GEOLOGY

of

RAMSEY COUNTY, NORTH DAKOTA

by

Howard C. Hobbs
Minnesota Geological Survey
St. Paul, Minnesota

and

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

1987

BULLETIN 71 -- PART I
North Dakota Geological Survey
Sidney B. Anderson, Acting State Geologist

COUNTY GROUNDWATER STUDIES 26 -- PART I
North Dakota State Water Commission
Vernon Fahy, State Engineer

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CONTENTS

ILLUSTRATIONS

Figures | Page

Figures	Page

Plates

Tables

ABSTRACT

Ramsey County, located on the eastern edge of the Williston Basin, is underlain by 2,800 to 4,000 feet of Paleozoic and Mesozoic rocks that dip westward toward the center of the basin about 200 miles to the west. The Cretaceous Pierre Formation shale underlies glacial sediment in most of the county except in the deepest meltwater valleys where Cretaceous Niobrara Formation shale directly underlies the glacial sediment and on a few upland areas in the western part of the county where Cretaceous Fox Hills Formation sandstone occurs beneath the glacial deposits. A total of six Quaternary formations consisting of glacial deposits, and deposits related to glaciation, are recognized within the Coleharbor Group in Ramsey County. These formations represent separate advances of glacial ice of various Wisconsinan and pre-Wisconsinan ages.

The now-buried, preglacial Cannonball River Valley underlies southern and western Ramsey County and contains the important Spiritwood Aquifer. A deep glacial diversion trench, the Starkweather Valley, also contains an important aquifer.

Ramsey County is located on the Glaciated Plains, an area of undulating to flat topography. The southern part of the county is dominated by landforms that resulted from intense glacial thrusting, which resulted in ice-thrust topography and a large, irregular depression, which marks the plain of glacial Lake Minnewaukan and its modern remnant, Devils Lake. Northern Ramsey County is characterized mainly by low-relief collapsed glacial topography with abundant washboard ridges and large numbers of small eskers.

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 Ramsey County Board of Commissioners. It is one of a series of county reports on the geology and groundwater resources of North Dakota. The main purposes of these studies are: (1) to provide geologic maps of the areas, (2) to locate and define aquifers, (3) to determine the location and extent of mineral resources in the counties, and (4) to interpret the geologic history of the areas. This volume describes the geology of Ramsey County. Readers interested in groundwater should refer to Part II of this bulletin (Hutchinson, 1977), which includes detailed basic data on the groundwater, and Part III (Hutchinson and Klausing, 1980) which is a description and evaluation of the groundwater resources in Ramsey County.

Parts of this report that are primarily descriptive include the discussions of the topography, rock, and sediment in Ramsey County. This information is intended for use by anyone interested in the physical nature of the materials underlying the area. Such people may be water-well drillers or hydrologists concerned about the distribution of sediments that have potential to produce usable groundwater; state and county water managers, consultants to water users; water users in the development of groundwater supplies for municipal, domestic, livestock, irrigation, industrial, and other uses; civil engineers and contractors interested in such things as the gross characteristics of foundation materials at possible construction sites, criteria for selection and evaluation of waste disposal sites, and 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 geological interpretations.

Previous Work

Early reports on the Devils Lake area included those by Babcock (1902) and Simpson (1912). Aronow (1957, 1963) studied the geology of the region, concentrating on the Pleistocene and postglacial drainage changes in the area. Several of the counties surrounding Ramsey County have been reported on as part of the present series of studies. Bluemle (1965) reported on the geology of Eddy and Foster Counties, south of Ramsey County; Carlson and Freers (1975) described the geology of Benson and Pierce Counties; Arndt (1975) described the geology of Cavalier and Pembina Counties; Bluemle (1973) described the geology of Nelson and Walsh Counties; and Bluemle (1984) reported on the geology of Towner County.

Local groundwater studies have been made in areas in and near Ramsey County. Paulson and Akin (1964) described the groundwater resources of the Devils Lake area, and Naplin (1974) described the groundwater resources of the Lawton area. As part of the present county groundwater study, Hutchinson (1977) compiled a report on groundwater basic data in Ramsey County, and Hutchinson and Klausing (1980) described the groundwater resources in the county.

Two University of North Dakota graduate students wrote Ph.D. dissertations on Devils Lake, but neither of these was published. The first of these, "The postglacial sedimentology of Devils Lake, North Dakota," was written in 1968 by Edward Callender. Callender studied cores of sediment taken from the bottom of Devils Lake. His studies concentrated on diatom frustule content of the cores, interstitial sulfate content, calcium/iron ratios, and magnesium-calcite/calcite ratios. The second thesis, "Postglacial ostracod distribution and paleoecology, Devils Lake Basin, northeastern North Dakota," was written in 1980 by James B. Van Alstine. Van Alstine also studied lake-bottom cores, comparing the paleoecology of the ostracod fauna as it changed through time, and relating the changes in ostracod fauna to environments in the lake at various times.

Methods of Study

Fieldwork for the present study was accomplished over a long period of time by several people. S. R. Moran made a preliminary surface map of the county in the early 1970s, and he supervised laboratory study of test-hole samples that had been collected during 1963-1964 as part of the preliminary engineering studies conducted in conjunction with the installation of the ICBM Minuteman Missile sites in the area. John Bluemle visited all of the missile sites while they were under construction in 1964, describing the geology of each site. In 1973, Bluemle mapped ten townships in the northern part of the county.

Howard Hobbs began working on the project during the summer of 1976, developing a preliminary Quaternary stratigraphy based mainly on State Water Commission well logs and the limited amount of laboratory data available at the time. He had analyzed some of this data in 1974 and 1975 while preparing a Ph.D. dissertation on the glacial stratigraphy of northeastern North Dakota. The stratigraphic model was tested and modified by further laboratory work. Lithologic data were collected in the field from road cuts and by using a truck-mounted soil probe. Hobbs used data from about 250 test holes in working out a scheme of glacial stratigraphy for the region.

The final surface map (pl. 1) is based on information derived from topographic maps, airphotos, and lithologic data collected during Hobbs' fieldwork during the summer of 1976. During the late summer of 1985, John Bluemle made a final field check of the geologic map, spot checking several dozen locations in the county.

Regional Setting

Ramsey County, in northeast North Dakota, has an area of 1,241 square miles in Tps151 to 158N and Rs60 to 66W. It is located between 47° 54' 24" North Latitude on the south, 48° 32' 36" North Latitude on the north, 98° 17' 32" West Longitude on the east, and 99° 11' 57" West Longitude on the west. The area lies within the Glaciated Plains of the Central Lowland Province (fig. 1). The Glaciated Plains are undulating to rolling plains underlain by glacial deposits of variable thickness, ranging from a few feet to several hundred feet in buried valleys. The landscape has been modified only slightly during postglacial time.

Shale of the Cretaceous Pierre Formation directly underlies Quaternary sediment over most of the county. An exception is in parts of central Ramsey County where a deep meltwater valley cuts through the Pierre so that Cretaceous Niobrara Formation shale directly underlies the glacial sediment. In a small area near the western edge of the county, a remnant of the Fox Hills Formation sandstone apparently overlies the Pierre and directly underlies glacial sediment. Ramsey County is situated on the extreme eastern flank of the Williston Basin, and the bedrock formations dip gently to the west.

The surface topography in Ramsey County slopes gently from the northeast corner of the county, where elevations exceed 1,600 feet, to the Devils Lake chain of lakes, which form the southern boundary of the county, at about 1,425 feet. Devils Lake receives all the drainage from the county except for a small area along the eastern boundary, which drains southeastward.

Much of the county lacks an integrated drainage system with well-defined natural channels. Runoff occurs in the form of overland flows, assisted by roadside drainage ditches. Some of the runoff makes its way into Devils Lake and some ends in lakes and sloughs, which have no outlets.

The most important drainage system in the county begins with Edmore Coulee and its tributaries. The

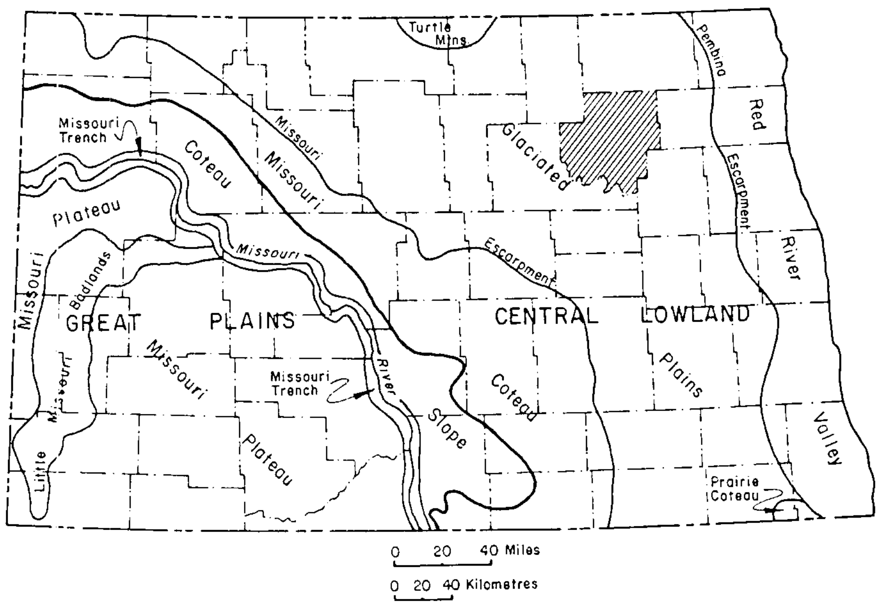

Figure 1. Physiographic map of North Dakota showing the location of Ramsey County.

system begins in the northeast corner of Ramsey County and trends southwestward to Sweetwater Lake. When Sweetwater Lake has filled sufficiently, it overflows to the north into Morrison Lake. When Morrison Lake fills to about 1,458 feet, it spills into Cavanaugh Lake, which in turn feeds a coulee leading to Dry Lake. Dry Lake is also fed by a system of intermittent streams draining the north-central part of the county. When Dry Lake has filled to a level of about 1,449 feet, it overflows to the northwest and takes a circuitous path to Lake Alice (sometimes known as Lac aux Mortes), which in turn flows into Lake Irvine. Mauvais Coulee enters Lake Alice from Towner County and drains Lake Irvine when it has filled to about the 1,445-foot level. Mauvais Coulee flows through Pelican Lake and enters Devils Lake through West Bay.

The potential annual evaporation in the area is much greater than the average annual precipitation, so the above-mentioned lakes are below their thresholds most of the time and no flow occurs in the coulees; the lakes sometimes dry up entirely. When this happens, the surrounding landowners farm the lake bottoms.

STRATIGRAPHY

General Statement

As much as 4,000 feet of Paleozoic and Mesozoic sedimentary rocks lie on the Precambrian basement in Ramsey County. The discussion that follows is mainly a description of the composition, sequence, and correlation of the geologic units that lie at and immediately beneath the surface in Ramsey County. The description proceeds from the oldest known materials, which are discussed briefly, to the younger materials which, because they are more easily accessible, are described in greater detail than are the older units. All of the landforms that occur at the surface in Ramsey County are composed of Pleistocene materials, which were deposited mainly by glacial action. The emphasis of this report will be on the stratigraphy, configuration, and origin of the landforms.

Precambrian Rocks

A total of ten wells have penetrated Precambrian rocks in Ramsey County. The buried Precambrian surface in Ramsey County ranges from a depth of about 2,800 feet in the east to about 4,000 feet in the west. It slopes west-southwestward at about 30 to 35 feet per mile. Elevations on the Precambrian surface range from about 1,300 feet below sea level in eastern Ramsey County to about 2,500 feet below sea level in the western part of the county.

Samples of cuttings from wells that have penetrated Precambrian rocks in Ramsey County were examined by E. G. Lidiak, whose findings have not been published. Lidiak named several rock-type "terranes" in North Dakota. Southeasternmost Ramsey County is part of his amphibole schist terrane, belts of low-grade metamorphic rocks extensive in the basement in eastern North Dakota (fig. 2). The remainder of the county is part of the Ramsey gneiss terrane, an extensive area of rocks of silicic to intermediate composition that are generally of gneissic fabrics. Three dates indicate an age of about 2.6 billion years for the gneissic rocks in Ramsey County.

Paleozoic Rocks

Paleozoic rocks range in thickness from about 1,000 feet in easternmost Ramsey County to about 2,000 feet in the west. At least part of the variation in thickness is the result of episodes of erosion that resulted in unconformities, especially in the Devonian and Mississippian sections. Most of the Paleozoic formations tend to thicken westward; the depositional or erosional edges of several of the Paleozoic formations pass through the county. For purposes of discussion, it is convenient to divide the stratigraphic section into sequences, a sequence being the preserved sedimentary record bounded by major regional unconformities (fig. 3). Paleozoic sequences recognized in Ramsey County are the Sauk, Tippecanoe, and Kaskaskia.

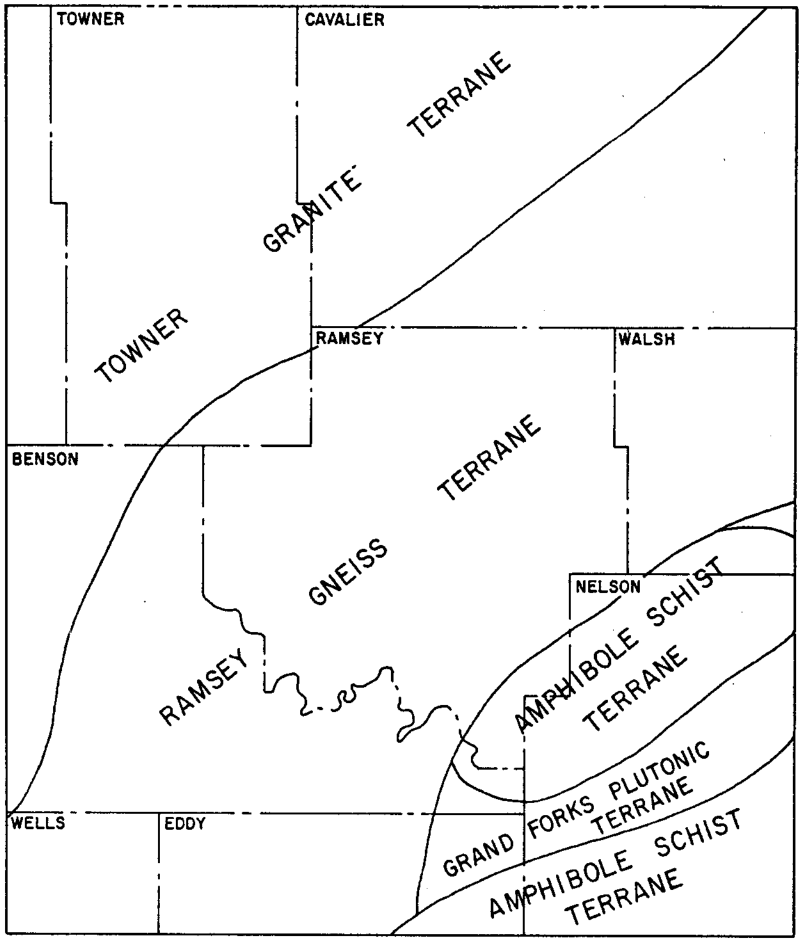

Figure 2. Geologic map of the basement rocks in the Ramsey County area. Adapted from an unpublished map by E. G. Lidiak.

