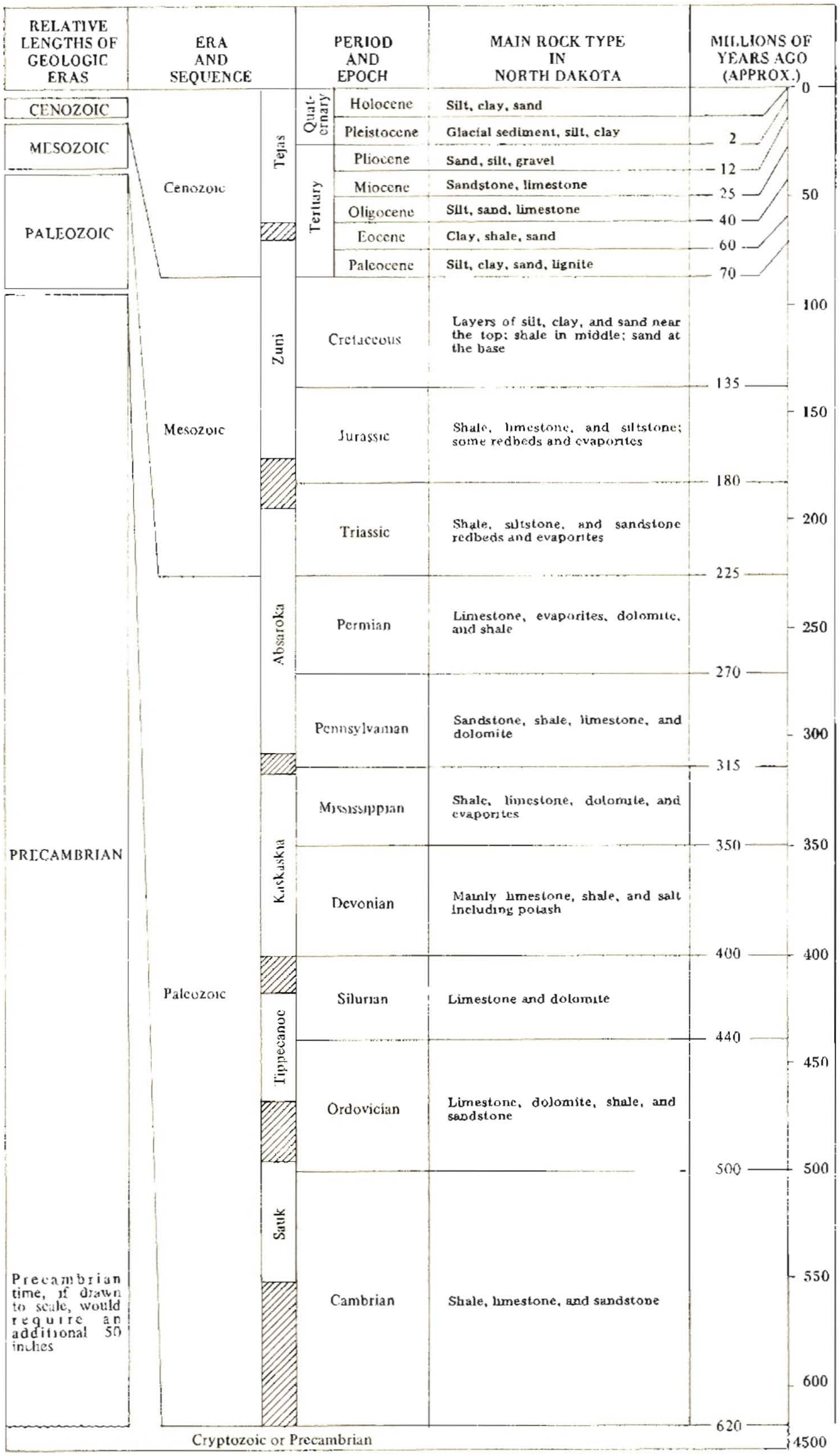
THE FACE OF NORTH DAKOTA

THE GEOLOGIC STORY

by John P. Bluemle

Educational Series 11
North Dakota Geological Survey
E. A. Noble, State Geologist



Precambrian time, if drawn to scale, would require an additional 50 inches

ERA AND SEQUENCE		PERIOD AND EPOCH		MAIN ROCK TYPE IN NORTH DAKOTA	MILLIONS OF YEARS AGO (APPROX.)
Cenozoic	Tejas	Quaternary	Holocene	Silt, clay, sand	0
			Pleistocene	Glacial sediment, silt, clay	2
		Tertiary	Pliocene	Sand, silt, gravel	12
			Miocene	Sandstone, limestone	25
			Oligocene	Silt, sand, limestone	40
			Eocene	Clay, shale, sand	60
			Paleocene	Silt, clay, sand, lignite	70
Mesozoic	Zuni	Cretaceous		Layers of silt, clay, and sand near the top; shale in middle; sand at the base	135
		Jurassic		Shale, limestone, and siltstone; some redbeds and evaporites	180
	Absaroka	Triassic		Shale, siltstone, and sandstone redbeds and evaporites	225
Paleozoic		Permian		Limestone, evaporites, dolomite, and shale	270
		Pennsylvanian		Sandstone, shale, limestone, and dolomite	315
	Kaskaskia	Mississippian		Shale, limestone, dolomite, and evaporites	350
		Devonian		Mainly limestone, shale, and salt including potash	400
	Tippecanoe	Silurian		Limestone and dolomite	440
		Ordovician		Limestone, dolomite, shale, and sandstone	500
	Sauk	Cambrian		Shale, limestone, and sandstone	620
Cryptozoic or Precambrian					4500

The Cover

The cover illustrations, drawn by Karol-lyn Knudson of the North Dakota Geological Survey, depicts a badlands landscape carved from Bullion Creek Formation sediment along the Little Missouri River in Billings County, North Dakota.

	Millions of Years Ago	Changes in Geology and Living Things	Era		System
Rock and sediment present at the surface in North Dakota	0.01	The glaciers melted as climates moderated. Grass became the dominant vegetation of the Great Plains. Many large land mammals became extinct; human cultures continued to develop.	Cenozoic ("recent life")	Quaternary	Holocene
	2	Glaciers repeatedly spread over North America; climates were cold when the glaciers spread, but warm during interglacial times. Herbs and grass increased in importance as trees decreased. Mammals grew large and varied; early man evolved.			Pleistocene
	12	The Rocky Mountains formed in Paleocene time; seas were drained from the continents during most of Tertiary time; there was an overall tendency toward more continental climates (hot summers; cold winters). Land plants became more like modern plants; grasses developed in Miocene time; coal formed in North Dakota in Paleocene time. Mammals became common and varied on land; sharks and bony fish were plentiful. Modern types of corals, clams, and snails became dominant in the seas; ammonoids and belemnoids died out, but squids and octopi became common.		Tertiary	Pliocene
	25				Miocene
	40				Oligocene
	55				Eocene
	70				Paleocene
	135	The land was generally low; climates were mild. Flowering plants became important and conifers decreased. Marine reptiles and bird-hipped dinosaurs were varied and abundant, but reptiles were generally decreasing.	Mesozoic ("middle life")		Cretaceous
Rock and sediment known only from well and testhole data in North Dakota	180	The land was low with deserts, volcanoes, and swampy forests in western North America. The first known flowering plants appeared as conifers and cycads dominated the vegetation. Ammonoids, belemnoids, and marine reptiles were common; dinosaurs dominated; the first birds appeared.			Jurassic
	225	Shallow seas covered many areas. Conifers became important and the first cycads appeared. Ichthyosaurs and early plesiosaurs evolved as the reptiles became more important; the first primitive mammals may have appeared; lizard-hipped dinosaurs became common, but they were still small.			Triassic
	270	Mountains formed in eastern North America; glaciers spread in South Africa. Ancient plant types dwindled as large amphibians and reptiles lived in swampy lowlands and reptiles on land; shark-like fish and early ammonoids were common.	Paleozoic ("ancient life")		Permian
	310	Coal was deposited in tropical swamps over much of North America. Amphibians dominated on land and reptiles became good-sized and common; crinoids became less abundant.			Pennsylvanian
	350	Seas covered much of North America; mountain-building took place in the east. First known mosses, seed ferns, and conifers; early coal forests. Sea lilies and sea buds (crinoids and blastoids) were abundant, brachiopods and trilobites less common; insects became more important.			Mississippian
	400	Most of North America was flat and low, covered by shallow seas. The first forests developed on low deltas; the first known liverworts, ferns, and horsetails. There was wide radiation in the early fishes; first amphibians appeared.			Devonian
	440	Most of North America was flat and low, covered by shallow seas. The first known land plants, the club mosses, evolved. Marine life was abundant; jawless fish continued to evolve; invertebrates became more varied.			Silurian
	500	Seas covered most of North America, but mountains formed in the east. Marine algae were the dominant life form. Early fish developed and brachiopods and trilobites became abundant.			Ordovician
	620	Most of North America was low after mountain building in the Great Lakes region at the end of Precambrian time. Marine invertebrates such as brachiopods and trilobites became common as did algae, fungi, and bacteria.			Cambrian
	Probably more than 4,500 my	Many changes occurred in lands and seas; mountain building took place in various parts of the world and there were great volcanic eruptions; important ore deposits formed. Traces of bacteria, fungi, and algae and a few primitive invertebrates.	Precambrian or Cryptozoic ("hidden life")		

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INTRODUCTION

This is not a technical geological report but is intended rather for the use of nongeologists who have little knowledge of geology. It is meant to be a source of geologic information to help people understand the changes in rocks, soils, and landforms that can be seen across North Dakota. Plate 1 (in the folder) shows the distribution and age of the surface materials of North Dakota. A highway map of the state was used as a base map to help the reader relate the geology to the locations of cities, towns, roads, lakes, and rivers. A minimum of technical jargon is included in the text, but certain geologic terms must be used in explaining the geology of specific features. Most of these terms have been defined as they are introduced.

A detailed knowledge of the subsurface rock units has been built from the large amounts of data that have been collected from over 6 000 oil tests that have been drilled since the early 1950s in North Dakota. Additional detailed geologic information has been obtained from surface mapping by the North Dakota Geological Survey for groundwater studies since the early 1960s. As a result of this information, we are beginning to understand the surface and near-surface geology of the state, the landforms that have been developed and preserved at the surface, the stratigraphic succession of rock units buried beneath the surface, and the geologic history of the state; and we are rapidly expanding our understanding of the availability, location, and extent of our mineral resources.

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TOPOGRAPHIC SETTING

North Dakota is predominantly a land of prairies and plains located in the center of the North American continent. The geographic center of North America is located near Rugby in Pierce County in the north-central part of the state. North Dakota has a total land area of 69 280 square miles (179 450 square kilometres), and water covers an additional 1 385 square miles (3 600 square kilometres).

All except the southwestern quarter and the eastern edge of the state is rolling land dotted by thousands of small lakes, ponds, and sloughs. This vast, grass-covered flatland slopes gently eastward, interrupted here and there by rounded hills and plateaus and a few low ranges of hills such as the Turtle Mountains near the Canadian border and the Prairie Coteau on the South Dakota border. Long escarpments separate the state into several distinct levels.

North Dakota's landscape southwest of the Missouri River has been carved by running water over a period of several million years. Rugged badlands are found in places, especially along the Little Missouri River. Only a few natural lakes and ponds are found southwest of the river, although man-made reservoirs are common. In contrast, the landscape north and east of the Missouri River was formed by glaciers as recently as 13 000 years ago. The glaciated areas have a landscape ranging from rolling plains to hummocky areas of closely spaced hills and sloughs. Lakes and ponds are abundant in most of the glaciated part of North Dakota. The eastern edge of North Dakota is especially flat. This part of the state, the Red River Valley, was covered by glacial Lake Agassiz, which extended far to the north into Canada and east into Minnesota. The Red River of the North follows a meandering route northward over the ancient lake plain.

North Dakota has traditionally been divided into two major areas—the Central Lowland, which includes the northeast half of the state, and the Great Plains, which includes the southwest half (fig. 1). The Central Lowland (the term refers to plant life, not geology) is the area that was covered by tall grass prairie prior to settlement; the Great Plains were covered by short grass and medium-grass prairie. Some botanists maintain that all of North Dakota is part of the Great Plains, but, as it is used here, the Central Lowland includes the Red River Valley, the Turtle Mountains, the Prairie Coteau, the Glaciated Plains, and the Missouri Coteau (fig. 1).

The Red River Valley occupies a strip of land about 40 miles (65 kilometres) wide along the eastern edge of the state. This flat area is characterized by lake-bottom sediment near the Red River and beach ridges farther west. An abrupt rise in elevation to the glaciated plains west of the lake plain occurs at the Pembina Escarpment at the edge of the lake plain. The Pembina Escarpment is most evident in the north where it is about 500 feet (150 metres) high; it becomes less prominent southward.

West of the Pembina Escarpment, the Glaciated Plains, a rolling area of glacial deposits, extends westward to the Missouri Escarpment, a second abrupt rise in elevation. Elevations over the Glaciated Plains average about 1 500 feet (450 metres) above sea level (fig. 2). Two hummocky plateaus, the Turtle Mountains and the Prairie Coteau, stand about 700 feet (200 metres) above the Glaciated Plains (fig. 1).

The westernmost part of the Central Lowland is a 30- to 50-mile-wide (50- to 80-kilometre-wide) strip of land known as the Missouri Coteau (Hills of the Missouri) that occurs immediately west of the Missouri Escarpment. The Missouri Coteau is a hummocky area over which glacial stagnation occurred. The boundary between the Missouri Coteau and the Coteau Slope also separates the Central Lowland, on the east, from the Great Plains, on the west.

The Great Plains are rolling to hilly, the result of erosion of generally flat-lying, easily eroded sedimentary rocks. Badlands topography has developed near some streams and rivers; badlands are especially prominent along the Little Missouri River.

North Dakota's surface slopes generally northeastward (fig. 2), and all of the state's drainage was directed generally east-northeastward toward Hudson Bay before the state was glaciated. The glaciers drastically changed drainage patterns. The Central Lowland is covered by a thick layer of glacial sediment that blocks old drainage routes and forced new ones to form. As a result, the glaciated area has numerous lakes and sloughs, but few streams. The Missouri Plateau part of the Great Plains, with only thin glacial deposits, is everywhere drained by streams.

About 60 percent of North Dakota is drained by the Missouri River; this runoff ultimately makes its way to the Mississippi River and the Gulf of Mexico. Major tributaries to the Missouri River in North Dakota include the Little Missouri, Knife, Heart, Cannonball, and James Rivers. The rest of the state is drained northward by such rivers as the Souris, Sheyenne, and Red River of the North; this runoff ultimately makes its way to Hudson Bay.

The Missouri River flows at nearly right angles to the overall northeasterly slope, a result of its being forced into that position along the edge of the glacier. The James River, which also flows in a route that was established by the margin of the glacier, flows into the Missouri in South Dakota.

Elevations over North Dakota range from 750 feet (230 metres) above sea level at Pembina in the extreme northeast corner of the state where the north-flowing Red River of the North enters Canada, to 3 506 feet (1 069 metres) above sea level at White Butte near Bowman in the southwest part of the state (fig. 2).

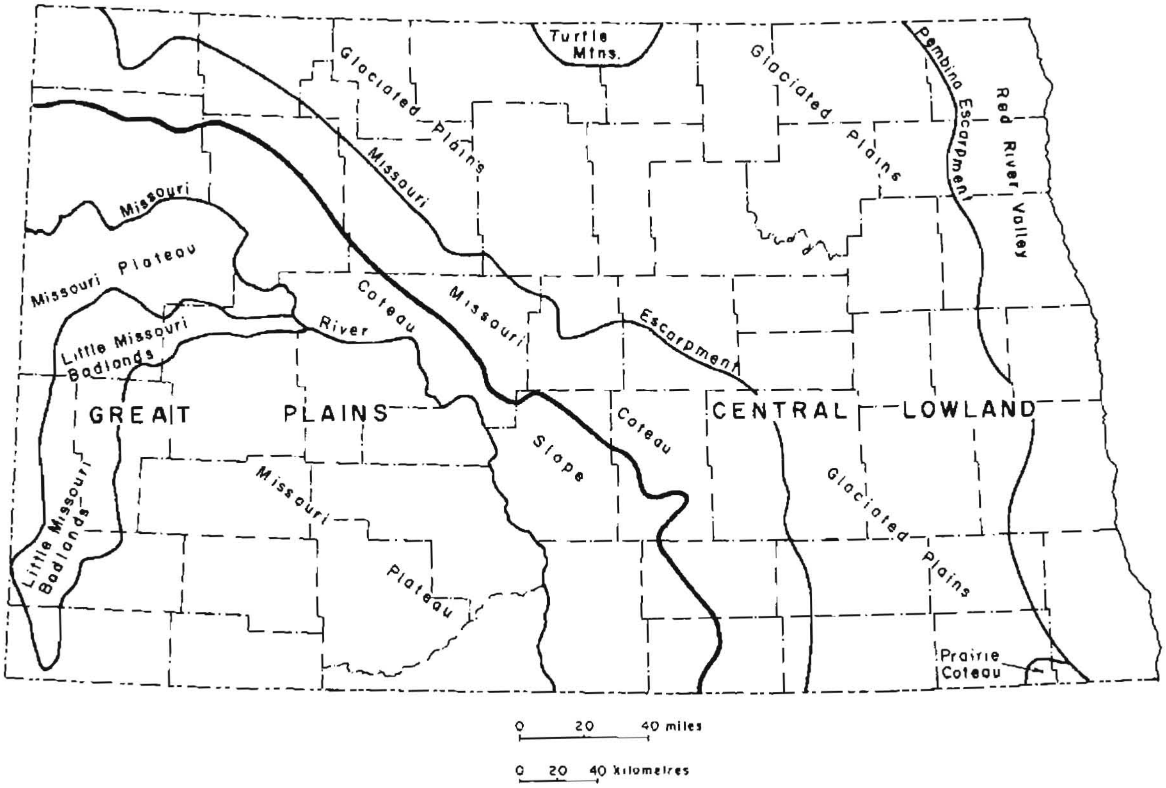


Figure 1. Map showing the main topographic areas in North Dakota. The term "gently sloping" refers to areas that have slopes of less than 8 percent (4° 35'). Local relief is defined as the maximum difference in elevation within any township-sized area.

EXPLANATION

CENTRAL LOWLAND

Red River Valley: Flat plain resulting from sedimentation on the floor of glacial Lake Agassiz; more than 95 percent of the area is gently sloping with local relief less than 25 feet in most places.

Pembina Escarpment: Steep, glacially-modified escarpment that marks the boundary between the Red River Valley and the Glaciated Plains.

Glaciated Plains: Rolling, glaciated landscape; more than 80 percent of the area is gently sloping with local relief generally less than 100 feet in most places, but ranging up to 100 to 300 feet in some places.

Prairie Coteau and Turtle Mountains: Hummocky, glaciated irregular plains that resulted from collapse of superglacial sediment; gentle slopes characterize 50 to 80 percent of the area and local relief ranges from 300 to 500 feet.

Missouri Escarpment: Steep, glacially-modified escarpment that marks the boundary between the Glaciated Plains and the Missouri Coteau.

Missouri Coteau: Hummocky, glaciated irregular plains that resulted from collapse of superglacial sediment; gentle slopes characterize 50 to 80 percent of the area and local relief ranges from 100 to 300 feet.

GREAT PLAINS

Coteau Slope: Rolling to hilly plains east of the Missouri River that have both erosional and glacial landforms; gentle slopes characterize 50 to 80 percent of the area and local relief ranges from 300 to 500 feet.

Missouri Plateau: Rolling to hilly plains except in badlands areas; some evidence of glaciation near the Missouri River; gentle slopes characterize 50 to 80 percent of the area and local relief ranges from 300 to 500 feet.

Little Missouri Badlands: Rugged, deeply-eroded, hilly area along the Little Missouri River; gentle slopes characterize 20 to 50 percent of the area and local relief is commonly over 500 feet.

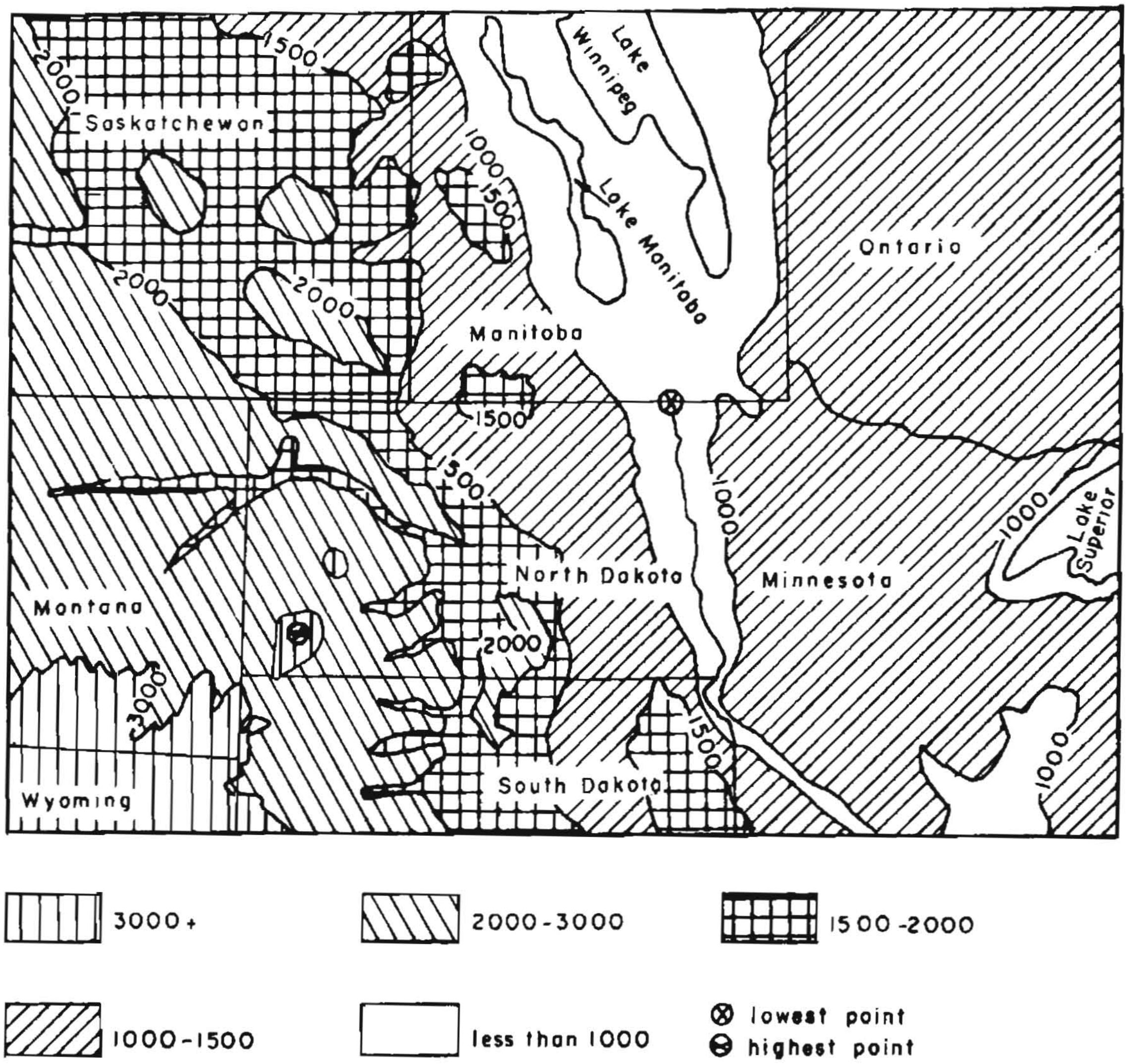


Figure 2. Map of North Dakota and the surrounding area showing elevation ranges. The highest point in North Dakota, in the southwest corner of the state, is 3 506 feet above sea level. The lowest point is in the northeast corner at 750 feet above sea level.

STRUCTURAL SETTING

North Dakota lies immediately west and southwest of the Canadian Shield. It is part of the Central Stable Region, a rolling, geologically stable area containing some of the oldest known rocks in North America. In northeastern Minnesota and adjacent Ontario, these ancient rocks are found at the surface, but they are buried beneath younger materials everywhere in North Dakota.

The western two-thirds of North Dakota, along with parts of southwestern Manitoba, southeastern Saskatchewan, eastern Montana, and northwestern South Dakota, an area of about 200 000 square miles (500 000 square kilometres) contain rocks of the Williston basin (fig. 3), which is both a structural and a sedimentary basin. The present configuration of the basin was shaped late in Cretaceous time. In eastern North Dakota in the Red River Valley, the Precambrian basement rocks, which consist of igneous and metamorphic rocks, are covered by a few hundred feet of glacial deposits. Increasingly thick accumulations of sedimentary rocks that fill the Williston basin slope to the west toward the center of the basin with the result that the crystalline Precambrian rocks are covered by at least 16 000 feet (4 800 metres) of sedimentary rocks near the basin's center a few miles southeast of

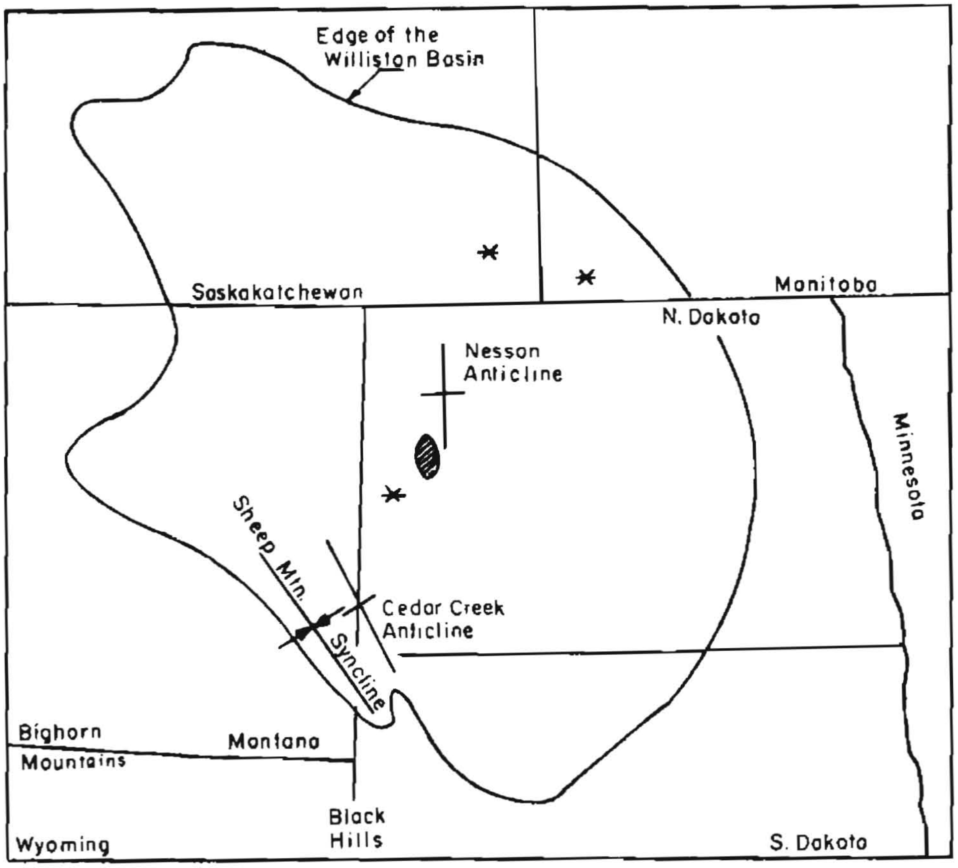


Figure 3. Map of the Williston basin showing the main structural elements. The shaded area is the deepest part of the basin. Starred locations are astroblems, places that were disturbed when they were struck by large meteors.

Watford City in McKenzie County in western North Dakota (fig. 3).

The regional slope of the sedimentary rocks into the center of the Williston basin averages about 60 feet in a mile (10 metres in a kilometre), less than one degree. It is interrupted by small geologic structures in many places.

Anticlines are upfolds in sedimentary rocks. The Nesson anticline in northwestern North Dakota (fig. 3) can be described as a north-south-trending fold about 75 miles long. Small structures are superimposed on the main trend. Its map pattern and a consideration of the tectonic style of uplifts in this part of the Great Plains suggest that the Nesson anticline is fault-controlled. (A fault is a fracture in the earth's crust along which movement has taken place.) The Cedar Creek anticline is a northwest-southeast-trending fold that crosses the southwestern part of Bowman County, though most of the anticline is in southeastern Montana and northwestern South Dakota. It is associated with faulting of Paleozoic rocks.

Recent earthquakes such as the one in the Bismarck area in 1968 indicate that North Dakota still has active faults. Earthquakes occur when two crustal blocks move relative to one another along a fault. Only seven weak earthquakes have been reported in North Dakota since 1909. They were centered on the following locations (but all were felt in North Dakota): Avonlea, Saskatchewan, 1909; Hebron, North Dakota, 1927; Newark, South Dakota, 1934; Roosevelt County, Montana, 1943; Williston, North Dakota, 1946; Huff, North Dakota, 1968; and Morris, Minnesota, 1975.

In places, salt in rock units of Paleozoic and Mesozoic age has been dissolved resulting in collapse of the overlying sediments and creation of small collapse structures. Some geologists have hypothesized that collapse of salt beds is responsible for certain surface features such as the looping route of the Souris River in north-central North Dakota, but such hypotheses are highly conjectural.

SURFACE GEOLOGY

Rock: Raw Material of the Landscape

Rock is the basic material of geology, and it is from rock that landforms are shaped. For this reason, it is helpful to know something of its general characteristics and its role in the development of landforms and scenery. Geologists consider rock to be naturally-formed physical material consisting of one or more minerals. Minerals, also naturally-formed materials, have a definite, characteristic internal structure determined by the arrangement of atoms within them. Mineral crystals are the external manifestation of this atomic arrangement. The chemical composition of a mineral is fixed or varies within a definite range.

All of the earth's rock has formed in one of three general ways. We therefore have three major varieties of rock: *igneous, sedimentary,* and *metamorphic* rocks. Igneous rock (from the Latin, *ignis*, "fire") was once hot, molten rock matter known as magma, which finally cooled to a firm, hard, crystalline material, much as water freezes to ice. Some igneous rock, such as volcanic lava, cooled on the surface of the earth, while others, such as granite, cooled and solidified before reaching the earth's surface.

Igneous rock, like granite, has been obtained from deep exploratory wells, but igneous rock cannot be seen outcropping in-place (that is, in the position in which it formed) anywhere in North Dakota. Boulders composed of igneous rock are scattered on the surface of the ground throughout the part of the state that was glaciated. These boulders were transported to their present locations from Canada, mainly Ontario and Manitoba, by the glaciers.

