GEOLOGY

of

DICKEY AND LAMOURE COUNTIES

by
John P. Bluemle
North Dakota Geological Survey
Grand Forks, North Dakota
1979

BULLETIN 70—PART 1
North Dakota Geological Survey
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COUNTY GROUNDWATER STUDIES 28—PART 1
North Dakota State Water Commission
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**Prepared by the North Dakota Geological Survey
in cooperation with the North Dakota State Water Commission,
Dickey County Water Management District,
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This is one of a series of county reports published cooperatively by the North Dakota Geological Survey and the North Dakota State Water Commission. This report is in four parts: Part I describes the geology, Part II presents groundwater basic data, Part III describes the groundwater resources, and Part IV describes a digital model of the groundwater flow system in the Oakes area.

Additional copies of this bulletin are available from the North Dakota State Water Commission, Bismarck, North Dakota 58501

CONTENTS

ILLUSTRATIONS

ABSTRACT

Dickey and LaMoure Counties, located in southeastern North Dakota on the southeastern edge of the Williston Basin, are underlain by 1 000 to 3 500 feet of Paleozoic and Mesozoic rocks that dip gently to the northwest. The Cretaceous Niobrara and Pierre Formations lie directly beneath the glacial drift and shale of the Pierre Formation is exposed in several places just east of the Missouri Escarpment. The Pleistocene Coleharbor Group, which covers most of the area, consists of glacial, fluvial, and lake sediment. The Coleharbor Group averages about 200 feet deep in the east; over 300 feet deep on the Missouri Coteau. It reaches a maximum thickness of over 500 feet in places on the Missouri Coteau.

The eastern seven-eighths of the two-county area is part of the Glaciated Plains, which are characterized by broad areas of low- to moderate-relief collapsed glacial sediment that is dissected by numerous stream valleys, the largest of which is the James River valley. Associated with the areas of collapsed glacial sediment are numerous glaciofluvial and glaciolacustrine landforms. The glacial Lake Dakota plain, which extends into southeastern Dickey County, is characterized by a sandy, wind-worked surface.

The western eighth of the two-county area, the Missouri Coteau, is characterized by hilly areas of collapsed glacial sediment with numerous sloughs, lakes, and closely spaced hills. Ice-thrust topography and collapsed flood plains and lake plains are also common on the Missouri Coteau. The Missouri Escarpment, a 300- to 400-foot-high, east-facing escarpment, marks the boundary between the Glaciated Plains and the Missouri Coteau.

Pre-Wisconsinan glacial deposits were tentatively identified, but the detailed stratigraphy of these deposits has not yet been worked out. Nearly all of the landforms that can now be seen in Dickey and LaMoure Counties formed during the late Wisconsinan time.

Economic mineral deposits in Dickey and LaMoure Counties include the gravel and sand on the James River terraces and on terraces of some of the smaller streams; groundwater; and surface water. No commercial hydrocarbon production has been found, but the many possibilities for stratigraphic and structural traps along with shallow depths allowing easy and rapid drilling should help to promote exploration in the area.

INTRODUCTION

Purpose

This report is published by the North Dakota Geological Survey in cooperation with the North Dakota State Water Commission, the United States Geological Survey, and the Water Management Districts of Dickey and LaMoure Counties. It is one of a series of county reports on the geology and groundwater resources of North Dakota. This volume describes the geology of Dickey and LaMoure Counties. Readers interested in groundwater should refer to Part 2 of this bulletin, which includes detailed basic data on the groundwater; Part 3, which is a description and evaluation of the groundwater resources of the two counties; and Part 4, which presents the results of the hydrologic systems modeling of proposed irrigation areas in the two counties.

The present report is a description and interpretation of the geology of Dickey and LaMoure Counties. Parts of the report that are primarily descriptive include the discussions of the topography, rock, and sediment of the two counties. This information is intended for use by anyone interested in the physical nature of the materials underlying the counties. Such people may be water-well drillers or hydrologists interested in the distribution of sediments that might produce usable groundwater; civil engineers and contractors interested in the gross characteristics of foundation materials at possible construction sites or the locations of possible sources of borrow material for concrete aggregate; industrial concerns looking for possible sources of economic minerals; residents interested in knowing more about the area; and geologists interested in the physical evidence for the geologic interpretations.

Previous Work

The earliest reference to the geology of Dickey and LaMoure Counties was by T. C. Chamberlin in 1883. Chamberlin briefly described the moraine of the Missouri Coteau in the western part of the two counties. In 1886, J. E. Todd described the moraines located in the area between the Missouri and James Rivers, between Jamestown, North Dakota, and Huron, South Dakota. He also discussed the glacial Lake Dakota deposits and other glacial features in the area, which includes that part of the two-county area west of the James River.

D. E. Willard in 1904 wrote several articles on the glacial deposits, soils, and water supply of southeastern North Dakota and on the geologic history of eastern North Dakota. In 1909, Willard described the geology, including the Cretaceous, Tertiary, and Quaternary deposits, and groundwater of the

Jamestown-Tower district, which includes a portion of LaMoure County.

In 1923, H. A. Hard published the results of an investigation to determine the cause of water-level decline in the artesian wells of the state, especially in Dickey and LaMoure Counties. In the same report, Hard reported on natural gas in artesian wells of Dickey, LaMoure, and Stutsman Counties. Hard (1929) reported on the surficial Cretaceous and Quaternary geology of the Edgeley and LaMoure Quadrangles, an area that includes most of Dickey County, two-thirds of LaMoure County, and small portions of Ransom and Sargent Counties. He included discussions of water resources, artesian conditions, and natural gas possibilities in the report.

O. E. Meinzer and H. A. Hard (1925) discussed the topography and geology of the Edgeley Quadrangle, emphasizing the artesian water supply of the Dakota Formation sandstone.

H. E. Simpson published several papers during the 1920s and 1930s on the artesian water supply of eastern North Dakota. The most exhaustive of these, titled "Geology and groundwater resources of North Dakota" (Simpson, 1929), dealt with the geology and water content of the water-bearing formations. Reports on Dickey and LaMoure Counties are included in the report. L. K. Wenzel and H. H. Sand (1942) wrote on the water-bearing formations of parts of Stutsman, Barnes, LaMoure, and Dickey Counties, emphasizing the Dakota "Sandstone," and artesian wells in the area.

W. C. Rasmussen (1947) reported on the hydrology, potential development of the groundwater resources, quality of water, and geologic history of the glacial Lake Dakota deposits. In addition to Rasmussen's report, two studies in the North Dakota State Water Commission's current groundwater studies series have been completed for the two-county area. Both studies dealt with the Ellendale area (Lindvig, 1965; Naplin, 1973).

Early soil surveys completed for Dickey County (Bushness and others, 1916) and LaMoure County (Anderson and others, 1917) included brief descriptions of the geology. In the current Soil Conservation Service series, the one for LaMoure County and parts of the James River valley (Thompson and Sweeney, 1971) has been completed.

John A. Brophy (1961) reported on the geologic history of the Oakes area, emphasizing the geology of glacial Lake Dakota. Ronald J. Kresl mapped the geology of most of Dickey County in 1964 as part of a doctoral dissertation project. Although his map was not published, the geologic map for Dickey County in the present report is based largely on Kresl's map.

A comprehensive study of the Paleozoic bedrock of eastern North Dakota (Ballard, 1963) includes the area covered in this report. A geologic report on Logan and McIntosh Counties

(Clayton, 1962) and two reports in the current county series, Barnes County (Kelly and Block, 1967) and Stutsman County (Winters, 1963), have been completed. In addition, a report on the geology of Marshall County (Koch, 1975), which adjoins Dickey County on the south, has been completed.

Methods of Study

The geology of a large portion of Dickey County was mapped during the 1964 field season by Ronald J. Kresl. I mapped LaMoure County and part of Dickey County not mapped by Kresl during the 1970 field season; minor changes were made on Kresl's map at that time.

Data were plotted on 1:24 000-scale topographic maps where available. In other areas, county highway maps, scale 1:63 360, were used. Aerial photographs, scale 1:20 000, taken in 1964 in LaMoure County and 1957 in Dickey County, were used to accurately place geologic contacts. The surficial mapping was done by driving along all section-line roads and trails, recording lithologies at all roadcuts or exposures. Certain less accessible areas were covered on foot. A shovel and soil auger were used to obtain lithologic information in areas of poor exposures. Several holes were bored by the North Dakota Geological Survey truck-mounted auger in southern Dickey County during the 1977 field season. The North Dakota State Water Commission provided rotary drilling equipment that was used during the 1973, 1974, and 1975 field seasons for about 40 000 feet of test drilling. In addition, earlier test drilling by the Water Commission in the Ellendale area amounted to about 1 000 feet in 1964 and about 15 000 feet in 1968.

Acknowledgments

I gratefully acknowledge Ronald J. Kresl, who mapped most of Dickey County during the 1964 field season. Clarence Armstrong, U.S. Geological Survey, Bismarck, North Dakota, supplied test-hole data and other information. The North Dakota State Water Commission supplied cuttings from the test holes they drilled in the area. Howard Hobbs supervised the laboratory analysis of till samples from seven LaMoure County test holes. I also wish to thank Ken Harris of the North Dakota Geological Survey for reviewing this report.

Regional Topography and Geology

Dickey and LaMoure Counties, in southeast North Dakota, have a combined area of 2 282 square miles (Dickey, 1 144; LaMoure, 1 138) in Townships 129-136 North and Ranges 59-66 West. Dickey County is located between 98° 00' West Longitude

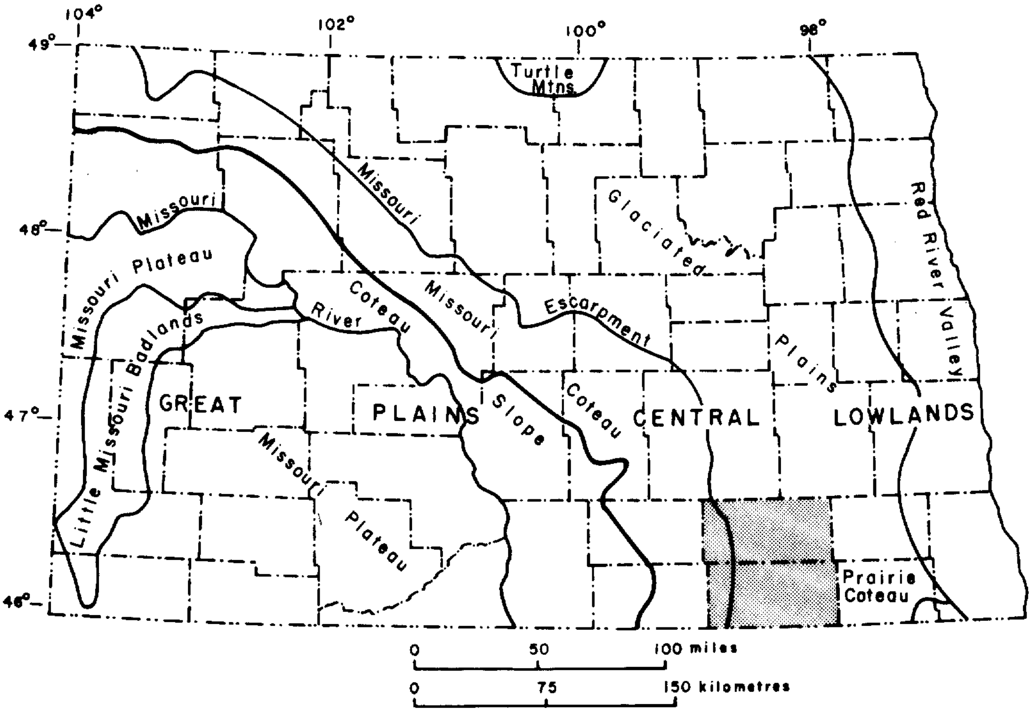


Figure 1. Physiographic map of North Dakota showing the location of Dickey and LaMoure Counties.

on the east and 99° 00' 20" on the west; 45° 56' North Latitude on the south and 46° 17' on the north. LaMoure County is located between 98° 01' 30" West Longitude on the east and 99° 02' 20" on the west; 46° 17' North Latitude on the south and 46° 38' on the north. Lakes cover about three square miles of the total area.

The Missouri Escarpment extends from north to south near the western border of the two-county area, dividing it into the Missouri Coteau on the west and the Glaciated Plains on the east (fig. 1). Elevations west of the Missouri Escarpment average between 300 and 400 feet higher than on the east. The Missouri Coteau is characterized by numerous sloughs, lakes, and closely spaced hills. Many poorly drained depressions receive runoff water from nearby higher areas. Elevations range up to 2 250 feet above sea level in western Dickey County.

The Glaciated Plains, approximately the eastern seven-eighths of the area (fig. 1), are nearly level to undulating, although some rolling to steep land is found in the western part of the area and along the banks of the James River valley. Relief is generally less than 20 feet locally and elevations range from about 1 300 feet above sea level in the southeastern corner of Dickey County on the glacial Lake Dakota plain to about 1 700 feet in the northwestern part of LaMoure County immediately east of the Missouri Escarpment. Surface drainage between the escarpment and the James River is directed generally eastward from the higher elevations on and near the Missouri Coteau. The James River, which parallels the escarpment at a distance of about 20 miles, drains the two-county area, flowing into the Missouri River in South Dakota.

Dickey and LaMoure Counties are situated on the southeastern edge of the Williston Basin, an intracratonic structural basin consisting of a thick sequence of sedimentary rocks. The youngest sediments are the alluvium in the river valleys and the silt and sand of glacial Lake Dakota. Beneath these sediments is a layer of glacial deposits, which forms the surface mantle over most of the area; these glacial deposits belong to the Coleharbor Group. The Coleharbor Group deposits are underlain by the Cretaceous Pierre Formation shale except in eastern Dickey County where the Cretaceous Niobrara Formation lies directly beneath the Coleharbor Group. Approximately 1 200 to 3 700 feet of Paleozoic and Mesozoic rocks occur beneath the area. All the formations below the Coleharbor Group have a northwesterly regional dip and become thicker northwestward.

STRATIGRAPHY

Nearly all the surficial materials in Dickey and LaMoure Counties were deposited during the Pleistocene Epoch and during the time since then, the Holocene Epoch. The entire area was glaciated and the landforms there are largely the result of glacial and post-glacial processes. They consist of glacial sediment, glacial meltwater sediment, and post-glacial alluvium. The cover of Pleistocene and Holocene deposits ranges up to about 600 feet thick.

The most common surface material is glacial sediment (till), which covers more than 90 percent of the two-county area. The deposits left by glacial meltwater were carried by water flowing from the melting ice and deposited on outwash plains and terraces, as valley trains, and in glacial lakes. Most of the bottomland areas along the larger streams are covered by recent alluvium deposited by streams during the Holocene Epoch. The most extensive deposits of alluvium are found on the floor of the James River valley.

The discussion of the stratigraphy on the following pages is a description and correlation of the geologic units that lie at and beneath the surface in Dickey and LaMoure Counties. The description proceeds from the oldest known materials, which are deeply buried and known only from test-hole data, to the younger, more easily accessible, geologic units, which are exposed at the surface over the two counties (fig. 2). The landforms that occur at the surface over the two-county area are composed of the younger geologic materials, which were deposited by glacial action. These glacial landforms will be discussed in more detail.

Precambrian Rocks

Precambrian basement rocks range in depth from about 1 200 feet in southeastern Dickey County to about 3 700 feet in northwestern LaMoure County. The Precambrian surface in the two-county area slopes in a west-northwesterly direction at approximately 25-30 feet in a mile. The basement rocks in Dickey and LaMoure Counties consist predominantly of two main types: those found in the amphibole schist terrane are mainly low-grade schists and gneisses; those found in the McIntosh granite terrane are mainly coarse-grained granite (fig. 3). The rocks of the amphibole schist terrane appear to be the oldest in the area; but, in general, all of the basement rocks of Dickey and LaMoure Counties are of Early Precambrian age (older than 2.6 billion years).

Paleozoic Rocks

Rocks of Paleozoic age range up to 1 300 feet thick in the northwest corner of LaMoure County. They thin eastward and are absent in extreme southeastern Dickey County (fig. 4). The Deadwood Formation in the western part of the two-county area is an onlap depositional sequence that includes a basal quartzose sandstone overlain by a sandy glauconitic limestone that grades to a glauconitic dolomitic sandstone. This unit is overlain by a sandstone. The Deadwood Formation is present only over the western quarter of the two counties where it ranges up to about 90 feet thick.

Ordovician carbonate and clastic rocks of the Winnipeg Group (Black Island, Icebox, and Roughlock Formations) overlie the Deadwood Formation. These range up to 220 feet thick in western LaMoure County. The Red River Formation, which consists primarily of limestone, overlies the Winnipeg Group sediments and is as much as 550 feet thick in northwestern LaMoure County. Sediments of Ordovician age are absent in extreme southeast Dickey County and range up to about 750 feet thick in western LaMoure County.

Only the western edge of the two-county area has deposits of Devonian and Mississippian age (fig. 4). The Devonian Duperow Formation carbonate and shale is about 75 feet thick in northwestern LaMoure County and the Mississippian Madison Formation is about 350 feet thick in western LaMoure County.

AGE	UNIT NAME		DESCRIPTION	THICKNESS
Quaternary	Oahe Formation (Holocene)		Sand, silt, and clay	?
	Coleharbor Group (Pleistocene)		Till, sand, gravel, silt, and clay	0- 600
Tertiary				Absent
Cretaceous	Pierre Formation		Shale	1 200-1 800
	Niobrara Formation		Calcareous shale	
	Carlile Formation		Shale	
	Greenhorn Formation		Calcareous shale	
	Belle Fourche Formation		Shale	
	Mowry Formation		Shale	0- 420
	Newcastle Formation		Sandstone	
	Skull Creek Formation		Shale	
	Fall River Formation		Sandstone and shale	100- 300
	Lakota Formation		Sandstone and shale	
Jurassic	Morrison Formation		Siltstone and claystone	0- 150
Triassic				Absent
Permian				
Pennsylvanian				
Mississippian	Madison Formation		Limestone	0- 350
Devonian	Duperow Formation		Dolomite and shale	0- 75
Silurian				Absent
Ordovician	Red River Formation		Limestone and dolomite	0- 550
	Winnipeg Group	Roughlock Formation	Shale and siltstone	0- 220
		Icebox Formation	Shale	
		Black Island Fm.	Sandstone	
Cambrian	Deadwood Formation		Sandstone and limestone	0- 90
Precambrian basement rocks			Schist and granite	——

Figure 2. Stratigraphic column for Dickey and LaMoure Counties.

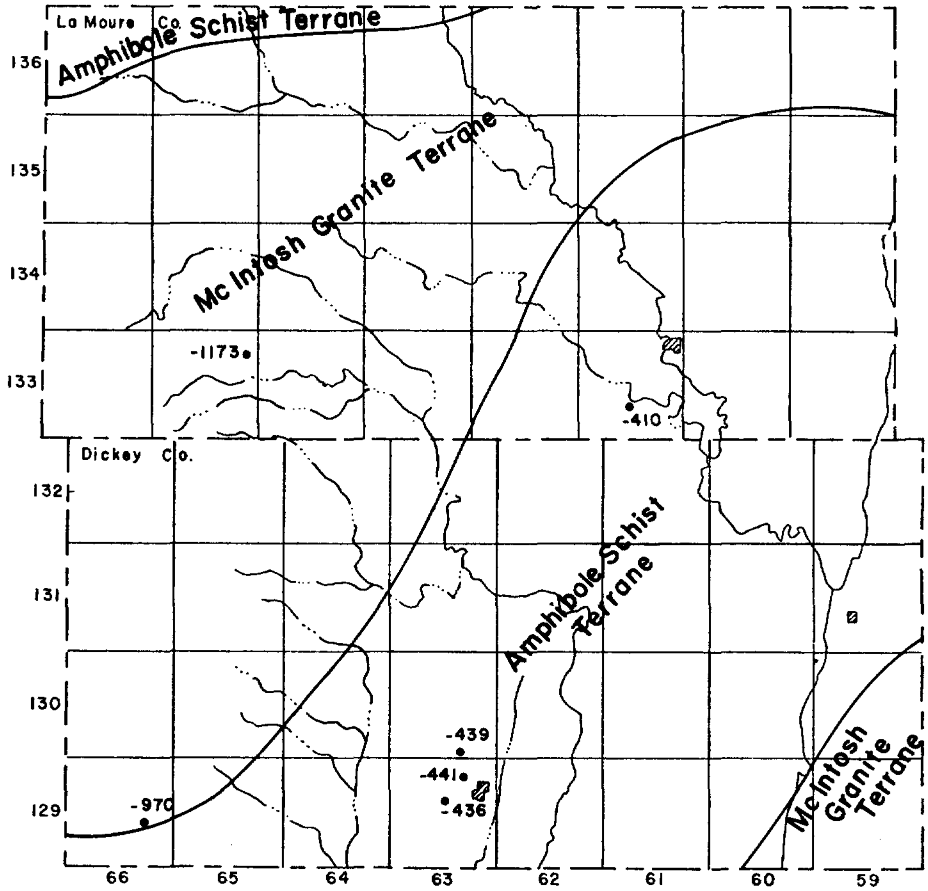


Figure 3. Geologic map of the Precambrian basement rocks in Dickey and LaMoure Counties. From an unpublished map by E. G. Lidiak.