Sauk Sequence

All the rocks of the Sauk Sequence are included in the Deadwood Formation, which consists of interbedded clastics and carbonates. The Deadwood Formation occurs in the southwestern part of Ramsey County, reaching a thickness of about 60 feet.

AGE	SEQUENCE	UNIT NAME	DESCRIPTION	THICKNESS (feet)
HOLOCENE	TEJAS	OAHE FORMATION	Sand, silt, and clay	0 - 25
QUATERNARY	TEJAS	COLEHARBOR GROUP	Till, sand, gravel, silt, and clay	0 - 650
CRETACEOUS	ZUNI	FOX HILLS FORMATION	Marine sandstone	(Possible)
		PIERRE FORMATION	Shale	0 - 600
		NIOBRARA FORMATION	Calcareous shale	80 - 150
		CARLILE FORMATION	Shale	250 - 350
		GREENHORN FORMATION	Calcareous shale	110 - 160
		BELLE FOURCHE FM.	Shale	75 - 135
		MOWRY FORMATION	Shale	35 - 70
		NEWCASTLE FORMATION	Sandy silt	0 - 110
		SKULL CREEK FM.	Shale	50 - 75
		INYAN KARA FM.	Sandstone and shale	0 - 110
JURASSIC		UNDIFFERENTIATED	Shale, sandstone, carbonates, and gypsum	150 - 650
TRIASSIC	ABSAROKA	SPEARFISH	Siltstone and sandstone (redbeds)	0 - 75
PERMIAN			(Absent in Ramsey County)	-
PENNSYLVANIAN				
MISSISSIPPIAN	KASKASKIA	MADISON GROUP	Limestone, dolomite, and anhydrite	0 - 150
DEVONIAN		BIRDBEAR FORMATION	Limestone	0 - 40
		DUPEROW FORMATION	Dolomite and limestone	0 - 290
		SOURIS RIVER FORMATION	Dolomite and limestone	0 - 210
		DAWSON BAY FORMATION	Dolomite and limestone	0 - 130
		PRAIRIE FORMATION	Anhydrite, halite, potash	0 - 50
		WINNIPEGOSIS FM.	Limestone and dolomite	0 - 60
SILURIAN	TIPPECANOE	INTERLAKE FORMATION	Dolomite	40 - 150
		STONEWALL FORMATION	Dolomite and limestone	60 - 70
ORDOVICIAN		STONY MOUNTAIN FM.	Dolomite, limestone, and shale	120 - 140
		RED RIVER FORMATION	Limestone	540 - 590
		WINNIPEG GROUP	Siltstone, sandstone, and shale	160 - 200
CAMBRIAN	SAUK	DEADWOOD FORMATION	Limestone, dolomite, shale, and sand	0 - 60
PRECAMBRIAN BASEMENT ROCKS			Gneiss and schist	Unknown

Figure 3. Stratigraphic column for Ramsey County.

Tippecanoe Sequence

Rocks of the Tippecanoe Sequence range in thickness from about 1,000 feet in the south and southeast parts of Ramsey County to about 1,100 feet in the northwest. The relatively uniform thickness reflects stable conditions during deposition of these rocks and a location where the depositional thickness of all the formations, except the Interlake Formation, have been preserved. The Tippecanoe Sequence began with clastics of the Winnipeg Group, followed by carbonates and minor evaporites of the Red River, Stony Mountain, and Interlake Formations.

Kaskaskia Sequence

Rocks of the Kaskaskia Sequence range in thickness from zero in the extreme eastern part of Ramsey County to approximately 900 feet in the northwest corner of the county. The Devonian rocks are mostly carbonates with minor amounts of evaporites and shales. They thin southeastward and eastward due to both depositional thinning and erosion on top of some of the Devonian Formations. Only the basal Mississippian rocks of the Bottineau Interval (=Lodgepole Formation) occur in Ramsey County, and these only in the extreme westernmost part of the county. These consist mainly of cherty and argillaceous carbonates.

Extensive erosion during Pennsylvanian and Permian time resulted in an unconformity on top of the Devonian rock units in Ramsey County. If Mississippian sediments younger than those of the Bottineau Interval were ever present in the area, they were also removed during this period of erosion.

Mesozoic Rocks

Absaroka Sequence

Mesozoic rocks are mainly fine-grained clastics that range in thickness from about 1,400 feet in eastern Ramsey County to about 2,000 feet in the west. These rocks are divided into two sequences, the Absaroka and the Zuni. Absaroka rocks are those of the Spearfish Formation, red beds that overlie the pre-Mesozoic unconformity. No rocks of Pennsylvanian or Permian age are present. These red beds are generally less than 75 feet thick in Ramsey County.

Zuni Sequence

Jurassic shales, sands, and some carbonates and gypsum overlie the Spearfish red beds throughout Ramsey County. They range up to 650 feet thick in the southwestern part of the county. Overlying the Jurassic sediments are the lower Cretaceous Inyan Kara sandstones and shale, which range up to just over a hundred feet thick in north-central Ramsey County. The Inyan Kara is absent in some west-central parts of the county. Water from the Inyan Kara aquifer (known also as the Dakota Aquifer) was used for domestic purposes in the past in spite of the fact that it is quite saline (Hutchinson and Klausing, 1980).

Overlying the Inyan Kara Formation is a series of gray marine shale formations. The shale of the Skull Creek Formation apparently overlies the Inyan Kara everywhere in the county. In places, the Skull Creek is overlain by a non-shale unit, the Newcastle ("Muddy") Formation sandstone, which is as thick as 69 feet in parts of central Ramsey County, but absent in the southwest and northern parts of the county. It is likely that the saline water in the Newcastle was commonly mistaken for the "Dakota Aquifer" when water wells were drilled in the area. Overlying the Newcastle are the marine Mowry, Belle Fourche, Greenhorn, Carlile, Niobrara, and Pierre Formations. The Pierre Formation lies beneath the glacial sediment cover in most places. Its thickness is quite variable due to erosion on its surface during Tertiary time. It is possible that small amounts of Cretaceous Fox Hills Formation sandstone overlie the Pierre shale in parts of western Ramsey County.

The Pierre Formation shale is exposed in about two dozen places along the southern edge of Devils Lake, especially around the base and sides of Sullys Hill. However, many of these outcrops are probably in blocks of shale that were emplaced by the glacier and they do not represent Pierre Formation "in place."

Cenozoic Rocks

Tejas Sequence

Tertiary materials are not present in Ramsey County. All of the sediment considered to belong to the Tejas Sequence is of Quaternary age and consists of rock and sediment related to glacial deposition, that is, all the materials that were deposited by the glacial ice as well as by flowing and ponded water associated with the ice. These materials, which reach a maximum thickness of about 650 feet in Ramsey County, are collectively referred to as the Coleharbor Group. Holocene sediments are referred to as the Oahe Formation.

The Coleharbor Group has been subdivided into a large number of informal units and formal formations by various geologists studying the glacial geology of North Dakota. Most of the stratigraphic work has concentrated on eastern North Dakota (Harris, et al., 1974; Salomon, 1975; Arndt, 1977) and part of central North Dakota (Ulmer and Sackreiter, 1973). Stratigraphy of the Holocene deposits has been studied in some detail on a statewide basis (Clayton, et al., 1976). Howard Hobbs studied the glacial stratigraphy in northeastern North Dakota as part of his Ph.D. research (Hobbs, University of North Dakota unpublished Ph.D. dissertation, 1975) and he has worked out a detailed Quaternary stratigraphy for Ramsey County. His several Quaternary formations will be treated in some detail in the part of this report dealing with the Quaternary stratigraphy.

Bedrock Topography

The topography of the bedrock surface in Ramsey County (pl. 2) consists of a gently rolling plain sloping from an elevation of more than 1,600 feet in the extreme northeast corner of the county to less than 1,400 feet in the southwest corner. Numerous valleys cut across this plain; many are shallow, but some are as much as 600 feet deep and the elevation of the bedrock surface in these valleys is below 900 feet elevation in places. The valleys were formed at different times and they intersect each other in a complex fashion. They are now essentially filled with glacial sediment. Some of the buried valleys are probably preglacial; the others are glacial diversion trenches.

The most important of the buried valleys are given names that are used in the discussion of the Quaternary stratigraphy and history. The deepest valley in the county is named the "Starkweather Diversion Trench." It extends approximately through the center of the county, from the northeastern part of Ramsey County to near East Devils Lake. Because it is quite narrow and deep, it is almost surely a meltwater diversion trench that formed when a north-flowing river in Towner County, the preglacial northeastward extension of the Cannonball River, was blocked by early glaciers causing the water to flow southeastward around or along the edge of the ice.

The Starkweather Diversion Trench is almost totally buried, filled with glacial, lake, and meltwater sediment, and not apparent to the ground-based observer. Its trace can be seen on airphotos for a few miles north and west of East Devils Lake (pl. 1), but in this area it is also a partly buried, later-generation meltwater trench. The Starkweather Trench has been partly filled and eroded again several times during its history. The later-generation valleys tend to follow the same general courses, but with minor changes. Valleys that were not completely filled with glacial and glaciofluvial sediment tended to be re-excavated by the meltwater from succeeding glacial advances, because they provided the easiest paths for water to follow.

Another deep valley, the preglacial Cannonball River Valley, passes beneath southern and western Ramsey County, sloping northward and joining the Starkweather Diversion Trench in Towner County, about 15 miles north of the Ramsey-Towner County line.

The Cannonball River Valley enters Ramsey County from the south, from Benson County. Even though the Cannonball Valley is preglacial, it has experienced repeated cut and fill by glacial advances and glacial meltwater diversion events. Some of the streams that occupied the Cannonball River Valley probably flowed, at times, in a direction opposite to the northerly bedrock slope of the main valley floor (and, of course, resulted in proglacial lakes in the lowland areas).

The Spiritwood Aquifer largely occupies the same trench as the Cannonball Valley in Ramsey and Towner Counties. The Spiritwood Aquifer system appears to underlie almost the entire Devils Lake chain of lakes. In the area beneath Sixmile Bay, the relationships are confusing. The width, depth, and exact extent of the aquifer materials are poorly defined because test-hole data are not available for areas under the water of the lakes. The subglacial and glacial geology in the area underlying the Devils Lake chain is extremely complex because extensive thrusting by the glacial ice has greatly disrupted the materials there; it is difficult to determine which buried low areas formed as river valleys and which are depressions excavated by the glacier.

The Cannonball Valley intersects the mouth of the Starkweather Diversion Trench approximately at East Devils Lake. Stratigraphic evidence at the juncture indicates that the fluvial materials in the Starkweather Valley are older than those in the Cannonball Valley because the Cannonball Valley has cut across unit B of the Cando Formation (see discussion of the glacial stratigraphy). However, a short distance away, a later-generation valley has cut across the Cannonball Valley and the overlying silt. This indicates that later-generation valleys do not occupy exactly the same positions as the earlier ones.

Just east of East Devils Lake another valley intersects the Cannonball-Starkweather Valley. It has been referred to as the McVille Channel because it is the same valley that contains the McVille Aquifer in Nelson County (Downey, 1973). Its age and relationship to the Cannonball-Starkweather Valley are obscure. Several stratigraphic units appear to be present in the McVille Channel, but they cannot be correlated at the present time.

The area north and northwest of the city of Devils Lake, between the Cannonball and Starkweather Valleys, is an area of shallow, buried valleys separated by broad divides and knobs (pl. 2). In this area, subglacial shearing has brought shale blocks close to the surface in some places, most notably southwest of Dry Lake and Cavanaugh Lake (pls. 1, 2). In other less obvious places the apparent bedrock surface may in fact be the top of the shale blocks that were not completely penetrated by the drill.

The portion of Ramsey County east and north of the Starkweather Valley consists of an almost flat surface on the Pierre Formation, sloping gently to the southwest. The few valleys found in this area are shallow; one valley enters the county near Hampden and slopes southwestward to the Starkweather Valley. This valley is filled largely with till of the Gardar Formation. Major aquifers do not exist in this area, though it is possible that some small valleys might have been missed in the drilling program.

Glacial Stratigraphy

Introduction

Three types of data were used in the compilation of the stratigraphy: descriptive logs of samples made by the well-site geologists; electric logs (resistivity and spontaneous potential) of the test holes; and studies of the samples themselves. The samples obtained from test holes drilled during the installation of the Minuteman Missile ICBM sites in 1963 were mainly intact cores; no electric logs were taken at those test holes. Drill cuttings were taken from the State Water Commission test holes. Electric logs are available for most of the State Water Commission test holes.

The stratigraphic units used in this report are defined as lithostratigraphic units that are defined on the basis of lithology and position in sequence. In most cases, a formation or member represents an event--a glacial advance and retreat. Each formation or member consists of a basic, defining lithologic unit that is widespread and traceable, such as a layer of till. Other minor lithologic units such as sand and gravel bodies or silt layers are assigned to the unit that surrounds them or overlies them if there is not sufficient lithologic basis to assign them to another formation or member.

The Quaternary and Recent deposits in Ramsey County are divided into six formations. From bottom to top they are the Cando, Camp Grafton, Churchs Ferry, Gardar, Dahlen, and Oahe Formations. The first three of these formations are either newly defined or redefined in this report; the last three have been described in previous publications (Salomon, 1975; Clayton, et al., 1976). The first five units are Pleistocene, included in the Coleharbor Group (Bluemle, 1971); the Oahe Formation is Holocene.

The Cando Formation is divided into five units, consisting of deposits of at least three glacial advances and associated stratified glaciofluvial and glaciolacustrine deposits. The Cando Formation is restricted mostly to buried preglacial valleys.

The Camp Grafton Formation is composed of well-sorted sand and gravel. It occupies a valley that was presumably cut by an ice-marginal stream, but it extends laterally several miles on either side of the valley, in what appears to be a buried outwash plain. The Camp Grafton Formation is an aquifer, apparently the same unit generally referred to as the Spiritwood Aquifer.

The Churchs Ferry Formation is divided into three members and probably represents the deposits of three glacial advances. The Gardar Formation contains deposits of a glacial advance from the northeast, probably in Early Wisconsinan time.

The Dahlen Formation contains deposits of the main Late Wisconsinan glacier, which advanced across Ramsey County from the northwest. The upper member, the Hansboro Member, represents a minor readvance of the generally receding glacier late in the Wisconsinan Epoch.

The Oahe Formation consists of sediment deposited in postglacial lakes, sloughs, and streams.

