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FIELD TRIP GUIDEBOOK FOR GEOMORPHOLOGY AND QUATERNARY STRATIGRAPHY OF WESTERN MINNESOTA AND EASTERN SOUTH DAKOTA

PREPARED FOR THE ANNUAL MEETING OF
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GEOMORPHOLOGY AND QUATERNARY STRATIGRAPHY OF WESTERN MINNESOTA AND EASTERN SOUTH DAKOTA

Leaders

C.L. Matsch, Merlin Tipton, F. Steece,
R.H. Rutford and W.E. Parham

Special Papers

QUATERNARY GEOLOGY OF NORTHEASTERN SOUTH DAKOTA AND SOUTHWESTERN MINNESOTA, Charles L. Matsch, Robert H. Rutford, and Merlin J. Tipton

ICE-STAGNATION DRIFT, COTEAU DES PRAIRIES, SOUTH DAKOTA, Fred V. Steece

POSTGLACIAL ENVIRONMENTAL HISTORY OF THE COTEAU DES PRAIRIES, H.E. Wright

A POSSIBLE PENEPLAIN OF EARLY LATE CRETACEOUS AGE IN MINNESOTA, Walter E. Parham

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QUATERNARY GEOLOGY OF NORTHEASTERN SOUTH DAKOTA AND SOUTHWESTERN MINNESOTA

Charles L. Matsch, Robert H. Rutford, and Merlin J. Tipton

INTRODUCTION

The land surface of eastern South Dakota and southwestern Minnesota is underlain mainly by sediments of Quaternary age, and most of the land forms themselves are the result of erosional and depositional events that were closely controlled by climatic fluctuations during the Pleistocene Epoch. As a result of climatic changes, glacier ice advanced and retreated across the region, leaving a complicated stratigraphy of glacier-derived sediments. So recently did the last glacier deteriorate that the present landscape still retains the forms impressed by that complicated process.

Even though geologists have been studying the Quaternary sediments of the region for almost 100 years, their interpretations are still controversial. Fundamental questions still incompletely answered are (1) how many drift sheets are present?; (2) where do the drifts fit into the mid-continent Quaternary time scale?; and (3) what is the surface distribution of each of the major drift units?

During the last two decades the availability of aerial photography and topographic maps has facilitated detailed surface mapping projects. Absolute age determinations have been helpful in establishing a chronology for events during the last 40,000 years. The recognition, definition and tracing of lithostratigraphic units, begun several years ago, have added new dimensions to Quaternary studies in the region.

PREVIOUS WORK

Warren Upham was the first to map the glacial deposits of western Minnesota and northeastern South Dakota. His initial reports (Upham, 1880, 1881, 1884) traced the deployment of ice lobes in Minnesota, the Dakotas, and Iowa, and outlined the history of development of Glacial Lake Agassiz. His monograph on Lake Agassiz (Upham, 1896) is a marvelous record of keen observation and astute deduction. Chamberlin (1883) incorporated much of Upham's work into his own grand summary of the last major glaciation of the United States. Chamberlin (1894) assigned the surface deposits of northwestern Iowa, eastern South Dakota, and southwestern Minnesota to three different ice sheets: Kansan, East Iowan (later called Iowan), and East Wisconsin (subsequently shortened to Wisconsin). Todd (1899) refined these glacial boundaries in southeastern South Dakota.

During the succeeding 20 years, the Iowa Geological Survey sponsored field work in northwestern Iowa that resulted in a variety of interpretations. At first Bain (1897, 1898) agreed that three drift sheets were present, but later he (Bain, 1899) rejected the existence of the Iowan. Based on work by Wilder (1900), and especially by MacBride (1900, 1901), the Iowa Geological Survey published a "Preliminary Outline Map of the Drift Sheets of Iowa" (Calvin, 1901) that designated a considerable area in northwestern Iowa as "Wisconsin" but lying outside of the "Wisconsin Moraine." Reflecting the work of Carman, a "Map of Iowa Showing Drift Sheets", published as Plate LXV of the Iowa Geological Survey's Annual Report for 1913 designates all of the drift outside the "Wisconsin Moraine" as Kansan. Four years later, Carman (1917) reproduced this map to reaffirm his belief that no drift sheet younger than Kansan existed outside the limits of the "Wisconsin Moraine". Rothrock (1926) extended this correlation into South Dakota with the designation of all the drift in the interlobate area between the James and Des Moines lobes as Kansan.

Frank Leverett held similar views regarding contiguous drifts in southwestern Minnesota. A map published by the Minnesota Geological Surbey (Leverett and Sardeson, 1919) shows two drifts in southwestern Minnesota: (1) Old Gray Drift, "a drift older than the Wisconsin", and (2) Moraines and till plains of Wisconsin age ("Young Gray Drift").

During the time of Carman's and Leverett's work in the west, many geologists were questioning the existence of an Iowan drift sheet in eastern Iowa, the type region for this drift. In 1917 Alden and Leighton published a report that reaffirmed the existence of a drift sheet younger than the Illinoian and older than the Wisconsin. The general acceptance of this report inspired Leverett (1922a, p. 101) to designate a strip of drift in southwestern Minnesota outside the Bemis moraine as "apparently somewhat older than the Wisconsin drift, and referred provisionally to the Iowan stage of glaciation". Carman (1931) revised his earlier interpretation of the distribution of drifts in northwestern Iowa to include recognition of an area of Iowan drift that he had previously called Kansan. Leverett's (1932, p. 29) final map of southwestern Minnesota delineated the distribution of three drifts: (Late) Wisconsin, Iowan, and Kansan.

By 1929, no one seriously doubted the existence of Iowan drift; however, geologists familiar with the area continued to debate its relationship to the other glacial stages. Leighton (1931) considered it to be the earliest substage of the Wisconsin, whereas Leverett (1939) favored its representing a late substage of the Illinoian. Leverett (1942) later conceded that the Iowan was an early Wisconsin drift. Kay and Graham (1953) concurred, and labeled the deposits of northwestern Iowa as Wisconsin (Iowan) and Wisconsin (Mankato). The vision of the Iowan as a separate glacial stage faded away.

The boundaries established by Carman (1931) in northwestern Iowa were redefined by Smith and Riecken (1947) on the basis of topography and loess texture and thickness. Their interpretation expanded the area of surface exposure of Iowan drift at the expense of the Kansan. Mainly

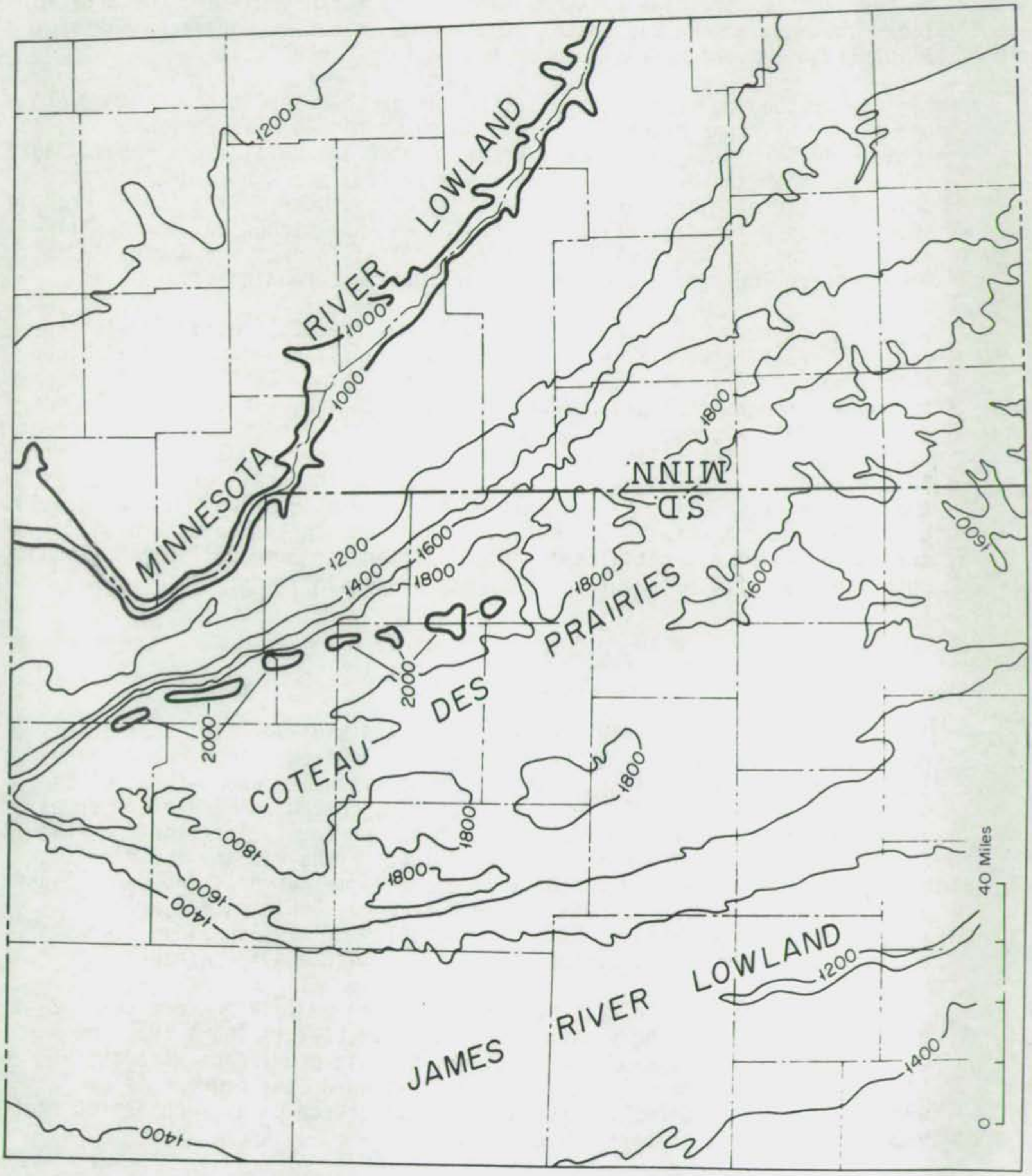

Figure 1. Generalized topographic map of the Coteau des Prairies and flanking lowlands, northeastern South Dakota and southwestern Minnesota.

on the basis of drainage patterns Ruhe (1950) further divided the area into four substages of the Wisconsin: the Iowan, Tazewell, Cary, and Mankato. Flint (1955) extended this interpretation into South Dakota.

In succeeding years, the existence of an Iowan drift again came into question. After an extensive study, Ruhe and his colleagues (Ruhe, Rubin, and Scholtes, 1957; Ruhe, Dietz, Fenton and Hall, 1968; Ruhe, 1969) concluded that the drift mapped as Iowan in Iowa was Kansan drift from which the Yarmouth and Sangamon Soils had been eroded. Ruhe (1969) dropped the Iowan as a substage of the Wisconsin, and now recognizes three till sheets -- Kansan, and two Wisconsin-age drifts, Tazewell, and Cary -- in northwestern Iowa and, by extension, in southwestern Minnesota.

In eastern South Dakota, Tipton and Steece (1965) could find no topographic break between Flint's and Ruhe's Tazewell and Iowan and combined them into an "Early Wisconsin" mapping unit. Mainly by the use of air photos a topographic break was delineated in their Iowan drift in the vicinity of Dell Rapids, South Dakota. The drift to the south of this break was assigned to the Illinoian (Tipton, 1959; Steece, 1959) and the drift to the north "Early Wisconsin". Also mainly on the basis of topography, the moraine marking the "east limit of the Dakota ice lobe" was correlated with the Altamont moraine of the Des Moines lobe instead of the Bemis moraine as Flint has postulated. Also, Tipton and Steece (1965) assigned both the Bemis and Altamont to the "Late Wisconsin".

REGIONAL GEOMORPHOLOGY

The landscape of eastern South Dakota and southwestern Minnesota is dominated by the Coteau des Prairies, a broad regional topographic highland shaped like a flatiron, with the point extending about three miles into North Dakota (fig. 1). On the south the Coteau des Prairies merges into the general upland surface of northwestern Iowa. The highland reaches altitudes of over 2,100 feet. It is drained on the east by the Minnesota and Des Moines Rivers and on the west by the James River. The Vermillion and Big Sioux Rivers originate on the Coteau des Prairies and drain southward into the Missouri River. The valley of the Big Sioux River is a prominent cleft in the central part of the Coteau des Prairies.

A comparison of the altitude of the buried bedrock surface (fig. 2) with the altitude of the present land surface (fig. 1) shows that the Coteau des Prairies owes much of its topographic prominence to a thick blanket of glacial drift. The highest altitude of the bedrock is generally about 1400 feet. Thus, a drift thickness of as much as 700 feet underlies the highest part (2100 feet).

To the west of the Coteau des Prairies, the James River valley follows the south-trending axis of a topographic low that is over 200 miles long and 100 miles wide. This trough has a thin drift cover (50-100 feet). It reflects a similar configuration of the underlying bedrock. The

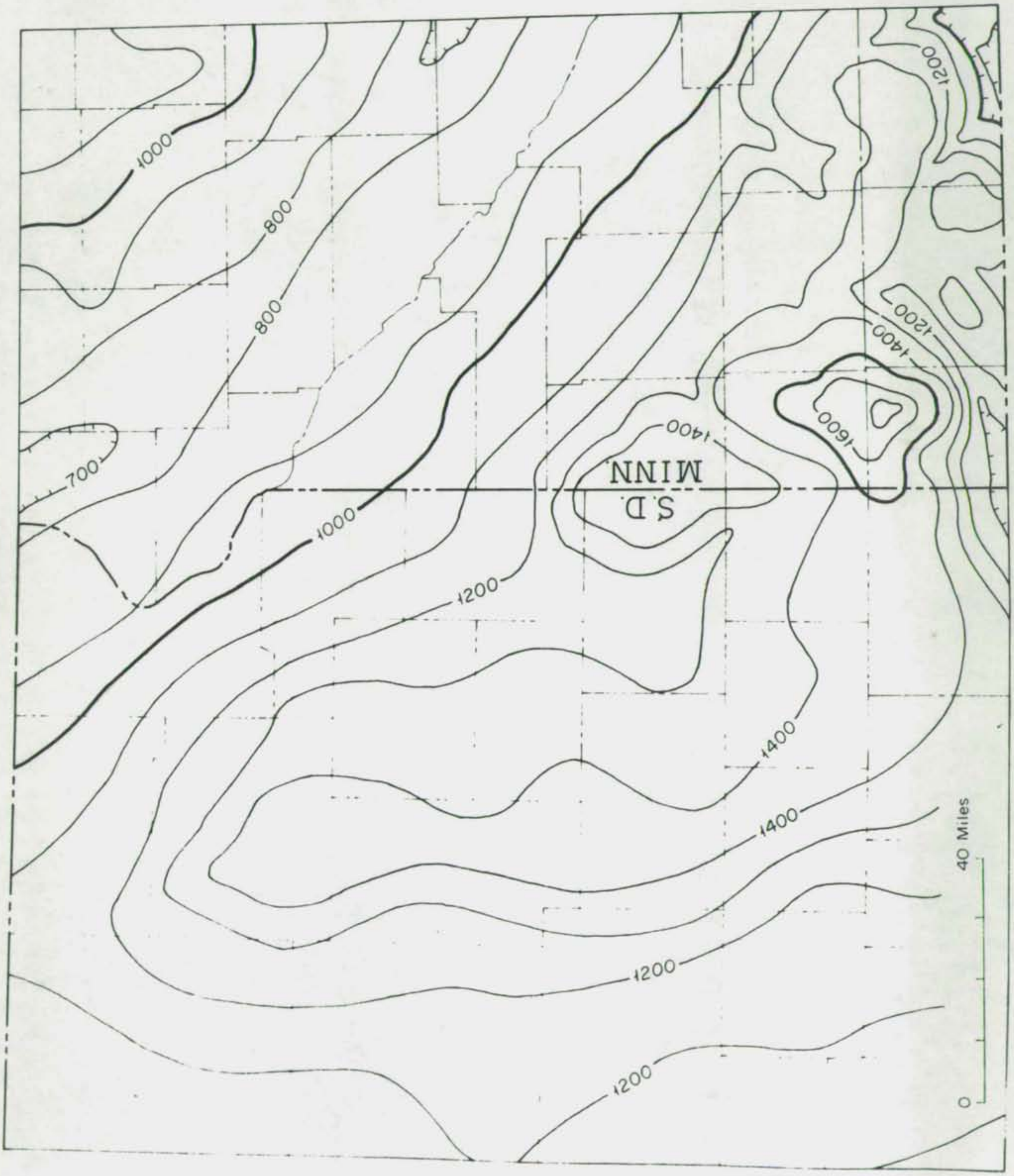

Figure 2. Generalized configuration of the top of the bedrock of northeastern South Dakota and southwestern Minnesota.

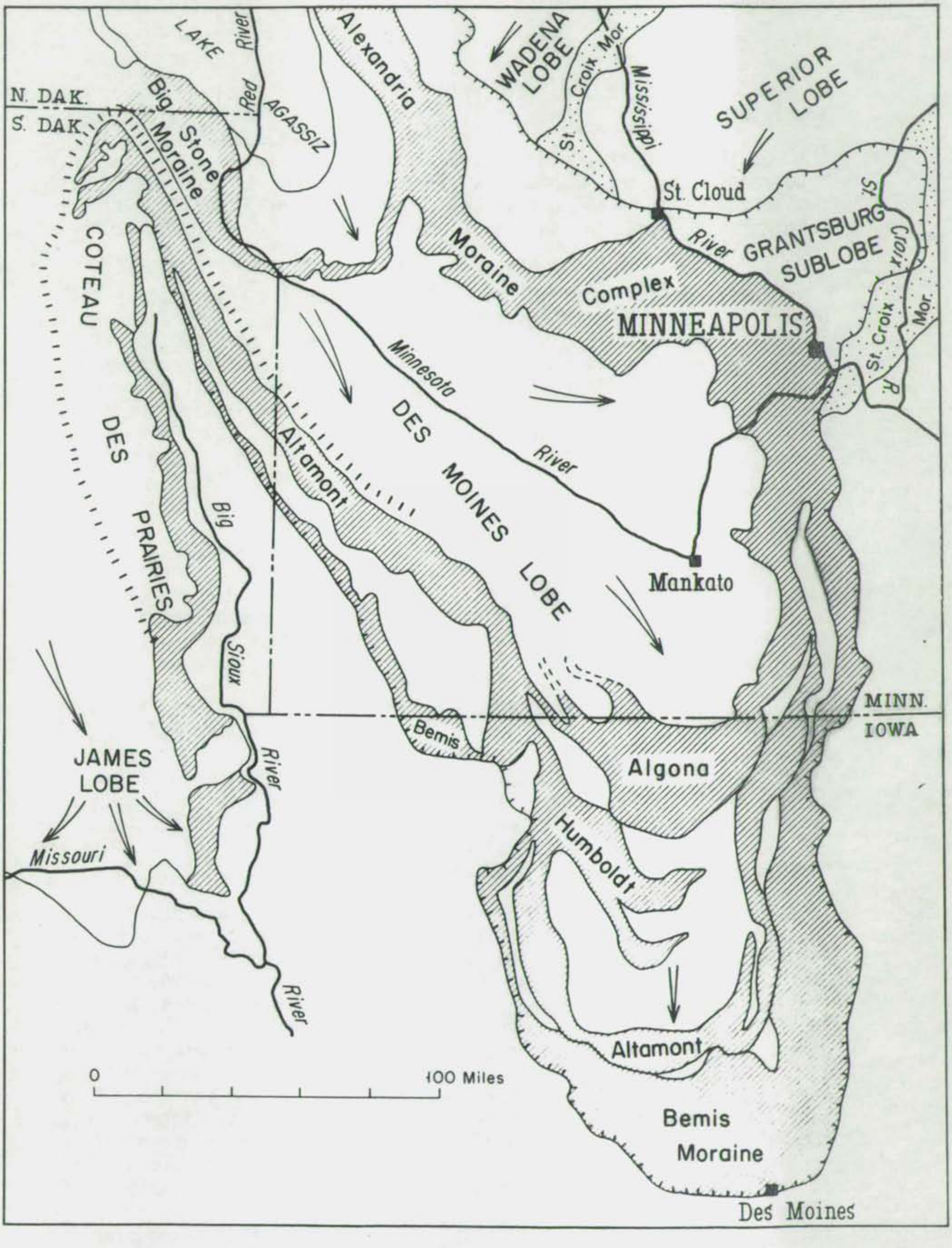

Figure 3. Glacial lobes and moraines of eastern South Dakota, southern Minnesota, and northern Iowa.

general elevation of the bedrock in the trough is about 1200 feet above sea level (fig. 2).

On the east, the Coteau des Prairies is bounded by a more profound topographic sag, the Minnesota River lowland. The Minnesota River valley, a wide and deep trench that served as the southern outlet for Glacial Lake Agassiz, marks the southeast-trending axis of this drift-mantled bedrock lowland.

These troughs on either side of the Coteau des Prairies, as well as other low topographic trends elsewhere in the region, served to channel the last continental ice sheet into discrete lobes (fig. 3). West of the Coteau des Prairies flowed the James lobe, and on the east side, the Des Moines lobe. An earlier glacier with a more easterly axis of flow is known as the Wadena lobe. The Superior lobe followed a low trend southward from the Lake Superior region.

BEDROCK

Three major rock types underlie the glacial drifts of eastern South Dakota and western Minnesota: (1) poorly consolidated marine and continental Cretaceous shales and sandstone, (2) the Precambrian Sioux Quartzite; and (3) high-grade metamorphic and igneous rock complexes of Precambrian age.

The Pierre Shale underlies the northern four-fifths of the Coteau des Prairies (fig. 4) and crops out on both the east and west flanks in Marshall, Day, and Roberts Counties, South Dakota. It is a soft, dark-gray shale that is in part calcareous, with occasional thin bentonite beds. Detailed knowledge of the Cretaceous strata in Minnesota is lacking because exposures are rare, and subsurface information is scarce. Generally, these sediments consist of poorly consolidated quartz sand, lignitic clay, and soft, dark-gray shale.

The southern one-fifth of the Coteau des Prairies is underlain by the Sioux Quartzite. This resistant rock is exposed extensively in Minnehaha County, South Dakota, and Cottonwood, Nicollet, Pipestone, and Rock Counties, Minnesota. It is a dark-pink to dark-red, coarse to fine-grained silica-cemented clastic rock that breaks across the interlocking quartz grains. The quartzite contains beds up to thirty feet thick of red to purple and blue shale, and catlinite, better known as pipestone.

East of the Coteau des Prairies, and especially along the valley bottom and sides of the Minnesota River, metamorphic and igneous rocks, some of which are among the oldest known on Planet Earth, crop out extensively. Coarse-grained, pink or white granitic gneiss probably is the major constituent of this Precambrian crystalline complex with minor rock bodies of more mafic composition. At many places along the valley, a soft, kaolinitic regolith as much as 100 feet thick overlies

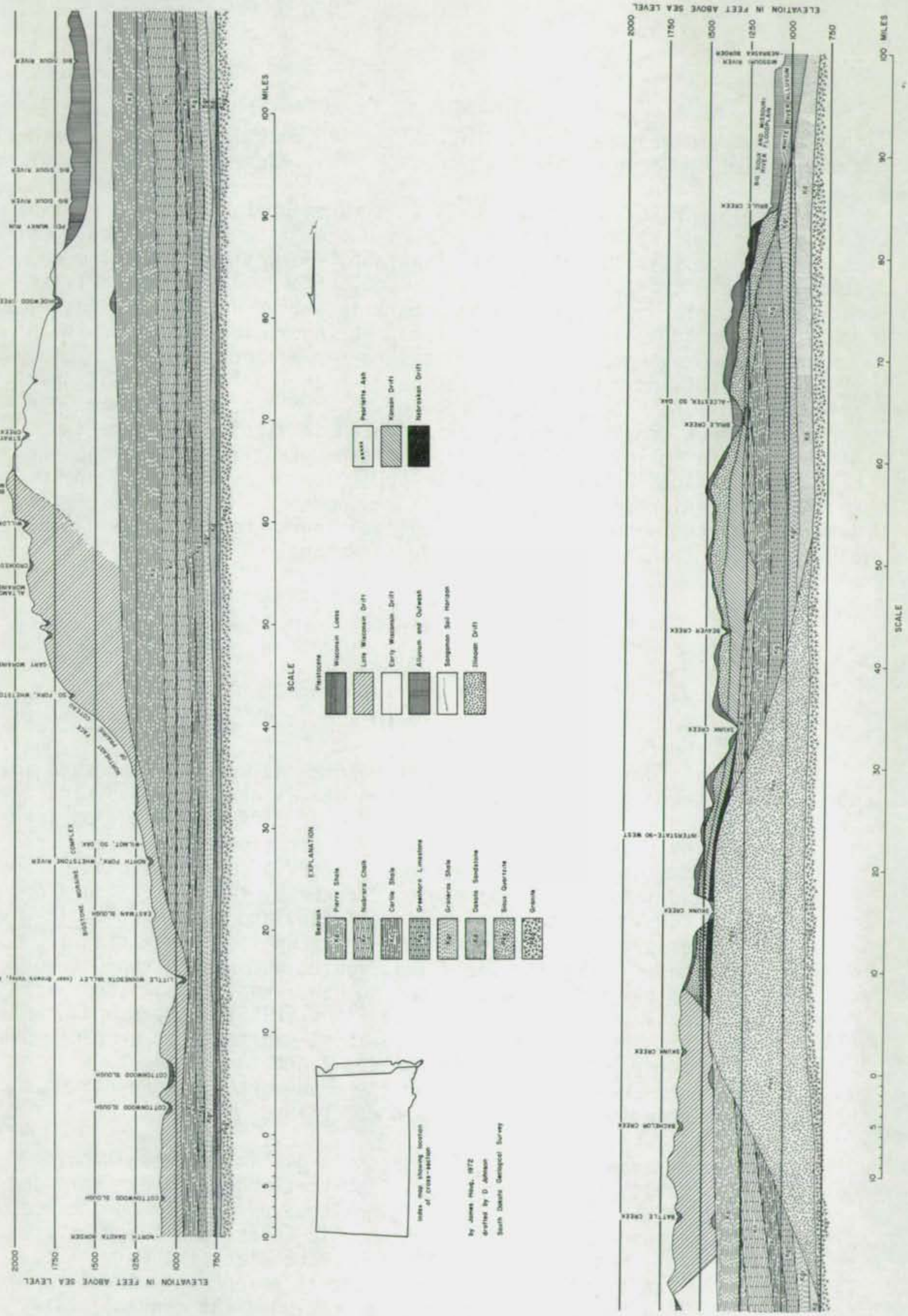

Figure 4. Cross section of the Coteau des Prairies of South Dakota.