Sedimentary rock (from the Latin, *sedimentum*, "settling") occurs in layers or strata. This layered, or stratified, rock was derived from pre-existing rock by erosional processes. Rain, glaciers, and wind are powerful destructive forces that constantly tear down the earth's surface and reduce its topography. The particles worn from any eroded rock mass are eventually carried by rivers and streams to lakes and seas. After they were deposited as layers of sediment, they eventually hardened into beds of sedimentary rock. In North Dakota, sedimentary rock such as limestone, sandstone, and shale lies above the igneous rock everywhere except in southeastern North Dakota. It formed when sediment washed into the seas that covered the state during much of the past 600 million years. In the same way, topsoil today is washed from the badlands by the Little Missouri River and deposited in the Gulf of Mexico.

All the rock already mentioned may be subjected to changes that alter or modify their texture, mineralogy, or chemical composition. Rock that has changed is known as metamorphic rock (*metamorphic* means "to have changed"). It begins as one kind of rock and is changed to another kind. The change to metamorphic rock may be accomplished by heat, pressure, or the action of hot gas from deep within the earth. For example, when heat and pressure are applied to a fine-grained limestone (a sedimentary rock), the limestone may change to a harder metamorphic rock known as marble. Similarly, shale may be transformed to slate. Some of the deepest crustal rock that has been studied from North Dakota is Precambrian metamorphic rock, which was sampled from deep, exploratory oil wells. Boulders of metamorphic rock are also found at the surface in the glaciated part of the state.

Bedrock

Two kinds of sedimentary deposits are found in North Dakota: bedrock and glacial sediment. (Webster defines "bedrock" as the solid rock beneath the soil, but in North Dakota, the term bedrock refers to the older rock that lies beneath the glacial sediment.) The bedrock, which is much older than the glacial sediment, is found at or near the surface in most places southwest of the Missouri River as well as along certain valley walls throughout the remainder of the state (pl.

1). Bedrock is found in most places where it is not covered by glacial sediment or by a layer of topsoil. Glacial sediment covers the bedrock in most places north and east of the Missouri River, and it covers patches of land southwest of the river. In some places, especially in river valleys, modern stream sediment covers the bedrock.

Bedrock is exposed at the surface over much of southwestern North Dakota (pl. 1). Most of the bedrock was deposited by water, some in shallow seas, some in lakes, and some by streams and rivers. Generally, the oldest bedrock that can be seen exposed in North Dakota is marine sediment that formed in shallow seas. Most of this marine bedrock is gray to black shale that was originally deposited as thick layers of sediment at the bottom of the seas. For millions of years the silt and clay settled in the seas, gradually becoming more compact as it changed to shale. This shale is not very hard; if a small piece of it is placed in a glass of water, it may soften and change back to mud. Shale can be found in areas designated as the Carlile, Niobrara, Pierre, and Cannonball Formations (pl. 1). In some places, marine sand was deposited in the water near the shores of the shallow seas. This sand, which is not usually cemented into hard rock, is found in areas designated as the Fox Hills Formation (pl. 1).

Another common type of bedrock consists of materials that were deposited on land by water and wind. These materials are referred to as continental sediment, meaning they were deposited on land. Continental sedimentary rock is found over much of southwestern North Dakota, especially in areas designated as the Hell Creek, Ludlow, Slope, Bullion Creek, and Sentinel Butte Formations (pl. 1). The continental sedimentary rock includes silt, clay, sand, lignite, petrified wood, sandstone, flint, scoria, and occasionally freshwater limestone. It ranges from soft material that can be easily crushed in the hand to extremely hard rock, like flint.

Most of North Dakota's continental sedimentary rock was deposited by the running water of streams and rivers. Sediment built up on the floodplains of these rivers and streams and on deltas where the rivers entered the same shallow seas in which shale was building up offshore. This fluvial sediment consists mainly of sand, silt, clay, and occasionally gravel.

The remaining bedrock found at the surface in North Dakota is also of continental origin. It includes materials such as the Golden Valley Formation and White River Group sediment, which includes siltstone, clay, sand, and limestone. These materials accumulated in a variety of situations such as in lakes, streams, and as wind-blown sediment.

Glacial Sediment

Glacial sediment is another type of continental sediment which was deposited in a variety of ways, all either directly or indirectly associated with glaciation. In North Dakota, all the glacial sediment belongs to the Coleharbor Group. Most North Dakota glacial sediment is not cemented or hard and it does not hold together well; loose materials are common, although some cobbles and large boulders of hard rock may be found. The glacial sediment can be categorized into three main types: material deposited directly from the glacial ice, material deposited in lakes associated with the glacier, and material deposited by water flowing on and near the glacier.

The Coleharbor Group consists of a mixture of eroded materials which the glacier carried from areas it moved over in Ontario, Manitoba, and Saskatchewan, as well as materials it eroded from the local bedrock over which it moved in North Dakota. Most of the glacial sediment was deposited when it slumped or flowed to its present position as the last glacial ice melted. It consists largely of pebbly, sandy, silty clay. Lake sediment that consists mainly of layers of silt and clay was deposited in lakes that formed on and near the glacier. The last major type of glacial sediment consists of material that was deposited by running water, mostly loose sand and gravel, which washed out of the glacier. Some of the sand and gravel is beach sediment that was deposited along the shores of lakes on and near the glacier. Loose, fine, wind-blown sand is also found in several places throughout the glaciated part of North Dakota.

North Dakota's Landforms

Geologic processes of various types are responsible for the landforms one sees today in North Dakota. Some of these processes have operated beneath the earth's surface, while others are limited to the surface in their action. Volcanism, for example, has its origin in pockets of molten rock within the earth, but it has affected the landscape in states west of North Dakota by building volcanic mountains and spilling to the surface as lava flows. The importance of faulting (fracturing and displacement of the rocks within the stratigraphic section) is difficult to evaluate, partly because the near-surface materials mask the older rocks and partly because of the scarcity of subsurface control data. Certain topographic features, such as parts of the Missouri Escarpment, may have formed due to faulting.

Weathering has also played an important role in shaping the face of the land. When surface rocks are continually exposed to atmospheric agents such as wind, rain, and frost, they gradually undergo chemical change and physical breakdown.

Most of the geologic processes that have shaped the North Dakota landscape did so by acting on the surface. Running water and wind have carved most of the landforms southwest of the Missouri River. The part of North Dakota north and east of the Missouri River is mantled by a cover of glacial sediment that is as much as 800 feet (250 metres) thick. Most of the topographic features and subtle changes in the landscape in this area were the result of glaciation and processes closely allied to glaciation. The overall shape of the landscape, however, originated before the area was glaciated during a prolonged time of weathering and erosion by wind and running water. This landscape was a mature one that may have taken several million years to develop. It was built on materials such as shale and soft sandstone so that most of the features were smooth and subdued. The preglacial landscape was probably similar in its overall appearance to the rolling uplands of southwest North Dakota today.

Perhaps the most distinguishing characteristic of the ancient preglacial landscape in North Dakota was the presence of long escarpments, low buttes, and mesas. Features such as the Missouri Escarpment and the Turtle Mountains already existed before the state was glaciated even though they were probably less pronounced than they are today. For purposes of illustration, it is interesting to consider how the Red River Valley formed. Many of the other large topographic features in North Dakota have had similarly complex histories, but it would be impractical to attempt to discuss the detailed geologic origin of all of them here.

The Red River Valley: Origin of a Major Landform

The Red River Valley is not a true "river valley" in the traditional sense. The modern Red River of the North did not carve the Red River Valley in the way in which a river normally carves a valley. Rather, the Red River Valley is an example of a feature that is the result of the interaction of a considerable variety of conditions and geologic processes such as the configuration of the Canadian Shield, the movement of groundwater through the underlying rock strata, differential erosion by running water over a long period of time, modification by glaciers, and recent wind, stream, and soil-forming events.

The Red River Valley was already a major physiographic feature long before North Dakota was glaciated, even though its floor at that time was a rolling surface rather than the exceptionally flat one there today. The history of the Valley as a major geologic feature goes back several million years.

The Red River Valley was initiated as a narrow, shallow valley whose axis was several miles east of the position of the modern Red River. This initial position probably corresponded to the location in Minnesota in which the Dakota Group sandstone was exposed at the surface (fig. 4). Artesian groundwater, which flows eastward through the sandstone and deeper

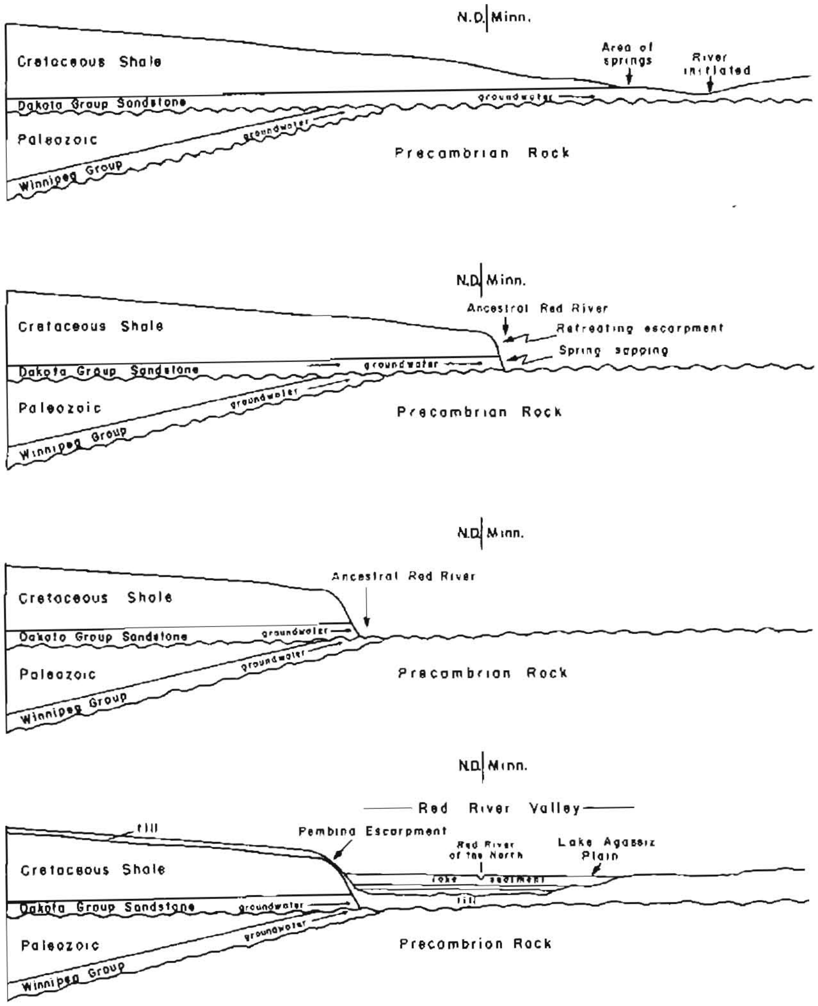


Figure 4. Diagrams illustrating the formation of the Red River Valley. The upward movement of artesian groundwater helped to initiate a valley in the area of springs (top diagram). The river cut down to the hard, Precambrian rock, then shifted its course westward as it eroded away the Cretaceous shale and sand forming the Pembina Escarpment as it did so (second and third diagrams). When glaciers deposited a layer of till over the area, the upward flow of groundwater was sealed off and the river erosion ended (lower diagram). Lake Agassiz sediment now covers the Red River Valley and the modern Red River of the North flows on top of the lake plain.

formations, seeped to the surface of the ground as springs along this outcrop.

With time, the ancient Red River eroded its way down to the hard, igneous rock of the Canadian Shield and, rather than continuing to carve into this hard material, it tended to shift its course gradually westward, where the igneous rock was found at increasing depths (fig. 4). As it shifted westward, it carved away the soft shale and sandstone that lay on the granite, forming an east-facing escarpment. The west wall of the valley was probably always marked by numerous springs where the Dakota Group aquifers and, as erosion continued, the lower Paleozoic aquifers, were intersected and exposed; and the seepage of this water from the valley walls tended to remove sediment from the surface and transport it to the river. Eventually, a relatively steep escarpment formed along the west side of the valley. This escarpment, which is today the Pembina Escarpment, gradually migrated westward as erosion continued, becoming steeper and higher as it did so (fig. 4).

The face of the Pembina Escarpment was eroded and probably steepened by glacial ice, which flowed southward through the Red River Valley during the Pleistocene Epoch. The valley itself was also eroded by the glaciers, and it served as a sedimentation basin for the lakes that formed ahead of the melting ice several times during the Pleistocene Epoch. The modern flat surface of the Red River Valley was formed at the floor of the most recent of the glacial melt-water lakes to occupy the valley, the glacial Lake Agassiz.

Landforms in Unglaciated Areas

All the land south and west of the Missouri River in North Dakota as well as a 20- to 50-mile-wide (30- to 80-kilometre-wide) strip of land north and east of the river is considered to be part of the Missouri Plateau. Most of the rock and sediment throughout southwest North Dakota ranges in age from Late Cretaceous through Paleocene, about 130 million years old to 65 million years old. Patches of bedrock that range in age from Eocene to Miocene, about 60 million to 15 million years old, are also found in places, particularly on some of the buttes.

Rolling plains, buttes, and badlands have been carved from the surface sediment to form the modern landscape southwest of the Missouri River. Erosion has continued intermittently ever since the bedrock formations were deposited. The erosion that has shaped western North Dakota has been selective in its action. Hard, relatively resistant sandstone and limestone beds have remained as protective caps on buttes and ridges while the softer silt and clay layers have been washed away. Areas covered by grass sod are resistant to erosion. Other materials that effectively resist erosion include layers of reddish scoria, a natural brick that formed when the heat from buried seams of burning coal baked the adjacent sediments; layers of exceptionally hard chert, which were probably deposited in ancient swamps as silt that was later silicified; concretions, which form pedestals as they weather out of the softer surrounding sediment; and, in some places, beds of snail and clam shells and layers of petrified wood.

Even though much of the area southwest of the Missouri River in North Dakota was glaciated at various times during the Pleistocene Epoch, erosion has largely erased the evidence of these early glacial events except in a narrow area adjacent to the Missouri River, where the glacial deposits are still young and fresh. The small amounts of glacial deposits found throughout most of the glaciated portions of southwest North Dakota are preserved mainly on drainage divides and, to a lesser extent, in deep valleys.

In a few places, gravel deposits are also found on relatively high areas. Most of these deposits, which are sometimes referred to as the "Flaxville" gravel, are probably either Pliocene or early Pleistocene in age. They were originally deposited in valleys, probably by streams that had their origins in the Rocky Mountains. In areas where such gravel is found on drainage divides, the topography has been inverted since the gravel was deposited. Areas that were valleys when the gravels were deposited are now ridges and buttes.

Southwest of the Missouri River in areas that have been glaciated (pl. 1), the glacial deposits are generally scanty and consist mainly of scattered boulders and a few areas of thin glacial sediment. Some of these deposits may be early Wisconsinan in age, perhaps 75 000 years old, and it is likely that sufficient time has not elapsed since they were deposited to allow drastic changes in the overall shape of the topography. Relief throughout southwest North Dakota is mainly the result of erosion rather than glacial deposition and, in contrast to most of the land east of the Missouri River where hills and valleys tend to be close together and rather small, the land southwest of the river is characterized by gently rolling uplands with scattered large hills, buttes, and well-developed valleys.

Rolling uplands

Most of North Dakota southwest of the Missouri River is a rolling upland developed mainly on the bedrock formations. Subtle, but real, differences in the landscape can be related to the underlying formations. Perhaps the most apparent differences are the changes in vegetation, which in turn are related to the type of soil that has developed. Soils formed on the Hell Creek Formation, in Sioux and Grant Counties, for example, tend to be of rather poor quality, and they result in an overall "scrubby" appearance to the landscape. By contrast, soils developed on the smooth, rolling landscape of the Cannonball and Bullion Creek Formations in the same area, are fertile, a fact that is reflected in the overall good range and crop land.

Large tracts of the rolling upland areas have been modified by the action of the wind. Even though recognizable dunes are rare, many of the small irregularities in the surface were shaped largely from wind-blown silt and fine sand and wind-carved grooves in the bedrock surface. This wind-shaped landscape is widespread in many areas, yet it is subtle because modern soil processes have modified it almost beyond recognition.

The effects of permafrost (permanently frozen ground), which modified the landscape probably several times during the Pleistocene Epoch, are even more subtle. Ice-wedge fillings are common and permafrost polygons can be seen on aerial photographs of some areas. These polygons are not readily apparent to the ground-based observer.

Pediment surfaces are common throughout the unglaciated part of the state. These eroded surfaces are commonly covered by a few inches to a few feet of locally-derived gravel. They are apparently the same age or older than most of the permafrost features because polygons and frost-wedge fillings can commonly be identified on the surfaces. In some places, the pediments cut across ancient deposits of glacial sediment.

Badlands

The Sioux Indians referred to the badlands as "makosica" ("land bad"), and early French explorers translated this to "les mauvais terres a' traverser" ("bad land to travel across"). The badlands of southwestern North Dakota began to form when a glacier diverted the Little Missouri River about 40 miles (65 kilometres) south of Williston causing it to flow eastward. Prior to the diversion, not only the Little Missouri River, but also the Yellowstone and Missouri Rivers, flowed north into Canada and east to Hudson Bay. As a result of its diversion by the glaciers, the Little Missouri River flowed over a shorter, steeper route than before; and, because of this, the river cut rapidly downward, causing extensive erosion and the carving of the badlands.

In the southern part of the Little Missouri Badlands near its headwaters, the river has cut down about 80 feet (25 metres) below its preglacial level. In its lower reaches, in the northern part of the badlands area, the valley floor is about 300 feet (90 metres) below its preglacial level (fig. 5). The eastward-flowing portion of the river, which has been cut since the glaciers diverted the river, is in a valley that is about 500 feet (150 metres) deep.

The erosion has not been at a constant rate. Since their excavation began, the badlands have undergone many periods of erosion and deposition. Erosion is most intense during periods of drought because the vegetative cover is insufficient to keep the sediments in place at such times. During the past few hundred years, the badlands have undergone four separate periods of erosion and three periods of deposition. New gullies have been cut to their present depth since about 1936.

Buttes

The southwestern North Dakota landscape is characterized by hundreds of hills and buttes, some of considerable size. Many of the smaller ones are capped by layers of sandstone, scoria, chert, or other erosion-resistant materials that belong to the same formation that covers the surrounding areas. Some of the larger buttes are capped by younger bedrock formations than those in surrounding areas. Sediment of the Eocene Golden Valley Formation caps some of the higher buttes and the Oligocene White River Formation contains resistant beds of limestone that form a caprock on some of the larger southwestern North Dakota buttes such as the Killdeer Mountains, Bullion Butte, and

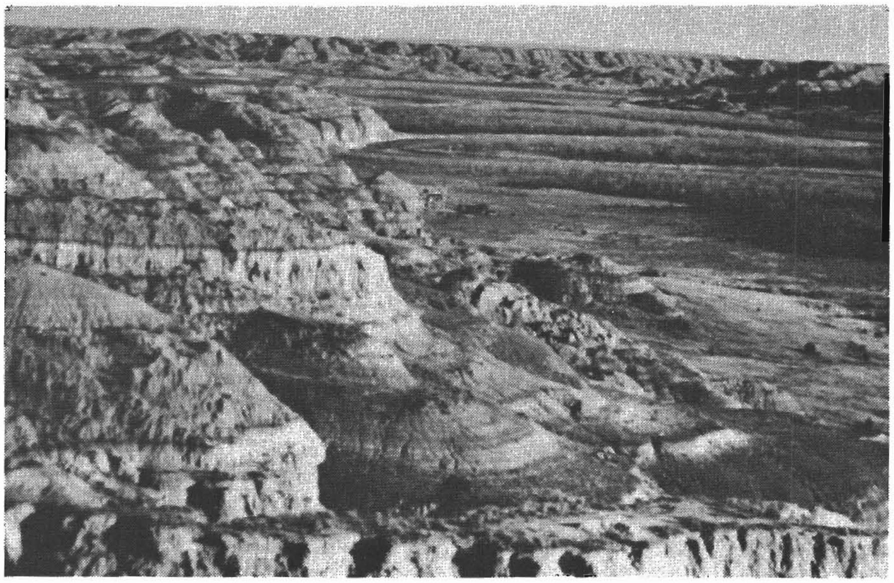


Figure 5. Little Missouri River badlands in McKenzie County, North Dakota. The river is carving its way through sediment of the Sentinel Butte Formation.

Sentinel Butte.

Materials Found in Unglaciated Areas

Lignite

Lignite coal is found throughout the part of North Dakota that is underlain by Ludlow, Slope, Bullion Creek, and Sentinel Butte sediments (pl. 1). Its economic potential will be discussed in the section of this report dealing with mineral resources but, in general, lignite is a soft, low-rank coal. It consists of fragments of plants that grew in a warm and humid climate in ancient swamps that existed along streams that were flowing generally eastward from the newly-formed Rocky Mountains during Paleocene time, about 65 million years ago. As the plants died and fell into the swamps, they began to decay due to the action of bacteria. However, before the plants could be completely decomposed, the bacterial action stopped because the bacteria "committed suicide" by filling the stagnant swamp water with their body poisons to such an extent that they died. When the streams changed course, as the Mississippi River does on its delta in the Gulf of Mexico at times, they deposited sand on top of the partially decomposed vegetation, burying it and allowing lignite to form.

Scoria

Reddish layers and brick-like masses of baked and fused clay, shale, and sandstone are found in many parts of western North Dakota where seams of lignite have burned, producing heat that baked the adjacent sediments to a form of natural brick. The baked material is known locally as "scoria."

Range fires ignited some lignite beds. Spontaneous combustion, lightning, and the actions of man have been responsible for other burned lignite seams. Such a large number of lignite seams have burned over such a broad area and under such a variety of situations that it seems likely spontaneous combustion has been responsible for most of the fires. Lignite that contains a high percentage of moisture and sulfur is most likely to ignite spontaneously. The ideal situation for such combustion is a finely-divided condition of the coal, a slight amount of heat from an outside source, and several feet of overburden to retard heat losses by radiation.

Lignite exposed to air by the removal

Figure 6. Collapsed materials above burned-out lignite seam. The burning of coal beds results in collapse of the overlying materials. The cracks that form in the beds above the coal allow air to reach the burning lignite.

of the overlying sediment due to erosion loses moisture and tends to slack or crumble to fragments. The powdered coal, with a greatly increased surface area, promotes rapid oxidation; in fact, powdered coal absorbs oxygen in quantities at least two to three times its own volume. This absorption of oxygen takes place at ordinary temperatures and, because the process generates heat, it is self-accelerating.

The presence of the minerals pyrite and marcasite (forms of iron sulfide) and moisture results in the production of heat; and, as this chemical reaction takes place at ordinary temperatures, it is one means by which the coal is heated to the point at which it ignites. Pyrite and marcasite are nearly always present in relatively large quantities in and near lignite seams that have ignited.

Burning is most likely to take place where coal beds crop out on a fairly steep bank, making it possible for large quantities of fine coal dust to accumulate over the lower part of the outcrop. Thin lignite beds commonly do not burn because piles of powdered coal large enough to retain self-generated heat cannot accumulate along their outcrop. An overburden thickness of 100 feet (30 metres) or more over the coal also prevents ignition unless the coal bed is exceptionally thick.

As lignite beds burn, the heat produced bakes and fuses the overlying sediments. As the lignite burns out to an ash that takes up little space, the overburden collapses into the burned-out space (fig. 6). By the time the overlying materials collapse, they have been baked to a hard material, and they are commonly partially fused as well. As they slump, they hold together, producing a rock that is as much as 75 percent air space. Oxygen is then admitted through this porous, fractured rock, and combustion gases are carried out so the coal can burn farther back. After the scoria cools, the spaces that resulted from collapsing of the materials are convenient places in which rattlesnakes and other animals can live.

Scoria commonly contains fragments

that look as though they have melted. According to one theory, these fragments were formed when the material overlying a burning coal bed collapsed, plunging it into the exceptionally hot areas beneath so that it melted.

The intensity of the reddish color of scoria is governed by the mineral composition and grain size of the material that was baked and by the intensity of the temperature reached during the baking process. The reddish color is due primarily to the presence of the mineral hematite (iron oxide, the same as common rust). All of the southwestern North Dakota sediments contain some iron-bearing minerals, although not in concentrations great enough to make them commercially valuable. Since iron is more easily oxidized at high temperatures than at normal temperatures, hematite forms when the sediment is baked.

Much of the scoria in western North Dakota is now found at elevations where the water table is too high for lignite to burn. This scoria probably formed at a time when the climate was drier and the water table was lower than it is today. This may have happened, for example, during what is known as the "hypsithermal interval" ("hypsithermal" means "maximum temperature"), a warm, dry period of time that lasted from about 7 000 years ago until about 2 500 years ago.

Petrified wood

Petrified wood is found in numerous places in western North Dakota. It is especially common in badlands areas where stumps and intact trunks have weathered from the surrounding sediments (fig. 7). Although most of the area that is now western North Dakota was probably forested during Paleocene time, the preservation of the wood required that the trees be rapidly buried by sediment so that they escaped decay. This probably happened only when streams changed course or flooded their banks, depositing sand or silt on the trees.

After a tree was buried, groundwater began to circulate through it. With the help of bacterial action, the water dissolved out the softer cellulose material of the wood. The water also carried dissolved minerals, among them silica (SiO_2), which were deposited in the spaces left in the decaying plant tissue. This went on for a long time so that the replacement was gradual, a molecule of plant tissue being simultaneously replaced by a molecule of silica. In this way, the original cellular structure of the wood was preserved so that, in many cases, the petrified stumps look exactly like old wood stumps except that they are stone. The petrified wood found in southwest North Dakota is mostly light brown or cream colored on the surface; black or dark brown on broken surfaces. Petrified wood seems to be more abundant in the Sentinel Butte Formation than in other formations.

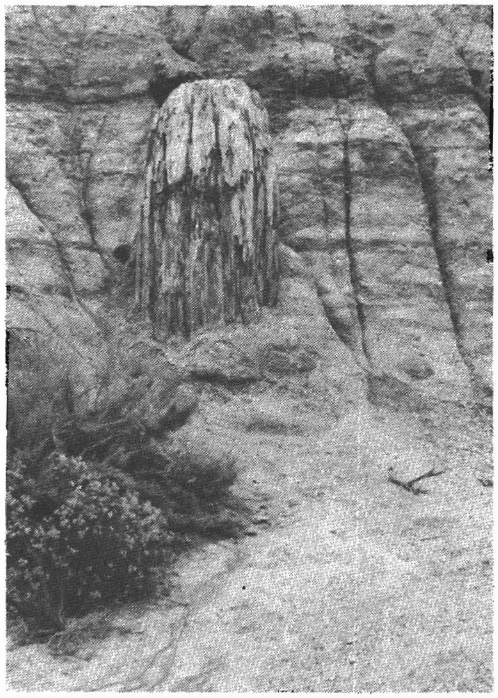


Figure 7. Petrified wood stump in Theodore Roosevelt National Memorial Park.

Concretions and nodules

Concretions are rock structures that have essentially the same composition as the sediments that contain them, but they are generally more resistant than the surrounding sediments. They are the result of the selective deposition from water of cementing materials in the pores of the sediment. Nodules, like concretions, are

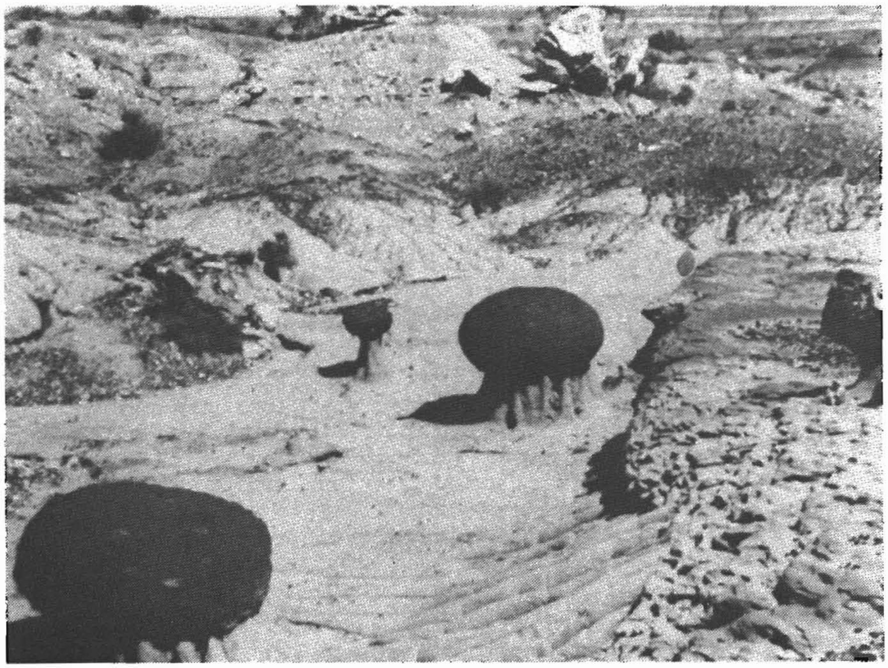


Figure 8. Nearly spherical concretions weathering out of the Bullion Creek Formation sediment in Billings County, North Dakota.

also harder than the surrounding sediments, but they are of a different composition than the sediments that surround them.

All the geologic formations in western North Dakota contain concretions and nodules of all sizes and shapes. Some concretions are nearly spherical (fig. 8). In some badlands areas, the surface is covered by nodules of siderite (ironstone) which, as they weather out of the surrounding materials, form an erosion-resistant layer. Among the more interesting of the various types of concretions are the "logs," which are elongate sand bodies that have been cemented, in most cases, by calcium carbonate. The log-like concretions formed when mineral-rich groundwater flowed through porous and permeable zones in the subsurface, depositing the minerals in the pores and thereby cementing them to concretions.

Chert

Chert is essentially pure, extremely hard, microcrystalline quartz. The term "chert" is used loosely here and several types of siliceous materials can be conveniently grouped under this heading. They include the boulders of material that have been called "pseudoquartzite" or "gannister"; chert derived from Paleozoic limestone and dolomite formations in Manitoba and now found in the glacial deposits; and chert found in late Cenozoic gravels (including quartzite, chalcedony, agate, and volcanic rocks) that were carried to western North Dakota by streams flowing from the Rocky Mountains and Black Hills areas.

The type of chert sometimes referred to as pseudoquartzite or gannister is abundant on the surface throughout much of southwestern North Dakota (fig. 9). Its original source is unknown, but it may have formed when silt and very fine sand composed mainly of quartz was blown into swamps where it accumulated and eventually solidified as the swamps dried. Some of the chert beds probably are ancient soil zones. This gray, unbedded material has an irregular fracture and is characterized by the presence of numerous petrified plant stems and hollow stem molds of grooved plant roots or stems. Much of it may have formed as a result of silicification processes similar to the petrification of wood. It is likely that the chert beds do not represent any single

Figure 9. Chert-covered ridge in Adams County. The rocky ridge along this stream valley is covered by an accumulation of chert (sometimes referred to as "pseudoquartzite" or "gannister").

event, but rather a geologic process that was repeated often. Chert of this type is commonly found in the Ludlow, Slope, Bullion Creek, Sentinel Butte, and Golden Valley Formations. Many ridges and buttes in southwestern North Dakota have a cover of chert boulders that help to protect the underlying sediment and minimize erosion. Typical examples of such chert-covered hills are Pretty Rock Butte in southwestern Grant County and Rocky Ridge north of Hettinger in Adams County. The angular and wind-worn chert boulders are locally abundant, literally paving many of the hilltops in places near the Cannonball River in Hettinger and Grant Counties. They are strewn so thickly in places that it is practically impossible to walk over the areas.