In the discussion that follows, the formations included in the Quaternary Coleharbor Group in Ramsey County are discussed, the order of treatment progressing, generally, from oldest to youngest. This treatment of the glacial stratigraphy is based largely on research by Howard Hobbs several years ago as part of his effort toward a Ph.D. degree.

Cando Formation

The Cando Formation was described by Howard Hobbs in an unpublished dissertation, and the name has been used without formal definition by Moran and others (1976). The Cando Formation includes all the glacial deposits in the buried Starkweather and Cannonball River Valleys stratigraphically below the Camp Grafton Formation (described below). The main thing that distinguishes the sediments of the Cando Formation is that they occur in deep bedrock valleys, stratigraphically below the Spiritwood Aquifer. Probably several glaciations are represented by the Cando Formation, but it is not certain how many. It appears as though the valleys have undergone several episodes of cut and fill.

No type section is given for the Cando Formation. The Cando Formation is a complex unit consisting of many subunits; many of these subunits that were probably not penetrated in Ramsey County should be included in any comprehensive definition of the formation. Furthermore, later workers may prefer to subdivide the formation differently than we have in this report. For these reasons, the Cando Formation is subdivided into lettered units rather than members; the lowermost unit is E, the uppermost one is A.

Unit E of the Cando Formation consists primarily of extremely shaly till at the base of the Quaternary section, lying directly on Cretaceous shale. In places, the till is interbedded with silt and interbedded with or underlain by shaly sand and gravel. In test holes where the lithology of the very coarse sand was studied, shale amounts to 80 percent or more of the very coarse sand fraction, and crystalline grains are abundant relative to carbonate grains (normalized crystalline ratio is greater than 0.80). The Cando Formation is commonly described on the descriptive logs as "very shaly" or "abundant shale fragments." The curve of the resistivity log is commonly far to the left compared to the overlying materials, and almost as far to the left as it is for the underlying shale bedrock.

The shaliness and basal stratigraphic position suggest that unit E is composed of material deposited during the first glacial advance to reach Ramsey County. Although the first glacial advance brought material from the Canadian Shield and the northern Red River Valley, these crystalline and carbonate grains were diluted by enormous amounts of weathered shale that the glacier had to pass over to reach the area. The predominance of crystalline over carbonate grains suggests that the ice advanced from the east-northeast, largely bypassing the carbonate bedrock north of Ramsey County.

Unit D overlies unit E. It consists of till and some associated stratified glaciofluvial sediment. It is preserved primarily in the western part of the county, and all the samples for which laboratory data are available are from that area. Till of unit D is moderately shaly, ranging from 43 percent in test-hole 8832 to 67 percent in test-hole 8879. The normalized crystalline ratio ranges from 0.56 in test-hole 9036 to 0.85 in test-hole 8879. This degree of variability is unusual for a till unit in Ramsey County, and it may be that unit D represents more than one glacial advance. However, it is not possible to subdivide the unit in any logical way, and two different units do not occur in unit D in any of the test holes from which data are available.

Unit D is equivalent to the Cando Formation described by Hobbs, at least in test-hole 8830. This unit was recognized in widely scattered locations in northeastern North Dakota. However, its extent may not be as great as was once thought, because it is lithologically similar to the lower member of the Churchs Ferry Formation, which is higher in the section and thus more likely to be preserved. In Ramsey County little reason exists for confusion because the Cando Formation and the Churchs Ferry Formation are commonly separated by the Camp Grafton Formation, an excellent stratigraphic marker.

The third unit of the Cando Formation is unit C, which consists of till and an underlying sand. Unit C directly overlies unit D in test-hole 9036, and is distinguished from unit D by its much lower shale content in the very coarse sand fraction. This is the only test hole for which data on unit C is available, and unit C occurs in only a few other test holes. Nonetheless, its considerable lithologic difference from unit D makes it worth distinguishing as a separate unit.

Unit B, overlying unit C, is composed predominantly of silt and sand; no till is included in unit B. Both the Starkweather and Cannonball River Valleys contain unit B. Unit B was deposited when the two valleys were dammed by glacial ice and proglacial lakes, or a proglacial lake, formed.

Unit A, the uppermost recognizable unit in the Cando Formation, consists of shaly sand and gravel deposited in a valley cut into units B and C. Unit A forms the Starkweather Aquifer in the Starkweather Valley. It occupies an area about a mile wide and 25 miles long and ranges in thickness from 35 to over 250 feet. The thinner figures probably are from holes drilled near the edge of the valley.

Camp Grafton Formation

The Camp Grafton Formation is named for the National Guard training camp near Devils Lake. It is composed of sand and gravel with some thin silt and clay layers. The Camp Grafton Formation occurs mainly in a valley that is cut partly into bedrock and partly into older glacial deposits. Where it occurs in the valley, the formation is thick, ranging from 100 to 200 feet; in places, however, the sand and gravel has "spilled out" of the valley to form a thinner and more extensive plain. In these places, the fluvial deposits average 30 to 50 feet thick. The fluvial deposits of the

Camp Grafton Formation are referred to as the Spiritwood Aquifer.

Sand and gravel of the Camp Grafton Formation was consistently described as "clean" and well sorted by the well-site geologist. It was probably deposited by a meltwater stream. The sand and gravel were deposited during periods of full flow, whereas the thin silt and clay layers represent periods of slack water, perhaps during the winter periods.

Very coarse sand of the Camp Grafton Formation is fairly shale-poor, ranging from 12 percent in test-hole 9036 to 36 percent in test-hole 8975. These averages conceal a great variation from sample to sample, however. For example, in test-hole 9046, the individual samples range from 10 percent shale to 52 percent, with a mean of 30 percent. Lignite grains also occur in the very coarse sand fraction of the Camp Grafton Formation; in some places they are so abundant that the driller has noted "coal" on the driller's log. Lignite abundance is even more variable than shale abundance. Variability of these constituents is understandable in sand and gravel deposits, because they were washed and sorted by running water. In contrast, till tends to be much more uniform because it is unsorted.

The upper member of the Camp Grafton Formation consists of silt with some sand and gravel locally (this member has also been referred to informally as the "Devils Lake Silt"). The upper member is widespread in southern Ramsey County and extends northward as thick valley fills in the Starkweather and Cannonball River Valleys. These valleys were filled practically to the top with fluvial and lacustrine sediment and were not subsequently re-excavated, except for a later trench in the Starkweather Valley in the southern part of the county. The upper member of the Camp Grafton Formation extends northward into Towner County and southward into eastern Benson County. In the area north of the Devils Lake chain, the unit ranges in thickness from 4 to 109 feet, averaging about 35 feet thick; in the buried valleys it ranges from 14 to over 350 feet thick. The thinner figures are presumably from test holes drilled near the edge of the valleys it occupies. In test-hole 9069 (pl. 4) the unit is 260 feet thick, including 80 feet of shale and till, which probably represents a major slump into the valley while it was filling with silt.

The upper silt member of the Camp Grafton Formation was deposited in a glacial lake, which probably formed during the wasting of the glacier. The sediment appears to be glacial lake sediment because sand and small pebbles are present. These are unlikely to have been deposited in a nonglacial lake, but they are normally present in glacial lake sediment. These large particles were derived from melting icebergs in the lake. The elevation of the top of the unit is irregular due to post-depositional erosion, but it follows a pattern of general decrease southward through the Cannonball River Valley and its tributary, relative flatness in the area north of the Devils Lake chain, and further decrease north along the Cannonball Valley. If this represents the original depositional surface, it is likely that the sediment was deposited by turbidity currents derived from the Starkweather Valley and that the currents continued to flow northward along the Cannonball Valley to an unknown destination. The average gradient of the top of the sediment is about 2 feet in a mile along that route. Alternatively, the decrease in elevation may represent an erosional surface related to the elevation of the valley walls.

Churchs Ferry Formation

The Churchs Ferry Formation, newly named in this report, is named for the village of Churchs Ferry, in western Ramsey County. Its type area is eastern and southern Ramsey County and its type section is test-hole 9037, in the NW¼NW¼NW¼sec 3, T155N, R66W. The formation is divided into three members: lower, middle, and upper, parts of all of which are present at the type section. The lowermost, shaly member can be subdivided into a shale breccia and a shaly till unit. At test-hole 9037, the Churchs Ferry Formation consists of 70 feet of till and associated sand, overlain by the Dahlen Formation and underlain by the Camp Grafton

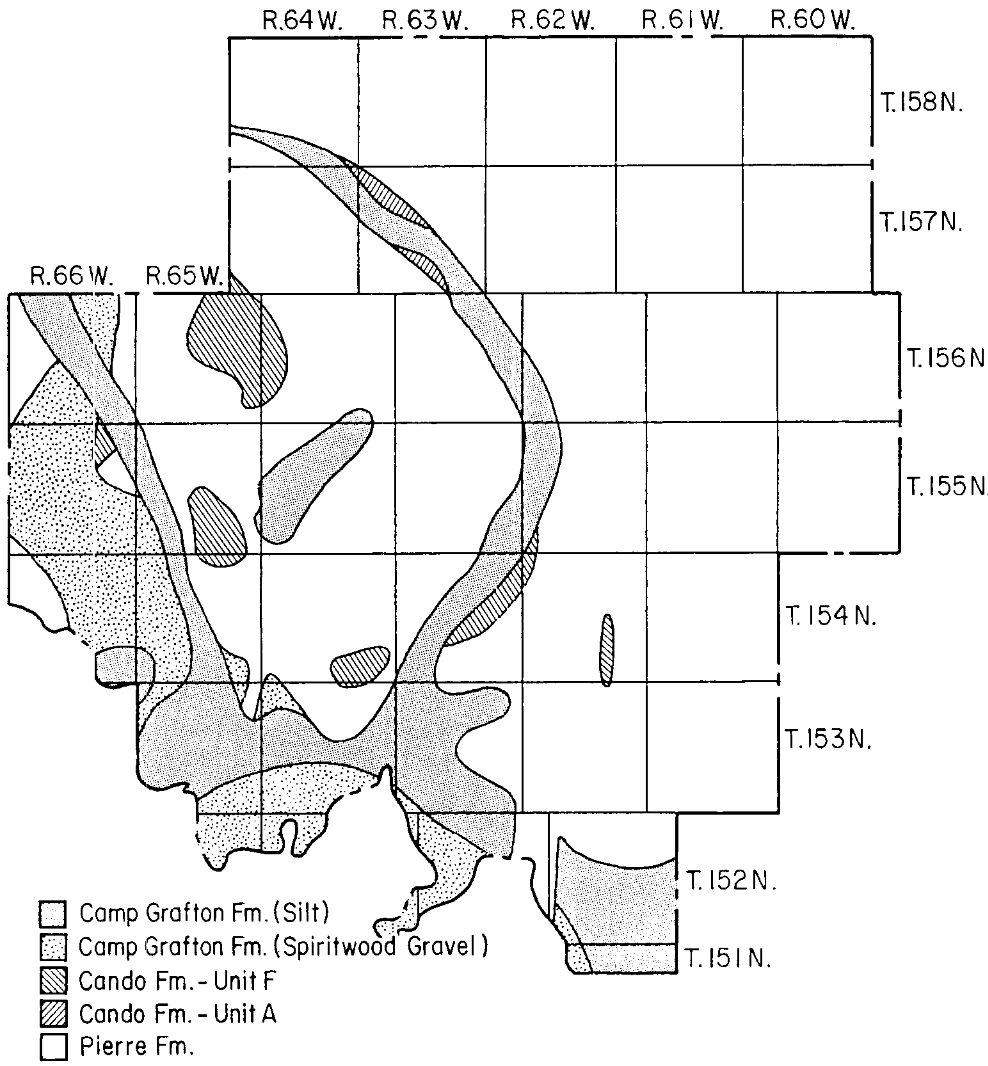

Figure 4. **Paleogeologic map of the surface beneath the Churchs Ferry Formation in Ramsey County.**

Formation. The Churchs Ferry Formation is defined as the sediment stratigraphically above the Camp Grafton Formation, as described in this report, and below the Gardar Formation, which is not present at the type section. Figure 4 shows the materials that directly underlie the Churchs Ferry Formation.

The subdivision of the Churchs Ferry Formation is based primarily on shale abundance in the very coarse sand fraction. The lower member (except for the basal shale breccia) ranges from 60 percent shale in test-hole 8851 to 37 percent in test-hole 8830. The modal average for the county is about 50 percent. The middle member ranges from 23 percent shale in test-hole 9037 to 26 percent in three different test holes. The upper member ranges from 9 percent shale in test-hole 9036 to 19 percent in test-hole 8830. In both the upper and lower members, the high figure is about twice the low figure, but the middle member shows little variation. The lower member commonly occurs as a fill in valleys cut into the underlying Camp Grafton Formation. At test-holes 1813 and 9092 on plate 4, the lower member occupies a valley cut in bedrock. This unit is more widely preserved than any lower unit composed dominantly of till. Combined with the common occurrence as a valley fill, this indicates that the lower member was deposited after a considerable period of weathering and erosion.

The lowermost part of the lower member of the Churchs Ferry Formation consists of very shaly till, directly overlying shale bedrock. Because of its position at the base of the section and its shaliness, it appeared at first that this unit was part of unit E of the Cando Formation. However, two differences are apparent. The normalized crystalline ratio is much lower, ranging from 0.52 to 0.57 (compared to a range of 0.81 to 0.91 for unit E of the Cando Formation). Secondly, unit E is restricted mostly to deep valleys and is overlain by other units of the Cando Formation, but the lowermost part of the Churchs Ferry Formation occurs on "upland" areas of the shale and is overlain by no sediment older than the overlying unit of the Churchs Ferry Formation. For this reason, the unit is assigned to the Churchs Ferry Formation.

The lower part of the lower member of the Churchs Ferry Formation is probably a basal, shaly facies of the till that overlies it, not the deposit of a separate glacial advance. It is common in northeastern North Dakota for the lowest unequivocal "till" to be underlain by a layer composed predominantly of angular shale fragments in a silt matrix. These shaly units are sometimes referred to as "crushed shale" or "shale breccia." The material was apparently crushed and sheared by a glacier, but not "digested" or incorporated into the main body of glacial sediment by the time the ice melted. The stratigraphic treatment of a unit of this type is problematical. We prefer to consider it as a basal facies of whatever unit overlies it, but not include its very coarse sand data in the averages computed for the overlying till.

The middle member of the Churchs Ferry Formation also commonly occurs as a valley fill, above the lower member. It does not occur as a basal valley fill. The middle member is generally thinner and less widely preserved than the lower member.

The upper member of the Churchs Ferry Formation was consistently described as "very sandy" by the well-site geologist. Although lab analysis reveals that till from this member is not much, if any, sandier than average, the unit appears sandy because it contains very little shale, and is thus light-colored. The description is consistent enough that the unit can be correlated with some confidence in holes with no lab data. The upper member of the Churchs Ferry Formation forms an almost continuous layer over western Ramsey County, and extends, as patches, some distance to the east and south. It does not occur in the northeastern half of the county. Since the upper member is not far down the stratigraphic column, one would think that it would have been preserved somewhere in the northeastern half of the county if it had ever been deposited there.

