DICKINSON GEOLOGY

A Guide to the Geology, Mineral Resources, and Geologic Hazards of the Dickinson Area

by
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Geologic Investigation No. 1
North Dakota Geological Survey
John P. Bluemle, State Geologist
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Acknowledgments

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Preface

This guidebook to the geology of the greater Dickinson area has been adapted from NDGS Open-File Report 95-1, *Geology of the Davis Buttes, Dickinson North, Dickinson South, and Lehigh Quadrangles, Stark and Dunn Counties, North Dakota.* It differs from the earlier report in that it is less technical in scope and contains more information on the general geology of southwestern North Dakota. The accompanying geologic maps have been reduced from the original 1:24,000-scale versions of the Davis Buttes, Dickinson North, Dickinson South, and Lehigh quadrangles. Those seeking a more technical treatment of the area's geology, including more detailed geologic maps, should consult the open-file report.

The first two chapters, "Geology Underfoot" and "Geology at the Surface", offer, respectively, a general geological background on deeply buried rocks under Dickinson and a detailed description of the rocks and landforms visible at the surface. Each contributes to the geologic history of the area and gives perspective to the third chapter, "Practical Geology". This last chapter should be useful to city and county officials, businesses, homeowners, and others who want to learn more about the geologic resources and hazards of the greater Dickinson area.

Throughout the text we give the locations of numerous instructive or unusual rock exposures. Many of these are located on private land, and you should obtain permission if you wish to investigate these areas. The fieldtrips at the end of this book discuss many additional exposures, most of which are located on public lands or rights-of-way.

Introduction

We tend to think of the history of North Dakota beginning with European settlement, or, at best, to the even older history of Native Americans. Yet there is a much more ancient history to behold - a geologic history that literally provides the foundation upon which our lives are set. Just as every city has its own personality, its own human history and traditions, each city also has a geologic history that reaches much farther back in time. Grand Forks, Fargo, and the other cities and towns of the Red River Valley lie on the former floor of Glacial Lake Agassiz, once the largest freshwater lake in North America; Jamestown, Valley City, Minot, and many other towns are nestled along scenic, wooded valleys carved by catastrophic floods of glacial meltwater; Williston, and our state's capital, Bismarck, lie in the Missouri River Valley, a "composite" valley created by the linking of old, preglacial segments and relatively new ice-age channels; Medora is cradled in the deeply carved badlands along the Little Missouri River. Dickinson, too, has its own special geologic history, one that is reflected today in wide, rolling plains and sandstone-capped buttes.

In the chapters that follow, we explain the geologic history of the greater Dickinson area. We talk, too, about the region's mineral resources and geologic hazards, and just what it is, geologically speaking, that makes the area what it is. A remarkable geologic diversity underlies this sea of grass: oil and gas production, including the prolific wells in the Lodgepole Formation; the story behind mining of lignite, clay, building stone, and sand and gravel; and interesting rocks and minerals, including petrified trees and swamp debris. At the end of this book, we offer a fieldtrip where you can see much of what is discussed in the text.

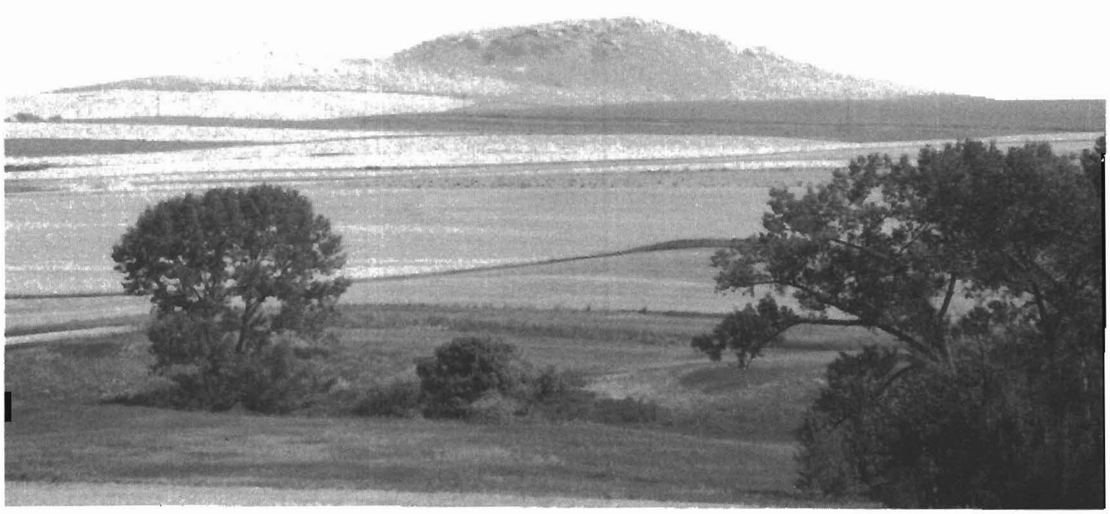


Figure 1. Beneath the rolling prairie surrounding Dickinson lies a geological story, recorded in layer upon layer of sedimentary rock, that spans over 500 million years of Earth's history. The rocks that we see at the surface, such as these at Camels Butte, represent just the latest chapter, one that provides the foundation upon which our daily lives unfold. Camels Butte is located just north of Dickinson in southern Dunn County.