Mesozoic Rocks

The Mesozoic rocks in the two-county area consist mainly of clastics that were deposited in widespread Jurassic and Cretaceous seas. These rocks range in thickness from about 1 200 to 2 200 feet from southeastern Dickey County to northwestern LaMoure County. The Cretaceous Pierre and Niobrara Formations occur directly beneath the Pleistocene Coleharbor Group sediments (fig. 5) throughout the area and the Pierre Formation is exposed in many places immediately east of the

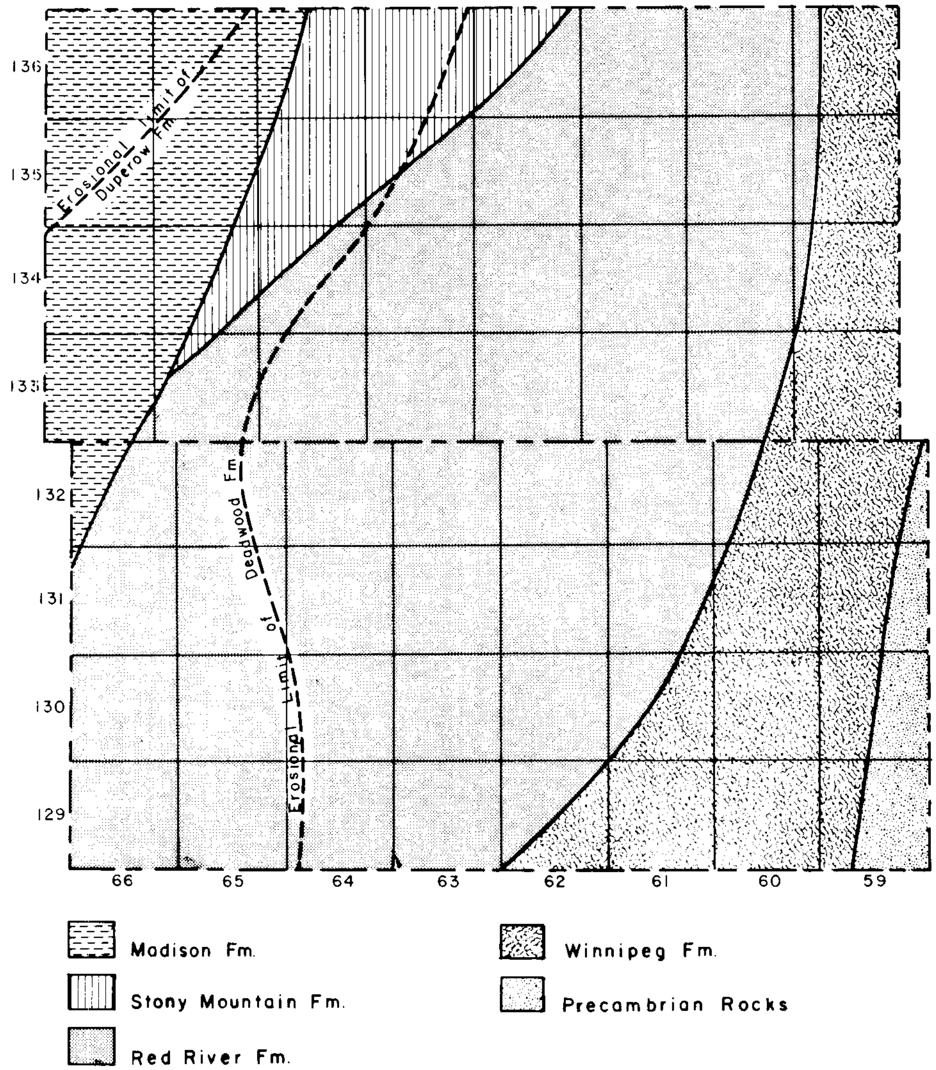


Figure 4. Pre-Mesozoic paleogeologic map of Dickey and LaMoure Counties. Precambrian granite and schist, the Ordovician Winnipeg, Red River, and Stony Mountain Formations, and the Mississippian Madison Formation (Lodgepole Facies) subcrop beneath the Mesozoic and Cenozoic cover. The dashed lines represent the erosional limits of the Cambro-Ordovician Deadwood and Devonian Duperow Formations, which lie beneath the units shown on the map. Adapted from Ballard (1963) and Anderson (1974).

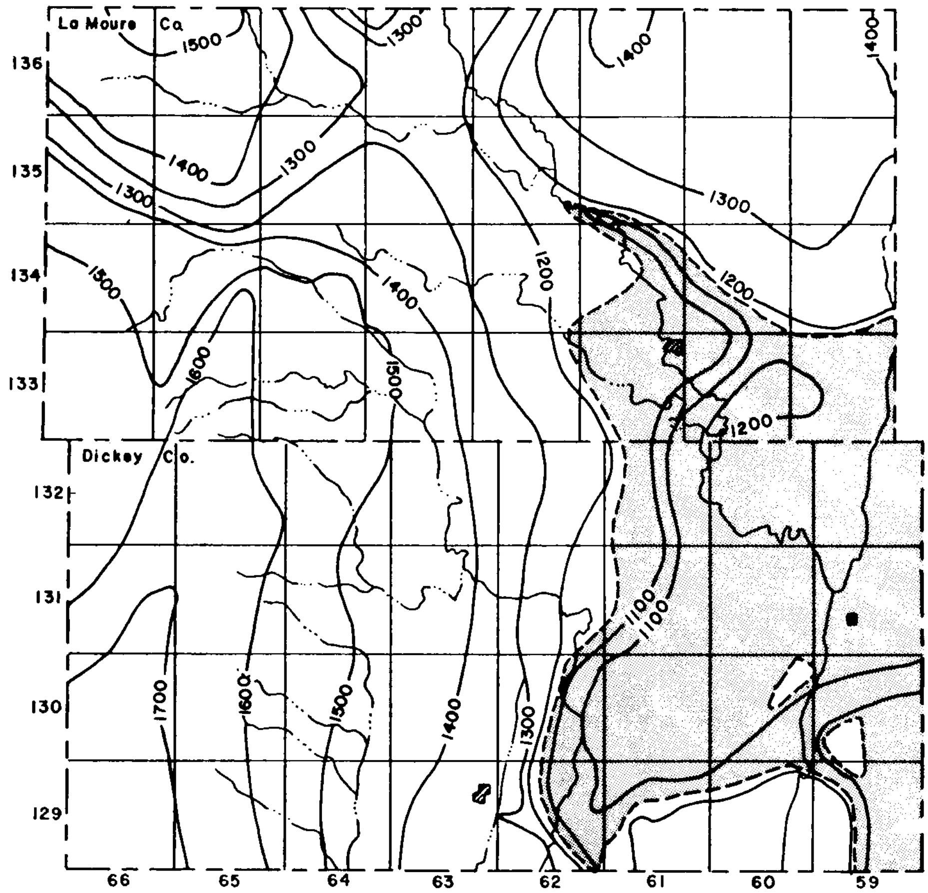


Figure 5. Map of Dickey and LaMoure Counties showing the configuration of the bedrock (subglacial) surface. Shaded area is Niobrara Formation. Unshaded area is Pierre Formation.

Missouri Escarpment where the Coleharbor Group sediments are thin (fig. 6).

Jurassic strata consist of reddish-brown siltstone, claystone, and fine-grained sandstone of the Morrison (?) Formation. Jurassic strata are absent over the southeast half of the two-county area, but they are up to 150 feet thick in northwestern LaMoure County.

The lowermost Cretaceous rocks in Dickey and LaMoure Counties are the Fall River and Lakota Formations, which consist of pale-red and light-gray claystone and siltstone inter-

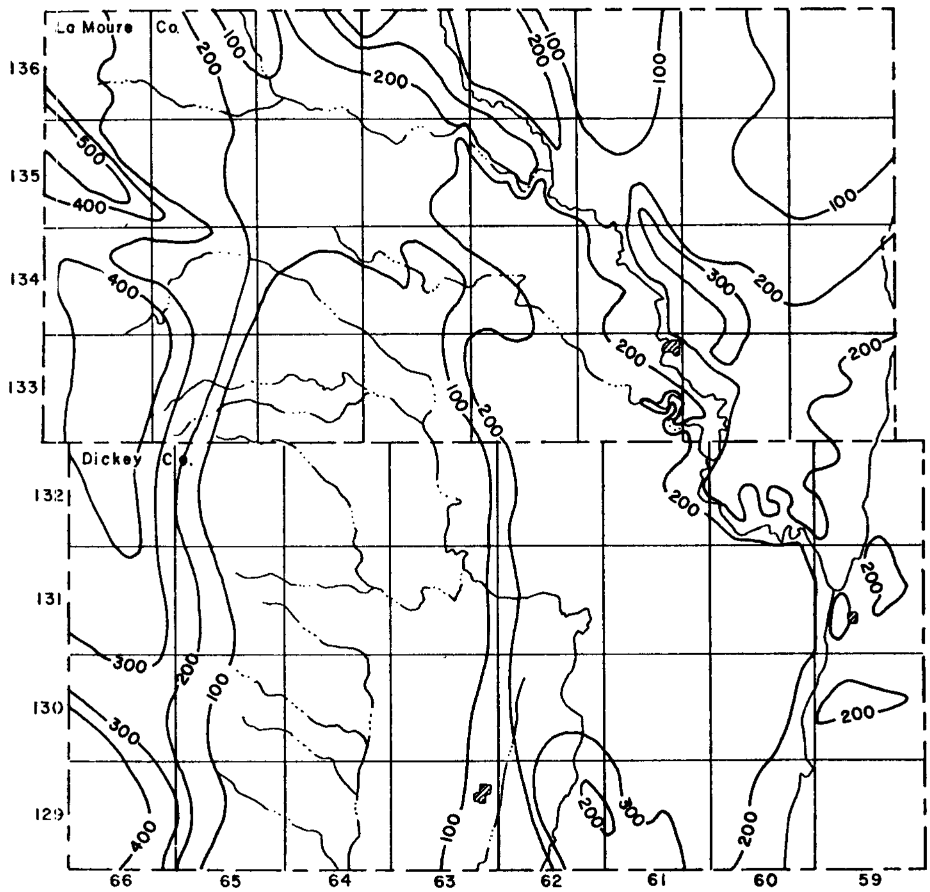


Figure 6. Map of Dickey and LaMoure Counties showing the thickness of glacial and related deposits on top of the preglacial bedrock surface.

bedded with fine-grained quartzose sandstone. These rocks range from mainly sand in the southern part of the two-county area to about half sand in the north. The thickest accumulation is about 300 feet in the southwest corner of Dickey County.

The Skull Creek, Newcastle, and Mowry Formations together with the Fall River and Lakota Formations, comprise the Dakota Group. The Skull Creek Formation, which overlies the Fall River Formation, is a medium- to dark-gray, silty and sandy shale. It is overlain by the Newcastle Formation, a medium-grained sandstone interbedded with some shale. It, in turn, is overlain by dark-gray, bentonitic shale of the Mowry Formation.

The Skull Creek, Newcastle, and Mowry Formations have a total combined thickness of about 420 feet in western Dickey County.

The remaining Cretaceous rocks over the two counties consist mainly of marine shales. The Belle Fourche Formation, a dark-gray, flaky to massive, spongy shale, overlies the Mowry Formation. The rest of the Cretaceous rocks consist of gray shale formations, some of which are calcareous, with some thin bentonitic layers. In ascending order, these formations include the Greenhorn, Carlile, Niobrara, and Pierre. The total thickness of the marine Cretaceous rocks ranges from about 1 200 feet in southeastern Dickey County to about 1 800 feet in northwestern LaMoure County.

Shale of the Pierre Formation is at or near the surface, mantled by a discontinuous cover of glacial deposits, in a two- to four-mile-wide area that extends southward from the Edgeley area to the South Dakota State line. In this area it can be found along most streams and in numerous roadcuts. Unweathered samples of the Pierre consist generally of a hard, medium-dark-gray to grayish-black, noncalcareous shale. Iron concretions are common in the shale.

Most outcrops of the Pierre Formation are weathered. In such outcrops, the shale breaks down into small flakes, which are light-bluish-gray when dry and dark-gray when wet. The shale is commonly highly jointed and fractured to a depth of several feet below its contact with the overlying glacial deposits. In some exposures, its bedding has obviously been disturbed by the action of the glacial ice. Surface exposures of the shale are generally small and shallow and no attempt was made to study the stratigraphy of the Pierre Formation based on surface exposures. No fossils were observed in the shale.

Pleistocene Sediment

All the sediment related to glacial deposition in Dickey and LaMoure Counties, that is, all the materials that were deposited by the glacial ice and by flowing and ponded water associated with the ice, are collectively referred to as the Coleharbor Group. Sediment of the Coleharbor Group is exposed throughout Dickey and LaMoure Counties. The Coleharbor Group in the two-county area ranges up to about 600 feet thick (fig. 6). It consists of three main textural facies: glacial sediment (till); sand and gravel; and silt and clay.

Till Facies

Composition.--The till found at and near the surface in Dickey and LaMoure Counties is most commonly a mixture of varying proportions of sand, silt, clay, pebbles, cobbles, and boulder-sized particles. The matrix, composed mostly of silt and clay-sized particles, is usually yellowish-brown to brownishgray in oxidized exposures and light-olive-gray where it is unoxidized. The coarser-grained materials are generally angular to subrounded and consist of carbonate, igneous, metamorphic, and shale rock fragments with small amounts of lignite. The till found near the surface in the two counties is mostly poorly indurated and it may be weakly jointed, but it has no other structure, such as bedding or sorting.

Simple counts of boulders at two locations in eastern Dickey County resulted in the following percentages: granitic boulders--86%; basic igneous boulders--7%; carbonate boulders--5%; and metamorphic boulders--2%. In general, the igneous and metamorphic rock fragments in the till were ultimately derived from the Precambrian rocks of the Canadian Shield, to the east and northeast of Dickey and LaMoure Counties. Carbonate rock fragments were derived from Paleozoic rocks of the northern Red River Valley, to the north and northeast of the two counties, and shale rock fragments were derived largely from the Niobrara and Pierre Formations, which are the surface bedrock formations under much of eastern North Dakota, including Dickey and LaMoure Counties. Many of the grains were not transported directly from their outcrop areas to their final resting place during a single ice advance. An undetermined proportion of the sediment from each glacial advance was derived from older glacial sediment.

Stratigraphic correlation.--Dickey and LaMoure Counties were probably glaciated many times during the Pleistocene Epoch. Several layers of till were penetrated in the test holes, but the earlier deposits are discontinuous. Typically, only two or three layers of till are found in any single outcrop or test hole (figs. 7 and 8). The most recent till sheet, which underwent little erosion, is as much as 165 feet thick in LaMoure County, but it is only a foot thick or less in many areas.

Camara (1977) recognized seven different till sheets in southeastern North Dakota, in an area that includes Dickey and LaMoure Counties. Table 1 summarizes the grain-size distribution and lithologic composition that Camara found for these seven units.

As a part of the present study of Dickey and LaMoure Counties, grain-size distribution (gravel-sand-silt-clay percentages) and lithologic composition (igneous+metamorphic-carbonate-shale percentages) analyses were performed on the sand-sized particles from the glacial deposits in seven test holes in LaMoure County (see appendix 1 for a review of the procedures used in determining texture and composition). Most of these test holes are represented on cross-section B-B' on plate 3. A total of 148 samples of till were analyzed from test holes that ranged in depth from 250 feet to 500 feet and averaged about 325 feet deep. Samples were taken at ten-foot intervals.

Figure 7. Boulder pavement separating two till units near Adrian in LaMoure County (center sec 32, T136N, R62W). The upper surfaces of many of the boulders have been striated by the overriding glacier. The lower till is more gravelly and more shaly than the upper one.

In analyzing the till samples, the total percentage (by weight) of gravel in each sample was calculated (column 6 on table 2) and the sand, silt, and clay percentages of the remaining portion of the sample were then calculated (columns 7, 8, and 9 on table 2). The percentages (by weight) of igneous, carbonate, shale, and other lithologic types were calculated for each sample (columns 10, 11, and 12 on table 2). Finally, for purposes of further comparison, a "normalized crystalline" ratio (column 13) was calculated (crystalline/crystalline + carbonate) to eliminate the effect of shale on the percentages (in this discussion, "crystalline" refers to igneous and metamorphic lithologies). A summary of the physical characteristics of the tills from the seven test holes is given on table 2.

Figure 8. Striated upper surface of one of the boulders in the pavement shown in figure 7. The striations indicate that the overriding glacier moved in a north-northwest to south-southeast direction.

Obvious measurable differences in both texture and composition were noted among the various layers of till sampled in the test holes and it was possible to make some tentative correlations of till units from hole to hole. It should be emphasized that the till unit groupings shown on table 2 are simply interpretations based on a combination of (1) the physical characteristics determined in the laboratory; (2) stratigraphic position in the hole; (3) electric log correlations; and (4) sample descriptions by the well-site geologist. No attempt is made to assign formal designations, such as formation names, to the till units.

Based on a combination of the criteria listed in the preceding paragraph, but with heaviest reliance placed on the first criterion, I have designated five till units, P through T from bottom to top, in the seven LaMoure County test holes that were studied in detail. These five units are designated in the test holes where they occur on cross-section A-A' (pl. 3). Gaps, which may be due to either the absence of till (intervals where sand units occur, for example) or lack of information, are designated by an "X" on the cross section. The correlations among the five till units are still too tenuous to be relied upon. In many instances, obvious electric log markings do not coincide with breaks between till units and, in fact, they may not be reflected at all in the laboratory data. It is not possible, at this time, to confidently describe a lithostratigraphic frame-

TABLE 1. Grain-size distribution and lithologic composition of the very coarse sand fraction of the glacial sediment (till) in the area studied by Mike Camara (see text). No attempt is made to correlate Camara's stratigraphic units with those shown on table 2.

Unit	% Sand	% Silt	% Clay	% Igneous & Metamorphic Fragments	% Limestone & Dolomite Fragments	% Shale	Normalized Crystalline Value
Unit E	34	43	23	67	23	10	0.74
Unit D	33	40	27	52	29	19	0.64
Dahlen Formation	30	43	27	31	25	44	0.55
Gardar Formation	22	49	29	19	16	65	0.54
Unit C	29	41	30	40	30	30	0.57
Unit B	37	42	21	29	23	48	0.56
Unit A	29	43	28	38	26	36	0.59

work. Continued study of the glacial stratigraphy of southeast North Dakota with the addition of test-hole data from Ransom and Sargent Counties, which adjoin Dickey and LaMoure Counties on the east, may make it possible to decipher the glacial stratigraphy of the area in more accurate detail.

A few preliminary observations are possible at this time. It appears that essentially the same units of Coleharbor Group glacial sediment are represented on both the Missouri Coteau (test hole 9170) and on the Glaciated Plains (test hole 9202 and composite of test holes 9205 and 9206). Comparable units on the Missouri Coteau are thicker than they are on the Glaciated Plains.

The lowermost unit, P+P', is probably a composite of several different till deposits of various ages. In the four test holes examined in which unit P occurs, it lies directly on shale. The percentage of shale in unit P is generally quite high. Texture and composition studies of samples from additional test holes in the area might make it possible to differentiate unit P into more than one unit. If unit P is pre-Wisconsinan glacial sediment, it is probably quite discontinuous and preserved only in the bottoms of some of the deeper valleys. The occurrence of till designated P' in test hole 9170 may be a weathered zone on top of the underlying till. A relatively lower shale percentage is common in weathered till layers.