Gardar Formation

The Gardar Formation consists of till and associated sand and gravel. It was named by Salomon (1975) from exposures near Gardar, North Dakota, and it has been widely recognized in eastern North Dakota (Moran and others, 1976). The Gardar Formation's distinguishing characteristic is its high shale content which, in eastern Cavalier County, ranges up to 95 percent of the very coarse sand fraction. In Ramsey County, the Gardar Formation is not that shaly. The highest shale value is 81 percent in test-hole N-1229, the lowest value is 56 percent in test-hole N-582, and the median for the county is 68 percent. The median is higher than that for most other tills in the county, although unit E of the Cando Formation and the lower member of the Churchs Ferry Formation, both of which are much lower in the section, have higher shale contents. Till of the Gardar Formation is consistently, though not invariably, described as "very sandy, gravelly" by the well-site geologist. The Gardar Formation till actually does contain more gravel than average for till in the county, most of it shale fragments. This characteristic has made it possible to distinguish between the Gardar Formation and other glacial units, especially the upper member of the Churchs Ferry Formation, in test holes which have no laboratory data.

The Gardar Formation is quite widespread in the northeastern two-thirds of the county (fig. 5), but it has been removed by erosion over much of the area. It is generally 30 feet or less thick, except where it fills valleys, where it reaches a maximum recorded thickness of over 200 feet (test-hole 9073). The Gardar Formation commonly occurs as a valley fill, in places as the basal fill (test-hole 8780, pl. 4), and in other places above the lower member of the Churchs Ferry Formation. For this reason, it is reasonable to conclude that the Gardar Formation was deposited after a period of erosion between glaciations.

Dahlen Formation

Salomon (1975) named the Dahlen Formation and found it to contain the surface layer of till over much of northeastern North Dakota. Moran and others (1976) extended its area of occurrence to most of eastern

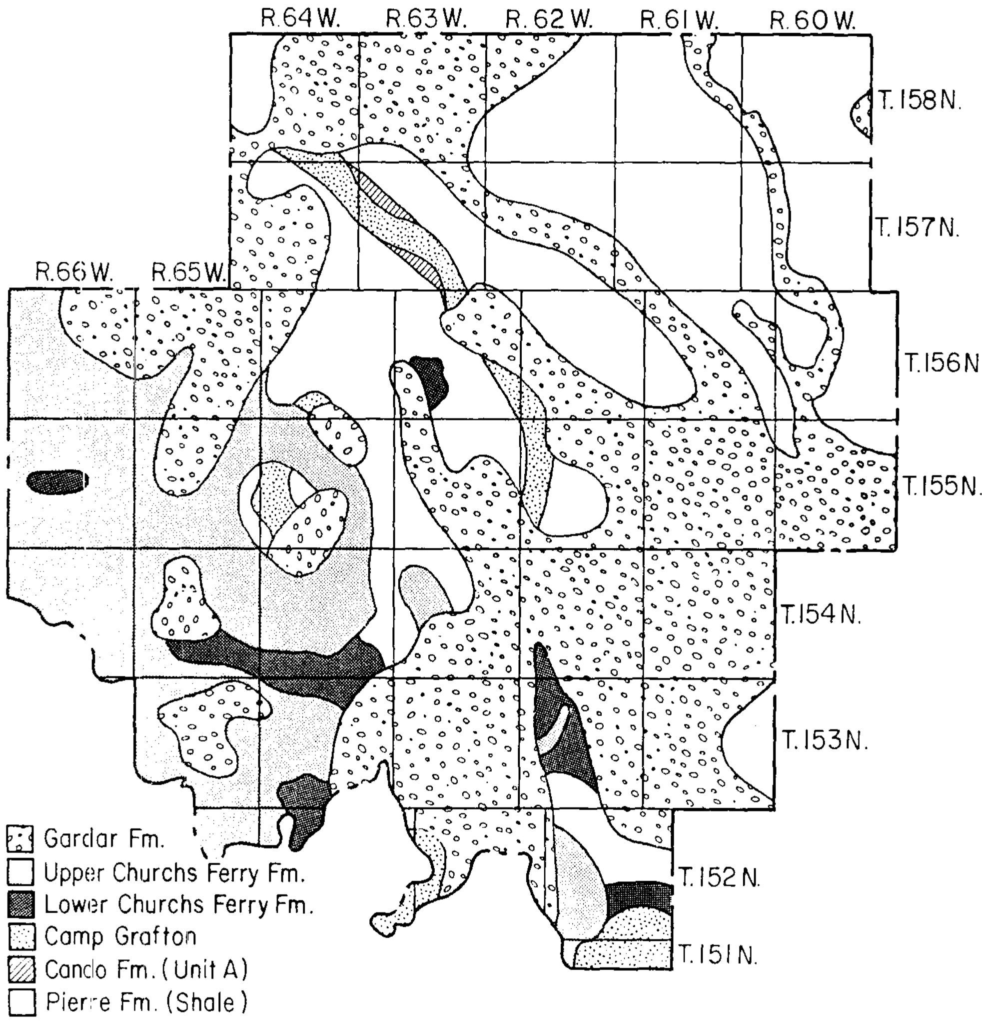

Figure 5. Paleogeologic map of the surface beneath the Dahlen Formation (the pre-Late Wisconsinan surface) in Ramsey County.

North Dakota and recognized a till overlying the Dahlen Formation in some areas. This unit was called the Hansboro Formation in the north and Lower Fort Ransom #10 in the south, because of uncertainty as to whether it was the same till in both areas. We consider the Hansboro to be a member of the Dahlen Formation, but the term "Dahlen Formation" is used in this report in the sense that Salomon defined it, excluding the Hansboro Member, unless it is specifically mentioned.

All of the units below the Dahlen Formation are beneath the oxidation zone, with a few local exceptions. Figure 5 shows the units directly overlain by the Dahlen Formation. The upper part of the Dahlen Formation, including the Hansboro Member, is oxidized, buff-colored when dry and brown when wet. The depth of oxidation averages 25 to 30 feet; the bottom of the oxidation zone is marked with a line labeled "ox" on the cross sections (pl. 4). Below the oxidation zone, the Dahlen Formation is generally medium to olive gray when wet and light gray when dry.

The Dahlen Formation covers nearly all of Ramsey County. With its Hansboro Member and the deposits of glacial lakes, it is the surface layer of sediment throughout the county except where Holocene lake, stream, and slough sediments cover the older materials. Figure 6 shows the extent and thickness of till of the Dahlen Formation including the Hansboro Member. A bare patch in the center of the county was drawn around a test hole which penetrated lake silt over shale breccia over shale. Another bare patch occurs in southern Ramsey County, where the Dahlen Formation has been partly eroded from the bottom of a channel leading from East Devils Lake to Stump Lake.

The area in which the Hansboro Member of the Dahlen Formation occurs is indicated on figure 6. Till of the Hansboro Member is distinguished from till of the Dahlen Formation by its lower shale content in the very coarse sand fraction. The Hansboro ranges from 16 percent to 28 percent, the Dahlen from 28 percent to 54 percent. In general, the Dahlen Formation is shalier to the south.

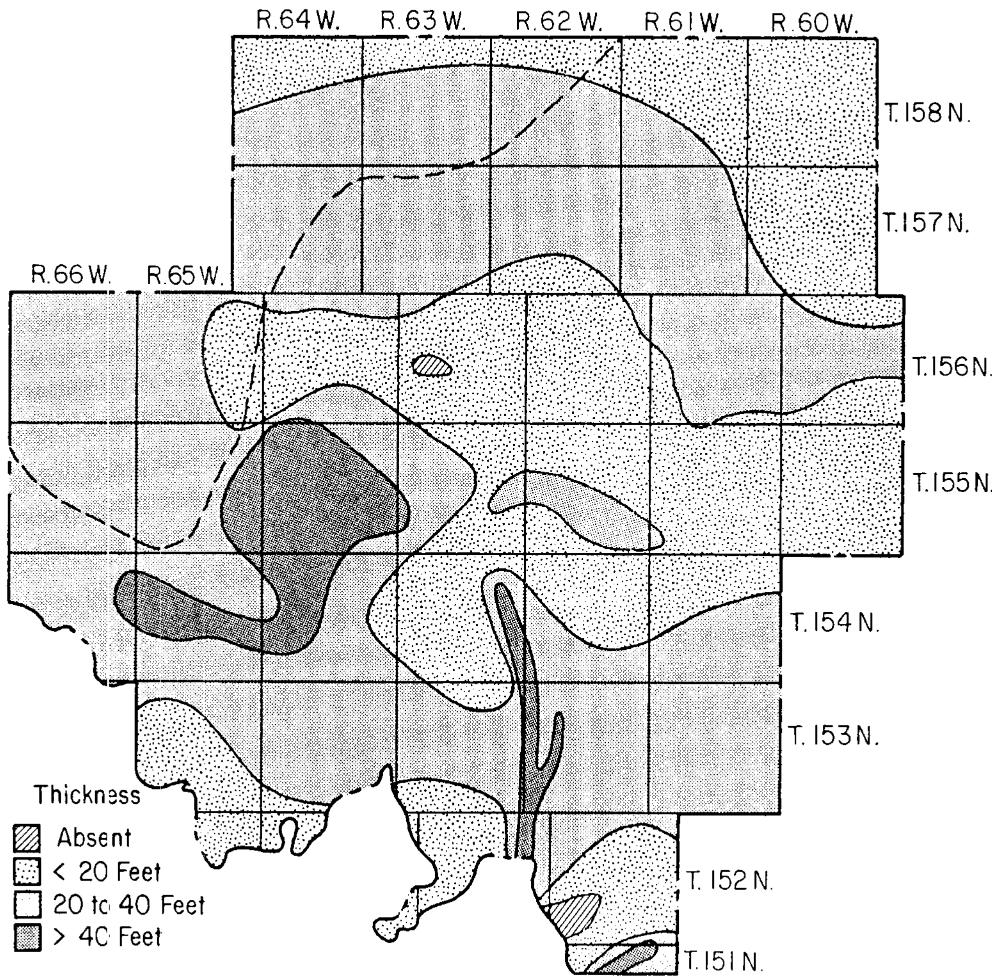

Figure 6. Extent and thickness of the Dahlen Formation in Ramsey County. The Hansboro Member is present mainly in the area north and west of the dashed line.

The distribution of the Hansboro Member of the Dahlen Formation is not so straightforward and simple as might be suggested by figure 6. Two isolated occurrences of the Hansboro Member are not shown. One is located four miles north of Lawton in eastern Ramsey County; the other is located at the city of Devils Lake. In addition, not all of the test holes located within the area shown as being underlain by Hansboro are actually known to have penetrated the Hansboro Member. Laboratory data are not available from some of the test holes, and the Hansboro Member cannot be distinguished from the underlying parts of the Dahlen Formation without laboratory data. Some of the holes from which laboratory data are available do not indicate a shale-poor zone at the top of the Dahlen Formation. This may be due partly to the nature of sampling. The Hansboro Member is commonly 10 feet thick or less, the uppermost sample is taken between the surface and 5 feet deep by the State Water Commission and between 5 and 6.5 feet by Porter and O'Brien (the engineering firm that collected data for the installation of the ICBM sites in the area). The State Water Commission normally chose roadside ditches as test-hole sites; these may be 5 feet below the general level of the land.

The pattern of occurrence of the Hansboro Member of the Dahlen Formation remains puzzling if it is considered to represent a distinct glacial advance. Another puzzling fact is the lack of an end moraine or other visible ice-margin position between the area in western Cavalier County, where it is present, and eastern Cavalier County, where it is not present. Hobbs (1975) postulated that the Hansboro was deposited during an advance of active ice into an area of stagnant ice.

Alternatively, the lower-shale till of the Hansboro Member could merely represent debris derived primarily from an area up-ice from the Pierre Formation shale. Far-travelled debris tends to overlie locally-derived debris in the sediment column in the ice, though this distinction is commonly obscured by mudflows and collapse during deglaciation.

The thickness of till of the Dahlen Formation, including the Hansboro Member, is shown on figure 6.

The area of occurrence has been divided into three zones: thickness less than 20 feet; thickness between 20 and 40 feet; and thickness greater than 40 feet. Since the thickness of any till sheet is highly variable from place to place, due to the hummocky nature of its surface, the areas were smoothed out on the map by disregarding small patches of one zone within another.

The area of greatest thickness occurs in three places: in an end moraine in extreme southern Ramsey County; in a buried valley north of East Devils Lake; and over a broad area northwest of the city of Devils Lake. The first two areas may be explained in terms of their depositional settings. The third area of accumulation is not so easily understood, but it appears to coincide generally with an area that contains numerous ice-thrust features (pl. 1). The areas of medium thickness coincide, in large part, though not perfectly, with the areas on plate 1 in which washboard moraines are mapped.

The Dahlen Formation was deposited during the main Late Wisconsinan ice advance. The overlying Hansboro Member, which can be considered to be part of the Dahlen Formation, represents deposits of a minor readvance within the generally wasting glacier. The Hansboro and other units that overlie the Dahlen were formed at different times in different places, but probably all during the few thousand years between the time the Des Moines Lobe reached its greatest extent and the time it finally melted from North Dakota. The relationships among these Late Wisconsinan units should be envisioned, not as a stack of pancakes, but as a shingled roof.

Postglacial Stratigraphy

Oahe Formation

The Oahe Formation was defined by Clayton, Moran, and Bickley (1976) to include all the well-sorted silt above the Coleharbor Group near Riverdale in McLean County. It was redefined by Clayton and Moran (1979) to include material of all grain sizes above the Coleharbor Group. The Oahe differs from the Coleharbor in that it lacks glacial sediment. In general, the non-glacial sediment at the top of the Coleharbor can be distinguished from sediment of the Oahe by its better sorting and lack of dispersed organic matter; the Oahe is typically shades of brown or black due to organic material that was probably derived from topsoil.

In Ramsey County, the Oahe Formation consists primarily of stream overbank sediment (alluvium) (Qor) and slough sediment (Qos). Little wind-blown sediment was noted in the area. The alluvium is mainly poorly sorted and bedded silt and clay with some disseminated organic matter.

Sediment covering the bottoms of sloughs and temporary lakes consists primarily of silt and clay of the Oahe Formation. It is highly organic, at least in the upper layer, because it accumulated along with dense swamp vegetation. Bickley and others (1970) excavated a slough in southeastern North Dakota and described seven units of sediment above the uppermost glacial sediment. These layers were deposited in different environments and represent a record of changing climate and hillslope conditions since the ice melted. No such excavations have been made in Ramsey County, but it is reasonable to expect that the slough sediments in the county would show similar characteristics.

GEOMORPHOLOGY

Introduction

This section of the report should be used in conjunction with the surficial map of Ramsey County (pl. 1). The map is primarily a materials map, but it has aspects of a morphogenetic map (a map that shows surface morphology and interprets its origin). This is true especially of the glacial lake plains, ice-thrust hills, and eskers, described below. These features are clearly recognizable on maps and airphotos, but they are differentiated from other landforms primarily by their shape and inferred origin rather than their composition.