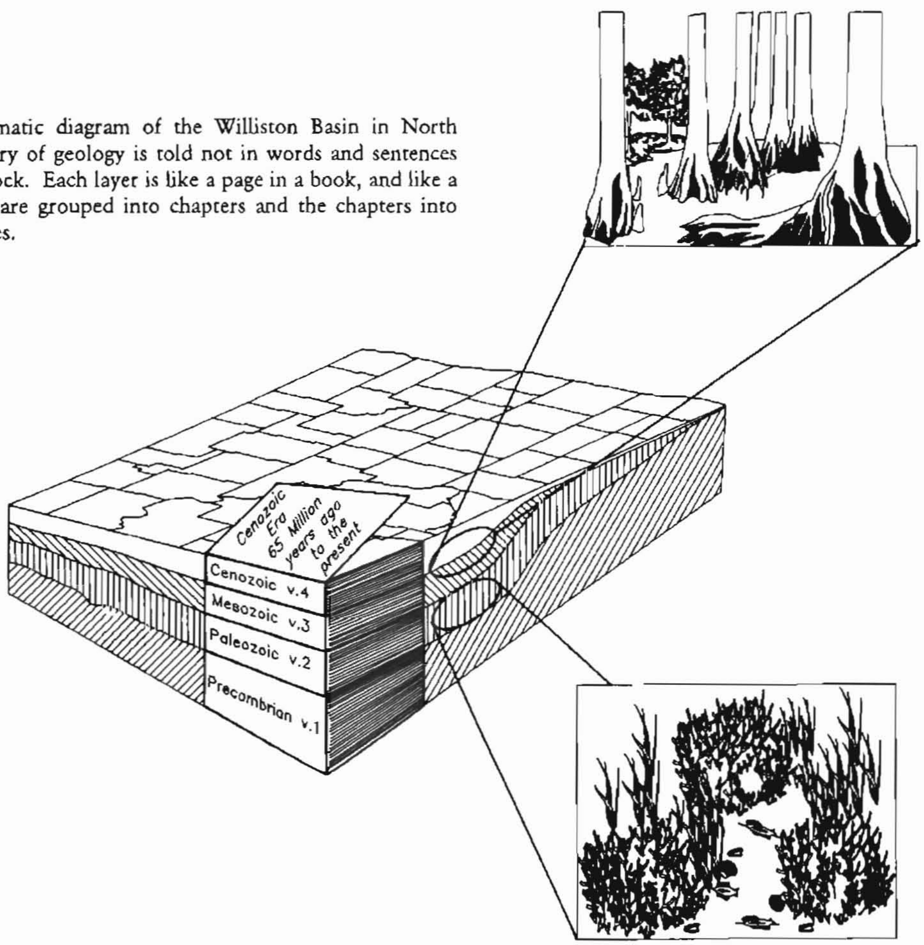
Geology Underfoot

Geologists often view the earth as a book. The story is not told in words and sentences, however, but in layers of rocks that record geologic history. Each layer is like a page in a book; the pages themselves are grouped into chapters and the chapters into four great volumes.

One layer of the geologic book might tell us that 20,000 years ago, much of North Dakota looked like modern-day Antarctica, covered by vast sheets of glacial ice. Another layer, 55 million years old, reveals western North Dakota forests that were as lush and diverse as those now growing in the southeastern United States. Still another deeper layer, a 350-million-year-old limestone with fossil corals, sea lilies, and brachiopods, bespeaks of a long-vanished, warm, shallow, Caribbean-like sea.

The difference between a real book and the book of geology, however, is that in the latter many pages and even whole chapters are missing. The book of geology is perhaps better visualized as an incomplete diary, with many gaps in the record of continuous time. Sometimes sediments are not deposited, and sometimes existing layers are removed by erosion; either condition creates a gap in the rock record that geologists call an unconformity. The pages or layers that remain can themselves be torn (faulted), crinkled (folded), or removed from the book and reinserted out of sequence (thrusted). The book of geology has, by

Figure 2. Schematic diagram of the Williston Basin in North Dakota. The story of geology is told not in words and sentences but in layers of rock. Each layer is like a page in a book, and like a book, the layers are grouped into chapters and the chapters into four great volumes.



any librarian's standards, been horribly abused. Even so it is a record that with careful observation can be pieced back together.

