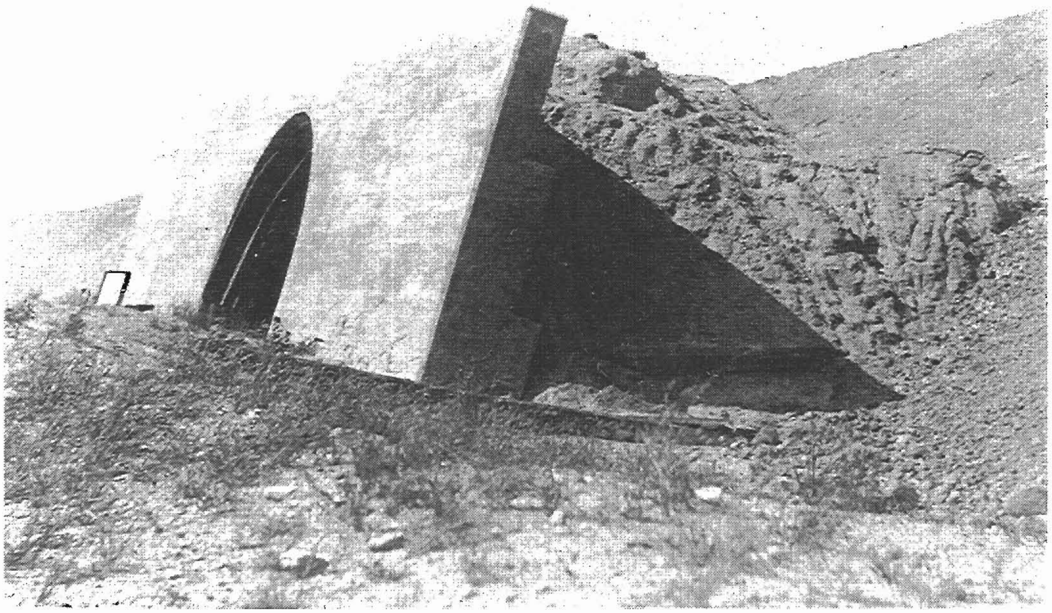

Figure 8. Collapsed archway, Stockwood Fill, *ca.* fall, 1909. View is to the northwest. (A.F. Rusten photo, Clay County Historical Society).

taken with the photographer facing northwestward toward the archway's south entrance. Measurements taken in September, 1909, showed the south end being forced upward 2 ft, the north end forced upward 3 ft, and the center section dropping 12 ft. The archway was abandoned as a project, and over the years it continued to sink until much or all of it disappeared. The inferred position of the arch in 1955 is shown in the architect's plans for the railroad bridge accommodating the present Highway 9 underpass (Fig. 6), later constructed across the former position of the structure. On the bridge design is noted, *"the exact location and extent of buried concrete arch undetermined"* (Minnesota Dept. Hwys. Project #1409-06, Bridge #5535, March, 1955). The foundation plans (Minnesota Dept. Hwys. Project #1409-06, Bridge #25-245.3, October, 1957) call for removal of the *"top portion of exist. conc. arch. to elev. 943.00 and fill with sand-gravel backfill . . . "*

The 1955 bridge design provides the only other soil engineering data that we could access for this region. These are minimal, consisting of soundings and a descriptive profile (Fig. 6) from the construction site. An attempt to correlate McCoy's profile (August 18, 1907) with the, presumably more-detailed, 1955 profile (Fig. 6) suggests that McCoy may have significantly underestimated the thickness of sand underlying the region of station #1262.

A Reluctant Acceptance of Equilibrium

"We ought to . . . perhaps give up the absolute completion of the grade until the question of settlement is over."
(Letter from N.P. President H. Elliot to N.P. General Superintendent G.T. Slade, July 17, 1909)

In September, 1909, with the project two years behind schedule and $700,000 over budget, the N.P. gave in and began using the embankment as it stood. However, for years afterwards, the N.P. tried to restore the intended grade of the Stockwood Fill. Thousands of yards of fill were added, only to have the embankment settle and the adjacent compressional ridges rise. The N.P. finally abandoned all of its efforts, and the sag in the grade became permanent. Pusher engines were still required to assist eastbound trains, until the arrival in the 1930's of the more powerful W-3 class locomotives. In all, it is estimated that 5,155,000 cubic yards of fill had been emplaced, of which only 4,067,000 remained above the original surface. The rest, presumably, sank. At least seven workers had lost their lives in this gigantic, but largely futile, construction effort.

In the absence of modern data, important clues still exist as to why soil loading by the embankment resulted in such dramatic and rapid settlement:

1. *Compression induced the lateral and then upward displacement of soil*. The evidence for this response is available in the historic and photographic records of compressional ridge formation, as well as in the presence of these ridges as landforms today. All such evidence shows that the tracks and fill settled vertically, while the compressional ridges rose symmetrically on each flank of the embankment. These observations contrast with those of other engineering failures tied to weak soils in the southern Lake Agassiz basin, where rotation induced by soil shear has generally been demonstrated (e.g., Nordlund and Deere, 1970). We have no data on the shear strengths of the soils underlying the Stockwood Fill, but they are undoubtedly low in the clays and essentially nil in the cohesionless sands. Alternatively, the ridges may represent displacement induced primarily by flow within fully hydrated, smectite-rich clays and/or in the saturated sands. However, soil displacement was apparently not the only mechanism, as the volume of up-squeezed sediment does not seem to have approached that which must have been displaced by settlement.

2. *Compression removed fluid pressure from confined bodies of cohesionless sands, causing permanent compaction*. Sands with quick properties were mapped throughout the site at the time of fill settlement, and the existence of artesian groundwater flow has since been well established. Although sediment compaction might seem to be the greatest factor behind the grade's settling, none of the often-detailed historic documents describing settlement present observations of water being forced to the surface. It seems probable therefore that any fluid displacement took place primarily through flow into interconnected aquifers.

The rails on top of the Stockwood Fill today support one of the busiest freight routes in the United States, and modern diesel engines hardly acknowledge existing problems with the grade. The Burlington-Northern Railroad, which maintains this line, reports no problems either with further fill settlement or with grade stability (David Douglas, B-N Engineering Division, pers. comm., 1996).

From the railroad overpass bridge at Highway 9, however, one can still view physical evidence of the engineering dilemma once faced by McCoy and Birdsall. Over a distance >1 km, the railroad grade sags markedly downward. Facing westward toward Glyndon, one can see the tracks rise, when they should drop. To the east, they rise prominently out of the sag, throwing up a sudden 0.7 % grade instead of the intended 0.2%. The remains of compressional ridges prominently flank both sides of the embankment in the sag area. Despite all of these features, the trees on the ridges stand tall and straight: evidence of decades of balance between the embankment and its underlying soils.

Acknowledgments

We are deeply grateful to the Minnesota Historical Society and to their staff for their assistance and for allowing us access to the North Pacific Railway Company records. We also thank David Douglas of the Burlington-Northern Railroad, Fargo, for helping to document foundation conditions for the grade.

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ARCHAEOLOGICAL EXCAVATIONS AT THE RUSTAD SITE

by

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Introduction

The Rustad Site (32RI775) is located in nw/ne, section 13, T136N, R51W, (USGS Barrie Quad, 7 1/2' series), Barrie Township, Richland County, ND. The site is in a soil quarry about 5 km. southwest of the city of Kindred (Roadlog, Fig. 26). The site was discovered in 1992 when the quarry wall profile was being examined for geological information. Despite damage to the cultural deposits, those portions of the site not removed by quarry work are in very good condition.

The site is on the south side of the Sheyenne River where the river exits the Lake Agassiz beach deposits and the Sheyenne delta onto the floor of the Lake Agassiz plain (Roadlog, figure 22). To the south and west of the site the landscape is slightly rolling and relatively high; to the north and east the landscape is flat and lower. The topography in the immediate vicinity of the site is dominated by floodplain features including the trench of the Sheyenne River, abandoned meander scars, point bar features and erosional cuts extending to the river valley from higher ground to the south. The site is at an elevation of about 300 meters above sea level.

Archaeology at the Rustad Site

Archaeological work at 32RI775 began in 1992 with a brief four day salvage effort. Subsequent to this, full scale (5 weeks/season) work was undertaken in 1993, 1994 and in 1995. Over 3600 person/hours of fieldwork have been devoted to the site, and several thousand person/hours of laboratory effort. Approximately 150 m^2 of site area have been excavated.

The site is an active quarry and the research design was geared toward simple recovery of material from the surviving cultural deposits on the periphery of the quarry. During initial excavations a thin (5-8 cm thick) soil horizon containing cultural material about 2 meters below the original land surface was taken out as a unit. As work proceeded from north to south, the culture-bearing horizon thickened and excavations were modified to allow removal in 5 cm levels. In 1994, at the south end of the site, the stratigraphy around the cultural layer was recognized as somewhat more complex, and soil lenses were removed as natural layers. Most of these lenses were less than 5 cm thick.

From indicators in the quarry wall, and from excavations around the perimeter of the quarry, 32RI775 is estimated to have covered over 3000 m^2. It is not clear, however, whether the density of cultural materials and features throughout the site was comparable to that found in the excavated remnants.

Geomorphology and Soils

The description and interpretation of the deposits were completed by Running (1995)(Roadlog, figures 24-25). Exposed at the base of the deposit are lacustrine sediments from Lake Agassiz. The upper portion of these sediments were weathered into a thick soil. Overlying this are alluvial fan deposits containing the archaeological materials. The fan was laid down as a series of mudflow events, and these are observable in a number of buried A-horizons in the profile. Above the fan deposits are eolian sediments representing downwind materials from the Sheyenne delta or sediment from exposed point bars on the Sheyenne River. The buried A-horizons represent periods of landscape stability, whereas the unweathered sediments represent depositional events from the uplands to the south of the site. The A-horizons in the profile are relatively well developed and probably formed under grassland conditions into mollic soil units. The mature appearance of the underlying lacustrine soil suggests a long period of development, possibly in excess of 1000 years after the recession of Lake Agassiz around 9000 years ago. This would place fan formation after 8000 years ago. The most recent portion of the soil profile has been lost to quarrying; however, the date for the uppermost existing buried soil is about 4900 BP.(all dates used here are uncorrected radiocarbon years). Above this are eolian deposits, indicating that the alluvial fan deposits containing the site were laid down between about 8000-5000 years ago. This is coincident with the Atlantic climatic episode.

Climatic conditions may be inferred from the erosional episodes responsible for the formation of the fan, by soil morphology, and by carbon isotope fractionation (unfortunately, pollen is not preserved in the sediments, and phytolith analysis is incomplete at this date). The evidence indicates increasingly arid and warm conditions over the course of time the fan formed. Bt-horizons are either well developed or weakly developed respectively, for the Ab3 and Ab2 horizons, whereas no Bt developed with Ab1. This may reflect increasingly arid conditions as the fan built up, assuming more moisture was required to form a Bt in the time available. Carbon-13 levels in samples from the soils become less negative from the lowest portion of the fan to the 4900 year old soil. This suggests either an increase in C4 vegetation, or C3 plants that discriminate less against Carbon-13. Either of these might be an indication of increased temperature.

The soils containing archaeological materials are in the middle to lower portion of the fan sediments and are dated to 7700-7200 BP. The site deposits have been disturbed by burrowing animals, root penetration, and frost action. Soil pH is neutral to high, providing good bone preservation, but poor conditions for retrieval of plant macrofossils and pollen. A simplified profile for the site from a few meters north of the excavations is given below.