The scale of the geologic map (pl. 1) is 1:125,000, or two miles to an inch. The narrowest linear features shown on the map are about 1/20 of an inch wide, which represents 1/10 mile on the ground. Some narrow, but important features, such as beach ridges and eskers, were widened slightly on the map. Conversely, some small eskers and beach ridges were judged too narrow to map, but not important enough to exaggerate, so they were omitted. Sloughs (Qos) and lakes larger than about 40 acres were mapped, but smaller ones were omitted.

The shoreline of Devils Lake was mapped as though the water level was at about 1,425 feet. The topographic maps and airphotos from which the map was compiled show the shore at lower elevations, but not at the same elevation on every map. A lake level of 1,425 feet was chosen because the lake stood at about that level during the last summer of fieldwork.

Beach Ridges

Beach ridges occur along the shorelines of many of the larger lakes in Ramsey County. They are composed of well-sorted to moderately sorted sand and gravel that grades lakeward to fine sand. The bedding, where it has been observed, is a rather vague low-angle cross-bedding that dips toward the lake.

Most of the mapped beaches (Qob) are of recent (Holocene) age. A few of the higher Devils Lake beaches, at elevations up to 1,450 feet, are at least partly of late Pleistocene age. The beaches are probably more extensive than shown on the map, but they are easily visible on airphotos only if they are in a baymouth position. It was not possible to recognize beaches on the wave-cut slopes of Devils Lake, but a veneer of beach sediment probably exists in many places.

The Holocene beaches are much more extensive than are the Pleistocene beaches. As with the Pleistocene beaches, they were mapped on the basis of ridges visible on topographic maps and airphotos; thus, the

Figure 7. Exposure of bedded, shaly gravel in a pit in a beach remnant south of Devils Lake (SE¼NE¼sec12, T152N, R65W). This is probably a Holocene Beach. The elevation of the deposit is about 1,430 feet.

area covered by sand and gravel is greater than that shown on the map. The higher Holocene beaches along Devils Lake have ridge crests at about 1,435 to 1,440 feet high, indicating that the water stood at that level for some period of time. A good example is the beach ridge south of the city of Devils Lake (fig. 7). Some beaches also occur at about 1,425 feet, such as along the east shore of East Devils Lake, but these are not as well developed, which may indicate that the water did not stay at that level as long.

Under the proper conditions, beaches can form in a short time. For example, a road at one time crossed Dry Lake in section 11, T155N, R65W; it was built when the lake was at a lower level. The road is flooded now and, where it enters the lake on either side, it has been eroded and covered with gravel. On the west side of the lake, the road has been covered by a beach ridge about 2 feet high (the feature is too small to show on the map).

Along other lakes in the area, beach ridges are better developed on the east and southeast sides of the lakes. This is due to the fact that the prevailing wind, which is from the northwest, has subjected the southeast sides of the lakes to greater wave action.

Modern Flood Plains, Sloughs, and Temporary Lakes

Stream overbank sediment has been mapped as modern flood plains (Qor). This alluvial sediment, along with the Holocene beaches and slough sediment, is included in the Oahe Formation. Stream bedload sediment, predominantly sand, covers areas too small to be mapped separately.

Slough sediment (Qos) was mapped where swamps or temporary lakes are shown on topographic maps and airphotos. Similar sediment underlies shallow permanent lakes. The distinction between areas mapped as water and the areas mapped as slough and pond sediment is not permanent or absolute.

Glacial Lake Plains

The glacial lake plains are underlain by slightly pebbly silt and clay (Qcl, Qclt), in Ramsey County. Unlike the modern alluvial and slough sediment, the glacial lake sediment is free of organic matter, except in the modern soil profile. Most of the glacial lake sediment is deep-water sediment from glacial Lake Cando (Qcl). Some patches of lake sediment also exist in the southern part of Ramsey County, where glacial lakes formed in partly buried meltwater valleys.

In some places, the glacial lake bottoms are not covered everywhere by lake sediment (Qclt). The surface material is predominantly till covered by patches of silt and clay (offshore lake sediment) or sand (nearshore or beach sediment). Such areas can be easily recognized on topographic maps and airphotos because they are smooth and lack the hummocks or irregularities characteristic of glacial topography. In the glacial Lake Cando basin, the surface is relatively flat; in some parts of the Devils Lake basin the surface slopes rather steeply toward the lake.

Flat topography in a glacial lake basin is sometimes the result of wave washing. Wave washing occurred over parts of the glacial Lake Agassiz plain, but it is doubtful that it played a significant role in creating the flat glacial Lake Cando plain. The process of wave washing develops a lag of cobbles and boulders too big to be moved by the waves. In most wave-washed areas numerous boulder piles are found in the fields. Over the glacial Lake Cando plain, however, a surface lag is not common and large numbers of boulder piles are not seen.

It is likely that the glacial Lake Cando was ice-walled; that is, confined by ice rather than being a basin of rock or sediment. Part of the lake plain east of Dry Lake is at an elevation of 1,490 feet, so the water level must have been that high or higher, yet the elevations at the edge of the lake plain, where smooth topography merges into hummocky glacial topography, are lower, ranging from about 1,480 feet along the northern boundary to about 1,460 feet along the southern boundary. An "island" of hummocky collapsed glacial topography occurs within the lake plain east of Dry Lake. Elevations over this island range from greater than 1,480 feet to less than 1,450 feet, so this was not an island of higher ground.

Except for some low beaches that were seen in the area west of Dry Lake, few beach ridge remnants were noted in association with glacial Lake Cando. The lake was large enough to produce large waves, and it must have lasted long enough for the waves to have had some effect, because 10 feet or more of silt and clay was deposited on the lake floor. The only way to explain the elevation anomalies and the apparent lack of beaches in many places is to assume that the edges of the lake were held by the remnant of the last glacier to cover Ramsey County and the area to the north. The island east of Dry Lake must have been an island of ice that did not melt until after the lake drained.

The shores of glacial Lake Cando can be envisioned as steep cliffs of ice, perhaps undercut by melting and wave action. Large blocks of ice probably fell into the water occasionally and floated away as icebergs. As the icebergs melted, they dropped their load of sediment on the bottom, accounting for the fact that the silt and clay deposits of the lake contain occasional pebbles, which could not have been carried out in suspension. The water was too deep, in most places, for waves to erode the bottom. The flatness is not due entirely to lake deposition either because much of the bottom is covered by little or no lake sediment. The surface is predominantly glacial till, some of which may have been deposited as subaqueous flow till.

Hummocky Glacial Topography

Most of the surface of Ramsey County is covered by till, an unsorted mixture of clay, silt, sand, and gravel, containing rocks up to several feet in diameter (areas designated Qccl, Qccm, Qcch on plate 1). This material was eroded and transported by a glacier and deposited as the glacier melted. Glacial till generally formed hummocky topography because, as the sediment-laden ice melted, the sediment accumulated on the surface of the glacier. In places where the sediment was thicker, the ice melted more slowly than under adjacent areas where the sediment was thinner. The surface of a melting stagnant glacier becomes pock-marked with depressions where the ice melts more rapidly. Mud, composed of water-saturated glacial sediment, flows and slides down from the higher areas into the depressions. Once the depressions are filled with sediment, the ice beneath them melts more slowly because of increased insulation, and the ice melts more rapidly where its insulating cover has slid off. A new generation of depressions forms, and the former depressions become high areas relative to the new depressions. Mud flows into the new depressions, and the process continues until all the ice has melted.

As a result of this melting process, small inhomogeneities of sediment distribution are magnified many times, and a glacier which originally advanced over a relatively flat landscape may leave behind a chaotic, hummocky landscape when it melts. Glaciers also may melt from the bottom upward, but much more slowly because the supply of heat from the ground is much less. Till that melts out from the bottom of a glacier is redistributed in a different way than till that melts out from within and on top of the ice. Consequently, a glacier resting on a flat surface and melting primarily from the bottom might result in a flat, rather than a hummocky landscape.

The pre-existing topography was not flat in many areas. In some parts of Ramsey County hummocky deposits of the last glacial advance are draped like a rumpled bedspread over pre-existing hills and valleys. The various types of hummocky glacial topography are distinguished from one another by the average elevation difference between the hummocks and the adjacent hollows. Areas of low-relief hummocky glacial topography (Qccl) generally have less than 10 feet of relief. Areas of medium-relief hummocky glacial topography (Qccu) have between 10 and 20 feet of relief, and high-relief hummocky glacial topography (Qcch) commonly has more than 20 feet but less than 40 feet of relief in Ramsey County. The contacts separating the various "degrees" of hummocky glacial topography are inexact. This is due partly to the difficulty in separating out other factors, such as subglacial topography and eskers, and because the units are transitional to one another.

Having examined the reasons hummocky glacial topography forms, the question of why the glacial Lake Cando plain is not hummocky has still not been answered. The processes of supraglacial deposition are reasonably well understood, but depositional processes operating under water in glacial lakes have not been studied much, probably because of the difficulty of studying modern glaciolacustrine processes at work. The tendency has been to automatically consider a flat, till-floored lake plain to be a "wave-washed surface." It may be, however, that the hummocks simply never formed on the glacial Lake Cando plain.

Glacial Lake Cando, in addition to being ice-walled, was probably also partially ice-floored, at least in its early stages. As the glacier melted down, it reached an elevation below which the meltwater could not drain away fast enough, and water was ponded on the ice. Some of the water may have drained away through tunnels in and under the ice. The lake was apparently fed by a large drainage system from the north, through Towner County (Bluemle, 1984). Once water was ponded on the surface of the ice, depressions may not have formed as readily under the more uniform water environment. They may also have filled more quickly because the till was highly saturated. In any case, the original differences in thickness were not magnified under water as they were under air, and hummocks did not develop.

The glacial Lake Cando plain is bordered by an irregular zone of low-relief glacial topography that merges into a zone of medium-relief glacial topography farther from the lake. The zone of low-relief topography may be a transition zone between subaqueous and subaerial glacial deposition, at least in part.

Clayton and Moran (1974) developed a glacial process-form model that deals with supraglacial morphology in more detail than presented here. They contend that the average thickness of supraglacial sediment is approximately equal to the average relative relief of the surface after the ice has melted. They were, however, referring to subaerial deposition rather than subaqueous deposition, and they did not take into account sediment deposited beneath the glacier.

Ice-Thrust Topography

Isolated hills or hilly areas found in parts of Ramsey County apparently formed as glacial shear blocks (Qct, Qcth). Hills of this kind were first noted in North Dakota by Bluemle (1970, 1971), who called them "anomalous hills" or "large glacial erratics." In some instances, a depression of about the same size and

Figure 8. Two views of Devils Lake Mountain in southeastern Ramsey County (secs3 and 4, T151N, R62W). The upper photo shows Devils Lake Mountain, an ice-thrust hill, on the right and a slough in a depression formed at the time the glacier thrust the hill into place. Total relief from the floor of the slough to the adjacent hill top to the south is about 125 feet. The lower photo is of rugged ice-thrust topography on Devils Lake Mountain.

shape as the hill occurs immediately upglacier from the ice-thrust hill. A good example is Devils Lake Mountain in extreme southern Ramsey County (fig. 8). A slough is located immediately to the northwest of Devils Lake Mountain, in the direction from which the last ice sheet advanced. Another example of a large ice-thrust hill is Sullys Hill. The depression that now contains Devils Lake is located to the north of Sullys Hill.

Many of the glacial shear blocks are composed largely of shale that is veneered by till. Some of them may be composed of till from earlier glacial advances. A cut in the NE¼SE¼sec 34, T152N, R62W on the north side of Devils Lake Mountain exposes contorted, apparently shoved beds of lake silt. None of the visible ice-thrust hills in Ramsey County were penetrated during drilling, but some test holes in Ramsey County have penetrated shear blocks that are not apparent on the surface because of more recent erosion and deposition. In test-hole 9040, a block of shale occurs within the upper member of the Churchs Ferry Formation, and in test-hole N-1228, a block of till of the Gardar Formation is present within till of the Dahlen Formation. In places on Sullys Hill, the "till" was seen to be composed almost entirely of shale. The deposit shown on figure 9, although it is similar to some of these shale breccia deposits, is composed of chunks of shale that were moved by running water and should thus be considered to be fluvial rather than glacial in origin. The deposit was, however, probably emplaced during the thrusting episode that formed Sullys Hill.

It is not possible to state precisely why shear blocks occur where they do, but some generalizations about their origin may be made. They tend to form near ice margins, because the ice is moving up as well as forward near the glacier margin, and perhaps also because glaciers tend to be frozen to their beds near the margins, making it easier to lift the blocks. Bluemle and Clayton (1984) pointed out that groundwater plays an important role in initiating ice thrusting; the very rapid decline in groundwater head at the edge of a glacier may help to provide the motive force. Bluemle and Clayton also showed that the presence of an aquifer

Figure 9. Exposure of "shale breccia" on Sullys Hill. This is a fluvial deposit with many rounded pieces of shale that are now weathering and breaking up along old bedding planes. The deposit probably accumulated during the thrusting of Sullys Hill. Exposure is in the NW$\frac{1}{4}$ of sec13, T152N, R65W near the ski lift.

is important in determining whether thrusting will occur. The Devils Lake basin overlies an aquifer, the Spiritwood Aquifer System, and it is near the former ice margin (fig. 10). These circumstances help to account for the fact that such intense thrusting has occurred in the area. The North Viking end moraine (Carlson and Freers, 1975), south of Devils Lake, is composed largely of shear blocks which were apparently derived from the Devils Lake basin. In fact, the very presence of the large Devils Lake drainage basin is probably a result of the large-scale thrusting that has occurred in that area.