Another variety of chert is the Knife River Flint, which is of particular interest because it was used extensively as a raw material for tools by prehistoric man in the Northern Plains and the Midwest. The term "Knife River" is the English translation of an Indian name, which is said to have been given because flint for knives was quarried along the river. The Knife River Flint is found as pebbles, cobbles, and boulders that are as much as 2 feet in diameter. It litters the surface of hill slopes in parts of Dunn and Mercer Counties. It is generally a nonporous, dark brown rock with a conchoidal fracture, making it an excellent material for tools.

Flint nodules a few inches in diameter are scattered on the surface of Sentinel Butte in Golden Valley County. They probably were derived from beds of Oligocene or Miocene age. This flint is more homogeneous than the Knife River Flint and has no visible internal structure and a uniformly dull luster on fracture surfaces. It is also more translucent and lighter colored and grayer than Knife River Flint.

Glacial Landforms

The great diversity of glacial landforms in North Dakota has made it necessary to subdivide the glaciated part of the state into several topographic units (pl.

1). Areas of glacial moraine ("moraine" means any glacial topography) consist of materials that were deposited directly by glacial ice (areas of glacial moraine are shown in shades of green on plate 1). The slowly advancing glaciers plowed up the soil and loose rock, plucked and gouged boulders from outcrops, and carried this material forward, grinding it into a mixture that ranges from clay-sized particles through sand, gravel, and boulders. This mixture of glacial sediment is commonly referred to as "till." The clayey fraction of the till commonly forms a sort of matrix that contains the larger particles. The manner in which the till was deposited and the amount that was available to be deposited determine the type of glacial moraine that resulted. The movement of a glacier over any given area resulted in a great variety of landforms (fig. 10).

Certain glaciated areas southwest of the Missouri River and areas northeast of the river have only a veneer of glacial sediment lying on bedrock (pl. 1). This lack of thick deposits of glacial sediment in some cases is due to the fact that the areas were glaciated so long ago that most of the glacial deposits have since been removed by erosion. In other places, only small amounts of glacial sediment were deposited. In areas where the glacial deposits are too thin to greatly modify the shape of the underlying preglacial surface, the topography is essentially of non-glacial origin. In some of these areas of thin glacial sediment, the only evidence of glaciation is an occasional boulder or patch of till or gravel.

Ground moraine

Moderate amounts of till that were deposited at the base of the moving glacier and by collapse from within the glacier when it eventually melted, formed a gently rolling landscape commonly referred to as "ground moraine," which has only a few potholes and hills. Much of eastern and northern North Dakota is covered by ground moraine (light green areas on pl. 1).

Drumlins

In some places where the glacier was not depositing large amounts of sediment, streamlined ridges and grooves formed on the ground moraine surface, parallel to the direction the ice was moving. Such areas commonly consist of a thin layer of glacial sediment, which was deposited by the last ice that moved over the area, overlying older material, either preglacial bedrock or older glacial sediment. The last movement of the glacier molded the underlying materials into streamlined ridges and grooves by shearing beneath the ice. The ridges, known as "drumlins," may be several miles long, a few hundred feet wide, and a few tens of feet high. Most of the drumlins are not conspicuous to the observer on the ground, but air views can be striking. Particularly excellent examples of drumlins of the type that formed in North Dakota are found near Verendrye and Balfour in the north-central part of the state.

Washboard moraine

Areas of low, irregularly-shaped and irregularly-spaced ridges are referred to as "washboard moraine." Washboard moraine ridges formed parallel to the edge of the glacier in many places. The ridges consist mainly of material that was carried upward through the ice along shear planes in the glacier (fig. 11), although it has been suggested that some of the ridges may have formed as annual accumulations of material at the edge of the glacier while its margin was stationary. Washboard moraine is found in association with ground moraine. Ponds are numerous in areas where "washboard moraine" is common.

Thrust moraine

Large-scale shearing by the glacier moved huge blocks of material short distances in some places. Whenever the glacier continued to advance over such sheared materials, they were effectively masked by subsequent erosion and deposition of glacial sediment. Most areas of thrust moraine consist of a thin layer of till, which blankets ice-thrust slabs or folds of either pre-glacial bedrock or glacial sediment, or, occasionally, gravel and sand.

If the glacier stopped advancing soon after it moved a large block, the result was commonly a hill and an adjoining depression, the hill consisting of material

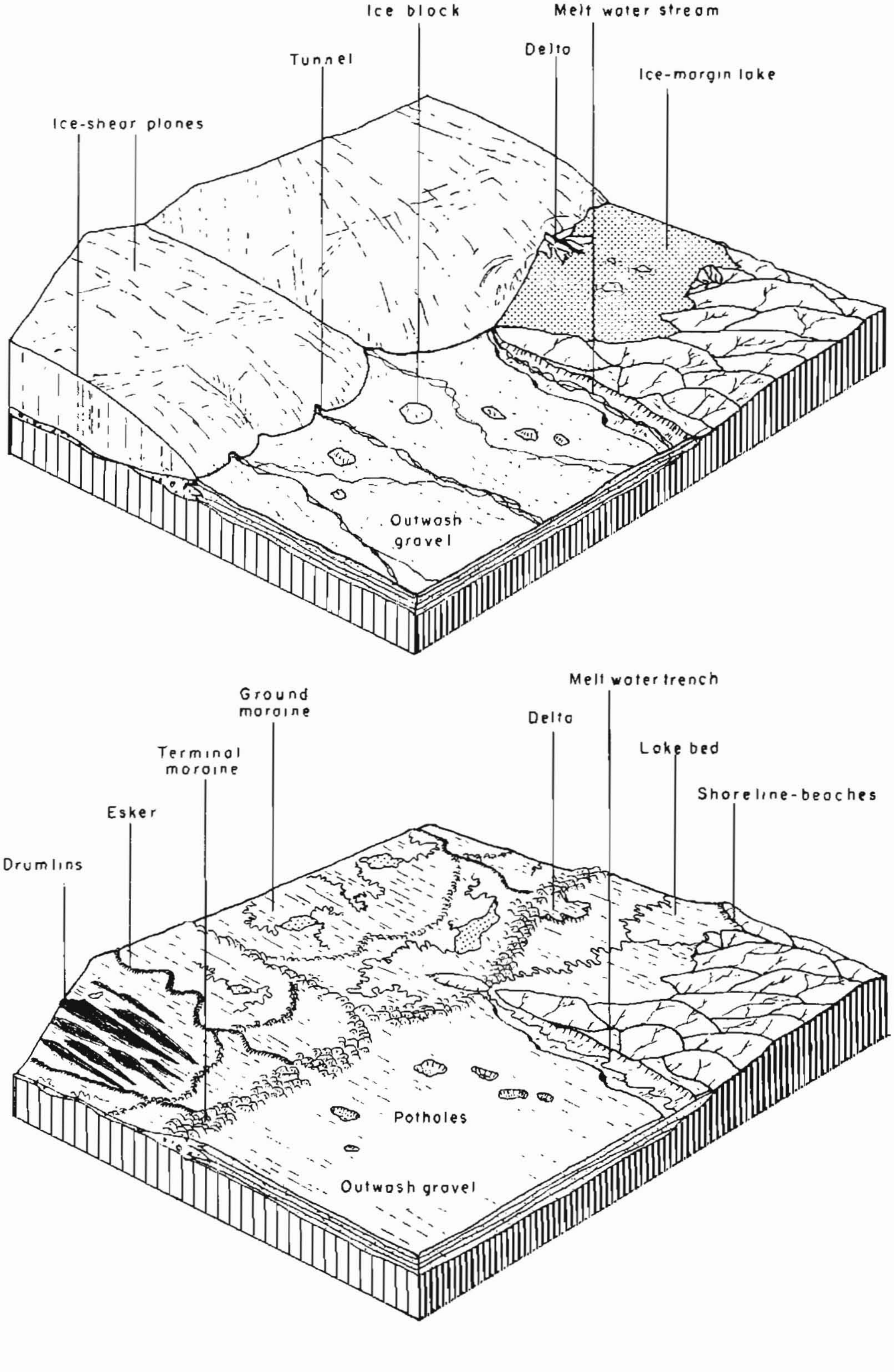


Figure 10. Schematic drawing of a glaciated North Dakota landscape. The upper diagram illustrates conditions as they may have been about 14 000 years ago, as the ice age came to a close in North Dakota. Several features of a glaciated landscape are shown forming as the glacier recedes from the area. The lower diagram shows the post-glacial landscape.

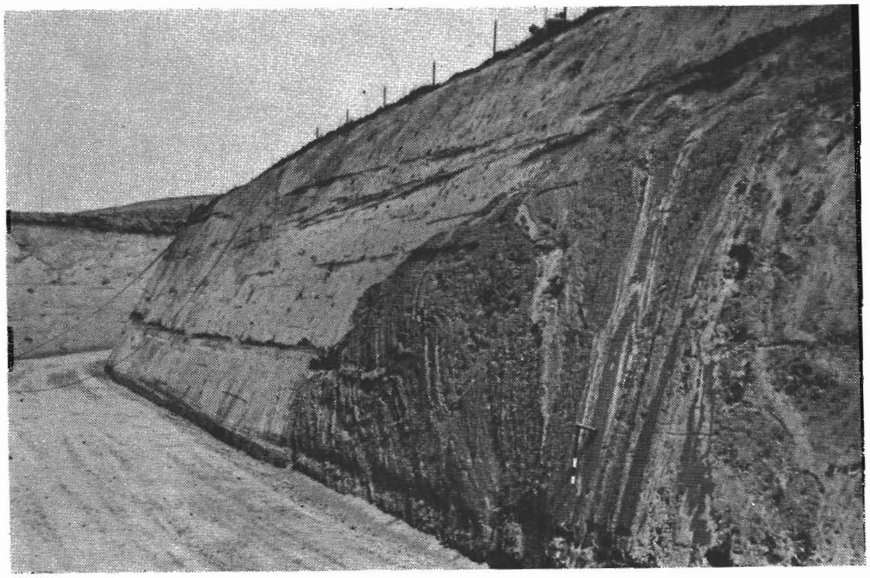


Figure 11. Ice-thrust material in an area of washboard moraine in Steele County, North Dakota. The excavation exposes folded lake sediment consisting of fine sand and silt. As the glacier advanced from right to left, it moved over a small lake deposit and sheared the lake sediment upward, resulting in the folding and slight surface ridge of a washboard moraine (to the left of this photo).

that was transported from the depression by the ice. Hill-depression combinations are numerous in central North Dakota near Harvey and south of Devils Lake, but isolated examples of them can be found in nearly all glaciated parts of the state.

Some areas of thrust moraine cover several square miles; several areas in northern Sheridan County include six to eight square miles each. The thickness of the ice-thrust blocks may range from a few feet to several hundred feet. The formation of such features calls for a hydraulic mechanism that greatly reduces friction between the material being transported by the glacier and the underlying sediment (fig. 12). An outstanding example of a relatively isolated ice-thrust block is Sully's Hill, and the range of associated hills near Fort Totten in Benson County is a good example of a large area of ice-thrust moraine. The depression from which Sully's Hill was excavated now contains Devils Lake. Other notable examples of ice-thrust moraine include Blue Mountain in Nelson County (fig. 13); Dogden Butte in McLean County; the Prophets Mountains in Sheridan County; Standing Rock Hill in Ransom County; and the Grasshopper Hills in Stutsman County.

Terminal moraine

At times, till was deposited at the edge of the glacier while the ice margin was melting back at about the same rate at which the ice was moving forward, so that the margin remained stationary (fig. 10). This condition resulted in a "terminal moraine" or "end moraine," a hilly accumulation of till that is commonly a few miles wide and several tens of miles long.

Dead-ice moraine

The most rugged topography of glacial origin in North Dakota is dead-ice moraine, found on the Missouri Coteau, which extends from the northwest corner to the south-central part of the state; in the Turtle Mountains, which are an isolated plateau in north-central North Dakota; and on the Prairie Coteau in southeastern North Dakota (pl. 1). Thousands of lakes and sloughs are found in areas of dead-ice moraine. In most respects, the landforms of the Turtle Mountains are similar to those of the Missouri and Prairie Coteaus, but the Turtle Mountains have a woodland cover that is generally lacking in the other two areas.

The landscape of the Missouri Coteau,

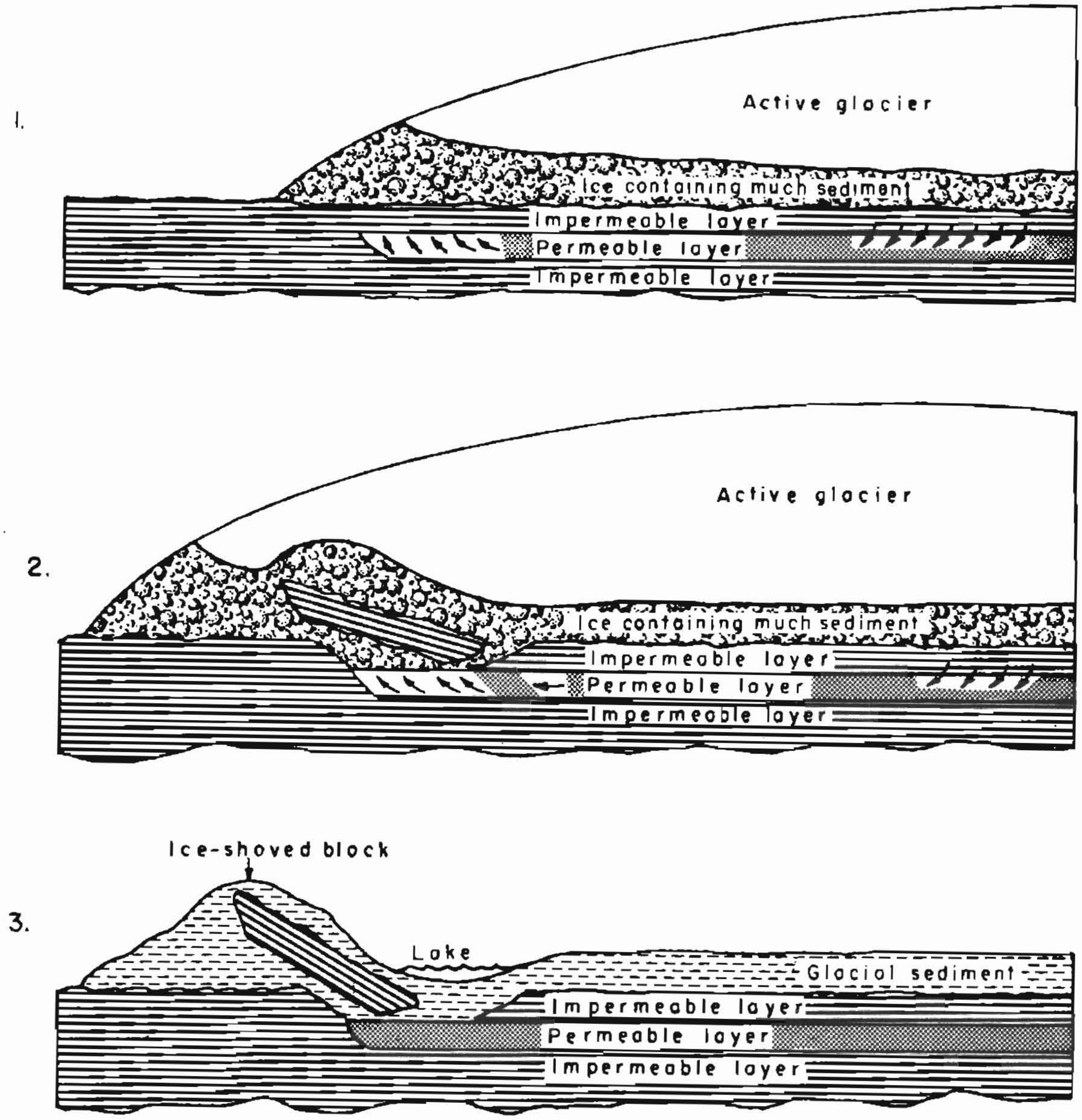


Figure 12. Three-part diagram showing how thrust-moraine forms. The first diagram shows how water beneath the glacier is forced into the permeable zone. This water, which is under great pressure due to the weight of the overlying ice, moves toward the margin of the glacier to zones of decreased pressure. If the water reaches an area where the overlying, impermeable materials are less strong, it may force these overlying materials up into the path of the advancing glacier (second diagram). The result may be a large ice-shoved block with an adjacent, lake-filled depression in the area from which the block was moved (third diagram).

Prairie Coteau, and Turtle Mountains owes its origin to the fact that the glacier had to advance over steep escarpments before it flowed onto the uplands. Elevations rise as much as 600 feet in less than a mile along parts of the Missouri Escarpment, which marks the northeastern edge of the Missouri Coteau, and similar changes in elevation occur along the escarpments that border the Prairie Coteau and the Turtle Mountains. When the glacier advanced over these escarpments, the internal stress resulted in shearing in the ice (fig. 14). Large amounts of rock and sediment beneath the ice were carried into the glacier and to its surface along shear planes in the glacier as it moved onto the uplands.

As the stagnant glaciers melted, the

Figure 13. Two photos of a typical example of thrust moraine, Blue Mountain in Nelson County, North Dakota. The upper photo, a ground view, shows Blue Mountain in the distance with the lake plain of the West Bay of Stump Lake in the foreground (view to the north). The air view below shows the three ridge structure of Blue Mountain, formed as a result of thrusting by the glacier (view southeastward). Photos by Roger Reede.

glacial sediment tended to accumulate on the top of the ice because the ice at the top of the glacier melted first. The melting cover of sediment helped to insulate the underlying ice so that it took several thousand years for it to melt. Ice on nearby areas of the Glaciated Plains where there was no insulating cover melted in a few years. When the stagnant ice finally did melt, the cover of glacial sediment slumped and slid, forming dead-ice moraine, the hilly landscape we see over the Turtle Mountains, Missouri Coteau, and Prairie Coteau today (fig. 15). It is practically impossible for the ground-based observer to distinguish between dead-ice moraine and

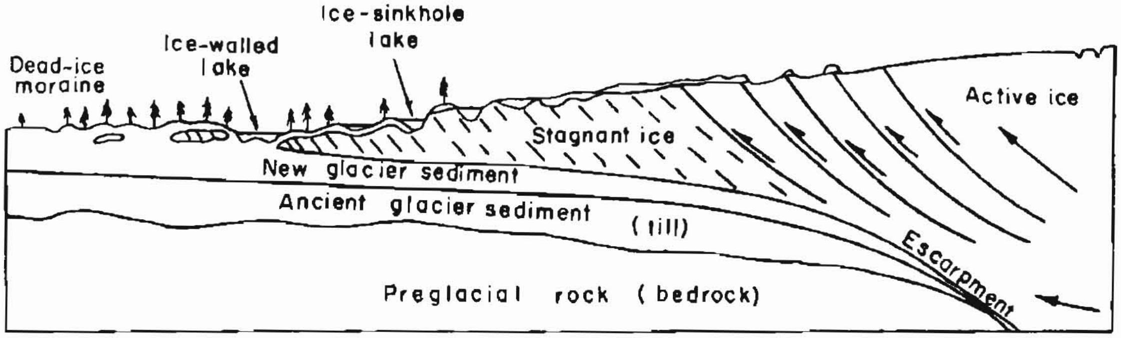


Figure 14. Schematic diagram through the edge of a glacier. This illustration depicts a situation similar to the one that developed when the glacier moved over escarpments such as those at the edge of the Missouri Coteau, Turtle Mountains, and Prairie Coteau. As the glacier pushed into the escarpments, it was compressed, resulting in shearing within the ice. The shearing brought large amounts of material to the surface of the ice. The cover of superglacial material that built up on the glacier kept the ice from melting rapidly, and vegetation formed on top of the debris-covered glacier. When the ice eventually melted, dead-ice moraine resulted. Illustration adapted from one drawn by Lee Clayton.

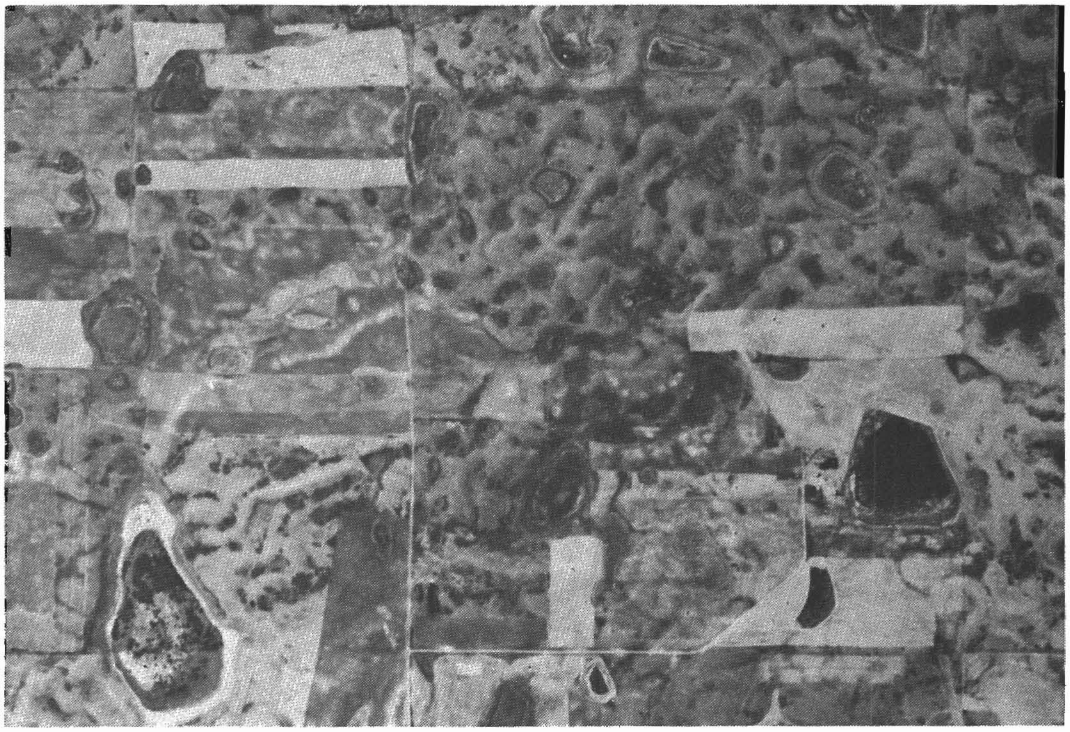


Figure 15. Vertical air photo of dead-ice moraine in Sheridan County, North Dakota. Numerous undrained depressions result in ponds and sloughs in places. The area shown is approximately 1¼ miles by 2 miles.

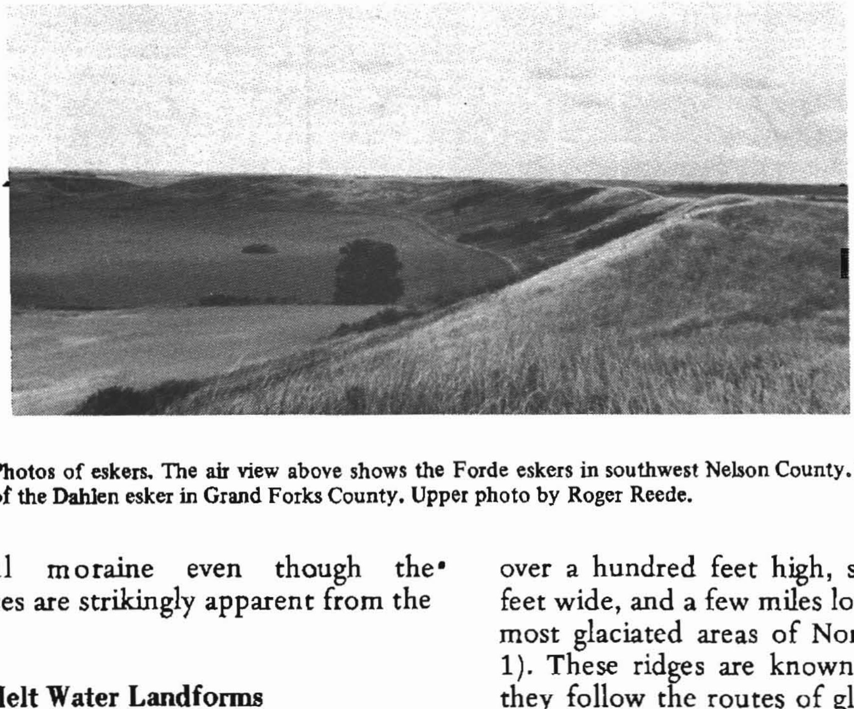


Figure 16. Photos of eskers. The air view above shows the Forde eskers in southwest Nelson County. The lower picture is of the Dahlen esker in Grand Forks County. Upper photo by Roger Reede.

terminal moraine even though the differences are strikingly apparent from the air.

Glacial Melt Water Landforms

Large volumes of water resulted from the melting glacial ice and from precipitation that fell on and near the margins of the glaciers. The landforms discussed in this section were formed through the action of this water.

Eskers and kames

Ridges of gravel and sand that may be over a hundred feet high, several hundred feet wide, and a few miles long are found in most glaciated areas of North Dakota (pl. 1). These ridges are known as eskers, and they follow the routes of glacial rivers that deposited them. In glacial times, melt-water rivers flowed in cracks in the glacier or tunnels beneath the ice, depositing gravel and sand on their beds just as modern streams deposit material on their beds. Typically, the gravel is coarse and contains large amounts of silt and clay. When the glacier melted, the gravel remained as esker ridges standing above the surrounding area

Figure 17. Kame in Benson County near Tokio. This prominent hill, known locally as Devils Heart Butte, stands about 200 feet above the surrounding landscape and is composed mainly of gravel that was deposited by a river plunging into a hole in the ice near the edge of the glacier.

(fig. 16). Several thousand eskers occur in North Dakota, but only a few of the more prominent ones are shown on the geologic map (pl. 1).

Kames consist of about the same materials as eskers, mainly gravel and sand, along with large amounts of silt and clay. They were deposited in depressions in the glacier, which eventually melted, causing the materials to slump into mounds and conical hills (fig. 17).

Glacial outwash

Broad, flat plains of sand and gravel known as glacial outwash plains are common on the Glaciated Plains (fig. 18). Outwash plains consist of material that was deposited by water flowing from the melting glacier, and by runoff from precipitation that occurred while the glaciers were melting. In some places, the glacial outwash has been blown into sand dunes (pl. 1).

Collapsed glacial outwash

Glacial outwash was also deposited on top of stagnant glacial ice on the Missouri Coteau, Prairie Coteau, and Turtle Mountains; but when the ice melted, this sand and gravel slumped down, resulting in an irregular, hilly surface we refer to as collapsed outwash (fig. 19). The largest area of collapsed glacial outwash gravel is in Kidder County, in the south-central part of the state (pl. 1).

Glacial lake plains

Flat plains are found today in areas that were flooded by lakes of glacial melt water. Sediment deposited from the still, lake waters formed smooth lake floors that we refer to as glacial lake plains. Several thousand lake plains that range in size from a few acres to several hundred square miles are found throughout the glaciated part of North Dakota. The largest glacial lakes formed when glaciers blocked the routes of major drainage ways. The largest such lake was glacial Lake Agassiz, which covered the Red River Valley of North Dakota as well as large parts of Manitoba, Saskatchewan, Ontario, and Minnesota (fig. 20). Other large glacial lakes in North Dakota included glacial Lake Souris in the north-central part of the state, glacial Lake Minnewaukan in the Devils Lake area, and glacial Lake

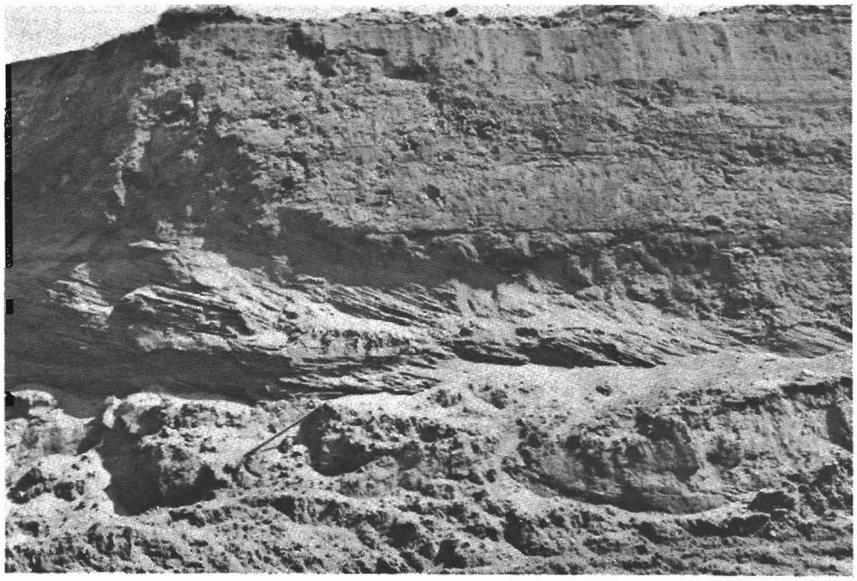


Figure 18. Exposure of glacial outwash, the sand in the bottom half of the picture, covered by a layer of glacial sediment. Deposits of finely-bedded silt can be seen in the upper right-hand corner of the picture. This silt is probably a local lake deposit.

This sequence of sediments in Griggs County indicates that water flowing from an advancing glacier deposited sand and then the ice advanced over the sand, depositing glacial sediment. Later, silt accumulated in a small pond near the melting glacier.

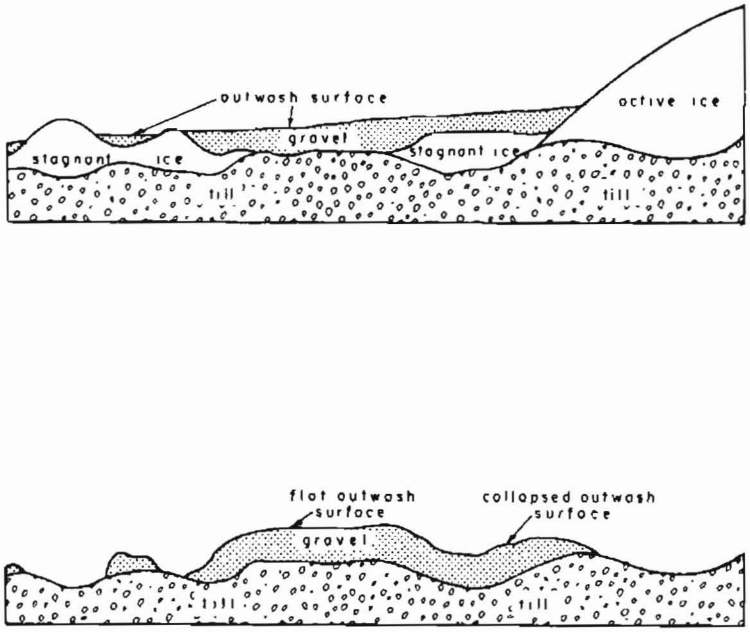


Figure 19. Schematic diagrams illustrating how collapsed glacial outwash formed. On the upper diagram, sand and gravel were deposited on the surface in front of the glacier. In places, this sand and gravel was deposited on stagnant ice; in other places on top of till; and in still other places it was not deposited because the stagnant ice was too thick. On the lower diagram, the ice has melted and only the gravel and till remain. In places where stagnant ice had been absent, a flat outwash surface resulted. Where there was once stagnant ice, an irregular outwash surface formed. In areas where no gravel was deposited, till covers the surface.