Table 1
32RI775: Soil Profile

Horizon	Color	Texture	Genesis
A	10YR2/1	sandy loam	eolian
AB	10YR4/2	sandy loam	eolian
C	10YR5/3	loamy sand	eolian
Ab1	10YR3/1	sandy loam	alluvial fan
Bwb1	10YR4/2	sandy loam	alluvial fan
Cb1	10YR5.5/3	silt	alluvial fan
Ab2	10YR4/1	loam	alluvial fan
Ab3	10YR4.5/2	loam	alluvial fan
Bb3	10YR5/3	loam	alluvial fan
Ab4	10YR6/3	silty loam	lacustrine

Aside from the main occupation layer, there were two other possible occupational components at the Rustad site. About 70 meters west of the main excavations three test units were placed in minimally disturbed sediments. Here, the main cultural level was about 1m below the present surface, but with greatly diminished quantities of artifacts and bone. Much of the overlying sediment was eolian sand with several very weak soil units visible. In this area a Samantha projectile point was found in a shallow machine cut. Also in this area two cordmarked potsherds were recovered, the only pottery from the site. These were found in the eolian sediments above the fan deposits, and are clearly younger than the main occupation. The potsherds are not diagnostic, but pottery use in this region is not known before about 2200 BP. Samantha points are normally dated to roughly 1600 BP. This constitutes some evidence of ongoing use of the site in the late Holocene, although this use is not comparable in intensity to that from the middle Holocene.

In the main excavation area a buried soil below Ab3, and truncated above Ab4, was identified and proved to contain a small amount of cultural debris. This soil is dated to 8400 BP. Bison bone, flaking debris, burnt bone and at least one fish vertebra were found here. This occupation could be isolated and documented in only three units.

Chronology

Four dates are available for the archaeological living floor, and five dates for the soil horizons. The soil dates are on organic residues from the buried A-horizons. All dates from the living floor are on archaeological charcoal from features, or from charcoal concentrations on the living floor. It is important to note that horizons Ab2 and Ab3 converge in some portions of the site. Dates on organic residue from soils that contain cultural material, and dates from charcoal found on the occupation surface provide a range of dates from about 7100-7700 BP. The radiocarbon dates and the stratigraphy of the soils at the site raise minor interpretive difficulties. The soil layers extending through the quarry separate and merge across the site. Most artifacts and features are associated with Ab3, although smaller amounts of cultural material are found in adjacent soils, and in the unpedogenized sediment between the soils. Assay A-7551, Beta-70150 and Beta-85217 are consistent with each other and would seem to date the Ab3 and the artifacts contained therein very well. A-7552, Beta-58200, and Beta-70149 seem to be consistent as a group, and date the Ab2. The problem here is that the later dates on archaeological charcoal of 7180 and 7240 BP. are from the same occupation surface as the older dates of 7550, 7590 and 7675 BP. Beta-70149 and 70150 were on charcoal samples recovered from the same surface and only a few meters from each other. Sample 58200 is from charcoal that was partially exposed on the surface of the quarry and collected the first day of work at the site. While radiocarbon dating does not solve the problem of precisely when the site was occupied, it clearly establishes rough chronological parameters.

Table 2
32RI775: Radiocarbon Dates

Lab #	Uncorrected date	Material	Horizon
A-7550	4925±65	organic residue	Ab1
A-7552	7370±150	organic residue	Ab2
A-7551	7675±175	organic residue	Ab3
A-8484	8480±95	organic residue	above Ab4
A-7553	9045±90	organic residue	Ab4
Beta-58200	7240±150	charcoal	occupation
Beta-70149	7180±90	charcoal	occupation
Beta-70150	7550±80	charcoal	occupation
Beta-85217	7590±90	charcoal	occupation

Living Floor and Features

The occupation surface, or living floor at the site, consists of a rich layer of artifacts, ecofacts, and features associated with buried soils described as Ab2 and Ab3. Most cultural material was found in an area where these two soils merge. The upper 5-7 cm of the cultural deposit contains a large quantity of bone fragments and lithic debris. Below this are larger, more intact bones, but far fewer cultural items. The actual occupation surface is defined by features which are on a downward-sloping surface from south to north. All of the features seem to be in the middle portion of the merged Ab2/3 soils. In the main excavation all features were found 5-10 cm into the dark Ab2/3 soil horizon. Along the east wall of the quarry, about 50 meters north of datum, a clear separation of the Ab2 and Ab3 soils was found, and here most cultural material was in Ab3. Furthermore, one fire hearth (named feature 15), was resting in the upper portion of Ab3. For these reasons it is probably best to regard the main portion of the site as resting in Ab3. Less intensive use of the site may have occurred in Ab2. Thus, the primary zone of cultural material may represent more than one use of the site. This would also make sense of the two clusters of radiocarbon dates at around 7600 BP. and 7200 BP. The cultural material in the soil unit above Ab4, and in the late Holocene, reflect additional uses of the area by people, although these are only poorly understood at Rustad.

Thirteen features of various types were identified on the living floor, including bone concentrations, debris concentrations (bone, burnt bone, lithics, charcoal), and five hearths. One of the hearth features is associated with a circular pattern of debris around it in a "halo" fashion, with a cleared space between the debris scatter and the hearth. The debris was concentrated in a narrow band, suggesting it had been pushed against a barrier, or wall. This may be the remnant of a small structure. The features and debris scatter on the living floor are indicative of a temporary camp representing at least three domestic groups, presumably families.

Ecofacts

Over 50,000 bone and bone fragments were recovered at the site. Most identifiable remains are bison, although a small number of other animal remains have been identified as canids (dog or wolf), beaver, skunk, mustelids, turkey and fish. Gnawing marks on bison bone suggests the canids may have been domestic dogs. Rodent bones are also present, and although not used by people, were probably responsible for some dislocation of cultural debris.

Most of the bison elements are limb bones, with heavy representation of "rider" elements, brought to the site attached to larger meat bearing body parts. These include phalanges, sesamoids, carpal/tarsals and metapodials. Second in abundance to these are major limb bones, including scapula. These are followed in abundance by ribs, vertebra, and a limited number of skull parts. The minimum number of elements for specific bones is generally no more than 19 or 20. Minimum number of individual animals calculated for the bison bone collection is estimated at 8 or 9, including at least two juveniles. Applying Duffield's (1973) index to first front and rear phalanges results in a bimodal distribution of values, which indicates a mixed herd. Skulls are not available for measurement; however, values for the sizes of the tarsals, carpals and phalanges are larger than average for modern bison. This indicates these may belong to the taxon Bison occidentalis.

Long bones are broken, often into small pieces. Only about 670 bison bone are identifiable. The break patterns on the bones reflect the final stages of the butchering process. The lack of axial elements, the predominance of appendicular and "rider" elements along with the high quantity of small fragments supports the interpretation of this site as a base settlement processing camp (Enloe 1993).

Other ecofacts include a few seeds; only a very small number was associated with the living floor. These were identified as Chenopodium. Unionid clam remains were fragmentary and difficult to identify. Gastropods from living floor waterscreen samples were identified as belonging to three taxa, Heliodiscus parallelus (Say), comprising the greatest portion of the sample, Oxyloma or Succinea sp., and several specimens of an unknown gastropod. The identifiable gastropods are common in riparian woodlands.

Flaking Debris

The flaking debris sample includes over 5000 items. A variety of raw materials are represented in this collection, including Swan River chert, Knife River flint, a greenish rhyolite, a dull grey chert locally known as Red River chert, and other lithics including quartz, quartzite, and chalcedony. A very few pieces of jasper taconite were identified, and these were small (under 1 cm diameter). Swan River chert is the predominant lithic material, comprising about 77% of the assemblage. Knife River flint is rare at approximately 3%. The lithic collection is clearly one of local origin. About 93% of the debris is similar to material common in glacial deposits in and around the Red River and Sheyenne valleys. Jasper taconite and Knife River flint are exotic lithic materials obtained from the Lake Superior basin and the Missouri River area of North Dakota respectively. Archaeological sites from later periods contain far larger percentages of Knife River flint, normally between 12-25%. The Knife River flint sample at the Rustad site is less than 1/4 of the expected amount.

On the basis of flaking debris size grades and flake characteristics, the collection of lithics is interpreted to represent tool manufacture, finishing, and maintenance. Several core fragments were also recovered from the site, as well as three stone hammers. This indicates some primary reduction and biface fashioning.

Tools

Artifacts from the site include projectile points, scrapers, bifaces, hammerstones, and used and modified flakes. The artifact collection represents a variety of functional categories. The number of tools and worked pieces is 185. This total includes 42 points and small point fragments, 53 bifacial tools, 17 scrapers, and several other tools such as unifaces and hammerstones. Sixty-seven worked flakes were also recovered. There are 24 cores, including several bipolar cores. Bipolar flaking is often associated with a scarcity of flakable material. Over 80% of the formal tool collection is broken. The ratio of curated (formal) to expedient (flakes) flaked stone tools is 115/67 (63:37%). This ratio, along with the presence of hammerstones and cores, is indicative of tool manufacture at the site, which reinforces the conclusions reached in the study of the flaking debris. The formal:expedient tool ratio may also reflect a forager adaptation in which entire groups moved as units from one settlement to another, rather than establishing base camps out of which special hunting, gathering, and special task groups operated.

Most of the projectile points are classified as belonging to the Logan Creek/Mummy Cave complex (Archaeology and Historic Preservation Division 1990), although two larger notched points found on the surface are probably from late Archaic/early Woodland times. Several thin, bifacially flaked "point tips" were recovered, and at least three fragmented haft elements (notches). The total collection of classifiable points from the living floor includes 28 specimens. Twelve of these are thin triangular points, here classified as DeLong points (Ahler and Toom 1989:116). Another point is a triangular to lanceolate form with a diminutive flute on one side. It is reminiscent of a Dalton point. Fifteen points and broken points are notched on the side or corner and small in size. Stylistically they are similar to Prairie Side notched from a much later period. The collection is comparable to point samples from Itasca, Cherokee II, Logan Creek, Medicine Crow, and the Gowan sites. These small notched forms were common across the northern Plains during the Early Archaic. The presence of several point tips and notch segments (ears/tangs) might be a reflection of point rejuvenation (Towner and Warburton 1990).

Conclusions

The Rustad site is found on an alluvial fan formed between 8000-5000 BP. The main occupation of the site dates to between 7700-7200 BP, although limited human activity at the site is indicated for about 8400 BP, and during the late Holocene. Warmer and possibly drier than present climatic conditions are inferred at the site on the basis of fan development, soil morphology, and on 13C/12C ratios in soils.

The site was occupied during the Early Archaic at approximately the same time as the Itasca bison kill site, the middle component (II) at the Cherokee site, The site is approximately 1000 years earlier than the occupations at Gowen, Hawken, and Smilden-Rostberg. The style of the projectile points indicates affiliations to these sites, as well as Logan Creek and Medicine Crow. The points are primarily notched and unnotched triangular forms. These are remarkably small for Archaic period projectiles, and might be mistaken for, and have been compared to, Late Woodland Plains projectile points. Such diminutive points have been observed at other sites mentioned above, and are obviously common in the Early Archaic. One of the interesting aspects of these points is that their size would, in a later period, qualify them as arrow points, but few archaeologists are prepared to define the bow and arrow for this early period in prehistory. Most Plains archaeologists believe the bow and arrow was introduced onto the Plains in late prehistoric times, when small projectile points (2-3 cm length) become common.

The style and size of these points have geoarchaeological significance. Some archaeologists have argued that the lack of sites dating to the middle Holocene is due to an abandonment of the Plains during the Altithermal. Others have suggested that sites from this period are deeply buried in some areas, and that in those instances where sites have been found in shallow upland deposits, the diagnostic artifacts, or points, have been misidentified as belonging to later cultural periods (cf. Artz 1995). The point collection from the Rustad site would support the latter position.

Most of the raw material represented in the lithic sample from 32RI775 is available locally. Exotic lithics are rare, particularly Knife River flint. This pattern of local:exotic lithic material presence is unusual for sites in the Sheyenne Valley. Sites of later time periods contain 3-5 times as much Knife River flint. The Knife River quarries were used during the Paleo-Indian period, and Paleo-Indian artifacts from the Red River Valley are made from this material. The very low representation of this highly regarded resource during the Early Archaic may be related to arid conditions on the Plains during the Altithermal.

A warm season occupation is suggested by the presence of clam shells, small game animals and birds. This site itself is clearly not a kill, but a processing site. The lack of large quantities of fire cracked rock is counterindicative of bone grease boiling. The bison bone are probably Bison occidentalis. The size of the occupation is difficult to determine because quarry work has removed a large portion of the cultural deposit; however, remnants of the cultural horizon to the north and west indicate that this was a substantial settlement. On the remnant living floor that has been excavated and mapped were at least five well defined and hearth features, two of which were associated with substantial cultural debris scatters. Presumably, at least three centers of domestic activity are represented by these features, and perhaps more. This is in a small area representing less than 5% of the total site. Although an estimate of 20 times more activity areas for the entire site would be highly speculative, it is likely that if the $150m^2$ excavated area does represent the activity of at least three domestic units, the entire site must represent a considerably larger number of similar activity areas.