New pages of the book of geology continue to be discovered all the time. The oil wells near Dickinson each show how the geologic history at that point has changed over millions of years. Collectively, they serve as a three-dimensional framework upon which geologists can reconstruct ancient depositional environments, such as the prolific oil- and gas-producing, 360-million-year-old carbonate mounds of the Lodgepole Formation. Even a shallow excavation for a basement can provide new information on surficial sediments and how and when they were deposited. Good exposures may be too few and far between to suit our needs, but none is so small that it fails to add another paragraph or page to our book.

The book of geology is arranged in chronological order, with each era a separate volume. The oldest era is called the Precambrian. The Precambrian spans 80% of earth's history, from its beginning up until the first appearance of hard-shelled (and thus more easily preserved) life forms. The next volume contains the record of the Paleozoic era, so named from the Greek *palaios* meaning "old" and *zoo* meaning "life." The Mesozoic era, from the Greek *mesos* meaning "middle," was the age of the dinosaurs, spanning the time from their emergence to extinction. The Cenozoic era, meaning "recent life" from the Greek *kainos*, contains all the time since the extinction of the dinosaurs. Eras are further subdivided into periods and epochs, which for the uninitiated is but a bewildering stack of arcane terms. Each name of course has a meaning, and each has a history. For example, Paleocene (the first Period of the Cenozoic "recent life" Era) means "old recent"; Eocene, "dawn of recent"; Oligocene, "more or less recent." Holocene, the epoch in which we live, means "entirely recent." Except for the comparatively young sediments of modern and Ice Age rivers, the rocks found at the surface in the greater Dickinson area were deposited in the Paleocene, Eocene, and Oligocene Epochs, from about 60 to 35 million years ago. The terminology reminds us of what geologist, author, and historian Stephen Jay Gould (1985) once wrote:

> *My standard response to generations of student groans (at the imposed necessity of memorizing all those funny names from Cambrian to Pleistocene) reminds my charges that they are not learning capricious words for the arbitrary division of continuous time, but rather the dates of major events in the history of life.*

Geologists summarize the four-volume book of geology by using a stratigraphic column. Each volume is divided into chapters called "rock units." One chapter in the Paleozoic volume, for example, is titled the Madison Group, which itself is divided into the Charles Formation and the prolific oil-producing units known as the Mission Canyon and Lodgepole Formations. Formations can be further subdivided into members, beds, or intervals to help refine the geologic picture, but the "Formation" is the principal rock unit that most geologists work with. The numbers at the side of the chart tell us how long ago in millions of years each chapter began.

There is no single place, such as a library, where the great thickness of sedimentary rocks that these volumes represent can be seen. In North Dakota, most of these rocks, or chapters, are deeply buried in the Williston Basin. They are known only from cores and samples taken for petroleum and other exploration, and from exposures of equivalent rock layers in neighboring states and provinces, such as the Black Hills of South Dakota. Still, geologists have been able to reconstruct the main

ERA AND SEQUENCE	Preserved	PERIOD	MAIN ROCK TYPE IN NORTH DAKOTA	MILLIONS OF YEARS AGO
Cenozoic (recent life)		Quaternary	Glacial Sediment	1.6
		Tertiary	Sandstone, siltstone, shale, lignite	65
Mesozoic (middle life)		Cretaceous	Layers of silt, clay, and sand near the top; shale in the middle; sand at the base	144
		Jurassic	Shale, limestone, and siltstone; some redbeds and evaporites	208
		Triassic	Shale, siltstone, sandstone, redbeds and evaporites	245
Paleozoic (ancient life)		Permian	Limestone, evaporites, dolomite and shale	286
		Pennsylvanian	Sandstone, shale, limestone and dolomite	320
		Mississippian	Shale, limestone, dolomite, and evaproites	360
		Devonian	Mainly limestone,shale, and salt including potash	408
		Silurian	Limestone and dolomite	438
		Ordovician	Limestone, dolomite, shale, and sandstone	505
		Cambrian	Shale, limestone, and sandstone	570
Cryptozoic (hidden life)		Precambrian	Igneous and metamorphic crystalline rocks	

Figure 3. Generalized stratigraphic column for North Dakota. This stratigraphic column serves much the same purpose as a table of contents does for a book - it gives us an outline of the geology of the state. However, our book is incomplete; gaps resulted because rocks were often either not deposited or else eroded away. The parts of the sedimentary record that are preserved are shown by shaded bands. The gaps in the rock record are called unconformities. It is as if whole pages and even chapters never made it into our book of North Dakota geology. Still, geologists have pieced together fascinating details of this geologic history, and research continues to add new pages all the time (modified from Bluemle et al., 1986).

features of this four-volume set, and new pages continue to be added all the time.