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the Precambrian bedrock. This thick clay-rich zone is part of a weathering profile developed during the Cretaceous Period (Parham, 1970; this volume).

A large part of the rock debris that makes up the glacial drift of this region consists of lithologic types quite different from the local bedrock. Especially abundant are clasts of fine-grained limestone and dolomite derived from the Winnipeg lowland. There, a belt of early to middle Paleozoic sedimentary rocks occurs in a zone up to 140 miles wide and more than 400 miles long that trends northwestward across southern Manitoba, and southeastward into Minnesota for a short distance. One of the drifts contains a distinctive suite of rock fragments that is characteristic of the Precambrian bedrock of a large area around Lake Superior. This rock province, though complicated in detail, consists in general of the following diagnostic rock types (not in order of abundance): black fine-grained basalt that may be vesicular or amygdaloidal; purple to red felsites (rhyolites and andesites), some of which are prophyritic; grayish gabbro; red granophyre (adamellite); dark gray to black diabase; and red to pink shale and pink arkosic sandstone.

PLEISTOCENE STRATIGRAPHY

Introduction

The glacial drift in eastern South Dakota and western Minnesota in the region between the Big Sioux and Minnesota River valleys is stratigraphically complex. Superposed tills, some of different lithology, that are separated by paleosols, accretion gleys, striated boulder pavements, or forest beds point in a grand way to a history of multiple glaciation. At least three drifts within the region crossed by the field excursion are presently considered to be of Wisconsin age, and most of the discussion that follows will describe those drift units. Other glacial drifts, not exposed along the field trip route, but within the Coteau des Prairies region, have been ascribed to Nebraskan, Kansan, and Illinoian glacial activity, most recently by Flint (1955), Steece and others (1960), and Tipton and Steece (1965). Glacial sediments of probable pre-Wisconsin age are exposed in several places along the Minnesota River Valley, but their true position within the framework of mid-continent Pleistocene glaciation has not yet been determined.

The current subdivision of the Wisconsin glacial events in northeastern South Dakota is little changed from that published by Lemke and others (1965). This system of subdivision is based largely on the recognition of geomorphic rather than stratigraphic units, and the maps presented show only the moraines marking the limit of each glacial event. The lithologic similarity of the tills, the general absence of stratigraphic markers, and a paucity of C-14 dates have precluded the conventional methods of till stratigraphy (Lemke and others, 1965).

The detailed studies of the surficial deposits of eastern South Dakota since 1965 have been mainly concentrated in the areas affected by glacial events associated with the James lobe. On the eastern side of the Coteau des Prairies in the region glaciated by the Des Moines lobe, preliminary work has begun for county studies in Hamlin and Deuel Counties. (The type areas for the Bemis, Altamont, and Gary moraines are located in Deuel County.) Portions of Grant and Roberts County have been the object of some fairly detailed study for the past three years.

The studies in Grant and Roberts Counties originally were concerned with the problems of ground water contamination and the geohydrology of the glacial deposits marginal to Big Stone Lake. In the course of this study some preliminary observations were made on the stratigraphy of the area. During the past year the study was expanded to include a detailed mapping of the South Dakota portion of the Big Stone Lake and Ortonville 7 1/2-minute quadrangles, and a regional reconnaissance of till stratigraphy on the eastern flank of the Coteau des Prairies was initiated.

In Minnesota stratigraphic studies have been carried on since 1968 under the auspices of the Minnesota Geological Survey. Work is continuing on a regional mapping project that includes all of southern Minnesota.

Major Till Units

Numerous exposures of Quaternary sediments along Big Stone Lake and the Minnesota River Valley between Ortonville and Mankato, and along tributary streams that cut into the upland, show three different glacial tills in superposition: From oldest to youngest these are (1) the Hawk Creek Till[1], a pink to reddish-brown sandy till with stones of Lake Superior region aspect; (2) the Granite Falls Till, a yellow to yellow-brown calcareous loamy till, with mostly carbonate and granitic pebbles; and (3) the New Ulm Till, a light olive-brown calcareous clay loam till, with pebbles of siliceous Cretaceous shale, carbonate, and granitic rocks predominating. In many places the two upper tills are separated by a planed and striated boulder pavement that is usually one-boulder thick. In several exposures the Hawk Creek Till is seen to lie on top of an older calcareous drift.

Hawk Creek Till

The Hawk Creek Till, named for exposures along Hawk Creek in Sec. 16, T. 116 N., R. 38 W., a few miles south of Maynard, Minnesota, is distinguished from other Quaternary deposits in the region by its distinctive color, texture, and lithology. The color ranges from pink (5YR 7/3) on dry, oxidized exposures, to reddish-brown (5YR 4/3) on wet, oxidized till, to dark reddish-brown (5YR 2/2) on wet exposures of

[1] All names of lithostratigraphic units are provisional.

unoxidized till. In all of the samples analyzed the sand fraction exceeds 50 percent by weight in the less than 2 mm size fraction (fig. 5). The till contains a large percentage of rock types from the Lake Superior region, such as red felsite, pink sandstone, gabbro, and even banded Lake Superior agates. Cretaceous shale is absent, and carbonate rocks generally comprise less than 20 percent of the 2 mm to 1 mm size fraction. Total carbonate averages 5 percent.

The Hawk Creek Till is not a continuous sedimentary unit in the region; however, the scattered exposures so far discovered indicate that it once covered an extensive area. No geomorphic features have yet been recognized that are related to this till sheet.

Exposures along Big Stone Lake were first described by Upham (1884). He reported the occurrence of this red till in deep wells as far west as Twin Brooks, South Dakota (Upham, 1884, p. 628). Cores obtained during soil testing studies for the Big Stone Power Plant northwest of Big Stone City, South Dakota, penetrated 20 feet of this till at an elevation of about 1030 feet (90 feet below the surface in sec. 12, T. 121 N., R. 47 W.). In Minnesota, the red sandy till is extensively exposed along Watson Sag, in the vicinity of Watson, Minnesota, where two drifts overlie it. Elsewhere along the Minnesota River, southeast of Granite Falls, it is rarely encountered. However, exposures have been found at Franklin, and near Henderson, Minnesota, the latter site over 80 miles southeast of Hawk Creek.

At this type section about five feet of the Hawk Creek Till is superposed atop a shale-free gray calcareous, clay loam till, with an intervening 12 inches of leached silt that contains thin layers of blackish plant fragments. Along the west bank of the Whetstone River in South Dakota, sec. 13, T. 121 N., R. 47 W., at water level in June, 1972, the unoxidized base of the Hawk Creek Till was seen to lie on top of a dark-gray, silty, carbonaceous non-glacial sediment that contains abundant snail shells, which has an age greater than 25,000 radiocarbon years. Wood found enclosed within the Hawk Creek Till near its base, about one mile northeast of this site, gave an age of 20,067 radiocarbon years.

The Hawk Creek Till was deposited during an early Wisconsin advance of the Superior lobe from the Lake Superior region all the way into eastern South Dakota. It, therefore, must have left a girdle of red till across the entire mid-section of Minnesota. The history of advance and retreat of this glacial lobe is almost completely obscured by later glacial deposits. Even more obscure are details relating to the activity of the ice that deposited the calcareous gray drift found beneath the Hawk Creek Till at the type section. All that can be said at present is that this older till represents a glacial advance from the Winnipeg lowland prior to the intrusion of the Superior lobe.

Granite Falls Till

The most common Quaternary stratigraphic succession in the deep cuts

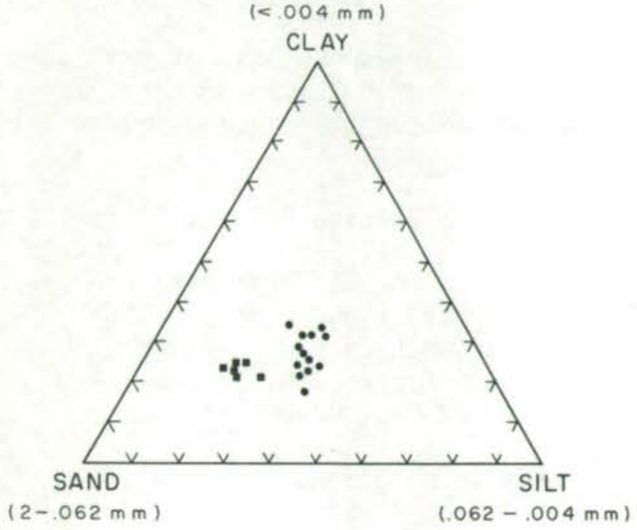

Figure 5. *Grain size distribution in the Hawk Creek Till (squares), and the Granite Falls Till (dots).*

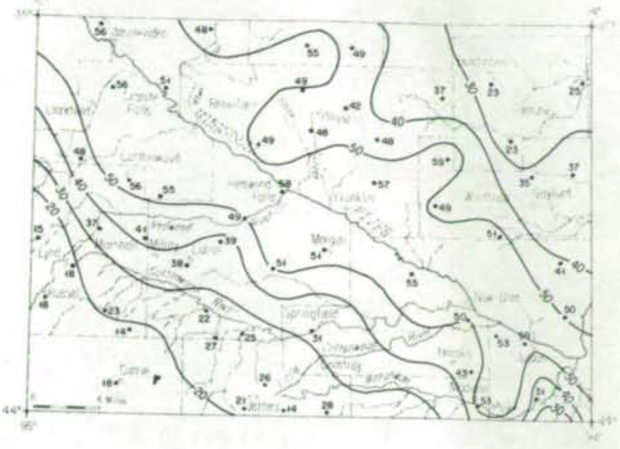

Figure 6. *Distribution of siliceous Cretaceous shale, in percent, in the sand size grade 2 mm to 1 mm, New Ulm Till, southwestern Minnesota.*

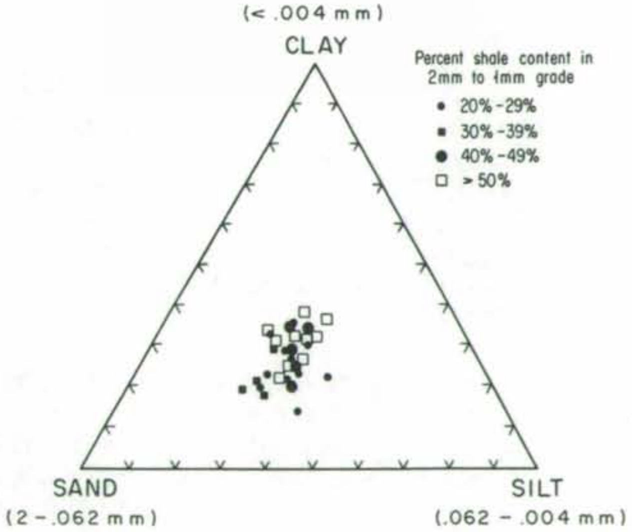

Figure 7. *Grain size distribution, New Ulm Till, southwestern Minnesota.*

along the Minnesota River valley and its tributaries consists of two calcareous tills separated by a variable thickness of outwash, or a boulder pavement, or marked by a contact between unoxidized till over oxidized till. The lower unit is named the Granite Falls Till.

The most distinctive characteristic of the Granite Falls Till is its stone content. Shale is absent, or present in small amount (1 percent to 5 percent). Most of the rock fragments greater than 1 mm in diameter are carbonates (up to 50 percent), and granitic rocks (30 percent). Total carbonate averages 20 percent. It is not uncommon to find a few rock fragments that were derived from the Lake Superior region. Presumably, these were incorporated from the underlying red Hawk Creek Till.

Texturally, the till ranges from sandy loam to loam to clay loam (fig. 5). In many exposures, masses of silt, sand, and gravel are part of the main body of till. Typically, the dry oxidized till is pale yellow (2.5Y 8/4) or yellow (2.5Y 8/6), and light yellowish brown (2.5Y 6/4) or light olive brown (2.5Y 5/4) when wet. Unoxidized till, rarely exposed, is gray (10YR 6/1) dry and dark gray (10YR 4/1) when wet.

In many places the till is underlain or overlain by locally very thick bodies of sand and gravel. These outwash bodies are generally free of shale, and contain mostly limestone, dolomite, and granite fragments. In the subsurface these well-sorted, rounded, and usually cross-bedded sands and gravels are important groundwater reservoirs. They are widely exploited at the surface as sources of good-quality gravel.

Closely spaced joints that are coated with iron and manganese deposits occur to depth greater than 50 feet. Not only do these joints contribute to a crumbly overall aspect to the till, but they also enhance the permeability of the formation.

The Granite Falls Till is found almost continuously along the Big Stone Lake trench and the Minnesota River valley. Even shallow incisions by tributary streams have exposed it. Several good cuts show that it lies on top of the Hawk Creek Till. At Watson Sag the contact shows mixing of the two tills. On the east bank of Hawk Creek, sec. 16, T. 116 N., R. 38 W., the two tills are separated by up to 7 feet of clay, silt, and sand containing mollusk shells and pollen grains. In other places its rests directly on bedrock.

Because it is relatively free of Cretaceous shale fragments, the Granite Falls till must have been deposited by an ice sheet that bypassed the broad region underlain by the Pierre Shale in the eastern Dakotas. Lithologically, it is similar to the highly calcareous till which is the surface deposit in the Wadena region, 130 miles north of Granite Falls. Such a correlation extends the range of the Wadena lobe far south and west of the Alexandria moraine, the limit of the glacier proposed by Wright (1962).

Two Carbon-14 age determinations on wood discovered at the base of this till near Morton, Minnesota are equivocal. One sample gave a finite age of 34,000 years B.P. (GX-1039). The other, on wood from the same site, was dated at greater than 39,000 years B.P. (I-4932).

New Ulm Till

The surface deposits over most of the region crossed by the field trip consist of till, outwash, and lake sediments associated with the last glaciation of eastern South Dakota and western Minnesota. The till, provisionally named the New Ulm Till, is different from both the Hawk Creek and Granite Falls Tills in that it contains abundant siliceous Cretaceous shale fragments, along with carbonates and granitic rocks. The source of the shale is thought to be a siliceous, brittle member of the Pierre Shale, which has a wide distribution in southern Manitoba, and the eastern Dakotas. Carbonate pebble content ranges from 10 percent to 40 percent; total carbonate averages 10 percent. Granitic composition is consistently high. Noteworthy is the absence of rock fragments from the Precambrian terrain of the Lake Superior region.

The shale content of the New Ulm Till is not constantly high, but throughout a long stretch within the Minnesota River valley the percent of shale in the 2 mm to 1 mm size decreases systematically on either side of a fairly high-abundance trend that coincides with the topographic axis of the Minnesota River lowland (fig. 6). The non-random distribution might reflect progressive dilution from the center of the glacial lobe toward the margins as the result of differential subglacial erosion along this stretch. In this model the ice sheet initially carried a fairly constant and high charge of shale, but when it became lobate and constricted within the Minnesota River lowland, the physics of the glacier changed in response to the new geometry. Whatever the physical characteristics were, the glacier accomplished very little erosion along its axis, where the ice was thickest. Toward the thinner margins, erosion of the underlying till sheet was fairly active. As a result, the original shale-rich load was diluted with locally-derived shale-poor debris from the Granite Falls Till, mostly limestone and granite, and the shale content was progressively lowered with increasing dilution.

In color this till, where oxidized ranges from pale yellow (2.5Y 7/4) to light olive brown (2.5Y 5/4). In the unoxidized state it is dark gray (5Y 4/1) to very dark gray. Texturally, the New Ulm Till ranges from clay loam to loam (fig. 7).

The New Ulm Till constitutes the largest volume of the surface deposit called "young gray drift" by Leverett (1932). Long ago Upham (1896) ascribed this drift to the activity of an ice lobe, now called the Des Moines lobe, that flowed south and southeasterly along the axis of the Red River-Minnesota River lowland. Exposures of this till in the vicinity of Mankato, Minnesota, were the basis for the recognition of the Mankato Substage, a controversial subdivision of the Wisconsin (Leighton, 1933, 1960; Zumberge and Wright, 1956; Wright and Rubin, 1956; Wright, 1964; Frye and others, 1968; Ruhe, 1969). In Iowa this deposit is called the "Cary glacial drift", and its base has been dated at about 14,000 radiocarbon years B. P. (Ruhe, 1969). Nowhere else has suitable material been discovered to date the base of this drift. In South Dakota, this till, within the confines of the Bemis moraine, is classified as "Late Wisconsin" (Tipton and Steece, 1965). In Minnesota, the New Ulm Till is traceable all the way into the Twin Cities, where it lies on top of the red sandy till of the Late Wisconsin Superior lobe in the St. Croix moraine.

In southwestern Minnesota, both the Bemis and Altamont moraines are composed chiefly of this distinctive silty, shale-rich till. Beyond the Bemis moraine in Lincoln, Pipestone, Murray and Nobles Counties, a narrow belt of loess-covered till is also lithologically similar. This is the "young-looking till outside the Wisconsin moraine" of the early workers in Iowa, the "Iowan" of Leverett (1932), the Tazewell of Ruhe (1969), and part of the "Early Wisconsin" of South Dakota workers (Tipton and Steece, 1965). In Minnesota this deposit of shale-rich drift is considered to be part of the New Ulm Till sheet, therefore, representing an extra-morainic position of the Des Moines lobe during its general late-Wisconsin activity (Matsch, 1972).

Dates from organic materials collected from the basal sediments of bogs on top of the New Ulm Till range from 12,650 years B.P. (Jelgersma, 1962) to 10,850 years B.P. (Matsch, 1972).

Boulder Pavement

In many exposures a stone line separates the New Ulm Till from the underlying Granite Falls Till. The stone lines are outcrops of a boulder pavement that can be traced from Sisseton, South Dakota, southeastward to Redwood Falls, Minnesota, and beyond. In South Dakota, excellent exposures of the two tills and the intervening boulder pavement can be seen in SE1/4, sec. 29, T. 122 N., R. 48 W., and along the south edge of sec. 12, T. 121 N., R. 48 W., just west of the Whetstone River. In Minnesota a typical exposure is found at the type section for the Granite Falls Till, in Center, sec. 28, T. 116 N., R. 39 W.

Faceted and striated boulder pavements separating two tills have been reported elsewhere in South Dakota (Flint, 1955, p. 58), and in North Dakota (Clayton, 1966). An extensive deposit of this type occurs in west-central Saskatchewan (Christiansen, 1968), and exposures have been described in west-central Manitoba (Klassen, 1967).

Stone lines between the two tills along the Minnesota River valley are generally one-stone thick. The boulders are predominantly coarse-crystalline igneous rocks, but limestone is not a rare constituent. The plane of contact with the upper till is often a polished and striated horizontal facet on the boulders. In some places, the stones in the pavement have mutual contact in a tight-fitting mosaic.

The present hypothesis is that the pavement is a lag deposit concentrated by various processes of subaerial erosion acting upon the Granite Falls Till when that unit was the surface deposit in the region. Its preservation beneath the New Ulm Till indicates that, whatever the physical properties of the Des Moines lobe at its base, the glacier did little or no erosion throughout the long stretch covered by the boulder pavement.

Two mechanisms have been suggested by which a glacier entrains rock materials from its base into englacial positions: (1) thrusting (Goldthwait, 1951), and (2) regelation of water beneath the debris-rich glacier sole (Weertman, 1961; Boulton, 1970). Thrusting requires a compressive flow field; regelation, to be effective, demands a continuous regime of basal melting and refreezing. The ice that moved along the axis of the Minnesota River lowland exhibited neither of these conditions.

Other Quaternary Deposits

Drifts other than those just described are known to exist in the thick pile of Quaternary sediments that makes up the Coteau des Prairies. Important sections in eastern South Dakota, not to be seen on this excursion, have been described by Tipton and Steece (1965). They believe that all four Glaciations of the Pleistocene Epoch are represented by glacial sediments in exposures along the Big Sioux River Valley. Complex stratigraphic sequences have been encountered in drilling across the prow of the Coteau des Prairies in Marshall and Day Counties, South Dakota (fig. 8), but detailed studies have not yet been accomplished. Some of the drifts that comprise the surface deposits along the central part of the Coteau des Prairies outside the Wisconsin moraines are likely extensions of these subsurface formations.

In Minnesota several deep cuts along the Minnesota River valley in the vicinity of North Redwood and Morton expose a variety of Quaternary sediments that are older than the Granite Falls Till. Figure 9 summarizes two of these sections. All the tills found below wood horizons contain limestone and granite fragments but have sparse siliceous Cretaceous shale. Textures are generally clay-rich (Fig. 10).

Some of the deposits that lie between the tills have the characteristics of accretion-gleys, as defined by Frye and others (1960). Mollusk fragments, plant detritus, and pollen grains have been observed in them. These deposits between tills prove multiple glaciation, but they do not necessarily represent long interglacial climatic episodes in the Pleistocene sequence. Deeply weathered horizons developed on till that correspond to gumbotil have not been observed in the region.

Correlations of these older deposits in the Minnesota River valley to Quaternary sediments elsewhere have not yet been accomplished. Some of the tills mapped as "Old Gray Drift" (Leverett and Sardeson, 1919), "Kansan" (Leverett, 1932) and "Iowan" (Ruhe, 1950) in southwestern Minnesota; and as "Illinoian" (Tipton, 1959) in eastern South Dakota have the same general lithologic characteristics as the older tills near the base

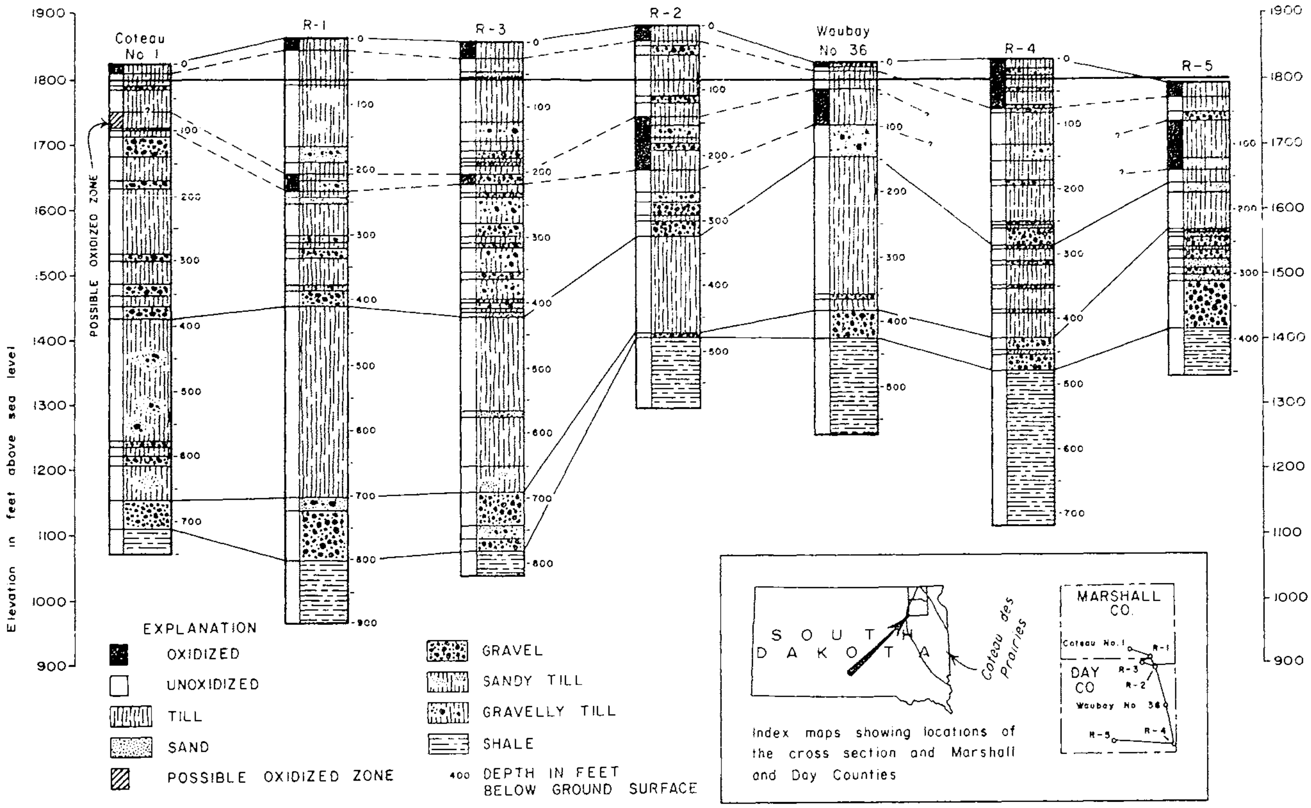

Figure 8. Cross section showing lithology and thickness of the glacial drift on the Coteau des Prairies.