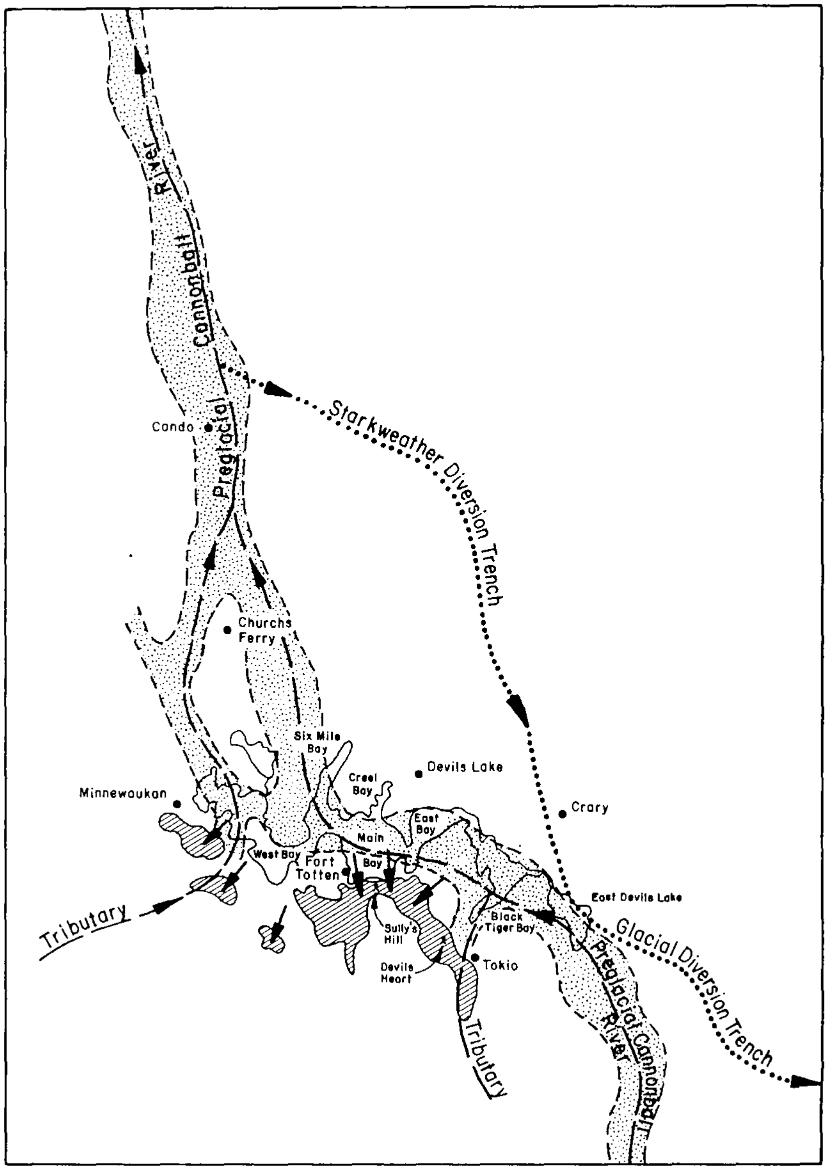

Figure 10. Generalized map of the Devils Lake area showing the main geologic relationships. The preglacial routes of the Cannonball River and some of its tributaries are shown along with the extent of the Spiritwood Aquifer in the area (stippled pattern) and the route of the Starkweather Diversion Trench. Areas of ice-thrust topography are shown (lined pattern), all immediately south of (downglacier from) the Spiritwood Aquifer.

Eskers

Streams flowing in tunnels in and under the ice deposit sand and gravel on their beds. These fluvial deposits remain as irregular ridges--eskers--after the ice has melted. Gravel does not generally occur at the surface of an esker because a mantle of till overlies the ridge. Generally, as much as 10 feet of till overlies the gravel in eskers in Ramsey County.

Eskers were recognized on airphotos and topographic maps as irregular, discontinuous and slightly sinuous ridges, 5 to 25 feet higher than the surrounding topography (Qcre). The ridges are discontinuous, partly because of irregular deposition, and partly because of masking by the hummocky supraglacial till that overlies them. Some eskers lead to a small valley which marks the continuation of its course, indicating a change from subglacial deposition to subglacial erosion or subaerial erosion. A good example is found in the Doyon Quadrangle (1:24,000), where a north-south trending esker in sections 25 and 36, T153N, R62W changes to a shallow channel in section 36 and continues into sections 2, 11, and 10, T152N, R62W. The change from deposition to erosion corresponds to the beginning of a slope to the south. The esker, but not the continuing channel, is mapped on plate 1.

Gravel in eskers is generally rather poorly sorted and bedded because it accumulated rapidly. The sediment was not reworked by water as much as beach sediment, for example. The coarser portion contains considerable amounts of shale, which renders it unsuitable for high-quality uses, such as concrete aggregate, but adequate for road surfacing.

Some of the larger eskers in Ramsey County are associated with ice-thrust hills (fig. 11). Apparently, large amounts of groundwater flowed to the surface at the point where the thrusting occurred, carrying gravel and sand upward and out from beneath the glacial ice.

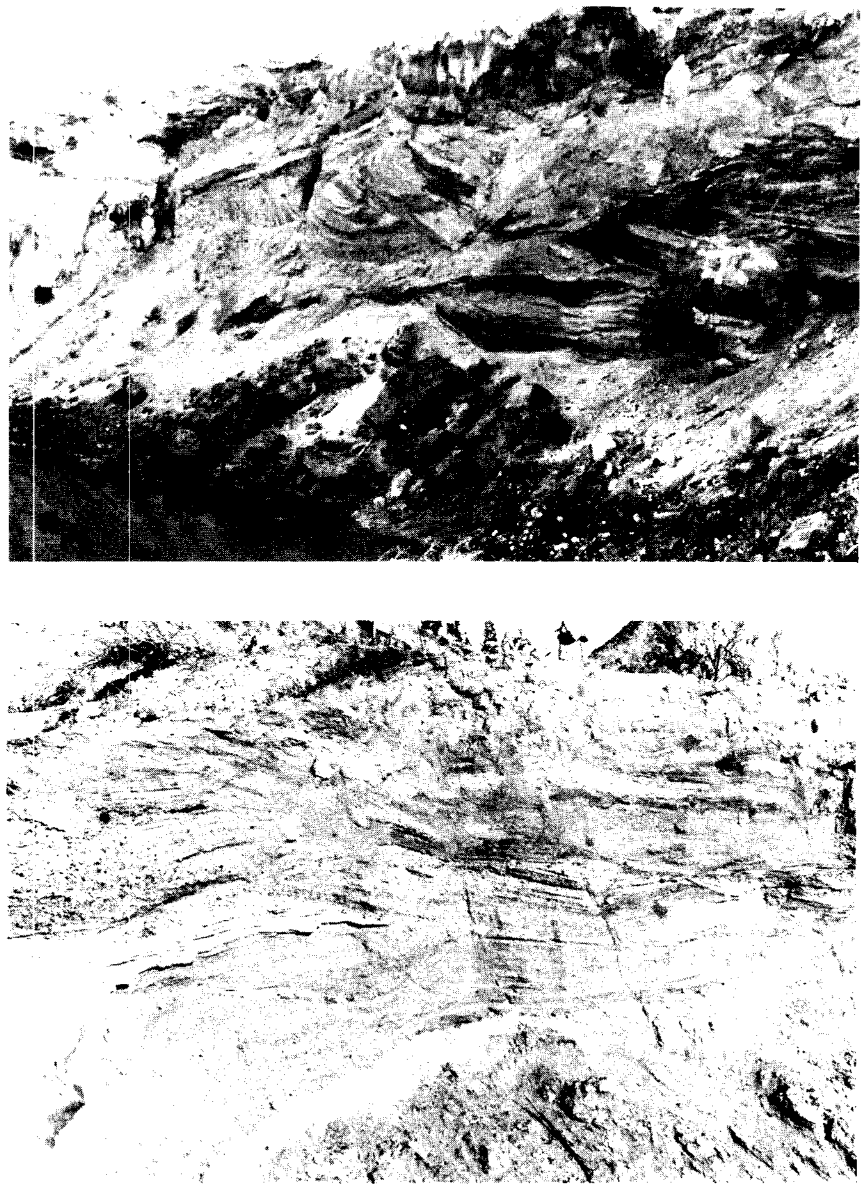

Figure 11. Two views of crossbedded gravel and sand in an esker leading away from a large ice-thrust hill south of Dry Lake. This exposure is in the NE¼NE¼sec2, T154N, R65W.

Glacial Outwash Plains

Sand and gravel underlie the glacial outwash plains in southern Ramsey County (Qcr). The material is moderately well bedded and sorted. Beds differ from one another both in the size of the particles they contain, and the proportion of shale to non-shale particles. Most of the glacial outwash contains too much shale for commercial purposes.

A major outwash plain that lies largely south of Ramsey County in Benson and Eddy Counties contains the Warwick Aquifer, an unconfined (surface) aquifer from which the city of Devils Lake gets its water. The aquifer is used also for irrigation, an ideal situation, because any excess water quickly percolates down to the water table, preventing salt buildup in the soil.

Washboard Moraines

Washboard moraines are shown on the geologic map (pl. 1) as slightly arcuate lines, although the representation on the map is schematic, that is, each line on the map represents many ridges on the ground. Washboard moraines occur in association with relatively low-relief collapsed glacial topography as low, hummocky ridges, generally 5 feet high or less, composed of till. They are slightly arcuate with a typical radius of curvature in Ramsey County of about 10 miles, concave upglacier. The washboard moraines are believed to represent concentrations of glacial sediment along glacial shear planes near the margin of the ice sheet (Clayton and Moran, 1974). The curvature of the washboards is more or less parallel to the lobate ice margin. Where they are well-developed, as in some southern parts of the county, as many as 10 or more washboards may occur in a mile.

Partly Buried Valleys

Partly buried valleys can be recognized on maps and airphotos by linear or chain-like lakes, sloughs, and depressions, or by bands of topography that differ in some respect from the nearby topography. Most parts of the buried valleys have been totally obliterated by younger glacial erosion and deposition. Although they are potential sites for aquifers, only a few test holes have been drilled into the known buried valleys in Ramsey County. Test-hole 8851 penetrated a valley which trends north-south to the northwest of Devils Lake, and test-holes 8854 and 8855 penetrated a valley that trends due east from East Devils Lake.

In northeastern Ramsey County, extending southward from approximately sections 2 and 3, T158N, R61W, through Tps155-158N, to sections 33, 34, and 36, T155N, R60W, is a poorly defined, one-mile-wide band of slightly lower and smoother topography that serves in part as the route of Edmore Coulee. During the summer of 1985, it was noted that numerous springs are located throughout the area and water was coming to the surface in many places. The feature appears to consist of pre-last glacial outwash deposits veneered by till. It may be a pre-Dahlen fluvial deposit that was covered by till during the advance of the Dahlen ice.

SYNOPSIS OF QUATERNARY HISTORY

General Discussion

The Precambrian, Paleozoic, and Mesozoic history of Ramsey County is summarized earlier in this report, in the section dealing with stratigraphy. No Tertiary rocks are known to occur in Ramsey County. The Tertiary was a time of uplift and erosion in eastern North Dakota, though early Tertiary sediment is thick and widespread in the western part of the state. It is probable that some marine sediments were deposited in Ramsey County in the Cannonball sea--Cannonball sediments are present on the Turtle Mountains--but it seems likely that, during most of Tertiary time, the area was emergent and subject to erosion. This erosion removed large amounts of late Cretaceous (and possibly early Tertiary) sediment, presumably transporting it to Hudson Bay. It should be noted that, since the shale of the Pierre Formation is so well consolidated, it may be that it was once covered by several hundred feet of younger sediment that was later removed by erosion.

The late Tertiary landscape in Ramsey County was carved largely from Pierre Formation shale with scattered patches of Cretaceous Fox Hills Formation sand in the west. The area drained northward via the ancestral Cannonball River and its local tributaries. The Cannonball River system apparently drained most of western and central North Dakota prior to the earliest glacial events. Its tributaries included the preglacial Knife and Heart Rivers as well as now buried tributaries that flowed to it from the east and southeast. The preglacial Cannonball River apparently flowed northward (actually northwestward in the Devils Lake area) through the area now flooded by the several lakes that comprise the Devils Lake system (fig. 12).

During Quaternary time, numerous cold-climate events that culminated in glaciation alternated with periods of warm climate. The climatic cycles were extremely complex, but they have been generally divided into glacial and interglacial periods or stages. These glacial stages have been further subdivided into stades (periods of ice advance) and interstades (periods of time when the area was free of ice). For example, the Wisconsinan glacial period, the most recent one, has been divided into an Early Wisconsinan stade and a Late Wisconsinan stade, separated by a period during which the glaciers melted back and the climate warmed to something resembling our modern climate. This same pattern seems to apply to the earlier glacial stages, though information about the earliest stages is much less complete than it is for the more recent ones. It is not known how many major glacial stages affected North Dakota. In areas to the south of North Dakota, four glacial stages (the Nebraskan, Kansan, Illinoian, and Wisconsinan) have traditionally been identified, but it is likely that, in North Dakota at least, more than four major glacial events occurred. In Iowa, geologists have developed a relatively complex pre-Illinoian glacial stratigraphy and have abandoned the terms "Nebraskan" and "Kansan" as being overly simplistic and not well

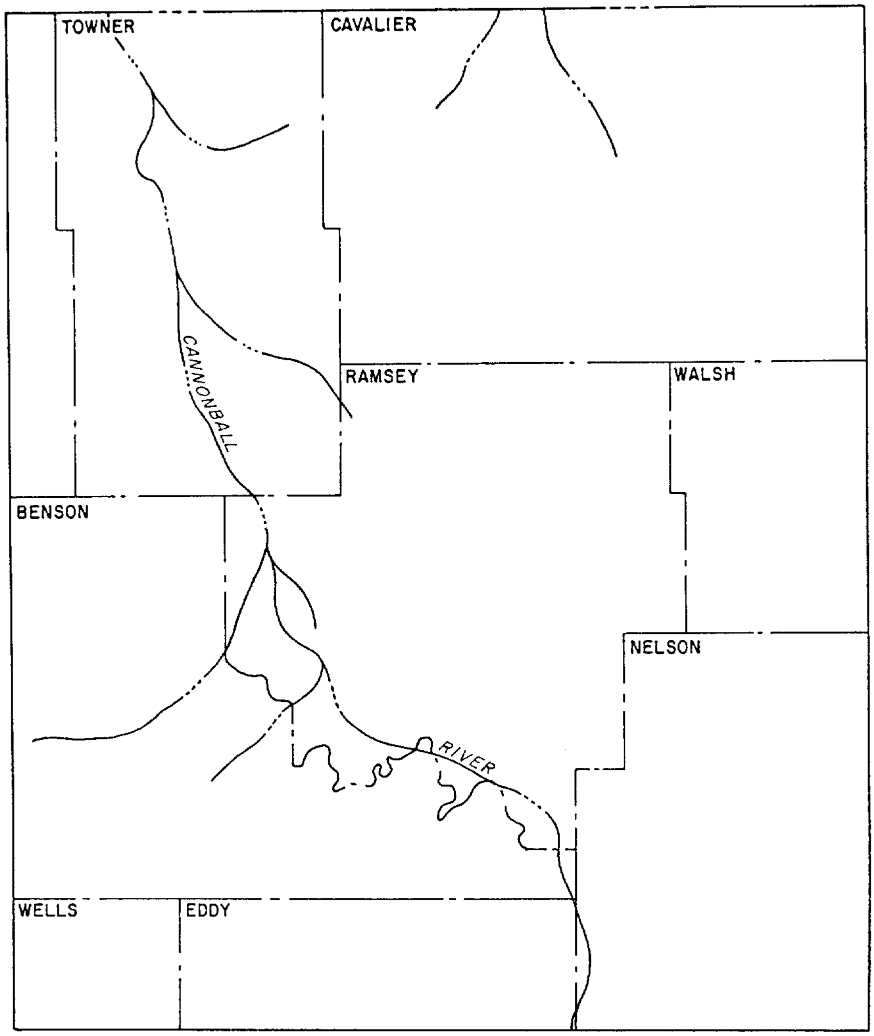

Figure 12. Preglacial drainage pattern in the Ramsey County area. The north-flowing Cannonball River drained the area. The buried Spiritwood Aquifer follows the route of the ancestral Cannonball River in this area (see fig. 10).

defined. However, no new time-stratigraphic system has been developed to replace the old one, probably because dating the older glacial deposits is a problem. It is not yet possible to decide whether each separate glacial deposit represents a discrete glaciation or merely a stade.