Acknowledgement:

Funding for work at the Rustad site was provided by Moorhead State University, and by National Science Foundation Grant # SBR-9408735. The ideas expressed are the author's, and do not necessarily reflect the views of the National Science Foundation, or Moorhead State University.

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THE SHEYENNE DELTA FROM THE CASS PHASE TO THE PRESENT: LANDSCAPE EVOLUTION AND PALEOENVIRONMENT

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Introduction

The Sheyenne Delta is located in Southeastern North Dakota and covers 2180 km^2 (840 $miles^2$) in eastern Ransom, western Richland, and southern Cass counties (Harris 1987, Brophy and Bluemle 1983) (Figure 22). The Sheyenne Delta is the southernmost of several underflow fans that formed during the terminal Late-Pleistocene along the western shore of Glacial Lake Agassiz (Brophy and Bluemle 1983, Fenton and others 1983). It formed early in Glacial Lake Agassiz history after part of the ice-marginal Milnor Channel was abandoned by the ancestral Sheyenne River in favor of a shorter, steeper route to the lake.

Landscape elements in the trench and on the delta surface have had a dynamic terminal late-Pleistocene and Holocene history. Landscape stability/instability on the northern Great Plains has important paleoenvironmental implications. Increased eolian activity, alluvial fan formation, and larger, wider and shallower, less sinuous but more actively migrating and erosive stream channels have all been linked to xeric environmental episodes where xeric equals: a decrease in annual precipitation, a greater variability in mean annual precipitation (and temperature?), an increase in potential evapotranspiration, a greater frequency of "droughty years", a higher frequency of high magnitude/ low frequency convective storms, and a greater component of westerly air flow (after Katz and Brown 1992). The purpose of this paper is to provide a brief description of the geomorphic units on the Sheyenne Delta, the chronostratigraphic relationships among them and briefly outline the paleoenvironmental implications related to their formation.

Geomorphology

The landscape of the Sheyenne Delta is divisible into three main landform classes. They are: fluvial, alluvial fans, and eolian. Little remains of Cass/ Lockhart Phase fluvial sediments in the Sheyenne River Trench. However, three large-scale entrenched meanders are located high up in the trench walls (Figure 30). They are about 425 to 450 m wide, and between 12 and 17 m deep. The channel cross-section preserved in the meanders is orders of magnitude larger than the modern Sheyenne River. Channel morphology is wide and shallow supporting the assumption that the ancestral Sheyenne River was swollen with glacial meltwater and was transporting mostly coarse glacially-derived bedload during the Cass and Lockhart Phases. The ancestral Sheyenne River appears to have had a discharge between 700 and 1400 cms during this time (see #13 in the Road Log for the Sheyenne Delta, Running this publication and Figure 31). Two short, steep, scarps, separated by narrow, flat benches are visible near the meander scars. The flat benches, terrace remnants associated with the entrenched meanders, indicate three short-lived floodplains. Sandy fluvial sediments deposited in these floodplains are exposed at the Pfingsten site (Table 3). Relatively coarse fluvial sand at the base of this deposit have high-angle cross-beds and some channel forsets are 1 to 2 meters high.

Remnants of a predominately fluvial terrace (the "Moorhead Terrace") deposited during the Moorhead low water Phase are widely preserved in the trench. (Figures 27 and 28). Fluvial sediments in the Moorhead Terrace are the lithostratigraphic equivalent of the Poplar River Formation found on the lake plain to the east (after Arndt 1977). Much of the trench was an estuary during the Emerson Phase (9,900 to 9,500 BP) (Brophy 1967, McAndrews 1967, Brophy and Bluemle 1983, Fenton and others 1983). Remnants of the Moorhead Terrace downstream from the Ransom/Richland County line (below about 301.7 m/990 ft in elevation) are draped by up to 2 m of lacustrine sediments (the lithostratigraphic equivalent of the Sherack Formation found on the lake plain to the east after Arndt 1977) (Table 3).

The lacustrine sediments that drape the Moorhead Terrace are lithologically distinct from other deposits in the trench. They commonly exhibit thin planar bedding (1 mm to 2 cm thick). A readily identifiable soil formed in the lacustrine sediments in the trench is a useful stratigraphic marker and separates eolian and alluvial fan sediments from underlying lacustrine and fluvial sediments. It is characterized by a well-developed, thick, dark, Mollisol-like A-horizon and a well-developed Bt-horizon. The Bt-horizon often qualifies as an argillic horizon, and clay skins on peds in the Bt-horizon often produce higher chromas on ped surfaces than in ped interiors (slickenslides are occasionally present). The presence of high chroma mottles suggests an aquic or ustic soil moisture regime. The lacustrine soil grades into a peat deposit in poorly-drained settings on the Moorhead Terrace. The peat contains identifiable wood fragments, other identifiable plant macrofossils and pollen, and is up to 80 cm thick (McAndrews 1967) (Table 4).

From channel bed to the top of cutbank exposures, modern floodplain sediments are usually about 4 to 6 m thick (Table 3). Two distinct sedimentary facies can be observed in cutbank exposures. The basal unit is composed of coarse-textured lateral accretion deposits. The upper unit is composed of finer-textured, vertical accretion overbank deposits. Thin, weak buried A-horizon(s) are locally present in this unit. Most exposures show a somewhat thicker buried A-horizon between 25 to 80 cm below the modern surface. This buried soil, referred to as the Iron Creek Paleosol (Hopkins and Arndt 1991) (Table 2) is widely observed in modern floodplain and appears to be the local equivalent of the pre-settlement soil widely identified throughout the midwest. Brophy (reported in Moran and others 1974) sampled organic-rich sediments and wood fragments exposed in the bases of channel scars visible in cutbanks along the modern Sheyenne River channel and

Table 3. Pedologic and sedimentary data from selected representative profiles on the Sheyenne Delta. More such data is presented in Running (1995b).

Soil horizon	depth (in cm)	parent material	% sand	% silt	% clay	USDA texture	% $CaCO_3$	% $MgCa(CO_3)_2$	% total carbonate	% organic matter	Munsell color dry;wet
Rustad Fan											
Profile 92-6											
C (truncated)	0-25	eolian	50	40	10	L	0.0	0.0	0.0	0.1	10YR4/3;3/3
IIAb1	25-40	alluvial fan	59	34	8	SL	0.0	0.0	0.0	0.8	10YR4/2;3/1
IIBtb1	40-63	alluvial fan	63	29	8	SL	0.6	0.2	0.8	0.3	10YR4/2;3/2
IIAb2	63-70	alluvial fan	63	28	8	SL	1.7	0.6	2.3	0.2	10YR5/3;3/2
IIBwb2	70-80	alluvial fan	62	29	9	SL	4.2	1.4	5.6	0.4	10YR5/2;4/2
IIAb3	80-105	alluvial fan	73	21	6	SL	4.7	0.9	5.6	0.3	10YR4/2;3/2
IIBwb3	105-124	alluvial fan	79	16	5	LS	2.1	1.7	3.8	0.1	10YR5/3;4/3
IIBtb3	124-130	alluvial fan	56	34	10	SL	7.5	2.1	9.6	0.2	10YR5/3;4/2
IICb3	130-140	alluvial fan	70	21	8	SL	2.9	1.6	4.5	0.2	10YR5/3;4/2
IIIAkb4 "Lacustrine Soil"	140-160	lacustrine	22	65	13	SiL	6.8	1.6	8.4	0.6	10YR4/2,3/1
IIIBtk1b4	160-210	lacustrine	4	69	27	SiCL	8.7	4.3	13.0	0.3	10YR5/2;5/2
IIIBtk2b4	210+	lacustrine	1	60	39	SiCL	9.0	4.3	13.3	0.3	10YR6/2;4/2
Delta surface											
Nesemeier Clay Pit											
spoil	0-38										
A1 (truncated)	38-54	eolian	79	14	7	LS	0.0	0.0	0.0	2.2	10YR3/1;2/1
A2	54-64	eolian	81	13	6	LS	0.2	0.0	0.2	0.9	10YR3/1;4/1
Ab1	64-74	eolian	84	8	8	LS	0.0	0.1	0.1	1.0	10YR2/1;3/1
Cb1	74-91	eolian	86	12	2	S	0.0	0.1	0.1	0.4	10YR3/1;4/2
Ab2	91-110	eolian	63	26	11	SL	0.2	0.1	0.3	0.9	10YR3/1,2/1
IIABtb3	110-150	deltaic	32	53	16	SiL	0.4	0.1	0.5	0.4	2.5Y4/2;5/4
IIBtkb3	150-200	deltaic	3	77	20	SiL	7.7	6.6	14.3	0.3	2.5Y7/2;6/2
IICkb3	200+	deltaic	1	76	23	SiL	6.0	5.8	11.8	0.2	2.5Y6/2;5/2
modern alluvium											
4-H Cutbank											
A upper	.	overbank	33	61	6	SiL	0.9	1.9	2.8	0.4	10YR4/1;3/1
fluv. sand	300	point bar	88	6	5	S	2.1	2.5	4.6	0.1	10YR5/2;3/2
fluv. sand/silt	310-320	point bar	57	31	12	SL	4.7	4.2	9.0	0.3	10YR5/3,3/2

Table 3. Continued.

Soil horizon	depth (in cm)	parent material	% sand	% silt	% clay	USDA texture	% $CaCO_3$	% $MgCa(CO_3)_2$	% total carbonate	% organic matter	Munsell color dry;wet
Deltaic settings											
Pfingsten Site											
sand	0-50	eolian	51.0	36.0	13.1	L	0.0	0.0	0.0	0.40	10YR4/3;3/2
Ab2	50-60	eolian	77.6	13.6	8.7	SL	0.0	0.0	0.0	0.30	10YR4/3;2/2
Bb3	60-90	eolain	78.3	9.0	12.7	SL	0.0	0.0	0.0	0.23	10YR5/3;3/3
Ab3	90-100	eolian	82.3	5.3	12.3	LS	0.0	0.0	0.0	0.79	10YR3/2;2/2
coarse sand	100-280 (125)	fluvial	96.4	2.1	1.5	S	0.1	0.2	0.3	0.00	10YR5/4;3/4
coarse sand	100-280 (175)	fluvial	93.0	2.4	4.6	S	0.0	0.0	0.0	0.21	10YR6/4;5/3
coarse sand	100-280 (225)	fluvial	95.2	2.5	2.2	S	0.0	0.0	0.0	0.00	10YR6/4;4/3
silt	280-?	deltaic	5.9	85.8	8.3	Si	6.8	9.0	15.8	0.24	10YR7/3;5/3
till matrix	1300+	diamicton	32.7	58.7	8.6	SiL	5.0	9.8	14.8	0.90	10YR7/1;4/1
parabolic dune											
Soo Dune A											
profile 3											
modern A-C	0-54	eolian	94.2	2.4	3.4	S	0	0	0	0.45	10YR4/2;3/2
Ab1	54-60	eolian	87.2	6.7	6.0	LS	0	0	0	0.51	10YR3/2;2/1
CBwb1	60-66	eolian	95.5	1.6	2.9	S	0	0	0	0.23	10YR4/2;3/2
Cb1	66-70	eolian	95.3	1.8	2.9	S	0	0	0	0.27	10YR4/3;3/2
Ab2	70-92	eolian	94.2	2.6	3.2	S	0	0	0	0.36	10YR4/2;2/2
Cb2	92-150	eolian	94.4	3.0	2.5	S	0	0	0	0.32	10YR4/3;3/2
Ab3-upper A	150-169	eolian	93.9	2.7	3.4	S	0	0	0	0.52	10YR4/2;3/2
Ab3-upper C	169-173	eolian	94.4	2.5	3.1	S	0	0	0	0.32	10YR4/2;3/2
Ab3-middle A	173-183	eolian	92.5	3.1	4.4	S	0	0	0	0.54	10YR4/2;2/2
Ab3-middle C	183-190	eolian	91.8	3.3	4.9	S	0	0	0	0.38	10YR4/2;3/2
Ab3-lower A	190-207	eolian	94.7	1.6	3.7	S	0	0	0	0.37	10YR4/2;2/2
Cb3 lower C	207-231	eolian	94.1	2.2	3.8	S	0	0	0	0.37	10YR5/3;3/2
Cgb3	231-271	eolian	94.0	3.2	2.9	S	0	0	0	0.27	10YR5/3;3/2