Units Q and R have physical characteristics closely approximating those of the Gardar and Dahlen Formations, which have

TABLE 2. Summary of physical characteristics of till samples from seven test holes in LaMoure County

1	2	3	4	5	6	7	8	9	10	11	12	13
					Texture				Composition			
						Remaining Percentage						
Till Unit	Test Hole	Thick-ness (ft.)	Depth Range	No. of Spls.	Gravel %	Sand %	Silt %	Clay %	Igneous %	Carbonate %	Shale %	Normalized Crystalline Ratio
T	9170	10	0- 10	2	2	23	41	37	78	16	6	.83
	9203	20	0- 20	4	5	37	37	26	72	23	5	.76
	9208	15	5- 20	3	5	37	37	26	72	23	5	.84
	9206	20	0- 20	4	3	34	35	31	63	31	6	.67
	9202	5	5- 10	1	6	32	38	30	57	22	20	.72
S	9168	70	0- 70	9	3	29	39	33	54	26	20	.67
	9170	60	10- 70	7	3	28	40	32	48	29	22	.62
	9205	30	30- 60	3	14	40	36	24	44	27	29	.62
	9203	40	20- 60	4	4	37	36	27	47	24	29	.67
	9202	40	20- 60	4	5	34	37	29	52	23	24	.69
R	9168	70	70-120	5	3	29	43	29	34	19	47	.63
	9203	20	160-180	2	7	42	35	23	29	13	58	.68
	9202	10	80- 90	1	4	42	34	25	29	22	49	.57
	9205	70	80-150	7	5	38	34	28	29	20	51	.58
	9208	20	30- 50	2	13	37	37	26	35	19	46	.65
	9206	80	20-100	6	7	41	34	26	36	23	41	.61
	9170	80	70-150	8	3	30	38	32	29	23	48	.62

TABLE 2. Summary of physical characteristics of till samples from seven test holes in LaMoure County--Continued

1	2	3	4	5	6	7	8	9	10	11	12	13
					Texture				Composition			
						Remaining Percentage						
Till Unit	Test Hole	Thick-ness (ft.)	Depth Range	No. of Spls.	Gravel %	Sand %	Silt %	Clay %	Igneous %	Carbonate %	Shale %	Normalized Crystalline Ratio
Q'	9205	10	150-160	1	8	31	46	23	64	24	24	.73
	9170	50	150-200	5	4	32	39	30	56	25	28	.65
Q	9202	90	90-180	8	7	36	33	32	24	15	61	.62
	9208	110	50-160	9	12	41	32	27	24	18	58	.57
	9206	20	100-120	2	10	54	26	21	24	16	60	.59
	9203	120	180-300	14	5	24	40	34	18	14	68	.56
	9170	140	260-400	13	6	40	33	27	25	16	59	.61
	9205	50	160-210	5	9	34	40	26	20	21	59	.50
P'	9170	30	410-440	3	10	53	24	18	39	19	46	.67
P	9202	70	190-240	7	3	19	42	39	15	12	74	.56
	9170	20	440-450	2	9	49	32	19	17	8	76	.67
	9205	50	210-230	5	3	19	38	42	12	12	76	.50
	9208	10	200-210	2	10	27	23	51	36	15	50	.72

been recognized in northeast and east-central North Dakota (Salomon, 1975; Moran, and others, 1976). The Gardar Formation is considered to be early Wisconsinan, more than 40 000 years old. In at least two LaMoure County test holes (9170 and 9205) the upper portion of the Gardar Formation (Q') appears to represent a weathering profile with unusually low percentages of shale. The Dahlen Formation (equivalent to unit R?) is considered to be late Wisconsinan, deposited more than 20 000 years ago as the glacier advanced southward. In the LaMoure County test holes, unit S may represent the recessional phase of the late Wisconsinan Dahlen glacier and unit T probably represents the post-depositional weathering profile on unit S.

Boulders in the till.--About two-thirds of the boulder-sized rocks found on the till surface in most places in Dickey and LaMoure Counties consist of grayish or pinkish granite. The remainder are mainly dolomitic limestone, gneiss, and dark basaltic rocks in about equal proportions. Many boulders are striated or polished (figs. 7 and 8). Small pieces of lignite are found in places in the till and occasionally a large, boulder-sized piece of lignite is found.

One boulder, found in western Dickey County, contained an appreciable percentage of silver and, early in the century, people in western LaMoure County reported finding boulders in T135N, R66W that yielded gold and silver. Their occurrence in western LaMoure County led to considerable excitement among the early settlers, who staked out claims on nearly all the land in secs 25 and 26, T135N, R66W, about four miles southwest of Jud.

The face of the Missouri Escarpment in Dickey County is covered by abundant boulders in places (fig. 9). Many hills in the Lake Oakes Hills in eastern Dickey County are also extremely bouldery. Generally, concentrations of boulders probably occur in areas that have been washed by running water and the finer fraction of the till has been removed, leaving the boulders behind.

Gravel and Sand Facies

The gravel, gravelly sand, silty sand, and sandy silt deposits in Dickey and LaMoure Counties include both well sorted cross-bedded and plane-bedded material. Compared to other glaciated areas in North Dakota, the two counties have relatively small amounts of sand and gravel at the surface. However, thick layers of sand and gravel are found buried in several places. The Spiritwood sand and gravel aquifer is probably the most extensive such buried deposit in the two counties.

Statistical studies of gravel and sand samples obtained during the drilling of test holes by the North Dakota State Water

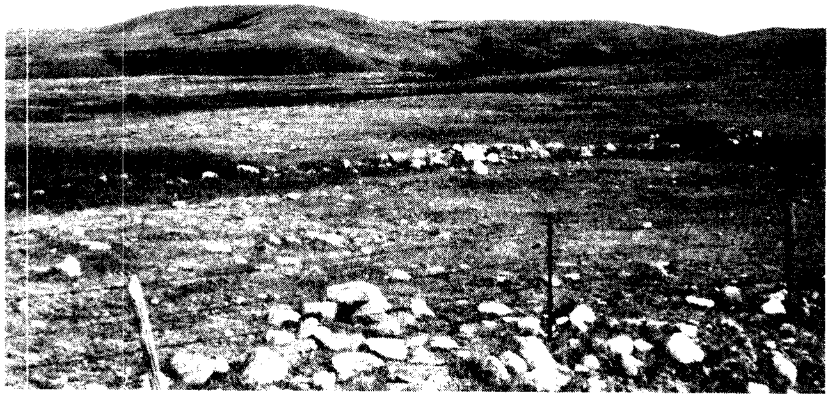


Figure 9. Bouldery slopes of the Missouri Escarpment in Dickey County (sec 18, T129N, R65W). The bouldery surface in this area is apparently the result of slopewash that carried away the finer materials.

Commission are summarized in tables 3, 4, and 5. The carbonate fraction of the gravel was derived from the Paleozoic carbonate sequences of southern Canada, the granitic and basic igneous rocks from the Canadian Shield, and much of the shale was probably locally derived. The most abundant fraction in the gravel and sand is quartz; the least abundant is the basic igneous fraction.

Percentages of the various fractions vary only slightly between the two counties. The only exceptions are where less than 20 samples were studied and, in these instances, the number of samples may have been insufficient to be statistically valid.

The gravel and sand facies was deposited by meltwater rivers and by running water that resulted from precipitation that fell during and immediately following glaciation. Included are deposits of glacial outwash, which are found mainly on the Missouri Coteau, and which are collapsed in many places. Also included are materials on terraces along the major valleys, particularly the James, and on the floors of meltwater trenches where they are not covered by modern alluvium.

Silt and Clay Facies

The laminated silty clay, clayey silt, and fine sand consist of materials that were deposited in lakes. Areas that were

TABLE 3. Percentages of quartz, carbonate, basic igneous, and shale fractions in samples of gravel and sand in Dickey and LaMoure Counties. Samples were taken: (1) from all depths; (2) from near the surface; and (3) from the deepest horizons (gravel and sand layers buried beneath three or more tills). The number of samples used in computing the percentages is given in parentheses beneath the county name in each column.

	All samples--all depths		Near-surface deposits		Deepest deposits	
	Dickey (103)	LaMoure (198)	Dickey (29)	LaMoure (44)	Dickey (10)	LaMoure (16)
Quartz (%)	42	39	44	41	60	39
Carbonate (%)	30	31	34	32	17	29
Basic Igneous (%)	5	8	6	9	7	6
Shale (%)	23	22	16	18	16	26

flooded by lakes in Dickey and LaMoure Counties are colored blue on plates 1 and 2 and designated Qes. In these areas, exposures of bedded, sandy silt and clay are common. Most of the lakes in the two counties were small and shallow so that little offshore, deep-water sediment accumulated. As a result, shore sand is commonly mixed with the silt and clay. The glacial Lake Dakota sediments in southeast Dickey County are poorly exposed due to a covering of wind-blown sand and silt. Samples taken from below the upper, wind-blown zone are generally somewhat sandy, consisting of layers of silt and clay that are interbedded with sand that was delivered to the lake by the James River.

Holocene Sediment

The Oahe Formation sediment consists of a variety of clay, sand, silt, and gravel deposits that accumulated during Holocene and latest Wisconsinan time. It consists of river, pond, wind-blown, and mass-movement sediment. In Dickey and LaMoure Counties, three main facies are included in the Oahe Formation. These are the clay facies; the bouldery, gravelly clay facies; and the sand and silt facies.

Clay Facies

The clay facies of the Oahe Formation (Qoc) in Dickey and LaMoure Counties consists mainly of pond and slough sediment,

TABLE 4. Percentages of quartz, carbonate, basic igneous, and shale fractions in samples of gravel taken from all depths and from at and near the surface in Dickey and LaMoure Counties. The number of samples used in computing the percentages is given in parentheses beneath the county name in each column.

	All gravel samples--all depths		Near-surface gravel samples	
	Dickey (40)	LaMoure (86)	Dickey (8)	LaMoure (17)
Quartz (%)	18	12	20	13
Carbonate (%)	42	47	48	50
Basic Igneous (%)	7	10	8	13
Shale (%)	33	31	24	24

which is dark-colored, obscurely bedded organic clay along with some silt and fine sand. Deposits of the clay facies are found in small ponds and sloughs throughout the area, but especially on the Missouri Coteau. Only a few of the ponds and sloughs are shown on plates 1 and 2 as most were too small to map.

The sediments of the clay facies were brought to the ponds and sloughs through slopewash processes, and, to some extent, eolian processes, and redeposited by the pond water. They are typically a few feet thick. Most areas covered by clay deposits are characterized by flat topography with less than 1° slopes.

Bouldery, Gravelly Clay Facies

The bouldery, gravelly clay facies of the Oahe Formation in Dickey and LaMoure Counties (Qob) is highly variable from place to place. It consists of colluvial materials that were deposited by slopewash, slumping, sliding, and earth creep and it is commonly found along the fronts of steep slopes, notably the Missouri Escarpment.

The thickness of the colluvial materials ranges from less than a foot to perhaps 50 feet in a few places. Landslide topography is common in places and relief may exceed 100 feet locally.

As its name implies, the bouldery, gravelly clay facies consists of a wide range of grain sizes and lithologic types. It can be distinguished from glacial till in places only because of its position and topography. Shale particles constitute a high percentage of the content in some areas where the underlying Pierre Formation is near the surface as it is near Merricourt.

TABLE 5. Percentages of quartz, carbonate, basic igneous, and shale fractions in samples of sand taken from all depths and from at and near the surface in Dickey and LaMoure Counties. The number of samples used in computing the percentages is given in parentheses beneath the county name in each column.

	All sand samples--all depths		Near-surface sand samples	
	Dickey (63)	LaMoure (112)	Dickey (25)	LaMoure (27)
Quartz (%)	55	59	50	58
Carbonate (%)	22	19	30	21
Basic Igneous (%)	6	7	6	7
Shale (%)	17	15	14	14

Sand and Silt Facies

The sand and silt facies of the Oahe Formation in Dickey and LaMoure Counties consists of river and wind-blown sediment. The river sediment (Qosr) is found along the James, Maple, and Elm Rivers, and along some of the smaller stream valleys. It is generally light- to dark-gray sand and silt commonly with organic fragments and with obscure bedding. It is thickest near the streams and forms flat to gently rolling topography. The flood plain of the James River is characterized by numerous meander scars and cutoff meanders.

Most of the wind-blown sediment is found south of Oakes over an area of about 50 square miles east of the James River (Qosw). Low sand dunes and shallow blowouts are common in the former lake bottoms, giving the landscape a gentle hummocky appearance. This is particularly true along the east side of the Lake Dakota basin where sand was apparently the main component of the uppermost lake deposit, and where prevailing westerly winds tended to concentrate the sand. The only area of high dunes is at the southeast end of a broad, low ridge that extends from sec 7, T130N, R59W to the southeast corner of that township. Here, the northwest winds, which swept the length of the ridge, built a large dune complex that is over 45 feet high just across the Dickey County line in Sargent County.

Eolian activity has complicated the pattern of materials on the surface of the Dakota Lake plain, scooping out hollows in the lake deposits, re-sorting them by removal of finer materials and leaving behind coarser sediments, and by piling up dunes.

Buried soils, overblown by up to four feet of sand, occur in several places (Brophy, 1961).

Loess was found in two locations. It overlies till on the upland east of the James River just above the terrace remnant in the NW¼ sec 5, T131N, R59W. The river here has a broad northwest-southeast trending segment and the loess was probably blown from the valley train of which the terrace is a remnant. The loess here is massive, well-sorted silt, five feet thick, and apparently not widely distributed. The second occurrence, less typically loess, is on the west slope of the Oakes moraine in the SE¼ sec 1, T130N, R59W. Here, the loess is at least ten feet thick, but shows faint bedding and approaches fine sand in texture.

GEOMORPHOLOGY

General Description

The modern landscape in Dickey and LaMoure Counties is the surface that was formed by the advance and retreat of the glaciations that occurred in Wisconsinan time. Early Wisconsinan glacial sediment and associated stream and lake sediment was apparently not eroded and altered greatly, except for weathering and soil development at the surface, before the area was glaciated again in late Wisconsinan time. By contrast, erosion that occurred after the pre-Wisconsinan glaciations was apparently prolonged and sufficient to remove much of the glacial sediment that had been deposited, resulting in a landscape similar to the preglacial landscape, although the drainage pattern subsequent to pre-Wisconsinan glaciation and prior to late Wisconsinan glaciation is not known.

The two-county area can be subdivided into two well-defined areas, the Missouri Coteau in the west, and the Glaciated Plains in the east. These two areas are separated by the Missouri Escarpment. Most of the landforms on the Missouri Coteau in Dickey and LaMoure Counties formed due to the collapse of glacial sediment that covered a nearly continuous sheet of stagnant glacial ice, which melted between about 9 000 and 12 500 years ago. Typical landforms of the Coteau include hilly areas of collapsed glacial sediments, collapsed flood plains and lake plains, elevated lake plains, and various types of ice-disintegration features. Areas of steeply-thrust glacial sediment are found in places. The glacial sediment on the Missouri Coteau in the two counties averages from 300 to 400 feet thick, reaching to over 500 feet in some places, and thinning to about 200 feet near the Missouri Escarpment.

Surface elevations rise as much as 300 to 400 feet along the Missouri Escarpment, and even though elevations on the buried bedrock surface beneath the escarpment do rise westward, no pronounced "escarpment" was present on the bedrock surface in Dickey and LaMoure Counties prior to glaciation. The Missouri Escarpment in the two counties is formed largely of glacial sediment in contrast to parts of northwestern North Dakota where it is built of preglacial bedrock. The escarpment is steepest in Dickey County and becomes somewhat more gentle northward.

It appears that the modern Missouri Escarpment formed as the glacier flowed westward, up the gradual rise in elevation on the bedrock surface. The upslope movement of the glacier caused compressive flow within the ice and resulted in the initiation of large-scale thrusting near the glacier terminus. Repeated stagnation of the glacier terminus over the higher elevations of the area now known as the Missouri Coteau resulted in a progressively steeper slope for succeeding glaciers to flow over. Possibly, glacier flow direction east of the Missouri Escarpment shifted as portions of the glacier on the Coteau stagnated; the resulting change in flow direction from mainly westward to mainly southward in the area east of the Missouri Escarpment may also have helped to shape and steepen the face of the escarpment.

The face of the modern Missouri Escarpment is deeply channeled in places by numerous deep, dry coulees (fig. 9). Materials that washed from the slopes during both Pleistocene and Holocene time are found at the base of the escarpment as fans and, in some places, as accumulations of colluvial debris. Most of the gullies that head into the Missouri Escarpment do not extend any appreciable distance into the Missouri Coteau. Exposures of Pierre Formation shale are found in some places along the base of the Missouri Escarpment, but in most places the entire face of the escarpment is composed of glacial sediment.

The Glaciated Plains extend over the entire area of the two counties east of the Missouri Escarpment. Landforms found here include those formed by the moving glacier. They range from pre-last glacial till-draped topography through ice-thrust features and various degrees of rolling to hilly collapsed glacial sediment, although large-scale glacial stagnation was not a significant land-forming process on the Glaciated Plains.

The glacial landforms of the Glaciated Plains have been modified by running water, which has washed the surfaces in some places and deposited gravel and sand in other places. Meltwater trenches dissect the till plain. The James River flows through the largest such trench. Its valley is a rather steep-sided, flat-bottomed trough about a mile wide. Extensive gravel terraces occur in the valley. The James River valley broadens into the glacial Lake Dakota plain in southeastern Dickey County. The lake plain is about six to ten miles wide and 15 miles long in North Dakota, but much more extensive in South Dakota. The plain is nearly level and covered by a sheet of wind-blown silt and small sand dunes in most places. Numerous smaller flat areas covered by flat-bedded clay, silt, and fine sand occur in places that were flooded by lakes as the glacier melted from the area.

Glacial Landforms

Most of the landforms that will be described were formed by the late Wisconsinan glacier, especially as it receded from the two-county area. Certain features, such as Cannon Hill, which is an overridden esker in southern Dickey County, may date to pre-last glacial time. The configuration of the surface topography is unrelated, or is related in only a general way, to the topography on the bedrock surface (fig. 5).

Areas in which the till facies of the Coleharbor Group are exposed are represented by shades of green (pls. 1 and 2) and designated by the symbol Qct. These areas are characterized by landforms composed mainly of glacial sediment, materials that were deposited from the last glacial ice.

Collapsed Glacial Sediment

At the end of the last glaciation, an irregular thickness of insulating sediment (superglacial sediment) on top of the stagnating glaciers resulted in irregular glacial decay, rather than an orderly retreat of the ice margin. Broad patches of stagnant ice, many counties in area, persisted for several thousand years. Large-scale glacial stagnation occurred on the Missouri Coteau in western Dickey and LaMoure Counties, but stagnation also occurred on a smaller scale east of the Coteau. Slough-bottom C-14 dates from counties adjoining Dickey and LaMoure Counties indicate a climatic change marked by the start of slough deposition when the last buried ice melted several thousand years after the Laurentide ice was active (Moran and others, 1973) about 9 000 to 10 000 years ago. C-14 dates from wood under glacial sediment commonly indicate landslide activity resulting from the melting of buried ice rather than glacial readvance.

Collapsed superglacial sediment covers much of the two-county area (pls. 1 and 2). This sediment consists mainly of mudflow materials that slid into position as the ice melted. In general, the thickness of the superglacial sediment (in metres) approximates the maximum slopes now found on the land surface (Clayton and Moran, 1974). Relief is gentle in most places east of the Missouri Coteau; it is rolling to hilly on the Coteau.

Undulating surface.--Gently undulating to undulating surfaces with poorly integrated drainage are found over broad areas of the Glaciated Plains east of the Missouri Coteau (Qctu on pls. 1 and 2). Essentially similar areas with comparable topography and relief have been termed "ground moraine" in many previous North Dakota Geological Survey publications. However, the term "ground moraine" is vague. It is partly genetic, variously defined by some geologists as a kind of topography, or a kind of sediment that was produced by glacial deposition, especially subglacial deposition. (However, most "ground moraine" is probably composed of superglacial sediment.) It can be used in a descriptive sense as "flat or undulating, having less than 20 feet of local relief (or whatever), or lacking transverse topographic lineations." Such a term can be used without confusion in only the most casual situations (Clayton, 1970, p. 43).