With no single, complete exposure to refer to, it requires careful observation to know where we are within the sedimentary sequence at different places across the state. Index fossils, distinctive fossils from creatures known to have lived only during a particular span of time, serve as page numbers and can tell you exactly where you are in the four-volume book of North Dakota geology (or at least what chapter you are in). Fossils are especially useful because they can tell us not only what page we are on, but also what the environment was like when they lived. Turtles, crocodile-like champosaurs, and huge petrified trees tell of a time of vast floodplains and everglade-like swamps. Limestone with corals, brachiopods, and sea lilies reveal warm, shallow, Caribbean-like seas. While the use of fossils can give relative ages of rock layers, radiometric dating provides "absolute" ages. Radiometric dating is based on the fact that radioactive elements such as carbon and uranium decay at constant and measurable rates, and so provide us with a measurement in thousands or millions of years before the present. Recognizing one's position in the stratigraphic column also requires that geologists know the rock units and be able to recognize distinctive layers or groups of layers.

Eras of Geologic Time

The huge thickness of sedimentary rocks in the Williston Basin (over 15,000 feet thick at the basin's center in Dunn County) were deposited during three eras (Paleozoic, Mesozoic, and Cenozoic) of geologic time ranging from 570 million years ago to the present. The stage on which these sediments rest is called the

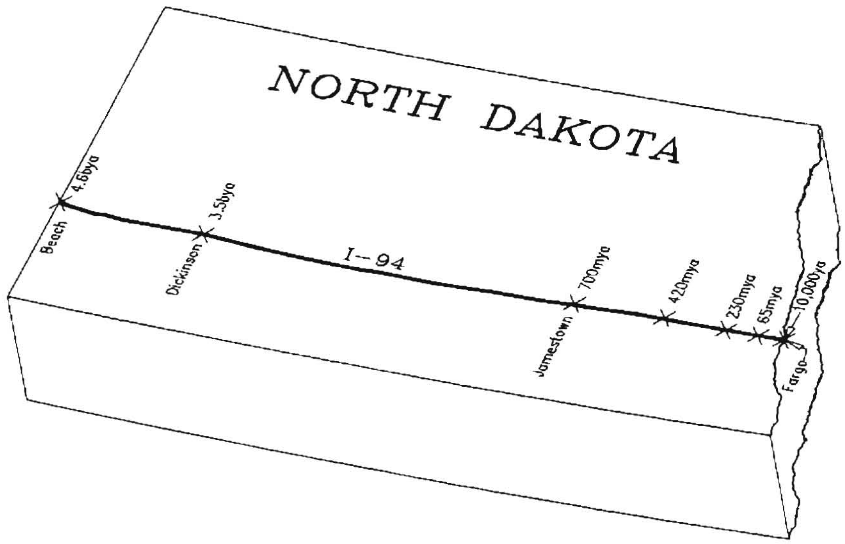


Figure 4. Geologic time compared to the distance across North Dakota. This great span of geologic time, beginning with the formation of the Earth about 4.6 billion years ago, is difficult to comprehend. To get a sense of the enormity of that time, imagine traveling eastward on Interstate 94 from Montana to Minnesota. The illustration shows the number of miles you will have traveled as you "witness" great events in the history of the Earth (modified from Schwert, 1993).

Precambrian basement, which consists of very old crystalline igneous and metamorphic rocks. Precambrian time is from the beginning of the creation of the earth (approximately 4.6 billion years ago) to the beginning of the Paleozoic. In other words, the Precambrian represents 88 percent of all geologic time.

Although exposed in adjacent states and provinces, Precambrian rocks are not exposed in North Dakota, and so at least here are poorly understood. Geologists have divided them into rocks of the Wyoming Craton underlying extreme southwestern North Dakota and the Superior Craton to the east. These two cratons, extremely old and deformed but geologically stable regions, are separated by the Western Dakota Mobile Belt, a group of slightly younger rocks that were caught between the two cratons as they collided during the Precambrian. While all of these ancient rocks are deeply buried in western North Dakota, boulders of the same composition are scattered across glaciated parts of the state. Ice Age glaciers brought these boulders to North Dakota from Canada and Minnesota.

Information obtained from oil well tests that penetrated Precambrian rocks in southern Dunn County and eastern Stark County indicates that the top of the Precambrian basement lies approximately 13,000 feet beneath Dickinson.

Paleozoic Era

In North Dakota, the oldest Paleozoic rocks are contained in the Deadwood Formation. The basal Deadwood Formation consists of sandstone derived primarily from reworked, weathered Precambrian rocks. As the sea transgressed, or flooded the area as it expanded, carbonate rocks were deposited over the sandstone. When the sea retreated, more sand and shale were deposited in shallower water. This basic succession of clastic-carbonate-clastic sediments is typical throughout the Paleozoic and Mesozoic Eras, and represents the initial transgression of the sea (and a complex succession of deltaic, nearshore, and shallow marine environments), its maximum stand, and the eventual regression (and similarly complex sequence of continental and shallow marine environments). The most common fossils found in the Deadwood Formation in North Dakota are a variety of conodonts, small tooth-like fossils of an early eel-like vertebrate.