Table 4. Radiocarbon ages from the Rustad Fan site, Soo Dune A, and the Durler Dunes.

provenience	laboratory number *	material/fraction	radiocarbon age
Rustad Quarry Fan			
Ab1	A-7550	buried A/organic residue	4925 +/- 65 BP
hearth feature in Ab2	Beta 70149	archaeological charcoal	7180 +/- 90 BP
disseminated within the "Cultural Soil"	Beta 70150	archaeological charcoal	7550 +/- 80 BP
Ab2	A-7552	buried A/organic residue	7370 +/- 150 BP
Ab2**	A-7552.1	buried A/humates	6480 + 310/- 300 BP
hearth feature in Ab3	Beta-85217	archaeological charcoal	7590 +/- 90 BP
Ab3	A-7551	buried A/organic residue	7675 + 175/- 170 BP
Ab4 upslope ("Lacustrine Soil")	A-8484	buried A/organic residue	8480 +95/- 90 BP
Ab4 downslope ("Lacustrine Soil")	A-7553	buried A/organic residue	9045 +/- 90 BP
Mirror Pool peat ("Lacustrine Soil" equivalent) #	I-1982	wood	9130 +/- 150 BP
Soo Dune A			
Ab1	CAMS-18069β	buried A/ humate fraction	580 +/- 60 BP
Cumulic A lower (upper 5 cm)	CAMS-18067β	buried A/ humate fraction	890 +/- 50 BP
Durler Dunes			
Maddock Paleosol α	CAMS-18068β	buried A/ humate fraction	2,370 +/- 60 BP

** Beta = Beta Analytic, A = University of Arizona, I = Isotopes Inc. ** This radiocarbon age is too young. # This radiocarbon age was first reported In McAndrews (1967). α sample collected by Dave Hopkins. β AMS dates courtesy of Dan Muhs, USGS Denver; graphite targets prepared by Tom Stafford (University of Colorado at Boulder, Institute of Arctic and Alpine Research, Laboratory for Accelerator Radiocarbon Research) and submitted to the Lawrence Livermore National Laboratory, Center for Accelerator Mass Spectrometry.*

submitted them for radiocarbon analysis. It appears that the alluvium in the modern Sheyenne River floodplain is no older than about 3,620 BP.

There are also extensive eolian deposits in the Sheyenne River Trench. With the exception of the eolian sands that buried the Mirror Pool peat sometime shortly after 9,130 BP, most eolian deposits in the trench appear to be late-Holocene in age. For example, eolian deposits that bury the Rustad Quarry Fan contain diagnostic artifacts approximately 2,500 years old (Michlovic this publication). Eolian sands are found at other localities, notably the Pfingsten site where only weakly to moderately developed soils have formed on them.

The Rustad Quarry Fan is located in Richland County (NW 1/4, NE 1/4, Sec. 13, R51W, T136N, Barrie Quadrangle) about 5 km south of Kindred, North Dakota (for a more extensive discussion see Running 1995b) (Figures 24, 25, 26 and Tables 3, 4 and 5). Prior to quarrying activity the alluvial fan was approximately 90 meters long, 120 m wide, and up to 2 m thick at the proximal end. Since 1983 the western half of the fan has been removed leaving a 70 m long longitudinal profile available for study (Figure 25). Fan and underlying sediments were truncated on the east by a cutoff meander and a gully system that formed subsequent to the meander (Gustavson Draw) and to the north by a county road (Figure 26). Fan sediments grade into colluvium to the west and overlie the "lacustrine soil" and Sherack Formation sediments.

The Rustad Quarry alluvial fan is composed primarily of sediments deposited during three depositional events. A lack of fining upward sequences, cross-bedding, or clast support suggest these were mudflows (Bull 1977). A number of thinner mudflow deposits are also present, particularly toward the top of fan sediments (and in proximal settings). The Rustad Quarry Fan was buried by eolian sediments sometime after 4,925 BP, the radiocarbon age of Ab1 (Table 4). Fan formation began sometime after the development of the lacustrine soil. The strong degree of development exhibited by the lacustrine soil suggests it formed over about 1,500 years (Hopkins personal communication 1994, Mermut and Acton 1984, Turchenek and others 1974). Since pedogenesis of the lacustrine soil began at approximately 9,500 BP at the end of the Emerson Phase, the initial mudflow in the fan occurred about 8,000 BP.

A moderately well-developed, well-drained, Boroll-like soil (Ab1, Ab2, and Ab3) formed in each of the three relatively thick mudflow deposits (Table 3). The moderately well-developed buried soils have dark, thick A-horizons (6-27 cm) typical of soils formed under grassland vegetation (Buol and others 1989: 294-305, Birkeland 1984: 260-262). Their B-horizons all have some structural development (Bw-horizon) and the older two show at least some evidence for clay illuviation (Bt-horizon). They all show clear evidence of leaching and reprecipitation of pedogenic calcium carbonate. Radiocarbon ages on archeological charcoal and from bulk samples of A-horizons (organic residue fraction) from the Rustad Quarry Fan are in close agreement (Table 4).

Alluvial fans are also present below the wave-cut escarpment (see Harris 1987) on the north side of the trench (Figure 22). The upper 90 to 170 cm of three such fans have been examined by Michlovic and others (1988). From one to three weakly developed Boroll-like buried Inceptisols are present in the upper 90 cm. Their degree of development suggests that at least the upper parts of these fans are late-Holocene in age. They have been buried by recent mudflows like that described by Ashworth (1978).

Harris subdivides the eolian landforms on the Sheyenne Delta into high-relief dunes, low-relief dunes, and sandsheets (Figure 22). High-relief dunes are generally restricted to within 1.5 to 2.5 km from the Sheyenne River Trench. They are generally northwest to southeast oriented transverse ridges (see #7 in the Road Log for the Sheyenne Delta, Running this publication and Figure 29). They become markedly smaller and more closely spaced away from the trench and are mapped as low-relief dunes when they are no longer > 10 m high. On the north side of the trench in particular, they appear to be migrating in a southeasterly direction today (Figure 29). Elsewhere, numerous blowout scars on south-facing slopes are overprinted onto the transverse ridge morphology.

The age and origin of the high-relief dunes is not known. David (personal communication 1995) suggests they formed from sandy alluvium deposited during later stages in Sheyenne Delta formation and were later reworked by wind. This hypothesis is strongly supported by the presence of the Lockhart Phase terrace remnants discussed earlier. Sandy sediments in these terraces are likely sources for the sand in the dunes. David's hypothesis implies these dunes formed during the early to mid-Holocene independent of eolian activity in the trench, with more recent remobilization merely modifying preexisting forms. An alternate hypothesis was proposed by Running (1995a) suggesting a more complex mode of origin where eolian activity is closely tied to fluvial response to environmental change (see Muhs and Holliday 1995). There is circumstantial evidence to support Running's hypothesis for the origin of the transverse ridge dunes on the delta surface, 1) the presence of often thick, often late-Holocene age eolian deposits in the trench that become thinner and finer textured away (downwind) from the floodplain, 2) transverse ridge dunes are only found near the Sheyenne River on the margins of the trench, 3) the thickest and most extensive eolian deposits favor the south, downwind side of the trench, and 4) at least one transverse dune may be late-Holocene in age (see I-2092, Moran and others 1974). Despite the circumstantial evidence supporting the Running hypothesis, further data are required before either hypothesis can be accepted.

The low-relief dune mapping unit (Figure 22) includes at least three distinct dune types. Transverse ridges under 10 m high occupy a belt about 1 to 2 km wide downwind and adjacent to high-relief dunes on the south side of the trench. They are replaced by parabolic dunes farther from the trench. David (personal communication 1995) divides the parabolic dunes into two subtypes. Both are crescentic ridges. Their morphology indicates dune formation, in brief pulses, in the presence of sparse vegetation. Most have migrated very little from the deflation hollow they are associated with and are referred to as "blowout dunes". In many cases a deflation hollow/crescentic ridge complex is observed inset, *en echelon,* into another deflation hollow/crescentic ridge complex, indicating more than one episode of dune formation. A few larger and higher crescentic dunes which have migrated

Table 5. Stable carbon isotopes from organic carbon in buried soils. Isotopic analysis by Tom Boutton (Texas A & M University, Department of Rangeland Ecology and Management) using methods described in Nordt and others (1994).

sample	sediment type	$\delta^{13}C$ (OC)	% C^4	% C^3	carbonate $\delta^{13}C$	carbonate $\delta^{18}O$
Soo Dune A						
Ab1	eolian	-21.27	40.93	59.07	NA	NA
cumulic A upper	eolian	-19.27	55.21	44.79	NA	NA
cumulic A middle (upper 5 cm)	eolian	-19.76	51.71	48.29	NA	NA
cumulic A middle (lower 5 cm)	eolian	-20.04	49.71	50.29	NA	NA
cumulic A lower (upper 5 cm)	eolian	-20.15	48.93	51.07	NA	NA
cumulic A lower (lower 5 cm)	eolian	-20.06	49.57	50.43	NA	NA
Durler Dunes						
Maddock Paleosol	eolain	-22.14	34.71	65.29	NA	NA
Rustad Quarry Fan						
A upper (10 cm)	eolian	-18.33	61.93	38.07	NA	NA
A lower (10 cm)	eolian	-17.49	67.93	32.07	NA	NA
AB	eolian	-17.59	67.21	32.79	NA	NA
Bw	eolian	-18.08	63.71	36.29	NA	NA
Bwk	eolian	-18.68	59.43	40.57	NA	NA
Ab1	alluvial fan	-19.16	56.00	44.00	-4.91	-11.7
Bkb1	alluvial fan	-19.79	51.50	48.50	-3.83	-9.96
ABkb2 (local bed)	alluvial fan	-20.32	47.71	52.29	-4.45	-10.4
Bk1b2 (local bed)	alluvial fan	-20.82	44.14	55.86	-3.02	-9.62
Bk2b2 (local bed)	alluvial fan	-21.27	40.93	59.07	-3.51	-9.9
ABk1b2	alluvial fan	-21.37	40.21	59.79	NA	NA
ABk2b2	alluvial fan	-21.76	37.43	62.57	-3.04	-10.41
Bk1b2	alluvial fan	-22.31	33.50	66.50	NA	NA
Bk2b2	alluvial fan	-22.51	32.07	67.93	-3.34	-9.42
Ab3 (upper 10 cm)	alluvial fan	-23.02	28.43	71.57	-5.83	-11.26
Ab3 (lower 10 cm)	alluvial fan	-23.57	24.50	75.50	-6.47	-11.46
Btkb3 (upper 10 cm)	alluvial fan	-23.04	28.29	71.71	NA	NA
Btkb3 (lower 10 cm)	alluvial fan	-22.52	32.00	68.00	-5.51	-11.35
Ab4	lacustrine	-21.76	37.43	62.57	-5.64	-10.81

farther from their deflation hollow are also observed on the Delta surface. David (personal communication 1995) notes their similarity to the North Battleford dunes in central Saskatchewan (David 1977) and other dunes on the Assiniboine Delta in south-central Manitoba (David 1971).

The parabolic dunes on the Sheyenne Delta surface are centered on the southeast sides of elliptical to elongate deflation hollows. The deflation hollows range in size from a few to 500 m in diameter (long axis). Blowout depth is usually about a meter and appears to be controlled by the watertable. A typical blowout dune has a crescent-shape ridge about 50 m wide and 2 to 3 m high (Figure 32). The highest part(s) of the ridge is located to the southeast of the deflation hollow. The wings (or horns) of the dune point to the northwest. Numerous exposures in blowout dunes have been examined (Tables 3, 4 and 5 and Figure 32). All exposures have the following characteristics in common. First, several buried A-horizons are visible in these exposures (Figure 32). An "Ab1-like" buried soil and a "Cumulic A-like" soil are present in the same stratigraphic positions as seen in Soo Dune A. Second, blowout and fill sequences are present in southerly exposures on dune crests. These sequences vary in detail from dune ridge to dune ridge.