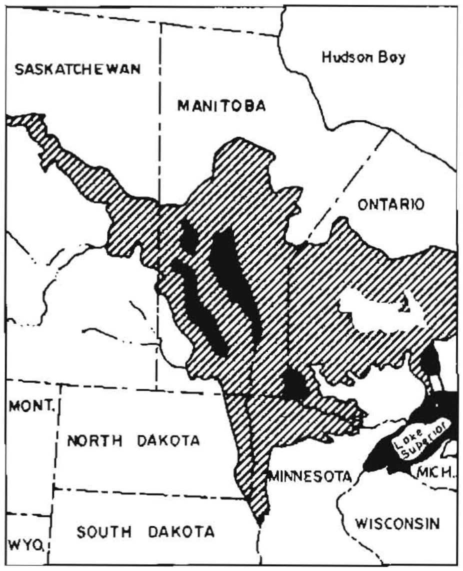


Figure 20. Map showing the area covered by glacial Lake Agassiz (shaded area). A few of the larger existing remnants of Lake Agassiz are shown as dark areas. They include Lakes Winnipeg, Winnipegosis, Manitoba, Nipigon, and Lake of the Woods.

Dakota in the southeast part of the state.

Over that part of the glacial Lake Agassiz plain near the Red River, one finds flat-bedded lake sediment: clay, silt, and sand, on the surface (fig. 21). These materials were deposited in deep, still water, some distance from shore. In places, the horizontal bedding was disturbed by such things as mud-flows in the loose, wet lake sediment, by boulders dropped from icebergs floating on the surface of the lake (fig. 22), by squeezing of the lake sediments between cakes of lake-surface ice that sank as the lake drained, by collapsing of lake sediments that were deposited on top of stagnant ice that later melted, or by overriding by a glacier.

Near the edges of the glacial Lake Agassiz plain, bouldery, wave-worn deposits of till are common. Beach ridges are also found along the edges of the lake plain (fig. 23). Some of the beaches are hundreds of miles long, more prominent in some places than others, generally a few hundred feet across, and composed of from 5 to 25 feet of gravel and sand. In some places the beaches are absent and wave-cut scarps are found instead.

To the ground-based observer, the glacial Lake Agassiz plain appears featureless in most places, but it takes on a new dimension when viewed from the air, from where one can see numerous markings. An example is the five- to ten-foot-deep grooves that were gouged out by floating lake ice when Lake Agassiz was shallow. Although the grooves themselves are difficult for the ground-based observer to see, they are reflected in the "beaded windbreaks" that are visible from Fargo northward to Gimle, Manitoba. The tallest trees in windbreaks that cross the ice-gouged grooves stand in the grooves themselves, because the soil there is less salty than is the soil on the intervening higher areas where the tree-growth is stunted.

Another example of patterned ground on the glacial Lake Agassiz plain that can be observed from the air is the network of intersecting ridges in the area north of Grafton. These apparently formed when large floes of lake ice sank into the soft bottom sediment as the lake drained, squeezing material out around their edges.

Long, low ridges called differential compaction ridges are found in several places on the glacial Lake Agassiz plain. They trend generally eastward or northeastward toward the Red River. Differential compaction ridges coincide with old stream routes that crossed the lake plain before it flooded for the last time. The last flooding of the lake caused a layer of silt and clay to be deposited on top of the stream deposits (fig. 24). Eventually, when the lake bottom materials dried out, the areas adjacent to the old, now-buried stream channels settled more than did the stream deposits so that they were left as compaction ridges.

The gradient on the glacial Lake Agassiz plain is slight, and streams that cross it follow strongly meandering routes. Oxbows and cutoffs can be seen along the routes of the Red River and its tributaries. The airborne observer can readily trace the many routes that streams such as the Park, Forest, Turtle, Elm, and Goose Rivers have

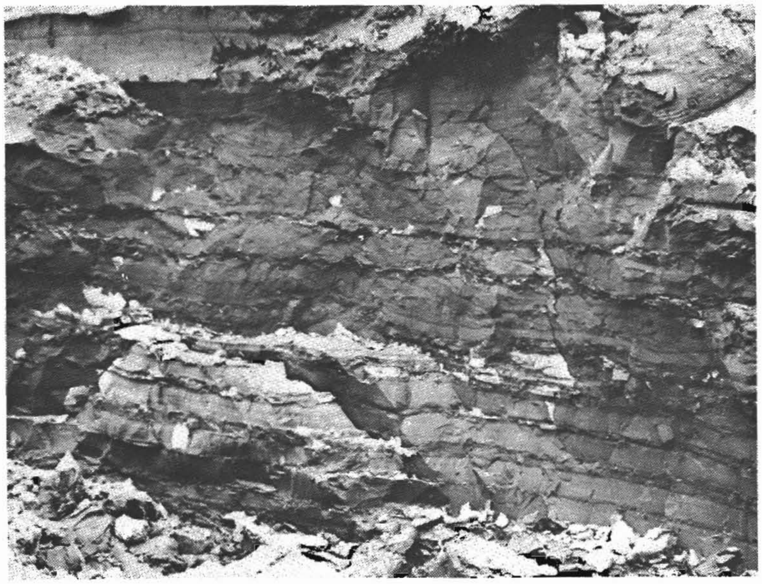


Figure 21. Layers of silt that were deposited in a lake of glacial melt water in southern Griggs County. The layers of iron-stained, generally light brown uniform silt, each about 4 inches thick, are separated by thin bands of darker-colored clay. The silt layers probably were deposited during summer months, the clay in the winters. This lake deposit is about 40 feet thick.

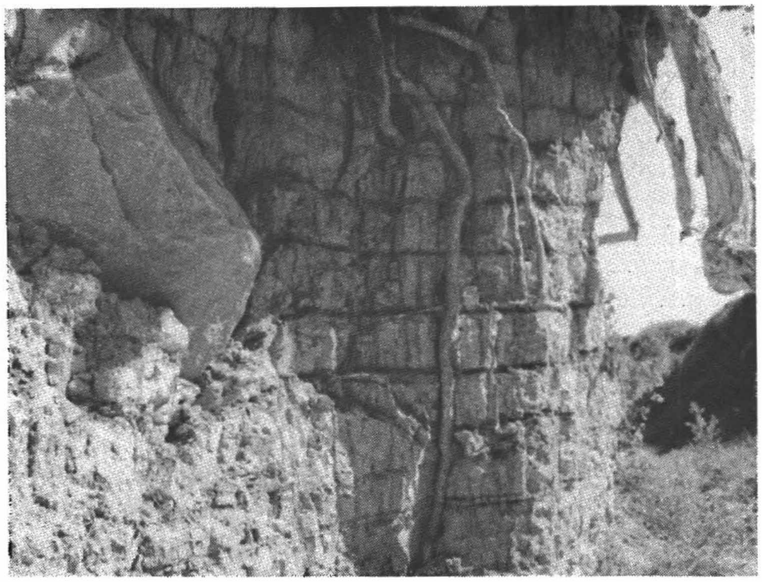


Figure 22. Banded lake sediment south of Mayville, North Dakota, in Traill County. The light-colored beds represent summer accumulation in Lake Agassiz, the material in the dark bands was deposited during the winters. The boulder was probably rafted by an iceberg and dropped into the lake at this point.

followed over the lake plain for a time, then abandoned when they built their beds too high.

The major river on the glacial Lake Agassiz plain is the Red River of the North. It was established in its present route about 9 300 years ago and, except for minor changes such as a few meander cutoffs and oxbows that have formed, its route has changed little since that time. Most of the meanders that were entrenched at the time the river first formed remain unchanged today.

Minor changes have resulted in the Red River Valley due to a buoyant process known as "isostatic rebound" (fig. 25). This rebound is a gradual rising of the earth's crust due to deglaciation of an area. It was greatest in the north because the glacier there was much thicker and heavier than it was in the south. As the earth's surface rebounded, the northward gradient gradually decreased, with the result that tributaries to the Red River tended to shift their courses so that they entered the Red River farther upstream. An example is the Red Lake River in Minnesota, which once entered the Red River about 20 miles downstream from its mouth at Grand Forks. An incidental, secondary effect of this shifting of the Red Lake River caused the flow downstream from Grand Forks to increase to an amount too great for the meandering route of the Red River to handle so that its meanders were "washed out" and the channel straightened as far as the old Red Lake River-Red River confluence.

Wherever large rivers flowed into glacial lakes, sandy deltas were built. Deltas that formed at the mouths of the Pembina and Sheyenne Rivers where they entered Lake Agassiz, at the mouth of the James River where it entered Lake Dakota, and at the mouth of the Souris River where it entered Lake Souris consist of irregular accumulations of sand. The surfaces of the deltas have been blown into dunes by the wind in places.

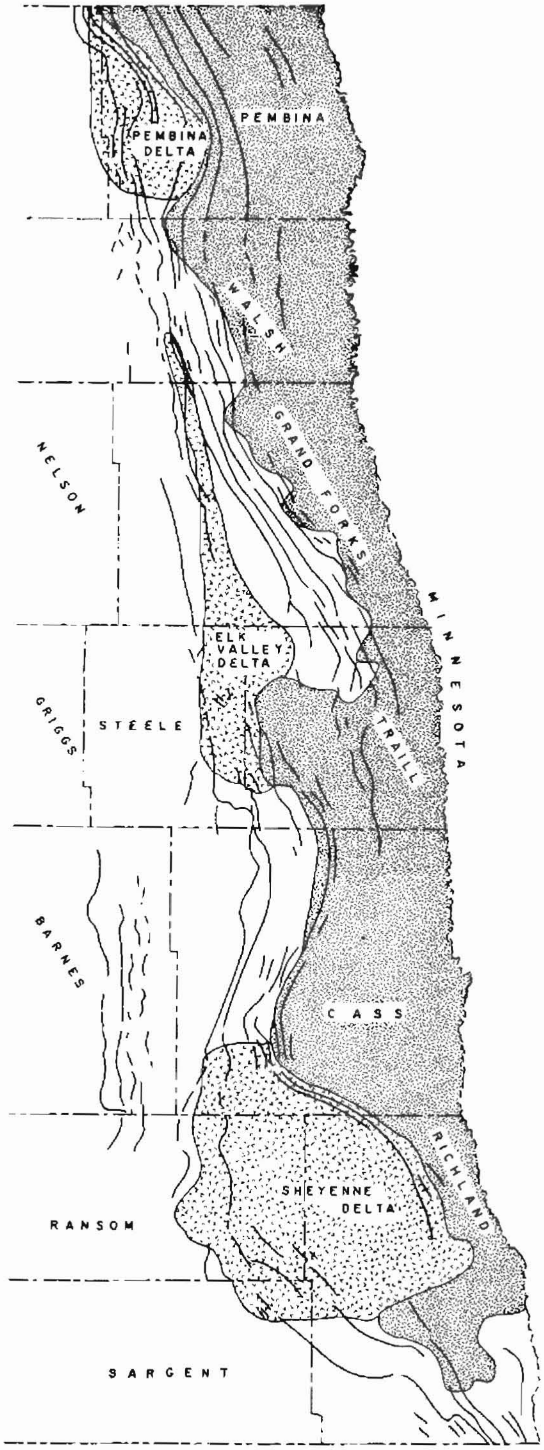
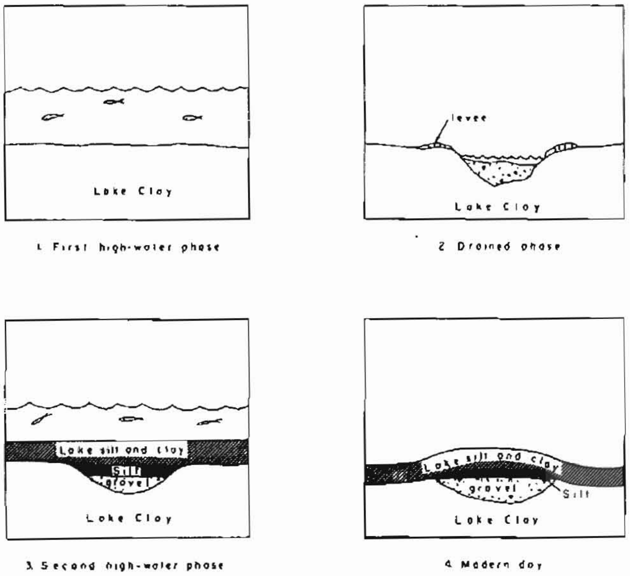


Figure 23. Map of easternmost North Dakota showing the locations of the Lake Agassiz beaches (the lines), the areas of offshore lake sediment (dark shading), and areas of delta deposits where rivers emptied into Lake Agassiz (light shading).

Lake shorelines

Many of the old shorelines of the larger glacial lake plains, such as Lake Agassiz, Lake Souris, Lake Dakota, and Lake Minnewaukan (pl. 1) are marked by beach deposits of sand and gravel or by wave-cut scarps (figs. 26 and 27). The most prominent glacial lake shore features in North Dakota are found along the former shorelines of glacial Lake Agassiz (fig. 23). The Lake Agassiz beaches or scarps are developed best where wave action was concentrated; larger beaches formed on the east side of Lake Agassiz in Minnesota than on the west in North Dakota because prevailing westerly winds resulted in greater wave activity on the east shore of the lake. The action of the waves tended to sort the lake deposits into silt and clay which were carried to deeper water, and sand and gravel which were reworked along the shore and deposited as extensive beaches in places. In other places, where only small amounts of sand and gravel accumulated, the old shorelines are marked by wave-cut scarps.

The levels of glacial lakes rose and fell often while the lakes existed. Well-defined beaches and scarps probably developed when the lake level remained stationary for a period of time. It is also possible that intense storms, events lasting only a matter



1. First high-water phase
2. Drained phase
3. Second high-water phase
4. Modern day

Figure 24. Steps in the formation of a compaction ridge. Clay is first deposited at the bottom of the lake. The lake then drains and a stream flows over the lake plain, depositing gravel and sand in its channel. The area is then flooded by the lake once again and a layer of silt and clay is deposited over the gravel. When the lake finally drains and the sediments dry, the fine-grained materials settle much more than the coarser gravels, which cannot be compressed.

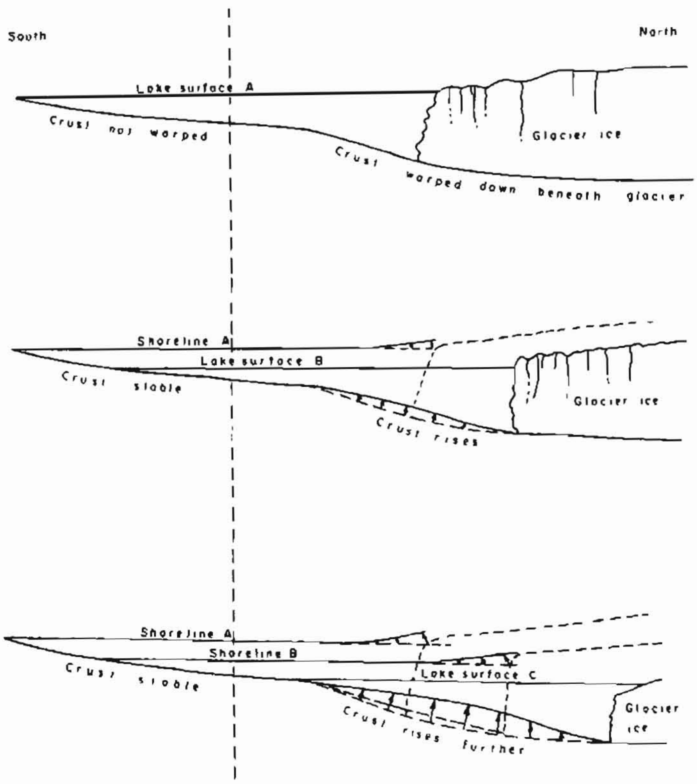


Figure 25. Three-part diagram illustrating why the old Lake Agassiz shorelines rise in elevation northward. The weight of the glacier in the upper (earliest) diagram has depressed the earth's crust. As the glaciers wasted northward from the Red River Valley at the end of the ice age, the earth's crust rose as the weight of the overlying ice was removed. Continued retreat of the ice allowed further bouyant rebound and both the first and second (A and B) shorelines were tilted upward toward the north.

Figure 26. Herman Beach deposits in Steele County. Lake Agassiz was to the east (right) of the exposure shown on this photo.

Figure 27. Closer view of a part of figure 26 showing sand and gravel in the Herman Beach. The lake was to the right.

Table 1. *This table shows how the various Lake Agassiz shorelines rise northward as a result of isostatic rebound, rise in the earth's crust that resulted when the weight of the overlying glacier was removed. The oldest and highest beaches rise the most because when they formed, much of the area was still glaciated. The younger, lower beaches do not rise much because, by the time they formed, much of the rebound had already taken place.*

	Southeastern North Dakota (elevation)		International Boundary (elevation)	
	ft.	m.	ft.	m.
Herman Beach	1 080	330	1 280	390
Norcross Beach	1 050	320	1 180	360
Tintah Beach	1 020	310	1 120	340
Campbell Beach	990	300	1 070	325
McCauleyville Beach	970	295	1 015	310
Blanchard Beach	945	290	985	300
Hillsboro Beach	910	277	950	290
Emerado Beach	890	270	925	280
Ojata Beach	850	260	880	268
Gladstone Beach	830	253	850	260
Burnside Beach	820	250	840	256

of days, may have built large beaches, so the size of the beaches is not necessarily an indication of the relative length of time a lake level persisted.

The former shorelines of glacial Lake Agassiz have been named and correlated (table 1). The correlations are based mainly on relative position and elevation. Thus, the highest continuous shoreline of Lake Agassiz is called the Herman level or the Herman Beach (after the town of Herman in Minnesota). The elevations on the Herman Beach in southeastern North Dakota are about 1 080 feet (330 metres) above sea level. The elevation of the beach rises northward to about 1 280 feet (390 metres) at the Canadian border. The northward rise in elevation of the beach is a result of the rebound of the earth's crust caused by deglaciation (discussed previously). Even though the beaches were essentially level when they formed, they rise northward markedly today.

Elevated lake plains

Countless small lakes flooded low areas on the insulated glacial ice of the Missouri Coteau, Prairie Coteau, and Turtle Mountains before the ice melted. As the ice melted, the sediment that had been deposited on the floors of these lakes slumped into an irregular surface (fig. 28) not at all like the small, flat lake plains of the Glaciated Plains. Some of the lakes were surrounded by glacial ice; when the ice around these lakes melted, the lake sediment that had been deposited in the lakes remained as lake plains that today stand above the surrounding land.

Melt-water trenches

Hundreds of melt-water trenches occur throughout the glaciated part of North Dakota. Most of these valleys were carved by rivers and streams of water flowing from the melting glaciers. Some of the melt-water trenches carried large rivers; an example is the valley in which the Sheyenne River flows today (fig. 29). Part of the time the Sheyenne River valley was being carved, it carried overflow from glacial Lake Souris in north-central North Dakota into glacial Lake Agassiz. At the height of its flow, it has been theorized that the Sheyenne River filled the trench from brim to brim, and its flow compared in volume with the modern flow of the Mississippi River downstream from St. Louis.

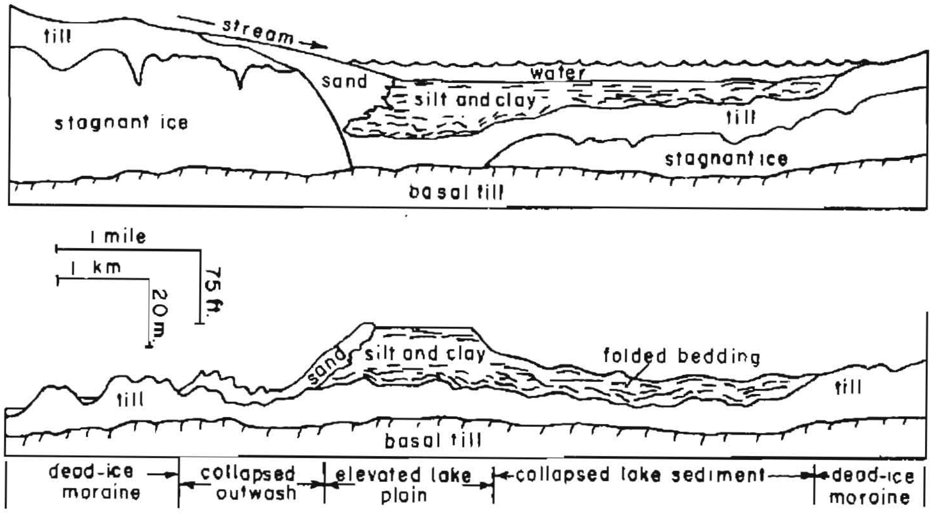


Figure 28. Schematic diagram showing conditions that led to the development of an elevated lake plain. The upper diagram shows silt and clay being deposited in the lake, which was situated over an area that was partially covered by stagnant glacial ice. The lake was insulated from the ice by a layer of till and it was warm enough to support abundant aquatic life such as snails and clams. Numerous fossil shells are commonly found in elevated lake deposits. The materials on top of the stagnant ice collapsed when the ice melted. This resulted in areas of dead-ice moraine and collapsed lake plains in places where stagnant ice had been present. In areas where stagnant ice was absent, the lake sediments did not collapse and they stand today as elevated lake plains.

Glacial erratics

Glacial erratics are found throughout the glaciated portion of North Dakota, and in certain places they are abundant. The lithologies of erratics have been studied in various parts of the state. Generally, in locations where large boulders are numerous, igneous and metamorphic rocks are most common, ranging from 50 to 70 percent of all the boulders. Limestone and dolomite commonly account for 5 to 15 percent of the boulders, and locally-derived bedrock types make up the balance in these areas. In locations where smaller boulders are numerous, carbonates and local bedrock types tend to constitute a larger proportion of the total, whereas if exceptionally large boulders occur, igneous and metamorphic rock may account for 90 percent of the total.

Glacial erratics are extremely abundant in certain areas. It is impractical to provide an exhaustive listing of bouldery areas, but a few places where erratics are particularly abundant include the south-central part of Walsh County; along the shore of Devils Lake in Benson County; the Lake Sibley-Lake Addie locality in Griggs County; near Milnor in Sargent County; near Hankinson in Richland County; on the Missouri Coteau between Minot and Williston; along the south edge of the Turtle Mountains near Dunseith in Rolette County; and east of the Missouri Coteau in Dickey and LaMoure Counties. Boulders are abundant in certain areas that have been washed by running water such as along the walls of melt-water trenches and on the shores of lake plains where wave action has removed the finer materials. Examples include the old Lanona lake plain near Karnak in southern Griggs County and along the former shore of Lake Agassiz in Grand Forks County. A particularly bouldery area occurs near Forman in Sargent County on the Prairie Coteau where boulders are at least 50 times more numerous than they are in otherwise similarly smooth areas of till in North Dakota.

In some places, unusually large boulders are abundant. Examples include stream valley walls such as the Sheyenne Valley near Fort Ransom (fig. 30); many of the high bluffs along the Missouri River; along the Des Lacs River near Velva, and

Figure 29. Two views of the Sheyenne River valley, a large melt-water trench that carried water from glacial Lake Souris in north central North Dakota to glacial Lake Agassiz in southeast North Dakota at the end of the ice age. Upper, air view is near Pekin in Nelson County (photo by Roger Reede). Lower photo is in southern Griggs County near Hannaford (photo by James Merritt).

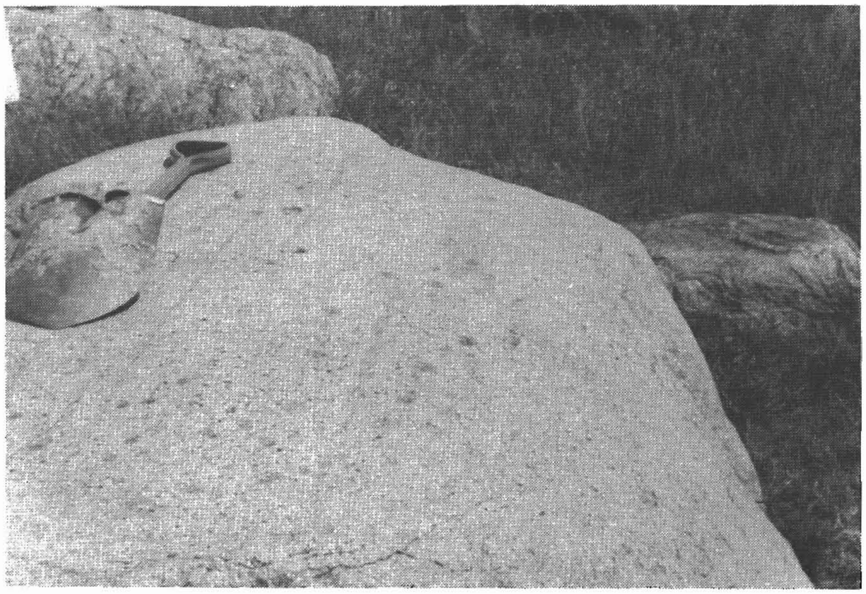


Figure 30. Large glacial erratic boulder near Fort Ransom in southeastern North Dakota. The upper surface of this 200-ton granite boulder was flattened as the glacier scraped its surface. Long grooves were carved in the flattened surface (parallel to the shovel handle).

along White Earth Creek in Mountrail County.

Glacial erratics have been used in the construction of foundations and, in a few places, for complete buildings. They have also been utilized for concrete aggregate and as rip rap to stabilize stream channels and on the faces of dams.

Many glacial erratics are grooved or polished due to abrasion by the moving glacier (fig. 31). Commonly, large isolated erratics stand in depressions or they are surrounded by a depression, a result of animals such as bison, and later cattle, using the boulders as rubbing stones, and loosening the soil around the boulders with their hooves (fig. 32). The wind then carried the loose soil away, forming the depressions.

Relationship of North Dakota's Soil and Vegetation to the Geology

Even though climate, topography, and groundwater have had the most direct influence on the formation of soils, the material the soils are formed from and the vegetation growing on the soils also contribute to soil development. The sediment in glaciated areas of North Dakota is a mixture of materials deposited by two glaciers. One moved out of central Manitoba and Saskatchewan and the other out of northwestern Manitoba. As they advanced, the glaciers ground up and homogenized the granite, limestone, and shale that they engulfed. The resulting glacial sediment is a mixture rich in the mineral nutrients on which plants thrive. Unglaciated areas of North Dakota, usually covered by a single parent rock such as shale, do not have such a diversity of mineral nutrients and, as a result, soils there are commonly less fertile than soils in glaciated areas.

Most of North Dakota's soils developed beneath grassland areas, although their overall characteristics are the result of soil-forming processes that were controlled by all of the different climates and types of vegetation that existed during the time the soils were forming, including the cool, moist period when spruce forest was widespread over the state at the end of the glaciation.

In grasslands, the dense organic "sod" or "turf" accumulates as it dies. The living grass forms a dense, matted root network in the subsurface. The humus that results from the decaying root network is implanted in the soil in a finely-disseminated form. The intimate

Figure 31. Limestone quarry at Stonewall, Manitoba, about 75 miles (120 kilometres) north of North Dakota. When the glaciers moved over rock like this limestone, they picked up large chunks of it, carried it southward, and dropped it as erratics. The long, straight line in the surface of the limestone, which extends toward the lower right-hand corner of the picture, is a striation that was carved by the moving glacier.

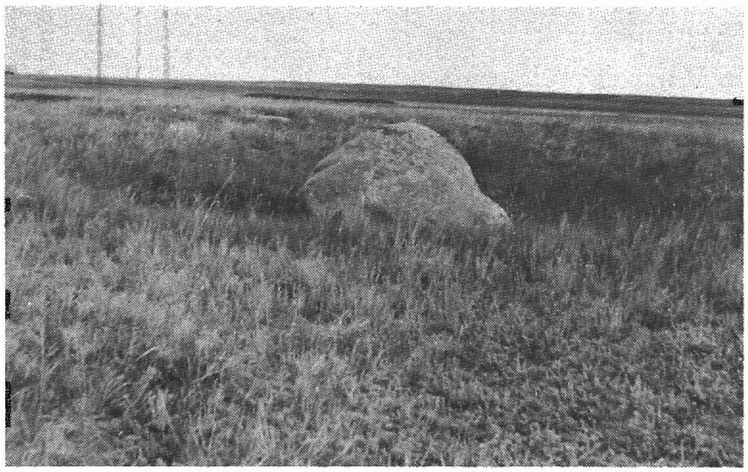


Figure 32. A glacial erratic, "buffalo boulder," in Divide County. This boulder is surrounded by a depression that was formed by animals such as bison rubbing against the boulder, working the soil around the boulder loose with their hooves. The loose soil was blown away by the wind. Photo by Ted Freers.

penetration by roots and humus insures a deep, inherent fertility and helps to give the soil a fine crumb structure and permeability provided that suitable parent materials are present. Grasses assimilate great quantities of nutrients, especially calcium, and they return large amounts of the nutrients .to the soil. As the grass decays, the efficient rooting system reassimilates the nutrients, thus maintaining an efficient and rich nutrient cycle.

Microclimates of prairie soils differ from those of the forest. More rapid evaporation of wind and sun takes place in grasslands than in forests, and the rapid transpiration of grasses draws on the soil-water around their roots. In North Dakota's wettest season, summer, the soil dries rapidly and moisture usually percolates only to root depth. In western North Dakota the subsoil is almost always dry.