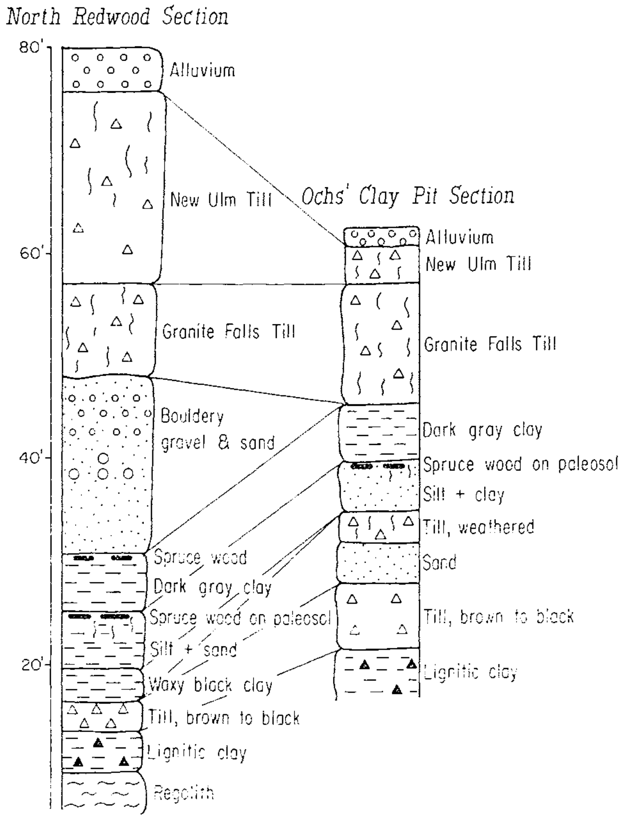

Figure 9. Stratigraphic sections at North Redwood and Morton, Minnesota.

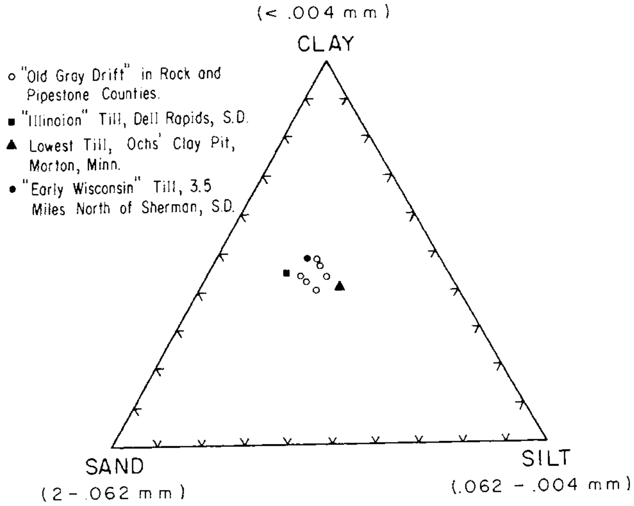

Figure 10. Grain size distribution of older tills in southwestern Minnesota and eastern South Dakota.

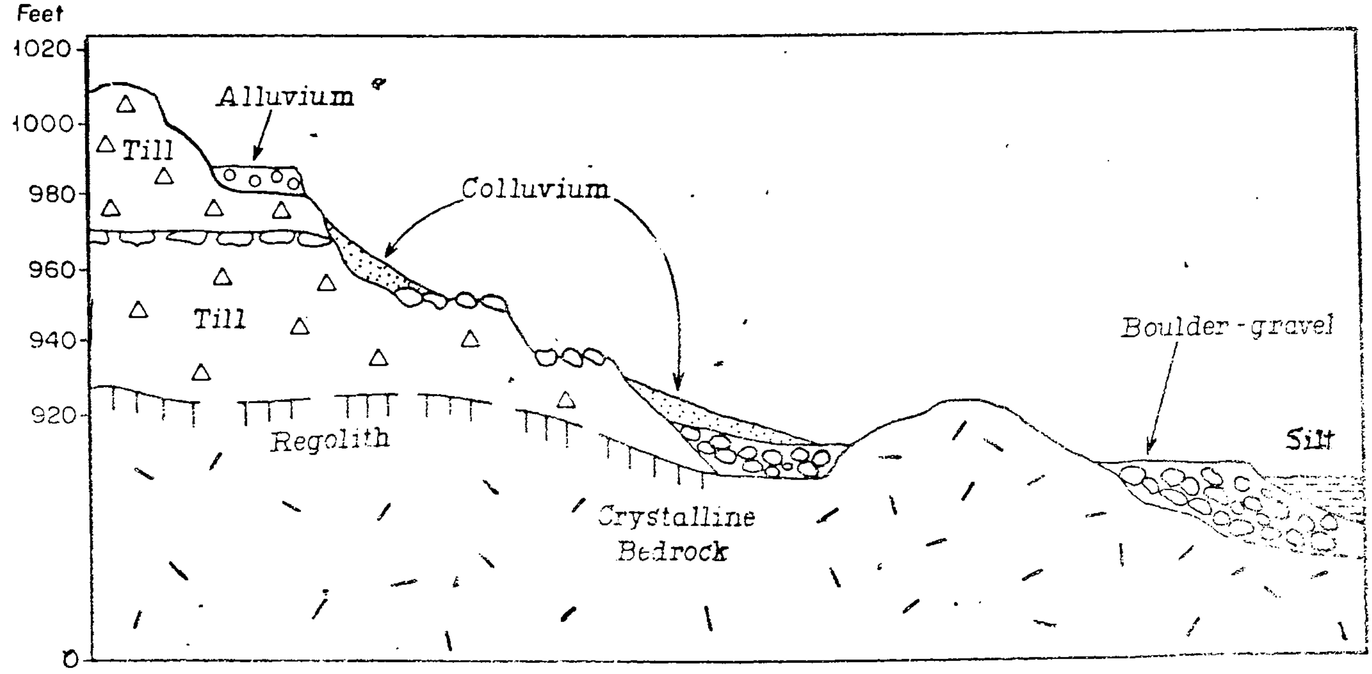

Figure 11. Generalized cross section of the Minnesota River Valley, Granite Falls, showing the various terrace surfaces.

of the Quaternary sequence near Morton -- a clay-rich texture and a coarse sand fraction rich in carbonates and granitic rocks, and poor in siliceous shale.

Summary of Stratigraphy

Four superposed tills of contrasting lithology separated by non-glacial sediments are exposed along the eastern flank of the Coteau des Prairies, and within the Minnesota River lowland. The upper three tills are exposed extensively enough to earn provisional rock-stratigraphic names: from oldest to youngest, the reddish brown sandy Hawk Creek Till, the silty, calcareous, relatively shale-free Granite Falls Till, and the silty to clayey calcareous, shale-rich New Ulm Till, which is the surface formation over a wide area in South Dakota, Minnesota, and Iowa.

No Carbon-14 dates are available in Minnesota and South Dakota to place the last advance of the Des Moines lobe into an absolute chronology. Age determinations in Iowa (Ruhe, 1969) indicate the lobe had reached nearly to Des Moines by 14,000 years B.P. An eastern branch, the Grantsburg sublobe, had flowed into the Twin Cities basin somewhat earlier (Wright and others, 1972). More closely dated is the retreat of this late-Wisconsin ice.

According to dates beneath outwash (Ruhe, 1969), the lobe had retreated from Iowa by 13,000 years ago. By 12,650 years B.P., peat was accumulating in bogs just south of Mankato, Minnesota (Jelgersma, 1962). Waves of Lake Agassiz had constructed the Herman Beach by 11,740 years B.P. (Shay, 1965). This chronology indicates that during the span of little more than 2,000 years, the leading edge of active ice had retreated at least 350 miles northward, and probably much farther.

None of the other glacial deposits can yet be placed into an absolute time framework. The few ages so far determined for the Hawk Creek and Granite Falls Tills are contradictory, and therefore not helpful. The presence of non-glacial deposits between tills that show no sign of deep weathering suggests that four of the tills may have been deposited during the last stage of glaciation. The consecutive deposition of the Hawk Creek Till by the Superior lobe, the Granite Falls Till by the Wadena lobe, and the New Ulm Till by the Des Moines lobe indicates a westward shift of the ice centers that affected this part of the continent.

Morphostratigraphy

Most of the landforms along the field trip route are the result of erosional and depositional processes associated with the advance and retreat of the Des Moines lobe. Till in the form of end moraines and ground moraine covers the greater part of the area. The stagnation and melting of the Des Moines lobe, which was essentially a broad valley glacier along its course in Minnesota, was accompanied by temporary ponding in many places that resulted in the accumulation of fine-grained lake sediments, as well as strand features. The activity of slope processes on a landscape cored by stagnant ice, and deposition in sedimentary environments associated with ice disintegration resulted in a variety of landforms (Steece, this volume). Runoff from the melting Des Moines lobe and discharge from glacial lakes established a network of meltwater channels and lake outlets that have a variety of alluvial sediments associated with them.

Moraines

Upham (1881) designated the one- to three-mile wide drainage divide that is the crest of the east flank of the Coteau des Prairies as "the outer terminal moraine" of the last ice advance in the region. He had earlier traced a continuous loop of morainic topography from Minneapolis southward into Iowa, and then northwest to the Coteau des Prairies. Chamberlin (1883) formally named this loop of hilly topography the Altamont moraine, for the village of Altamont in eastern South Dakota. Leverett (1922b) found that the moraine on which the village of Altamont is situated does not connect with the outer moraine as previously mapped. He then proposed the name Bemis for this outer moraine and retained the name Altamont for the feature that Upham had termed the "inner moraine".

The Bemis moraine extends from southern Roberts County, across Grant and Deuel Counties, South Dakota, and in Minnesota continues southeastward into Lincoln, Pipestone, Murray, and Nobles Counties, then turns southward into Iowa. As a height of land it acts as a drainage divide between the Big Sioux River and the Minnesota River. The crest decreases in altitude from northwest (2000 feet or more) to southeast (1700 feet near the Iowa border). Undrained depressions are rare. For the most part it does not have a loess cap. On its southwest side, aprons of very bouldery, silt-capped gravel grade away from the moraine.

The moraine is breached in several places by impressive gorges that served as outlets for ponded waters between the moraine and receding glacier ice. These capacious valleys, at places, have lakes at their heads, as for example Clear Lake, and Lakes Hendricks, Benton, and Shokatan, which resulted from damming by fans as the abandoned outlets were filled with silt.

Traditionally, the Bemis moraine has been interpreted to mark the margins of the late-Wisconsin Des Moines lobe, but in fact, this feature does not coincide with the limit of the distinctive shale-rich till associated with that lobe. The James lobe on the west side of the Coteau has no comparable morphological feature associated with its margin. Nor do the eastern margins of the Des Moines lobe.

A much more continuous geomorphic feature is the Altamont moraine, a poorly drained complex of ice-disintegration features that can be traced for hundreds of miles, not only within the region of the Coteau des Prairies, but across a great part of central Iowa and eastern Minnesota as well.

Within this region the Altamont is the second, or inner moraine of the Des Moines lobe; it is the outer moraine of the James lobe (Tipton and Steece, 1965).

The Altamont moraine along the southwest side of the Des Moines lobe is a 5- to 12-mile wide belt of poorly drained, hummocky terrain whose trend closely parallels that of the Bemis moraine until the vicinity of Lake Shetek, Minnesota. There it diverges eastward, then turns southward to cross into Iowa in the vicinity of Spirit Lake. This remarkable complex of ice-stagnation features lies at altitudes several hundred feet lower than the Bemis moraine throughout its course in southwestern Minnesota, and is separated from that moraine by a strip of low-relief, poorly drained ground moraine. Individual features characteristic of the Altamont moraine are described elsewhere (Steece, this volume).

Some geologists consider the Altamont moraine to mark a recessional position of the Des Moines lobe (Upham, 1896; Leverett, 1932; Ruhe, 1969; Matsch, 1972) while others believe that it marks a distinct readvance of the ice (Ruhe, 1952; Flint, 1955). Whatever its relationship to the activity of the Des Moines lobe, the moraine is not much younger than the Bemis, according to Carbon-14 dates in Iowa (Ruhe, 1969). There the base of the Bemis moraine is 14,000 radiocarbon years old. Outwash associated with the Algona moraine in northern Iowa which lies behind the Altamont moraine, has been dated at about 13,000 years B.P. Thus, the Altamont moraine should date somewhere in between the two.

Both Upham (1896) and Leverett (1932) designated a variety of other geomorphic features as successive recessional moraines of the Des Moines lobe. Leverett chose to call a belt of disintegration ridges on the northeast side of the Altamont moraine, but slightly lower in elevation, the Gary moraine. But the close association makes this differentiation questionable. A high topographic trend Leverett called the Antelope moraine is a large crevasse-filling. The belt of high relief that he called the Marshall moraine is not a constructional feature, but rather terrain left standing high along meltwater channels inset in ground moraine.

Another high topographic trend, that Leverett (1932) designated the Big Stone moraine, loops across the Minnesota River lowland near Ortonville. Leighton (1957) considered this to mark the southern limits of an ice advance that he correlated to the Valders of the Michigan lobe. Much of the relief in this moraine might reflect buried topography developed on older till sheets.

To the east, the Big Stone moraine merges with the long and broad Alexandria moraine complex, an arcuate belt of lake-dotted stagnation moraine that in part is associated with the disintegration of the Wadena lobe (Wright, 1962). The Alexandria moraine contains drift from both the Wadena lobe and the Des Moines lobe; therefore, both glaciers must have played a role in its formation. Neither the Big Stone moraine nor the Alexandria moraine has been studied in detail. Until such studies are accomplished, the significance of these features remains vague.

Strand Features of Lake Agassiz

About 12,000 years ago the Des Moines lobe retreated northward from the Big Stone moraine, and meltwater became ponded between a topographic divide near Browns Valley and the receding ice margin. Eventually this body of water expanded across an area of approximately 200,000 mi^2 (Elson, 1966) to become the largest glacial lake in North America. For a time, a single outlet drained water from this lake. That spillover, called Glacial River Warren, cut the magnificent valley now occupied by the Minnesota River.

Careful mapping by Upham (1896), Leverett (1932), and others showed that before this southern outlet was abandoned, Lake Agassiz stood at four successively lower levels, long enough to produce extensive, well-developed strand features. These strands and their elevations near the outlet are the Herman (1060 feet), Norcross (1040 feet), Tintah (1020 feet), and Campbell (980 feet), all named for towns in western Minnesota located near these features.

Most of these strand features are in the form of beach ridges, long shore bars, spits, and wave-cut benches. They are easily discernable on topographic maps having a 10-foot contour interval. No detailed work has been accomplished on these features in Minnesota or South Dakota. Many of the deposits, such as the Herman beach near its type locality, consist of well-stratified gravel and coarse sand displaying cross-bedding, graded bedding, and imbricate structure.

Terraces Along the Minnesota Valley

Terrace segments are preserved at various heights above the floodplain of the Minnesota River. The materials underlying the terraces fall within three major categories that relate to the history of the valley (Fig. 11). The highest surface, only slightly inset into the till plain, is underlain by flat-bedded and cross-bedded coarse sand and cobbly, well- to poorly-sorted gravel 10 to 40 feet thick. These sediments are remnants of an extensive braided stream system that drained the margins of the retreating Des Moines lobe ice.

Another set of terrace surfaces at intermediate heights is distinguished by a veneer of lag boulders that lies atop older Quaternary sediments or bedrock. These boulder-armoured surfaces are remnants of successively lower channel bottoms of Glacial River Warren.

A third type of sediment is found both slightly higher than the modern floodplain and locally buried beneath the floodplain sands and silts. These alluvial deposits are boulder-gravel beds composed of well-rounded boulders and cobbles in a matrix of coarse gravel and sand. Commonly the dominant size reaches as large as 12 inches in diameter. These deposits were once part of the bed-load of River Warren and lagged during the waning stages of its discharge through the present Minnesota

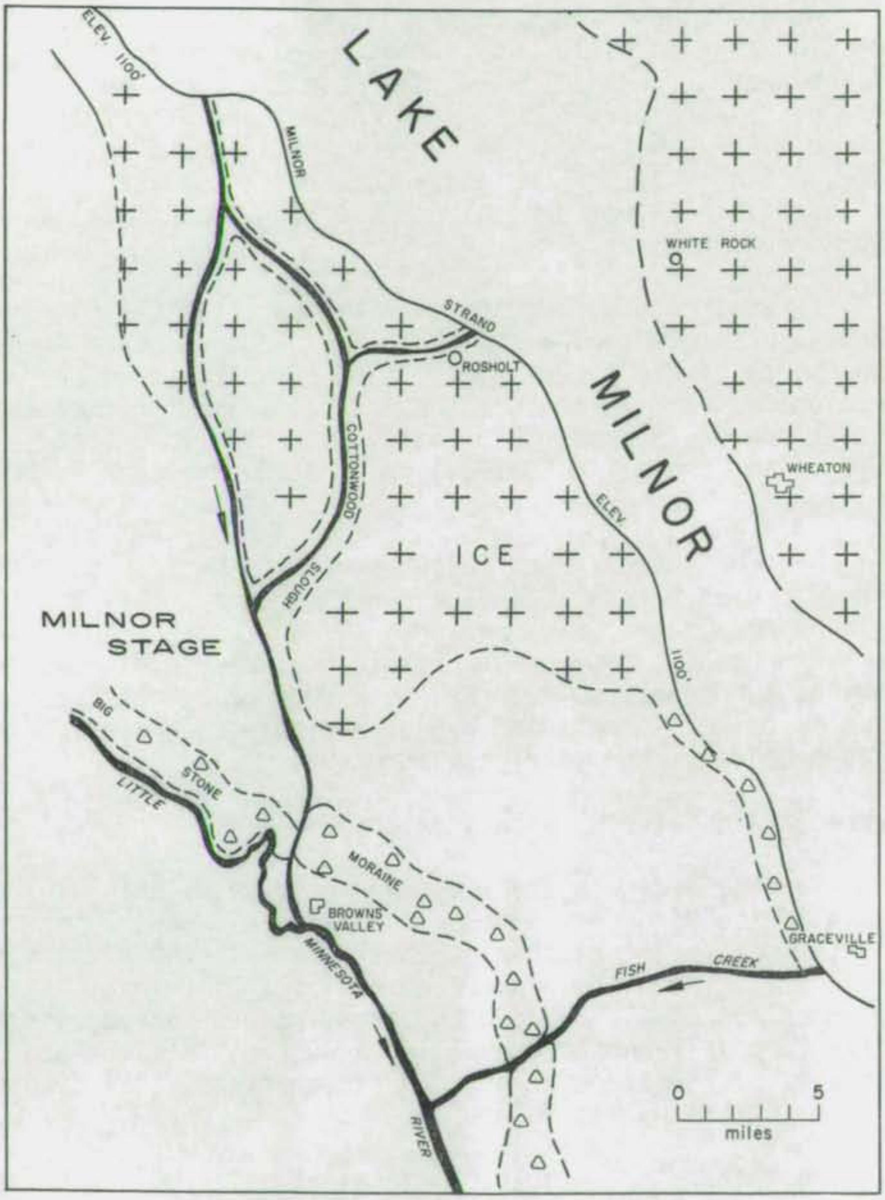

Figure 12. Lake Milnor stage of Glacial Lake Agassiz. Early outlets drained through stagnant ice blocks to the incipient Little Minnesota River.

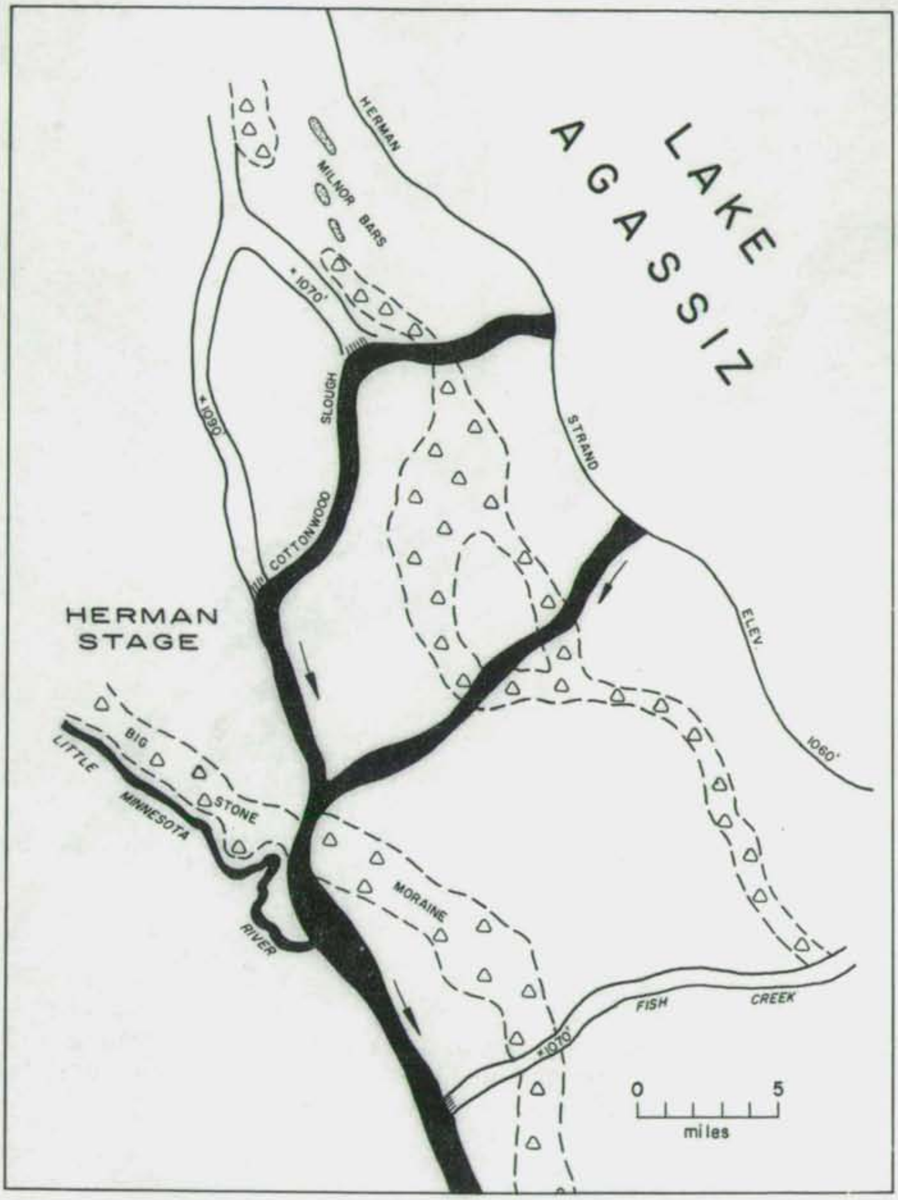

Figure 13. Herman stage of Lake Agassiz. Some earlier outlets are abandoned. Lake level is stabilized by development of a boulder pavement in the gorge downstream from the Big Stone Moraine.

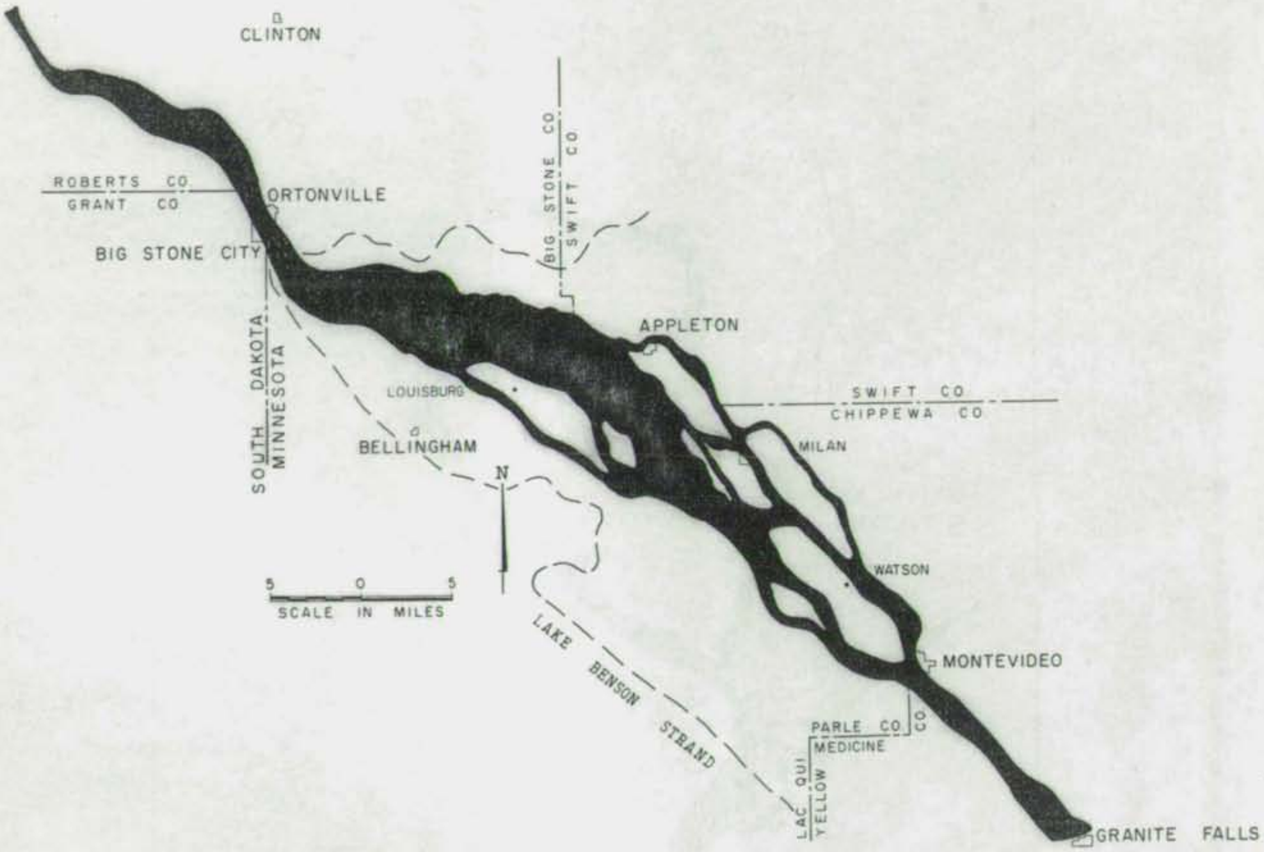

Figure 14. Herman stage downstream from Ortonville. The wide, shallow river flows along the axis of the just-drained Glacial Lake Benson, branching around islands of drift.