Areas of till with gently undulating to undulating surfaces have local relief of less than ten feet in most places. The most common characteristic markings on these surfaces in Dickey and LaMoure Counties are areas of "washboards" which are well developed over the northern part of the area and immediately east of the Missouri Coteau. Washboards consist of alternating transverse ridges and trenches spaced about 650 feet apart, with local relief of five to ten feet. They are best seen on air photos. The ridges and trenches are gently curved, with a radius of curvature of 6 to 12 miles, concave upglacier (that is, north and northeast immediately east of the Missouri Coteau; northwest in the eastern parts of the two counties). The ridges apparently formed as the result of greater concentrations of glacial sediment along periodically spaced transverse shearing zones near the margin of the glacier. In some parts of North Dakota, longitudinal shear markings (drumlins and flutings) are common on the undulating stony loam surfaces; these were not found in Dickey and LaMoure Counties.

The total thickness of glacial sediment beneath areas of undulating till ranges from about a foot to as much as 300 feet. However, the uppermost layer of till, the one that forms nearly all of the most prominent surface features, is generally only about 5 to 15 feet thick. The most recent glacial advance, which formed the undulating surface, deposited only about 5 to 15 feet of sediment and the larger topographic features (changes in elevation on a several-square-mile scale), are related to pre-last glacial topography.

Rolling surface.--Rolling surfaces of till have numerous ice-disintegration features, which are readily apparent only on air photos. These rolling areas have more potholes than do the undulating till surfaces. Rolling till surfaces are found in several places throughout the two-county area (Qctr on pls. 1 and 2). Similar areas in other parts of North Dakota have been variously termed "ground moraine" or "low-relief dead-ice moraine" in previous county studies. For reasons already stated in the discussion of the undulating surfaces, these terms are not appropriate. Rolling surfaces of collapsed glacial sediment have relief that ranges from 30 to 60 feet locally. Higher relief is found on the Missouri Coteau; lower relief characterizes areas east of the Coteau. The total thickness of glacial sediment beneath the rolling surfaces may be great, but the uppermost layer of till is generally only moderately thick, about 10 to 25 feet in most places.

Washboard ridges are not associated with the rolling surfaces. Rather, numerous ice-disintegration markings such as "doughnuts" and short linear disintegration ridges are apparent on air photos; these are generally not obvious to the ground-based observer, but apparent on air photos. Small eskers are also much more common on the rolling surfaces than on the undulating surfaces.

Collapsed glacial sediment with rolling surfaces occurs east of the Missouri Escarpment in areas where the rate of ice margin retreat was relatively slow or where patches of the glacier stagnated. Small areas of bedded silt are found in rolling areas in Dickey County. These silt deposits occur in both high and low areas so they probably accumulated in ponds that existed adjacent to and on the melting stagnant ice. The reason for the distribution pattern of the rolling as compared with the undulating surfaces is not immediately apparent, although in a later section of this report--the discussion of the Fullerton Escarpment--I will speculate on the reasons for the occurrence of a rolling area in Dickey County near Ellendale.

Hilly surface.--Hilly areas of collapsed glacial sediment (Qcth on pls. 1 and 2) are found over much of the Missouri Coteau west of the Missouri Escarpment. This type of landform has commonly been referred to as "dead-ice moraine" or "hummocky moraine" in most previous county groundwater studies.

The hilly surfaces in Dickey and LaMoure Counties have relief of 50 to 175 feet locally. Large kettle holes, commonly containing sloughs or lakes, are abundant in these areas.

The hilly topography is the result of large-scale glacial stagnation, and most of the landforms are ultimately the direct result of mudflows. As the stagnant glacier melted, topography on the surface of the ice was continually inverted. When sinkholes in the stagnant glacier finally melted through to the solid ground beneath, circular holes formed in the glacier. Material (till) flowing down the sides of these holes completely filled the holes in some cases, resulting in hills of material occupying the positions of the former sinkholes when all the ice finally melted. If the amount of till flowing into the holes was not enough to completely fill it, the till formed doughnut-shaped ridges at the base of the sides of the hole; these ridges are commonly called "circular disintegration ridges" or "doughnuts." If, in the final stages of topographic inversion, thick deposits of till in the bottoms of sinkholes caused them to invert into ice-cored cones, the till may have flowed down the sides of the cones, producing, when all of the ice had melted, doughnut-shaped ridges, also called "circular disintegration ridges." Any ridges formed by till moving down ice slopes and collecting at their base are called "disintegration ridges." They generally form random patterns and they may be any shape, from circular to straight, depending on the shape of the former ice slope and the fluid content of the sediment as it slid into place.

The maximum diameter of the hummocks in collapse topography is about 650 feet; the diameter of circular disintegration ridges is about 650 feet (Clayton and Moran, 1974). Differences in the steepness of hillslopes in hilly collapse topography are mainly the result of differences in the viscosity of the superglacial sediment. As the grain size and clay mineralogy of all of the late Wisconsinan till in Dickey and LaMoure Counties was probably essentially similar everywhere, the variable that produced the largest differences in flowability was water content. Water content was related to the rate of ice melting, which, in turn, was related mainly to the thickness of the insulating cover of superglacial sediment. Thicker superglacial sediment has less water in it, is more viscous, and produces hummocks with steeper sides. As a result, local relief in collapse topography is related to the thickness of superglacial sediment. The uppermost layer of glacial sediment on the Missouri Coteau in Dickey and LaMoure Counties, where hilly surfaces are found, ranges from about 25 to 100 feet, thickest in the areas with the steepest topography.

Linear patterns.--The overall pattern of disintegration features--ridges, potholes, and other markings--is mainly random in most collapsed glacial sediment. However, certain areas, otherwise similar to hilly or rolling collapsed glacial sediment, do have either an overall linear pattern or internal linearity or, sometimes, both. These linear patterns are typically obvious on air photos, but difficult for the ground-based observer to perceive. The linear elements (ridges and rows of potholes) generally parallel the overall linear configuration of the areas.

Presumably, most linear patterns are the result of a combination of shearing at the ice margin (see the discussion of ice-thrust topography), glacial stagnation, and ablation while the active ice margin remained in the same location for a relatively prolonged time, melting at about the same rate as the glacier advanced.

Landforms of the type just described have commonly been termed "end moraine." Although some linear features probably did form at the margin of the active glacier and in the manner just described, others are merely narrow areas of hilly or rolling collapsed topography, unrelated to significant ice-margin positions. Such an area of collapsed glacial sediment is found adjacent to (north of) Bone Hill Creek in northern LaMoure County. Average relief is about 30 to 60 feet. Here, the overall linearity of the feature (Qctl on pl. 2) may have formed at the ice margin during a glaciation prior to the most recent one, or it may consist of a row of ice-thrust blocks that were subsequently overridden by the glacier. It is, however, not an "end moraine" in the sense that this term has been most commonly used previously because the most recent till layer extends over the feature and is present to both the north and south of it.

Ice-Thrust Blocks

Several areas of rugged topography with intense internal linearity are found on the Missouri Coteau in the western part of the two-county area. These areas of ice-thrust blocks (Qctt on pls. 1 and 2) have local relief exceeding 175 feet.

Large blocks of shale, dislodged by the ice from the Pierre Formation, which underlies the area, are found as unbroken inclusions in the till in exposures in secs 25 and 26, T135N, R66W. Boulders of shale several tens of feet in diameter protrude from the hillsides. The original bedding is tipped at various angles as shown by the bedding planes, which are still preserved, even though the shale is soft and friable. One of the shale boulders was excavated to a depth of more than 25 feet by early settlers searching for gold, which was reported to have been found as small drift inclusions along the draw leading to the northwest. The bottom of the shale block was not reached in any of the shafts. These blocks of shale were transported by the glacier, and they are underlain by about 400 feet of glacial sediment.

Ice-thrusting occurred near the terminus of the active glacier where the ice was frozen to its bed so that compressional folds and thrusts of the subglacial sediment resulted. Vertical displacement was typically tens of feet and the individual folds or thrust masses are commonly about 600 feet across. The folds are commonly overturned. Their axial plane and the thrust faults dip upglacier at 30° to 60°. The strike is parallel to the ice margin. In map view, the thrust masses are concave upglacier, commonly with a radius of curvature of about 3 miles.

A large ice-thrust mass is found in Townships 134 and 135 North, Ranges 65 and 66 West in LaMoure County (pl.2). The surface of this mass is bouldery and areas of gravel and sand occur in places. Many smaller ice-thrust masses occur in the same area in association with the large one. Some of the smaller masses are prominent hills with a depression upglacier from each hill; the thrust mass came out of the depression (Bluemle, 1970). Much of the rugged relief in the Alfred area of extreme northwestern LaMoure County is apparently the result of thrusting. No attempt was made to separate this ice-thrust topography from the adjacent hilly collapsed glacial sediment.

Another area of thrusting occurs in Dickey County at the junction of State Highways 11 and 56.

Ice-thrust masses of this type form in the marginal part of a glacier where the glacier is (1) decelerating; (2) frozen to its bed; and (3) where there is excess groundwater pressure (Bluemle, 1970; Moran, 1971). Deceleration is necessary to cause the compression and to cause upward shearing of the material. A frozen bed is necessary so that the subglacial material can be incorporated into the glacier; the effective base of the glacier, as a flowing mass, is beneath the ice-sediment interface. Excess groundwater pressure is needed to reduce the shear strength of the rock, helping the glacier to move the sediment. Compressional features are most commonly found in North Dakota and Saskatchewan associated with buried valley-fill deposits because of the extremely high excess pore-water pressure that developed over buried aquifers. They also occur where the glacier advanced against an upland under which the groundwater-flow systems hindered the dissipation of the excess pore-water pressure.

Buried Features

Areas covered by a thin layer of till.--In some places, the most recent, uppermost layer of till is only a veneer (1 to 3 feet) that is draped over and only slightly modifies the pre-existing topography. Where they were recognized, such areas of thin till were designated Qctd on plates 1 and 2. In these areas, the relief consists of the pre-existing topography.

The most widespread area in the two-county area that could be identified as thin till over older topography is located about four to five miles east of the Missouri Escarpment. It is about three to four miles wide and extends northward from the South Dakota line to near Edgeley (pls. 1 and 2). Throughout this area, Cretaceous Pierre Formation shale is widely exposed in many places, especially along the Elm River and in the area immediately south of Edgeley. Apparently, the most recent important geologic process in this area was erosion, which stripped the glacial sediment off the preglacial bedrock surface, leaving only a small amount of till on the surface. Relief is only three to six feet locally.

Other areas of thin till occur farther east. Near Guelph, several prominent hills are probably pre-last glacial topography that was draped with a veneer of till during the last glaciation. Undoubtedly, many similar areas of thin till were not recognized in Dickey and LaMoure Counties. Most such unrecognized areas are probably shown on plates 1 and 2 as undulating till surfaces (Qctu). Areas of thin till are most easily recognized on hills, which may be pre-last eskers, kames, ice-thrust blocks, or hummocks of hilly collapsed glacial sediment (in which case recognition would be difficult unless the uppermost till was different in composition or texture from the underlying till).

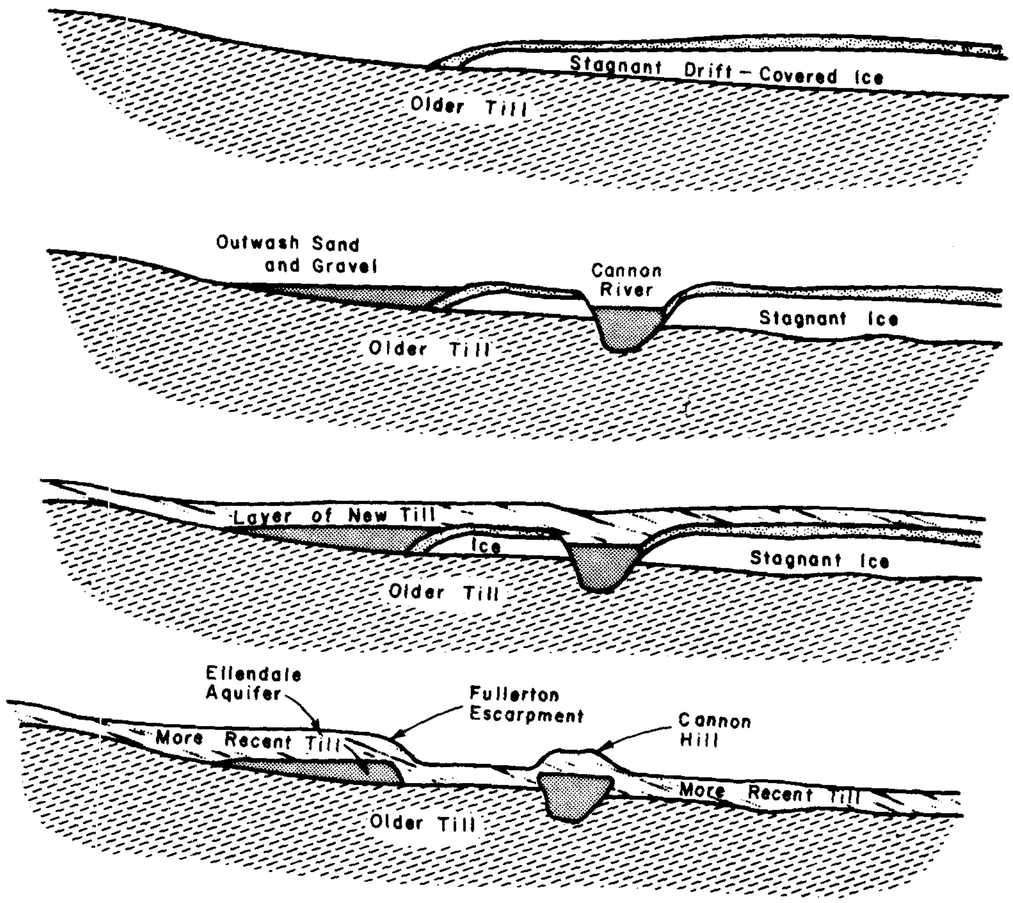
The Fullerton Escarpment.--In some areas east of the Missouri Escarpment where rolling till surfaces occur, the elevations tend to be lower than in adjacent areas with undulating surfaces. Such a situation occurs east of Fullerton in Dickey County where a 15- to 30-foot-high "escarpment," (referred to here as the "Fullerton Escarpment") extends for about 15 miles from sec 15, T132N, R61W to sec 31, T130N, R61W (pl. 1). Elevations on the rolling till surface immediately east of the Fullerton Escarpment average about 1 360 to 1 380 feet above sea level; west of the escarpment elevations on the undulating surface average about 1 410 to 1 425 feet.

A layer of glacial outwash sand and gravel known as the Ellendale aquifer (Naplin, 1973) lies buried under about 50 feet of till in the area northeast of Ellendale. As a result of the information obtained from numerous test holes that were drilled into the aquifer as part of groundwater studies of the Ellendale area (Lindvig, 1965; Naplin, 1973), the limits of the aquifer are well defined. The eastern edge of the aquifer coincides with the Fullerton Escarpment, and it seems probable that the escarpment is a surface expression of the edge of the aquifer.

The probable circumstances leading to the formation of the Fullerton Escarpment can be illustrated by a series of diagrams (fig. 10). Large portions of the melting late Wisconsinan glacier stagnated in many places on the Glaciated Plains of eastern North Dakota. The stagnation process on the Glaciated Plains was not on the large scale found on the Missouri Coteau, but rather it was discontinuous and resulted in numerous patches of stagnant ice, some as much as several hundred square miles in area, which took somewhat longer to melt than did the ice in adjacent areas.

The western edge of the stagnant ice body in the area east of Ellendale coincided with what is now the eastern boundary of the Ellendale aquifer. Water flowing southward from the melting glacier flowed along the western edge of the stagnant ice, depositing the gravel and sand of the Ellendale aquifer. A subsequent readvance of the late Wisconsinan glacier overrode both the stagnant ice body and the glacial outwash, depositing a fresh layer of till over the entire area. When the glacier finally receded for the last time, and the buried stagnant ice melted, the Fullerton Escarpment remained as a marker for the edge of the now-buried outwash (fig. 10). A rolling surface of collapsed glacial sediment with abundant typical low-relief stagnation features formed east of the escarpment as the stagnant ice melted.

Cannon Hill.--A ridge, known locally as Cannon Hill, parallels the Fullerton Escarpment on the east, extending from sec 18, T131N, R60W southward into South Dakota. The ridge is as



1. The first stage involves the stagnation of a large area of glacial ice. This stagnant ice was probably insulated by a covering of debris.
2. During the second stage, water flowing from melting glacial ice some distance to the north deposited outwash sand and gravel in the area between the higher land farther west and the western edge of the area of stagnant ice. Shortly after the outwash was deposited, the meltwater became confined to a south-trending valley a short distance to the east, the Cannon River valley. Sand and gravel were deposited in the Cannon River valley, which may have been ice-walled in places.
3. A readvance of glacial ice over the area resulted in the deposition of a layer of fresh till over the sand and gravel of both the outwash plain and the Cannon River valley as well as over adjacent areas of debris-covered, stagnant ice.
4. When the stagnant glacial ice finally melted, the result was 1) an east-facing escarpment located along the former contact between the sand and the stagnant ice, and 2) the Cannon Hill ridge. The buried sand and gravel of the buried outwash plain is the Ellendale aquifer.

Figure 10. Four-part diagram illustrating the formation of the Fullerton Escarpment and Cannon Hill.

much as a mile wide where it enters South Dakota, but it narrows northward and averages about 0.3 to 0.5 mile wide along most of its length in Dickey County. It rises as much as 40 feet above the adjacent rolling surface, averaging perhaps 30 feet high.

A test hole (North Dakota State Water Commission test hole 5637) drilled in 1970 on the ridge in the northwest corner of sec 17, T129N, R61W, penetrated about 70 feet of till overlying 60 feet of sand and gravel, and it is theorized that the ridge may be an overridden river deposit (the Cannon River--see figure 9 discussion) that was mantled with till by the readvance of the glacier. If the ridge is an overridden esker, it was deposited by a large river; even exceptionally large eskers such as the Dahlen Esker in Walsh and Grand Forks Counties are only about 0.1 mile wide at the base.

The Cannon Hill ridge, if it is extended northward, joins the James River valley. The buried Cannon Hill gravel may thus have been deposited by the early James River before the east-trending portion of the valley (in T132N, R60W) had formed or at a time when the valley east of approximately sec 32, T132N, R60W was still blocked by the glacier.

Lake Oakes Hills.--A hilly area is found east of Oakes in Dickey County. This area has well-developed glacial topography and weak internal linearity. It extends from near Fort Ransom in Ransom County, southeastward past Oakes into Sargent County and then, as discontinuous patches of hilly topography, into Marshall County, South Dakota. It loops northward near Britton, South Dakota, and back into Sargent County where it merges with the Prairie Coteau. The hilly area has commonly been known as the Oakes moraine (Hard, 1929) and it has most often been considered to be a recessional feature formed at the glacier margin as a lobe of the glacier receded northward west of the Prairie Coteau. Nielson (1973) named the hills the "Lake Oakes Hills" and his terminology will be used here.

Lineations on the Lake Oakes Hills indicate that, in the area near Oakes, the glacier receded northeastward rather than in a direction normal to the overall north-northwest to south-southeast trend of the hills. In the area near Oakes (T131N, R59W), the Lake Oakes Hills consist of numerous isolated knobs with about 50 feet of relief; in Sargent County, local relief reaches 200 feet in places. Low areas between the knobs are covered by flat-bedded lake silt deposits and the sides of the knobs also have a "washed" appearance with patches of silt and bouldery slopes in places suggesting that the hills existed as islands in glacial Lake Dakota. The hills are generally lower than, or accordant with, elevations on the undulating surface of collapsed glacial sediment just west of Bear Creek.

Large chunks of sand, bedded silt, gravel, and silty till are exposed in a cut in sec 4, T131N, R59W. These materials have been combined by the glacier into a till in which the various components remain as discrete bodies. Apparently the glacier that reworked these materials--fluvial, lake, and earlier deposited till--was in contact with the lake water as it receded from the area.