The chernozem soils exist beneath the eastern edge of the mixed prairie and the prairie grasslands of North Dakota (fig. 33). Typically, chernozems are such a deep brown color that they appear black in a

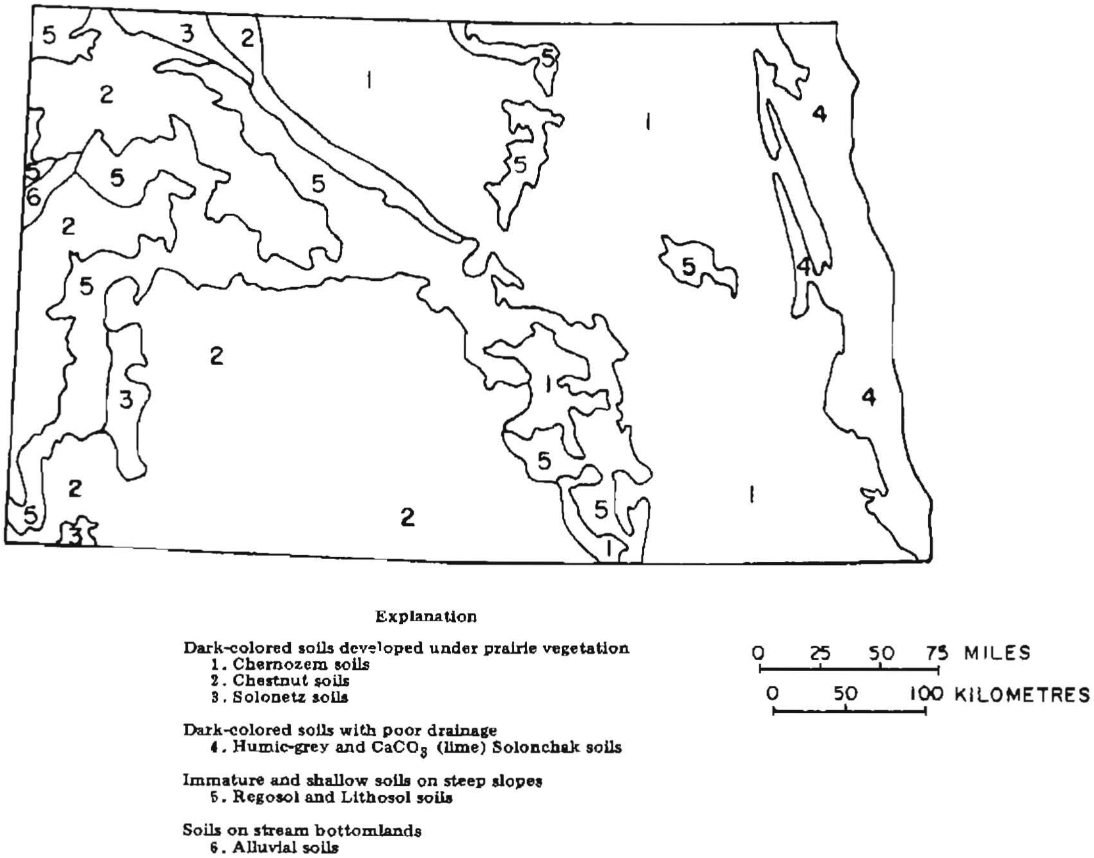


Figure 33. Generalized soil map of North Dakota. Adapted from Ableiter and others, 1960.

freshly-plowed field. Most of this deep brown color is due to organic content, humus. This dark-colored humus is so evenly distributed throughout the chernozem profile that even small amounts give a misleading impression of the amount present. The average chernozem in eastern North Dakota has an organic content of less than 10 percent. More than 16 percent is rare, but chernozems with as little as 4 percent humus still have the typical black coloration.

In western North Dakota, beneath the drier areas of mixed prairie, chernozems grade first to chestnut soils and finally, farther west in Montana, to brown soils. The chestnut soils, which are closely related to the chernozems, owe their paler coloration merely to the fact that they contain, on the average, only 2 to 3 percent organic material. This is partly due to the fact that in the drier climate of western North Dakota, the annual production of vegetable matter per unit area is reduced. The brown soils in Montana are even more lacking in organic matter and quite often contain no more than 1 percent humus. The actual depth of the soil zone also decreases with increasing aridity, and the horizon of lime accumulation thickens and occurs at progressively shallower depths. Alkalinity also tends to increase with increasing aridity.

Other soils found in North Dakota include the solonetz soils, which are associated with the chestnut soils in parts of western North Dakota (fig. 33). These alkaline soils form in areas of poor drainage and in areas where saline groundwater is escaping to the surface. Calcium-carbonate (lime) solonchak soils and humic-gley soils are found in the Red River Valley, the old glacial Lake Agassiz plain (fig. 33). These fertile grassland soils form in areas that tend to be poorly drained. Regosol and lithosol soils occur in areas where unconsolidated or slightly consolidated geologic materials are found. They are common in areas of steep topography such as on the dead-ice moraine of the Missouri Coteau and in the badlands (fig. 33). Alluvial soils are found on stream-laid sediments of flood plains of rivers and small streams (generally over areas too small to show on figure 33). Alluvial soils are extremely variable in composition, texture, and natural drainage, depending on the material they are developed on.

FOSSILS

Fossils are abundant in only a few places in North Dakota, and the casual observer may not be successful at finding them. The following discussion is not a catalog of fossil localities, but rather a general review of what some of the formations contain.

Fish scales and coccoliths are commonly found in exposures of the Cretaceous Niobrara Formation, which is exposed in several places in eastern North Dakota. The Cretaceous Pierre Formation, which is exposed in many eastern North Dakota river valleys, as well as in the southwest corner of the state, has produced some fossils, including some echinoids, a mosasaur in Barnes County near Kathryn, and abundant fragments of the clam *Inoceramus* from many outcroppings.

The Cretaceous Fox Hills Formation contains several kinds of clams, snails, fossil crab burrows, and at least one type of cephalopod. The formation is especially fossiliferous in parts of south-central Sioux County, a few miles east of Selfridge, where oysters and clams are abundant, and in parts of Emmons County.

The Cretaceous Hell Creek Formation contains some dinosaur bones. Bone fragments can be found in most badlands exposures of the formation and occasionally an entire bone, or even an entire skeleton may turn up. Part of a skeleton of the dinosaur *Triceratops* was taken from Hell Creek Formation sediments in Slope County in southwestern North Dakota. Fish bones are common in the Hell Creek Formation near Huff in Morton County, and mollusk shells can also be found in places.

The Paleocene Cannonball Formation contains lobster, crab, and clam fossils. It also contains Teredo-bored petrified wood, North Dakota's official state fossil. Teredo-bored petrified wood was bored by worm-like clams known as shipworms before it was petrified. It is less commonly found in the Pierre Formation. The Ludlow Formation, which was being deposited on land at the same time the Cannonball Formation was being deposited off shore, contains an abundant fossil assemblage, including fossil fish and turtles which have been collected at one site in Billings County. Fossilized crocodiles up to 16 feet long have been found along with fossil champsosaurs, which were similar to crocodiles, but not so large. A few small primate fossils and primitive horse and cow-like fossils have been found in Ludlow Formation sediment in North Dakota.

The Paleocene Bullion Creek and Sentinel Butte Formations contain fossil mollusks, but the most obvious fossil from these two formations is the abundant petrified wood and lignite, which is an accumulation of fossil plant material. It is possible to collect excellent fossil leaves and plant casts from the lignite in some places.

Well-preserved plant and animal fossils occur in the Eocene Golden Valley Formation sediments and the Oligocene White River Group sediments in some places. At White Butte, south of Dickinson, fossil fish, frogs, reptiles (including four genera of crocodilians), a small bird, and mammals, including rodents, carnivores, pantodonts, perrisodactyls, and artiodactyls, have been collected from the Golden Valley Formation. The White River Formation has yielded a few fossils in North Dakota, including titanothere bones and a rhinoceros.

The Pleistocene Coleharbor Group sediments have produced abundant fossil assemblages. These include pollen from a large variety of trees and smaller plants as well as assorted plant remains, both of which were especially common in lakes and sloughs that existed during and at the end of the ice age. Numerous fish, aquatic snail and clam shells, and land snails have been collected from glacial and postglacial lake sediments. Insect fossils and ostracodes are also found in lake sediments. Larger fossils dating to the Pleistocene in North Dakota include such animals as beaver, caribou, and mammoth remains. Bones of bison are commonly found in the banks of streams throughout the state. They date from a few hundred years old to several thousand years old.

At one fossil location in Stutsman County, North Dakota, the Seibold Site, more than 160 species of mollusks, ostracodes, insects, fish, amphibians, mammals, and plants were found. These animals and plants lived in and near a lake that came into existence while glacial ice was melting from the area. The lake persisted for several thousand years.

ROCK AND MINERAL COLLECTING

The gem stones of North Dakota are principally those formed by the precipitation of silica from cold water solutions. Moss agates are found in the gravels of the Yellowstone and Missouri Rivers in McKenzie County, especially on gravel bars where the Yellowstone and Missouri Rivers join, and near the town of Cartwright. Scenic agate, tube agate, iris agate, jasper, and sard are all commonly found in western North Dakota. Lake Superior type agates have been found along the Red River in places and in the old beaches of Lake Agassiz.

Petrified wood is found in areas where the Hell Creek, Ludlow, Slope, Bullion Creek, and Sentinel Butte Formations are exposed, especially in badlands areas. It is common along the Little Missouri River in McKenzie County. An excellent occurrence of petrified wood is located northeast of Searing in McKenzie County, and another location is 11 miles (18 kilometres) northwest of Mott in Hettinger County. Another outstanding location is about 10 miles (16 kilometres) north of Taylor in Dunn County. Petrified wood can be collected in many locations along the Cannonball River in Hettinger County and along the Cedar River in Adams County. The wood along the Cannonball River in Grant County is particularly well silicified.

Agatized fossil Sequoia cones and wood are recovered from the Hell Creek Formation near the junction of the Cannonball River and Cedar Creek in Grant County. The silicified, dark brown, walnut-sized cones, which belong to the species *Sequoia dakotensis*, may be exceptionally well preserved. Silicified pods of the extinct Katsura tree, the *Tempyska* fern, and *Osmundites* are also found with petrified wood.

Teredo-bored petrified wood is a fossil wood riddled with irregular, elongate borings that give the substance an abstract appearance. The borings were made by worm-like, bivalve mollusks ("clams") that are commonly called shipworms. (One genus of shipworm is *Teredo*; several other genera may have been responsible for the borings.) Modern species of shipworms bore their way into driftwood, pilings, and even ships. Teredo-bored wood found along the lower Sheyenne River in Ransom County is well silicified, jet black with the Teredo borings filled with amber-colored chalcedony. Teredo-bored wood is found in rock formations of marine origin. Most of the North Dakota Teredo wood has been collected from the Cannonball Formation, especially in the Bismarck-Mandan area. Teredo-bored wood has been officially designated as North Dakota's state fossil.

Rhombohedral gypsum crystals are common in places in the Cretaceous Hell Creek Formation and in the Tertiary Ludlow and Slope Formations where they crop out in Morton County. "Rosettes" of marcasite crystals are found in the Tertiary coal beds in many places. Gypsum crystals are also abundant in the shale of the Carlile Formation, exposed in the Pembina Hills area of northeastern North Dakota, in the offshore sediment of glacial Lake Agassiz, and in the glacial till throughout the state, especially in moist areas where springs are common.

Less well-known materials of potential interest to the rock hobbyist occur in the state, and still other materials not yet known to occur or not now exploited might well be searched for. Glassy clinker from burnt coalbeds, similar to obsidian and pitchstone, is apparently little used for gem purposes despite its attractive appearance. Prospecting could also be carried on for hard vitreous clots of coal from the vicinity of coal fires, which could be used like jet. The possibility exists that the bentonite beds in Stark and Bowman Counties, and elsewhere in the state, may contain opaline quartz, barite concretions, celestite crystals, zeolites, and other gem materials. Glacial erratic boulders, found throughout the glaciated areas of the state, may contain any of a large variety of gem minerals, but the occurrence of these is entirely unpredictable.

North Dakota, having no surface exposures of igneous or metamorphic rock in which deposits of the more valuable gem stones may have formed, is one of about 15 states each of whose annual production of gem stones, as estimated over the years by the U.S. Geological Survey and the U.S. Bureau of Mines, has been $1,000 or less.

GEOLOGIC TIME

A geologist, like an historian dealing with the development of civilization, needs some method of relating important events to one another. Unlike the historian, however, the geologist thinks in terms of millions of years, not years or centuries. Time is a fundamental consideration in all geological research, and yet it is difficult for many people to comprehend the immensity of geologic time. The earth is about 4½ to 5 billion years old according to most recent estimates. Suppose, for a moment, that all 5 billion years were compressed into a single imaginary year. At that scale, each second of our contemporary time is equivalent to 160 years of geologic time, each day to 14 million years. The earliest life on the earth appeared in late April of our imaginary year. Dinosaurs did not come on the scene until mid-December, and then they lasted only six days. The ice age began in North Dakota at about 6:45 p.m. on December 31 and ended only one minute before midnight. Primitive man arrived on earth between 10 and 10:30 p.m. in the midst of the ice age. At 13 seconds before midnight, Christ was born, and at 6 seconds, Leif Ericson discovered America. The United States of America, now celebrating its bicentennial, has existed for less than 2 seconds.

For geological purposes, a special geologic time scale has been devised (inside front cover) that consists of named units of geologic time during which the various rocks formed. The longest of these time units are referred to as eras. Each era is divided into periods, which in turn can be subdivided into still smaller units called epochs. These time units, arranged in chronological order, form a geologic calendar that provides a standard by which the ages of rocks can be referred to. Unlike years and days, the units of geologic time are of unequal duration. Through radiometric dating methods, we have determined the approximate ages in years of the various geologic time units.

Geologic time terms are frequently used in describing certain features and events in this report, and a knowledge of their origin may be helpful to the reader. The four geologic eras and their meanings are as follows: Cenozoic (recent life), Mesozoic (middle life), Paleozoic (ancient life), and Cryptozoic (hidden life). The Cryptozoic era is commonly referred to as Precambrian time. Precambrian time includes the interval from the beginning of the earth's history until the deposition of the earliest Cambrian sediments. It probably represents about 88 percent of all earth history.

In using the geologic time scale, notice that the oldest era is at the bottom of the chart (inside front cover). Successively younger eras are placed above it. Therefore, the geologic time scale is read from the bottom of the scale upward, the same order in which various geologic units were deposited, the oldest on the bottom, the youngest on top. Each era has been divided into smaller intervals of geologic time referred to as periods, which are named for the places where their rocks were first studied. Most of the periods derive their names from European localities.

The Paleozoic Era includes seven periods, each with its corresponding system of rocks. They are as follows, listed from oldest to youngest: Cambrian (from the Latin word *Cambria*, meaning Wales); Ordovician (for an ancient Celtic tribe that lived near the type locality in Wales);

Silurian (for the Silures, an ancient tribe of Wales); Devonian (for Devonshire, England); Mississippian (for the upper Mississippi Valley); Pennsylvanian (for the state of Pennsylvania); and Permian (for the province of Perm in the Ural Mountains of Russia). In Europe, the Mississippian and Pennsylvanian periods are commonly combined to form the Carboniferous Period (so named because it contains coal).

The Mesozoic Era includes the following three geologic periods, listed from the oldest to youngest: Triassic (from the Latin word *trias*, meaning "three," referring to the natural threefold division of these rocks in Germany); Jurassic (for the Jura Mountains between Switzerland and France); and Cretaceous (from the Latin word *creta*, meaning "chalk," referring to chalky limestones such as those in the White Cliffs of Dover).

The Cenozoic Era, which continues today, includes two geologic periods. The names of these two periods are derived from an outdated classification system that divided all the earth's rocks into four eras. The only names that persist are the Quaternary, implying "fourth derivation," and the Tertiary, implying "third derivation." The Quaternary follows the Tertiary in time.

The only epochs used in this volume are the five subdivisions of the Tertiary Period and the two of the Quaternary Period. The epochs are based on the relationships between life forms. The Tertiary epochs, from oldest to youngest, are the Paleocene ("ancient recent"), Eocene ("dawn of recent"), Oligocene ("little recent"), Miocene ("less recent"), and Pliocene ("more recent"). The Quaternary epochs are the Pleistocene ("most recent"), and Holocene ("recent"), which is the latest time division continuing to the geologic present.

The units discussed so far are the major divisions of geologic time. In addition to these, geologists work with smaller units of rock called "groups" and "formations." A geologic formation is identified and established on the basis of definite physical characteristics. Formations are usually given geographic names.

GEOLOGIC HISTORY

Sediment deposited by glaciers and their melt waters covers most of North Dakota, concealing the bedrock and landscape over which the glaciers moved. Even so, we can reconstruct the geologic history of the state long before the glaciers came by studying rock fragments and drill cores and geophysical logs obtained from the thousands of oil, gas, and water wells that have been drilled in the state, and by studying the rock exposed in southwestern North Dakota.

Precambrian History

Our knowledge of the Precambrian history of North Dakota is sketchy. It is based largely on information we have obtained from water, oil, and gas wells; from subsurface mineral exploration; and from studies of residual and observed gravity values and magnetic anomalies. No Precambrian rocks are exposed at the surface in North Dakota. Most of the information that has been collected on North Dakota's Precambrian rocks is from the eastern third of the state where the rocks are at relatively shallow depths. The discussion that follows is based in part on an unpublished manuscript dealing with North Dakota's buried Precambrian rocks prepared by Edward G. Lidiak of the Department of Earth and Planetary Sciences at the University of Pittsburgh.

The earliest recognizable geologic event in North Dakota was volcanic activity, which was widespread across the state in Early Precambrian time more than 2.6 billion years ago. This volcanic activity resulted in the deposition of ultramafic and mafic rocks (igneous rocks made up of dark-colored minerals composed mainly of magnesium and iron) and intermediate rocks (igneous rocks containing more silica than mafic and ultramafic rocks). Such rocks are found in the amphibole schist terrane (a terrane is simply an area where rocks of similar lithology predominate; amphibole schist is a foliated metamorphic rock that contains a large percentage of amphibole minerals), which occurs in several places in eastern North Dakota (fig.

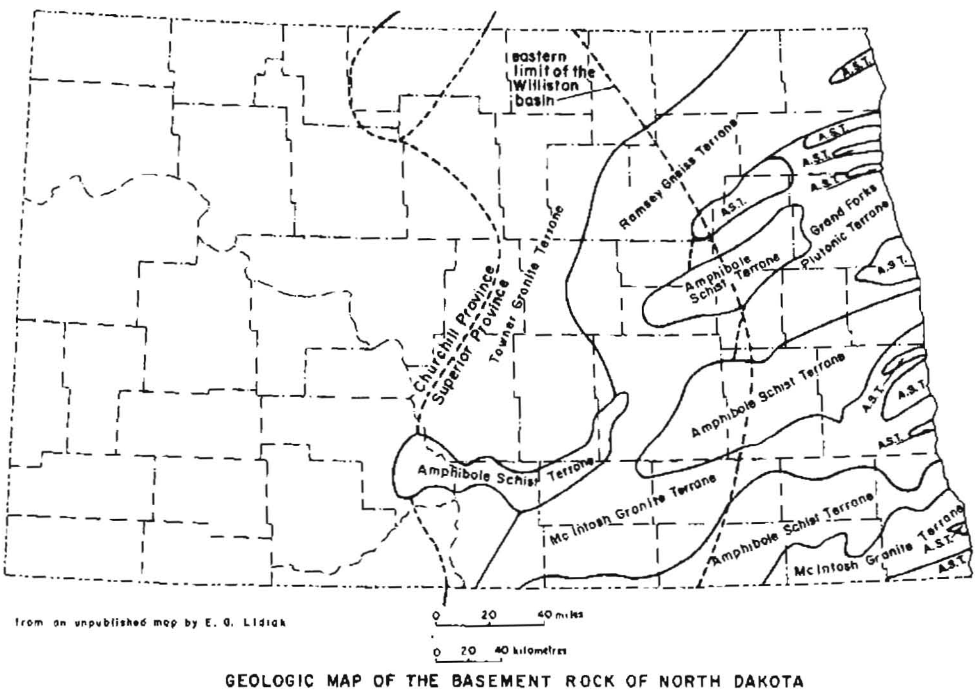


Figure 34. Map of the Precambrian surface. These Precambrian rock terranes are covered everywhere in North Dakota by younger sediments.

34).

The Precambrian rocks in the eastern part of North Dakota are granite and granite gneiss (a laminated metamorphic rock) with northeast-trending bands of schist. Magnetometer surveys have disclosed numerous local magnetic anomalies in eastern North Dakota. The anomalies are probably caused by magnetic iron-bearing rocks. They are commonly circular or ellipsoid in map view and they extend over a few square miles.

In Early Precambrian time about 2.7 to 2.4 billion years ago, the rocks of the amphibole schist terrane in eastern North Dakota were deformed and metamorphosed. The gneisses and schists of the other terranes probably formed during this time of orogeny (an orogeny is a mountain-building event) and large amounts of granite and granodiorite, which make up parts of the granitic terranes were emplaced.

A second major orogeny occurred between 1.9 and 1.6 billion years ago in western North Dakota. Metamorphism and igneous activity occurred at this time in western North Dakota. Only a few deep wells have penetrated Precambrian rock in western North Dakota, and it is not yet possible to subdivide that area into terranes. Four wells have penetrated Precambrian rocks in McKenzie and Williams Counties. Two of these wells penetrated altered monzonite and two penetrated orthopyroxine-bearing granulite gneiss. Two of the monzonites and one gneiss are situated on the Nesson anticline. Other wells in western North Dakota have penetrated biotite granite in Billings County and diabase in Oliver County.

The Williston basin probably owes its initial development to geologic processes operating late in Precambrian time or early in Cambrian time. Apparently, crustal uplift took place about this time in the interior of the Williston basin. The uplift resulted in erosion in an area that is now the location of a broad gravity high (a gravity high results from a concentration of higher-than-average density rocks, such as the granulites of Williams and McKenzie Counties). Subsidence then began early in Paleozoic time, perhaps as a result of buoyant readjustment of the dense, uplifted crustal block. Sediments that have accumulated in the Williston basin since the end of Precambrian time reach a maximum thickness of a little more than 16 000 feet (4 875 metres) a few miles southeast of Watford City in McKenzie County.

North Dakota's Sedimentary Sequences

Early in Paleozoic time, about 620 million years ago, North Dakota subsided relative to the Canadian Shield, and the smooth, eroded land surface sank beneath the seas, remaining submerged for much of the next 550 million years. During that time, thousands of feet of sediment that accumulated in the seas hardened into limestone, sandstone, and shale. The sea water, which was probably seldom more than a few hundred feet deep, was alive with a tremendous variety of marine plants and animals, some of whose remains decayed to form oil that became trapped within the rocks.

Even though the sedimentary rock in the Williston basin was deposited over a tremendous span of time, it does not record continuous deposition of sedimentary materials. The many gaps in the geologic record are known as *unconformities.* Sometimes unconformities resulted when certain layers were never deposited if, for example, the sea drained from an area for a time. In other areas sediments that were deposited were later removed by erosion. On the cross section beneath the geologic map of North Dakota (pl. 1), the major unconformities are represented by wavy lines.

The parts of the sedimentary record that are preserved, that is, the layers of sediment that represent intervals of time while seas covered an area, may conveniently be referred to as *sequences*. A sedimentary rock sequence normally begins (at the base) with the materials that were deposited when the sea flooded an area, and it includes all the materials that were deposited in the sea until it finally drained away. In North Dakota, six major sedimentary sequences are recognized. They are, in ascending order (from oldest to youngest): Sauk, Tippecanoe, Kaskaskia, Absaroka, Zuni, and Tejas. The Tejas sequence consists largely of materials that were deposited on land rather than in seas. Unconformities separate the sedimentary sequences. (Much of the material on North Dakota's sedimentary sequences which follows has been adapted from *Sedimentary and Tectonic History of North Dakota part of Williston basin* by C. G. Carlson and S. B. Anderson—North Dakota Geological Survey Miscellaneous Series 28.)

Sauk Sequence

The oldest sedimentary rock in North Dakota is sandstone, shale, and carbonate that was deposited in layers directly on an extensive and ancient unconformity, the eroded Precambrian basement surface described earlier. These sedimentary rocks belong to the Sauk Sequence, which in North Dakota has only one formation, the Deadwood. The Deadwood Formation was deposited in late Cambrian and early Ordovician time, about 500 to 550 million years ago, by a sea that flooded the area from the west, before the Williston basin started to subside appreciably. The Deadwood Formation is thickest in the western part of the state (fig. 35).

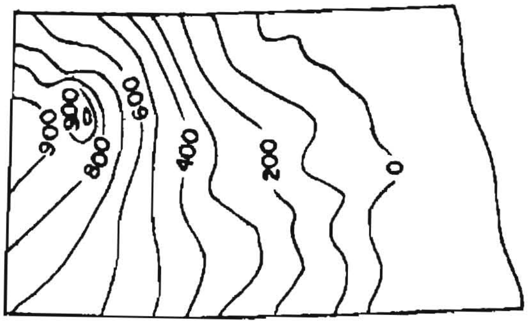


Figure 35. Sauk Sequence sediment. Contour lines indicate the thickness of sediment, in feet, that was deposited in seas from late Cambrian to early Ordovician time about 550-500 million years ago. This sediment constitutes the Sauk Sequence, which is represented in North Dakota by only one formation, the Deadwood. The area east of the zero contour was probably also flooded during this time, but sediment that was deposited there was later removed by erosion.

Tippecanoe Sequence

After the Deadwood Formation was deposited, the seas drained from North Dakota, leaving the land above water and subjecting it to erosion for about 30 million years, just as it is today. When the Williston basin began to subside in middle

Ordovician time, about 470 million years ago, seas again flooded the area, advancing from the south and east. The entire state was then flooded until middle Silurian time, a total duration of perhaps 50 million years. During this prolonged period of time, sedimentary rock of the Tippecanoe Sequence was deposited. Tippecanoe Sequence sediments are as much as 2 200 feet (670 metres) thick in western North Dakota (fig. 36).

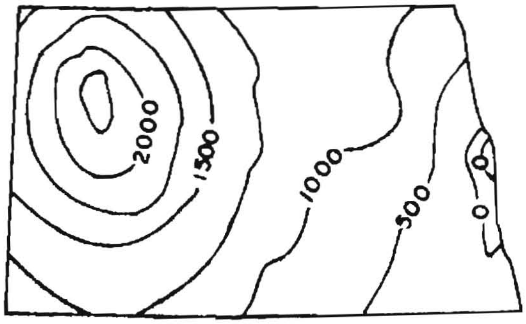


Figure 36. Tippecanoe Sequence sediment. Thickness, in feet, of the sediment that was deposited from middle Ordovician to middle Silurian time about 470-420 million years ago. The thickest preserved accumulation of sediment deposited during this period is about 2 300 feet (670 metres).

The oldest sediments of the Tippecanoe Sequence are sandstone, siltstone, and shale of the Winnipeg Group, which includes three formations: the Black Island, Icebox, and Roughlock Formations. The Black Island is a clean sandstone composed mainly of quartz; the Icebox is greenish gray, generally non-calcareous shale; and the Roughlock consists of fine-grained, calcareous siltstone and shale. The contacts between these three formations are mainly gradational.

Shallow-water marine deposition of carbonates followed the deposition of the Winnipeg Group; and thick layers of limestone and dolomite, along with minor amounts of shale and anhydrite, constitute the Red River, Stony Mountain, Stonewall, and Interlake Formations. The Red River Formation is mainly limestone and dolomitic limestone with thin beds of anhydrite in its upper part. The Stony Mountain Formation can be divided into a lower shaly limestone member that is known as the Stoughton Member, and an upper limestone known as the Gunton Member. The Stonewall Formation and the lower and middle portions of the Interlake Formation are mostly beds of finely crystalline dolomites. The upper part of the Interlake consists of a pelletoidal and fragmental dolomitic limestone.

Kaskaskia Sequence

During a 20-million-year interval of time beginning in middle Silurian time 420 million years ago, the surface of North Dakota was again above sea level so that deep weathering and intense erosion by rivers and streams resulted in a widespread unconformity. Then, from early Devonian time until late Mississippian time, a period of about 100 million years, the state was alternately flooded and dried as the sediment of the Kaskaskia Sequence was deposited. Limestone and dolomite were deposited in the seas, which dried repeatedly, causing thick layers of salt to build up as a result of evaporation.

While the Kaskaskia Sequence was accumulating, the Williston basin sank more than it had during the deposition of the previous two sequences, and the preserved accumulation of sedimentary rocks is more than 4 000 feet (1 200 metres) in part of western North Dakota (fig. 37).

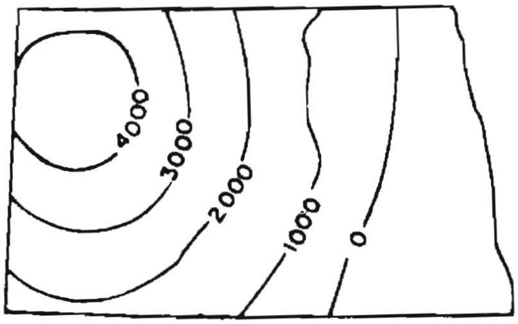


Figure 37. Kaskaskia Sequence sediment. Thickness, in feet, of sediment that was deposited from early Devonian time until late Mississippian time. The whole state was probably flooded during this time, but erosion has removed any sediment that was deposited in the area east of the zero contour. As much as 4 000 feet (1 200 metres) of the sediment that is included in the Kaskaskia Sequence still remains in northwestern North Dakota.

The reddish, weathered zone on the pre-Devonian surface that marks the unconformity between the Tippecanoe and Kaskaskia Sequences is commonly termed the Ashern. It is overlain by the Winnipegosis Formation, which consists of two members, a lower, fine-grained, silty and clayey limestone, and an upper limestone and anhydrite.

The Prairie Formation consists of evaporites, mostly halite (salt) and anhydrite. The evaporites, which are more than 500 feet (150 metres) thick in northwestern North Dakota, include several beds of potash. The Dawson Bay Formation is limestone and dolomitic limestone that overlies the evaporites of the Prairie Formation. The Souris River Formation consists of alternating limestone and thin shale beds that were deposited on a shallow shelf in the Late Devonian sea. The Duperow Formation consists of similar limestone and shale deposits, but it contains smaller amounts of shale than does the Souris River Formation. The Birdbear Formation consists mainly of limestone.

The Three Forks Formation consists of shale, anhydrite, siltstone, and dolomite. The present distribution of the Three Forks sediments reflects erosion that took place prior to Mississippian time on the edges of the Williston basin, but in the central part of the basin there was little, if any, erosion.

The Bakken Formation is divided into three units, a lower black shale, a middle calcareous siltstone, and an upper black shale unit. The lower shale is regarded as of Devonian age, with the upper two units being of Mississippian age. After deposition of the Bakken Formation about 350 million years ago, the Mississippian sea spread farther over the surrounding area as the Madison Formation was deposited.

In general, three subdivisions are recognized within the Madison Formation. They are the Lodgepole, Mission Canyon, and Charles Facies. The Lodgepole Facies is thin-bedded, clayey or cherty, mostly dense, light-gray to dark-gray limestone. The Mission Canyon Facies is massive-bedded, mostly clean limestone composed largely of fragmental and cemented pellets (oolites) ranging in color from brownish gray to light-yellowish gray. In the central part of the Williston basin, the Mission Canyon Facies is mainly fragmental limestone, whereas, on the margins of the basin, beds of oolitic limestone are more common. In some areas, the limestone has been partly to completely dolomitized. The Charles Facies consists of evaporites in association with thin-bedded carbonates. In the central part of the basin, the evaporites are mostly halite, whereas the basin margins contain mostly anhydrite.