With the retreat of the Deadwood sea about 480 million years ago, North Dakota lay bare and exposed to erosion for perhaps 15 to 20 million years; at that time, land plants had not yet evolved. This span of time is represented by an unconformity, a gap in the rock record. A new cycle of deposition began when warm, shallow seas again flooded the area in middle Ordovician time, about 460 million years ago. Sandstone and shale beds of the Winnipeg Group mark the return of the seas to this area. Overlying these are carbonates of the Red River, Stony Mountain, Stonewall, and Interlake Formations. Marine algae were probably the principal life form in these Ordovician seas, although early fish began to develop then, and corals, brachiopods, and trilobites were common. It was during this cycle of deposition that the Williston Basin became a discrete structural depression, which allowed the subsequent deposition and preservation of thousands of feet of sediments. By about 400 million years ago, the seas had drained from North Dakota.

A period of about 40 million years elapsed before seas again covered North Dakota about 365 million years ago. This long period of time is represented by a deeply weathered interval called the Ashern Formation which lies approximately 11,000 feet below Dickinson. Carbonates of the Winnipegosis Formation were deposited on top of the Ashern Formation, and these in turn were covered by evaporites, mostly salt and anhydrite, of the Prairie Formation. Over the next 70 million years, several thousand feet of carbonates, evaporites, and clastic sediments were deposited in the Williston Basin. The Mississippian sea reached its maximum size about 350 million years ago, when the Lodgepole and Mission Canyon Formations were deposited. These rocks lie approximately 9,000 to 10,000 feet below Dickinson. Fossil corals, crinoids, bryozoans, brachiopods, and other marine invertebrates are common in some of the Mississippian rocks, and reveal a warm sea bordered by reefs or carbonate mounds. As the Mississippian sea retreated and became shallower and even dried up completely at times, evaporites of the Charles Formation were deposited. Sand, shale, and carbonate of the Big Snowy Group were the last sediments deposited in the Mississippian sea, which retreated about 325 million years ago. These middle Paleozoic rocks contain some of the most important oil-producing horizons in the Williston Basin.

About 315 million years ago, shallow marine sand and shale sediments of the Tyler Formation were deposited over the top of the eroded Mississippian surface. The Tyler Formation is overlain by carbonates and clastics of the Amsden Formation and the sandy carbonates of the Broom Creek Formation. At the end of the Paleozoic Era, seas became shallower and even dried completely at times depositing salt beds and redbed sediments of the Opeche and Spearfish Formations along with limestone of the Minnekahta Formation. These rocks lie 6,500 to 8,000 feet beneath the city of Dickinson.

Mesozoic Era

The Mesozoic Era has often been called the age of the dinosaurs because they flourished during this period of geologic time. The bright red clastic sediments and evaporites deposited throughout the world during the Triassic Period, the early part of the Mesozoic Era, indicates that the climate throughout much of the world was hot and dry.

The unconformity that separates Triassic and Jurassic rocks represents about 45 million years (from about 220 to 175 million years ago), during which most of North Dakota was a low, forested land surface that was being eroded. In northeastern North Dakota and southern Manitoba, broad valleys were eroded by westerly flowing rivers. The valleys were later filled with Jurassic shales as seas once again flooded the area in middle Jurassic time. Ammonoids, belemnoids, and marine reptiles were common in these seas. The Jurassic was marked by deposition of sediments similar to the evaporites and redbeds of the underlying Spearfish Formation. As the seas became more open, shales of the Rierdon and Swift Formations were deposited.

During the Cretaceous, sands and shales of the Dakota Group were deposited over the Swift Formation, and as the Western Interior Cretaceous sea became deeper and more widespread, thick layers of marine shale were deposited. These shales are present at depths of 2500 to 5000 feet below Dickinson. As the Cretaceous sea regressed or retreated, fluvial, deltaic, and shallow marine sediments of the Fox Hills and Hell Creek Formations were deposited. These formations consist largely of sediments that were derived from the west, from the rising ancestral Rocky Mountains. The Hell Creek Formation is famous for its *Tyrannosaurus rex, Triceratops,* and other dinosaur fossils. These dinosaur-bearing rocks are exposed at the surface south of Bismarck and also near Marmarth but are situated approximately 2000 feet beneath the surface in the Dickinson area.

Cenozoic Era

The Cenozoic Era includes all of geologic time from the extinction of the dinosaurs, approximately 67 million years ago, to the present. Throughout most of the early part of the Cenozoic Era, North Dakota was covered by swamps and rivers. The Cannonball Formation contains the only sandstones and mudstones deposited in a marine environment during this time. The sandstone and shale of the Cannonball Formation was deposited in the only sea to reach North Dakota during Tertiary time. At the same time, river, lake, and swamp sediments of the Ludlow and Slope Formations were deposited along the coastal plain of the Cannonball Sea. The lignite-bearing sediments of the Bullion Creek and Sentinel Butte Formations record a time of lush, diverse forests and marshes, much like those of the southeastern United States today. The Golden Valley Formation also contains a sequence of sedimentary rocks deposited by rivers, lakes, and swamps.