The "Durler Dunes" are about 1.5 km northwest of the Soo Dunes. They include the heavily eroded and reworked crests of a North-Battleford-like dune (the Durler Dune). Smaller blowout dunes have developed in and around the remnants of the Durler North-Battleford-like dune. A buried soil deep in these smaller blowout dunes, the Maddock Paleosol, is widely observed (Table 4). It has a thick, dark organic-rich A-horizon and appears to have formed in a low landscape position on the flanks of the Durler North Battleford-like dune. The low landscape position origin of the soil is also supported by the high C^3 vegetation signal preserved in organic carbon in the Maddock Paleosol (Table 5).

Sandsheets downwind from low-relief dunes on the delta surface are more extensive on the south side of the trench. These sandsheets are between .5 and 3 m thick. They are the thickest near the trench. Locally, small blowout dunes are present within them. Buried soils, similar in morphology and stratigraphic position to "Ab1" and the "Cumulic A" soils in blowout dunes are widely observed in these sandsheets. A well-developed, truncated soil of unknown age, the Delta soil, is frequently observed below sandsheets on the north side of the trench (Table 4, Nesemeier Clay Pit).

Paleoenvironmental Implications

The terrestrial record of paleoenvironmental change on the Sheyenne Delta indicates a number of xeric excursions during the Holocene (Table 6). The lacustrine soil formed from 9,500 to 8,000 BP and indicates landscape stability from the end of the Emerson Phase until 8,000 BP. Synchronous with development of the lacustrine soil, a peat deposit(s) formed on more poorly drained settings on the Moorhead Terrace. Pollen and macrofossils from the peat indicate grassland vegetation and possibly stands of pine (jackpine with open canopies) on nearby sandy upland settings during this period (McAndrews 1967). The morphology of the lacustrine soil also indicates grassland vegetation.

The formation of the Rustad Quarry fan, from 8,000 to 5,000 BP, is indicative of particularly severe xeric conditions. Formation of the fan goes beyond the mere indication of a xeric conditions; it clearly indicates conditions that beyond being "effectively drier" were indeed both relatively hotter and relatively drier. First, the change in morphological characteristics of buried soils formed in fan sediments, where Bt-horizon development is replaced with Bw-horizon development indicate effectively drier soil moisture regimes through time. Second, the stable carbon isotope record at the Rustad Quarry fan indicates an increase in C^4 plants through time, and some corresponding increase in growing season temperature (Table 5). Third, a lack of eolian landforms on the delta surface of corresponding age probably indicates fully active dunes during all or part(s) of the time the fan formed, a magnitude of eolian response that has not been achieved during late-Holocene xeric excursions. The modern Sheyenne River floodplain contains sediments that range in age from about 3,700 BP to the present. The lack of older *in situ* alluvium is circumstantial evidence in support of relatively severe xeric conditions during the mid-Holocene. Older fluvial sediments were probably reworked during the heightened period of erosion, a function of a strong fluvial response to these relatively severe xeric conditions from 8,000 to 5,000 BP.

Eolian sediments derived from and overlying fluvial sediments in the modern Sheyenne River floodplain suggest the occurrence of other xeric climatic episodes since 3,700 BP. Because fluvial sediments from these time periods is present in the valley, these episodes appear to have been less severe and/or less lengthy than the mid-Holocene xeric episode. A better record of late-Holocene eolian activity is preserved on the delta surface. There, the two types of parabolic dunes indicate formation during relatively brief (decade long ?) periods when vegetation on the delta surface was sparse and climatic conditions were more xeric than present. The late-Holocene eolian record on the Delta surface appears to indicate a minimum of three periods with increased dune mobility. The largest and apparently oldest North Battleford-like dunes indicate the most xeric of these episodes and appear to have formed prior to about 2,400 BP. They appear to have been eroded beginning about 2,400 BP during another pulse of eolian activity. The latest and smallest parabolic dunes formed between 890 and 580 BP. Except for an occasional active crest or in disturbed settings, all parabolic dunes on the delta surface are stable today.

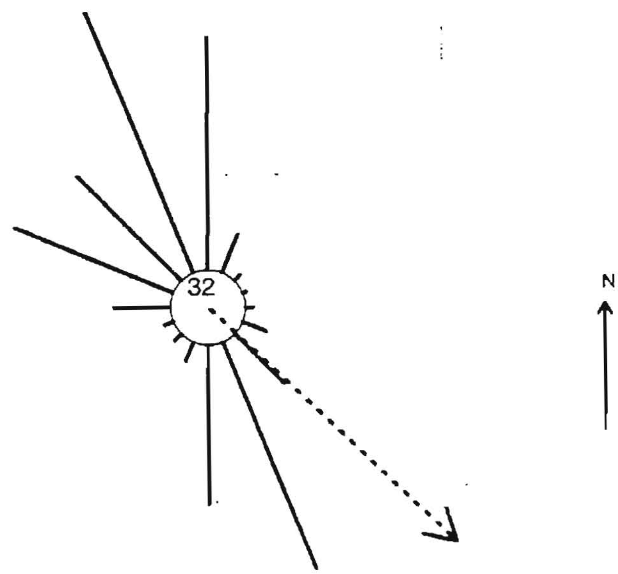
There appear to be two distinctly different degrees of "xeric" environmental conditions recorded in the geomorphic record on the Sheyenne Delta. The mid-Holocene, which was accompanied by alluvial fan formation, a strong fluvial response, and probably fully active dunes on the delta surface appears to have been the most severe. However, the mode of alluvial fan development indicates that this episode was not uniformly more xeric. Rather, it was a period characterized by more frequent extreme events and wider fluctuations in annual precipitation and potential evapotranspiration. Xeric environmental episodes of lesser magnitude appear to have characterized the late-Holocene. There is evidence for at least three periods of dune formation and xeric environmental episodes during the late-

Holocene. These episodes were not accompanied by alluvial fan formation, fully active dunes, or a strong fluvial response (there was alluvial fan formation during some part(s) of the late-Holocene below the wave-cut escarpment).

How xeric was xeric? The analysis of sand roses (methods after Fryberger 1979 using instrumental climate data from Fargo, North Dakota 1951-1980) (Figure 33) and dune mobility (Dune Mobility Index, M, after Lancaster 1988) (Table 6) clearly show that modern climatic parameters and wind regime are consistent with the morphology of parabolic dunes on the delta surface (wind regime = high energy, low variability, with an Obtuse Bimodal, NW and SSE vector distribution). Parabolic dunes on the delta surface are mostly stable now and modern mean annual precipitation (P), temperature (T) and W (% of annual winds above 6 m/sec.) values yield a mean M value of about 66. Dune crests must have been active during the brief periods of eolian activity (i. e., M values between 50 and 100) and such values can be generated by substituting modern T +1 standard deviation, and modern P -1 standard deviation into the Dune Mobility Index formula (Table 6). These values are well within the modern range of variation. This suggests that, as compared to the mid-Holocene, late-Holocene xeric episodes were characterized by climatic conditions that were either less severe and/ or the periods were relatively brief. Instead these episodes appear to have been similar in magnitude and duration to modern "droughty periods" like the 1930s, 1950s, 1970s and late 1980s. This reconstruction is in accord with new evidence from nearby lacustrine settings (Grimm 1995, Laird 1995).

Mid-Holocene xeric conditions are more difficult to explain using this technique. At that time, or some parts of that time period the parabolic dunes were probably characterized by fully active dunes (M values > 150). M values such as these can be generated by the substitution of greater values of average annual potential evapotranspiration (PE = 706.77 mm) coupled with very low P values (224.79 mm recorded in 1976). This PE value was derived by adding 1 standard deviation to mean monthly temperature values (t), then recalculating monthly evapotranspiration values (e). The monthly e values were then summed to derive PE. In this scenario T = 7.44°C a value 2.57°C higher than the modern T. This implies mean annual precipitation values considerably lower than present and may indicate mean annual temperature values considerably higher (Table 6).

The Dune Mobility Index is a measure of landscape stability/instability and the value of M fluctuates in accord with changing values of PE and not changes in T directly. Providing actual quantitative estimates of increases in T (and decreases in P) that correspond to the mid-Holocene xeric episode, which appears to have been more extreme than late-Holocene xeric episodes, is difficult using the geomorphic record because landscape stability/instability is a function of PE and P, not P and T (there is no statistical relationship between T and PE, $R^2 \approx -.03$). The estimated values for these climatic parameters given in Table 6 do provide some idea of P and T values corresponding to the geomorphic evidence for paleoenvironmental change on the Sheyenne Delta. However, further work is needed to develop transfer functions that can provide quantitative estimates of P and T from measures of



DP = 1370

RDP = 316

ANNUAL SUMMARY OF

SAND ROSE DIAGRAMS, DRIFT POTENTIALS, AND RESULTANT DRIFT DIRECTIONS FOR

Fargo 1953-1961

Figure 33. *DP (Drift Potential) derived by converting monthly summaries of hourly wind data into vector units. RDP (Resultant Drift Potential) indicates net sand movement after all wind vectors have been summed. The arrow points toward the Resultant Drift Direction, the net direction of sand movement. The number in the center of the sand rose indicates the dividend used to reduce the sand rose to an appropriate size. All sand roses for this study were derived from Fargo wind data and indicate a wind regime that is in: the high-energy class, the low variability class, and the Obtuse Bimodal vector distribution class (categories after Fryberger 1979).*

landscape response such as the Dune Mobility Index. Until such time, the estimates of P, PE and T in Table 6 should be considered preliminary and used with caution.

Acknowledgments

My work on the Sheyenne Delta was partially funded by Sigma Xi GIAR 9212 and 21174. Work at the Rustad Quarry archeological site was partially funded by NSF- SBR-9408735. Dan Muhs (USGS, Denver) funded the AMS radiocarbon analysis of the dune samples and provided the wind data. Tom Stafford (University of Colorado-Boulder, Institute for Arctic and Alpine Research) prepared the graphite targets for that analysis. Peter David (Universite' de Montreal, Geologie) generously offered his time and expertise and examined aerial photographs of the delta surface. His analysis of dune morphology and processes of formation shaped "order from chaos". Mike Michlovic (Moorhead State University, Anthropology and Sociology) and his crew have worked and continue to work at the Rustad Quarry site. I have benefited from his insights, logistical support and his generous philosophy as regards interdisciplinary research. Tom Boutton (Texas A&M, Rangeland Ecology and Management) provided the isotope analysis. Dave Hopkins (North Dakota State University, Soils) has provided hospitality and his vast experience with soils on the Sheyenne Delta. Thanks to my field assistants: Val Running, Dave Harkness (Nelson-MacIntyre Collegiate, Winnipeg), Ty Sabin (USGS, Madison), Bill Gartner (University of Wisconsin-Madison, Geography). Thanks to Vance T. Holliday (University of Wisconsin-Madison, Geography) for the use of the drill-rig, moral and financial support. Finally, thanks to all the landowners who allowed me access to their land (most notably, Don Rustad and Leon Pfingsten).

Table 6. A temporal framework for post-Glacial Lake Agassiz paleoenvironmental change based on the terrestrial record preserved in landforms and buried soils on the Sheyenne Delta, southeastern North Dakota.