According to Nielson (1973) most of the sediment in the Lake Oakes Hills consists of turbidity-current sediment that was deposited in a proglacial, ice-marginal lake, glacial Lake Oakes. Nielson states that the lake sediment was overridden by the last ice advance, as indicated by the presence of glacial sediment overlying the lake sediment in many parts of the hills. Till that was deposited by an earlier advance of the glacier is found beneath the lake sediment.

In South Dakota, Koch (1975) considers the Lake Oakes Hills to be a recessional moraine (he refers to it as the "Oakes moraine"), although he states that the feature contains "a large amount of stratified drift."

In view of the fact that a layer of till veneers the Lake Oakes Hills, extending over and beyond them, it is reasonable to conclude that the feature is not an "end moraine" that formed during the latest glaciation of the area. Nielson's contention that the Lake Oakes Hills are largely an area of turbidity-current sediment deposited in a proglacial lake seems logical.

Glaciofluvial Landforms

Relief over areas covered by sand and gravel in Dickey and LaMoure Counties ranges from less than ten feet in a mile on the river terraces and uncollapsed areas of outwash to up to 50 feet in areas of collapsed river sediment.

Uncollapsed Flood Plains

Most of the sand and gravel found east of the Missouri Escarpment in Dickey and LaMoure Counties is uncollapsed river sediment (Qcgu on plates 1 and 2). Much of this river sediment is found in small meltwater trenches, which trend southeastward from the Missouri Coteau. These meltwater trenches are shallow, mostly less than 50 feet deep from floor to rim, and narrow, but they commonly contain sand and gravel deposits that are several tens of feet thick. Several dozen gravel pits are situated in these deposits, but the quality of the material is generally poor, tending to be silty and shaly.

An area of uncollapsed river sediment that was probably deposited as a glacial outwash plain is found just east of the Missouri Escarpment in northwestern LaMoure County. This area is informally known as "Minneapolis Flats." Here, sand and sandy gravel veneers the surface. The running water had apparently dropped most of its bedload by the time it reached as far south as the Nortonville area and, southeast of there, some evidence (a bouldery, channeled surface) that the till plain has been washed by running water can be seen.

Another area of uncollapsed river sediment, this one just north of Oakes, consists of coarse gravel that was probably deposited by water flowing from melting ice a few miles to the east, along the Sargent-Dickey County line.

The best quality gravel and sand in the two counties is found on some of the terraces along the James River (Qcgt on plates 1 and 2). These deposits are substantial and they contain somewhat less shale and are better sorted than the river sediment found in the meltwater trenches and outwash plains.

Collapsed Flood Plains

Most of the gravel and sand found on the Missouri Coteau was originally deposited on top of stagnant glacial ice (Qcgc on plates 1 and 2). When the ice melted, this river sediment, which had been laid down in flat beds, slumped and slid resulting in faulting and other disruptions of the bedding and a hilly surface with relief up to about 50 feet locally. Minor folds, slumps, and faults are common and can be seen in some gravel pits. When the river sediment collapsed as the stagnant ice melted, it became mixed with glacial deposits contained in the ice and this resulted in rather silty gravel and sand.

Eskers

The eskers in Dickey and LaMoure Counties are composed of a mixture of glacial sediment and river sediment that was deposited in contact with the ice. The gravel and sand in the eskers is mainly a poorly sorted material, rather "dirty" with a ratio of sand to silt and clay of about 3:1. The shale content may also be high, up to 80 percent in some of the esker deposits north of Ellendale. Cobbles, boulders, and inclusions of glacial sediment are also commonly mixed in with or overlie the gravel in the eskers (fig. 11).

Only a few eskers were mapped in the two counties (pls. 1 and 2) although many small ridges of gravel and sand that were too small to map are found throughout the eastern two-thirds of the area. The eskers are small and segmented; continuous ridges longer than a half mile are uncommon. The ridges rise from 5 to 15 feet above the surrounding plain.

Meltwater Trenches

Several meltwater trenches occur in the two-county area. They are of several different types and formed during various stages of glacial melting. Some of the trenches are ice-marginal valleys and some are simple consequent valleys that carried water east to lower areas from the melting ice on the Missouri Coteau. Some segments of the James River valley were carved

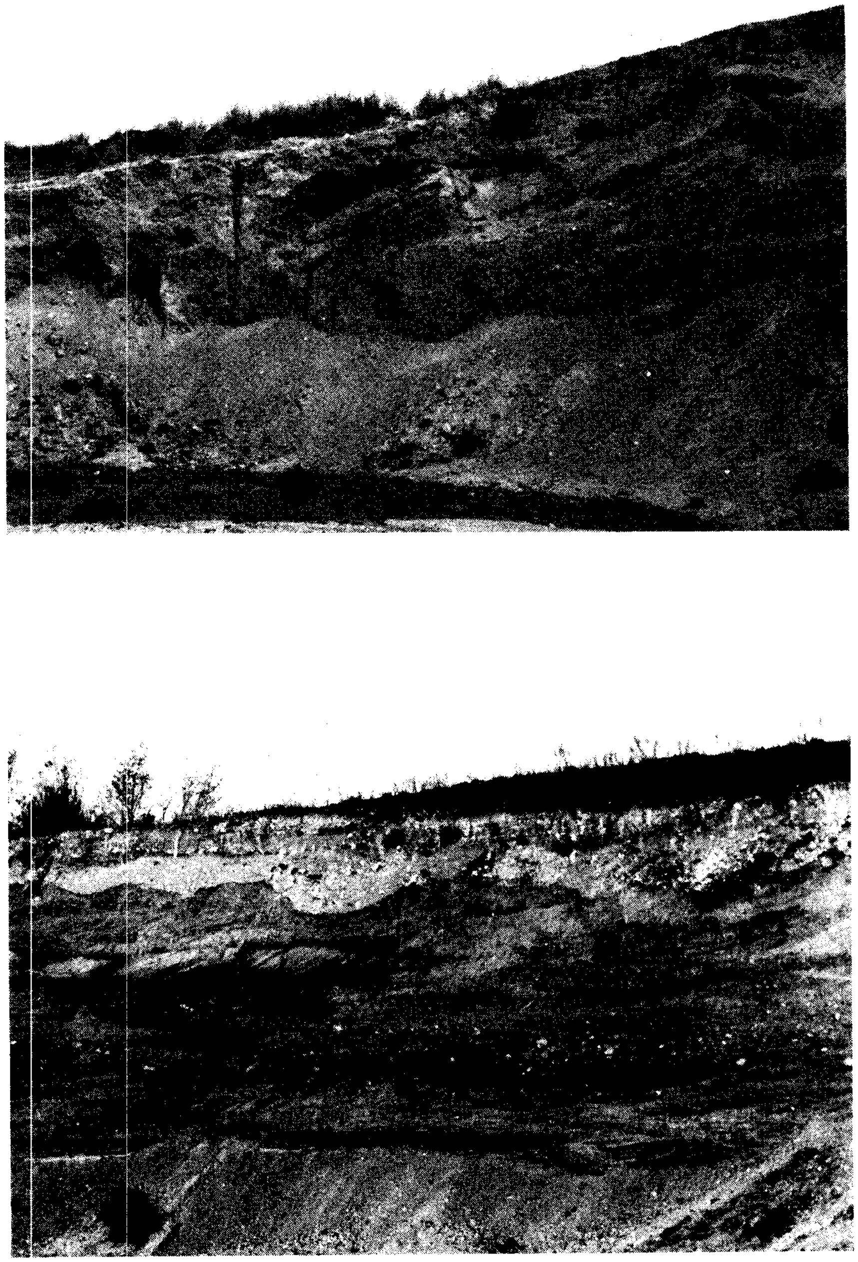


Figure 11. Two photos of sediment in esker near Oakes (SE¼ sec 4, T131N, R59W). In these exposures, till is seen overlying fluvial material.

by meltwater. Other segments are part of the paleodrainage system that existed prior to the last glaciation. The James River valley carried water from melting ice some distance north of the two-county area.

One of the earliest meltwater features to form in the area was probably the Minneapolis Flats in northeastern LaMoure County. This gravel deposit is located in a shallow valley that extends southward from Stutsman County. Minneapolis Flats was probably formed by glacial meltwater that flowed between the Missouri Coteau upland on the west and the still-active glacier to the east on the Glaciated Plains. Water flowing over the Minneapolis Flats apparently continued to flow southward after dropping its bedload of gravel and sand; it scoured the area mapped as Qctd, removing most of the glacial sediment cover, and exposing Cretaceous Pierre Formation in many places. The water eventually became confined to the south-trending Elm River valley in Dickey County. When the active glacier receded farther eastward, it eroded the Maple River valley.

Many small gullies that are carved into the face of the Missouri Escarpment probably began as streams that headed some distance back (to the west) on the Missouri Coteau. As the stagnant ice melted, the stream valleys were destroyed, forming areas of collapsed stream deposits (Qcgc on plates 1 and 2) on the Missouri Coteau. The gullies transect the Minneapolis Flats gravel deposits and they appear to merge with such ice-marginal valleys as Cottonwood Creek and Bone Hill Creek. These last two streams, as well as similar unnamed ones, apparently formed along the glacier margin as it stood in successively more northerly positions.

Once initiated, some of the ice-marginal stream valleys continued to carry meltwater and precipitation runoff for some time after the glacier ceased to be active in the immediate area. Some of the larger valleys, such as Cottonwood, Maple, and Bone Hill Creeks, have a single, well-developed terrace level part way up the valley wall (fig. 12). In some places, the terraces of these creek valleys are excellent sources of moderate to good quality gravel.

Based on washboard ridge trends, the last readvance of the glacier over northern LaMoure County appears to have been mainly from the northwest. The James River flows southeastward in that area so it was apparently not formed along the ice margin of that advance. However, it may have formed along the ice margin of an earlier advance.

The James River valley ranges from about three-quarters of a mile wide from rim-to-rim near Adrian where the flood plain is less than a half-mile wide, to about three miles wide near LaMoure where the flood plain is as much as two miles wide. It ranges from as much as 150 feet deep, from rim to flood plain near Dickey in LaMoure County, down to about 40 feet near

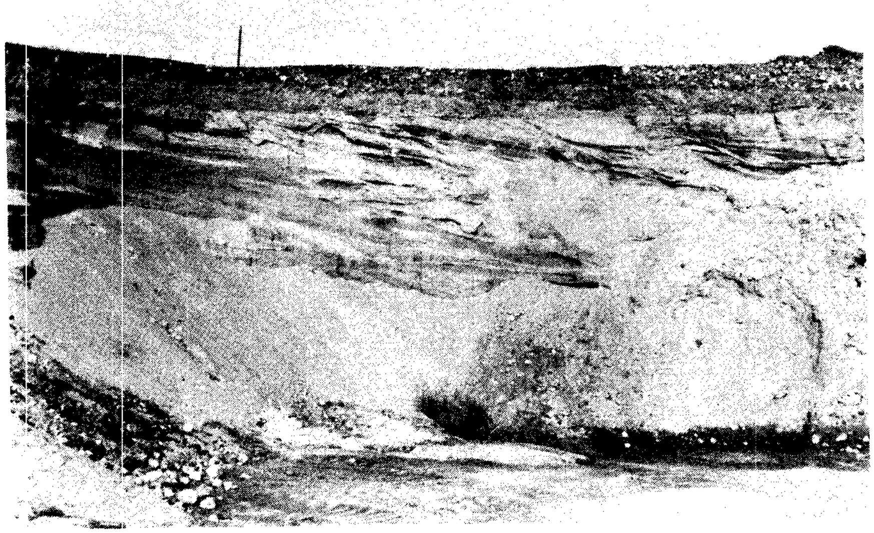


Figure 12. Two photos of Bone Hill Creek terrace gravel (NE¼ sec 8, T135N, R63W).

Figure 13. View westward across the James River valley from about a mile south of Dickey in LaMoure County. A single well-developed terrace level can be seen on the opposite valley wall.

Oakes where it merges with the glacial Lake Dakota plain. The valley walls are cut in till (Qcts) in most places.

Two main terrace levels can be identified in the James River meltwater trench in LaMoure County and in northern Dickey County. Near Grand Rapids, three levels are found. The uppermost of the terraces ranges from about 30 feet above the present flood plain at the LaMoure-Stutsman County line to 55 feet near Grand Rapids. The river that flowed on the uppermost terrace was broad. It flowed in a two-mile-wide valley in which it deposited large amounts of gravel. The single terrace level in Bone Hill and Cottonwood Creeks seems to be graded to the same level as the uppermost James River terraces.

The lower terraces of the James River valley are built of large quantities of gravel. They are especially well developed from Grand Rapids to a point about three miles southeast of LaMoure (fig. 13). The meltwater trench in this area is about three miles wide and apparently coincides with a preglacial valley (or a valley that dates to some time prior to the latest glaciation), which may trend generally southwestward (fig. 5). In places where the valley coincides with (either follows or transects) buried valleys, its course has been influenced by the buried features.

Before the modern route of the James River valley was established southward from the LaMoure-Dickey County line, the meltwater apparently flowed southeastward from the point where the valley now turns southwestward in T133N, R60W. This resulted in the extensive washing of the till surface (Qcte on plates 1 and 2). Similar washing of the till surface occurred in other areas when water overflowed the still-shallow James River meltwater trench (T134N, R62W).

The James River valley is the only major drainage in the two-county area that carried meltwater from distant sources. The valley for a time carried a large portion of the water from melting glaciers over much of central North Dakota. The flow probably decreased when the Sheyenne River meltwater trench formed to the north and east, but the James River valley continued to carry runoff from the melting stagnant ice on the Missouri Coteau for some time. The James River discharged into Lake Dakota while the glacier still covered much of Ransom and Sargent Counties to the east, building up a sandy delta in the lake.

River-Eroded Till Surface

Areas of glacial sediment that have been washed by running water (Qcte on plates 1 and 2) are found in association with the undulating collapsed moraine. These areas are mainly flat, with local relief generally less than a foot. They commonly have scattered patches of sand and gravel left by the water that washed the surface. In some places, large numbers of boulders occur. These boulders were left behind as a lag deposit when the running water that washed the surface removed the finer materials that had been associated with the boulders.

Areas of river-eroded till are most common near modern stream valleys. Apparently, running water washed the surface before it carved the valleys in which the streams presently flow. Several such areas occur along the James River valley.

Slopewash-Eroded Till Slopes

Steep till slopes occur along the sides of the James River valley and on the face of the Missouri Escarpment (Qcts on plates 1 and 2). These slopes consist of deeply incised topography that was eroded by slopewash and small streams. Relief ranges up to 50 and 100 feet locally and drainage is mostly integrated. In many places, the slopes are partially covered by colluvial debris of the Oahe Formation. Boulders are locally abundant.

Glaciolacustrine Landforms

Proglacial Lake Plains

A few low areas veneered by laminated clay and silt are found east of the Missouri Escarpment in Dickey and LaMoure Counties (Qcsv on plates 1 and 2). Many of these areas are too

Figure 14. Fissure in alfalfa field near Guelph in Dickey County (SW¼ sec 35, T129N, R61W).

small to show on the map and others are now covered by sloughs. The proglacial lake plains are mainly flat, but they may be rolling areas where the lake sediment is thin and does not completely cover the underlying topography. In these areas, a few boulders may be found. The proglacial lake plain in T132N, R59W in Dickey County (pl. 1) is an example of one where relief on the underlying till is greater than the thickness of the lake clay; the clay is found only in the lower areas. This clay is generally an unctuous, yellowish-gray material that contains some fossil shells.

A small lake plain (SW¼ sec 35, T129N, R61W) was augered in several places during July of 1977. This lake plain was of particular interest because numerous fissures had formed during the spring and summer of 1977 (fig. 14). The fissuring was in an alfalfa hay meadow in what is usually a low, relatively wet area. However, during the drought of the previous several years, the area dried to the extent that the alfalfa crop began to die. Growth during 1977 was best along and over the fissures, especially in locations where the ground had not yet collapsed.

The largest fissures occurred near what is the topographically lowest part of the meadow, radiating outward toward the edges of the meadow and forming a pronounced rectilinear pattern in aerial view. The presence of the fissures made it difficult to harvest the alfalfa as machinery fell into the openings in the ground.

Open fissures were as much as five feet wide, but averaged about two to three feet wide and ranged in depth to about five feet. The floors of the fissures consisted of topsoil that had dropped down. In areas where the topsoil had not yet fallen into the underlying fissures, the bottoms of the fissures were as much as ten feet below the ground surface.

The sediment found in the walls of open fissures consists (from the top downward) of as much as a foot of black topsoil (A horizon), which was bound together by the alfalfa rooting system. The black topsoil is five to ten inches thick in most places and its contact with the underlying sediment is extremely irregular. Beneath the black topsoil is a zone of limy silt, which contains abundant fossil shells; *Valvata tricarinata* and *Gyraulus parvus* are both common. The shell-bearing horizon becomes more sandy downward. Thin (less than an inch), discontinuous layers of limestone are found in some places at varying depths, but except for this limestone and the presence of the shells, the silt layer is fairly uniform and does not contain pebbles. The silt layer is up to about eight to ten feet thick in the central portion of the meadow. The deepest fissures occur in the area of thickest silt accumulation.

Augering showed that the silt is underlain by sandy glacial till at a depth of 8 to 12 feet. The silt was dry throughout when we augered it and auger returns consisted mainly of dry powder. The first discernable moisture was in the till beneath the silt.

It is clear that the fissures formed due to the drying of the slough sediments. The main shrinking of the sediment probably occurred during the 1976 summer season and the fissures may have formed beneath the topsoil at that time. Caving of the topsoil apparently did not begin until the following spring. The growth pattern in the alfalfa field seems at first to be a paradox since the best growth occurs in areas of already-formed fissures. However, it is possible that these plants, with their roots hanging downward into the void of the fissure actually received more moisture than did the plants rooted in the dry silt nearby. The moisture contained in the till at the bottom of the fissure vaporized, maintaining a high humidity in the fis-

TABLE 6. Chemical analysis of silt from slough in the SW¼ sec 35, T129N, R61W, Dickey County, North Dakota. Analysis provided by the Twin Cities Metallurgy Research Center, U.S. Bureau of Mines.

Component	Weight, percent	Component			Weight, percent
SiO_2	25.40	CO_2			25.7
Al_2O_3	4.50	LOI	110°C	1.8 (adsorbed H_2O)	
K_2O	0.90		400	.8)	
Na_2O	.53		750	27.7)29.0[2]	3.3
CaO	33.70		1 000	.5)	
FeO[1]	2.00				29.0
	67.00				+67.0
					96.0

[1] Fe total=1.6; assumed to be substitute for Ca in carbonate
[2] 29.0-25.7 CO_2=3.3 percent assumed structural water in silicates

sures, and condensed on the alfalfa roots hanging in the void. The roots were covered with water droplets.

The slough sediment lying on top of the till was analyzed by the Twin Cities Metallurgy Research Center of the U.S. Bureau of Mines. X-ray diffraction analysis showed that the sediment consists primarily of quartz and calcite with small amounts of illite (table 6). No montmorillonite was detected. Optical microscopic examination disclosed that the calcite and quartz range in the silt-size range, although some clay-size material was included.

Elevated Lake Plains

Areas covered by laminated silt and clay are found in several places on the Missouri Coteau (Qcse). Most of these are flat plains that are elevated as much as 115 feet above the surrounding hilly collapsed glacial sediment. The elevated lake plains formed in lakes that were surrounded by stagnant glacial ice and floored by solid ground, commonly till. Some of the elevated lake plains have slightly raised margins that slope toward a flatter central area. The raised margins or rims consist of a mixture of sand and till that slid off the glacier into the lake. Some of the lake plains have rims that are raised as much as 15 feet above the center of the plain.

Most of the elevated lake plains in Dickey and LaMoure Counties are covered by less than ten feet of silt and clay, along with small amounts of sand. In other areas, the lake sediment is as much as 50 feet thick. Pelecypod and gastropod shells are commonly found in the lake sediment of elevated lake plains. The surfaces are mainly free of boulders.

Collapsed Lake Plains

In places where silt and clay were deposited in lakes that flooded areas of stagnant ice, collapsed lake plains resulted. The topography is hilly, much like surrounding areas of hilly glacial sediment and the surface is free of boulders. The collapsed lake plains have numerous undrained depressions, much like areas of hilly collapsed glacial sediment and collapsed flood plains. In contrast to these landforms, the sediments of a collapsed lake plain are folded and contorted rather than faulted.