The Mission Canyon and Charles Facies boundaries cross time planes (as do other formation boundaries) appearing at gradually lower stratigraphic levels toward the edge of the Williston basin (fig. 38). In detail these facies have complex intertonguing relations that are important for oil exploration. In fact, oil accumulations in the Madison Formation account for about three-quarters of North Dakota's crude oil reserve.

The Big Snowy Group lies on top of the Madison Group. It is divided into three formations, which, in ascending order, are the Kibbey, Otter, and Heath. The Kibbey Formation is divided into three lithologic units: a lower siltstone and shale, a middle limestone, and an upper sandstone. The Otter Formation consists mainly of greenish-gray to gray shale and thin-bedded, light-gray limestone. The Heath Formation is mostly gray to black shale.

Absaroka Sequence

In late Mississippian time, perhaps 320 million years ago, the seas drained from North Dakota, and the area was eroded for a few million years until early Pennsylvanian time. When seas again flooded the state in early Pennsylvanian time, sandstone, shale, and carbonate of the Absaroka Sequence were deposited. The seas were discontinuous and shallow, and salt again accumulated during times when the seas evaporated, particularly in Permian time. About 1 500 feet (450 metres) of sediment was deposited from early Pennsylvanian until late Triassic time (fig. 39).

The lower part of the Absaroka

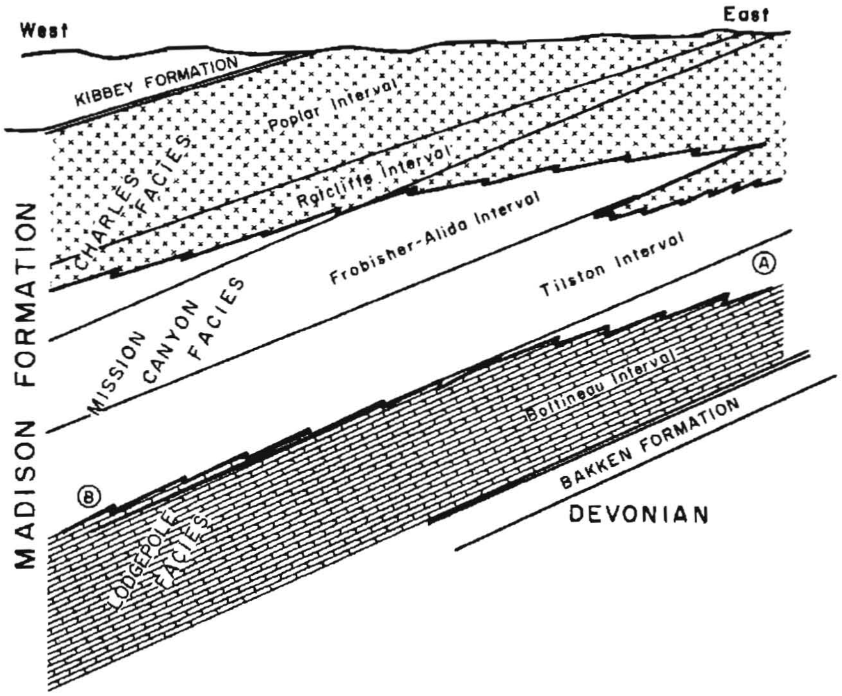


Figure 38. Generalized diagram of the Madison Formation. The straight lines separating the Intervals are time lines (the sediments along these lines are the same age everywhere). In contrast, the irregular lines separating the three facies of the Madison Formation cross the time lines so that the base of the Mission Canyon Facies (for example) is older in the east (at A) than it is in the west (at B) even though it is essentially the same material (limestone) in both places.

Sequence contains interbedded sandstone and mudstone beds of the Tyler Formation. These beds are overlain by interbedded carbonates and fine-grained clastics of the Amsden Formation. Above the Amsden, the Minnelusa Formation is mostly sandstone along with some limestone and shale.

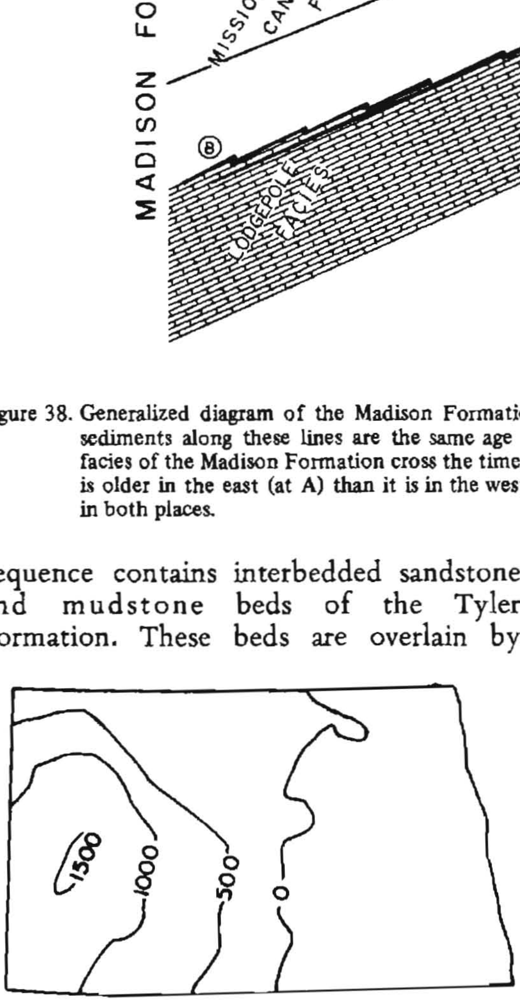


Figure 39. Absaroka Sequence sediment. Thickness, in feet, of the sediment deposited from early Pennsylvanian time until late Triassic time. The thickest preserved accumulation of sediment deposited during this time is about 1 500 feet (450 metres).

The Opeche Formation consists of red shale, siltstone, and evaporites, mainly halite. The Minnekahta Formation is limestone and anhydrite. The Spearfish Formation is divided into three units in North Dakota. They are a lower gray shale and red siltstone unit, a middle salt unit, and an upper red siltstone, sandstone, and shale unit. The lower two Spearfish units are marine deposits of Permian age, with the Permian-Triassic boundary somewhere in the upper unit.

Apparently a large meteorite impacted in McKenzie County in Triassic time (fig. 3). It disturbed the land over an area of several square miles and the underlying sediments to a depth of over 6 000 feet (1 800 metres). Similar meteorites struck in Manitoba and Saskatchewan at about the same time.

Zuni Sequence

In middle Jurassic time, about 160 million years ago, much of the state was once again flooded. Sandstone, shale, and carbonate of the Zuni Sequence were

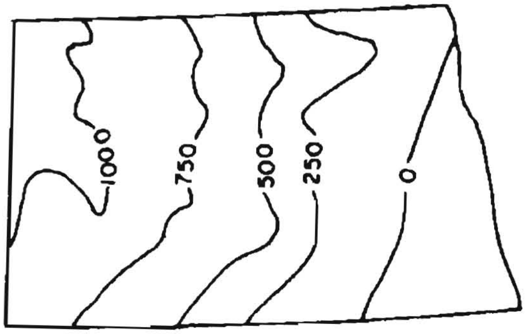


Figure 40. Thickness of Jurassic deposits.

deposited over most of North Dakota (figs. 40 and 41) in Jurassic time. The Zuni deposits include largely siltstone, shale, and sandstone. Throughout most of Cretaceous time, a period of perhaps 50 million years, silt and clay, which were later transformed to shale, were deposited in shallow seas.

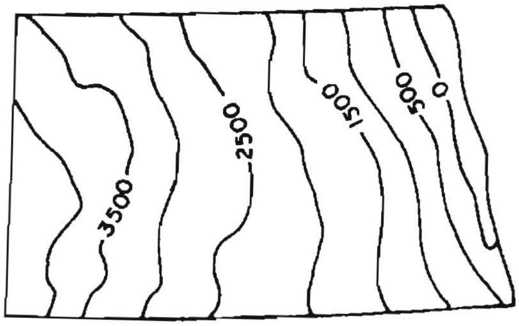


Figure 41. Marine Cretaceous deposits. As much as 4 000 feet (1 200 metres) of sediment accumulated in western North Dakota during Cretaceous time.

At the beginning of Jurassic time, beds of evaporites and red shale of the lower part of the Piper Formation were deposited. As the seas became more open, carbonates of the upper Piper were deposited, followed by silt and shale of the Sundance Formation.

Late Jurassic and early Cretaceous deposits include light-colored, nonmarine siltstone and shale of the Morrison and Lakota Formations. Little, if any, erosion took place in the Williston basin area before the Cretaceous sea inundated the area. Marine Cretaceous sediment is present in all but the extreme southeast corner of North Dakota, although it probably once covered the entire state. Cretaceous sediment has a thickness of over 4 000 feet (1 200 metres) in western North Dakota (fig. 41).

The Dakota Group has been divided into five formations. In ascending order, they are the Lakota, Fall River, Skull Creek, Newcastle, and Mowry Formations. The upper three formations are easily distinguished. However, the Lakota and Fall River Formations consist of interbedded sandstone and shale beds that thicken and thin abruptly and make correlation of separate beds and subdivision of the units difficult. The Lakota Formation consists of as much as 200 feet (60 metres) of lenticular sandstone, siltstone, and shale beds of both marine and nonmarine origin. The Fall River Formation consists of beds of sandstone and gray shale of mostly marine origin. The overlying Skull Creek, Newcastle, and Mowry Formations consist, in ascending order, of marine shale, sandstone, and shale.

The upper part of the Cretaceous System consists of clastic rocks that were deposited mostly in a marine environment; and, in fact, all the formations from the Belle Fourche through the Pierre are mostly thick beds of gray shale. As Cretaceous time drew to a close about 75 million years ago, the sand and silt of the Fox Hills Formation were deposited in the seas that were draining from the state by that time, although the seas may have persisted in extreme eastern North Dakota until well into Paleocene time, allowing slow but continuous marine deposition of the Pierre Formation until that time.

The Fox Hills Formation was deposited near the shore of a sea, and the materials washed into the sea were somewhat coarser than were the silt and clay of the underlying formations, which were deposited at greater distances from shore. The Hell Creek Formation, which was also deposited toward the end of Cretaceous time, consists of still coarser material, mainly sand, silt, and clay, that was deposited by running water flowing on deltas into the same seas in which the Fox Hills and Pierre Formations were being deposited. It was at the end of Cretaceous time, as the Hell Creek Formation was being deposited, that the last dinosaurs died.

The sandstone and shale of the

Ludlow, Cannonball, and Slope Formations were deposited at the beginning of Tertiary time, perhaps 70 million years ago, by the only invasion of Tertiary seas into North Dakota. As the Paleocene sea water gradually flooded the area, alternating layers of marine sandstone and shale of the Cannonball Formation were deposited. At the same time, silt, sand, and shale of the Ludlow and later, the Slope Formations were deposited on land. The Ludlow, Slope, and Cannonball sediments were then covered by the lignite-bearing sediments of the Bullion Creek and Sentinel Butte Formations. The Ludlow, Slope, Bullion Creek, and Sentinel Butte Formations, which crop out over much of western North Dakota, contain nearly all the state's coal. The sediments of these three formations were laid down in vast marshes, somewhat like those along the east coast of the United States today. Streams meandered through the low-lying swamps, but they flowed slowly and often became choked with silt, clay, leaves, and wood of the thick swamp vegetation. These materials were dropped in quiet areas and soon covered by sand and silt as the streams shifted course. This happened repeatedly so that great expanses of organic material were deposited and covered as time went on.

The overlying weight of sediment over long periods of time compacted and hardened the organic material to lignite coal. It took perhaps 150 years to accumulate enough material for a single foot of coal, and some of the coal beds in western North Dakota are up to 40 feet (12 metres) thick. While the coal was forming during Paleocene time, mammals were rapidly evolving and diversifying.

The Sentinel Butte Formation covers the Bullion Creek Formation in many parts of western North Dakota (pl. 1). While the Bullion Creek Formation was being deposited in central North Dakota, the swamps farther west were gradually filling as rivers carried sand and silt (now the Sentinel Butte Formation sediments) eastward over river plains onto the Bullion Creek sediments.

Bright-colored clayey and sandy layers of the Golden Valley Formation were deposited in lakes and rivers in latest Paleocene and early Eocene time. These layers can be seen on top of Sentinel Butte Formation beds in a few places in western North Dakota. During Eocene time, the climate gradually changed from a warm-temperate one to subtropical, although there was an overall tendency during Tertiary time toward colder climates.

Tejas Sequence

After the deposition of the Golden Valley sediment, much of western North Dakota was widely eroded and weathered. Following several million years of erosion, deposition of the Tejas Sequence began in Oligocene time. The first sediments, which were deposited in lakes and streams, were the pinkish siltstone, clay, freshwater limestone, volcanic ash, sand, and conglomerate of the White River Group.

Miocene- or (perhaps) Pliocene-age lake sediments containing considerable volcanic ash that blew into the lakes from the Rocky Mountain area, are preserved on top of the Killdeer Mountains and in other scattered areas of western North Dakota. The original maximum extent of the Oligocene and Miocene sediment (White River Group) in North Dakota is not known because large amounts of this sediment were removed during erosion that took place in Pliocene time. Streams flowing over the area in Pliocene and early Pleistocene time left some gravel deposits that are known as the Flaxville Formation. No Miocene or Pliocene deposits are shown on plate 1 because they are restricted to small areas. By the end of Tertiary time, western North Dakota had become a rolling upland.

Pleistocene Epoch

Throughout most of the past 600 million years, North Dakota's climate was warmer than it is now, more like Florida or the Bahamas than present-day North Dakota. Fossil records show, for example, that during Cretaceous and early Tertiary time (135 million years ago until 50 million years ago), palms, *Metasequoia, Sassafras, Gingko, Fagus*, and other typical temperate

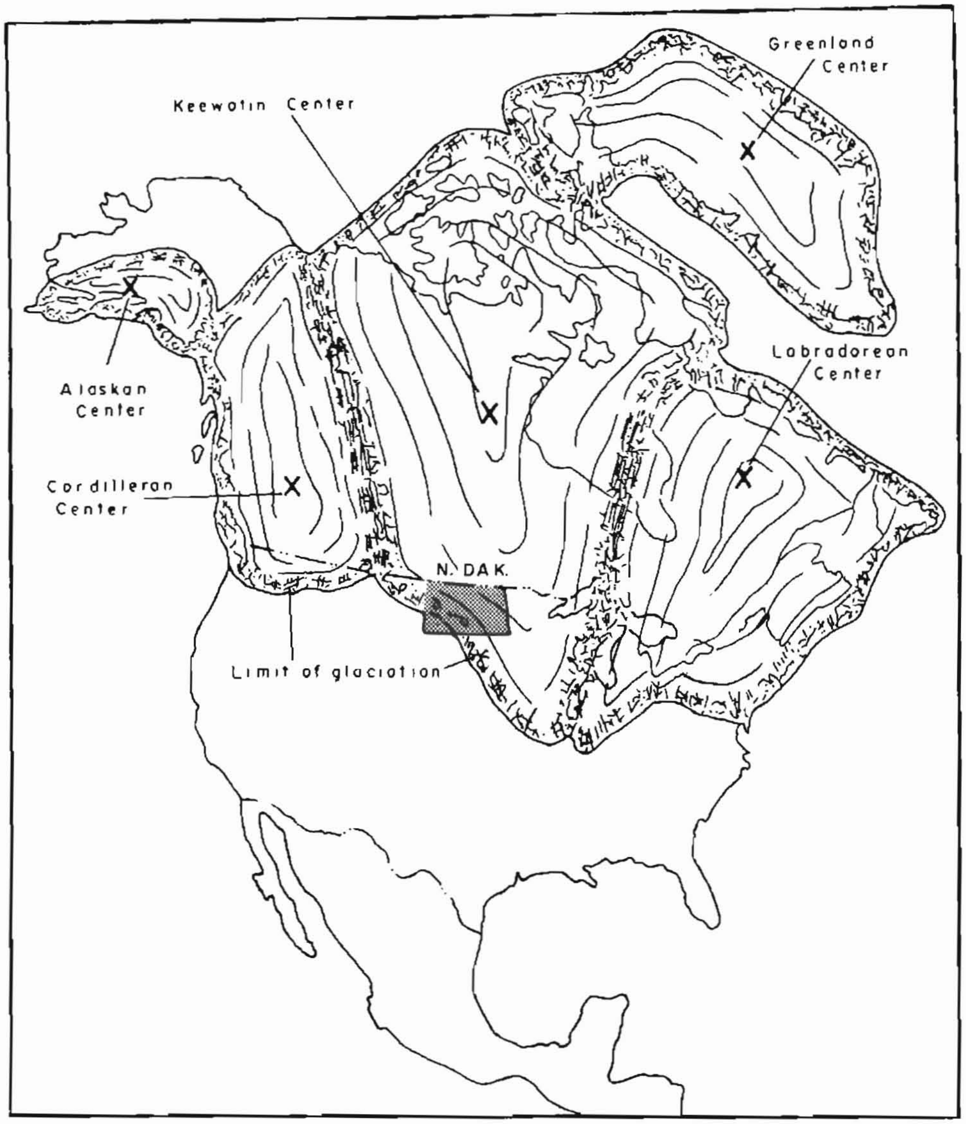


Figure 42. Map of North America showing the limits of continental glaciation during the ice age. The main centers of snow accumulation from which the ice moved are shown. North Dakota was glaciated by ice that moved from the Keewatin center west of Hudson Bay.

and subtropical plants ranged throughout North Dakota. Throughout much of Paleozoic time, 600 million until 200 million years ago, carbonates were deposited in warm seas. By contrast, since about mid-Pliocene time and continuing throughout the Pleistocene Epoch, North Dakota has had a continental climate with cold winters and hot summers. During much of this time, a succession of great ice sheets inched southward from Canada, across North Dakota and far to the south (fig. 42) drastically altering a landscape that had been developing for millions of years.

Each time glaciers advanced over North Dakota, they transported vast quantities of rock and soil that they picked up, pulverized, and re-deposited as glacial sediment. During the most recent glacial age, known as Wisconsinan time (approximately 70 000 years ago until 10 000 years ago), glaciers advanced over various parts of the state several times so that the Wisconsinan deposits at any one place generally consist of two to five layers of glacial sediment interbedded with either lake sediment or alluvial material (fig. 43). In some places, soils that had developed on a surface of glacier, river, or lake sediment

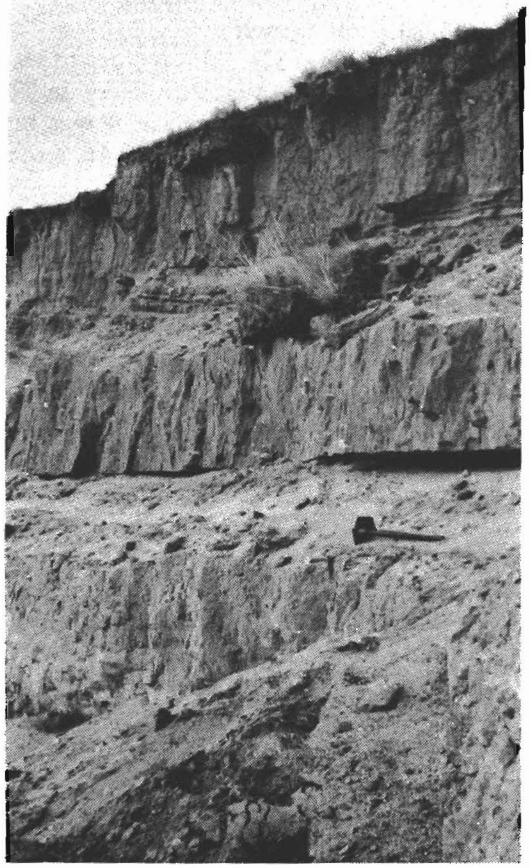


Figure 43. Three layers of glacial sediment exposed near Riverdale along Lake Sakakawea in McLean County. The layers of glacial sediment are separated by water-deposited sand and gravel.

were buried when a new layer of sediment was deposited on top of the soil. These old, buried soils (paleosols) are good markers for helping to determine the age of the buried layers of sediment.

The composition of the glacial sediment depends on the rock and sediment over which the depositing glacier flowed. For example, ice that advanced from the northeast into the Red River Valley deposited sandy, granite-laden sediment derived from the Precambrian rocks of northwest Ontario. Ice that advanced into the Red River Valley from the northwest deposited clayey, shale-laden glacial sediment derived from the Cretaceous shale in eastern North Dakota and southwestern Manitoba. Ice that advanced from the north into the Red River Valley deposited either sandy, lime-laden sediment in the northern part of the Valley where Paleozoic limestone and dolomite are exposed, or clayey sediment containing few pebbles in the south where thick layers of lake sediment cover the pre-Pleistocene rocks.

Coleharbor Group

All the sediment related to glacial deposition in North Dakota, that is, materials deposited by the ice and by flowing and ponded water associated with the ice, as well as sediment deposited since the ice melted, are collectively referred to as the Coleharbor Group. Sediment of glacial origin covers about three-quarters of North Dakota (fig. 44), mainly north and east of the Missouri River. Post-glacial sediment forms a discontinuous cover over the entire state. Detailed stratigraphic studies of the Coleharbor Group deposits have been completed in some parts of North Dakota, northwest Minnesota, and southern Canada, with the result that several formations have been recognized and named. However, correlations among the various formations within the Coleharbor Group are still the subject of lively debate, and the formations will not be dealt with in this report.

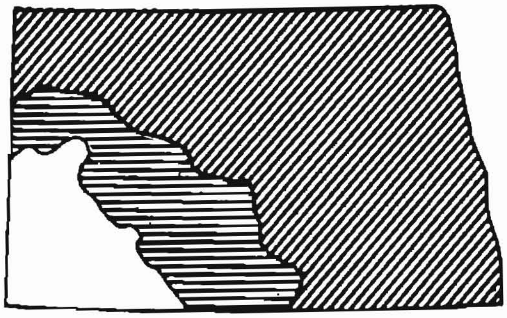


Figure 44. Map showing the part of North Dakota that was glaciated (shaded area). The diagonal pattern indicates the area that was glaciated during the most recent glaciation, the Wisconsinan. The horizontal pattern indicates the area that has earlier glacial deposits at the surface.

The thickness of the Coleharbor Group ranges up to over 600 feet (180 metres) in places on the Missouri Coteau and perhaps to over 800 feet (250 metres) on the Prairie Coteau (fig. 45). By volume, over 99 percent of the Coleharbor Group sediments in North Dakota are restricted to the part of the state north and east of the Missouri River. Over this area it averages

155 feet (47 metres) thick. The Coleharbor Group includes all materials that can be shown to have been distributed or disturbed by glaciers in some way; that is, any preglacial sediment that was obviously crushed or moved around somewhat by the ice is considered to belong to the Coleharbor Group.

Figure 45. Map of North Dakota showing the thickness, in feet, of the Coleharbor Group sediments. The thickest accumulations generally occur on the Missouri Coteau and in the Red River Valley. Black areas on the map represent areas of particularly thick glacial sediment.

In areas where the Coleharbor Group sediments are more than a few feet thick, the landscape is almost entirely the result of action by glaciers. Long, looping ridges of chaotically mixed clay, silt, sand, and boulders mark locations where the retreating ice front stood in a stationary position for a prolonged period of time. As the ice front retreated, melt water flooded low areas, forming shallow lakes. Here and there, melt-water streams deposited clean sand and gravel in their channels or in broad aprons.

Post-glacial sediments cover the glacial sediments to a depth of a few feet over much of North Dakota. Several tens of feet of stream sediment are found in many river valleys and, in areas where slopes are steep like in the badlands, several feet of material have washed into low areas from nearby uplands. Wind-blown silt covers the surface in many parts of North Dakota. It is thickest in areas where large amounts of nearby glacial outwash were available for the wind to erode. In ponds and sloughs, layers of silt and clay have accumulated to thicknesses of several feet since the end of the ice age.

Drainage Development During the Pleistocene Epoch

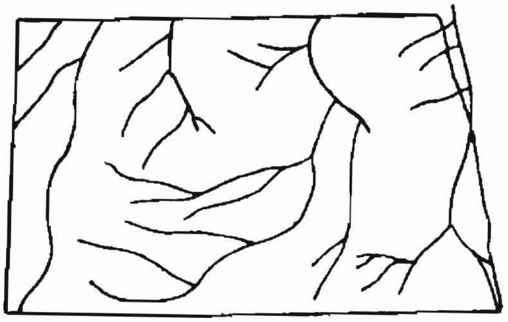


Figure 46. Drainage pattern in North Dakota before the state was glaciated. All major streams drained northward into Canada. When the glaciers advanced over the state, the drainage was blocked and diverted. Some of the valleys were completely filled with glacial sediment when the glaciers advanced over them; others were reoccupied by streams after the ice melted.

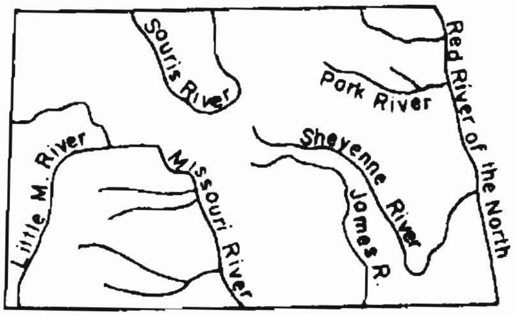


Figure 47. Modern drainage pattern in North Dakota. The Missouri River valley developed when north and east flowing streams were diverted along the margin of the glacier.

The overall drainage pattern southwest of the Missouri River in North Dakota is about the same as it was before the state was glaciated (figs. 46 and 47). Rivers like the Cannonball, Heart, and Knife all flowed northeastward as they do today, but they continued northeastward into eastern and northeastern North Dakota. During Pleistocene time, these and other streams were blocked in eastern North Dakota and forced to flow southward along the margin of the advancing glacier. Numerous diversion trenches formed along the margin of the glacier in this way, but most of these valleys were later buried beneath glacial sediment. Many of the rivers and streams southwest of the Missouri River follow routes that appear to be structurally controlled in places. An example is the Little Missouri River, which makes several unusually sharp right-angle turns.

The Missouri River valley is one of the diversion trenches that formed along the margin of the glacier and was not later buried. Certain parts of the Missouri River valley that trend northeastward are considerably older than parts that trend southward. They follow parts of old valleys that can be traced northeastward beneath the cover of glacial sediment. These older parts of the Missouri River valley are wider than are the younger, southward-trending segments of the valley.

In western North Dakota, a glacier blocked and diverted the Little Missouri River, causing it to flow eastward. Prior to its diversion by the glacier, the Little Missouri river flowed north into Canada. After the glacier changed its course, the river flowed over a shorter, steeper route than before, and as a result, it began cutting rapidly downward, eroding deeply and carving the badlands.

In addition to disrupting old drainage patterns, water flowing from the melting ice carved large new valleys such as those of the James, Sheyenne, and Souris Rivers. The southerly and southeasterly routes of several North Dakota streams tend to parallel the regional slope rather than to flow downslope as one might expect. As soon as these streams were forced into their present routes by the margin of the glacier, they rapidly carved valleys in which they remain entrenched.

As most of North Dakota's preglacial drainage was directed northward (fig. 46), the advance of the glaciers dammed many of the streams, causing lakes to form in their valleys. Evidences of numerous lakes are found in the layers of lake sediment that are commonly penetrated by wells located in valleys now buried beneath thick accumulations of glacial deposits. Most of these ice-dammed lakes were probably short-lived as the glaciers continued to advance over the valleys, obliterating the lakes. The largest ice-dammed lake that formed was Lake Agassiz in the Red River Valley.

Lake Agassiz

Rivers have flowed northward through the Red River Valley over routes similar to that of the modern Red River since long before the state was glaciated (fig. 46). This north-flowing runoff contributed to a large, ice-dammed lake, Lake Agassiz, south of the receding glacier in the Red River Valley. The combination of stream runoff and glacial melt water eventually caused Lake Agassiz to flood a large area of Canada, northwest Minnesota, and eastern North Dakota (fig. 20). As the glacier continued to shrink, the level of Lake Agassiz fell, leaving an array of beaches along the old shorelines and thick accumulations of bedded silt and clay where the water had been deepest. Lake Agassiz drained southward through the Minnesota River valley to the Mississippi River while it was at its higher levels, but as the water level dropped and the glacier continued to melt, the lake drained through lower, more northerly outlets.

The history of Lake Agassiz has been worked out in considerable detail. The lake began to form about 13 500 years ago when the glacier first receded far enough to expose the southern drainage divide, the extreme southeast corner of North Dakota. Considerable amounts of stagnant ice still remained behind, however, in Barnes, Cass, Ransom, Richland, and Sargent Counties as the main glacier receded. The melt water from the ice that flooded these areas deposited thin layers of sand, silt, and clay over the ice. When the stagnant ice eventually melted, these deposits slumped down, disrupting and destroying their original bedding planes.

A few hundred years later, about 12 800 years ago, the glacier in the Red River Valley stopped receding or perhaps even readvanced a short distance, resulting in a stabilization of the lake. The highest well-developed beaches, the Herman Beaches, were formed about this time.

In the center of the Valley, the offshore sediment, which is as much as 150 feet (45 metres) thick, can be subdivided into at least five separate, widespread units. Two, and perhaps three, glacial readvances of as much as 50 miles (80 kilometres) left layers of glacial sediment interbedded with the sediments of Lake Agassiz.

About 11 000 years ago, the glacial ice receded into northern Minnesota, allowing Lake Agassiz to drain eastward into Lake Superior. While the lake was drained, until 9 900 years ago, a boreal (northern) spruce forest grew in the Red River Valley. Then, about 9 900 years ago, the ice readvanced in northern Minnesota, blocking the drainage route to Lake Superior, causing Lake Agassiz to flood the Valley once again. The spruce forest was drowned and covered by a few feet of silt and clay as the water rose once again to the Campbell Beach, the largest and most extensive of the many Lake Agassiz beaches. Finally, about 9 300 years ago, Lake Agassiz drained for the last time as the ice receded, allowing it to drain eastward to Lake Superior.

Pleistocene Climates

The western United States mountains, the Rocky Mountains, began to form about 70 to 80 million years ago at the close of Cretaceous time and they have continued to rise to the present day. As they rose, they formed a barrier to the movement of east-flowing air masses and cut off the inflow of humid air and precipitation from the Pacific Ocean. As a result, the Great Plains gradually tended to become semiarid in Tertiary time.

The past two million years, the Pleistocene Epoch, and to a lesser extent, the Pliocene Epoch before it, have been a time of cooler, more humid climate marked by several periods of glaciation. It has generally been theorized that, as the glacial climate intensifies, tundra, scrub, conifer, and deciduous forests tend to shift as belts before the advancing ice and then follow it back as it melts. The ice that advanced into North Dakota probably moved into a semiarid grassland area as the North Dakota plains by that time were in the "rain shadow" of the western mountains. It seems likely that the ice age was preceded in North Dakota by cold, relatively dry conditions.

The cool, humid periods of glacial advance, alternating with the warmer, drier interglacial periods, resulted in successive destruction and reestablishment of all vegetation. Presumably, the glaciers moved southward from a region that was originally tundra and boreal, coniferous forest. Along their southwestern flank, the glaciers advanced over aspen woodlands into the prairies of Canada, North Dakota, and Montana. The advancing ice obstructed the north-flowing drainage systems, and the increased moisture that resulted from ponding of streams and decreased evaporation permitted the invasion of a few pioneer forest species.