It seems, then, that glacial advances came in "spurts" or "bundles"; glacial advances within a bundle are separated by short periods of non-glacial climate (like our modern post-Late Wisconsinan climate) and the bundles are separated by longer periods of non-glacial climate. As a consequence of this "bundle pattern" of glaciation, several groups or bundles of glacial deposits can be recognized in Ramsey County. These are grouped into formations based on stratigraphic criteria (see the discussion of glacial formations). Within each formation, the till members show a consistent pattern of decreasing shale from the lowest to the uppermost member.

The pattern of shale abundance is probably related to the pattern of glaciation. When a glacier first advanced into the Ramsey County area after a long interglacial period, it encountered a terrane covered primarily by weathered shale. The early Quaternary surface over which the first glaciers advanced must have been especially deeply weathered and the Pierre and Fox Hills shale and sandstone were probably subjected to considerable erosion by the early glaciers. Later, throughout the Pleistocene, the deposits of previous glaciations had been mostly eroded away (except where they filled buried valleys and lowlands or were otherwise somehow protected) and the underlying shale was weathered and exposed when successive glaciers advanced. The fragments of crystalline (igneous and metamorphic) and carbonate rocks that the glacier carried from farther north were diluted by the large amounts of locally-eroded shale that it picked up. By the time such a glacier reached Ramsey County, from whatever direction, its sediment was rich in shale.

If another glacial advance occurred after only a short interglacial period (a few tens of thousands of years), it encountered terrane still blanketed by shale-rich till. Erosion of this surface also provided shale to the second glacier, but not so much as was available to the immediately preceding glacier because the shale bedrock was exposed in a smaller proportion of the area, wherever the blanket of shale-rich till was absent. As a result, when the second glacier melted, it could be expected to deposit a layer of till that was only moderately rich in shale. If a third glaciation occurred after a similarly short interstadial period, it would leave a layer of shale-poor sediment behind. Only after a prolonged period of weathering and erosion during which most of the glacial sediment was removed would the cycle begin again with a terrane composed predominantly of shale.

This pattern of shale abundance was first noticed in Ramsey County and it may not apply to other areas, even to nearby counties. Near the edge of the shale terrane, shale abundance (and the relative abundances of the other constituents in the till) was certainly greatly affected by the direction of each ice advance, whether it traversed shale for a long distance or a short one. Also, the pattern would require that the till deposits from each glacier be thin enough so they could be eroded away during a glacial interstade. Using the hypothesis just described (the "bundle theory"), it was possible to work out a Quaternary history of Ramsey County. Of course, it is possible that gaps may exist in the stratigraphic record. Whole glacial periods may not be recorded if erosion was so extensive during an interglacial period that all the previous till deposits were removed (at least in the areas from which test-hole data are available). Even so, the events can at least be placed in a relative time sequence.

Earliest Glaciations

When the earliest glaciers advanced across southern Manitoba and eastern North Dakota, all of the north-flowing rivers and streams were dammed and lakes formed in their valleys, ahead of the advancing glaciers. Similarly, when the glaciers receded, lakes developed to the south of the ice. To the east, for example, in the Red River Valley, glacial Lake Agassiz formed south of the glacier during its retreat at the end of Late Wisconsinan time. It seems logical, then, that the earliest materials related to the advent of glaciation in Ramsey County should be lake sediments that would have accumulated in the north-trending valleys. However, the oldest deposits known to be related to glaciation are the till layers of the Cando Formation.

The lowermost, and oldest, glacial material (unit E of the Cando Formation) is considered to represent the first glacial advance because it is so shaly, and it is positioned at the base of the Quaternary section, at the bottom of the preglacial valleys, especially the Starkweather Valley. The Starkweather Valley is almost certainly a diversion trench, a fact that may explain the lack of proglacial lake sediments; since it was carved by overflow from a proglacial lake (the lake that flooded the Cannonball River Valley in Towner and, perhaps, in southern Ramsey County), it did not itself contain a lake (fig. 13). After the Starkweather Diversion Trench was formed, the glacier advanced over it, depositing the shaly till of unit E of the Cando Formation. The composition of unit E--much shale, little carbonate relative to crystalline (igneous and metamorphic) grains--may imply that the earliest glacier advanced from the northeast, bypassing the carbonate terranes to the north-northeast. Another explanation for the lower abundance of carbonate in the till of Cando unit E may be related to the fact that quartz grains should have accumulated over the Canadian Shield during preglacial weathering, whereas carbonate weathers by dissolution. Thus, the first glaciation, almost regardless of flow path, should contain abundant crystalline grains relative to carbonate. In subsequent glaciations, a higher proportion of unweathered rock was scoured and the proportion of carbonate should increase, since it is softer and more easily eroded.

Following a relatively short ice-free interval of time, another glacier advanced into the area, depositing unit D of the Cando Formation. Unit D rests on till or

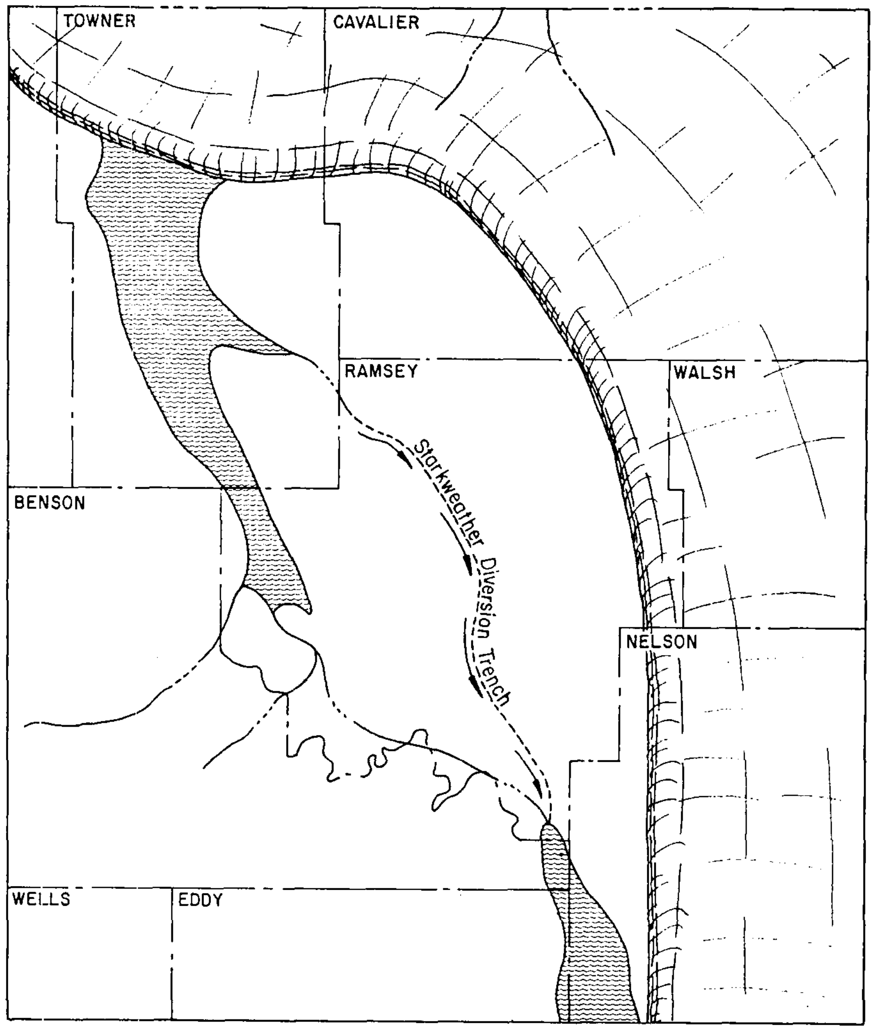

Figure 13. Early (pre-Wisconsinan) glacial advance. This highly hypothetical map is intended to show only that any early glacial advance must have resulted in the formation of a proglacial lake in the Cannonball River Valley ahead of the advancing ice. The Starkweather Diversion Trench must have formed during an early glacial advance.

gravel and sand of unit E in most places, but in at least one test hole, #8830, it rests on bedrock. This test hole is probably in a valley-side position, however, because the top of the bedrock is almost 200 feet higher than in nearby hole #8827. Test-hole #8830 is shown on plate 4; hole #8827 is not shown. In the latter hole, till of unit D overlies sand and gravel of unit D, which overlies bedrock, separated from the bedrock by 10 feet of boulders. These boulders probably are a lag resulting from stream erosion of unit E. This indicates that active stream erosion occurred during the interval of time between the two glaciations. The streams probably returned to a northerly flow direction as no south-flowing valley that deep has been found (about 950 feet elevation). Till of unit D is considerably less shaly than that of unit E, implying that the landscape was still mantled by a layer of till at the time the glacier that deposited unit D advanced.

After another relatively short, warm interval, another glacial advance deposited unit C, a till that is considerably less shaly than unit D. Unit C has been identified in only a few places in the county (unit C is not represented on any of the cross sections). The period of erosion that occurred between the deposition of units D and C may not have been so intense as that between units E and D because unit C is not observed to directly overlie bedrock.

Following another erosional event after unit C was deposited, the Cannonball and Starkweather Valleys were flooded by a proglacial lake in which the silt and clay of unit B of the Cando Formation were deposited. This glacial lake sediment was deposited when a glacier blocked the north-flowing drainage, although the glacier did not necessarily advance into Ramsey County as no till has been found associated with unit B. The valleys were filled with lake sediment to an elevation of about 1,350 feet, the elevation of the top of unit B in test-hole #8832. Even though the Cannonball River Valley was blocked by ice and partly filled by glacial sediment several times before, this episode was the first one in which the north-flowing drainage was not subsequently re-established.

Unit A of the Cando Formation overlies unit B and consists of fluvial gravel and sand, predominantly shale particles. It is not possible to be certain that it is actually related to the Cando glaciations--it may represent an initial event of a later glaciation, for example--but since no direct evidence of prolonged erosion on top of the units it overlies has been found, it is here considered to be associated with the Cando. Unit A forms the Starkweather Aquifer in the Starkweather Valley.

The Camp Grafton Formation overlies the Cando Formation and is also restricted mainly to buried valleys. The lower part of the Camp Grafton Formation consists mainly of fluvial deposits, which constitute the Spiritwood Aquifer in this area, and the upper part is mainly sand and silt. The Camp Grafton Formation was probably deposited by meltwater from a pre-Wisconsinan (but post-Cando) glaciation, possibly one of the Churchs Ferry glacial advances. The initial fluvial event resulted in the deposition of thick layers of gravel and sand. It can't be shown which direction the water that deposited the gravel was flowing, but it seems logical that it must have been ultimately southward because the drainage to the north must have been blocked by glacial ice. The upper member of the Camp Grafton Formation was probably deposited during the same glaciation as the lower member, because the two are not separated by a till. It seems likely that the meltwater channel was blocked by a minor readvance downstream; the fluvial deposition prior to and following that blockage then represent the lower and upper members of the Camp Grafton Formation.

The Churchs Ferry Formation, like the Cando Formation, consists of a "bundle" of till units which are successively less shaly upward. The shaliness of the lowermost member suggests that it was deposited following a prolonged period of erosion, probably an interglacial stage. Its three members probably represent successive glacial pulses within the glacial stage. It is possible, too, that the sandy upper member of the Churchs Ferry was deposited by ice that advanced from the west, over the sandy Tertiary formations.

Wisconsinan Glaciations

The Gardar Formation is probably early Wisconsinan in age. Like the lower members of the Cando and Churchs Ferry Formations, it too is a "high-shale" unit, indicating that it was deposited following a long period of weathering and erosion. Since the Gardar is almost surely early Wisconsinan in age, the weathering interval that preceded the Gardar glaciation probably coincides with the Sangamon interglacial period, which immediately preceded Wisconsinan time.

The Late Wisconsinan Dahlen Formation, which overlies the Gardar, is considerably less shaly than the Gardar. Presumably, the mid-Wisconsinan intraglacial epoch was insufficiently long to remove enough of the Gardar deposits to allow the Dahlen glacier to pick up large amounts of shale.

Most of the Ramsey County area does not have complex landforms, but many, or all of the larger, notable features that can be seen today were emplaced by the Wisconsinan glaciers. Perhaps the most outstanding glacial feature in the area is the ice-thrust complex along the Ramsey-Benson county line south of Devils Lake and the nearby Devils Lake basin, immediately to the north. Both glacial deposits and Cretaceous Pierre Formation shale were involved in the extensive excavation by the glacier of the Devils Lake basin. The excavated area, which constitutes the Devils Lake basin, encompasses approximately 500 square miles where the marine Cretaceous shale has been quarried at least 500 feet deep in places. The ice-thrust topography south of the basin covers another 300 square miles. Total relief between the bottom of the Devils Lake basin and some of the adjacent, ice-thrust Cretaceous shale blocks, such as Sullys Hill, exceeds 650 feet.

Ice-thrusting was initiated in the Devils Lake area when the south-flowing glacier reached the area of the buried Spiritwood Aquifer. High pore-water pressures built up in the aquifer, which was probably overlain by a zone of permanently frozen ground. The ice-thrusting process is described in more detail by Bluemle and Clayton (1984).

Following the main ice-thrusting event, the Late Wisconsinan glacier continued to recede through the Ramsey County area. The presence of abundant washboard ridges in places approximates the position of the ice margin at certain times. When the edge of the active glacier extended from west-northwest to east-southeast across the county (fig. 14), glacial Lake Minnewaukan formed along the margin of the ice. Lake deposits of silt, clay, and fine-grained sand, often containing a few small pebbles, can be found at elevations as high as about 1,450 to 1,455 feet. A strandline, consisting in places of a well-developed scarp, vague beach ridges in other places, can be recognized at an elevation of 1,453 feet in several places around the former shoreline of Lake Minnewaukan; this was probably the highest level that the lake stood at for a prolonged period. At this level, or higher, the lake would have overflowed southward through the Stony Lake-Long Lake channel or the Twin Lake channel in southern Benson County (Carlson and Freers, 1975). However, another well-developed meltwater trench, Big Coulee (known also as Seven Mile Coulee) southeast of Fort Totten apparently carried water southward from the Fort Totten area. Since the elevations on the floor of this valley are about 1,550 feet, it may be that, during the early stages of glacial Lake Minnewaukan, when the lake was still only a narrow pool dammed between the edge of the glacier on the north and the high, ice-thrust and ice-marginal topography immediately to the south, the water level stood at a level at least that high. Glacial Lake Minnewaukan also overflowed into Stump Lake in Nelson County through a spillway at a level of about 1,447 feet.