Several areas of collapsed lake plain occur on the Missouri Coteau in Dickey and LaMoure Counties (Qcsc on plates 1 and 2; many more areas too small to map also occur). Relief ranges from 50 to 150 feet. Some relatively flat, uncollapsed areas of lake plain are found along with the collapsed areas. The thickness of the collapsed lake sediment may be as much as 50 feet in some places, but the average thickness is probably less than 10 or 15 feet.

Glacial Lake Dakota Plain

Glacial Lake Dakota flooded part of southeastern Dickey County as the late Wisconsinan glacier melted from the area (fig. 15). The lake plain is covered by a veneer of wind-blown material with many small dunes and blowouts. At its north end, near Oakes, the sediments beneath the wind-blown zone range from fine to coarse sand and are mainly fluvial. Farther south, near the South Dakota border, the sediment ranges from silty clay to fine sand with silty sediment predominating. The surface of the lake plain is free of boulders. The lake plain covers approximately 85 square miles in Dickey County and 110 square miles in Sargent County to the east. The area of the plain in South Dakota is about 1 800 square miles.

The lack of an appreciable clay fraction in the lake deposits is probably due primarily to the movement of water through the lake basin. The upper stratigraphic sequence of lake deposits, the only sediments exposed, was laid down when the water was comparatively shallow and current velocities were correspondingly great. Under such conditions, most of the clay being transported would remain in suspension and leave the lake basin.

Although the exact depth of the lake at any time is unknown, the overall relief, shore features, and maximum sedi-

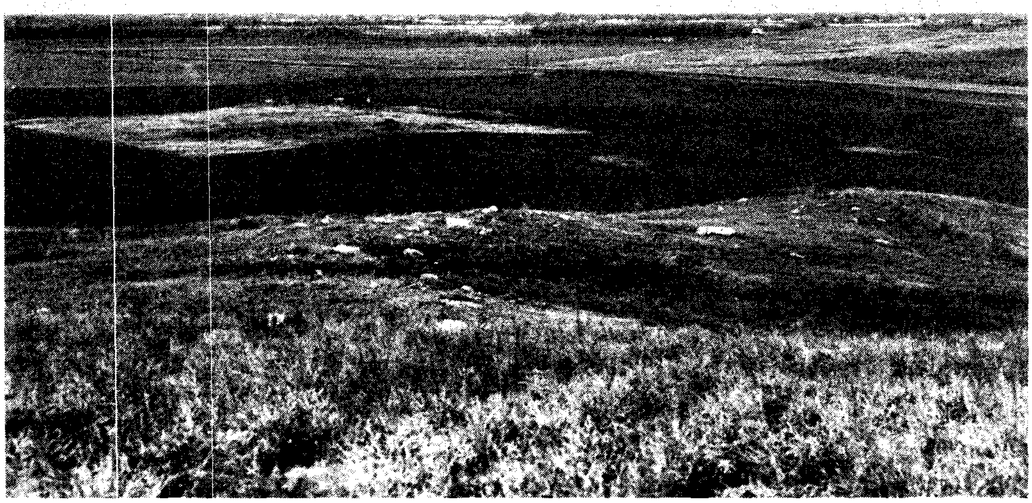


Figure 15. View to the northeast over the Lake Dakota plain from the Lake Oakes Hills. The town of Oakes can be seen in the distance.

ment thickness suggest that the total depth of the lake in North Dakota was never more than about 100 feet and the lake was not that deep most of the time. Probably a considerable current flowed through the lake most of the time it existed. This current, coupled with wave action in the relatively shallow lake, acted to keep the bottom deposits stirred up. It seems likely that conditions quiet enough to permit the settling of clay particles may have existed only locally and temporarily on the lake floor (Flint, 1955).

The water-laid sediments beneath the glacial Lake Dakota plain reach a maximum thickness of about 100 feet along the Dickey-Sargent County line. In places in Dickey County, they consist of interbedded layers of sand and silt that were deposited alternately by running water and in relatively quiet water (figs. 16 and 17).

No beach ridges were recognized along the Lake Dakota plain in Dickey County. Beaches are found locally along the eastern margin of the lake sediments in Spink County, South Dakota (Flint, 1955, p. 124). In that location they take the form of ridges as much as three miles long, 350 feet wide, and 18 feet

Figure 16. View of gravel pit in materials that were deposited in Lake Dakota at the mouth of the James River, the "Oakes Delta" deposit (NE¼ sec 17, T131N, R59W).

high. The elevation of the highest beaches is about 1 320 feet above sea level. Presumably this elevation marks the highest level of glacial Lake Dakota.

Nonglacial Landforms

River Flood Plains

The James River valley is the only valley in the two-county area that contains significant amounts of Holocene alluvium. Its flood plain, however, is built on glacial till, outwash, and terrace gravel as well as on Holocene alluvium. The percentage of the flood plain area actually covered by alluvium ranges from about ten percent near the LaMoure-Stutsman County line to about 75 percent in the Oakes area. The thickness of the modern alluvium ranges from 0 to about 20 feet. In some places, the alluvium grades downward into Pleistocene-aged fluvial sediment. The James River flood plain is highly dissected by old stream channels, oxbows, and meander scars in places.

Narrow flood plains are also developed along the Maple and Elm Rivers, but other smaller streams have only tiny areas that

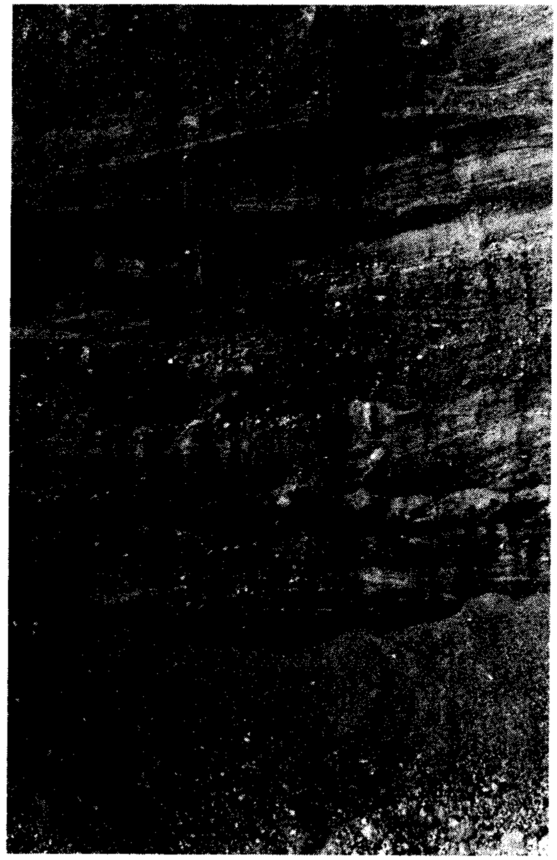


Figure 17. Bedded fluvial sediment of the "Oakes Delta" deposit near Oakes, North Dakota (NE¼ sec 17, T131N, R59W).

might be referred to as "flood plains." Only small amounts of alluvium are found along the smaller streams.

Sloughs

Several thousand sloughs occur in the two-county area. Only a few of the larger ones are shown on plates 1 and 2, and these were distinguished mainly from air photos. Sloughs occurring west of the Missouri Escarpment are associated with areas of hilly collapsed glacial sediment. They are generally larger than those east of the Escarpment. Some large sloughs are also found in areas of glacial sediment with undulating and rolling surfaces. Most of the sloughs occur in potholes, depressions left when buried blocks of stagnant glacial ice melted from the glacial sediment.

Some larger sloughs east of the Missouri Escarpment are found in depressions that mark the courses of buried valleys. Examples of such "kettle chains" are found at Marion in secs 3, 10, and 15, T136N, R61W and east of Grand Rapids from sec 26, T135N, R61W to sec 29, T134N, R60W, a distance of about seven miles.

On the Missouri Coteau, most of the sloughs are situated in depressions formed when broad areas of stagnant ice melted. Some of these sloughs are over a mile across. Other sloughs are located in depressions that may have resulted from large-scale ice thrusting.

In some places, deposits of peat and decomposed peat ("muck") are found in sloughs. This material is generally less than three feet thick. Sediment in the sloughs has been derived largely from adjacent hillslopes. It consists of dark, clayey material alternating with layers of lighter colored, more silty beds.

Dunes

Since it drained, the glacial Lake Dakota plain has been subject to widespread erosion and deposition by the wind. The many dunes and shallow blowouts on the lake floor impart a gently hummocky appearance to the landscape. Moderate-sized dunes are especially numerous along the eastern margin of the lake basin. Sand makes up a large proportion of the uppermost lake deposit (Brophy, 1961), and was concentrated by the prevailing westerly winds. The only area of substantial dune development is located at the eastern end of the Riverdale Ridge, just across the county line in Sargent County, where dunes up to 40 feet high are found. Most of the dunes are stable, but some active dunes occur in high areas where soil moisture is low.

Eolian activity has complicated the pattern of near-surface materials. Winds have scoured hollows in the lake deposits, re-sorted them by removing the finer fraction, and left the coarser constituent piled as dunes. Buried soils, covered by as much as four feet of wind-blown sand, occur in several places (Brophy, 1961).

Loess overlies till on the upland east of the James River just above a terrace remnant in the northwest corner of sec 5, T131N, R59W. The James River here flows in a broad, northwest-southeast-trending segment and the loess was probably derived from the valley train of which the terrace is a remnant. The loess is a massive, well-sorted silt, five feet thick, apparently not widely distributed. A loess-like material also occurs on the west slope of the Lake Oakes Hills in the southeast quarter of sec 1, T130N, R59W. This deposit is about ten feet thick, but it has faint bedding and approaches the texture of fine sand.

SYNOPSIS OF GEOLOGIC HISTORY

Preglacial History

Rocks of Precambrian age in Dickey and LaMoure Counties consist mainly of granite and amphibolite. These rocks are probably Early Precambrian in age (older than 2.6 billion years), but little is known of their geologic history. Since the Precambrian, the preglacial history of Dickey and LaMoure Counties has been largely a series of marine transgressions and regressions. As the two-county area is located on the southeast flank of the Williston Basin, much of the Paleozoic sedimentary section, which may once have been present in this area, was removed by erosion during times when the seas were absent from the area.

The oldest sedimentary rocks, which are Late Cambrian to Early Ordovician (Deadwood Formation), were deposited by a sea that flooded the area from the west, before the Williston Basin started to subside appreciably (Carlson and Anderson, 1965). Following a period of erosion, deposition resumed as the area was flooded from the southwest in the Middle Ordovician (Winnipeg Group). Deposition probably continued until Middle Silurian time. The period of erosion which followed developed a major unconformity, eroding all rocks above the Red River Formation in Dickey and LaMoure Counties.

During Late Devonian time, the Williston Basin became tectonically slightly more negative and seas transgressed the area. Cyclical carbonate deposition began at this time (Devonian Duperow Formation and Mississippian Madison Formation). Pre-Jurassic erosion removed any post-Madison Mississippian through Triassic rocks that may have been deposited in the area.

A time of marine transgression began in the Late Jurassic and deposition was essentially uniform through Cretaceous time in Dickey and LaMoure Counties. Near the end of Cretaceous time, the seas receded westward, with the Pierre Formation marking the end of marine deposition in the two counties. Since deposition of the Cretaceous sediments, erosion has been the dominant geologic process in Dickey and LaMoure Counties.

Erosion probably continued through most of Pliocene time. By the end of the Pliocene Epoch, a gently rolling landscape had developed on the shales of the Cretaceous Niobrara and Pierre Formations. The eastern third of Dickey County and the southeast corner of LaMoure County was a broad lowland with elevations generally between 1 150 and 1 300 feet (fig. 5). Elevations rose gradually to the west to over 1 700 feet in southwestern Dickey County to an upland area which coincides approximately with the modern Missouri Coteau. However, this preglacial upland was not bordered on the east by a prominent

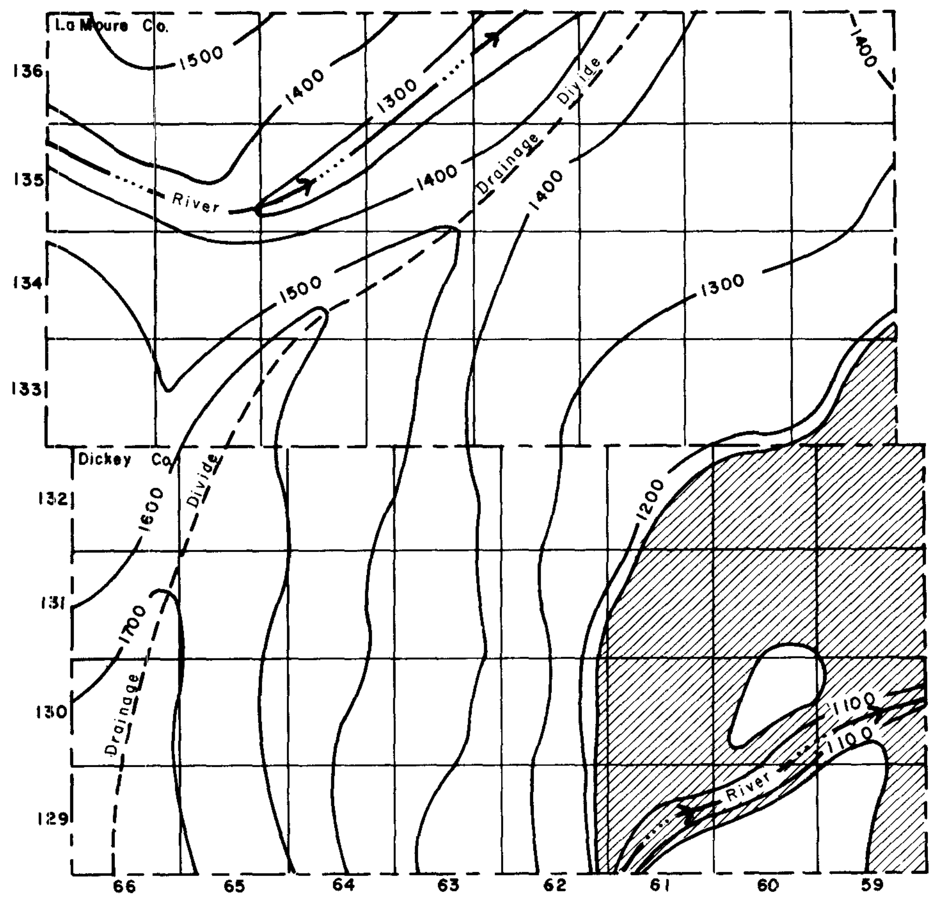


Figure 18. Conceptualization of the preglacial Dickey--LaMoure County landscape. The area was drained northeastward by two streams. Cretaceous Pierre Formation shale covered the western three-quarters of the area and the Niobrara Formation was exposed over much of the southeast quarter of the area.

escarpment comparable to the modern Missouri Escarpment (fig. 18).

Two main drainage basins existed in the two-county area before it was first glaciated. These basins were separated by a divide that extended from the northeast part of LaMoure County to the southwest corner of Dickey County. The northwestern third of the area was drained by a stream that probably flowed mainly northward, eventually entering Canada from Towner County. The remainder of the area was drained by a northeast-flowing stream that probably crossed southeastern Dickey County. This stream flowed into the ancestral Red River of the North (Bluemle, 1972).

Early Glacial History

The only till tentatively considered to be pre-Wisconsinan in age (till unit P on table 2) appears to have a weathering profile in its upper portion in at least one location. Elsewhere in eastern North Dakota and northwestern Minnesota, a period of extensive erosion that followed the deposition of certain deeply buried tills has been documented (Moran and others, 1976).

The younger units are much more shaly in this area and this is true also in LaMoure County. The increased shaliness of the overlying till units suggests that erosion that occurred after the deposition of the early tills lasted long enough to remove most of the cover of glacial sediment, exposing broad areas of shale. Subsequent glaciers advanced over the drift-free areas, resulting in shale-rich deposits (units Q and R on table 2).

Glaciers that flowed over the two-county area during early, pre-Wisconsinan glaciations diverted the northeast-flowing streams south and southeastward (fig. 19). Proglacial lakes formed ahead of the glaciers in the river valleys and the lake sediments that were deposited in these proglacial lakes are found in several places. These buried lake deposits occur at several different levels, as a result of the multiple episodes of drainage diversion that took place due to the multiple glacial advances (table 7).

The most deeply buried of the lake deposits is found in what is apparently a preglacial valley cut into the bedrock surface in the southeastern corner of the two-county area. These deposits, which occur at elevations between 1 085 and 1 200 feet, but mainly between about 1 100 and 1 150 feet, are mostly over a hundred feet below the surface in southeast Dickey County. In most of the test holes in which the lake sediments were observed, they overlie either fluvial deposits or till. For this reason, it appears that any glacial advances that may have occurred before the lowermost lake sediments were deposited did not result in drainage diversion in the Dickey and LaMoure County area, or, perhaps, the sediment was deposited in lakes as the glacier receded. The lowermost sequence of lake deposits is immediately overlain by fluvial deposits and then by till.

A second sequence of lake deposits is found at elevations between about 1 195 and 1 275 feet. These lake sediments are found in the same preglacial river valleys as are the lowermost ones.

Still another area of buried lake deposits is found in northern LaMoure County (T136N, Rs60 and 63W). These sediments, which are greater than 35 feet thick in places and generally