Glacial ice was still present on the Turtle Mountains and the Missouri Coteau between about 12 000 and 9 000 years ago, about the same time Lake Agassiz was in existence, but it was insulated by a layer of glacial sediment upon which dense forests grew. The stagnant ice was probably so well insulated by the cover of sediment that it had little effect on the climate of the region.

Holocene Epoch

The time since the end of the ice age, approximately the last 10 000 years, is referred to as the Holocene Epoch. Studies of highly fossiliferous slough sediments and wind-blown silt deposits in central North Dakota indicate that the Holocene Epoch has been characterized by periods of warm, dry climate when hillslope erosion and wind activity were intense, and large amounts of coarse, nonorganic sediment were deposited in sloughs alternating with periods when deep soils formed and were preserved, wind erosion was minimal, and only small amounts of organic sediment were deposited in sloughs. Sediments deposited during the Holocene Epoch are referred to as the Walsh Group.

Walsh Group

Walsh Group sediments include widespread wind-blown silt deposits (loess) found throughout the state. These wind-blown deposits are draped over the pre-existing glacial and preglacial topography and, although they may subdue the underlying topography somewhat, they are generally too thin to completely mask it. Wind-blown deposits of the Walsh Group are found mainly over gently-rolling upland areas.

In some places, deposits of wind-blown sand are found. These dune deposits consist of well-sorted, medium-grained sand that is crossbedded in places. Dunes are common in areas where large amounts of gravel and sand, such as melt-water deposits, were available. Prominent areas of dunes are found near Denbigh in Towner County, near McLeod in Ransom and Richland Counties, near Walhalla in Pembina County, and near Hamar in Eddy County.

Slough deposits consisting of fossiliferous bedded, organic clay and silt are found throughout the state, especially in areas of glacial sediment. Layers of bedded, organic silt, clay, and sand that were deposited by running water are common on modern stream floodplains.

Holocene Climates

During the 3 500-year interval between 12 000 and 8 500 years ago, eastern North Dakota had a cool, moist climate that may have allowed the growth of hardwood forests. As the glaciers melted from the state, until about 10 500 years ago, a spruce-aspen forest covered much of the northern plains, probably expanding into areas as they became deglaciated. The climate was more moist than today, summers were cooler, but winters were probably warmer. About 10 000 years ago, a sudden climatic change caused the continental ice sheet to melt back rapidly. This change marks the end of the Pleistocene Epoch and the beginning of the Holocene Epoch. The change is reflected by North Dakota's soils; black soils typical of prairie grasslands began to develop then. The climate changed to an increasingly continental one with warmer summers and colder winters.

Studies of pollen samples from sediments collected from potholes in the northern plains show that the composition and position of the major vegetation units has changed drastically several times since the end of the glaciation. As the climate became drier and warmer between about 8 500 and 4 500 years ago, prairie grasses replaced the woodlands and North Dakota became a semiarid grassland. Grassland probably reached its maximum eastern extent about 7 000 years ago, then receded westward again. The state was probably covered by sage and short grasses, much like parts of Wyoming and eastern Montana today. This time was characterized by recurrent summer droughts, soil erosion was extensive, and wind caused dunes to form in many places. The drier climate also resulted in lowered lake levels.

The climate became wetter again about 4 000 years ago, allowing woodlands to expand over much of North Dakota. Between 2 300 and 1 500 years ago, generally cool, wet conditions prevailed with heavy winter snowfall. Since about 5 000 years ago, North Dakota's climate has fluctuated between periods of cool, humid conditions similar to the climate during most of the 1960s and periods that were a few degrees warmer, like the 1930s.

In some places in North Dakota, running water has removed large amounts of sediment since the glaciers melted; the Little Missouri River badlands are the most conspicuous example. Those parts of the state that were glaciated most recently have landforms that have been modified only slightly from their glacially-derived forms. Running water has transported some sediment from the hillsides to depressions, but in most places drainage has not developed well enough for the material to be transported away. Drainage has become better integrated in parts of the state that were glaciated during early glaciations. In these areas, erosional landforms are found and the glacial landforms have been largely obliterated. In western North Dakota, burning lignite seams have baked the nearby sediments to scoria. This process is going on today, and it was probably common long before the ice age ended.

River floodplain deposits, which are thick only along the larger streams and rivers, consist mainly of silt and fine sand with coarser sand in places. These water-laid deposits have been deposited intermittently since the ice age. In sandy areas, wind has blown the sand into dunes, some of which are still active, particularly during periods of drought.

MINERAL RESOURCES OF NORTH DAKOTA

North Dakota is primarily an agricultural state and the production of agricultural products has traditionally been the most important industry in the state. The income from farm products in 1970, for example, was about seven times the income from mineral production (95 million dollars vs. 690 million dollars). Mineral production, however, is becoming increasingly important as a major source of income in North Dakota. Petroleum resources, along with natural gas and coal, have, in recent years, accounted for nearly 90 percent of the value of the state's mineral production. The remaining 10 percent is the result of the production of sand and gravel, clay, stone, salt, and small amounts of other mineral commodities.

The following discussion of North Dakota's mineral resources is only a brief review. Those interested in additional information should refer to one of the several North Dakota Geological Survey publications that deal with specific resources, or contact the Survey offices for current information. A 1973 publication, North Dakota Geological Survey Bulletin 63, entitled *Mineral and Water Resources of North Dakota*, is the best general reference on the state's mineral resources.

Oil and Gas

History of Development

From the south bank of the Missouri River, about 30 miles (50 kilometres) east of Williston, the slight arching of the Nesson anticline can be seen in the beds of lignite in the bluffs on the north side of the river. Lewis and Clark may have noted this, but they did not mention it in their journals. The first published description of the Nesson anticline was by A. J. Collier in 1919.

As early as 1909, a total of 25 gas wells had been drilled in Bottineau, Williams, and LaMoure Counties. The wells near Westhope in Bottineau County produced a low-heating value gas from depths of 150 to 200 feet (45 to 60 metres). This was probably a type of marsh gas that came from near the base of the glacial sediments. About 1910, near Edgeley, in LaMoure County, six artesian water wells yielded gas from depths of 1 150 to 1 450 feet (350 to 440 metres).

The first recorded well drilled for oil in North Dakota was plugged as a dry hole at about 2 100 feet (640 metres) depth in 1920. The well, drilled about two miles southwest of Williston, probably bottomed near the base of the Fort Union Group of Tertiary age, at least 6 000 feet (1 800 metres) above potential oil production. Five wells, all dry, were drilled between 1923 and 1928 in North Dakota. A commercial gas well was completed in 1929 on the Cedar Creek anticline in the southwest corner of the state. Gas is still produced there from the Eagle Sandstone reservoir in the Pierre Formation of Late Cretaceous age, at a depth of about 1 600 feet (500 metres). The nearby Little Missouri Gas Field was discovered in 1945.

Between July 1929 and May 1945, a total of 10 wells were drilled for oil in North Dakota. These were mostly in the central part of the state, but two were drilled in Williams County. One of these, drilled in 1938, was located only three-fourths of a mile from a presently producing well. It was drilled to the Devonian horizon, a depth of 10 281 feet (3 134 metres). Gas was discovered in 1945 in the Eagle Sandstone, about 6 miles (10 kilometres) southeast of the Cedar Creek discovery on the Cedar Creek anticline. In the late 1940s, five wells and three stratigraphic testholes were drilled. Again, the central part of the state drew most of the attention with only one well being drilled near a now productive area.

In August 1950, work began on the Amerada Petroleum Corporation's No. 1 Clarence Iverson well in Williams County. The well was located on the crest of the Nesson anticline, 8 miles (13 kilometres) south of Tioga. No shows were reported in the Madison Group, but oil was recovered on a drill-stem test in the Devonian. The well was drilled to a depth of 11 955 feet (3 644 metres) to the Silurian where oil was also found. It was plugged back and completed in the Devonian on July 20, 1951. The Iverson well is considered to be the discovery well in the Williston basin. Before the Iverson well was completed, Amerada had already begun to drill on its H. O. Bakken No. 1 about 12 miles north of the Iverson. In September 1951, a drill-stem test in the Madison, from 8 304 to 8 360 feet (2 531 to 2 548 metres), flowed oil to the surface in 40 minutes.

The Iverson well was plugged back and recompleted in the Madison in 1951. It was recompleted in the Devonian in 1959 and recompleted again, as a dual well with the Silurian, in 1963. In 1966, the Silurian tubing was found to have collapsed, and the well was plugged back to the Devonian. It is now (1977) producing from that interval. The field discovered by the Iverson well was named Beaver Lodge Field, and the one discovered by the Bakken was named the Tioga Field. These successes sparked an exploratory program that discovered seven additional fields over the next 2 years. Today, the Nesson anticline is nearly continuously productive over a distance of 77 miles (124 kilometres) north to south, and 15 miles (25 kilometres) east to west.

Oil was discovered in 1953 in Bottineau County and, due to the shallow depths involved in that area (3 200 to 3 600 feet) (975 to 1 100 metres), numerous independent operators were attracted there, and several fields are now producing in the area.

A third area of interest was opened by the discovery of oil at Fryburg, 19 miles west of Dickinson, also in 1953. The additional discovery of the Rocky Ridge-Heath Field 15 miles (25 kilometres) south-southeast of the Fryburg Field established the southwest corner of the state as a major producing area.

The Burke-Divide County area was established as an important producing area after the discovery at Flaxton in Burke County in 1956. The area now has 23 fields even though only the Madison Group has proved productive.

In 1972, oil was discovered in a highly deformed and uplifted geologic structure in McKenzie County. The oil field has proven to be a good one, producing about 1.5 million barrels in its first 3 years of production. Speculation about the origin of the feature, which is now known as the Red Wing Creek Structure, has not ended, but it is likely that the structure was caused by the impact of a large meteorite.

Occurrence

Both structural and stratigraphic traps, and combinations of the two, occur in the part of the Williston basin that lies in North Dakota. Farther to the southwest, in Bowman County, a number of structurally-controlled fields produce from Ordovician formations.

The Nesson anticline, the largest single geologic structure in the state (fig. 3), extends north from the Little Missouri River in northern Dunn County to the Burke County line. To the northeast of the Nesson anticline, the oil accumulations found in Burke County have been trapped by infilling of the limestone by anhydrite. A similar situation exists in Renville and Bottineau Counties, east of Burke County; but, in addition, some oil accumulations are found where limestone of Mississippian age is truncated by an unconformity, and the eroded edges of the limestone are covered by shales and silty sands of the Triassic Spearfish Formation.

Near Dickinson, in southwestern North Dakota, oil is trapped in beach and bar sands that were deposited along the south edge of the sea in the Williston basin as it existed in late Mississippian and early Pennsylvanian time. At Rocky Ridge, south of Dickinson, the oil-bearing sand fills an ancient stream channel that was probably related to the beaches in the Tyler Formation of Pennsylvanian age. In the western part of the state, oil accumulations are primarily structurally controlled, while in the north-central portion they are primarily stratigraphically controlled.

The Red Wing Creek Structure in McKenzie County was apparently formed by the impact of a meteorite. Mississippian age strata are uplifted 3 000 feet (915 metres) above surrounding sediments of comparable age. The deformed Mississippian limestone, dolomite, and evaporites are underlain and overlain by relatively undeformed formations. Approximately 6 000 feet (1 830 metres) of geologic section is disturbed. The

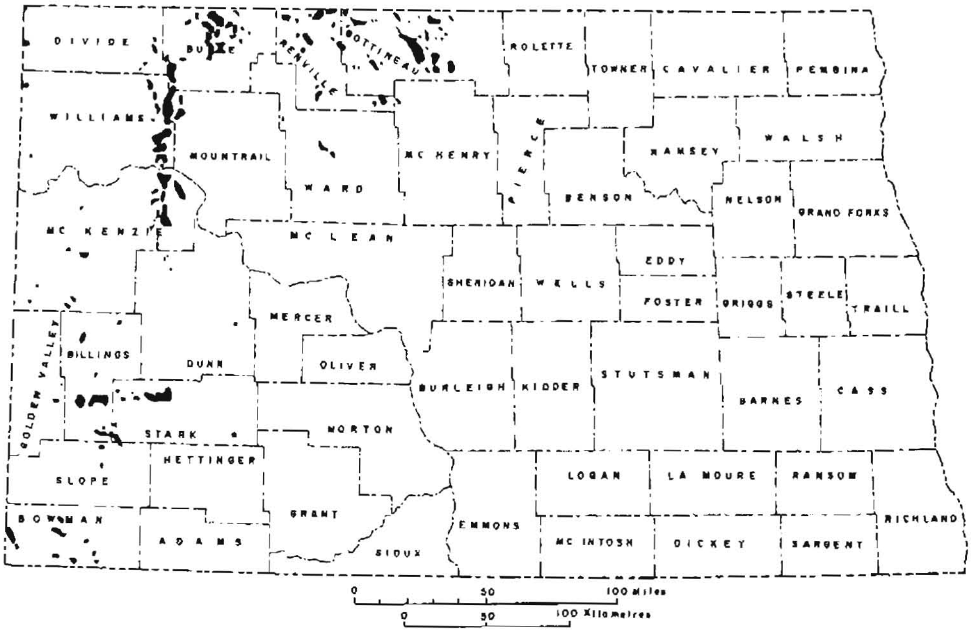


Figure 48. Oil fields in North Dakota. North Dakota has over 150 oil fields and, because of the scale of this map, many are not shown.

geologic structure is about 6 miles (10 kilometres) in diameter with a circular to slightly eliptical shape in plan view and a sombrero shape in cross-sectional view.

Presently, all of North Dakota's oil is produced from the western and north-central parts of the state (fig. 48). Oil and gas have not yet been found in eastern North Dakota, but if they are present there, they will most likely be found in beds of Lower Paleozoic age or in the Newcastle Formation, which is productive in southeastern Montana.

Lignite

History of Development

The earliest lignite mined in the United States or Canada was probably dug by the American Indians from outcrops in creek beds and hillsides where firewood was scarce. Lewis and Clark, in their journals, mention using lignite during the winter of 1803-1804 while they were camped along the Missouri River at Fort Mandan. While some of the early mining may have been from short drifts into the outcrops, the bulk of the operations consisted of removing shallow overburden and digging the lignite as is done in modern strip mining.

Production records for North Dakota start in 1884 when the state produced 35 000 tons. By 1900, output had increased to more than 100 000 tons. In 1922, one million tons were mined; in 1937, 2 million tons; in 1950, 3 million tons; in 1970, 5 million tons; and in 1975, 8 million tons.

Prior to 1902, about half of the output of North Dakota was from small strip pits along outcrops, where overburden was light. At that time, before power stripping equipment was developed, overburden of about 10 feet (3 metres) in depth was considered the practical maximum for a 6-foot (2-metre) seam. Between 1902 and 1919, underground mining on a larger scale developed, and for a time took the lead away from the strippers. In some places, the old underground lignite mine shafts have collapsed, causing the land surface above to become pitted (fig. 49).

The operations that led to the development of the modern lignite stripping industry began just prior to 1919 when the Whittier Coal Company and

Figure 49. Circular depressions caused by tunnel collapse of an abandoned coal mine in the Wilton, North Dakota, area. Photo by Jack Kume.

Truax Brothers began stripping lignite in Kincaid, in Burke County, with horse-drawn elevating graders and horse-drawn dump wagons. The wagons were used both to dispose of overburden and haul lignite to the tipple.

The first power equipment used to strip lignite in North Dakota was put into service by the Truax Brothers in 1919. This was a 1½-cubic yard steam shovel which replaced the elevating grader for loading overburden into dump wagons. The same shovel was also used to load lignite into narrow-gauge pit cars which were hauled to the tipple by steam locomotives.

By 1950, over 90 percent of North Dakota's coal was taken from surface mines. In 1970, only 12 tons of lignite were produced by the underground mining method and the mine that produced that, the Square Deal Coal Mine in Williams County, closed shortly thereafter.

In a typical modern surface mining operation, the overburden is removed without blasting, using draglines that have bucket sizes of 30 cubic yards (23 cubic metres) or more. An attempt was made several years ago to use a large bucket-wheel excavator for overburden removal. However, large, cemented sand concretions made it necessary to abandon the bucket-wheel in favor of conventional dragline stripping. The lignite itself is blasted to facilitate loading by power shovels, which are more effective than front-end loaders for digging in the thick seams.

Occurrence

Lignite underlies much of the western two-thirds of the state (fig. 50), but production is currently centered in Mercer and Oliver Counties in the west-central part of the state, Burke and Ward Counties in the northwest, and Bowman County in the southwest. Table 2 lists the counties in North Dakota that have lignite resources and the strippable reserve for each county. Estimates of strippable reserves are about 16 billion tons in beds greater than 5 feet thick, and another 17 billion tons in beds 2½ to 5 feet thick. This represents about 80 percent of the recoverable lignite reserves in the United States.

Most of the current lignite production in North Dakota is consumed in the generation of electric power. A much smaller amount is used for various

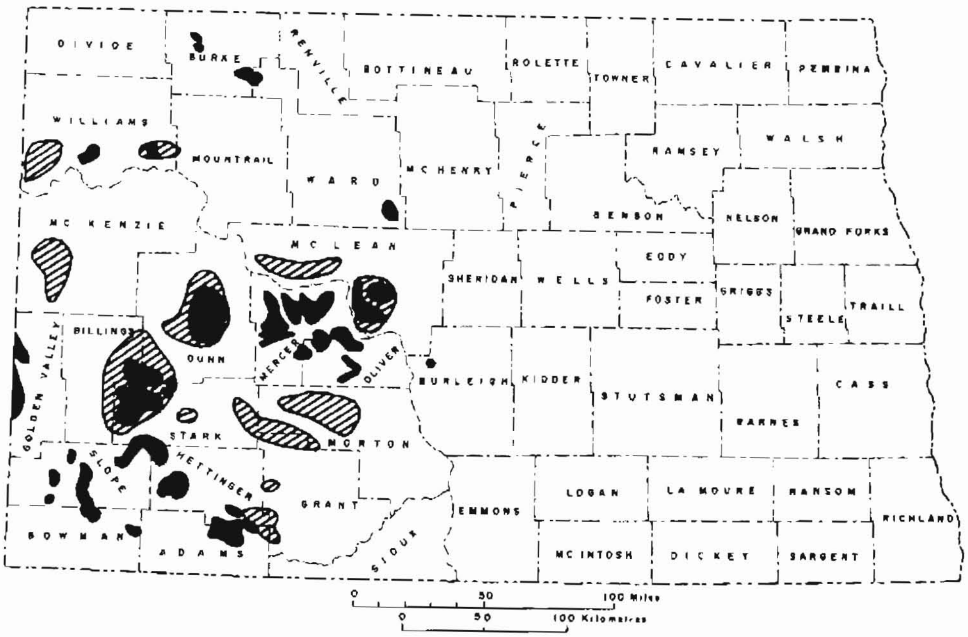


Figure 50. Map showing areas of lignite deposits in North Dakota. The approximate locations of presently-known, proven, strippable lignite reserves are shown by the black areas. Areas of known, but less well-defined strippable lignite deposits are shown by the lined areas.

industrial heating purposes. If lignite conversion plants for the production of synthetic natural gas and hydrocarbon liquids become a reality, production will increase dramatically. North Dakota's lignite resources would last over 1 300 years at the current rate of production (8 million tons in 1975). Even if large-scale coal gasification becomes a reality, North Dakota's lignite will go a long way. Assuming continued increases in electric generation capacity and six lignite conversion plants by 1990, the lignite would last over 150 years. The total amount of lignite produced in North Dakota to January 1, 1976, is approximately 173 million tons, or slightly over one percent of the total strippable resource.

Leonardite

Leonardite is formed by the natural weathering of lignite, although it can be artificially produced by partial oxidation of lignite in air at relatively mild temperatures. The term "leonardite" was chosen to honor Dr. A. G. Leonard, first director of the North Dakota Geological Survey, who took part in the initial investigations of the material.

North Dakota's leonardite is a soft, earthy, medium-brown, coal-like material associated with most lignite outcrops in the state. It is a poor fuel, but it can be used as a source of chemicals and for other nonfuel uses. It has been used commercially in small amounts for many years for such purposes as a dispersant and viscosity control in oil-well drilling muds, as a stabilizer for ion-exchange resins in water treatment, as a soil conditioner, and as a source of water-soluble brown stain for wood finishing.

Sand and Gravel

In terms of value, the production of sand and gravel ranks behind oil, gas, and lignite in North Dakota, but ahead of all other minerals. Since sand and gravel are low-value bulk products and must generally be produced as near to construction projects as possible, production by counties varies greatly from year to year depending upon local construction needs.

Table 2. *Strippable lignite reserves and total lignite resources in North Dakota. The original strippable reserve estimates (the center column) refer to coal seams 5 feet or thicker and overburden of 100 feet or less. Total resources refer to coal seams at least 2½ feet thick and overburden of 1 200 feet or less. With modern mining methods, it is possible to recover from 80 to 90 percent of the strippable reserve.*

County	Strippable Reserves (millions of tons)	Total Resource (millions of tons)
Adams	200	1 900
Billings	1 100	17 700
Bowman	800	7 000
Burke	100	6 600
Burleigh	200	1 200
Divide	100	8 300
Dunn	2 000	71 000
Golden Valley	300	8 300
Grant	100	4 700
Hettinger	1 000	12 600
McHenry		100
McKenzie	800	32 200
McLean	1 000	16 500
Mercer	2 000	29 900
Morton	300	15 300
Mountrail	200	15 400
Oliver	600	17 800
Renville		800
Sheridan		700
Slope	2 300	20 100
Stark	1 300	25 700
Ward	500	10 300
Williams	1 100	26 900
TOTAL	16 000	351 000

Most North Dakota sand deposits are suitable for use in plaster and mortar, and some deposits can be used as foundry sand. Some western North Dakota silica-sand deposits could be used to produce crude colored glass. Most of the gravel produced in North Dakota is used in highway and road construction, for concrete aggregate in paving, for road surfacing, and in the building industry. Most of the sand is used in building. The only other significant uses for sand and gravel are for raiload ballast and fill materials.

Much North Dakota gravel does not meet the concrete aggregate specifications of many governmental agencies because it contains large amounts of chert and shale. Much of the sand and gravel in the state has to be washed to remove the clay and silt. Large amounts of gravel are therefore imported into the state, mainly from Minnesota.

Sand and gravel are most readily available in the glaciated part of the state, mainly northeast of the Missouri River. They are generally scarce in the unglaciated part of the state. Most of the sand and gravel is found in two types of deposits: beaches of glacial melt-water lakes; and deposits of ancient or modern rivers and streams.

Beach deposits formed along the shores of lakes during and after the wasting of the last glaciers. Most of these sand and gravel deposits are located along the western edge of the Red River Valley, the former western shore of the glacial Lake Agassiz. Some beach deposits are also found in Ramsey and Nelson Counties around Devils Lake and Stump Lake (the glacial Lake Minnewaukan); in McHenry, Bottineau, Pierce, and Rolette Counties along the edge of glacial Lake Souris; and in scattered areas throughout the state along the shores of other small lakes, both ancient and modern.

Although some of the sand and gravel deposited as beaches was brought to the glacial lakes by streams, most of it was eroded by lake waves from the glacial sediment (till) that underlies the beach deposits. The finer-grained sediment was transported into the lake, leaving the coarser sand and gravel at the shoreline. The waves heaped this material into ridges parallel to the shoreline. Shale is close to the surface along most of the western edge of the Red River Valley, and pebbles of shale are abundant in the till. For this reason, the beach gravel derived from the till commonly contains considerable shale and is rather low in quality. A few of the beaches, however, were formed over long periods of time, and the continual reworking of the pebbles by the waves destroyed most of the shale pebbles. An example is the Campbell Beach, which contains large quantities of high-quality gravel.

The second major type of sand and gravel deposit was formed by rivers throughout North Dakota. The gravel occurs in point-bar deposits of both modern and ancient rivers; as broad, flat outwash plains formed by melt water flowing off the wasting glaciers; along large and small valleys as the deposits of sediment-choked, braided glacial melt-water streams; as isolated hills and ridges (kames and eskers) deposited by streams flowing on, in, and under melting glaciers; and where large melt-water streams formed deltas in lakes. The quality and quantity of gravel in the river deposits is highly variable. River gravel is generally more poorly sorted than gravel deposited on beaches. Abrupt changes in texture and sorting are common in river deposits.

Point-bar and braided-stream channel-bar deposits occur along the Sheyenne, James, Souris, and Missouri Rivers, and many smaller tributaries of these major streams also contain commercial amounts of gravel. In many places, the valleys have been cut into the underlying preglacial bedrock, which is commonly shale or sandstone, with the result that large amounts of these materials are included in the deposits, decreasing their value. Along the Missouri River, the gravel locally contains chert and other rock types that are also potentially detrimental constituents.

Extensive, sheetlike deposits of gravel and sand are found in Kidder, McLean, Eddy, Benson, Nelson, Logan, Ransom, and Sheridan Counties. These outwash plains, and other smaller ones scattered throughout the glaciated part of North Dakota, were deposited by numerous rivers and streams, which were fed by the melting glacier and by the large volumes of runoff from precipitation, which was much higher during and immediately following glaciation than it is now.

Several thousand kames and eskers, which contain small amounts of gravel and sand, are found throughout the glaciated part of North Dakota. These deposits commonly have abrupt changes in gravel quality and they sometimes contain large amounts of clay. They may provide gravel for local use, but most of them are of little commercial importance.

Gravel found on terraces and in point-bar deposits of modern streams is the only gravel available in parts of North Dakota southwest of the Missouri River. Some gravel was derived from rocks immediately upslope from where it was eventually deposited as alluvial fans and pediments. These deposits tend to be poorly sorted and, depending on the local source, they may contain shale, chert, or other detrimental materials. In some areas of southwest North Dakota where gravel is scarce, scoria and sandstone are mined and crushed for road surfacing material.

Uranium

The major known North Dakota uranium occurrences are found in thin lignite beds that overlie or underlie a sandstone that acted as an aquifer. Groundwater moving through overlying sediments that contain uranium-bearing volcanic ash took the metal into solution as it moved through these sediments. Then, as the water containing the uranium moved through the aquifer, it came in contact with the lignite, and when it did so, the organic compounds in the lignite extracted and concentrated the uranium from the water.

Although uranium in lignite and related carbonaceous or organic material is fairly common, the only commercial American production from this source has come from the southwestern North Dakota and northwestern South Dakota area. Ore-grade uraniferous lignite was found in 1955 between Belfield and Amidon in southeastern Billings County. The first shipment of North Dakota ore was made from this area in 1956, but only a few hundred tons were shipped from both North and South Dakota in the 1950s because the lignite was not amenable to milling by the methods applied to the common sandstone ore of the Colorado Plateau. From 1962 to 1967, uraniferous lignite of the Dakotas was burned in kilns or pits; the ash was then shipped to mills in South Dakota, Colorado, and New Mexico where it was blended and treated along with sandstone ores. Both the burning and mining had been discontinued by the end of 1967, apparently because market demand could be more profitably satisfied elsewhere.

Salt and Potash

Vast deposits of rock salt (halite) that were discovered during drilling for oil, lie buried beneath the northwestern North Dakota plains. At least 1 700 cubic miles (7 000 cubic kilometres) of salt is estimated to be present in the state. Salt is used chiefly in the chemical manufacturing industry, for snow and ice removal and road base construction, for stock feed, for food preservation, as an additive in oil-well drilling solutions, and in water softening.

Potash occurs with rock salt in the Prairie Formation of Devonian age as the mineral sylvite (KCl) in a mixture with halite (NaCl) known as sylvinite. Potash is used primarily as fertilizer for agricultural purposes. In North Dakota, the potash occurs at depths ranging from 5 600 feet to 12 500 feet (1 700 metres to 3 800 metres). North Dakota's potash resource amounts to over 500 billion tons. Both rock salt and potash can be recovered by solution-mining methods that require the injection of water into the salt bed and the pumping out and processing of the resulting brine. Solution-mining methods for recovering potash, as now used in Saskatchewan, appear to be feasible in North Dakota.

The thickest and economically most important salt and potash deposits are located in northwestern North Dakota. They accumulated during Devonian until Jurassic time (all the potash is Devonian in age). The salt and potash were precipitated from brines, extremely salty sea waters, in shallow, rapidly subsiding, evaporite basins where the normal influx and circulation of fresh and open marine waters were restricted. The barriers that caused the restrictions may have been physical ones, like reefs or shoals that grew above the sea bottom and restricted normal circulation, or chemical ones, such as layers or currents of high-density brine, which restricted the entry or passage of lower density saline and fresh waters. Only in rare instances did marine evaporite basins become completely cut off from the open sea by formation of offshore bars or other barriers that rose above the water surface. Other thinner, marginal marine salt deposits resulted from precipitation of salt brines in salt marshes, along marine shorelines. A third type of salt deposition resulted from precipitation in continental arms of the sea that became completely landlocked. The salt deposits found in North Dakota probably formed in three of the ways described: definitely in marine evaporite basins and shoreline salt marshes, and possibly in continental salt lakes.

At the present time (1976), salt is being produced from a 200-foot (60-metre) bed at a depth of 8 000 feet (2 450 metres) by the Hardy Salt Company plant at Williston. Recovery is by injection of fresh water into the salt bed to dissolve it and then by evaporation of the resulting brine. The salt being produced at Williston is Mississippian in age.

No potash is presently being mined in the state. It appears certain, however, that potash demand will continue to exceed current production capability, prices will continue to climb, and it will be necessary to add production to meet projected demands. United States production will increase only slightly, and most of the increased demand will have to come from Canada unless we develop new production. Currently, domestic production is centered in New Mexico, but the capacity for expansion there is small. No substitute exists for potash in agriculture, and its importance as an essential plant food cannot be overemphasized.

Clay

Clay materials form as alteration products of pre-existing rock materials as a result of weathering processes or hydrothermal alteration. Clay deposits may be residual (formed by weathering where they are found) or transported. If the clay, once formed, is removed and transported elsewhere, it may then be laid down as a sedimentary clay deposit. Montmorillonitic clay deposits appear to have formed by the alteration of volcanic ash beds, which consisted of material that was originally blown to North Dakota from areas to the west.

The useful clay of North Dakota is found in formations of Pleistocene, Tertiary, and Cretaceous age. Kaolinitic clays of potential economic importance are found in the Golden Valley Formation in southwest North Dakota, especially in Stark, Morton, Hettinger, Dunn, and Mercer Counties. Montmorillonitic clay beds occur in the White River, Bullion Creek, Sentinel Butte, and Ludlow Formations in Stark, Slope, and Billings Counties in southwest North Dakota and in the Carlile, Niobrara, and Pierre Formations in the eastern part of the state. The Bullion Creek Formation contains some clay that could be mined economically if lignite is also being mined.