The White River Group includes a distinctive conglomerate with volcanic porphyry and quartzite clasts that belongs to the Chadron Formation. Oligocene and early Miocene lake sediments cap the Killdeer Mountains and several other buttes in southwestern North Dakota. These rocks contain considerable amounts of volcanic ash that blew into the lakes from the Rocky Mountains.

These last three rock units, the Sentinel Butte and Golden Valley formations and the White River Group, can be viewed at the surface in the Dickinson area and will be discussed at length in following chapters.

During the Pleistocene Epoch, glaciers, such as those that now engulf Antarctica and Greenland, scoured North Dakota many times. They remolded the topography and left behind a layer of glacial sediments - a poorly-sorted mixture of clay, silt, sand, and boulders known as till; well-sorted sand and gravel river sediments; and fine-grained lake clays - that together belong to the Coleharbor Group.

The last three volumes of the book of North Dakota geology contain a record of over 15,000 feet of sedimentary rock. While many pages of that record are missing or incomplete, the story that is revealed is filled with interesting details. Even features of the ancient Precambrian basement (volume I in our book of North Dakota geology), though deeply buried and poorly understood, can be glimpsed by the casual observer, principally through the wide variety of glacial erratics - which include Precambrian rocks from the Canadian shield carried to North Dakota by Ice Age glaciers - that are strewn across the state.

Geology at the Surface

North Dakota has been divided into six major physiographic regions, each defined by a suite of characteristic landforms that serve to differentiate it from its neighbors. One of the best ways to "see" these physiographic regions is by using a shaded-relief map. Such a map vividly shows the dramatic differences in the landscape. Certainly the shaded-relief map of North Dakota dispels the myth of the uniform, monotonously flat countryside that many outsiders envision, and that sometimes even locals, traveling at highway speeds, experience. The great, wide open countryside at times makes it difficult to appreciate the diversity of landscapes within one's view. When compressed onto a page-size map, however, major topographic features are easy to visualize.

The boundaries and names of these physiographic regions are not arbitrary, not capriciously drawn like the misleading names hung on some suburban streets. Each line reflects an important underlying geologic feature. The Missouri Escarpment, for example, marks a prominent slope that advancing glaciers were forced to push up and over, eventually leaving behind a characteristic hummocky topography and innumerable prairie potholes. The remarkably flat floor of the Red River Valley mirrors the surface of the Ice Age lake, glacial Lake Agassiz, in which it formed. Beaches and wave-cut scarps now mark the lake's former shorelines and separate the valley from the glaciated plains to the west. Understanding the state's physiography is very much understanding an outline of the state's geologic history.

North Dakota lies within the Interior Plains, that vast region stretching from the Rocky Mountains to the Appalachians. In North Dakota, the Interior Plains are divided into two major physiographic provinces by the Missouri Escarpment. To the north and east of the escarpment lies the Central Lowlands Province, characterized by its glacially smoothed landscape. To the south and west, the Great Plains Province rises gradually westward toward the Rocky Mountains.

The Great Plains Province is divided into the Missouri Plateau (or Missouri Slope Upland), Little Missouri Badlands, Coteau Slope, and Missouri Coteau. The Great Plains Province thus contains both glaciated and non-glaciated regions. Southwest of the Missouri River, the broad valleys, hills, and buttes of the Missouri Plateau are largely the result of erosion of flat-lying beds of sandstone, siltstone, claystone, and lignite. These sediments belong primarily to the Paleocene-age Fort Union