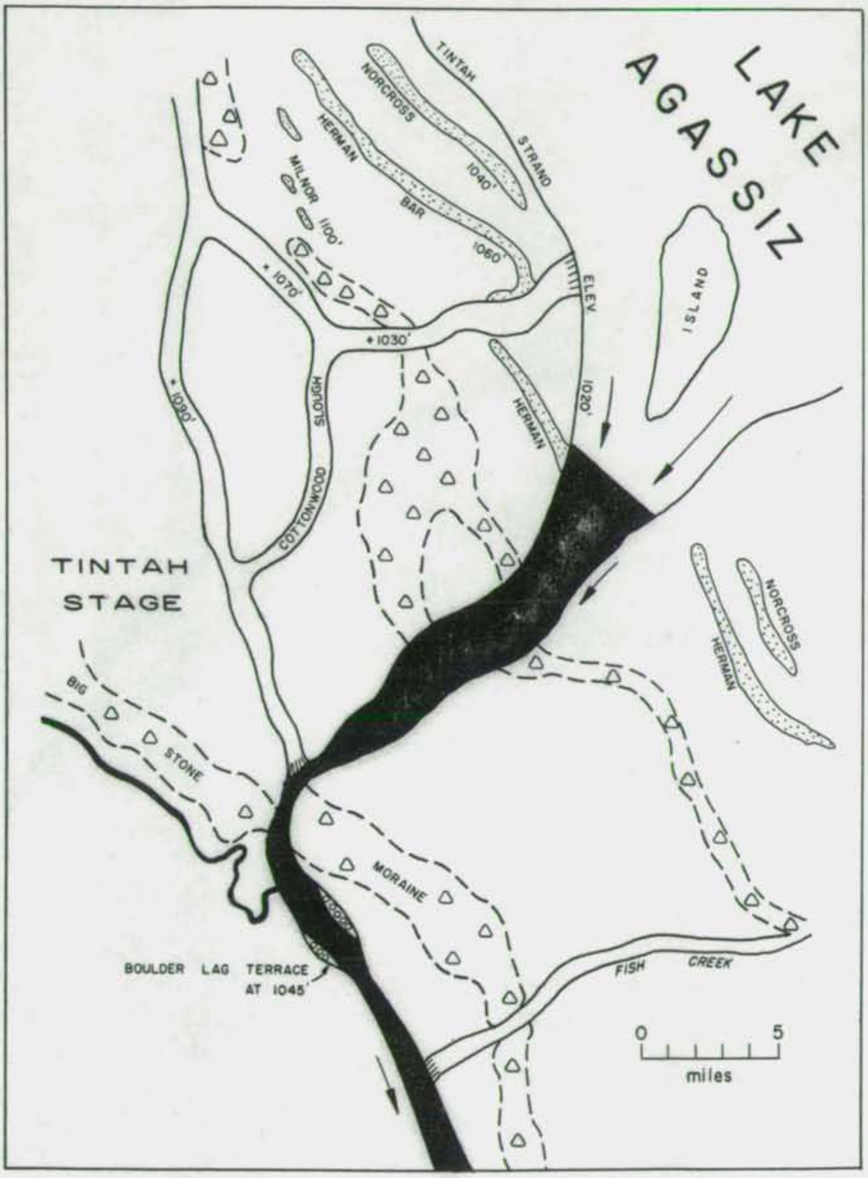

Figure 15. Tintah stage of Lake Agassiz. Cottonwood Slough is abandoned during deepening and widening of the outlet stream.

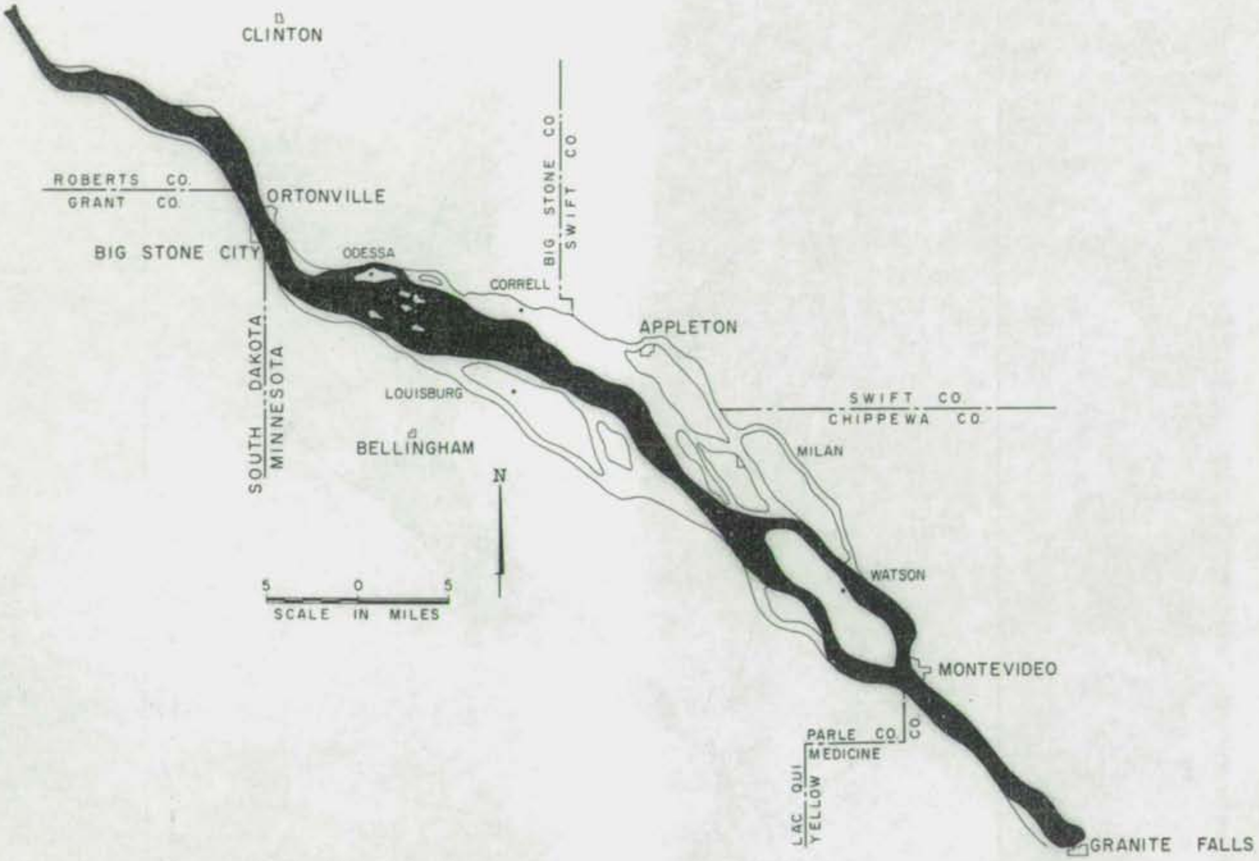

Figure 16. A post-Tintah stage downstream from Ortonville. The auxiliary channels are abandoned as the river trenches more deeply. A few islands, some of bedrock, appear in the channel near Odessa.

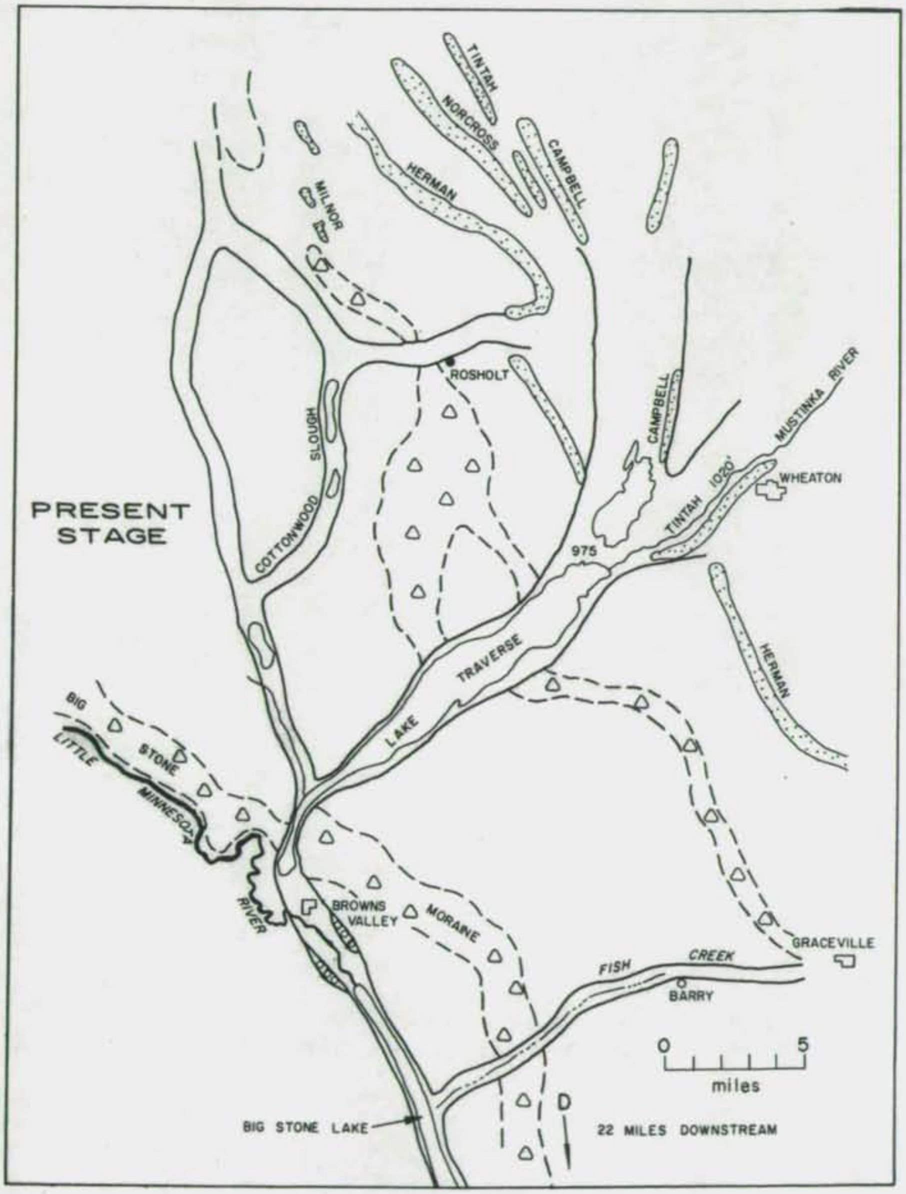

Figure 17. Lake Agassiz outlet area at the present time. An alluvial fan at the mouth of the Little Minnesota River dams Lake Traverse.

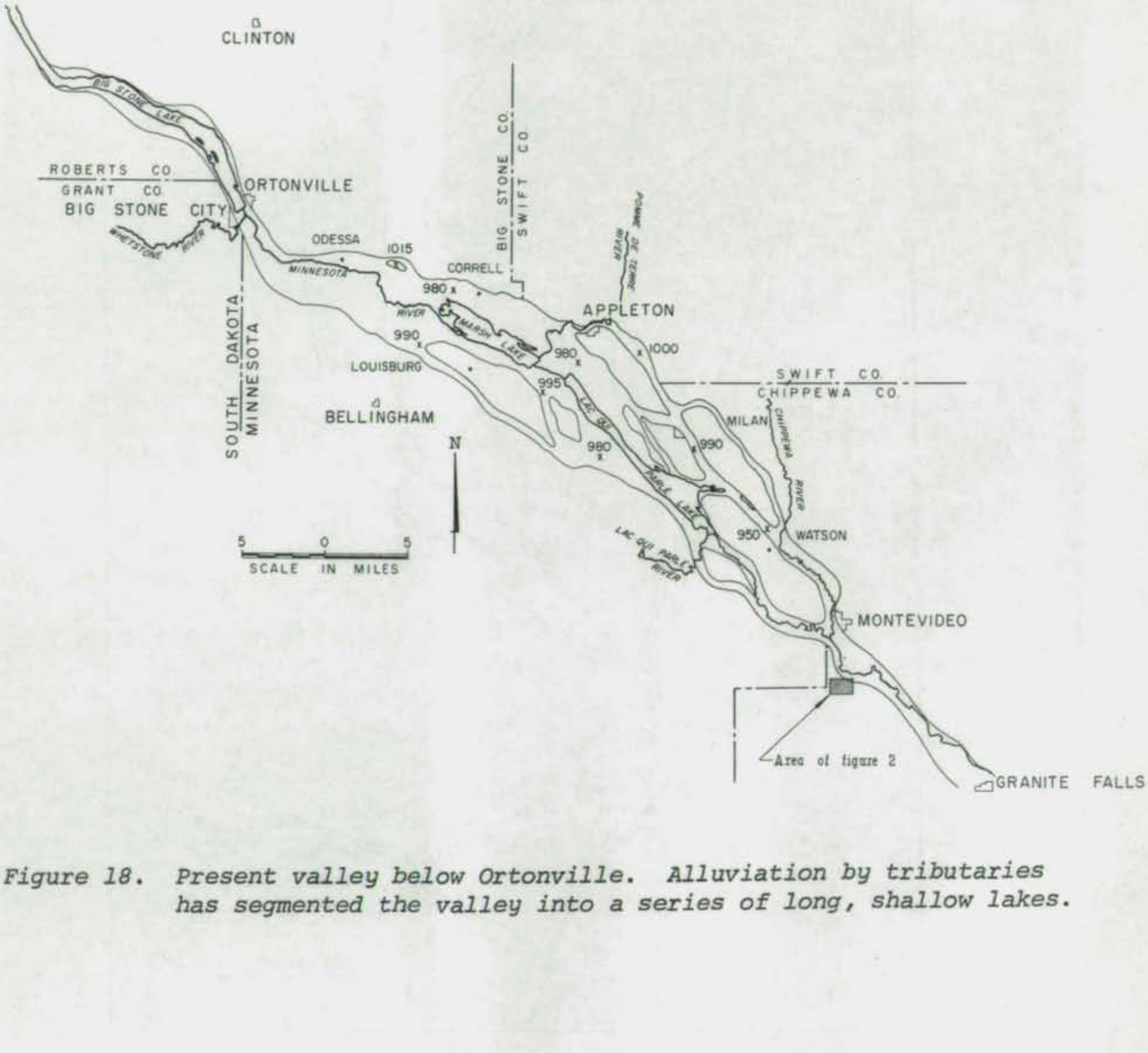

Figure 18. Present valley below Ortonville. Alluviation by tributaries has segmented the valley into a series of long, shallow lakes.

River Valley.

Summary of River Warren History

Matsch and Wright (1966) summarized the history of the southern outlet of Lake Agassiz in the following manner. As the Des Moines lobe retreated from the Big Stone moraine, water at first became ponded into a narrow lake named Lake Milnor (Fig. 12), which had an elevation of 1100 feet. The South Dakota portion drained across low points in the moraine, which may still have been ice-cored, resulting in the trenching of several small channels, including Cottonwood Slough. Near Browns Valley the spillover waters joined the Little Minnesota River, which thereupon cut into its outwash surface, leaving a terrace at 1100 feet. The Minnesota portion of Lake Milnor formed no strand and left only small patches of lake sediment, but in spilling across the moraine it cut the small channel of Fish Creek. From Browns Valley the now erosive waters flowed across the till upland to Ortonville, then southward, trenching the moraine and outwash fans of the Whetstone and Pomme de Terre Rivers.

Continued wastage of the ice resulted in the expansion of Lake Milnor into Lake Agassiz proper. Two lower spillways, one near Wheaton and the other at Cottonwood Slough, drained the lake as it stabilized at the Herman stage (Fig. 13). The stabilization was effected by the production of a boulder-armoured channel bottom on the outlet floor between Browns Valley and Ortonville that prohibited further downcutting. Downstream from Ortonville River Warren occupied a broader channel, and from Odessa south to Montevideo the water was dispersed throughout a wide system of auxiliary channels (Fig. 14).

Subsequent retreat of the ice allowed the lake to enlarge into Canada. The increased competence of the outlet stream allowed erosion of the channel floor and abandonment of the Cottonwood Slough outlet (Fig. 15). Lake stabilizations occurred at 1040 feet (Norcross), 1020 feet (Tintah), and 980 feet (Campbell), in response to halts in downcutting of this southern outlet. Boulder-armoured terraces in the gorge below Browns Valley are remnants of the floors of the successively lower outlet channels.

As the lake waters dropped from the Herman shoreline, River Warren between Odessa and Milan deepened its course, and the auxiliary channels were abandoned. Erosion after the Tintah shoreline had been developed resulted in the formation of a single channel in this stretch (Fig. 16). During this period of lake drainage (to the Campbell strand at 980 feet), the channel below Ortonville was being excavated partially through bedrock. Finally, about 9200 years ago, ice retreat uncovered lower Canadian outlets, and River Warren was beheaded.

Tributary streams thereafter deposited alluvial fans in the abandoned gorge, segmenting the floor of the outlet channel into a series of long, shallow lakes. The alluvial fan of the Little Minnesota River dams Lake

Traverse (Fig. 17), the fan of the Whetstone River dams Big Stone Lake, and that of the Lac Qui Parle River holds back Lac Qui Parle Lake (Fig. 18).

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ICE-STAGNATION DRIFT, COTEAU DES PRAIRIES, SOUTH DAKOTA

Fred V. Steece

INTRODUCTION

Glacial deposits have been studied in South Dakota for about ninety years, beginning with Chamberlin's monumental study in 1883. In succeeding years, a number of geologists have mapped these deposits in refinement of Chamberlin's basic work. It was not until the 1950's, however, that the concept of the widespread stagnation of continental ice sheets was introduced into the literature, chiefly by Hoppe (1952). Hoppe's ideas on ice stagnation and the resulting landforms have been accepted by many North American glacial geologists.

Experience in mapping glacial sediments of the Coteau des Prairies has shown that the traditional categorization of the glacial deposits into end moraine, ground moraine, and outwash is no longer universally applicable. Although still useful in certain regions, this classification cannot be used with success throughout the entire Coteau des Prairies because it does not take into account the wide variety of landforms and sediment associations which are now considered to have resulted from the stagnation of glacial ice.

Deposits ascribed to the stagnation and subsequent ablation of glacial ice have been referred to by such names as stagnation moraine, dead-ice moraine, hummocky moraine, hummocky disintegration moraine, collapsed drift, ice-stagnation drift, and kame and kettle topography. Even though this drift bears different names in different areas, the landforms are remarkably similar.

A distinctive characteristic of stagnation moraine is that much of the present topography resulted from an inversion of the dead-ice terrain: depressions on the stagnant ice filled with sediment, then converted to hills when the ice melted. Meltwater is disposed of in various ways. If it escapes through tunnels below the ice, such forms as eskers will result. If it emerges from the stagnant ice margin, an outwash plain, fan, or valley train may result. Most meltwater within the stagnant ice area will evaporate, transport debris locally, or become part of the water table. Thus, areas of stagnation moraine are commonly free of widespread outwash deposits. As a result of the retention of this meltwater the superlgacial deposits become saturated, and consequently flowing and sliding are important processes.

LATE-GLACIAL CHRONOLOGY ON THE COTEAU DES PRAIRIES

Late Wisconsin glacial ice advanced on South Dakota perhaps as early

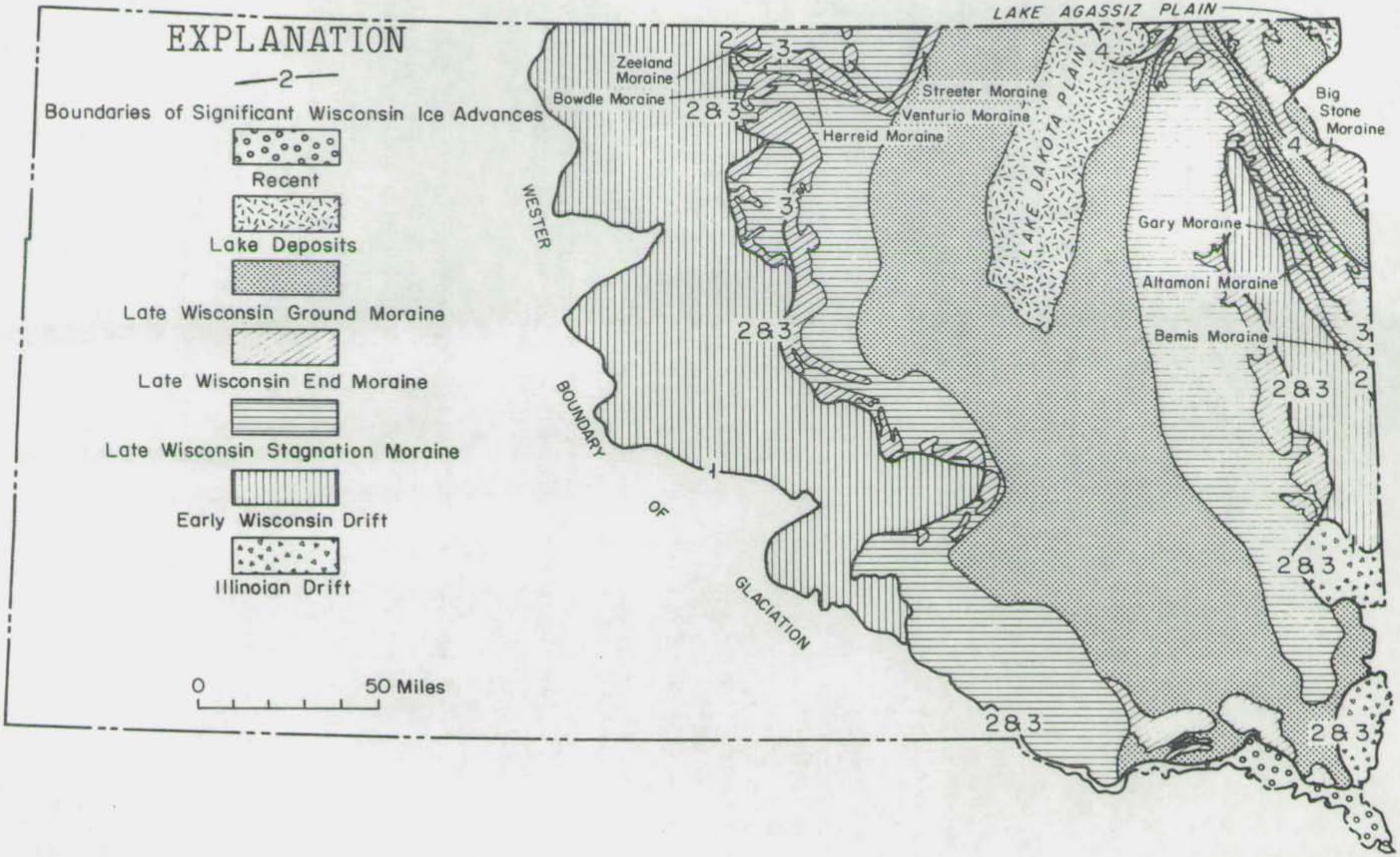


Figure 1. Generalized glacial map of South Dakota.

as 14,000 but sure by 12,760 years B. P. (Y-595). Ice had not completely melted from the vicinity of Sioux Falls in southeastern South Dakota by 11,770 years ago because snails still lived in an ice-walled lake at that time (Steece, 1966; Sample W-1775), nor had it melted from McPherson County in north-central South Dakota by 9,220 years B. P. (W-2305). This date, although on the Missouri Coteau about100 miles to the west, is from a site at about the same latitude and elevation as parts of the northern Coteau des Prairies. These dates are commensurate with dates for superglacial drift insulated and therefore preserved stagnant ice for as long as 3,500 years.