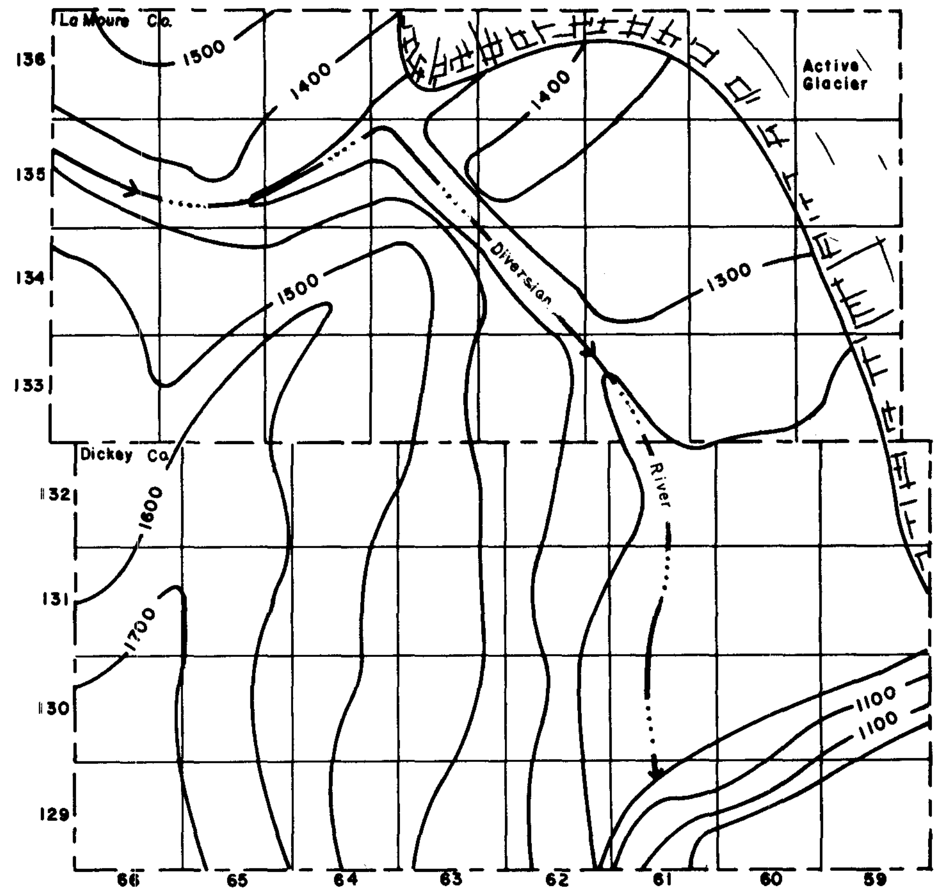
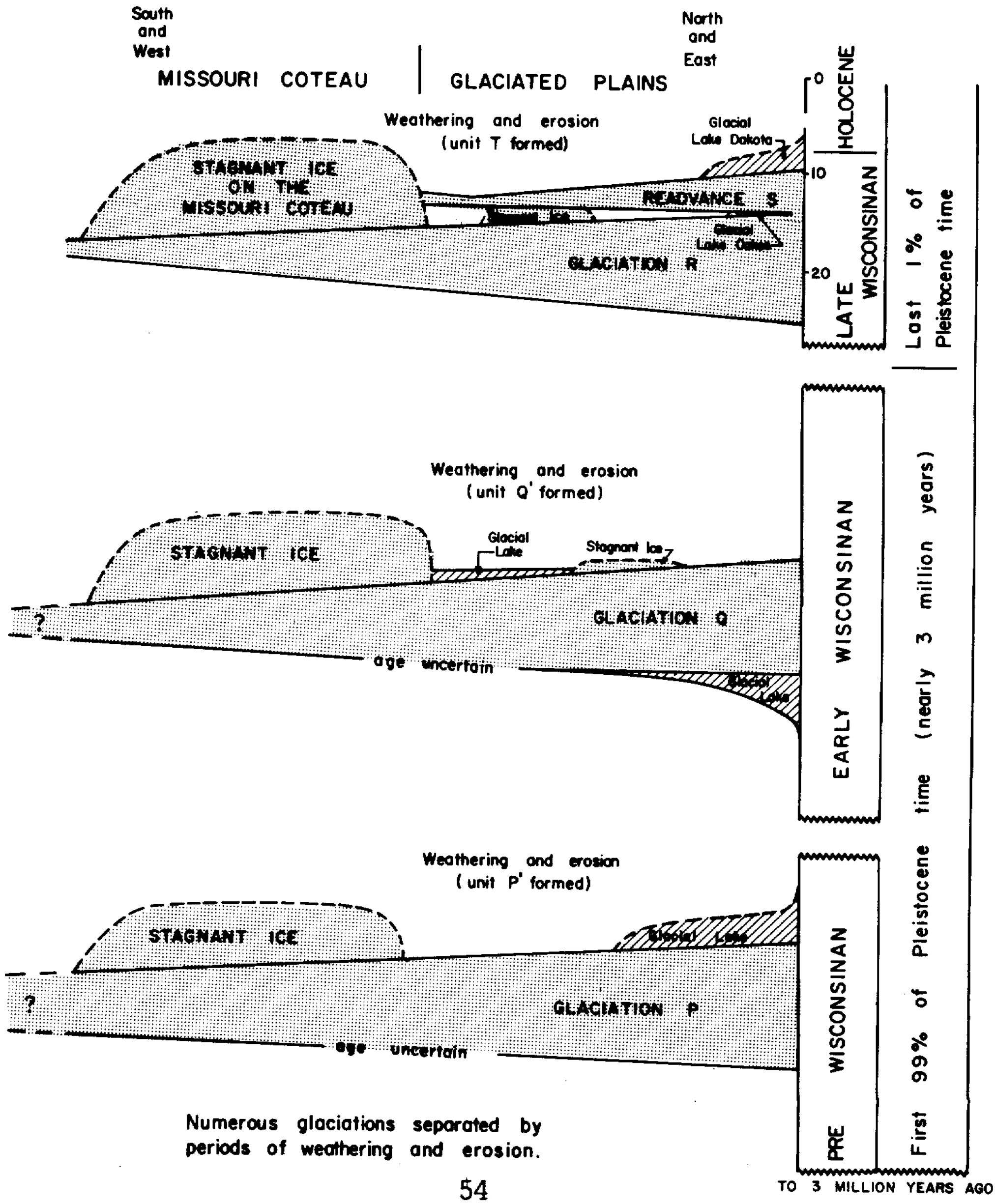


Figure 19. A conceptualization of conditions during an early, probably pre-Wisconsinan glaciation. Damming of preglacial drainage (the glacier was probably located to the east of the two-county area) resulted in a proglacial lake in a valley in southeastern Dickey County. The damming of a river valley in northwestern LaMoure County and/or perhaps the damming of rivers farther north, caused a proglacial lake to form. When this lake overflowed the drainage divide, a diversion river flowed southeastward, eroding a diversion trench through central LaMoure County.

underlain by glacial sediment, are found at depths of 40 to 175 feet (pl. 3, cross-section A-A'). The age of these buried lake sediments is not known. They may have formed when drainage in northern LaMoure County was blocked and diverted by the glaciers, possibly at the same time one of the two buried lake deposits in southern Dickey County accumulated. They cannot be correlated with the Dickey County deposits.

TABLE 7. Time-distance diagram of Pleistocene events from northern and eastern parts of the two-county area to southern and western parts of the area. Glacial deposits designated till units R and S formed during the most recent glaciation, the late Wisconsinan, which ended about 10 000 years ago, but stagnant ice persisted on the Missouri Coteau for several thousand years after that. Glacial lakes tended to form each time drainage was blocked. The only ones that can be dated reasonably accurately are glacial Lakes Oakes and Dakota; others are speculative.



Most of the glacial sediment in the two-county area was probably deposited by Wisconsinan glaciers. As much as 130 feet of till unit Q (test hole 9170) can be documented in western LaMoure County; till unit Q is tentatively considered to be early Wisconsinan in age, more than 40 000 years old. It is present on both the Missouri Coteau and on the Glaciated Plains.

A period of erosion and weathering followed the deposition of the early Wisconsinan glacial deposits. The upper surface of the early Wisconsinan deposits is weathered in places; the upper 50 feet of till unit Q is weathered in test hole 9170. The weathering episode is probably middle Wisconsinan in age.

Late Wisconsinan Glacial History

The series of diagrams that follow (figs. 20 through 24) illustrate, in part, the manner in which the late Wisconsinan glacier receded from the two-county area. The movement of this "most-recent" glacial ice and the action of the meltwater associated with the melting glaciers were responsible for the distribution of the surface materials and landforms found in the area.

In general, at the end of the late Wisconsinan glaciation and probably at the end of all earlier glaciations as well, the discontinuous covering of debris on top of the glacial ice resulted in extremely irregular melting of the ice. In some places, extensive areas of stagnant ice persisted for thousands of years; the most notable area of glacial stagnation in Dickey and LaMoure Counties is found on the Missouri Coteau (figs. 20 and 21).

As the late Wisconsinan glacier stagnated, extensive areas along the Missouri Coteau in western Dickey and LaMoure Counties became covered by a thick insulating cover of debris that had been lifted high into the glacier as it flowed up the underlying escarpment. This insulated stagnant ice persisted for several thousands of years and produced a suite of characteristic landforms that have been the subject of extensive study (Clayton and Freers, 1967; Parizek, 1969).

The lowermost unit considered to be late Wisconsinan age is till unit R. It was deposited by a glacier that advanced into the area about 22 000 years ago. Till unit S, which overlies R, was deposited as the glacier receded from the area about 14 000 years ago. The retreat of the ice was probably interrupted by intermittent periods when at least portions of the glacial mass were revitalized and readvanced as much as several tens of miles (Moran and others, 1976).

In LaMoure County, the pattern of washboard ridges on the undulating collapsed glacial sediment just east of the Missouri Escarpment in the area between Forbes and Merricourt indicates that the last movement of glacial ice there was from the north-

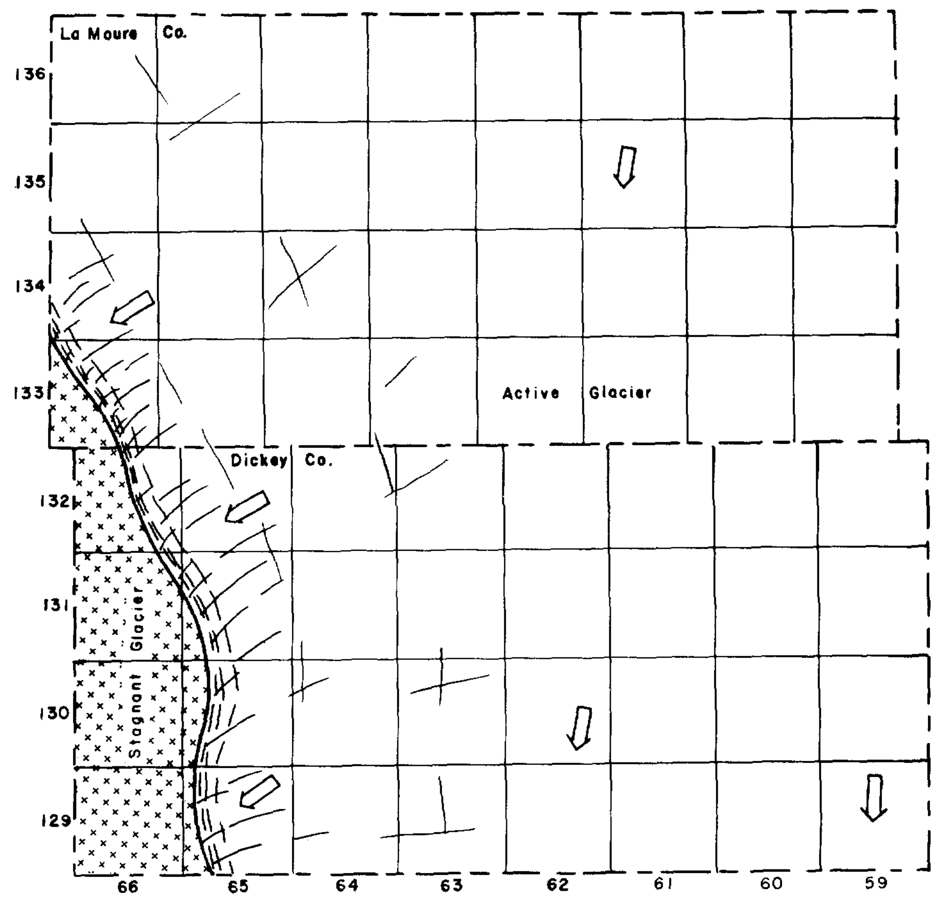


Figure 20. Recession of the late Wisconsinan glacier. On this diagram, the late Wisconsinan glacier margin is seen receding from the two-county area (the arrows on this and the following four diagrams show directions of main glacier flow). Here, a portion of the glacier has already stagnated on the Missouri Coteau in western Dickey County (x pattern) and it is likely that great amounts of gravel and sand were deposited on top of this area of stagnant ice by glacial meltwater. During the point in time depicted by this diagram, unit R was being deposited by the active glacial ice.

northwest (fig. 22). It is likely that this glacier movement was the result of rejuvenation of the stagnant ice on the Missouri Coteau, probably at about the same time much of the eastern half of the two-county area was overridden by a readvance of the late Wisconsinan glacier. Apparently, considerable thrusting took place on the Missouri Coteau during this period of rejuve-

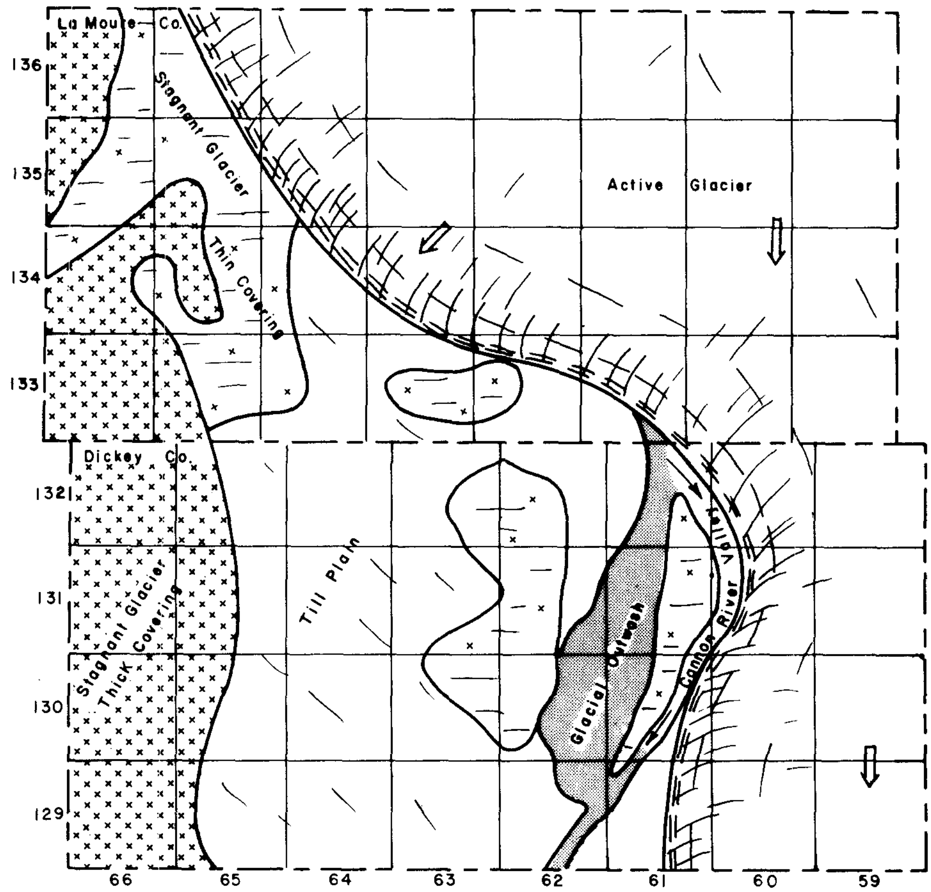


Figure 21. Deposition of the Ellendale aquifer. Here, the glacier has stagnated on the Missouri Coteau (x pattern) and scattered patches of stagnant ice remain on the Glaciated Plains (x and dash pattern). Areas of stagnant ice on the Glaciated Plains were generally not so thick as were those on the Coteau and they had a thinner mantle of debris on top. A lobe of the active glacier probably still extended through the eastern Dickey County lowland into South Dakota. The large volumes of water produced by the melting glacier flowed along the western edge of the active glacier and over adjacent lowland areas. This meltwater deposited gravel and sand (shading) in several places; some of this gravel and sand eventually became the Ellendale aquifer and some now lies beneath the Cannon Hill ridge.

nation resulting in many areas of ice-thrust blocks (Qctt on plates 1 and 2). Meltwater flowing between the glacier flowing southeastward off the Coteau and the southwest-flowing glacier on the Glaciated Plains eroded away the covering of glacial

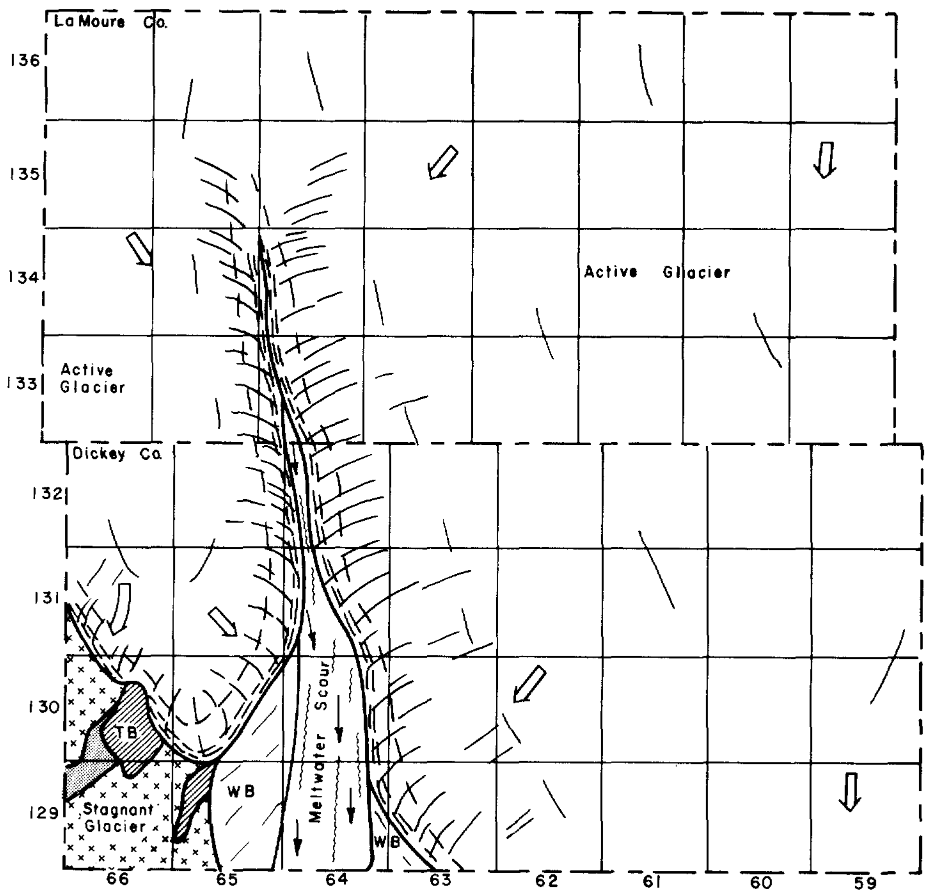


Figure 22. Revitalization of the late Wisconsinan glacier. With a revitalization of the late Wisconsinan glacier, much, and perhaps all, of the area was again covered by active glacial ice. The glacier expanded westward over the recently deglaciated area (fig. 21), covering it with a veneer of till. At the same time, the stagnant glacier on the Coteau was rejuvenated and expanded, flowing eastward and southeastward off the Missouri Escarpment. The rejuvenated stagnant ice apparently caused considerable thrusting in some places on the Missouri Coteau (TB=thrust block; only a few are shown). Unit S was deposited by the readvance of the glacier.

At the time depicted here, the revitalized glacier is already beginning to abate. East of the Missouri Escarpment, the receding ice margin resulted in areas of undulating topography with washboards (WB on the diagram). The glacier on the Missouri Coteau stagnated once again, although portions of it that had advanced off the Coteau may have marked a more-or-less orderly "retreat."

Meltwater from the wasting glacier eroded away the covering of glacial sediment in an area just east of the Missouri Escarpment, exposing shale in many places.

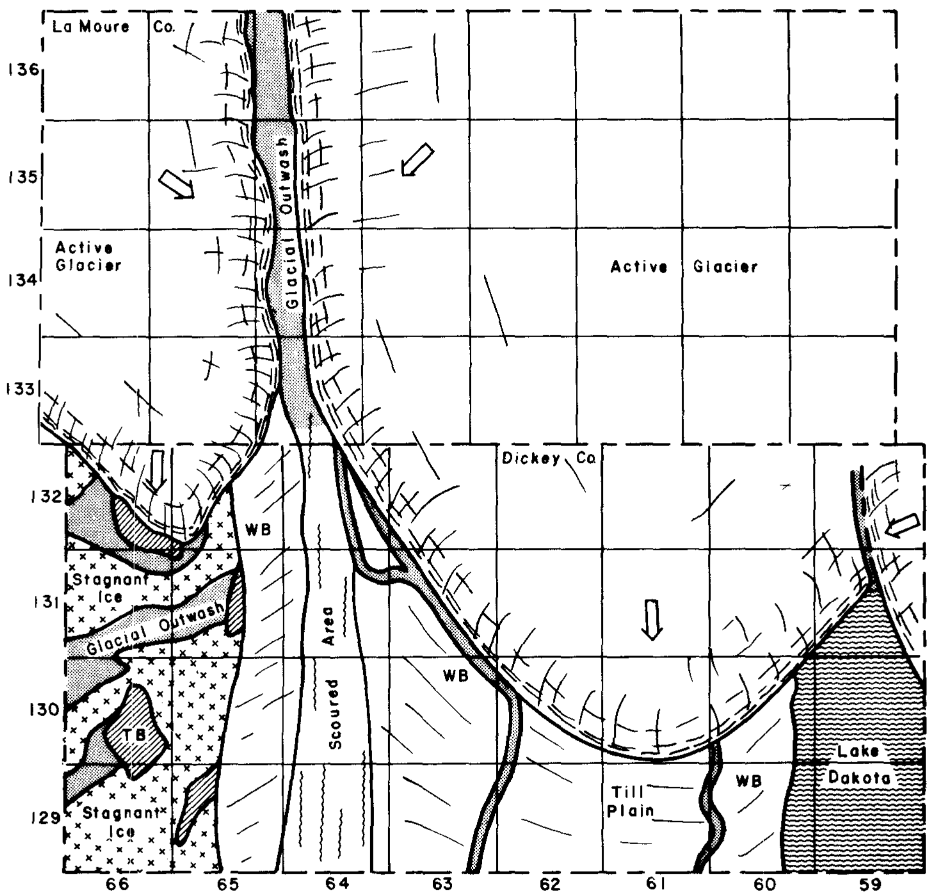


Figure 23. Second recession of the late Wisconsinan glacier. Continued melting of the glacier resulted in separation of the western and eastern lobes with sand and gravel being deposited on the Minneapolis Flats area by water flowing between the lobes. Repeated thrusting occurred on the Missouri Coteau and extensive deposits of gravel and sand accumulated on top of areas of stagnant ice. Water flowing from the melting glaciers carved numerous meltwater trenches and flooded the lowland in southeastern Dickey County to form glacial Lake Dakota.

sediment in a one- to four-mile-wide strip of land (Qctd on plates 1 and 2); Cretaceous Pierre Formation shale is exposed in most places in this area.