As the glacier continued to shrink in Late Wisconsinan time, glacial Lake Minnewaukan expanded its area northward (fig. 15) and stabilized at a maximum level of about 1,453 feet. Glacial Lake Cando formed ahead of the glacier in northwestern Ramsey and southern Towner County at elevations as high as 1,490 feet; for reasons discussed earlier, it seems likely that Lake Cando existed in contact with glacial ice during much of the time it existed at its higher levels. As the ice

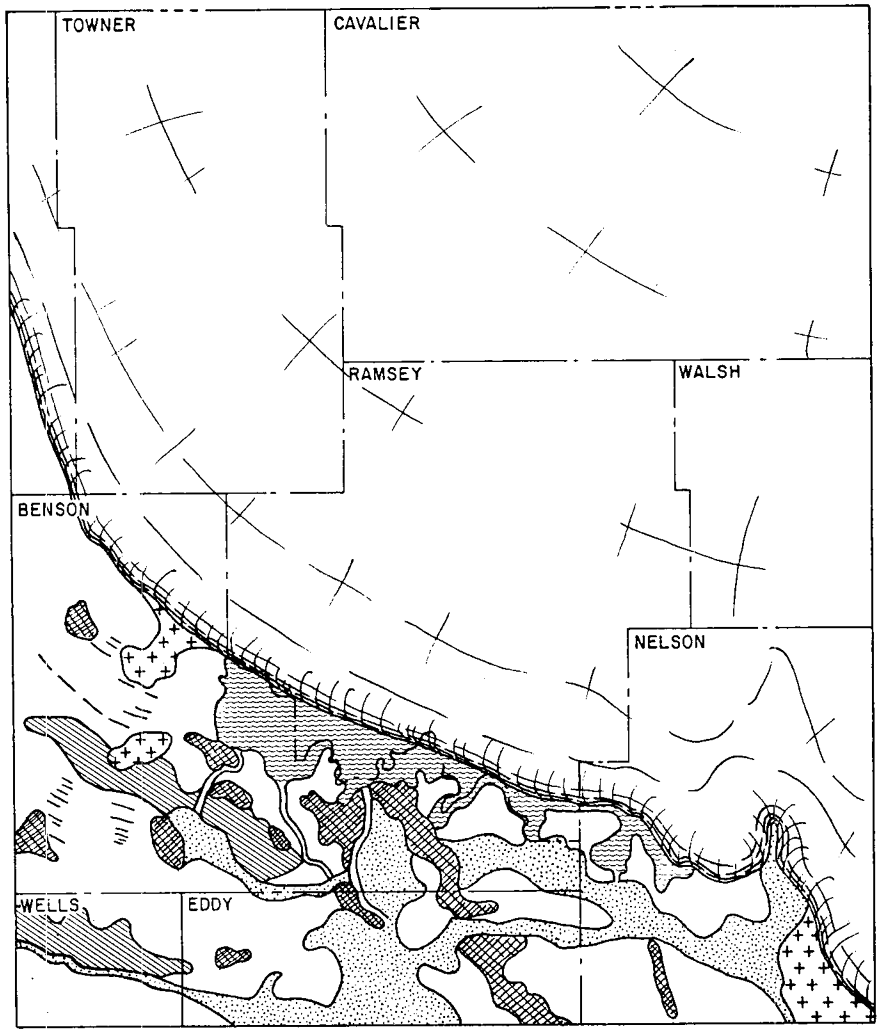

Figure 14. Formation of glacial Lake Minnewaukan in Late Wisconsinan time. As the edge of the Late Wisconsinan glacier receded through the area, water was dammed along the ice margin. Shortly prior to the formation of the lake (wave pattern), extensive ice thrusting had occurred (areas of ice-thrust topography shown by cross-hatched pattern), resulting in the depression in which the lake formed. Areas covered by fluvial deposits, mainly gravel and sand, are shown by the stippled pattern. Areas of stagnant glacial ice are shown by the cross pattern, and the till plains (hummocky topography) are white, unmarked areas.

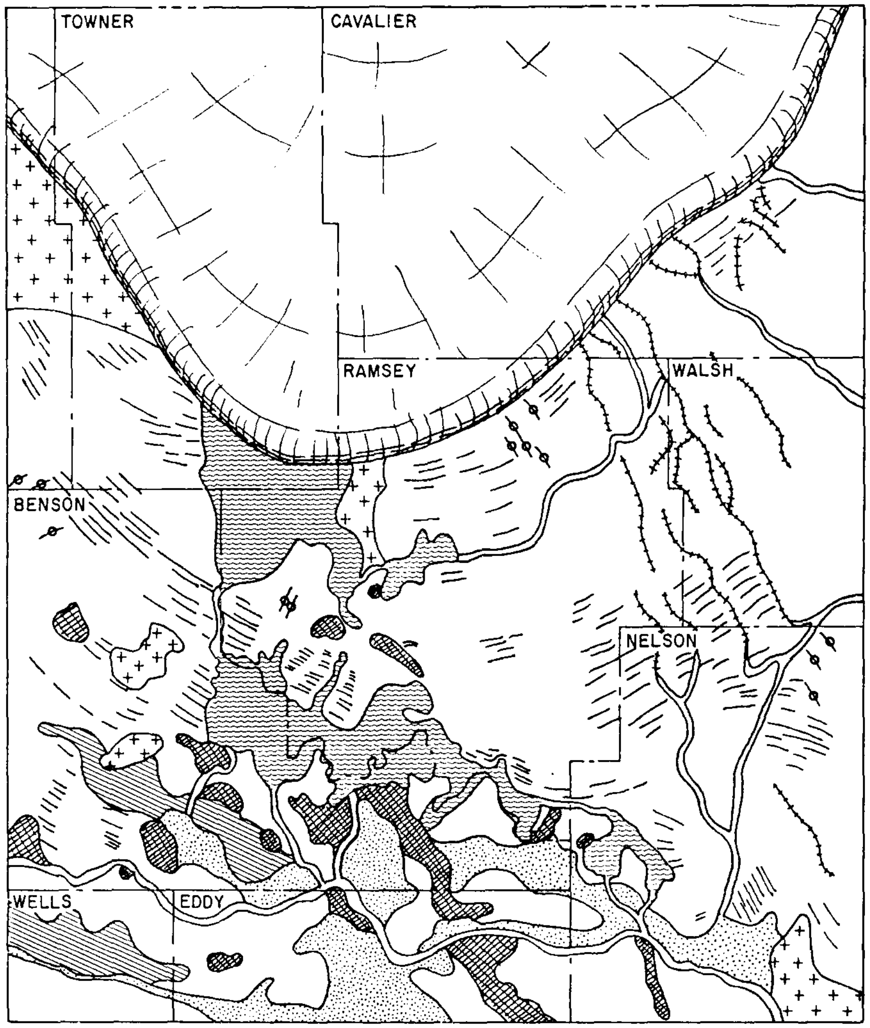

Figure 15. Formation of glacial Lake Cando in Late Wisconsinan time. As the Late Wisconsinan glacier continued to recede from the area, glacial Lake Minnewaukan expanded northward and glacial Lake Cando formed in northwestern Ramsey County and southern Towner County. Symbols on this diagram are the same as those used on figure 14. Tic marked lines represent eskers and the small lines with circles represent drumlins or other streamlined features.

receded, the lake stabilized at elevations below 1,460 feet (Bluemle, 1984), although in T156N, R65W, in the area north and west of Dry Lake, several quite well-developed beach ridges at elevations as high as 1,460 were seen. Glacial Lake Cando overflowed southward, into Lake Minnewaukan.

Postglacial History

The glacial deposits have been slightly modified in some areas by wind and water erosion. Wind erosion has removed some fine-grained silt from the floor of glacial Lake Cando and redeposited it nearby. Slopewash from topographically higher areas has washed sediment into low slough areas. Some thin silt and clay deposits are probably present in all of the undrained depressions.

The most notable postglacial process for which we have a record is the fluctuating level of Devils Lake, the largest existing remnant of glacial Lake Minnewaukan. As we mentioned earlier, the lake overflows into Stump Lake and to the Sheyenne River in Nelson County if the water level is above about 1,447 feet. Devils Lake has not been at its threshold since Late Wisconsinan time. When it dropped below the threshold elevation, it no longer drained out of the area and the modern closed-surface-drainage basin came into existence. The salts brought into the lake since that time, by runoff and groundwater seepage, have been concentrated by evaporation and the lake has become saline. In general, the lower the level of the lake, the more saline the water. The lake level has fluctuated considerably during historic time and before then (fig. 16), due to fluctuations in runoff and evaporation. When the area was first settled in the nineteenth century, the lake level stood at about 1,441 feet (in 1830) and the water was relatively fresh. It declined to less than 1,401 feet in 1940 and has since erratically risen to about 1,428 feet. Table 1 lists the area, in acres, that will be covered by Devils Lake at water level elevations ranging from 1,400 feet to 1,446 feet. The amount of water, in acre-feet, stored in the lake at each level is also listed in table 1.

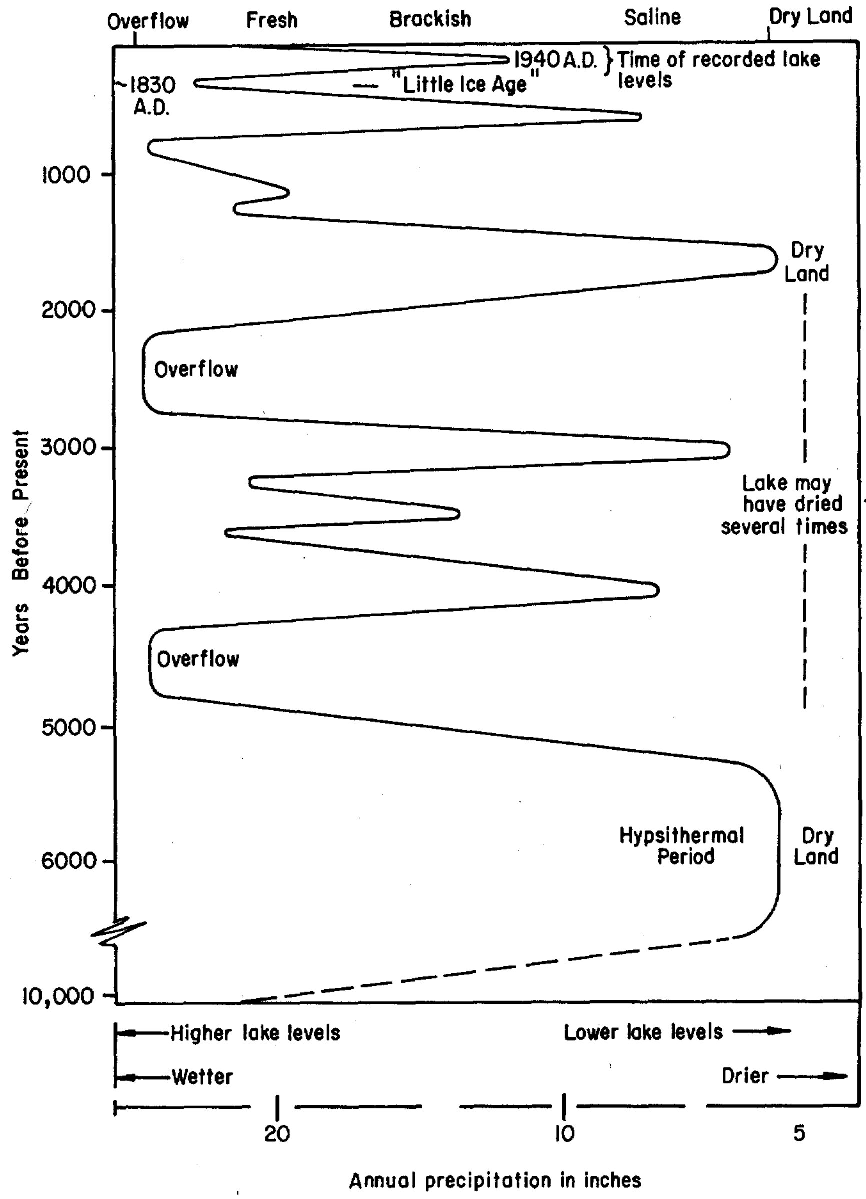

Figure 16. Chronology of fluctuating lake levels of Devils Lake. Adapted from Callender, 1968.

TABLE 1.--Area-Capacity Data for Devils Lake, North Dakota

ELEVATION (ft)	AREA (acres)	STORAGE (acre-ft)
1400		10,000
	10,000	
1401		20,000
	10,000	
1402		30,000
	10,000	
1403		40,000
	10,000	
1404		50,000
	10,000	
1405		60,000
	10,000	
1406		70,000
	10,000	
1407		80,000
	10,000	
1408		90,000
	12,000	
1409		102,000
	23,000	
1410		125,000
	25,000	
1411		150,000
	25,000	
1412		175,000
	25,000	
1413		200,000
	30,000	
1414		230,000
	30,000	
1415		260,000
	30,000	
1416		290,000
	35,000	

TABLE 1.--Area-Capacity Data for Devils Lake, North Dakota (Continued)

ELEVATION (ft)	AREA (acres)	STORAGE (acre-ft)
1417		325,000
	35,000	
1418		360,000
	35,000	
1419		395,000
	40,000	
1420		435,000
	40,000	
1421		475,000
	45,000	
1422		520,000
	45,000	
1423		565,000
	50,000	
1424		615,000
	50,000	
1425		665,000
	50,000	
1426		715,000
	50,000	
1427		765,000
	55,000	
1428		820,000
	55,000	
1429		875,000
	60,000	
1430		935,000
	60,000	
1431		995,000
	60,000	
1432		1,055,000
	65,000	
1433		1,120,000
	65,000	

TABLE 1.--Area-Capacity Data for Devils Lake, North Dakota (Continued)

ELEVATION (ft)	AREA (acres)	STORAGE (acre-ft)
1434		1,185,000
	65,000	
1435		1,250,000
	70,000	
1436		1,320,000
	70,000	
1437		1,390,000
	70,000	
1438		1,460,000
	70,000	
1439		1,530,000
	70,000	
1440		1,600,000
	70,000	
1441		1,670,000
	70,000	
1442		1,740,000
	70,000	
1443		1,810,000
	70,000	
1444		1,880,000
	70,000	
1445		1,950,000
	70,000	
1446		2,020,000

ECONOMIC GEOLOGY

Hydrocarbons

A total of 25 holes have been drilled in Ramsey County in search of oil and gas. Of these 25 test holes, 10 were drilled through the entire stratigraphic section into Precambrian rocks, and 19 were drilled to the Devonian or deeper. None of the wildcat wells was successful; no oil shows were reported from any of the wells.

Sand and Gravel

Reported sand and gravel production in Ramsey County for the past eight years (1977 to 1984) has averaged 180,000 cubic yards annually. In 1981, a total of 736,000 cubic yards were produced; production was insignificant in 1984.

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