A boreal forest existed in the Nebraska Sandhills, 150 miles beyond the ice margin. Dated material near Pine Ridge, South Dakota, is as old as 12,600 years (Watts and Wright, 1966). The same type of vegetation was present at Pickerel Lake, 300 miles to the northeast of the Sandhills 10,670 years ago (Watts and Bright, 1968). It is probable that deglaciation was well underway 150 miles or so north of Pickerel Lake at 10,670 years B. P., even though there were large areas of glacial ice buried by superglacial drift in the main part of the Coteau des Prairies.

Ice-Stagnation Features

Some of the most numerous and best developed stagnant-ice features preserved on the Coteau des Prairies are described below. These features are landforms that resulted from the inversion of ice-cored topography when the ice melted. All of these stagnant-ice features taken collectively can be termed stagnation moraine.

Disintegration Ridges

Probably the most widespread landforms comprising stagnation moraine, disintegration ridges, take many different shapes, but linear and circular forms are most common. Linear forms have been called linear disintegration ridges (Gravenor and Kupsch, 1959) and ice-contact ridges (Parizek, 1969); the latter term includes eskers and crevas e fillings. Circular forms have been referred to as prairie mounds (Gravenor, 1955), closed disintegration ridges (Gravenor and Kupsch, 1959), rim ridges (Hoppe, 1952), "doughnuts," (Clayton, 1967), rimmed kettles (Christiansen, 1956), and ice-contact rings (Parizek, 1969). Several types of these features are illustrated in Figs. 1 and 2.

These features originated in fields of stagnating ice that were fractured and contained diverse topographic relief. The ridges are formed in one of several ways. Saturated superglacial drift may be transferred to low areas and eventually into crevasses. When the ice melts, the drift is left as a ridge or a set of connected ridges. Alternatively, the origin of these ridges might involve the emplacement of saturated subglacial drift, squeezed up from below into crevasses and other hollows in the basal ice, produced by meltwater action. Some geologists (Hoppe,

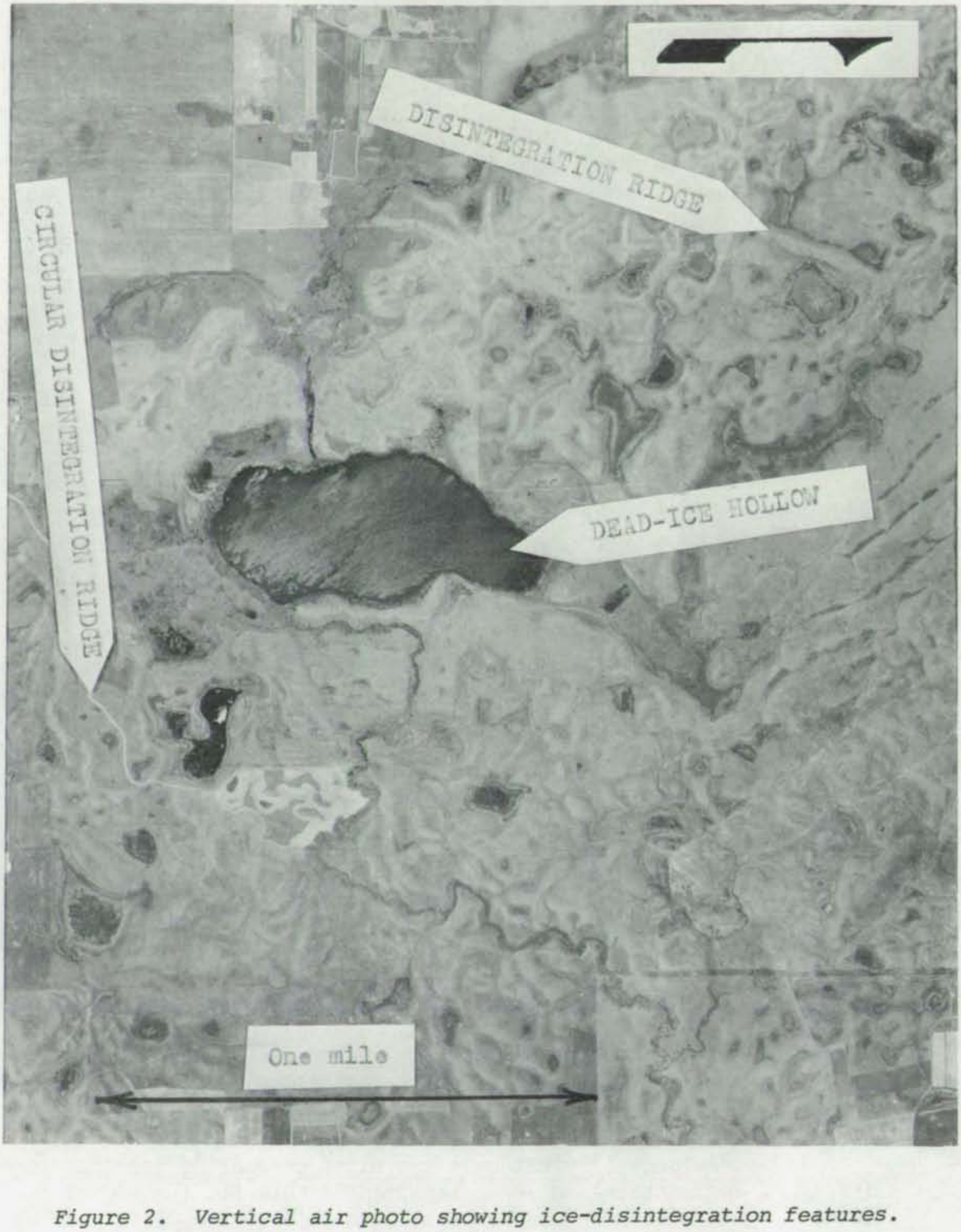


Figure 2. Vertical air photo showing ice-disintegration features.

Figure 3. Vertical air photo showing ice-disintegration features.

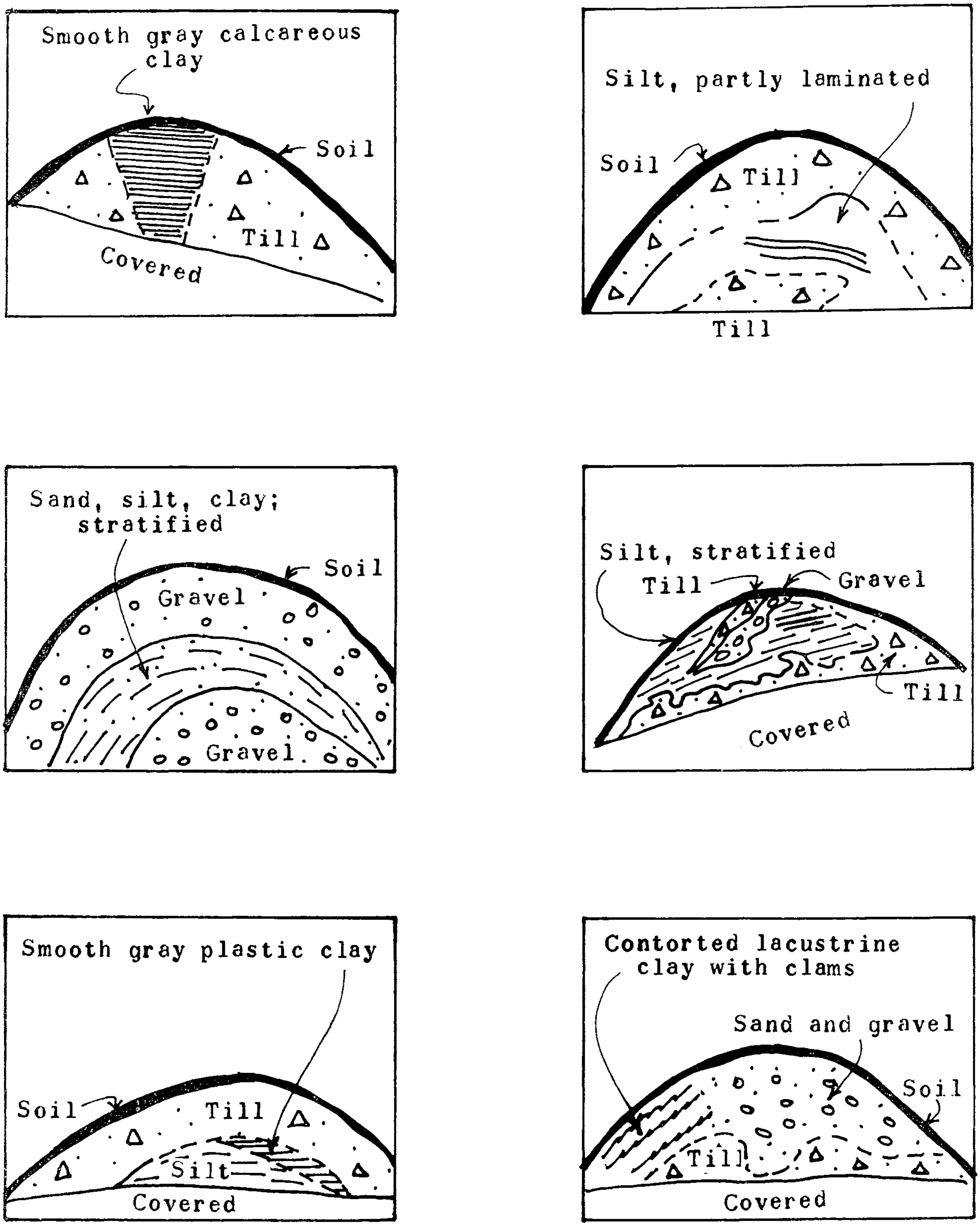


Figure 4. Generalized disintegration ridges showing varied internal structures.

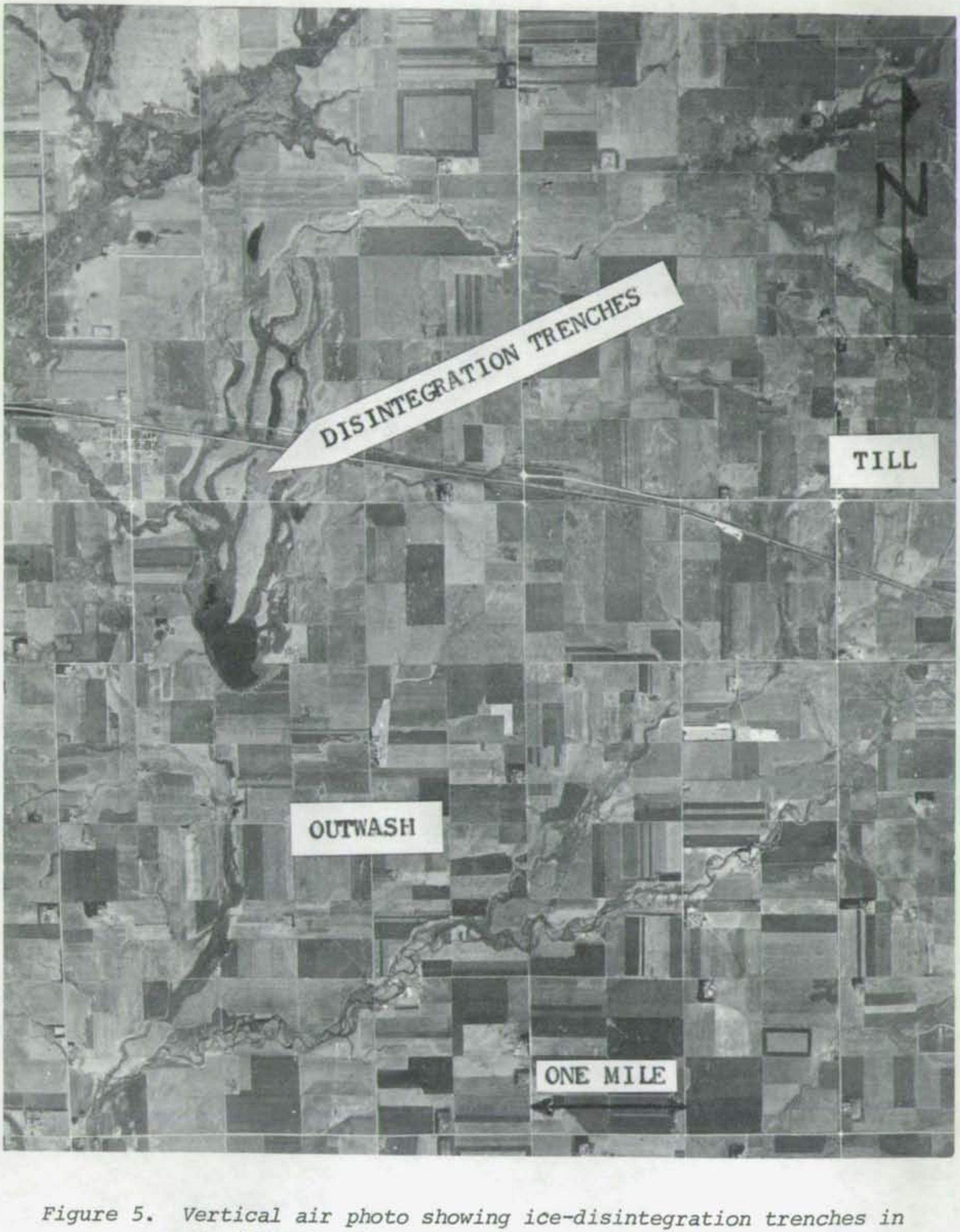


Figure 5. Vertical air photo showing ice-disintegration trenches in glacial outwash.

1952; Stalker, 1960) have used fabric analysis to show that the latter explanation is more tenable than the former. No such fabric studies have been made for stagnation moraine deposits in South Dakota. Therefore, it is not possible to tell which of these features may have formed in several ways. The structures of several types are shown in Fig. 3.

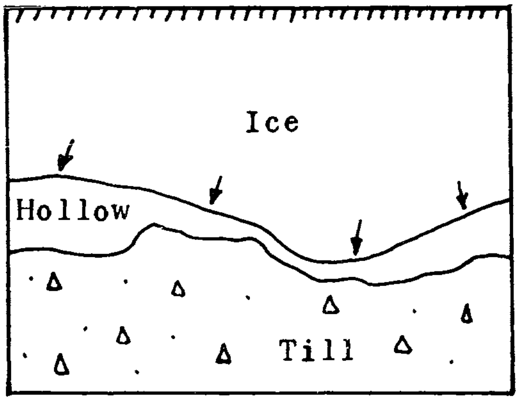
Disintegration Trenches

Disintegration trenches occur mainly in loosely consolidated material, such as outwash sand and gravel, that has been deposited on top of stagnant ice. As a buried ridge of ice melts beneath the outwash material, a channel or trench is formed by collapse of the unconsolidated sediments. Complex systems of such trenches may be formed under favorable conditions. Such a system is shown on the air photos, Figs. 2 and 4.

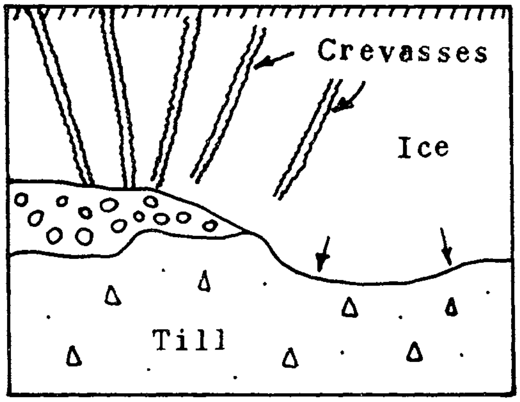
Associated with disintegration trenches are hollows or pits that characterize pitted outwash. Flint (1955) mapped several areas of collapsed outwash in eastern South Dakota. Additional areas of collapsed outwash have been identified in northeastern South Dakota (Steece, 1957).

Ice-walled Plains

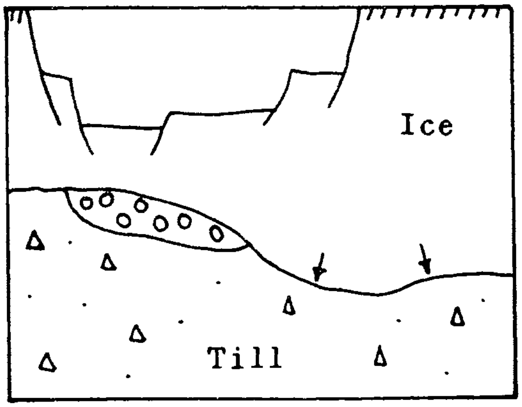
Elevated plains are a common feature in parts of the Coteau des Prairies. These features owe their origins to deposition of fluvial or lacustrine sediments in pits and holes of all sizes and shapes on stagnant glacial ice. The ice walls were removed as the ice melted, allowing the sediments to remain elevated above the general level of the glacier's base (fig. 5). Larger plains commonly have level upper surfaces and sloping sides, where exposures often reveal contorted sediments that resulted from slumping. Many smaller plains may not be recognizable as such unless the real geology is known. In composition, elevated plains range from well-sorted sand and gravel to silt and even clay. In fact, large numbers of smaller plains often clustered in groups are composed of a till foundation overlain by silt and smooth, pebble-free clay. Some of the larger plains stand as much as 150 feet above the surrounding terrain. In area the plains range from several acres to slightly more than three square miles. A number of plains and associated landforms are shown in Figs. 6, 7, and 8.



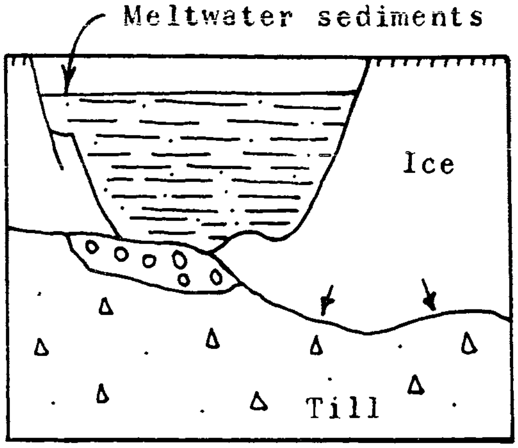
1. Ice stagnates, till is squeezed into sub-ice hollows.



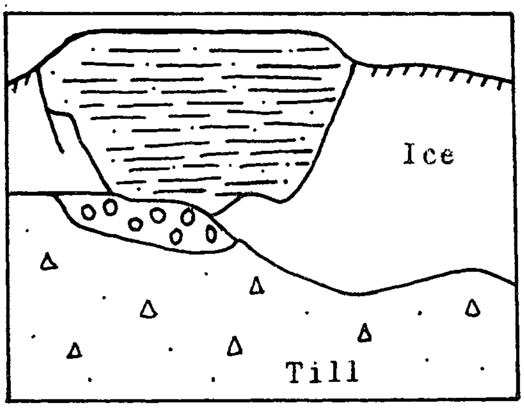
2. Crevasses form over sub-ice hollow; gravel may be washed in over till.



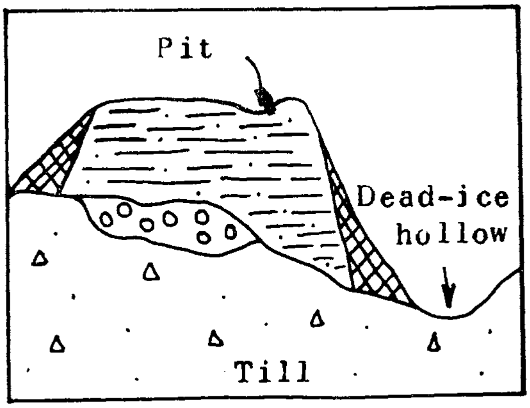
3. Ice collapses over sub-ice hollow.



4. Meltwater sediments are deposited in collapse-basin in ice.



5. Topography begins to invert as ice-melting progresses.



6. Ice melts and meltwater sediments are slumped at edges.

Figure 6. Idealized formation of elevated plains.

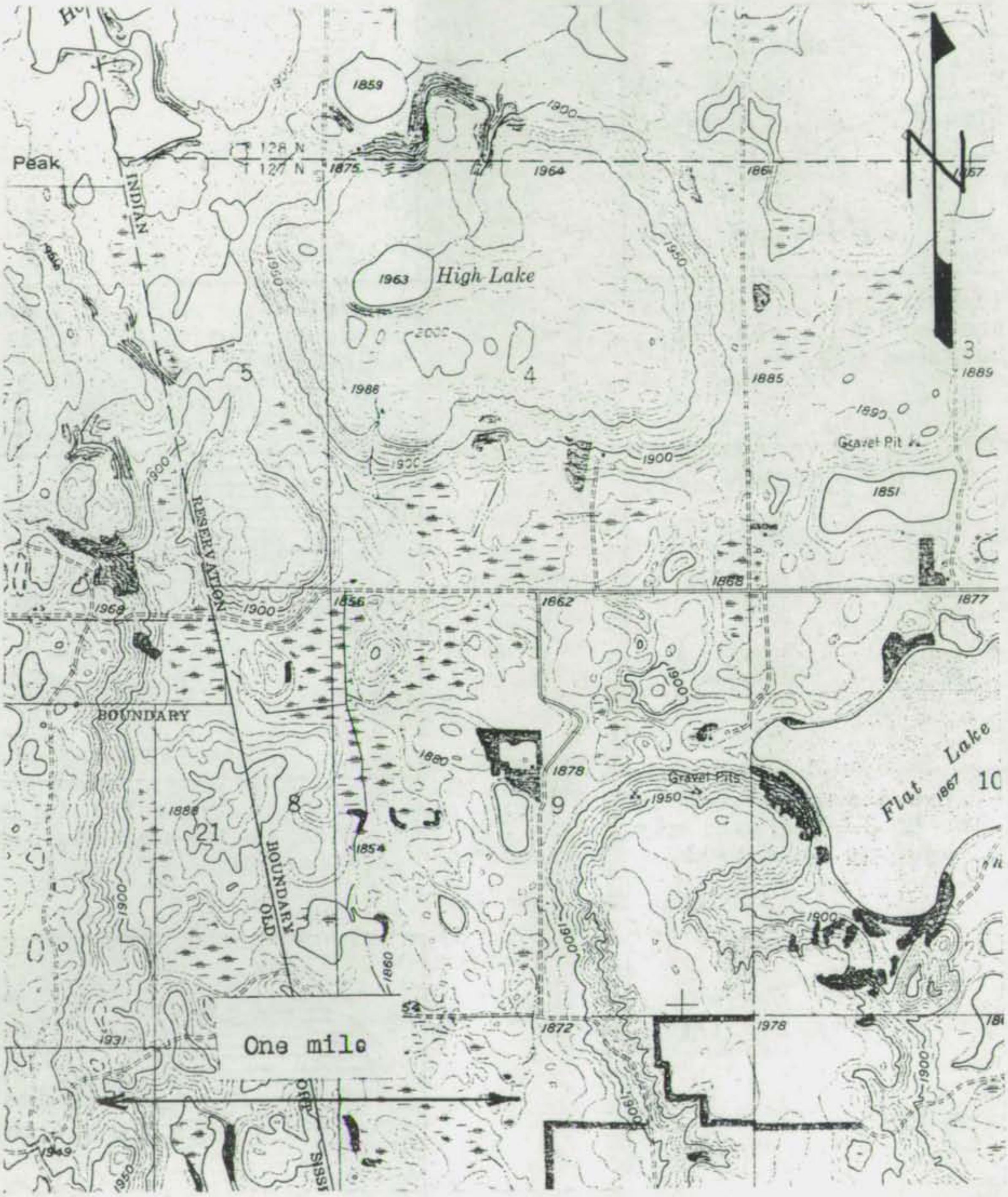


Figure 7. Part of the Hillhead 7.5-minute topographic quadrangle showing elevated plains.

Figure 8. Vertical air photo showing ice-stagnation features on the Coteau des Prairies.