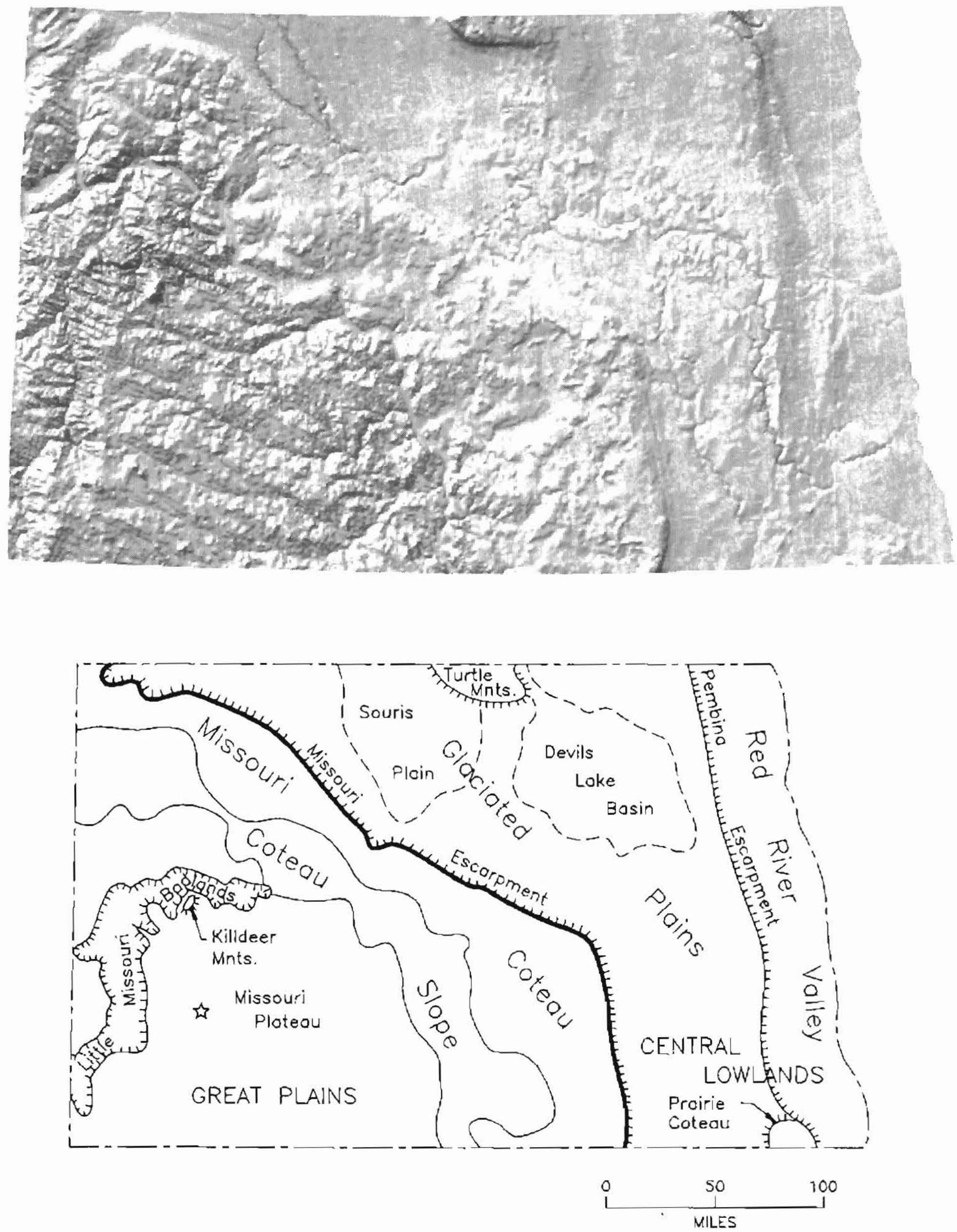


Figure 5. Physiographic regions of the state. Shaded-relief map from Bassler and Luther, 1996.

CENTRAL LOWLAND

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

Prairie Coteau and Turtle Mountains: Hummocky, glaciated irregular plains that resulted from collapse of superglacial sediment.

Glaciated Plains: Rolling, glaciated landscape.

Red River Valley: Flat plain resulting from sedimentation on the floor of glacial Lake Agassiz.

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

Souris Lake Plain: Flat to gently sloping plain resulting from sedimentation on the floor of glacial Lake Souris.

Devils Lake Basin: Closed drainage basin with drainage to Devils Lake; rolling, glaciated landscape.

GREAT PLAINS

Missouri Plateau: Rolling to hilly plains except in badlands areas and near prominent buttes.

Little Missouri Badlands: Rugged, deeply eroded, hilly area along the Little Missouri River.

Coteau Slope: Rolling to hilly plains east of the Missouri River that have both erosional and glacial landforms.

Missouri Coteau: Hummocky, glaciated irregular plains that resulted from collapse of superglacial sediment.

Group and were deposited by ancient rivers flowing away from the rising Rocky Mountains between about 65 to 55 million years ago. From about 10 to 5 million years ago, streams began eroding the sediments that had so long ago been deposited, dissecting the plateau with a series of rivers flowing northeast to Hudson Bay. The modern landscape over most of southwestern North Dakota thus formed over an exceptionally long period of time, unlike the much more recent topography of the glaciated portion of the state.

The spectacular variety of landforms found in the Missouri Plateau and Little Missouri Badlands results primarily from the differences in resistance to erosion among Fort Union Group strata. Buttes, for example, form when easily eroded sediments are protected or capped by a hard layer of sandstone or limestone. Where beds of lignite have caught fire and burned, adjacent sediments are baked and fused into a natural brick-like material called clinker or "scoria". The bright red clinker also shields underlying sediments from erosion. In other places, mineralized groundwater circulated through the sediments, forming flint, petrified wood, silcrete, and concretions and nodules of all shapes and sizes, all of which, being harder than the enclosing sediments, resist erosion and so accumulate at the surface.