Time	mean PE (mm/ yr)	from modern mean	mean P (mm/ yr)	from modern mean	mean T (°C)	from modern mean	Dune mobility (M)	Landforms
1951-1980: normal conditions	685.73	-----------	498.34	-----------	4.87	-----------	66	dune stability, soil formation, floodplain formation
"xeric conditions"*	694.3	+8.59	377.87	-120.47	5.69	+.84	88	parabolic dune formation
5,000 BP to Recent: normal conditions	685.73	-----------	498.34	-----------	4.87	-----------	66	dune stability, soil formation, floodplain formation
xeric episode 890-580 BP	694.3	+8.59	377.87	-120.47	5.69	+.84	88	blowout dune formation
xeric episode starting at 2,400 BP	694.3	> +8.59	< 377.87	-120.47 or more	5.69	> +.84	> 88	blowout dune formation
xeric episode ending by 2,400 BP	694.3	> +8.59	< 377.87	-120.47 o more	5.69	> +.84	> 88	blowout and North-Battleford-like dune formation, minor fluvial response
8,000 to 5,000 BP: normal conditions**	685.73	-----------	498.34	-----------	4.87	-----------	66	dune stability, soil formation, floodplain formation
8,000 to 5,000 BP: xeric conditions	> 706.77	> +21.04	< 224.79	-273.55	7.44	> +2.57	151.5	fully active dune field, transverse ridge, blowout, and North Battleford-like dune formation, major fluvial response, alluvial fan formation
9,500 to 5,000 BP	685.73	-----------	498.34	-----------	4.87	-----------	66	dune stability, soil formation, floodplain formation

** = T + 1 standard deviation (.84°C) and P - 1 standard deviation (120.47mm). ** = T when all mean monthly temperature values + 1 standard deviation are summed(7.44°C) and P = the actual 1976 value (224.79mm) (lowest value recorded between 1951 and 1980). Quantitative estimates of PE, P, and T for all xeric episodes = minimum increase in PE and minimum decrease in P needed to achieve an M value consistent with dune formation on the Delta surface (M: less than 50 = stability, 50-100 = active crests, 100-150 = active dunes except for plinths and interdunes, 150-200 = fully active dune fields). The dune mobility index, M, derived using the following formula from Lancaster 1988, M = W/(P/PE) where W = average amount of annual wind above 6m/second, the velocity necessary to entrain .3mm diameter sand grains (mean W = 48.1% from Fargo, North Dakota data), P = mean annual precipitation (modern mean from Fargo, North Dakota data = 498.34mm), T = mean annual temperature (modern mean from Fargo, North Dakota data = 4.87°C), and PE = mean annual potential evapotranspiration (derived using the modified Thornthwaite method, Thornthwaite and Mather 1957: modern mean from Fargo, North Dakota data = 685.73). Landscape stability is really a function of PE, not T. There is no statistical relationship between PE and T (R^2 is about -.2). Hence, estimates of T above are only estimates and should be treated as such.*

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Appendix A

APPENDIX A

DESCRIPTION OF SOME RED LAKE RIVER STRATIGRAPHIC UNITS

K. L. Harris, Minnesota Geological Survey, St. Paul, Minnesota

INTRODUCTION

The stratigraphic units we will see are described, from youngest to oldest, in the following pages. The information presented for each unit consists of the modified formal description of the unit (Harris, Moran, and Clayton, 1974) supplemented by recent work (Harris and others, 1995). All dates shown are interpreted by the author and based on Clayton and Moran (1982) unless otherwise indicated.

HUOT FORMATION (RRV01)

Source of name: The hamlet of Huot, Red Lake County, Minnesota, located on the Red Lake Falls 15-minute quadrangle.

Type section: Clearwater Section, NE/NW, sec. 22, T.151 N., R.44 W

Reference section: Snake Curve Section, NW/SW, sec 18, T. 151 N., R. 44 W.; Schist Cliff Section, SW/SE, sec.22, T 151 N., R. 45 W.

Description of unit: The Huot Formation is unbedded slightly pebbly clay. It is gray (5Y 5/1) when dry and very dark grayish brown (2.5Y 3/2) when wet. The formation is very hard and blocky when dry and very plastic when moist. The high clay content of the Huot Formation causes it to slump in outcrop, so most exposures are poor. Slickensides typically occur on shear faces in the Huot Formation.

The Huot Formation contains limestone pebbles and cobbles and numerous tan, chalky inclusions that range from about 2 mm up to 1 cm in diameter. A few pebbles of igneous rock are also present. Locally, boulder-size inclusions of a highly calcareous, pale-yellow glacial sediment are present.

The Huot Formation averages 7% sand, 22% silt, and 71% clay. The very coarse sand (1-2 mm) averages 44% igneous and metamorphic, 51% limestone and dolomite, and 5% shale rock fragments (Table 1; Figure 1).

Nature of contacts: The lower contact of the Huot Formation with the Wylie Formation is gradually interbedded to diffuse and locally is highly contorted. Boulder-size silt inclusions are associated with the areas of local disturbance.

The upper contact, where the Huot is overlain by the Poplar River or Sherack Formations, is sharp and erosional. The contact with the Brenna Formation has not been seen but is believed to be gradational.

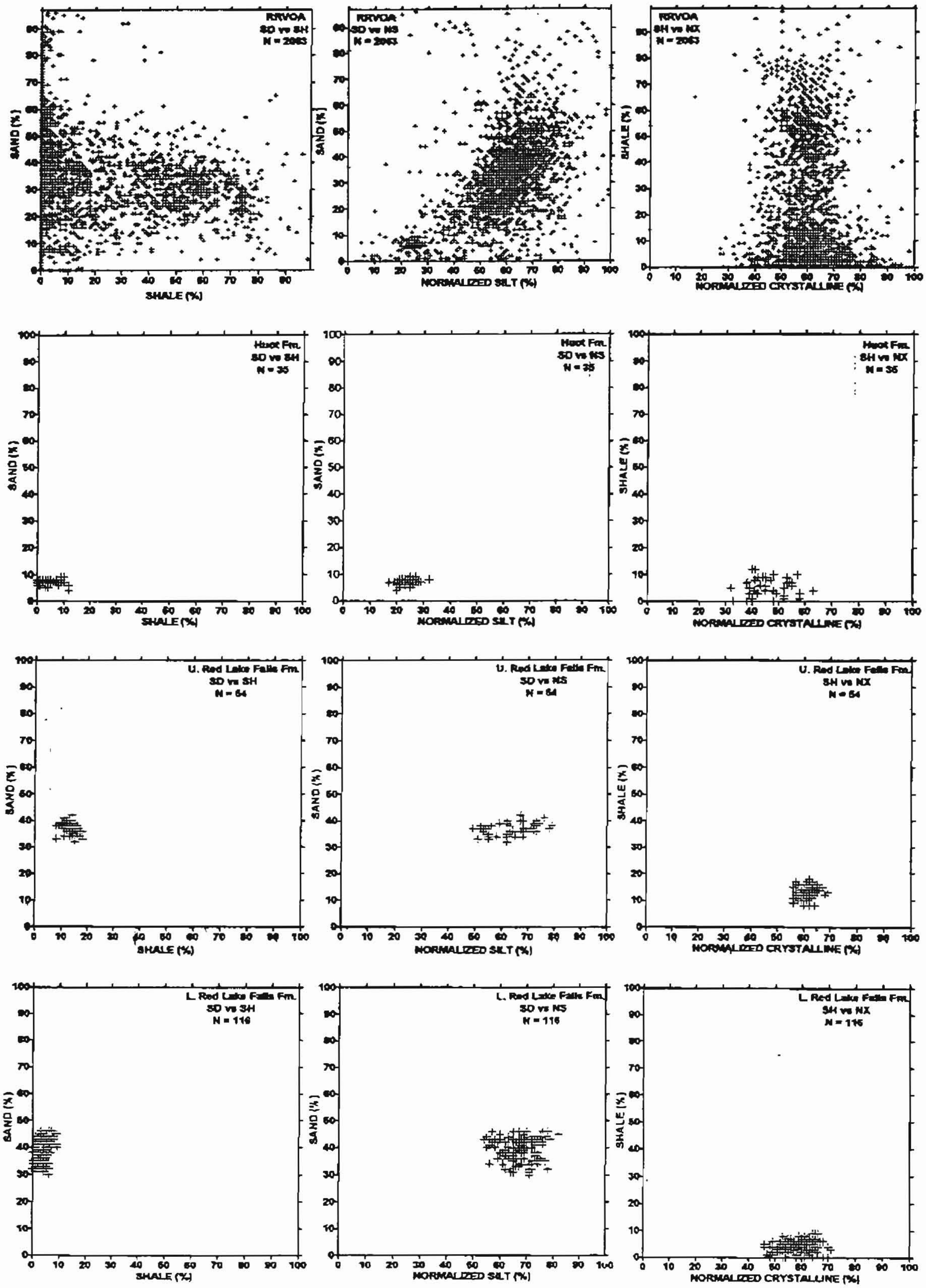

Figure 1 - Continued on the next page.

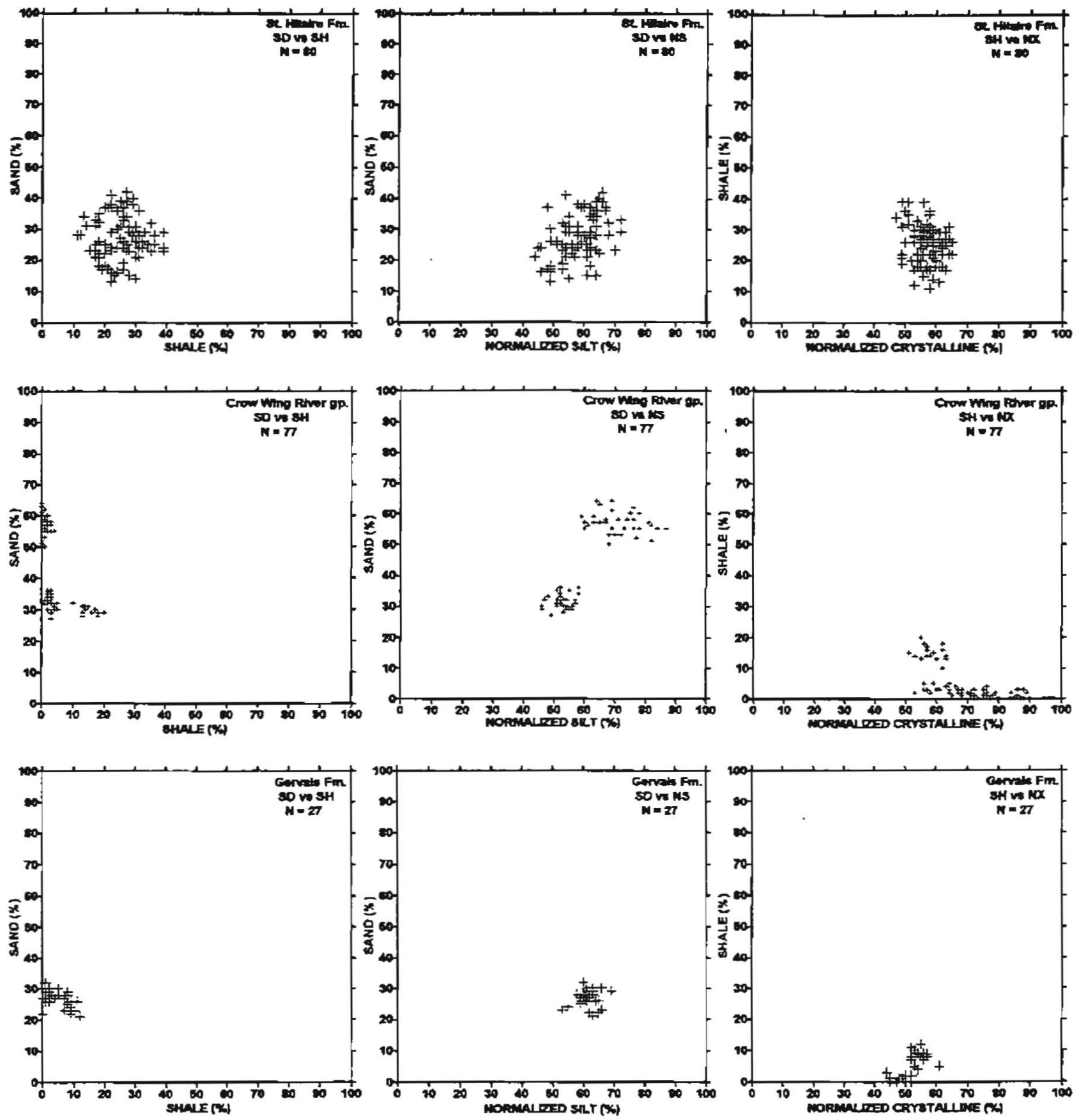

Figure 1 - Crossplots summarizing the sand-shale (left column), textural (middle column), and lithologic (right column) characteristics of the SRRV basic data (row 1; top); Huot Formation (RRV01) (row 2); U. Red Lake Falls Formation (row 3); and L. Red Lake Falls Formation (row 4); St. Hilaire Formation (row 5); Crow Wing River group (row 6); and Gervais Formation (row 7).