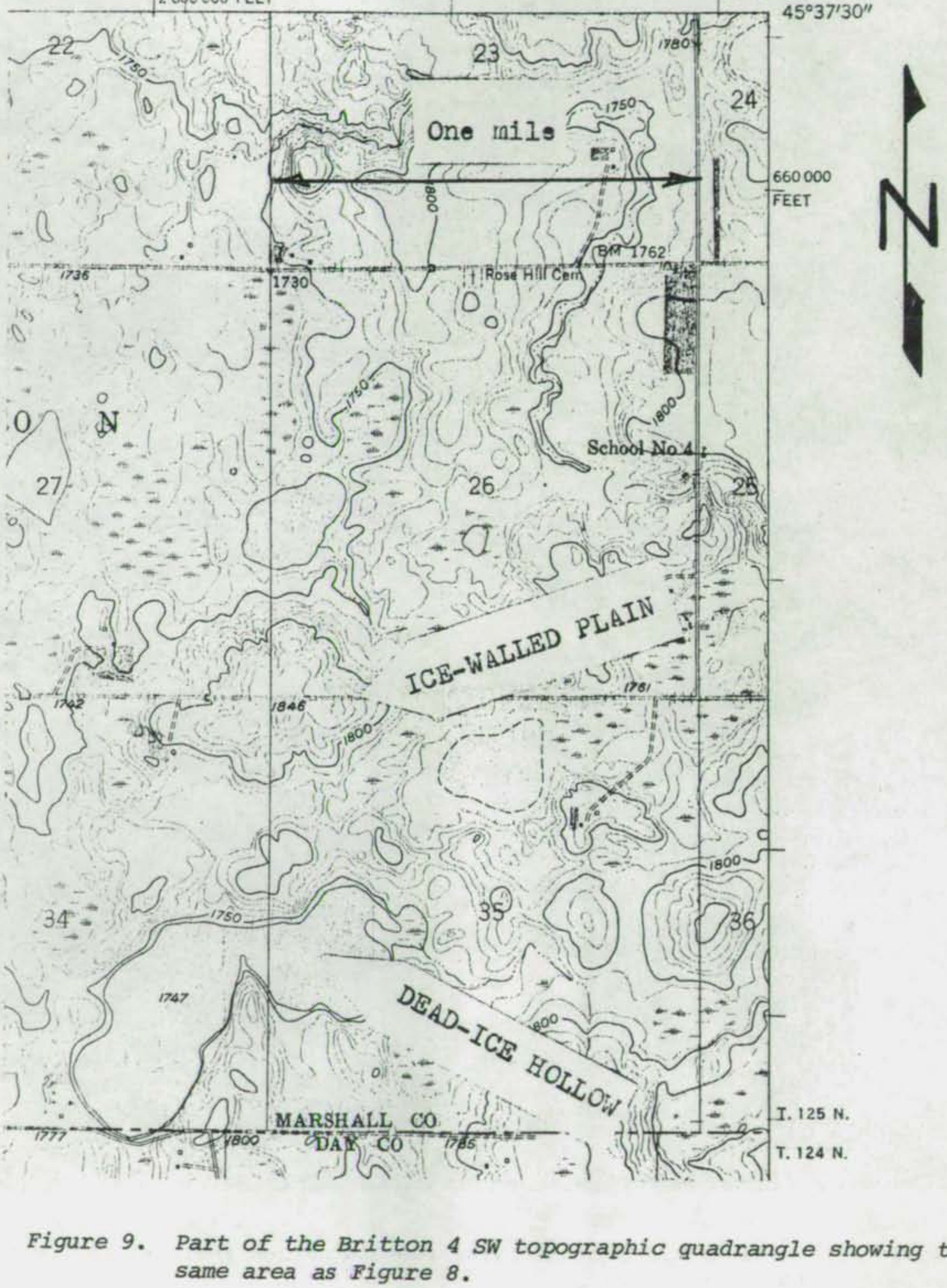


Figure 9. Part of the Britton 4 SW topographic quadrangle showing the same area as Figure 8.

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POSTGLACIAL ENVIRONMENTAL HISTORY OF THE COTEAU DES PRAIRIES

H. E. Wright

Today the Coteau des Prairies is in the heart of the American grasslands, with extensive agricultural fields covering most of the landscape; but a few stony morainic areas are restricted to grazing, and a few isolated woodlots surround depressions. During Wisconsin glaciation, two major ice lobes fringed the wedge-shaped plateau -- the Des Moines lobe on the east and the James lobe on the west. What was the country like in the intervening time, from the time of ice wastage until the present?

The Des Moines lobe stood at the Bemis moraine along the east edge of the coteau about 14,000 years ago -- if the carbon dates from the Bemis moraine in Iowa are applicable (Ruhe, 1969). The lobe then withdrew from this terminus, and Lake Agassiz, which formed in part in the area vacated by the ice, was in existence by 12,000 years ago.

Much of the subsequent environmental history of the Coteau des Prairies is recorded in the sediments of Pickerel Lake, in Day County, west of Sisseton, South Dakota, near the northern end of the Coteau (fig. 1). The lake is a long, narrow feature with a maximum depth of 13 m, located in an outwash valley train associated with the Bemis and Altamont moraines. Cores of sediment taken from the shallow northern end of the lake provide the basis for reconstructing not only the history of the lake since the time of its formation but also the regional history of the vegetation and climate. Analysis of pollen, seeds, and mollusks (Watts and Bright, 1968) and diatoms (Haworth, 1972) have so far been completed, as well as a study of the oxygen-isotope ratios of mollusk shells in the core (Stuiver, 1970).

The basal organic sediments of Pickerel Lake (figs. 2 and 3) contain fossils of spruce and tamarack and other conifer-forest plants -- seeds and other macrofossils as well as pollen grains (pollen zone 1). This type of spruce assemblage is characteristic of sites throughout central and eastern North America, from Saskatchewan to New England and south to Kansas (Wright, 1971), implying a very extensive spruce forest and relatively cool climate extending southward from the ice front. A tundra existed concurrently in northeastern Minnesota at this time, but there is no evidence for tundra on the Prairie Coteau or in southern Minnesota.

The spruce forest must have been remarkably uniform throughout most of its extent. The conifer forest of Canada today covers an area just as big, from the Rockies to the east coast and from Hudson Bay to the Great Lakes, but it is not a good analog, because it has jackpine as a principal component in all except its northern fringe, whereas the late-glacial spruce forest of the Middle West apparently had no jackpine, although in New England jackpine (or red pine) occurred along with the spruce, and southward along the Appalachian Mountains jackpine was dominant (Wright,

Figure 1. Air photograph of Pickerel Lake. The pollen and diatom cores were taken near the base of arrow number 2. From Watts and Bright (1968).

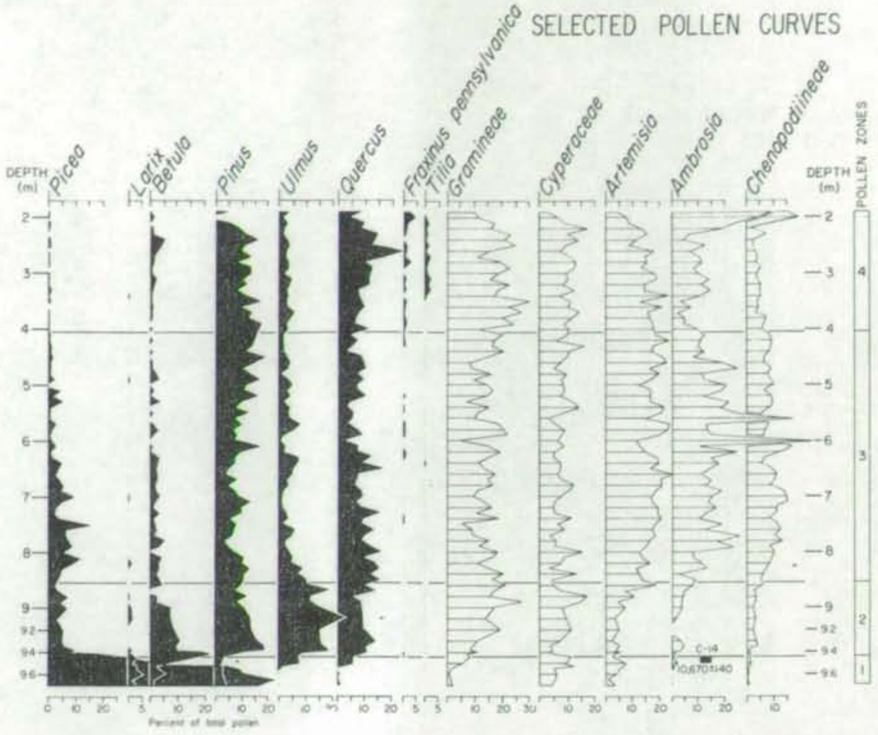

Figure 2. Abbreviated pollen diagram for Pickerel Lake. From Watts and Bright (1968).

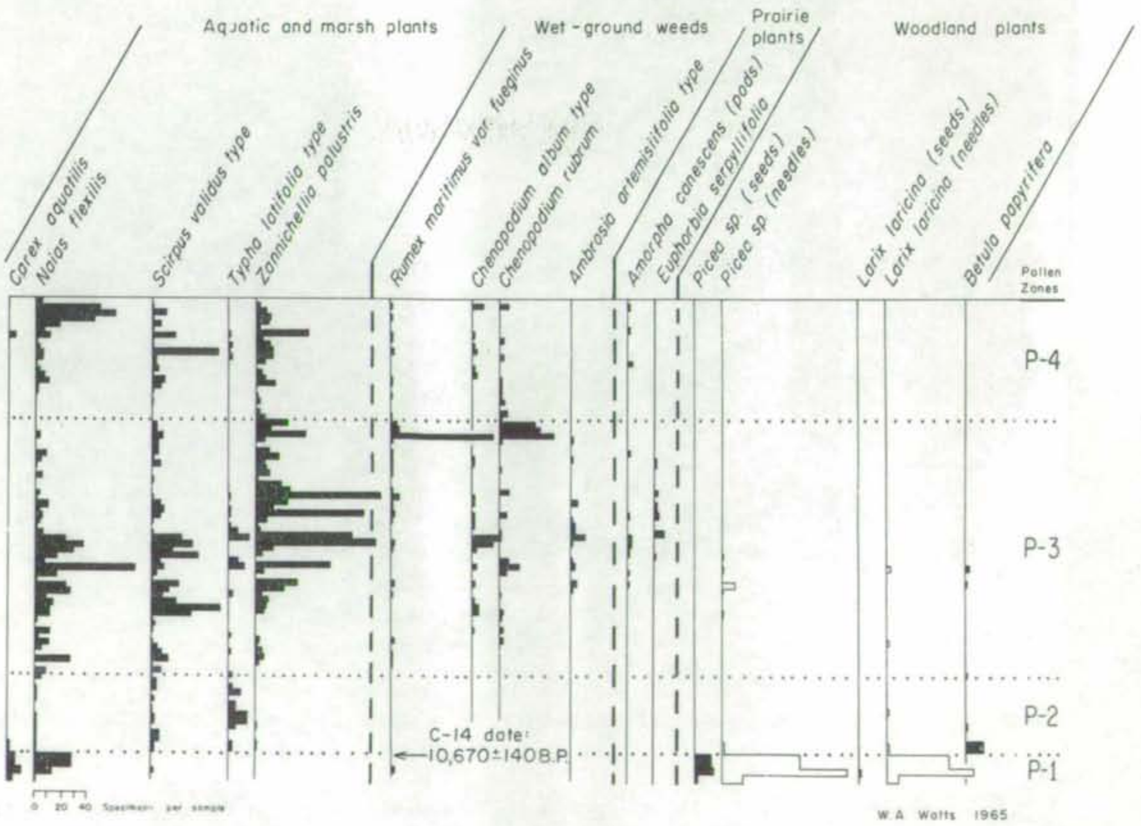

Figure 3. Plant-macrofossil diagram for Pickerel Lake, showing some of the environmentally most significant types. Zone designations and depths are the same as on Figure 1. From Watts and Bright (1968).

1971).

The spruce forest was not only uniform in composition over a wide area but also over a long span of time, at least in the periglacial area. The record on the Coteau des Prairies is limited to the very end of the spruce interval, but at a site 425 miles south in northeastern Kansas the spruce forest persisted from 22,000 to at least 16,000 and probably closer to 12,000 years ago with little change in composition (Gruger, 1972). This implies that the ice-margin fluctuations that are recorded by retreatal moraines of the Des Moines lobe (e.g. Altamont) or the James lobe were not reflected in vegetational shifts of a magnitude sufficiently large to be recorded by pollen analysis in the periglacial region. The same statement can be made for earlier ice-margin fluctuations within the main-Wisconsin glaciation (20,000-14,000), such as are represented by the various retreatal moraines of the Lake Michigan lobe in Illinois.

Pickerel Lake itself at the time of the spruce forest was sedimenting sand and silt at the coring site. The aquatic and semi-aquatic plants found as fossils in these silty sediments are characteristic of the basal layers of several Minnesota lake-sediment cores; they represent an assemblage of pioneer plants in newly formed lakes of conifer-forest areas (fig. 3). The few mollusks found in these sediments imply a lake only a few meters deep -- as does the concentration of terrestrial plant debris. But if the lake filled to the level of its outlet at this time -- and certainly the climate implied by a spruce forest should provide enough water tokeep the level high -- it would have been 9 m deep, contrary to evidence from the fossils. Therefore the floor of the lake must have been higher, by virtue of the persistence of stagnant glacial ice in the outwash valley train beneath the lake. Such relations are postulated as normal for the early phases of many Minnesota lakes, because of the common cccurrence of a basal layer of plant detritus in lake sediments (Florin and Wright, 1969). In fact, much of the terrain of the day -- not only outwash plains but also moraines -- may have been underlain by dead ice (Clayton, 1967). The persistence of dead ice over thousands of years implies mean annual temperatures in the sub-freezing range, for buried dead ice is geothermally the same as permafrost. If insulated by the debris cover from surface melting, the ice will melt only from the bottom upward under such a thermal regime. Flow of terrestrial heat is such as to be able to melt only about 0.5 cm/yr, so a mass of dead ice 30 m thick would require 6000 years to melt at that rate. It is therefore presumed that melting from the surface downward is the more likely, as a result of accidental removal of the insulational cover (Florin and Wright, 1969; Wright, 1972).

Such local exposure of buried dead ice can result in the formation of small ponds, which tend to enlarge by slumping and erosion of the unstable slopes that bound them. Under these conditions the inwash of silt and sand during the early stage of Pickerel Lake brought along not only forest-floor detritus but also Cretaceous microfossils eroded from the glacial drift. The diatom flora of the basal lake sediments does not contain the terrestrial forms found in a similar situation in a Minnesota lake (Florin, 1970), but it does contain some acid-loving forms that are generally associated with conifer-forest lakes (Haworth, 1972).

The spruce forest was terminated abruptly on the Coteau des Prairies about 10,700 years ago, according to a C-14 date, and was replaced by hardwood forest. This sudden change is seen also elsewhere throughout the central and eastern North America. The change was less pronounced in the north near the present range of spruce, and the forest that succeeded there was different. Available carbon dates and pollen diagrams suggest that the time of this event was younger to the north. The best control on the sequence is in Minnesota: in the south the spruce forest gave way 12,500 years ago to birch and alder; in east-central Minnesota a change to pine occurred very abruptly about 10,500 years ago; and in the northeast a more gradual transition is recorded as late as 9500 years ago.

This conspicuous vegetational change, by far the most important in the entire late- and postglacial history, must have been caused by climatic change -- presumably the same change that caused the accelerated wastage of the Wisconsin ice sheet in the Great Lakes region, as well as the final melting of most of the buried ice blocks. The rate of vegetational change at any one point, however, is not necessarily a true measure of the rate of climatic change. Pickerel Lake, for example, may have been in the heart of a homogeneous spruce forest 12,000 years ago that extended from Manitoba to Kansas. Somewhere farther south was the edge of the forest. When the warming interval started, it had little effect on the heart of the forest but caused the southern edge, which may have been quite sharp, as today, to migrate northward. When this edge, or ecotone, passed the Pickerel Lake area, the forest composition and thus the pollen rain changed abruptly. Although the duration of the transformation cannot be measured at Pickerel Lake, the change at a site in eastern Minnesota occurs in less than 5 cm of sediment in a 10-m core; radiocarbon dates indicate a duration of less than 100 years for spruce forest without pine to be transformed to pine-birch forest with negligible spruce.

The biogeographic and ecologic processes involved in this abrupt transformation are difficult to visualize. Apparently the climate simply became unfavorable for the regeneration of spruce, and the space made available by blowdown or fire was taken by whatever other tree types were in the vicinity. This event must have drastically changed the animal life of the area as well, and thus the population and economy of prehistoric man. The anthropological implications of these events have been discussed by Shay (1971).

On the Coteau des Prairies the spruce forest was transformed to deciduous woodland around depressions and north-facing slopes, with areas of prairie on dry exposures (pollen zone 2). The woodland contained more elm trees than today, and it even contained some birch and fir trees. The prairie areas were dominated by grasses and perhaps bracken fern, but the varied herb types of later prairies were not common.

Pickerel Lake itself at this time was deeper than before, according to the mollusk assemblage, and the buried ice had presumably melted out. The lake by this time was a typical hard-water lake with carbonate sedimentation. The changing diatom assemblage indicates increasing salinity, especially in the younger part of the deciduous woodland period (fig. 4).

About 9000 years ago, in response to continued climatic change, the woodland on the Coteau des Prairies diminished in extent in favor of prairie (pollen zone 3). The fringe of woodland around Pickerel Lake became not only less extensive but less diversified, with a probable dominance of xeric species such as bur oak. The prairie areas were characterized by ragweed, sage, and pigweed as the main pollen producers rather than grasses. Prairie may have covered many of the basin slopes as well as all of the upland, for numerous seeds of prairie plants were found in the sediments of zone 3. Lake levels were intermittently low, permitting the temporary spread of weedy annual plants over the lake margins, as recorded by both seeds and pollen grains in the sediments. Low lake levels are also implied by the admixture of redeposited pollen and needles of spruce and tamarack, presumably eroded from zone-1 sediments exposed around the margin of the diminished lake. A layer of sand and even gravel in zone 3 marks an unconformity that further implies erosion of previously deposited sediments. The mollusk assemblage in pollen zone 3 also suggests shallow but fluctuating water levels.

A condition of low water levels for the time of pollen zone 3 is supported by isotope studies of mollusk shells separated from the sediments: higher ratios of O^{18}/O^{16} and C^{13}/C^{12} indicate increased evaporation during that interval (Stuiver, 1970). Increased evaporation for zone 3 is also implied by the diatom profiles, which show higher proportions of diatom types that favor waters with greater alkalinity, salinity, and trophic status (fig. 4). Evaporation, however, was never enough to concentrate the salts in the lake water to the point where the aquatic macrophytes changed significantly (fig. 3). The lake probably overflowed periodically, so the ionic content never built up sufficiently to reach a brackish state. The diatom assemblage, however, does indicate a slight increase in alkalinity, salinity, and trophic status consistent with increased inwash of calcium and other nutrients and increased evaporation (fig. 4).

About 3500 years ago the long interval of prairie dominance in the Pickerel Lake area became modified slightly by the minor expansion of woodland on the slopes around the lake, leading to the present situation. Green ash and ironwood became more conspicuous, and basswood apparently immigrated for the first time. The ratio of grasses to other herbs (especially ragweed) increased, and the number of seeds of weedy annual plants decreased. All indications point to a gradual reversal of the earlier climatic trend, bringing more woodland and generally higher lake levels.

The natural sequence of environmental changes in and around Pickerel Lake, thus traced by microfossil studies of the sediments, clearly represents the postglacial trends that are now documented throughout the prairie border region and eastward into the conifer-forest region. The

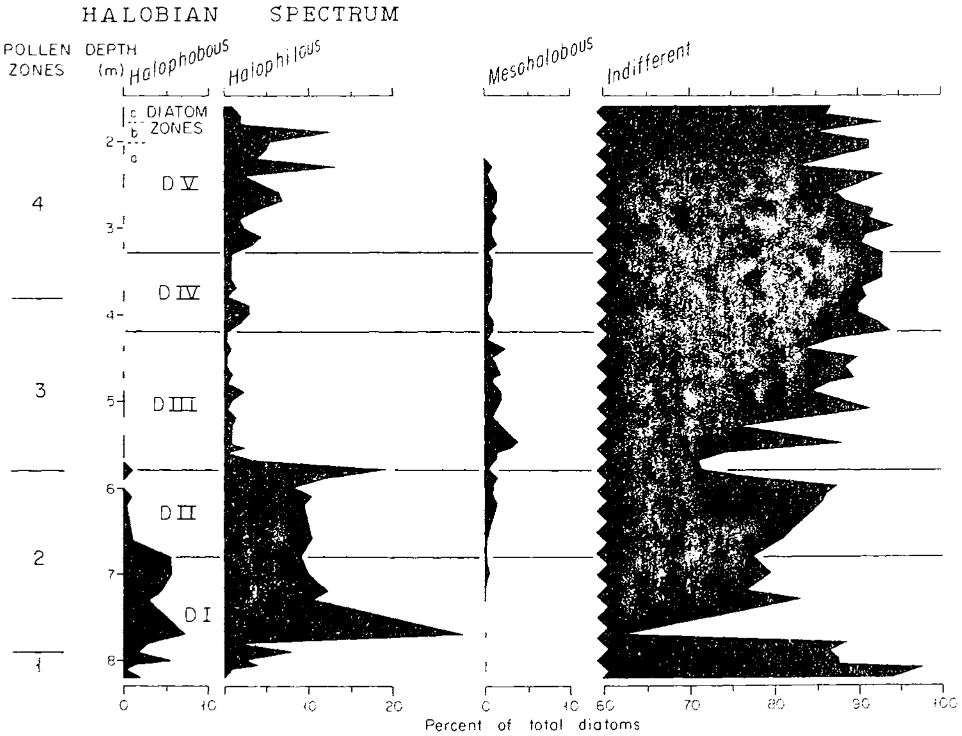

Figure 4. Summary of diatom stratigraphy at Pickerel Lake according to salinity preferences. Halophobous taxa are mainly found in chloride-deficient freshwater. Halophilous species can tolerate slightly brackish water. Mesohalobous species are found preferentially in brackish water. Depths in this core are different from those of the core of Figures 2 and 3, but the pollen zone boundaries permit a comparison. From Haworth (1970)

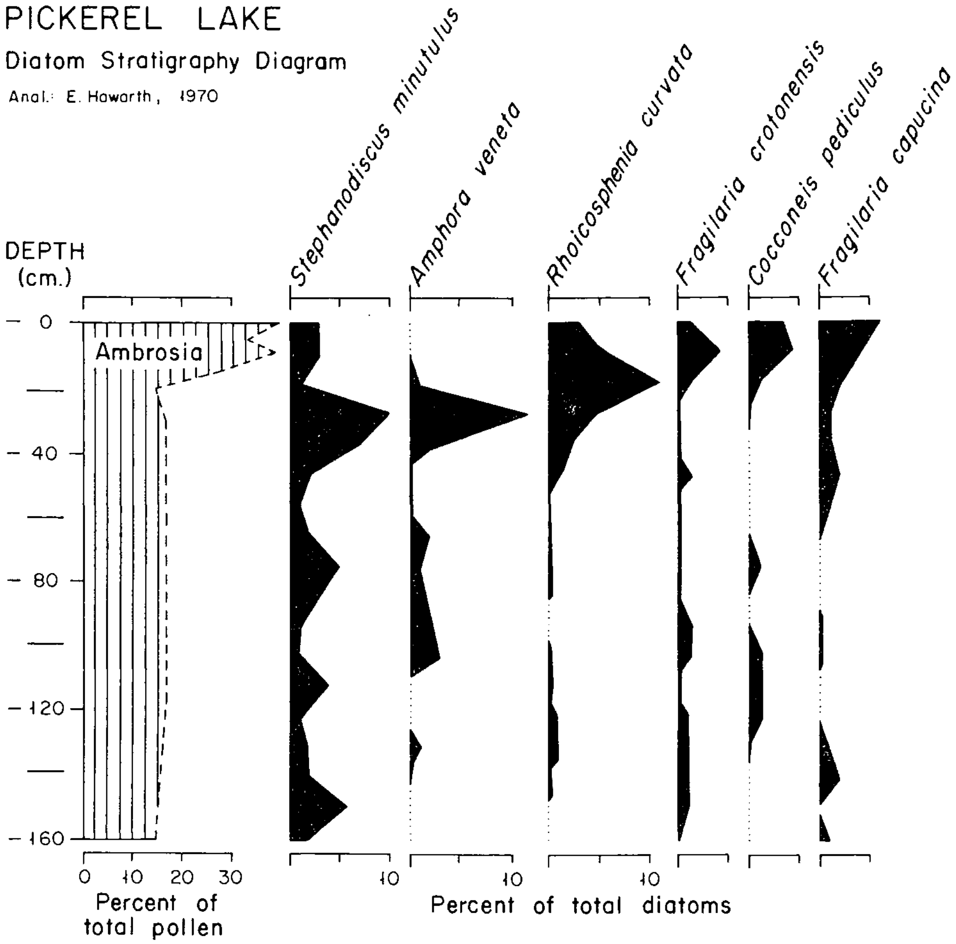

Figure 5. Selected diatom profiles from the upper part of the Pickerel Lake sediment, showing the abrupt changes in percentage of certain species, presumably related to pollution. Increase in Ambrosia (ragweed) pollen indicates time of agricultural land disturbance. From Haworth (1970).

rather rapid trend towards a warmer and drier climate following glacier retreat probably reached a maximum about 7000 years ago, and the reversal to the modern climate has been somewhat slower. The boundaries of the major vegetational belts moved in response to these climatic shifts, as did the lake types associated with these belts. When the boundary (ecotone) passes a particular lake, the stratigraphic succession records the passage. Thus the fully developed prairie reached Pickerel Lake (from the south?) about 9000 years ago and continued expansion eastward to southeastern Minnesota (Kirchner Marsh), which it reached about 8000 years ago. In reversal, the prairie border passed back across the Kirchner area 5500 years ago, but its influence was not felt on the Coteau until 3500 years ago. The same space/time shift of pollen-zone boundaries, and thus ecotones can be seen in Minnesota for other intervals of postglacial time, giving a strong dynamic flavor to the environmental history of the midcontinent. At the same time, the sequence indicates that the vegetation does not migrate completely without change, and that new dominant elements are introduced into long-established communities, perhaps as a result of differential rates of migration of different plants under the impetus of environmental change. This biotic factor provides an additional dimension to the dynamic character of vegetational change, which thereupon requires more extensive investigations of the time/space relations to lead to greater understanding of the natural world.