The sediments of glacial Lake Agassiz include a near-surface layer of silty clay that is from 15 to 20 feet (5 to 6 metres) thick and a slightly deeper layer of greenish gray, plastic clay that is 50 to 85 feet (15 to 25 metres) thick. These clays have been used in the manufacture of brick at various times in the past.

In the east-central part of the state, the shale beds of the Carlile, Niobrara, and Pierre Formations are mostly covered by a deep layer of glacial drift, but they are exposed in the river valleys of the Pembina Escarpment in northeastern North Dakota. The Pierre Formation is also exposed in the valleys of the Sheyenne and James Rivers. The lower part of the Pierre Formation is composed of black to dark-brown carbonaceous shales in which are found many seams of yellowish-white Fuller's earth. Near the Canadian border northwest of Walhalla, several acres of Fuller's earth occur under only a few feet of overburden. At Morden, Manitoba, just a few miles across the border, the Pembina Mountain Clays Mining Company, Ltd., is mining Fuller's earth.

Dark brown, montmorillonitic clays that are rich in organic materials are widespread in the Turtle Mountains. The clays are found as deposits of elevated lake plains that formed when stagnant ice covered the area. These sticky clays were used extensively as a mortar-like material in log structures in the Turtle Mountains.

Light-burning Tertiary clays of the Golden Valley Formation have been used in the manufacture of face brick, building tile, and fire brick, with plants located at Dickinson and Hebron. Operations ceased at Dickinson in the late thirties. A sewer pipe plant was opened at Dickinson in the early 1960s, but it operated only until 1970. The plant at Hebron is today the oldest (since 1905) and largest brick plant in operation in the state, producing 12 million brick units annually, and utilizing about 36 000 tons of clay.

In 1953 a lightweight aggregate plant began operation at Mandan, producing aggregate from shale of the Cannonball Formation. A similar plant, opened in 1954 at Noonan, used clay occurring above a lignite seam in the Bullion Creek

Formation. The latter plant was closed in 1971 because of freight costs. A third lightweight aggregate plant that began operations at Dickinson in 1968, utilizing clay from the Golden Valley Formation, is still in business (1976), producing about a hundred cubic yards a day during the summer months.

A plant at Belfield initially producing absorbent material for floors and cat litter material from clay and from volcanic ash was operated during 1971. Montmorillonitic clays have been used in small amounts for making prepared mortar. The success of ceramic plants in North Dakota has been hampered by transportation costs and lack of sufficient markets.

Stone

The stone industry in North Dakota deals mainly in crushed and broken stones. Sources for this are the Odanah Member of the Cretaceous Pierre Formation in the extreme northeast part of the state; the chert and scoria of southwest North Dakota; and glacial boulders from the glaciated areas.

Material from the siliceous Odanah Member of the Pierre Formation is crushed and used for road surfacing in Cavalier and Pembina Counties in northeast North Dakota. Chert that occurs in numerous areas of southwest North Dakota is composed of siliceous siltstone or mudstone that is hard and strongly weather-resistant. Currently, its only commercial use is as riprap on dams and stream channels. Chert was used as riprap on the face side of Garrison Dam.

Scoria, formed when clay beds overlying lignite were baked by the burning of the lignite, is widespread over the nonglaciated part of the state. It is used primarily for road surfacing as well as for driveways, walkways, and for decorative lawn material. Erratics present in glaciated areas are utilized for concrete aggregate, road surfacing, and for decorative purposes such as fireplaces.

Only a small amount of stone classified under the category of dimension stone (blocks or slabs of natural stone that are cut to definite shapes and sizes) are presently produced in North Dakota. However, dimension stone has been quarried in a few places. In Emmons County, a resistant bed of sandstone in the upper part of the Fox Hills Formation was used for a number of buildings in Linton and elsewhere in the county. These buildings were constructed around 1900 to 1909 and they are still in use. The sandstone is permeable so the stone shows some effects of weathering, but even though it is probably somewhat darker in color than when it was quarried, it is still a uniform color.

Sandstone beds of the Fort Union Group have been quarried and used for foundations in the Washburn area. Some hard sandstone from the Taylor Butte area near Dickinson was reported to have been used for dimension stone. An account in the second biennial report of the North Dakota Geological Survey tells of a "handsome and substantial building" in Velva, constructed from stone. Presumably this is also from the Fort Union Group, though it may have been from the Fox Hills Formation.

A sandstone bed in the Fort Union Group was quarried in northwestern Billings County, near the site of Theodore Roosevelt's Elkhorn Ranch. This stone was used mostly for indoor purposes such as fireplaces and decorative walls. A wall made from the stone decorates the entrance to the North Dakota Geological Survey offices in Grand Forks.

The value of crushed and broken stone produced in North Dakota in 1970 was $126,000. No sizable sustained increase in the amount and value of stone produced in North Dakota is expected unless a cement industry utilizing limestone deposits is developed.

North Dakota has considerable thicknesses of Paleozoic and Mesozoic limestone in the subsurface which include deposits of Ordovician, Devonian, Mississippian, Permian, and Jurassic age. However, with the exception of some limestone beds in the Red River Formation in eastern North Dakota, rocks of these ages are too deep to be considered for cement manufacture. In eastern Grand

Forks County, the Ordovician Red River Formation ranges in thickness from about 40 feet to 150 feet and is overlain by about 220 feet of glacial deposits. The limestone in the Red River Formation has an average calcium carbonate content of 85 percent, but it also has an undesirably large magnesium content of about 7½ percent. In order to utilize the Red River Formation limestone for cement manufacture, it would probably be necessary to blend it with limestone from the Cretaceous Niobrara Formation.

Limestone in the White River Group of Oligocene age occurs at the surface in southwest North Dakota. However, these deposits are too low in quality and too small to be considered for use in cement manufacture.

Other Mineral Resources

Additional mineral resources found in North Dakota include such things as volcanic ash, peat, sulfur, sodium sulfate, and molybdenum.

Volcanic ash, or pumicite, is present in south-central North Dakota near Linton. It may be used as an additive to fortify cement, as a soil conditioner, and as a water purifier.

Peat is partially decomposed vegetable matter that has accumulated under water or in a water-saturated environment. The main use for peat is by homeowners who use it as a soil conditioner in maintaining lawns, shrubs, and gardens. It is also used by landscape contractors for similar purposes, and it has been used as a filtering agent. North Dakota's peat resource is estimated at something less than 100 000 tons. The main area where it may be found is the Turtle Mountains where it has been mined for years.

Sulfur is produced as a by-product of North Dakota's gas-processing plants. Sulfur can be used in the manufacture of cellulose products, chemicals, dyes, fertilizers, iron and steel, pharmaceuticals, rubber, and for water treatment. As of January 1, 1972, 451 345 tons of sulfur with a value of $10 million had been recovered.

Sodium sulfate, used in the Kraft-paper industry and for glass, ceramic glazes, paints and varnishes, detergents, tanning processes, stock feed, dyes, textiles, medicines, and various chemicals, occurs in northwestern North Dakota in saline lakes or former lake basins that occupy undrained depressions in the glacial till. The sodium-sulfate deposits, which occur mainly as Glauber salt (mirabilite), are found in dry or brine lake beds. They range from mud-adulterated crust to permanent beds of crystalline material up to 80 feet thick. North Dakota has an estimated resource of about 28 million tons of sodium sulfate. Some development of the material was attempted in the 1930s and 1940s in Divide County and at White Lake in Mountrail County. Sodium sulfate was used experimentally as a supplement to stock feed early in the century, and small amounts were shipped in 1948.

Molybdenum is a silvery-white metal with an extremely high melting point that is used primarily in steel alloys and stainless steel; however, its usage is increasing in the space, nuclear, and electronics industries. It is also used in the paint industry, in the manufacturing of some lubricants, and as a catalyst in petroleum refining. In North Dakota, molybdenum is associated with uraniferous lignite deposits southwest of the Missouri River. Molybdenum was recovered as a by-product from the uraniferous lignite from 1964 to 1968, but no production has occurred in North Dakota since the mining of uraniferous lignite ceased. The last reported production of molybdenum from the state in 1968 was from stockpiled uranium ore. Unless it becomes economically attractive to mine the uraniferous lignite again, no further molybdenum production in North Dakota can be expected.

WATER

North Dakota's water resources occur both at the surface and underground. Large quantities of water are found in Lake Sakakawea and Oahe Reservoir. Normal maximum capacities of the reservoirs are 22 860 000 and 22 530 000 acre-feet respectively (995 trillion cubic feet and 930 trillion cubic feet). The remaining water is in the major streams and in underground aquifers throughout the state. The supply of water is uneven with respect to time, location, and quality so that numerous problems arise in obtaining good quality water for specific needs. Groundwater is the main source of supply for most municipalities and farms in North Dakota although larger cities like Fargo, Bismarck, and Grand Forks depend on river water. Recent years have also seen a growing demand for groundwater in irrigation, and irrigation wells producing several hundred to over a thousand gallons of water a minute have been constructed in several parts of the state.

General Hydrology of North Dakota's Groundwater

Much of the material in this section has been adapted from *Geology of Mountrail County* by Lee Clayton (North Dakota Geological Survey Bulletin 55).

Groundwater is found in minute pores or fractions in the sediment in North Dakota. Pores are the open spaces between individual pebbles or sand or silt grains or particles of clay. Fractures are found in the harder and more compact sediment such as sandstone, shale, clay, or lignite. Vertical fractures are seldom more than a fraction of an inch across, and horizontal fractures are generally closed tight.

Groundwater is found beneath the water table where the sediment is saturated with water. Above the water table, much of the pore space or fracture space is drained and filled with air. Most sediment beneath the water table contains between 10 percent and 35 percent of the volume in water. The rate at which water can seep through sediment is defined as its permeability. The permeability depends in part on the size of the pore spaces or fractures. For example, groundwater will seep through gravel, sand, or lignite more readily than it will seep through silt or clay. A "seam" of water-bearing sediment—an aquifer—consists of a permeable layer of gravel, sand, or other porous material beneath the water table. The water in the pore spaces or fractures seeps readily into any well that penetrates the sediment of such an aquifer. Even though a clay layer may contain a large amount of groundwater in its pore spaces, its permeability is too low to allow the water to seep into a well easily.

The water table comes to the land surface at groundwater discharge areas. Groundwater discharges into intermittent and perennial ponds and lakes, streams, and springs. Most of this water evaporates or is transpired by the vegetation that grows in discharge areas; only a small fraction of it leaves the immediate area of discharge.

The groundwater supply is replenished or recharged by infiltration of precipitation through the surface soil. The water table is commonly at depths of 20 to 50 feet in North Dakota, although it may be deeper than 100 feet in uplands that have good under-drainage through underlying layers of permeable sediment. The depth of the average low position of the water table in any area can be approximately determined in drill holes by noting the depth at which the color of the sediment changes from yellow and brown hues, which indicate that the iron minerals have been weathered (oxidized) to iron oxide, to shades of blue and green, which indicate that oxidation has not occurred. Sediment that is not oxidized is permanently saturated with water.

The level of the water table is controlled by recharge. In dry years when recharge is slight, the water table drops slightly; in wet years it rises slightly.

Groundwater seeps through the sediment along irregular paths from the recharge areas to the lowland discharge areas. Its movement is generally nearly vertical through materials of low permeability such as clay or silt and nearly horizontal through materials of high permeability such as sand or gravel. Flowing wells may occur in lowland discharge areas where the groundwater seepage is upward. The water level in wells in discharge areas rises higher as the wells are drilled deeper. In contrast, in upland recharge areas where groundwater seepage is downward, the water level in wells drops as the wells are drilled deeper.

The chemistry of the groundwater is controlled by its seepage path through the sediment. Near the recharge end of the seepage path where the water enters the ground, the sediment has been largely flushed of the more soluble material and the groundwater has been in contact with the sediment only long enough to dissolve small amounts of mineral material. As a result calcium-bicarbonate groundwater with small amounts of total dissolved solids commonly occurs in upland areas where the groundwater has either moved slowly through a few hundred feet of poorly permeable silty or clayey sediment, or moved rapidly through a few thousand feet of highly permeable gravel or sand. Such water tends to be hard.

Near the discharge end of deep seepage paths, such as areas in eastern North Dakota where the Dakota aquifer discharges as flowing wells, the more soluble material has not yet been flushed out of the sediment and the groundwater has been in contact with the sediment for a great length of time. As a result, sodium-sulfate or sodium-chloride groundwater with large amounts of total dissolved solids commonly occurs at great depths and in valley bottoms (such as the Red River Valley). This water tends to be soft.

Groundwater contamination can usually be prevented by determining the local groundwater flow pattern. Industrial wastes or sewage will not contaminate the groundwater if they are dumped in discharge areas that are permanently moist. Such moist areas are intermittent or perennial ponds or streams that are gaining water from the ground. Contamination of groundwater is likely if wastes are dumped in recharge areas such as dry uplands or temporary streams or sloughs that are losing water seepage into the ground.

North Dakota's groundwater resources are ultimately derived from precipitation. Water that enters the ground and contributes to groundwater aquifers is called recharge, and areas where water enters the ground are called recharge areas. Precipitation in North Dakota ranges from 13 inches (33 centimetres) in the northwest to greater than 20 inches (50 centimetres) in parts of the Red River Valley and in the southeast. However, of this amount, only a small proportion is available as recharge to aquifers.

The low recharge is due to several factors. Most of the precipitation falls during the growing season when crops and other plants consume large quantities of water, thereby preventing much of the potential recharge from penetrating beneath the root zone. Evaporation and transpiration losses are high during the growing season. Large areas of North Dakota are covered by glacial sediment and other fine-grained material, which, because of its low permeability, does not allow efficient movement of water. In addition, during the winter months, precipitation is held in the form of snow and ice, and, at this time, the top several feet of ground are frozen so that infiltration of water cannot take place.

Conditions are favorable for recharge to North Dakota's groundwater aquifers if precipitation is adequate. For example, glacial outwash deposits of gravel and sand, which are permeable and absorb precipitation readily are the most important sources of groundwater in the state. Most of these aquifers consist of gravel and sand that was deposited in valleys ahead of the melting glaciers or as outwash deposits.

Groundwater occurs in aquifers of Paleozoic age; in the Dakota, Pierre, and Fox Hills Formation aquifers of Cretaceous age; and in the Fort Union Group aquifers of Tertiary age.

Surface Water in North Dakota

Of the 13 to 20 inches of precipitation that falls on North Dakota each year, only about three quarters of an inch, equivalent to about 2½ billion gallons a day, escapes to the major drainage system. Evaporation and plant use consume most of the remainder, and a small amount is added to the groundwater supply.

The Missouri River, which drains about 58 percent of the state, is North Dakota's largest source of water; and, in fact, the mean flow at Bismarck is about 85 percent of the total stream flow for the state. Much of the flow on the Missouri River is derived from melting snow in the headwaters area of western Montana and Wyoming while large amounts of water are supplied to the river from groundwater. Except for the Missouri River, Red River, and lower reaches of the Sheyenne River, all streams in the state may be dry during long droughts.

LITERATURE AVAILABLE ON NORTH DAKOTA GEOLOGY

The North Dakota Geological Survey has published the results of numerous studies of various aspects of North Dakota geology. Most of these are technical reports dealing with specific problems in specific areas, but others are of a more general nature. North Dakota Geological Survey Bulletin 63, *Mineral and Water Resources of North Dakota*, a semitechnical report that deals extensively with the state's economic geology, includes an extensive list of references on North Dakota geology. North Dakota Geological Survey Miscellaneous Series 49, entitled *Annotated Bibliography of the Geology of North Dakota, 1806-1959*, contains information on references that deal with North Dakota geology prior to 1960.

The North Dakota Geological Survey makes geological educational aids available to North Dakota schools and other organizations. These include a series of six geologic guidebooks that cover the entire state. The guidebooks include geologic fieldtrips, at least one for each county in the state, and numerous geologic roadlogs along selected highways throughout the state. Other educational aids include taped lectures and collections of selected slides, both of which may be borrowed free of charge. Members of the Survey staff give illustrated lectures. Rock and mineral collections are available to schools. The Survey publishes a Newsletter, which deals with current topics of geologic interest in North Dakota. The Newsletter is published about twice a year and it can be obtained from the Survey free of charge.

A current listing of materials available from the North Dakota Geological Survey can be obtained by writing to the Survey office in Grand Forks. A similar listing of U.S. Geological Survey publications is available from the Denver Distribution Section, U.S. Geological Survey, Federal Center, Denver, CO 80225.

The selected bibliography that follows includes references that I judged to be most useful to people interested in studying the geology of North Dakota in somewhat more detail than I attempted in this report. The bibliography is by no means exhaustive, particularly with respect to many of the more technical materials available on North Dakota geology.

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APPENDICES

Facts About North Dakota

Total Area: 70 665 square miles (183 000 sq. kilometres)

Land Area: 69 280 square miles (179 500 sq. kilometres)

Water Area: 1 385 square miles (3 600 sq. kilometres)

Highest Elevation: 3 506 feet (1 069 metres) above sea level on White Butte in Slope County

Lowest Elevation: 750 feet (229 metres) above sea level at the point where the Red River of the North flows into Canada; Pembina County

Facts About North Dakota's Drainage

The Red River of the North flows to Lake Winnipeg, which drains by way of the Nelson River to Hudson Bay.

Red River of the North drainage basin in North Dakota: 29 900 square miles (77 400 sq. kilometres); 42 percent of North Dakota.

Major tributaries to the Red River of the North, wholly or in part in North Dakota: Wild Rice River, Sheyenne River, Goose River, Forest River, Pembina River, Park River, Souris River (by way of the Assiniboine River in Manitoba).

The Missouri River flows to the Mississippi River at St. Louis, Missouri, and on to the Gulf of Mexico.

Missouri River drainage basin in North Dakota: 40 700 square miles (105 400 sq. kilometres); 58 percent of North Dakota.

Major tributaries to the Missouri River, wholly or in part in North Dakota: Yellowstone River, Little Missouri River, Knife River, Heart River, Cannonball River, Grand River.

The longest river totally within the state of North Dakota is the Sheyenne River, which is 568 miles long (914 kilometres long).

The largest lake totally within the state of North Dakota is Lake Sakakawea, which covers 368 000 acres (575 sq. miles and 1 490 sq. kilometres). Lake Sakakawea is formed by the Missouri River, which is dammed behind Garrison Dam. The lake has a maximum depth of 180 feet (55 metres), and a shoreline that reaches its maximum length of 1 600 miles (2 575 kilometres) when the lake level is 1 854 feet (565 metres) above sea level. The area of 368 000 acres is reached when the level of the lake is 1 850 feet (564 metres) above sea level.

This map is intended primarily for non-geologists.
The large number of Quaternary and Tertiary units
made it convenient to deviate from common geologic
practice in the choice of letter symbols and colors

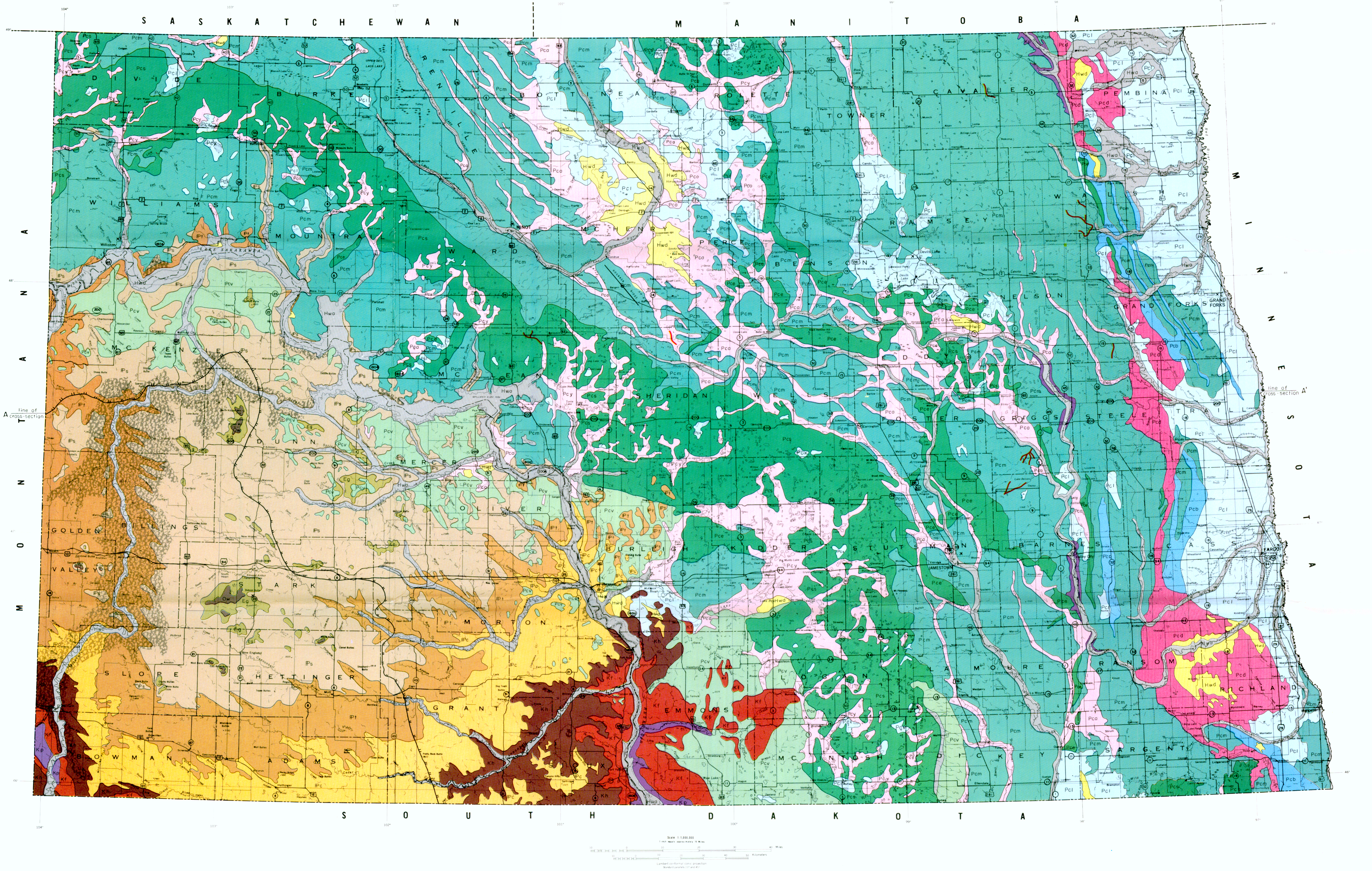
Educational Series 11
Miscellaneous Map 19

GEOLOGIC HIGHWAY MAP OF NORTH DAKOTA

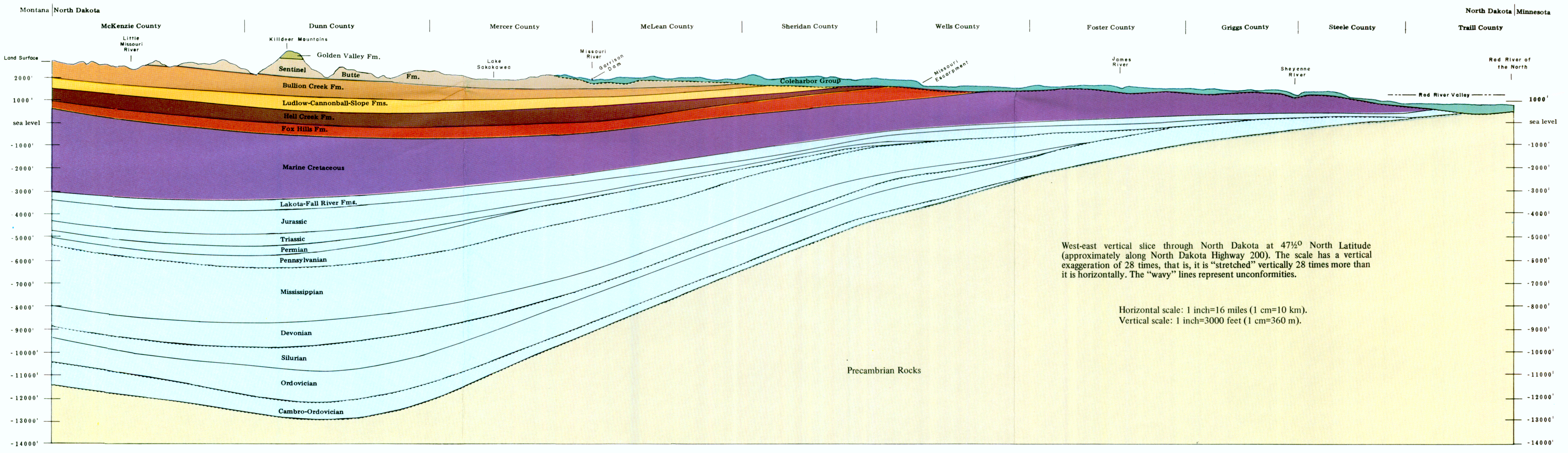
by John P. Bluemle

1977

North Dakota Geological Survey
E. A. Noble, State Geologist



Montana | North Dakota



West-east vertical slice through North Dakota at 47½° North Latitude (approximately along North Dakota Highway 200). The scale has a vertical exaggeration of 28 times, that is, it is "stretched" vertically 28 times more than it is horizontally. The "wavy" lines represent unconformities.

Horizontal scale: 1 inch=16 miles (1 cm=10 km).
Vertical scale: 1 inch=3000 feet (1 cm=360 m).

EXPLANATION

In some places, such as in badlands and in hilly areas covered by glacial deposits, the geologic materials indicated on the map may be seen at the surface of the ground. In many level areas however, soil completely covers the indicated geologic materials to a depth of several feet.

The composition, origin, and typical surface expression of each of the map units are included in the explanation. In all cases, the capital letter designation refers to the age of the unit. The first lower case letter identifies the formation or group and the second lower case letter (where applicable) identifies a particular type of lithology or topography that can be recognized within the formation or group.

Holocene

Walsh Group

Hwa **Silt and fine sand; coarse sand in places; considerable organic detritus in places.** River and stream alluvium or slopewash that has been intermittently deposited since the Pleistocene Epoch. Mainly level floodplains found along the larger streams and rivers.

Hwd **Sand.** Hilly areas of windblown dunes with 50 to 75 feet of local relief. The dunes may shift during periods of drought.

Pleistocene

Coleharbor Group

Pcx Pcl **Flat-bedded clay, silt, and sand.** Lake sediment. Level areas (Pcl) are the former floors of lakes of glacial meltwater. Hilly topography (Pcx) resulted when glacial lakes flooded areas of stagnant glacier ice, which later melted and collapsed resulting in an irregular surface.

Pcb **Gravel and sand, commonly clean and well-sorted.** Beach and shore sediment that was deposited along the shores of Lake Agassiz. Well-developed beach ridges occur in places, but in other places, the shore sediment is simply a sheet of sand and gravel with little relief. Similar shore sediment occurs in places along other glacial meltwater lakes in North Dakota, but it is too limited to show on a map of this scale.

Pcy Pca **Gravel and sand, commonly silty and poorly sorted.** Outwash sediment that was deposited by water flowing from melting glaciers as well as by runoff from precipitation that occurred while the glaciers were melting. Commonly broad, flat plains (Pca) except in places where the materials were deposited on top of stagnant glacier ice, where an irregular surface (Pcy) resulted when the ice melted causing the gravel and sand to slump down.

Pcd **Gravel and sand, commonly silty and poorly sorted.** Delta sediment that was deposited where rivers emptied into glacial lakes. Topography ranges from flat plains to hilly windblown dunes.

Pcs Pce **Unsorted mixture of clay, silt, sand, cobbles, and boulders (till).** Hilly topography. Glacier sediment that accumulated at the margin of a glacier (Pce refers to "end moraine") or was deposited from stagnant glacier ice as it melted (Pcs refers to "dead-ice moraine"). Deposited in sufficient amounts to mask pre-existing topography.

Pcm **Unsorted mixture of clay, silt, sand, cobbles, and boulders (till).** Nearly level to gently rolling topography commonly referred to as "ground moraine." Glacier sediment deposited directly by the glacier in sufficient amounts to mask pre-existing topographic features.

Pcv **Unsorted mixture of clay, silt, sand, cobbles, and boulders (till); consists only of scattered boulders in places.** Rolling to hilly topography. A discontinuous veneer of glacier sediment on pre-Pleistocene formations; the veneer does not greatly alter the pre-existing topography.

Oligocene

White River Group

Ow **Pinkish siltstone and dark clay with some sand and freshwater limestone; silty bentonitic claystone; pebbly in places.** Lake and river sediment. Commonly found on hills and buttes.

Eocene

Golden Valley Formation

Eg **Bright-colored, yellowish clayey and sandy layers.** Lake and river sediment. Commonly found on hills, along the sides of buttes, and over upland areas.

Paleocene

Sentinel Butte Formation

Ps **Dull gray layers of silt, clay and sand with interbedded sandstone, lignite, baked clay, and limestone.** Delta, lake, and river sediment. Forms rolling topography over broad areas and has been eroded to badlands near rivers.

Bullion Creek Formation

Pt **Yellowish layers of silt, clay, and sand with interbedded sandstone, lignite, baked clay, and limestone.** Delta, lake, and river sediment. Forms rolling topography over broad areas and has been eroded to badlands near rivers.

Ludlow and Cannonball and Slope Formations (undifferentiated)

Pc **Yellowish gray to brown (Ludlow) or drab brownish gray (Slope) beds of sandstone and unlithified clay, silt, sand and lignite (Ludlow and Slope) and yellowish sandstone and mudstone with some limestone (Cannonball).** Ludlow and Slope: delta, lake and river sediment; Cannonball: tidal flat, estuary, shore, and offshore marine sediment. Gently rolling topography.

Cretaceous

Hell Creek Formation

Kh **Dark gray maroon, bentonitic clay, shale, and gray to light-colored sand and silt; concretions and fossil dinosaur bones in places.** Delta, lake and river sediment. Forms rolling topography in most places, but has been eroded to badlands near buttes and along rivers.

Fox Hills Formation

Kf **Brown to gray shale and sandstone with loose sand in places; fossil oysters and clams common.** Mainly marine coastal sediment. Forms rolling topography with smooth slopes in most places.

Carlile, Niobrara, and Pierre Formations (undifferentiated)

Kp **Carlile: dark gray shale (exposed only in the Pembina River valley in the northeastern corner of the state); Niobrara: calcareous, medium gray shale (exposed only in eastern North Dakota); Pierre: light gray to medium gray shale with ironstone concretions.** All three formations are offshore marine sediments. Topographic expression is limited mainly to isolated exposures along river valleys.

MISCELLANEOUS SYMBOLS

Compaction ridge. Ridge on the Lake Agassiz plain that marks the former route of a river; usually gravel or sand.

Drumlin. Ridge that formed parallel to the glacier movement; usually glacier sediment, but may be other material.

Esker. Long, narrow, sinuous ridge of stratified glacier sediment, usually gravel, deposited by a stream that flowed on, within, or beneath the glacial ice.

▨ **Badlands.** Areas dissected by stream erosion into an intricate system of closely spaced, narrow ridges.

Maximum extent of glaciation.

Slough.

2115 • **Surface elevation.**