In several locations, 20 to 65 feet of gravel and sand, interpreted as glaciofluvial sediment, separates till units R and S. This sediment was probably deposited as outwash by the late

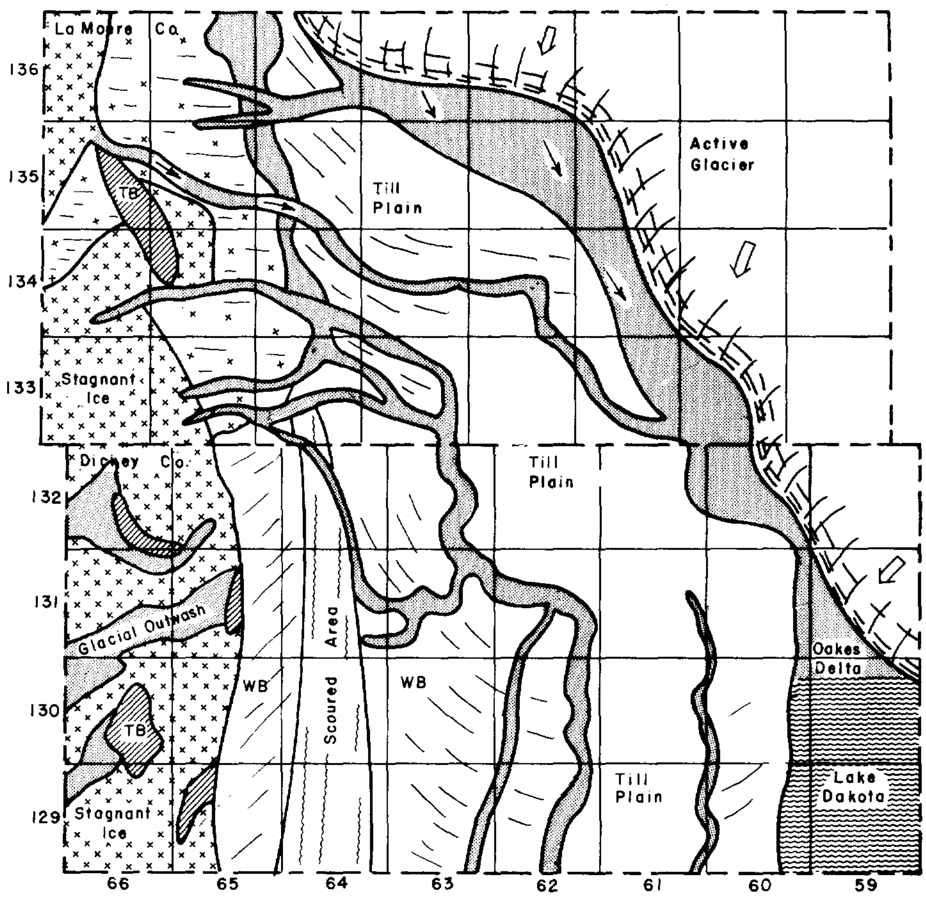


Figure 24. Formation of the James River valley and the Oakes Delta. Here, the glacier on the Missouri Coteau has again stagnated and numerous gullies and valleys have developed due to streams of water flowing eastward from the upland Coteau area. The route of the James River valley through the two-county area was along the active glacier margin; an outwash plain that formed along the margin is now a series of terraces that stand above the flood plain. Water flowing southward into Lake Dakota carried considerable sediment, which it deposited on the Oakes Delta. The Lake Oakes Hills may have formed about this time.

Wisconsinan glacier, during its receding phase. The outwash was overridden by the glacier during a period of revitalization.

Till unit T is the weathered upper portion of till unit S. It consists of the soil and oxidized material that has developed during Holocene time.

As the late Wisconsinan glacier finally melted over the area of the Glaciated Plains, depositing till unit S, the areas of thicker, sediment-covered ice tended to develop a rolling landscape with small, ice-disintegration features (areas of Qctr on plates 1 and 2), whereas thinner areas of ice with only small amounts of glacial sediment melted more rapidly and resulted in gently undulating topography (Qctu on plates 1 and 2) characterized by washboard ridges in places (figs. 23 and 24).

Kettle chains formed in some of the small buried valleys and numerous isolated potholes formed throughout the area as buried blocks of glacial ice melted. Many small esker ridges resulted from the numerous streams that flowed through the stagnant, melting glacier.

The large amounts of glacial meltwater, along with the high precipitation in the area as the last Wisconsinan glacier melted, resulted in considerable modification of the landscape. Water flowing down the Missouri Escarpment initially moved large volumes of material in the form of mudflows and colluvium, and carved numerous small valleys. Streams persisted in a few of the larger valleys and water from melting glaciers to the north of the two-county area continued to flow in these valleys. The largest meltwater trench is the one through which the James River now flows. The James River valley continued to serve as an outlet for meltwater as the ice melted back an unknown distance from the two-county area. The James River valley not only served as a drainage way for local meltwater, but also as a temporary outlet for glacial Lake Souris at a time when the Sheyenne River meltwater trench, which was the major Lake Souris drainage, was blocked by glacial ice.

History of Glacial Lake Dakota

As soon as the glacier receded from northern Beadle County, South Dakota, glacial Lake Dakota began to form in the lowland between the higher elevations to the south and the receding ice front. The lake expanded northward as the glacier continued to recede (figs. 23 and 24). The main axis of Lake Dakota was along the James River valley in South Dakota. At its largest, the lake extended northward about 100 miles from its most southerly point near Hitchcock, South Dakota, to near Oakes, North Dakota.

The geologic history of Lake Dakota in North Dakota has been worked out in some detail by John A. Brophy of North Dakota State University (Brophy, 1961). Much of the discussion of the history of the lake that follows is based on his ideas, although I have altered his interpretations of the role that the Oakes moraine played in the history of the lake (see discussion of the Lake Oakes Hills on page 34 of this report).

As the melting glacier front receded across the Lake Dakota basin, it apparently released its load of debris, some of it coarse, directly into the water ponded against it. The glacier may have receded and then readvanced into the lake, over and beyond the Lake Oakes Hills, which are composed mainly of turbidity current sediment. The presence of glacial ice directly in contact with the lake water may help account for the deposits of coarse sand and gravel at or near the surface of the lake plain far from the entrance of sediment-bearing streams such as the James River and Bear Creek.

The broad, low ridge that extends from sec 7, T130N, R59W to the southeast corner of that township (pl. 1) is known as the Riverdale Ridge (Brophy, 1961). It is probably a fluvial, ice-marginal deposit, and perhaps it marks the southernmost readvance of the glacier that overrode the Lake Oakes Hills.

The Riverdale Ridge is split at its northwest end by an abandoned channel of the James River. The upper ten feet of material underlying the ridge is primarily sand, which coarsens to gravel toward the northwest end where abandoned gravel pits (NE¼, sec 7) show that the gravel is at least ten feet thick. Thin deposits of poorly sorted sediments that lie above the gravel in several borings along the trend of Riverdale Ridge may be water-laid till (either mudflow or glacial sediment). The southeast end of the ridge is covered by windblown sand.

The Riverdale Ridge must have been a shoal area in Lake Dakota and part of it may have been emergent above the water. This shoal would have tended to divide the North Dakota portion of the lake into two depositional basins. Water northeast of the ridge was probably nowhere over 15 feet deep; water southwest of the ridge was somewhat deeper.

Northeast of the Riverdale Ridge is another, less conspicuous linear area, this one actually an interconnected series of low ridges, that may be of similar origin. This area extends northwestward from sec 13, T130N, R59W. In sections 3 and 10 of the same township, it splits into several distinct, though low, elements. Three of these trend westward through sections 4 and 9 of the same township, whereas a fourth branch trends northward where it breaks up into a series of ridges and isolated highs that trend in several directions.

South of the Riverdale Ridge, the dominant topographic trend is also northwest-southeast. Fluvial erosion, which occurred as the lake level dropped, modified what may have been depositional patterns produced by the retreating glacier. One such broad, shallow, erosional channel curves from southeastward to southward to southwestward through the east half of T129N, R59W. It continues into South Dakota where it deepens and provides the route for the Portage-Detroit drainage ditch.

Soon after the glacier receded after depositing the Lake Oakes Hills at its margin, Bear Creek came into existence along the western margin of the hills. When the sediment-laden water flowing down Bear Creek reached the head of Lake Dakota north of Oakes, formation of the Oakes Delta began. The coarser sand and gravel was deposited first and the finer sands, silts, and clays were carried out into the lake. Bear Creek then began aggrading its channel to the base level provided by Lake Dakota and built up a thick valley train of sand and gravel. Remnants of this channel stand as terraces 25 to 30 feet above the present channel. The James River also carried a large amount of sediment from the melting glacier to the north. These sediments built a valley train in the James River valley and were added to the rapidly building Oakes Delta.

As originally built, the Oakes Delta probably extended across the entire head of the lake basin and south to include the high areas of sand and gravel in the southwest part of the city of Oakes (Brophy, 1961). The west side of the delta was eroded to produce the James River and Bear Creek valleys. The erosion, most of which probably took place during Pleistocene time, cut off the southern part of the delta. The town of Oakes is situated in the broad, shallow channel that was eroded. An extensive accumulation of gravel is found on a terrace where Bear Creek valley opens onto the lake plain. This gravel has been incised by the modern stream that flows in the valley.

As the glacier retreated northward, the period of rapid deposition associated with the Oakes Delta ended. Less water flowed into it and the lake quieted. As distances to the melting glacier increased, the grain size of sediments entering the lake decreased. When the ice front had retreated as far as the present site of Fort Ransom, in Ransom County, a new drainage channel, named the Ransom River by Willard (1909), was formed behind the Lake Oakes Hills. A valley train of sand and gravel was built in this channel to a level of about 1 325-30 feet at its southern end and apparently graded to the 1 320-foot water level in Sargent County.

Several small cross-channels connect the Ransom River and Bear Creek. These low channels have sills at about 1 310 feet. The sills must have been formed during an erosional period following the lowering of Lake Dakota to about 1 310 feet. The valley train in the Ransom River channel is also trenched to this gradient.

The lowering of the outlet of Lake Dakota from the 1 320-foot level must have occurred sometime after the deposition of the valley train in the Ransom River and the trenching of that valley train. If the outlet had not already been lowered by the time the James River began to receive outlet water from Lake Souris, the addition of this water may have hastened the process. The trenching of the Ransom River valley train and of the Bear Creek valley train may have been accomplished by overflow of Lake Souris water that was later carried by the Sheyenne River.

During the draining of Lake Dakota, channels developed on the lake bottom, further complicating the depositional patterns by cutting out lake deposits and depositing fluvial silt and sand in the channels.

Postglacial History

From about 10 000 years ago until perhaps 8 500 years ago, the climate in Dickey and LaMoure Counties was cool and humid, probably somewhat wetter than it is today (Clayton and others, 1976). A warming trend that began about 10 000 years ago ended the forest cover over the area and transformed most of the lakes to sloughs (table 8). From 8 500 until 5 000 years ago, the area had a drier, slightly warmer climate than it does today. Several feet of wind-blown silt and sand were deposited in many places during this 3 500-year interval of time. The only noteworthy wind-blown deposits recognized in Dickey and LaMoure Counties are on the glacial Lake Dakota plain. Many ponds were transformed into sloughs, and the grass cover was greatly reduced over the two-county area during the warm, dry 3 500-year interval. Hillslopes became unstable, more erosion took place over the Missouri Coteau area, and sloughs received coarser sediment with less organic content. With the return to increased precipitation about 4 000 years ago, the grass cover again increased, effectively stabilizing most hillslopes in the two-county area.

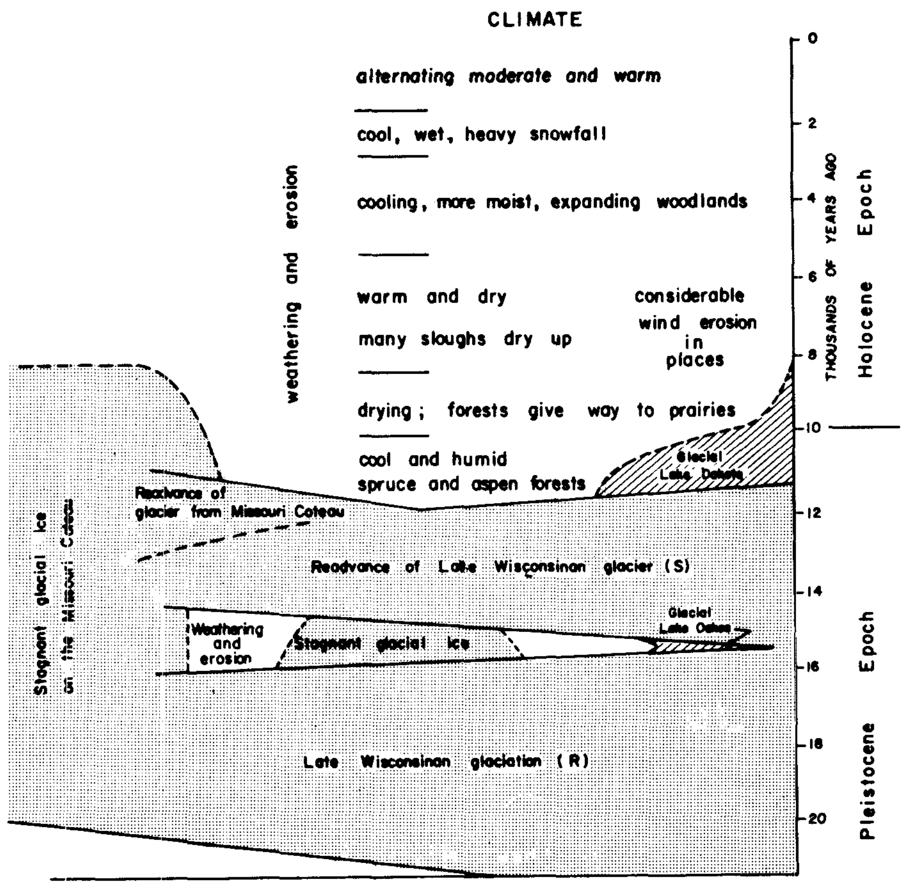
ECONOMIC GEOLOGY

Sand and Gravel

Sand and gravel are found in a variety of situations in the two counties. The most important source of relatively good quality gravel with a low percentage of shale is in the terraces of the James River valley upstream from Oakes to the Stutsman County line. Extensive, relatively good quality gravel deposits are also found along Bear Creek. Deposits of fair quality gravel are found on terraces of the Maple River and Cottonwood Creek. Fair to good gravel is found beneath the Minneapolis Flats in LaMoure County. All of these terrace gravel deposits are generally poorly sorted (well graded) with abrupt changes in texture and sorting.

Poor quality, generally shaly gravel is found in areas of collapsed flood plains on the Missouri Coteau. Similarly poor quality gravel is found in places along the edge of the Missouri

TABLE 8. Time-distance diagram (time is vertical, distance is horizontal) showing the changing climate in Dickey and LaMoure Counties since the last glacier melted from the area. The glacier stagnated on the Missouri Coteau and took somewhat longer to melt there than on the Glaciated Plains.



Escarpment in the form of colluvial deposits and in small gullies cut into the Escarpment.

Hydrocarbons

As of January 1, 1979, twelve exploratory oil wells have been drilled in Dickey and LaMoure Counties (7 in Dickey, 5 in

LaMoure). No production has yet been found and there is little evidence of petroleum resources in the area. Nonetheless, interest continues because of the presence of the Newcastle and other Cretaceous sands, which underlie the area. The Paleozoic formations that produce oil further west in North Dakota have porosity in Dickey and LaMoure Counties. The many possibilities for stratigraphic and structural traps along with shallow depths allowing easy and fast drilling should do much to promote exploration in the area.

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APPENDIX

Laboratory Methods

Several types of data were used in the compilation of the stratigraphy. These included descriptive logs of samples made by the well-site geologist, electric logs (resistivity and spontaneous potential) of the test holes, and the samples themselves. The samples taken from State Water Commission test holes were drill cuttings, mixed with drilling mud in some cases. Electric logs are available from most of the State Water Commission test holes.

Samples of till from seven test holes were analyzed in the laboratory. The till samples were laid out in order and described; color and gross texture were noted. An estimate was made of the amount of shale in the visible size fraction, gravel and coarse sand. Unusual features, such as lignite fragments and accumulations of secondary carbonate were noted where they were present.

About 45 grams of material was taken from each till sample for further analysis and the remaining sample was rebagged where necessary. The 45-gram samples were crushed and soaked in four percent Calgon for a day. Each sample was then agitated with a milkshake mixer for about a minute and poured into a one-liter settling tube. Distilled water sufficient to fill the tube was then added. After a batch (usually 30) of tubes had been filled, all the tubes were agitated and allowed to settle a measured time, the exact time depending on the temperature. After the silt had settled out, but while the clay was still in suspension, the density of the fluid was measured with a hydrometer. A control tube, which was filled with distilled water and four percent Calgon from the same batch, was measured at the same time. The control measurement was subtracted from each measurement to yield the weight of clay, in grams, for each sample. The hydrometer measurements were made with a precision of 0.5 grams.

After hydrometer measurements, the samples were wet-sieved through a .062 mm sieve; all materials larger than silt were retained. The samples were dried and dry-sieved with a standard set of sieves on a Ro-tap machine for five minutes. Each sample was divided into three fractions: .062 to 1 mm (sand); 1 to 2 mm (very coarse sand); and 2 mm (gravel). Each fraction was weighed. The weight of gravel was divided by the weight of the original sample to yield the "gravel percentage." The weights of sand and of clay were divided by the adjusted sample weight (original sample minus gravel) to yield percentages, and the silt percentage was determined by subtracting the sand and clay percentages from 100.

The 1-2 mm fraction was analyzed for the lithology of the grains. The grains were divided into the classes: crystalline, carbonate, shale, lignite, and others. Crystalline grains were defined as quartz and other clear minerals, igneous and metamorphic rock fragments, and sulfide grains consisting of one or a few crystals. (Virtually all the grains examined except lignite are composed of crystals, but the class "crystalline" is composed of grains whose crystals are easily visible under a low-power binocular microscope, which was used for counting grains.)

Shale grains were recognized as light-gray, soft, fine-grained fragments. The greatest part of the grains were of that type, and were derived from the Cretaceous Pierre Formation, whereas a smaller number of grains were gray-white mottled, calcareous grains from the Cretaceous Niobrara Formation. A small number of light-brown grains of the Fox Hills Formation were seen. A small number of white to buff grains made up of columnar crystals was classified under shale because the grains were observed to come from shale. The number was too small to make a significant difference in the percentages.

Carbonate grains were recognized by their color (white to buff, but not pure white), their softness (carbonate grains can be scratched by a dissection knife; chert cannot), and their luster and general appearance. Grains of secondary carbonate were not included under carbonate; these grains are soft and pure white. Most of the carbonate grains were from micritic limestone and dolostone; numerous small fossils were observed, but not studied.

Where secondary grains were distinguished from "others," they consisted mostly of iron oxides, secondary carbonates, and secondary gypsum. The greatest number of these grains was observed in samples taken from depths between 5 and 20 feet.

Lignite particles were recognized by their color, softness, and lightness. Few lignite grains were rounded; most had conchoidal fracture. It was difficult to keep an accurate count because the grains break while being counted, and probably many grains were broken during the agitation stages of sample preparation. The figures for lignite are therefore only approximations of their true abundance.

Grains classified as "others" included chert, ironstone, and fine-grained pyrite (perhaps derived from shale) and other fine-grained unidentified grains. The classification also includes secondary minerals where they were not separated in a class of their own. Lignite, secondary minerals, and others were calculated as a percentage of the entire sample. Crystalline, carbonate, and shale were calculated as a percentage of the fraction including only crystalline, carbonate, and shale.