Not to be neglected in any account of the environmental history of a particular area is the extent of the modern perturbation. The Prairie Coteau is now a region of extensive agriculture and, on some of the more rugged, stony moraines, of grazing activities. The epoch of land disturbance is recorded on the pollen diagram for Pickerel Lake by an increase in ragweed pollen in the uppermost levels of the sediment, accompanied by an increase in pollen of chenopods and other weedy plants. Such increases are recorded in short cores of lake sediment throughout the eastern half of North America, and it is a very useful marker to determine the time of agricultural development. At Pickerel Lake the rise in pollen percentages for these types is sharp indeed, and it means that the upper 20 cm of sediments were deposited within the last century. For the same interval, the diatom diagram (fig. 5) shows abrupt increases in certain forms that are associated with nutrient enrichment, indicating that the land disturbance or the subsequent dispersal of lake-shore cottages affected the water quality as well as the environs of Pickerel Lake. More detailed analysis of such a stratigraphic sequence can elucidate with remarkable detail the records of man's disturbance to the natural environment. Availability of the long record of all of postglacial history provides the perspective for appreciating the magnitude of the modern disturbances.

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A POSSIBLE PENEPLAIN OF EARLY LATE CRETACEOUS AGE IN MINNESOTA

Walter E. Parham

Meinzer, as early as 1911 (in Hall and others, 1911) suggested that a peneplain may have formed over a part of southern Minnesota as a result of an intense weathering episode that took place prior to Late Cretaceous sedimentation. He visualized the Sioux Quartzite, of southwestern Minnesota, as having formed prominent ridges or mesas surrounded by widespread flatter areas of deeply weathered granite. His suggestion seems reasonable with respect to observations and data assembled more recently regarding these weathering products and their mineralogy (Parham and Hogberg, 1964; Parham, 1970). However, the distribution of the weathered material suggests that probably at least the west one-half of Minnesota and the eastern extremities of North and South Dakota had undergone deep weathering as well, and that a peneplain had developed over much of this region. The peneplain surface is marked by a hard, iron-stained, pisolitic kaolin clay (fig. 1) which formed in Early Late Cretaceous time. The deeply weathered residuum, which is as much as 200 feet thick and which for the most part formed on Precambrian igneous and metamorphic rocks, is present beneath Pleistocene glacial deposits and Upper Cretaceous sedimentary rocks in much of the western half of Minnesota. However, in parts of southeastern Minnesota, the residuum formed on certain Paleozoic sedimentary rocks and it too is overlain by Pleistocene drift.

The residuum (unit 1) is rich in kaolinite and quartz, and the relative proportion of each mineral is directly related to the composition of the underlying parent rock. Reworking of the upper part of the residuum by running water during Early Late Cretaceous time produced kaolinitic quartz sands and sandy kaolinitic clays, nearly pure kaolinitic clays, and hard, iron-stained pisolitic kaolin clays (unit 2). Subsequent erosion of a part of the sedimentary and residual kaolins of units 1 and 2 resulted in redeposition of kaolinite in the lower few tens of feet in the overlying organic-rich Upper Cretaceous sediments (unit 3). The three units and their clay mineral assemblages are shown in Figure 2.

The general succession of rocks in unit 2 from the base upward is: (a)kaolinitic sandstone or sandy kaolinitic clay, (b) white kaolinitic clay, (c) grayish-white, pisolitic, kaolinitic clay, and (d)iron-stained, hard, pisolitic clay. Contacts between the four lithologies generally are transitional. The succession has a maximum observed thickness of approximately 45 feet, but commonly is much thinner. Its overall color depends upon the amount of oxidized iron present, which increases in abundance upward in the section, and manganese, which discolors the clays or sandstones to various shades of light purple, red, and black.

The uppermost part of unit 2 is an iron-stained, hard, pisolitic clay (fig. 1). Generally it is three to five feet thick, however, its

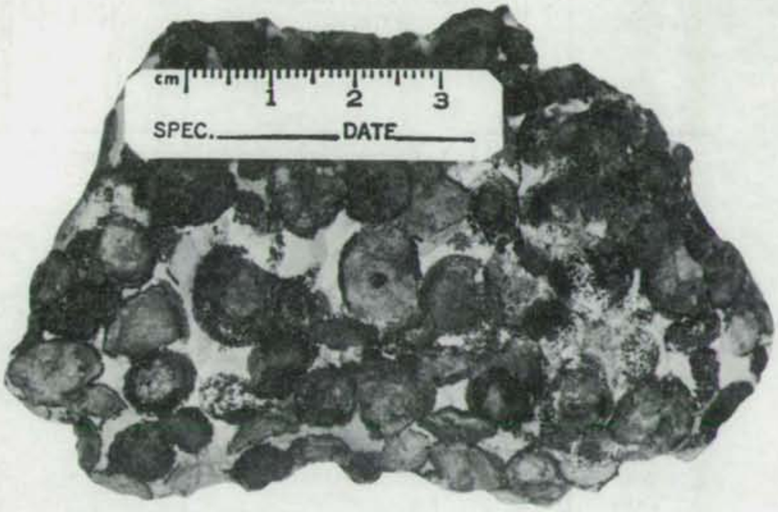

Figure 1. Iron-rich, hard, pisolitic kaolinite of Late Cretaceous age from sedimentary rock unit 2. White matrix is poorly crystalline kaolinite and the clay fraction within pisolites is mainly poorly crystalline kaolinite with lesser amounts of gibbsite and boehmite.

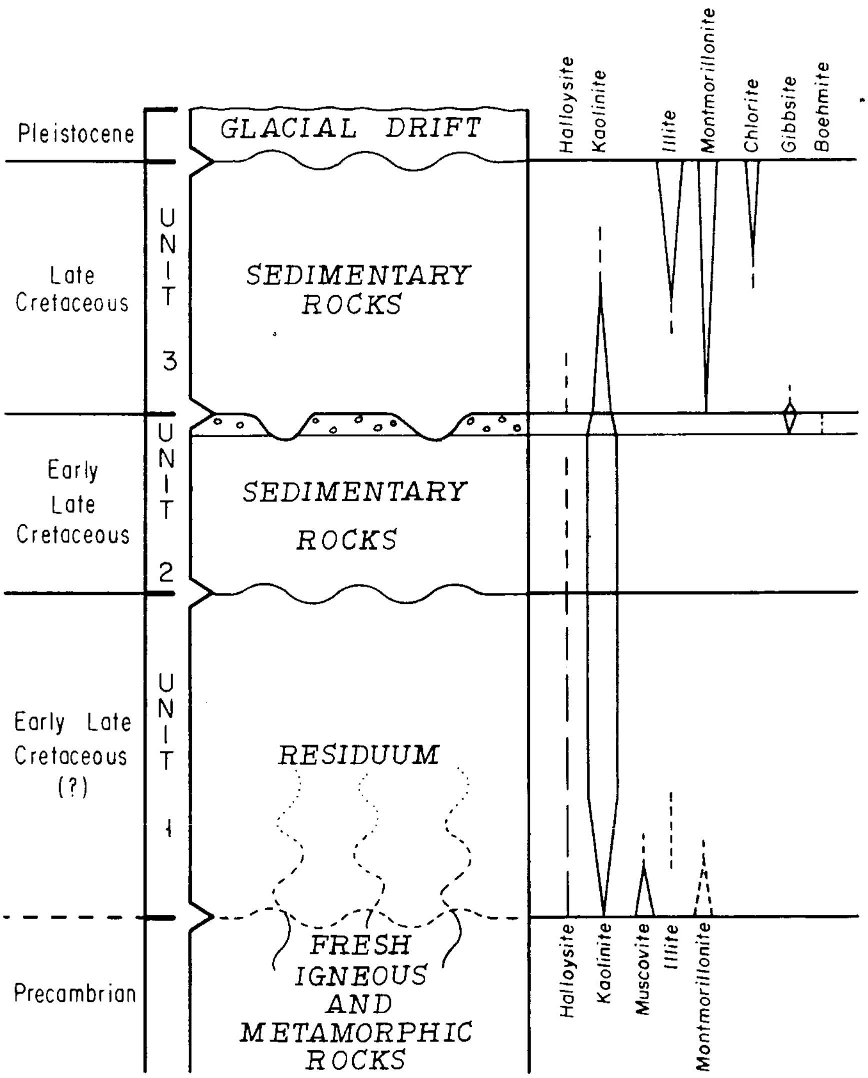

Figure 2. Vertical variations in the clay mineral assemblages of the weathered residuum and of the Upper Cretaceous sedimentary rocks of Minnesota.

maximum observed thickness is 15 feet. Texturally, this rock type is the most distinctive in the sedimentary succession of unit 2 in that it resembles many bauxites.

The iron-stained, hard pisolitic clay has been observed in the field or recognized in cuttings from drill holes from Stearns and Morrison Counties in central Minnesota to Blue Earth County in the southeast, westward through Brown, Renville, Redwood, Yellow Medicine, and Lyon Counties, and north to Ottertail County. It is resistant to erosion and forms ledges in outcrop whereas the sedimentary rocks beneath it are softer and slump more easily. Pre-Pleistocene erosion and Pleistocene glacial scouring removed much of the overlying soft shales and clays of unit 3. Commonly, glacial till lies directly on the hard pisolitic clay.

An incipient development of a pisolitic texture has been noted at a few localities in the clays and sandy clays that lie beneath the pisolitic clay capping unit 2. The pisolitic zones in this stratigraphic interval are thin and seem to be discontinuous laterally however, and generally the pisolites are as soft as the enclosing material. Some of the pisolitic zones have a pale green color, but most have a white or buff matrix with iron stain outlining soft pisolites. It is not difficult to distinguish the lower poorly developed pisolitic units from the iron-stained hard one that caps the sedimentary rocks of unit 2.

Minnesota was a land area during the last half of Paleozoic time until Early Late Cretaceous time. During the latter part of the Jurassic Period and/or during Early Cretaceous time an epicontinental sea encroached on Minnesota from the west; the decrease in altitude of land surfaces caused a warming climatic trend and accelerated the rate of rock weathering (Sloan, 1964). Sloan suggested that the climate in Minnesota during the weathering interval was most probably humid warm-temperate to humid subtropical. Weathering under humid subtropical or tropical conditions rather than under humid temperate conditions seems more likely to have been responsible for development of a residuum of several hundred feet in thickness. Such thicknesses do not commonly develop under humid temperate conditions nor are as widespread.

The residuum in Minnesota, which grades downward into fresh parent rock, does not contain gibbsite, $Al(OH)_3$, and thus two possibilities are suggested regarding the conditions of leaching during the residuum's formation: first, leaching of the parent rock might not have been sufficiently intense to remove enough SiO_2 to produce gibbsite, or secondly, if gibbsite had been produced during the weathering process it may have been resilicated later to form kaolinite. The first possibility seems more likely, because even bauxites do not develop to thicknesses of hundreds of feet; and it is also unlikely -- with the relatively high percentage of primary quartz still present in the residuum -- that the concentration of dissolved SiO_2 in leaching waters was sufficiently low during the weathering period to allow for formation of massive quantities of gibbsite. Very likely there was resilication of small amounts of gibbsite that may have formed along principal drainage pathways through the rock.

A thick weathered residuum probably did not develop on the Precambrian Sioux Quartzite as it did on granites, gneisses, and basic rock types because of the low permeability of the quartzite and because of its high quartz content and low content of aluminous minerals. However, a part of the weathered residuum is preserved, and is exposed in the New Ulm Quartzite Quarries, Inc. at SW1/4 sec. 35, T. 110 N., R. 30 W., Nicollet County. The quartzite at this locality has been weathered to a light pinkish white, friable sandstone. The clay fraction of the weathered quartzite is composed entirely of kaolinite. A detailed clay-mineral study of weathering products from this quarry has been made by Austin (1970). The fresh rock in the quarry has been shown by Miller (1961) to consist of (other than quartz) sericite, illite, and diaspore.

The question arises also as to whether or not the igneous and metamorphic bedrock terrane was covered by vegetation during the episode of weathering. If, as Sloan (1964) has suggested, the period of weathering that produced the thick kaolinitic residuum started in Late Jurassic time, it would seem likely that the land surface in Minnesota would have been covered with vegetation because, according to Arkell (1956), the later part of the Jurassic Period was generally marked by a very mild climate even in high latitudes and by the presence of abundant and varied vegetation. Ruxton and Berry (1957) have shown that when deforestation takes place in the humid tropics over hilly deeply weathered terrane, erosion will quickly remove much of the upper decomposed material and will expose unweathered core stones. Continued erosion will lead to the down-slope movement of core stones, and eventually to some of them being carried to valley bottoms. In Minnesota, core stones have not been observed at the contact of the residuum and the overlying sedimentary rocks. In fact, they are rare in outcrops of the residuum of weathered granites and gneisses in Minnesota, although drilling indicates that they most likely occur deep in the weathering profile. Thus, the lack of core stones at the upper surface of the residuum suggests the presence of a vegetation cover over the land during the time of weathering. Ruxton and Berry (1959) also point out that if weathering conditions persist for long periods of time after weathering has reached its deepest level, core stones in the residuum would continue to decrease in size, and if the weathering process continues even longer, all core stones would be destroyed and there would be an abrupt transition from weathered residuum into fresh parent rock. This might explain the observed sharp contact between fresh and highly weathered granite in Stearns County at the Cold Spring "crystal" quarry.

Further weathering and erosion of Precambrian rocks eventually provided sufficient sediment to fill the meandering stream valleys, and concurrently the hills were reduced to a rolling plain. Further lowering of the land surface resulted primarily from chemical weathering. Kaolinite, halloysite, and residual unweathered feldspars decomposed further as rainwater leached additional silica from their structures, forming gibbsite from the aluminous-rich residue.

During this late stage in the weathering history the pisolitic kao-

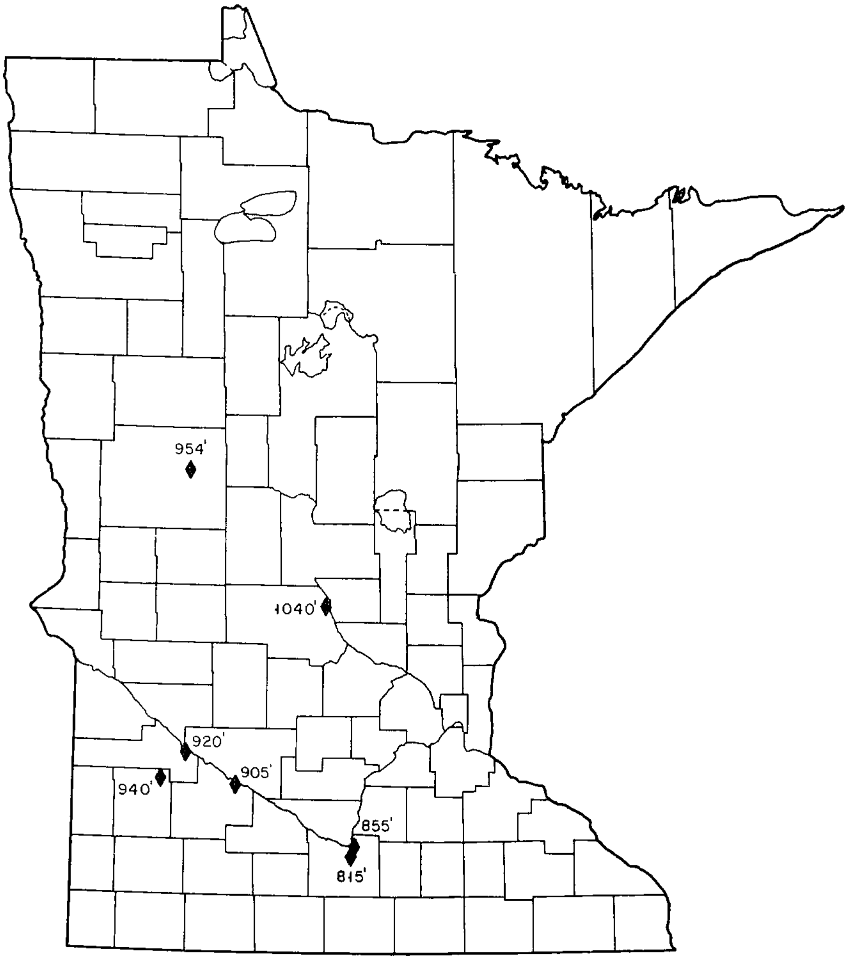

Figure 3. Map of Minnesota showing the altitude of the top of the Upper Cretaceous pisolitic kaolinite layer of unit 2.

linite layer formed. A bauxitic texture was formed in the clay, but decomposition of silicate minerals did not progress sufficiently to produce a weathering product rich enough in aluminum minerals to be considered bauxite.

Altitudes of the upper surface of the pisolitic kaolinite layer vary as much as 50 to 60 feet locally as in Redwood County, but regionally are relatively flat (fig. 3), suggesting that the layer formed on a widespread, flat, low-lying plain that covered a large part of western Minnesota. The change in altitude of the layer regionally is generally about one to two feet per mile. Laterite has formed on slopes in northern Australia commonly having gradients of 25 to 30 ft./mi. and on some up to 50 ft./mi. (Hays, 1964). A part of the local variation in altitude of the pisolitic bed in Minnesota probably is the result of differential compaction of the sediments of unit 2 over weathered bedrock hills.

The basic requirements necessary for designating a geologic surface as a peneplain as outlined by Thornbury (1956) seem to be fulfilled in this case. The stratigraphic and geomorphic evidence which Thornbury cites as support for existence of a peneplain is listed below as it relates to Minnesota.

1. The altitude of the upper surface of the pisolitic layer suggests development of a near-plain surface.

2. A thick, deeply weathered residuum is present beneath this surface.

3. There seems to be a general accordance of hill tops on the weathered Precambrian rocks. The pisolitic kaolinite layer in fact, has developed directly on Precambrian rocks at two localities.

4. Precambrian rock types and structures have been truncated by Cretaceous erosion and weathering. The Sioux Quartzite in southwestern Minnesota is an exception and was not reduced to the general level of the other Precambrian rock types; however, the quartzite is limited to southwestern Minnesota whereas the remainder of Minnesota, at least in the north-central part of the state, had developed to a general plain over a variety of Precambrian structures and rock types.

5. Sediment, derived from hills of weathered Precambrian rocks, has been preserved as a thin cover in the lower areas or valleys between the weathered hills. The sediment is represented by the Upper Cretaceous kaolinitic clays and sands of the sedimentary rocks of unit 2.

6. The plain that developed extended at least from Blue Earth County to Ottertail County, a distance of about 170 miles. Because detailed geologic data are lacking at present concerning the extent of the pisolitic kaolinite layer, the plain cannot be definitely extended further over Minnesota with greater certainty. Nevertheless, the existence of the kaolinitic weathered zone on Precambrian rocks of all of western Minnesota

and parts of adjacent states strongly supports an extension of the plain over a much wider area, perhaps as far north as Winnipeg, Manitoba.

It is believed that these points support the idea that a peneplain had developed over large areas of western Minnesota and the extreme eastern Dakotas during Early Late Cretaceous time, but confirmation of such a geologic feature awaits further detailed drill-hole data, particularly in the northwestern part of the state.

Local variations in the altitude of the surface on which the pisolitic kaolinite formed can account in part for the differences tn thickness of the iron-rich pisolitic layer. Although this layer generally ranges in thickness from three to five feet, at one locality it does reach 15 feet in thickness (Renville Co., SE1/4 NW1/4 SE1/4 sec. 3, T. 112 N., R. 34 W.). Here it rests on a thin, dark gray, clay-shale. The altitude of the top of the iron-rich pisolitic surface here is 880 feet, which is as low or lower than any measurements taken from other exposures in the area. Maignien (1966) has shown in a literature review on laterites that in environments where weathered crusts develop over relatively flat plains, those that form in topographically low areas always have a higher iron content than those formed on the slightly higher surrounding ground. The suggestion that the increased thickness of the pisolitic layer is related to its formation in a topographic low is also supported by the work of Simonett and Bauleke (1963). Their work on development of pisolites in modern tropical soils formed from basalt has shown that development of abundant pisolites is most closely related to conditions of poor drainage. Likewise, Mohr and van Baren (1954) have noted that in rainforests under the most advanced stages of lateritic weathering, lateritic concretions form below the surface of the soil in the zone that is constantly moist. Therefore, development of the pisolitic texture at the top of the weathered Precambrian rocks themselves, suggests not only that the countryside had been reduced to a low-lying plain but also that the water table at that time was relatively high, producing near-surface conditions of relatively poor drainage over wide areas.

Concentration of oxidized iron within the pisolitic kaolinite layer may have been the result of alternating wet and dry seasons or of short dry periods in a wet climate. The reduced iron in the lower part of the profile would have been removed by ground-water flow during wetter periods and as a result, clays below the pisolitic layer would tend to have white or very light colors. On the other hand, reduced iron, present in the lower part of such weathering profiles, would be carried upward during drier periods to bare surfaces at the top of the profile, where it would be oxidized and precipitated. However, if the weathered surface were forested, upward movement of ground water due to evaporation would be minimized. Mohr and van Baren (1954) have suggested that when deforestation takes place in such a situation, evaporation of moisture from the soil will bring reduced iron to the surface where it is oxidized and precipitated, and where it acts to cement the pisolitic clay layer. It is not uncommon in Minnesota to find that the iron content in the pisolitic layer is relatively low at one locality whereas it is relatively high at a nearby location. If forest cover had been complete, the effect of alternating wet and dry periods should have produced the same general concentration of iron over a wide region. This does not seem to have been the case. Rather, it would seem that during the last stages of weathering over the wide flat plain, gaps had developed in the forest cover and evaporation during the dry season or during drier periods allowed oxidation of upward-moving iron to take place in tree-barren parts of the plain, thus cementing those portions of the pisolitic layer with iron oxide. Tree-covered areas would have inhibited upward movement of ground water and subsequent oxidation of iron, thus leaving the pisolitic layer iron-poor and light in color. The variation in iron content for five samples of the pisolitic layer is shown in Table 1. No chemical analyses are available for samples from the most iron-poor areas; however, the chemical analyses of Table 1 show iron contents ranging from about 6 to 22 percent, which indicate in a general way, the common variability of iron content within the pisolitic clay layer.

The presence of incipient pisolitic textures in sediments at scattered localities below the pisolitic kaolinite layer capping unit 2 suggests that temporary base level had been reached within various sites of sedimentation prior to leveling of the entire countryside. It is probable that in most instances such features would have been destroyed by subsequent erosion as temporary base levels were eliminated.

By comparing the clay mineral assemblage of the sedimentary rocks of unit 2 with that of unit 3, it is evident that a pronounced change in certain environmental conditions had taken place in the interval between deposition of the sediments of units 2 and 3. The climatic conditions had become cooler and rainfall had probably decreased, resulting in a climate more typical of temperate areas today. Kaolinite and gibbsite were no longer forming, at least not in any abundance in Minnesota, during Late Cretaceous time. Kaolinite and gibbsite in the basal part of rocks of unit 3 were derived from reworking of the old land surface of unit 2, illustrating a general carry-over of one stable clay mineral assemblage into a time of new environmental conditions. Similar examples of clay mineral carry-over have been pointed out by Bentor and others (1963), and they visualize "a halo in space and time, within which the stable caly mineral composition can be easily recognized, regardless of transport and redeposition in a different environment." Under temperate climatic weathering conditions and with lower rainfall, the three-layer clay minerals, i.e., illite, smectite, and chlorite, would be the common clay minerals formed. These three-layer clay minerals do, in fact, comprise the great bulk of the clay minerals in stratigraphically higher parts of the Upper Cretaceous section.

In summary, it is suggested that a peneplain developed over most of western Minnesota and the immediately adjacent areas of North and South Dakota during Early Late Cretaceous time under a humid sub-tropical or tropical climate. The clay mineral assemblage of the weathered rock forming this ancient surface is composed predominantly of kaolinite with lesser amounts of halloysite, gibbsite, and boehmite. A climatic change to more temperate conditions took place in Late Cretaceous time as is reflected by the three-layered clays illite, smectite, and chlorite which predominate in the sediments overlying weathered surface in Minnesota.

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ROAD LOG AND STOP DESCRIPTIONS

First Day

Mileage		
0.0	0.0	Start. Intersection U. S. Hwys. 212 and 81, Watertown. Head east on U. S. Hwy. 212 on valley train outwash adjacent to Big Sioux River. Outwash had source in meltwaters from both James and Des Moines lobes.
1.9	1.9	Cross onto Early Wisconsin drift surface (Tazewell of Flint).
7.4	9.3	Village of Kranzburg on left. Crest of Bemis moraine ahead.
1.2	10.5	Rising onto the distal slope of Des Moines lobe Bemis moraine. Note the rolling topography; but in general an integrated stream network is present on the moraine.
0.6	11.1	Deuel County Line.
1.7	12.8	Intersection. Turn R (south) to village of Goodwin. Continue south through town. Follow slight jog in road to L, then R. Continue south toward village of Bemis. The crest of the Bemis moraine can be seen to the west and south.
4.0	16.8	Village of Bemis. Continue south. The route climbs to the crest of the Bemis moraine.
1.2	18.0	Crest of the Bemis moraine. Continue south down the distal slope. This slope displays generally smooth topography, well-integrated drainage. Crest of moraine can be seen to L (east).
1.7	19.7	Early Wisconsin drift. Note a general lack of boulders. To the southwest is the James lobe Altamont moraine across the interlobate valley now occupied by the Big Sioux River.
3.2	22.9	Intersection with S. D. Hwy. 22. Turn L (east). Continue east, climb back up on distal slope of Bemis moraine.