RRV	#		SD	SL	CY	XT	CO	SH	NS	NX
1	35	ave	7	22	71	44	51	5	24	46
		sd	1.08	3.05	3.39	7.17	7.28	3.36	3.39	7.42
2	10	ave	12	39	49	38	38	24	44	50
		sd	3.41	4.76	5.81	5.15	5.88	2.75	5.6	7.17
3	54	ave	37	40	23	54	33	13	64	61
		sd	2.17	4.63	5.22	2.72	2.91	2.56	7.79	2.96
4	116	ave	39	41	20	56	40	4	67	58
		sd	4.23	4.59	4	5.42	5.65	2.28	6.22	5.64
5	11	ave	47	35	18	44	23	33	66	66
		sd	2.97	3.73	2.76	2.15	2.55	3.6	5.04	2.5
6	32	ave	19	42	39	44	41	14	52	52
		sd	2.84	4.31	5.51	4.97	5.09	3.11	5.85	5.47
7	80	ave	27	42	31	43	32	25	58	57
		sd	7.17	5.01	6.47	5.23	3.77	6.39	6.44	4.27
8	174	ave	30	42	28	27	18	55	60	60
		sd	5.34	2.99	4.62	4.63	3.23	5.98	4.46	5.54
9	75	ave	36	39	25	35	23	42	61	60
		sd	3.62	2.18	3.88	3.56	4.15	4.5	4.44	5.5
10	32	ave	38	37	25	54	43	3	60	56
		sd	4.43	3.06	6.04	4	5.77	3.21	7.34	5.1
11	38	ave	44	39	17	66	33	1	70	67
		sd	5.25	5.73	3.01	4.66	4.35	1.15	5.74	4.42
12	26	ave	46	35	19	51	30	19	65	63
		sd	4.16	3.67	3.58	6.68	5.02	5.67	5.66	6.17
13	55	ave	30	43	27	16	11	73	61	59
		sd	3.8	3.88	4.4	3.49	1.61	3.64	5.34	6.66
14	27	ave	20	43	37	14	12	74	54	54
		sd	3.83	3.86	2.1	2.28	1.59	2.85	2.85	6.17
15	23	ave	32	35	33	61	36	3	51	63
		sd	2.2	1.98	2.77	5.18	4.82	1.14	3.21	4.95
16	11	ave	56	35	9	86	13	1	80	87
		sd	3.54	4.14	1.97	2.19	1.92	1.21	5.15	1.92
17	26	ave	57	29	14	74	25	1	67	75
		sd	3.13	3.31	2.65	3.35	3.15	1.21	5.88	3.23
18	17	ave	30	39	31	49	36	15	55	58
		sd	1.15	0.73	1.5	3.65	2.85	2.41	1.5	3.48
19	27	ave	27	45	28	50	45	5	62	53
		sd	2.73	2.78	2.76	2.92	5.06	3.75	3.34	3.97
20	12	ave	68	20	12	93	7	0	63	93
		sd	1.97	1.15	1.75	5.51	5.35	0.83	3.99	5.35

Table 1 - Number of samples, average values (bold), and standard deviation for correlation parameters used to define the twenty SRRV-RHA stratigraphic units.

Regional extent and thickness: The Huot Formation is present in the Red Lake River valley from Red Lake Falls to west of Crookston, where it is overlapped by the Sherack Formation (see Figure 5, Roadlog). It is at the surface in the area north and west of Red Lake Falls and in an arcuate belt a few miles wide across the Red River Valley (In pocket: Harris and others, 1995; Plate 2). Because the Huot Formation is the surface unit in exposures west of Red Lake Falls and generally is prone to slumping, its exposed thickness is variable. From 3 to 15 feet (0.9 to 4.6 m) of the formation are exposed in most outcrops. However, as much as 70 feet (21.4 m) of the Huot Formation is exposed in the Schist Cliff Section. As much as 100 feet (30.6 m) of the Huot Formation is present in the central part of the Red River Valley.

Differentiation from other units: The Huot Formation can be easily distinguished from other formations in the region by its texture, pebble content, unbedded, blocky structure, and color. The Brenna is the only formation resembling the Huot. They may be distinguished by stratigraphic position and the higher sand and pebble content of the Huot and the presence of obscure lamination in the Brenna.

Origin: The Huot Formation is glacial sediment deposited by ice moving southward down the Red River Valley.

Correlation: The Huot Formation is laterally and chronologically equivalent to the Falconer Formation in the central and western part of the Red River Valley.

Age: The Huot and Falconer Formations are thought to be have been deposited at about 11 KA.

WYLIE FORMATION

Source of name: The village of Wylie, Red Lake County, Minnesota, located on the Red Lake Falls 15 minute quadrangle.

Type section: Clearwater Section, NE/NW, sec. 22, T 151 N., R. 44 W.

Reference section: Old Dam Section, SE/NW, sec. 14, T.151 N., R. 44 W.

Description of unit: The Wylie Formation contains clay and silt that are generally thinly laminated. The clay is olive gray (5Y 5/2) when dry and dark gray (5Y 4/1) when wet. The silt is light brownish gray (2.5Y 6/2) when dry and olive brown (2.5Y 4/4) when wet. In outcrop, the formation is friable when dry and tough and plastic when moist. The silt laminae become thinner and the clay laminae become thicker upward. In most outcrops, the laminae range in thickness from a few millimeters to a centimeter.

Nature of contacts: The lower contact of the Wylie Formation with the Red Lake Falls Formation is gradual and interbedded. This contact is locally highly contorted.

The upper contact with the overlying Huot Formation is gradually interbedded or diffuse. Locally the contact is highly contorted, and boulder-sized masses of glacial sediment are present.

The upper contact of the Wylie Formation with the Falconer Formation has not been observed. It is believed to be similar in nature to the contact with the Huot Formation.

Regional extent and thickness: On the Red Lake River the Wylie Formation is exposed from the Needles Eye Section (SW/NE/SE, sec.22, T. 151 N., R. 43 W) downstream to the area of he Schist Cliff Section (SE/SE, sec 22, T.151 N., R.45 W.). It is exposed at the surface north of Red Lake Falls beyond the eastern limit of the Huot Formation. The Wylie Formation is discontinuously present beneath the Huot or Falconer Formations throughout the central part of the Red River Valley in Traill, Grand Forks, and southern Walsh Counties, North Dakota and in Norman and Polk Counties, Minnesota, (See Roadlog; Figure 2).

The Wylie Formation ranges in thickness from less than 2 feet (0.6 m) to more than 7 feet (2.1 m). Average thickness of exposures is about 5 feet (1.5 m).

Differentiation from other units: The Wylie Formation can be distinguished from all other named formations in the Red River Valley except the Sherack Formation by its distinct laminations. The Sherack Formation is separated stratigraphically from the Wylie Formation by the Brenna and Falconer or Huot Formations. Where these formations are present the distinction can be readily made.

Origin: The Wylie Formation is lacustrine sediment. Deposition occurred in an ice-marginal lake during the retreat of the ice sheet that deposited the U. Red Lake Falls Formation and the advance of the ice sheet that deposited the Huot Formation and Falconer Formation.

Age: The Wylie Formation is Late Wisconsinan in age. It was deposited during the Cass phase of Lake Agassiz (about 11.5 KA).

RED LAKE FALLS FORMATION
(U. Red Lake Falls Fm. (RRV03) and L. Red Lake Falls Fm. (RRV04))

Source of name: The city of Red Lake Falls, Red Lake County, Minnesota, located in the Red Lake Falls, Minnesota, 15-minute quadrangle.

Type section: Clearwater Section, NE/NW, sec 22,, T.151 N., R. 44 W.

Reference sections: Needles Eye Section, SW/NE/SE, sec.18, T. 151 N., R., 43 W. Damned

House Section. SW/NE/SE, sec.15, T. 151 N., R.44 W.

Description of the unit: The Red Lake Falls Formation is unbedded pebble-loam. It is brownish gray (2.5Y 6/2) when dry and olive brown (2.5Y 4/4) when wet. Vertical joints result in a strong columnar structure in dry, weathered outcrops and oxidation along the joints produces a reddish yellow (7.5 YR 6/6) stain. The Red Lake Falls Formation is hard and resistant to erosion in dry outcrops and is friable when moist.

Sand and Gravel inclusions are common; these include thin beds a few millimeters thick, channel fills, and contorted masses. Thin beds of laminated silt and clay as much as a few inches thick may be laterally persistent for tens of feet.

Two lithologies occur in the Red Lake Falls Formation. The differences are subtle enough that in most cases consistent field separation of the two units is difficult. The U. Red Lake Falls Formation is generally more conspicuously jointed than the lower, more massive unit. It averages 37% sand, 40% silt, and 23% clay and the coarse-sand fraction averages 54% igneous and metamorphic, 33%limestone and dolomite, and 13% shale rock types (Table 1; Figure 1). The L. Red Lake Falls Formation averages 39% sand, 41% silt, and 20% clay, and the coarse-sand fraction averages 56% igneous and metamorphic, 40%limestone and dolomite, and 4% shale rock types (Table 1; Figure 1). Pebbles, cobbles and boulders are abundant in both units and average about 2/3 limestone and dolomite; about 1/3 igneous and metamorphic rock types. The upper unit contains greater percentage of shale pebbles.

Nature of the contacts: The Red Lake Falls Formation overlies the St. Hilaire Formation along the Red Lake River north of the Powerline Section. The contact is sharp to diffusely graded. The Red Lake Falls Formation overlies the Crow Wing River group where the St. Hilaire Formation is absent in the Red Lake River trench, south and west of the Powerline Section. This contact is sharp, and sand and gravel is commonly present. The sand and gravel ranges from a few inches to 17 feet (5.2 m) thick. A boulder pavement is present at the contact in some outcrops. The upper contact of the Red Lake Falls Formation is a gradual interbedding with the overlying Wylie Formation. The Red Lake Falls Formation commonly becomes less sandy and more clayey near its upper contact. Where the Wylie Formation is absent, there is a diffuse contact with a contorted silty, pebbly clay containing the silt inclusions. This is probably a subaqueous mud flow deposit made up of material derived from the Red Lake Falls and Wylie Formations. At several locations the upper contact of the Red Lake Falls Formation is an erosional surface overlain by Holocene fluvial sediment. The contact between the U. Red Lake Falls and the L. Red Lake Falls is commonly marked by a cobble concentration similar to the solid, striated boulder pavement at the base of the formation.

Regional extent and thickness: The Red Lake Falls Formation is exposed along the Red Lake River trench from Thief River Falls to near Huot. The surface occurrence of the Red Lake Falls Formation is shown on SRRV-RHA Plate 2 (Harris and others, 1995). It is the surface unit on the eastern side of the Red River Valley from the Comstock, MN area north to Grand Forks, ND and is believed to extend westward, in the subsurface, into North Dakota. Insufficient data is available to reliably map surface units any further north than Grand Forks. However, it is thought to be present in surface exposures in northwestern Minnesota as far north as the Canadian border. to the Barnesville, MN area.

The Red Lake Falls Formation ranges in thickness from at least 70 feet (21.5 m) at Knife's Edge Section (NW/NW/SE, sec. 17, T. 152 N., R. 43 W.). The normal range of thickness is from 15 to 30 feet (4.6 to 9.2 m).

Differentiation from other units: The Red Lake Falls Formation can be distinguished from similar units on the basis of stratigraphic position, texture, coarse-sand lithology, pebble lithology, and color. It is sandier than either the silty Gervais or Falconer Formations or the clayey Huot Formation. It is lighter in color than both the Gervais and Huot Formations. Pebble lithology distinguishes the Red Lake Falls from the Crow Wing River group, and color distinguishes it from the St. Hilaire Formation which is much darker.

Origin: The Red Lake Falls Formation is composed predominantly of glacial sediment. In the Red Lake Falls area, minor amounts of lake and stream sediments are included in the formation. In the central part of the Red River Valley, in eastern Grand Forks County, as much as 20 feet (6.1 m) of laminated lacustrine clay lies between the two pebble-loam units of the formation in an area of several 10's of square miles. In some places, several 10's of feet of fluvial sand and gravel occur in the formation.