4.5	27.4	Cross crest of Bemis moraine.
3.0	30.4	Clear Lake Country Club on L.
0.4	30.8	Intersection S. D. Hwy. 22 and U. S. Hwy. 77. Turn R (south). If continued to the east, the route would cross a low area marked by Clear Lake and other lakes, that is covered with lacustrine silts and outwash gravels, and then into the Altamont moraine.
1.2	32.0	Cross channel of Hidewood Creek. This is one of several deep channels that cut through the Bemis moraine. It probably served as an outlet for water ponded between the Bemis and Altamont moraines. The largest of these sluiceways is located south of Lake Hendricks. Others are at Lake Benton and South Shore.
0.9	32.9	Retrace route back to town of Clear Lake.
0.9	33.8	Recross Hidewood Creek.
0.6	34.4	Window Stop. View to east shows Altamont moraine across interlobate valley.
0.4	34.8	Enter town of Clear Lake.
0.7	35.5	Descend from Bemis moraine onto intermorainic lowland. Note numerous gravel pits in outwash.
0.9	36.4	Clear Lake International Airport on L.
1.4	37.8	Begin climb onto distal slope of Altamont moraine. This slope represents a broad belt of stagnation moraine. Poorly drained, steep slopes, and many "potholes," the local name for kettle lakes.
3.2	41.0	Turn L (west) into village of Altamont. Continue through town on gravel.
1.2	42.2	At intersection with county road, take a very sharp turn R (east).
1.1	43.3	<u>STOP 1</u>. Moraines of the Des Moines lobe.

This is a short "bus window" stop to exhibit the character of the moraine that is associated with the first late Wisconsin advance of the Des Moines lobe in northeastern South Dakota and southwestern Minnesota. Although the Bemis moraine in South Dakota is not precisely dated, several C-14 dates in Iowa give an age of about 14,000 years B. P. (Ruhe and Scholtes, 1958). The moraine has been traced from the type locality into Iowa by Leverett (1932) and Ruhe (1950). Outwash associated with the Algona moraine in northern Iowa which lies behind the Altamont moraine, has been dated at about 13,000 years B. P. (Ruhe and Scholtes, 1959). Thus, the Altamont moraine should date somewhere between the two. Dates in the James lobe in southern South Dakota on drift behind the Altamont moraine range from 12,050 to 12,760 radiocarbon years (Lemke and others, 1965), slightly younger than the 13,000 Algona date in Iowa. Thus, the two lobes may have advanced independently, and the James lobe may be slightly younger than the Des Moines lobe. Dates of 9,000 and 10,000 years were determined on snail shells in lacustrine marls overlying late Wisconsin outwash in the central part of the James lobe, and give a minimum date for the late Wisconsin ice withdrawal from central South Dakota.

0.2	43.5	Intersection with South Dakota Hwy. 77. Turn L (north). Cross typical topography of Altamont moraine.
3.0	46.5	Junction U. S. Hwy. 212, South Dakota Hwy. 77. Turn L (west) on Hwy. 212. Another good look at Altamont topography as we head west.
4.8	51.3	Turn R (north) on Deuel County Rd. 443. The route continues north on this road for twenty miles, crossing the Altamont and Gary moraines at a very oblique angle. The topography here is typical of the entire east flank of the Prairie Coteau.
6.9	58.2	Perched lake plain to R (east).
3.8	62.0	Strandberg, continue to north.
2.2	64.2	Start descent from the Coteau. Good view of Minnesota River lowland to R (northeast).
1.5	65.7	Cross crest of Gary moraine. In this locality the Altamont and Gary moraines are crowded together and from here to north along the east side of the Coteau des Prairies the two cannot be separated.
0.4	66.1	Cross drainageway typical of those draining eastward off steep flank of Coteau. Note boulder-strewn valley floor.

0.2	66.3	Intersection South Dakota Hwy. 20. Continue to north.
0.1	66.4	Excellent view of Minnesota River lowland to R.
4.0	70.4	Base of Coteau. Continue north across till plain which in many areas is covered with veneer of colluvium or gravels washed off the flank of the Coteau.
4.0	74.4	Junction U. S. Hwy. 12. Turn L (west) toward Coteau. Excellent view of this topographic feature.
0.6	75.0	Leave U. S. Hwy. 12 on to gravel road.
0.4	75.4	Junction. Turn L (south) toward Twin Brooks.
0.2	75.6	Turn R (west) on gravel road, Grant County Rd. 8. Start ascent of Coteau.
4.1	79.7	STOP 2. Complex drift.
		This exposure shows sorted and bedded sediments enclosed within till. The till contains fragments of Cretaceous shale, indicating ice movement from the northwest. Does the close association of such sediments, and their structure, indicate a superglacial depositional environment, or could such drift be the result of subglacial deposition?
1.0	80.7	Blue Cloud Abbey to R (north). Order of priests that has served Indian schools and churches in South Dakota for many years.
3.1	83.8	STOP 3. Marvin soil site.
		Buried paleosol with sediment at base which contains pelecypod shells. C-14 on shells gave date of 13,360 ± 1500 years B. P. A date of 7920 was obtained on organic soil. These dates raise some questions about interpretation.
1.5	85.3	Crest of Altamont moraine. Bemis moraine crest straight ahead. Cross intermorainic lowland.
0.8	86.1	Start ascent of proximal slope of Bemis moraine.
0.4	86.5	Crest of Bemis moraine. James lobe Altamont moraine can be seen across Big Sioux Valley lowland.
1.4	87.9	Now on Early Wisconsin drift.
1.4	89.3	Jog in road marks edge of Sisseton Indian Reservation.

		A place where two township and range surveys, done independently, do not match up. Very confusing to workers in field.
1.5	90.8	Ignore boulder pile on L!
1.4	92.2	Junction U. S. Hwy 81. Turn R (north). Big Angus bull in pasture to R.
5.0	97.2	Roberts County line.
2.0	99.2	Junction U. S. Hwy. 12. Turn L (west).
2.3	101.5	Area of interlobate outwash. Over 80 feet of gravel known in many areas.
1.0	102.5	Cross outwash channels cut into outwash plain.
1.4	103.9	Ortley. Continue to west.
0.4	104.3	Distal slope of James lobe Altamont moraine straight ahead.
1.7	106.0	Crest of James lobe Altamont moraine. Note that Bemis moraine is NOT present here. Flint (1955) mapped this moraine as Bemis. We do not agree.
0.8	106.8	STOP 4. Bemis and Altamont moraines.

Flint (1955) identified the Des Moines lobe Altamont moraine as "Mankato" in age, but he mapped the Bemis moraine and outer James lobe moraine as "Cary" in age. On the basis of topography, the writers believe the outer moraine of the James lobe correlates with the second (Altamont) moraine of the Des Moines lobe.

At this stop we want to emphasize the remarkable similarity in topography of the James lobe Altamont moraine to the Des Moines lobe Altamont moraine, and point out the equally remarkable contrast to the Bemis moraine. The Altamont moraine of both lobes shows complete lack of drainage (except at the margins of the Coteau), and is characterized by a disordered arrangement of sharp hummocks and deep ice-block kettles, the latter occurring at discordant elevations. The Bemis moraine, on the other hand, is a smooth drained ridge that only locally exhibits constructional topography as described by Leverett (1932, p. 58).

Turn R (north) on Enemy Swim Lake Road. Continue north on James lobe Altamont. Note stagnation features in this area.

2.2 109.0 Doughnut on L (west). Possible stop.

1.0 110.0 Gravel pit. Gravel is abundant throughout this area. Many of the knolls are till, others gravel.

1.3 111.3 At this curve in road, the South Dakota Geological Survey drilled through over 500 feet of drift. In northeast Day County a drill hole penetrated over 800 feet of drift. As we jog to left note forest ranger tower ahead. South Dakota does have trees! Jog to R (north). Continue past Enemy Swim Lake on R.

5.9 117.2 Junction. Turn R (east) on road to south end of Pickerel Lake.

1.3 118.5 STOP 5. Pickerel Lake (1965 INQUA stop).

Pickerel Lake is located in a linear ice-block depression on the Coteau des Prairies in outwash deposits in front of (west of) the Altamont moraine of the Des Moines lobe of late Wisconsin age. The moraines in the immediate vicinity of Pickerel Lake were assigned by Flint (1955) to the somewhat older Bemis moraine. Pickerel Lake is located close to the interlobate junction of the Des Moines and James River lobes.

Pickerel Lake is a permanent lake more than 60 feet deep. Because of its permanence it was selected as a prairie lake from which a continuous sediment record of postglacial time could be studied paleontologically to reveal the history of the prairie environment. Analyses of pollen, seeds, mollusks, and ostracods so far completed show that in late-glacial time (before 10,500 years ago), the area was marked by a boreal spruce forest but that prairie has dominated the region ever since (see Wright, this volume). The other paleontological studies provide environmental details.

The lake today is surrounded by an outlier of eastern deciduous forest, including *Quercus macrocarpa* (bur oak), *Fraxinus sp*. (ash), *Tilia americana* (basswood), *Acer negundo* (box elder), and other trees.

0.6 119.1 Junction, turn L (north).

1.8	120.9	Turn R (east) for two miles on gravel road.
1.1	122.0	Stagnation drift.
0.9	122.9	Junction. Turn L (north) one mile.
1.0	123.9	Junction, turn R (east) on One Road Lake Rd.
1.4	125.3	One Road Lake.
0.8	126.1	West edge of rimmed kettle. Continue across kettle.
0.2	126.3	STOP 6. East edge of rimmed kettle. Continue to east.
0.3	126.6	Junction. Turn R (south) on Roberts County Rd. 28. Note boulder-strewn hill on L (east).
2.5	129.1	Good photo view to R (west). We are still on James lobe Altamont, but just to the east the James lobe Altamont, Des Moines lobe Altamont, and Des Moines lobe Bemis all intersect in a very complex area.
5.2	134.3	Leave James lobe Altamont, cross onto interlobate lowland.
6.5	140.8	Junction U. S. Hwy. 12. Turn L (east). Start rise onto Des Moines lobe Bemis moraine.
5.2	146.0	Crest of Bemis moraine. Continue off moraine onto intermorainic area.
1.4	147.4	Start onto distal slope of Altamont moraine.
0.4	147.8	U. S. Hwy. 81 turns L, we turn R (south) toward Summit (elevation 2,000 feet above sea level).
1.0	148.8	Turn L (east). Head toward Milbank, 22 miles to east. As we descend off the Coteau we will cross a jumble of drift where it is almost impossible to distinguish the Gary moraine. It may be the slight ridge near Marvin and the Blue Cloud Abbey.
7.5	156.3	Marvin. Gary moraine (?).
5.0	161.3	Base of Coteau.
2.5	163.8	Twin Brooks to R (south).
2.2	166.0	Crossing moraine crest (?) mapped by Flint.
4.8	170.8	Milbank -- Junction of U. S. Hwys. 12 and 77.

SECOND DAY

0.0	0.0	Assemble at intersection of U. S. Hwys. 12 and 77, Milbank, South Dakota. Head east on U. S. Hwy. 12.
5.0	5.0	Red sandy till of the Superior lobe exposed in road cut on R (south). We will not stop.
1.5	6.5	Turn L (north) on gravel road.
1.0	7.5	Turn L (west), cross Whetstone River. Observe red till on bank to R.
6.2	13.7	Junction with Grant County Rd. 15. Turn R (north).
1.5	16.7	Roberts County line.
1.0	17.7	Turn L (west) on gravel road. Note boulders in field. On distal portion of the Big Stone moraine.
2.2	19.9	Cross north fork of Whetstone River. The Whetstone River marks the west edge of Big Stone moraine and occupies a glacial marginal valley filled with gravel.
0.8	20.7	Junction. Turn R (north).
0.1	20.8	<u>STOP 1</u>. Boulder pavement between two tills.
		The one-stone-thick, faceted and striated boulder pavement separates tills of different lithologies. The upper unit is rich in fragments of Cretaceous Pierre Shale, whereas the lower unit contains much less shale and generally displays a more sandy texture. The boulder pavement is interpreted as a lag deposit produced by subaerial processes, most likely running water. We would like to discuss alternative interpretations, and possible implications relating to subglacial activity.
		Continue to north, cross Whetstone River.
0.9	21.7	Junction, turn R (east). Continue on Big Stone moraine three miles east to Grant County Rd. 15.
3.0	24.7	Junction with Grant County Rd. 15. Turn L (north). Cross channel which roughly parallels Big Stone Lake.
3.0	27.7	Junction with Grant County Rd. 15A. Continue L on County Rd. 15.

1.8	29.5	Entrance to Hartford Beach State Park. Turn R (east). Proceed to overlook.
0.3	29.8	STOP 2. Big Stone Lake.
		This short stop is to view the sharp gorge cut across the till upland by the southern outlet stream of Lake Agassiz. This river, called Glacial River Warren, was for a time, the only outlet to Lake Agassiz; it had ceased to flow at least by 9,000 B. P. The sharp-crested ridges of low relief that parallel the shoreline may be eroded slump blocks. Westward rises the Coteau des Prairie. Return to Grant County Rd. 15.
0.3	30.1	Junction. Go R (west) on Grant County Rd. 15.
7.2	37.3	Junction Roberts County Rd. 4. Turn R (north). On Big Stone moraine. Highest portion is to west, Big Stone Lake Trench is to east.
10.8	48.1	STOP 3. Southern outlet of Lake Agassiz.
		Armored terrace and Carlile Shale. The boulder-strewn terrace at this point and across the valley has an elevation of about 1,045 feet. The terrace is a channel-bottom pavement of lagged boulders that established a temporary base level for erosion of the outlet of Glacial Lake Agassiz. The stabilized lake level is marked by the Herman Beach at an elevation of 1,060 feet at the entrance to the gorge about 10 miles north of here. The boulder terrace is traceable downstream in patches for about 20 miles to the Fish Hatchery 6 miles above Ortonville, where it has an elevation of about 1,040 feet. The only other terrace in the section of the valley has an elevation of 1,000 feet. It may be correlative with the Tintah strandline of Lake Agassiz at 1,020 feet. The periodic dissection of these armored surfaces may be attributed to increase in the volume of the outlet stream as a result of ice retreat and consequent enlargement of Lake Agassiz. The valley floor was eventually eroded to an elevation at least as low as 965 feet, when Lake Agassiz stood at the Campbell beach at 980 feet.
		Further retreat of the ice uncovered lower outlets to the northeast and north, and the southern outlet was abandoned. Tributary streams deposited alluvial fans in the abandoned gorge, thereby segmenting the floor of the gorge into a series of long shallow lakes.

		The alluvial fan of the Little Minnesota River at Browns Valley allowed Lake Traverse to form, and this dam is now the Continental Divide.
		Continue to north.
2.2	50.3	Browns Valley -- Intersection with U. S. Hwy. 10. Turn L (west). Road runs along Continental Divide between Gulf drainage to south, Hudson's Bay drainage to north.
		In 1933 a burial site containing one human skeleton and some projectile points was discovered in the small gravel knoll at the southern end of Browns Valley. On the basis of typology of the parallel-flaked points, Browns Valley Man has been dated at about 8,000 years old.
1.3	51.6	Bear R (north) on Roberts County Rd. 7. Follow along west side of Lake Traverse.
3.8	55.4	Milnor outlet with hanging valley to L (northwest).
15.0	70.4	Rosholt. Turn R onto U.S. Hwy. 81.
5.0	75.4	Turn R off of Hwy. 81.
2.7	78.1	State line. Bois de Sioux River. Proceed east on Minnesota Hwy. 236.
1.3	79.4	STOP 4. Norcross Beach.
		Lake Agassiz strandlines clearly record long periods of stable lake level. This exposure is typical in lithology and structure of the many miles of beaches and bars that mark former water levels of Lake Agassiz. In the southern outlet area four strong beaches were established: Herman (1060 feet), Norcross (1040 feet), Tintah (1020 feet), and Campbell (980 feet). An earlier proglacial lake, Lake Milnor (1100 feet), formed no good strandlines, so it probably did not persist at any level very long. Its presence is recorded only by patches of lake sediment above the Herman level and by several outlet channels.
		The Herman Beach was abandoned before 11,740 years ago (Shay, 1965), and the Campbell Beach by 9200 years ago according to a C-14 date on wood in a beach ridge of the Campbell series at Williams, Minnesota, near the Canadian border.

		The southward tilting of these beaches provides the evidence for crustal uplift caused by glacial unloading. Continue east on Minn. Hwy. 236.
2.8	82.2	Turn R onto U. S. Hwy. 75.
2.9	85.1	Mustinka River. The rise just ahead is mapped as the Tintah beach by Leverett.
0.7	85.8	Wheaton City limit.
0.5	86.3	Junction Minn. Hwy. 27. Continue south on U. S. Hwy. 75. The route crosses "wave-washed" till and lake sediments for the next 12 miles.
6.4	92.7	Village of Dumont.
5.4	98.1	Village of Collis. Herman beach here marks the highest stand of Lake Agassiz.
5.3	103.4	Junction Minn. Hwy 28. Continue south on U. S. Hwy. 75.
7.8	111.2	Clinton City limits.
11.7	122.9	Junction U. S. Hwy. 12 at Ortonville. Continue on U. S. Hwy. 75.
0.6	123.5	Junction Minn. Hwy. 7. Outcrops of Precambrian igneous and metamorphic rocks are exposed for many miles along the Minnesota River Valley.
5.1	128.6	Village of Odessa.
2.2	130.8	Junction U. S. Hwy 75 and Minn. Hwy. 7. Continue on Minn. Hwy. 7.
1.4	132.2	Large glacial erratic of granite on R.
5.6	137.8	Village of Correll.
7.5	145.3	Junction U. S. Hwy. 59. Turn R into Appleton.
0.8	146.1	L on Hwys. 7 and 59.
7.9	154.0	Village of Milan.
0.8	154.8	Junction Minn. Hwy. 40. Continue on Hwys. 7 and 59.
4.5	159.3	Watson Sag.

3.2	162.5	Turn L (east) onto blacktopped section road.
0.8	163.3	Intersection and stop sign. Turn L (north).
0.4	163.7	Bear L at "Y" intersection.
2.1	165.8	Turn L onto farm road to Dennis Norby farm. Park in farmyard. Walk southwest about 250 yards to the edge of Watson Sag. Exposure is an excavation for a stock pond.

STOP 5. Watson Sag Section.

Three tills are exposed in this section. At the base is the reddish-brown, sandy Hawk Creek Till, with stones from the Lake Superior region. Overlying the till is the Granite Falls Till, a buff, sandy, limestone-rich till that contains very little Cretaceous Shale. An intermittent stone line separates this till from the upper unit, called the New Ulm Till, which has a silty texture and contains abundant fragments of Cretaceous Shale. From bottom to top the tills represent successive glacial activity of the Superior, Wadena, and Des Moines lobes.

Return to section road. Turn R (south).

2.1	167.9	Bear R (south) at intersection.
0.5	168.4	Intersection. Continue south to village of Watson.
0.9	169.3	Intersection in downtown Watson. Turn R to U. S. Hwys. 7 and 59.
0.1	169.4	Junction U. S. Hwys. 7 and 59. Turn L to Montevideo.
6.6	176.0	Junction Hwys. 7, 59, and 29, Montevideo. Turn R onto Hwy. 59.
0.2	176.2	Junction U. S. Hwy. 212. Proceed east on Hwy. 212.
1.7	177.9	Outcrops of Precambrian Montevideo Gneiss on L.
10.8	188.7	Junction Minn. Hwys. 67 and 23. Continue on Hwy. 212 into Granite Falls.
1.2	189.9	Junction Minn. Hwy. 67. Continue on Hwy. 212 across bridge.

Entrance to scenic overlook.

STOP 6. Minnesota River Valley

Terrace segments are preserved at various heights above the floodplain of the Minnesota River. The materials underlying the terraces fall within three major categories that relate to the history of the valley. Braided stream deposits at high levels were deposited by meltwater that drained the margins of the retreating Des Moines lobe ice. Boulder veneers at intermediate levels are remnants of successively lower channel bottoms of Glacial River Warren, and boulder-gravel beds just above or buried beneath the modern floodplain sediments are bedload sediments lagged during the waning stages of River Warren discharge.

On the north side of the highway are exposed two tills separated by a one-stone-thick boulder pavement. The lower of these two glacial deposits, the Granite Falls Till, is characterized by a rarity of shale in its pebble content (less than 5%) and by high percentages of limestone, dolomite, and granitic rocks.

The upper deposit is the New Ulm Till, the surface deposit over a wide area in Minnesota that was known as the "young gray drift" (Leverett, 1932). Typically the till is a calcareous loam to clay loam sediment with between 20% and 50% of siliceous Cretaceous shale fragments in the coarse sand fraction, along with substantial volumes of carbonate and granitic rocks.

Continue east on U. S. Hwy. 212.

4.3 194.2 Junction Minn. Hwy. 23. Turn L.

3.7 197.9 Turn R onto Renville County Rd. 11.

1.4 199.3 STOP 7. Hawk Creek.

Walk north along the east bank of Hawk Creek about 550 feet.

Type area of Hawk Creek Till. At low water level is exposed the distinctive Hawk Creek Till, a glacial drift that must have been deposited by ice that had moved across the Lake Superior district in northeastern Minnesota. Here it is separated from the overlying Granite Falls Till by clayey to silty and sandy interglacial sediments. The hills that surround the area are underlain by the shale-rich New Ulm Till. Faceted and striated boulders similar to those found in the boulder pavement along the sides of the Minnesota River Valley are found in the stone piles nearby, suggesting that the contact between the Granite Falls Till and the New Ulm Till lies within the nearby slopes.

Continue east on Renville County Rd. 11.

1.7	201.0	Junction Renville County Rd. 10. Continue east.
2.0	203.0	Bear south on blacktop road.
1.0	204.0	Bear L on blacktop road.
1.0	205.0	Junction Renville County Rd. 9. Turn R.
3.3	208.3	Junction U. S. Hwy. 212. Sacred Heart. Turn L.
6.1	214.4	Junction Renville County Rd. 6. Turn R.
8.6	223.0	Junction Renville County Rd. 4. Bear R and continue on Renville County Rd. 6.
0.8	223.8	Roadcut on L exposes two tills, the New Ulm Till on top, and the Granite Falls Till, which is unoxidized at the base of the cut.
4.6	228.4	Junction Renville County Rd. 9. Turn L into Delhi.
2.1	230.5	Junction Renville County Rd. 17. Continue straight onto gravel road.
4.1	234.6	Historical marker for Camp Pope on L is situated on a boulder bed terrace remnant.
0.8	235.3	Road intersection. Bear L onto Redwood County Rd. 25. Continue straight into the town of North Redwood.
0.7	236.0	Bear R across railroad tracks. Proceed straight south on Redwood County Rd. 101, to a small side road.
0.3	236.3	<u>STOP 8</u>. Cretaceous weathering and peneplain.

Regolith developed on Precambrian crystalline rocks. Samples from this site were extensively analyzed as part of the classic study of rock weathering by S. S. Goldich.

In a chemical and mineralogical comparison between weathered residuum such as exposed here to the fresh

Morton Gneiss, the probably parent material, Goldich was able to trace the sequence of alteration resulting from weathering. More recently W. E. Parham has done an extensive resurvey of the Kaolin clays in Minnesota. He suggests that the evidence is impressive for the existence of a peneplain during late- and post-Cretaceous time.

Notice the gneissic texture preserved in the base of the exposure. The upper units are till, lignitic clay, pisolitic clay, and sandy clay.

Turn L back onto Redwood County Rd. 101.

0.1 236.4 Junction Minn. Hwy 19 and Redwood County Rd. 101. Turn R onto Minn. Hwy 19.

0.4 236.8 <u>STOP 9</u>. North Redwood, section SW1/4, sec. 29, T. 113 N., R. 35 W.

In this 80-foot-thick stratigraphic interval a variety of glacial sediments rests upon Cretaceous clay. The lower part of the section exposes two distinct zones of buried wood and one paleosol. The upper part of the section is mainly till of the Des Moines lobe. Some of the Quaternary sediments here are most certainly pre-Wisconsin in age.

Continue south on Minn. Hwy. 19.

2.8 238.0 Junction U. S. Hwy. 71. Turn L.

3.1 241.1 Exposures of Cretaceous lignitic clay on R.

0.4 241.5 <u>ALTERNATE STOP 9</u>. Ochs Morton claypit section. (Park vehicle at entrance to claypit and proceed by foot 100 yards).

A complex sequence of Quaternary sediments lies stop lignitic Cretaceous clay with bentonite layers. Wood collected from the base of the Granite Falls Till, exposed in 1968, gave an age of 34,000 years (GX-1309). Spruce wood collected from the same site in 1969 gave an age of greater than 39,900 years (I-4932). Several tills lie stratigraphically below this dated horizon.

Continue east to Morton.

2.0 243.5 "Y" Junction. Follow Minn. Hwy. 19 to R. Tri Court Motel.

0.6	244.1	Stop sign in beautiful downtown Morton. Turn R. After one block, continue straight on unpaved road across railroad tracks.
0.2	244.3	Turn L just after railroad crossing.
0.3	244.6	<u>STOP 10</u>. Morton Quarry.

The Morton Gneiss and the Montevideo Gneiss in the Minnesota River Valley are among the oldest rocks that have been found in North America. They are dated at 3550 m.y. ago.

This ends the field trip. The bus will proceed to Minneapolis via Minn. Hwy. 19 and U. S. Hwy. 169.