On the basis of pebble and coarse-sand lithology we believe that the lower pebble-loam unit of the Red Lake Falls Formation was deposited by a glacier that advanced from the north. On the same basis we believe we believe that the upper pebble-loam unit of the formation was deposited by a glacier that advanced from the northwest.

Correlation: Correlations of SRRV-RHA stratigraphic units with units other workers in northwestern Minnesota and eastern North Dakota are shown in "Computer-assisted Lithostratigraphy" (Table 3, this volume).

Age: The Red Lake Falls Formation is believed to be Wisconsinan (about 11.7 KA).

ST. HILAIRE FORMATION (RRV07)

Source of name: The village of St. Hilaire in Pennington County, Minnesota, located on the Thief River Falls 7.5 minute quadrangle.

Type Section: Powerline Section, SE/SE/NE, sec 5, T. 151 N., R. 43 W.

Reference sections: Opernockity Section, SE/NE/SE, sec.32, T. 152 N., R. 43 W. Small

Creek Section, SE/SW/SE, sec. 17, T. 152 B., R. 43 W.

Description of the Unit: The St. Hilaire Formation is unbedded pebble-loam. It is gray (5Y 5/1) when dry and very dark gray (10Y 3/2) when wet. Weak vertical joints are common and result in a moderately columnar structure. The pebble loam of the formation consists of 27% sand, 42% silt, and 31% clay, and the coarse-sand fraction averages 43% igneous and metamorphic, 32% limestone and dolomite, and 25% shale rock types (Table 1; Figure 1). Pebbles and cobbles are abundant and consist of about 40% igneous and metamorphic rock types, 40% limestone and dolomite, and about 20% shale pebbles. Lignite pebbles are commonly present in amounts as great as 5% of the total pebble fraction.

Nature of contacts: The St. Hilaire overlies the Crow Wing River group in the Red Lake Falls area. The contact between them is sharp, and typically there is a cobble concentration or boulder pavement present. In some places as much as 18 inches (0.46 m) of fine sand is present at the contact. The upper contact with the overlying Red Lake Falls Formation is sharp to gradational. Discontinuous and contorted sand beds are commonly present.

Regional extent of thickness: In the Red Lake River valley the St. Hilaire Formation is exposed only from Thief River Falls, south to the Powerline Section. In this area the unit is from 1 to 4 feet thick. Its characteristic dark color makes it a useful stratigraphic marker.

The St. Hilaire Formation thickens to the south. At the Twin Valley Section on the Wild Rice River near Heiberg, Minnesota, about 10 feet (3 m) of the formation is exposed. The St. .Hilaire Formation is though to extend throughout northeast North Dakota, southern Manitoba and northwestern Minnesota (SRRV-RHA Plate 2; Harris and others, 1995).

Differentiation from other units: The St. Hilaire Formation is easily distinguished from the Crow Wing River group and Red Lake Falls Formations by pebble lithology and color. The Crow Wing River group consists predominantly igneous and metamorphic pebbles and the Red Lake Falls Formation contains largely limestone and dolomite pebbles. Neither of these formations contains appreciable amount of lignite and both are lighter in color than the dark gray St. Hilaire. The Huot and Gervais Formations contain significantly less sand than the St. Hilaire Formation.

Origin: The St. Hilaire is glacial sediment. The occurrence of appreciable quantities of shale in the pebble fraction suggests a western or Northwestern source. The shale appears to be derived from the Pierre and Riding Mountain Formations in eastern North Dakota and southern Manitoba.

Correlation: Correlations of SRRV-RHA stratigraphic units with units other workers in northwestern Minnesota and eastern North Dakota are shown in "Computer-assisted Lithostratigraphy" (Table 3, this volume).

Age: The age of the St. Hilaire is unknown, but stratigraphic position suggests that it is Wisconsinan age (about 12 KA).

CROW WING RIVER GROUP (RRV15, RRV16, RRV17, RRV18)

Tills of the Crow Wing River group are thought to have been deposited by glacier ice advancing into the Red River Valley from the east and northeast. They make up a complex of similar tills that collectively constitute the Alexandria Moraine in the southern part of the study area. In the Red Lake Falls area they have been overridden and eroded by younger Rainy/Wadena Lobe and Red River Lobe advances. Consequently, their thickness in this area is highly variable. The stratigraphic occurrence of the Crow Wing River group exposed along the Red Lake River is predictable, but individual tills in the group occur unpredictably, often in repeated sections. This suggests that the tills of the buried Alexandria Moraine were extensively thrust and then truncated.

RRV15, RRV16, and RRV18

These informal units were define by the SRRV-RHA study (Harris and others, 1995). They are all unbedded, pebble loam to sandy pebble loam. Their color ranges from light gray (5Y 6/1) when dry to grayish brown (2.5Y 5/2) when wet. The results of textural and coarse sand analyses of these tills is given in Table 1.

Variable textures and coarse-sand lithology suggest changing source areas, but their occurrence seems to be associated. Consequently, they have been treated as a group for this summary. Limited sample data is available for the "older, deeper" tills, and future investigations will may change this association.

Marcoux Formation (RRV17)

Source of Name: Marcoux Formation (RRV17) is named for Marcoux Corners, Red Lake County, Minnesota, located on the Red Lake Falls 15-minute quadrangle.

Type area: Red Lake Falls area, Minnesota

Type Section: Clearwater Section, NE/NE, sec.22, T. 151 N., R. 44 W.

Reference section: Needles Eye Section, SW/NE/SE, sec. 18, T. 151 N., R.43 W. and Damned House Section, SW/NE/SE, sec. 15, T. 151 N., R. 44 W.

Description of unit: The Marcoux Formation is unbedded, very sandy pebble-loam. The formation is light gray (5Y 6/1) when dry and grayish brown (2.5Y 5/2) when wet. In weathered outcrops it is extremely hard and stands in nearly vertical slopes. It is weakly jointed. Pebbles, cobbles and boulders are abundant in this formation. Rapids along the Red Lake River are generally associated with outcrops of the Marcoux Formation. The pebble loam of the Marcoux Formation averages of 57% sand, 29% silt, and 14% clay, and the coarse-sand fraction averages 74% igneous and metamorphic, 25% limestone and dolomite, and 1% shale rock types (Table 1; Figure 1). The abundant pebbles consist of roughly 2/3 igneous and metamorphic rock types and 1/3 limestone and dolomite.

Nature of contacts: The lower contact of the formation has been seen only at the Three Creeks Section, where the Marcoux Formation overlies the Gervais Formation. Here the contact is sharp, and cobbles are concentrated at the contact.

North of the Powerline Section (SE/SE/NE, sec.5, T. 151 N., R. 43 W.), the Marcoux Formation is overlain by the St. Hilaire Formation (see Roadlog; Figure 4). The contact between these formation is sharp and generally marked by a boulder pavement. Where the boulder pavement is absent, a bed of sand as much as 18 inches (.5 m) thick is commonly present.

South and west of the Powerline Section, the Marcoux Formation is overlain by the Red Lake Falls Formation (see Roadlog; Figure 4). The contact between these formation is sharp and marked by a bed of sand of sand and gravel ranging in thickness from a few inches to 17 feet. (5.2 m). A boulder pavement is present in some outcrops but is not common.

Regional extent and thickness: The Marcoux Formation and other members of the Crow Wing River group are exposed in the Red Lake River trench for a distance of about 20 miles (32 km), from south of Thief River Falls to west of Red Lake Falls (see Roadlog; Figure 4).

It has been seen in outcrop from Florian, in Marshall County, Minnesota, to Ulen, in Clay County, Minnesota, a distance of about 100 miles (160 km). A sandy, Pebble-loam believed to be the Marcoux Formation occurs in the subsurface throughout the Red River Valley (SRRV-RHA Plate 2; Harris and others, 1995).

Exposed thicknesses of the Marcoux Formation range from 6 inches to 27 feet (0.15 to 8.25 m). Attempts to penetrate the Marcoux Formation with a truck-mounted power auger have been frustrated by the large number of boulders and extreme hardness of the formation. Borings in the Grand Forks area penetrated as much as 64 feet (19.57 m) of the Marcoux Formation.

Differentiation from other units: Only the Marcoux Formation and RRV16 contain as much sand and as little clay. Both also contain a preponderance of igneous and metamorphic rock fragments in the coarse-sand fraction, but the Marcoux should contain 25% limestone and dolomite pebbles compared to about 10% for RRV16. The abundance of stones, relative content of igneous-metamorphic and carbonate pebbles, hardness, and weak jointing are all characteristic of the Marcoux Formation .

Correlation: Correlations of SRRV-RHA stratigraphic units with units other workers in northwestern Minnesota and eastern North Dakota are shown in "Computer-assisted Lithostratigraphy" (Table 3, this volume).

Age: The age of the Marcoux Formation is unknown, but stratigraphic position suggests that it is Early Wisconsinan or pre-Wisconsinan in age.

GERVAIS FORMATION (RRV19)

Source of name: Gervais Township, Red Lake County, Minnesota

Type area: The Red Lake Falls are of Minnesota

Type Section: Three Creeks Section, NE/NE/NW, sec. 21, T. 151 N., R. 44 W.

Reference section: Moo Point Section, NE/NE/NW, sec. 19, T. 151 N., R. 44 W.

Description of unit: The Gervais Formation (RRV19) is unbedded silty, very slightly pebbly clay-loam. It is light olive gray (5Y 6/2) when dry and very dark gray (5Y 3/1) when moist. It outcrop, it tends to part or flake along joints that are oxidized to dark brown (7.5YR 3/2), giving the outcrop a brownish cast. Abundant wood chips, twigs and logs up to 6 inches (.15 m) across occur in the Gervais Formation (RRV19). Fragments of mollusk shells, insects, and carbon flakes, and green moss are also present. Abundance of all organic material decreased upward, and the abundance of pebbles increases upward. A few cobbles are present near the upper contact. Though not abundant, sand lenses a few millimeters thick are present with increasing abundance upward.

The Gervais Formation (RRV19) contains 27% sand, 45% silt, and 28% clay, and the coarse-sand fraction averages 50% igneous and metamorphic, 45% limestone and dolomite, and 5% shale rock types (Table 1; Figure 1).

Nature of contacts: At the Three Creeks Section, the contact of the Gervais Formation (RRV19) with the overlying Marcoux Formation is sharp, and cobbles are concentrated along the contact. At the Moo Point Section, the Marcoux Formation is absent and the Gervais Formation is in sharp to gradational contact with the Red Lake Falls Formation. Cobbles are concentrated at the contact here also. The lower contact of the formation has not been observed, and its nature is unknown.

Regional extent and thickness: The Gervais Formation is exposed at only two known outcrops in the Red Lake River valley (See Roadlog; Figure 4). It is at least 40 feet (12.25 m) thick at the Three Creeks Section.

Differentiation from other units: The Gervais Formation (RRV19) is overlain by the

Marcoux Formation at the Three Creeks Section and by the Red Lake Falls Formation at the Moo Point Section. It may be differentiated from both of these other formations on the basis of its finer texture, darker color, and the presence of organic debris.

Origin: The Gervais Formation probably consists of glacially modified fluvial or lacustrine sediment. The sediment of the formation becomes progressively more homogeneous upward. The silt and clay was probably derived locally.

Correlation: The Gervais Formation (RRV19) may be correlative with a silt and sand unit found in well borings in the Lake Bronson, Minnesota area. These borings ranged in depth from 90 to 140 feet (27.5 to 44.0 m) and produced abundant organic material. Radiocarbon dates on the organic debris recovered are: > 19,000 B.P. (C-496), > 36,000 B.P. (W-102), > 36,000 (W-498), and > 38.000 (W-1028). Correlations of SRRV-RHA stratigraphic units with units other workers in northwestern Minnesota and eastern North Dakota are shown in "Computer-assisted Lithostratigraphy" (Table 3, this volume).

Age: The Gervais Formation is Early Wisconsinan or pre-Wisconsinan in age. Radiocarbon dates obtained from logs near the base of the Three Creeks Section are > 39,900 B.P. (I-5317) and > 46,900 (BIRM-522).