Although part of the Missouri Plateau south and west of the Missouri River was glaciated during the Pleistocene, in most places the only visible evidence of glaciation is an occasional erratic boulder or thin patch of glacial sediment. The glaciations that affected these areas were early ones that occurred long before the glaciations that affected the eastern and northern parts of the state. Presumably, most of the evidence of these early glaciations - thick glacial sediments and glacial landforms - was removed by erosion over the past several hundred thousand years.

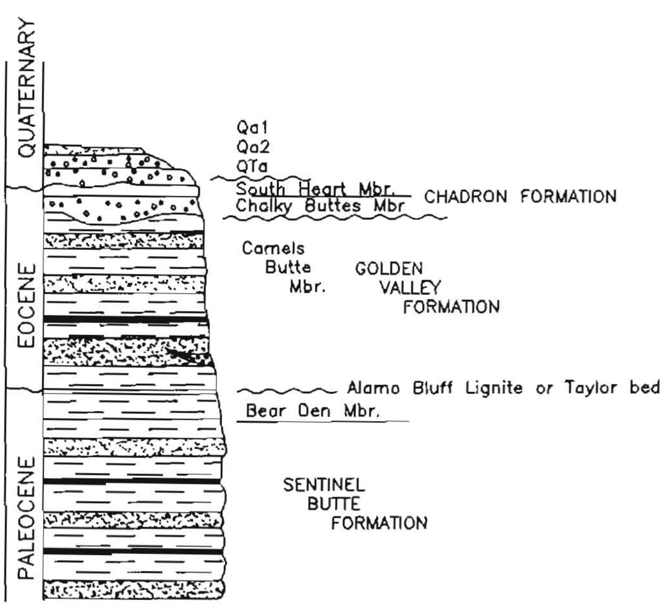


Figure 6. Stratigraphic column showing nomenclature used in this report.

Stratigraphy

The Sentinel Butte Formation is the oldest bedrock unit exposed in and near Dickinson. It, as well as the overlying Golden Valley Formation, is characterized by siltstone, claystone, and sandstone that was deposited in river, floodplain, and swamp environments. The Sentinel Butte Formation in particular contains numerous lignite beds, at least two of which have been mined in the area. The Chalky Buttes Member of the Chadron Formation unconformably overlies the Golden Valley Formation to the south of Dickinson. It consists of pebbly conglomerate and sandy mudstone deposited in river and floodplain environments. All three bedrock units locally form badlands topography.

Sentinel Butte Formation

The Sentinel Butte Formation consists of up to 600 feet of gray to brown siltstone, claystone, sandstone, and lignite that was deposited in river, lake, and swamp environments (Jacob, 1976). As is typical of other early Tertiary sediments in North Dakota, most individual beds are not well cemented and can commonly be dug into with a shovel. The well-cemented beds that are present typically are channel sandstones that, because they are harder than the enclosing sediments, form resistant ledges and caprock on buttes. The Sentinel Butte Formation takes its name from Sentinel Butte, North Dakota, where, near the turn of the century, these rocks were first studied in detail.

The Sentinel Butte Formation is the most widespread Tertiary formation exposed in North Dakota; it is also the most widespread unit exposed in the greater Dickinson area. Typically, the Sentinel Butte Formation forms gentle, grass-covered slopes. Good exposures are few and are restricted to buttes, areas of badlands topography, roadcuts and cutbanks, areas of shoreline erosion along Patterson Lake, and areas once mined for lignite.

Only about the upper 200 feet of the Sentinel Butte Formation is exposed in the greater Dickinson area. There it consists of variably lithified gray to brown mudstone, siltstone, claystone, sandstone, and lignite. Isolated, well-cemented, crossbedded, channel sandstones, encased in poorly lithified mudstones and siltstones, are common. Calcite-cemented sandstone and mudstone concretions, commonly highly jointed and partially healed by drusy calcite, are also common, as are siderite (iron carbonate) nodules.

From about 67 to 55 million years ago, during a span of time known to geologists as the Paleocene Epoch, southwestern North Dakota must have looked much like the modern-day coastal plain of Louisiana or Mississippi. Sediment-choked rivers meandered across what was then a coastal plain along the shores of the Cannonball Sea, the last sea to flood North Dakota. The sediments were derived from the ancestral Rocky Mountains and were deposited in river, lake, floodplain, and swamp environments. As the rivers meandered across their floodplains, old swamp deposits were buried and new ones formed. Under the weight of overlying sediments, the soggy, half-rotten vegetation-peat-was transformed into lignite.

Figure 7. The countryside north of Dickinson. In the Dickinson area, the Sentinel Butte Formation typically forms gentle, grass-covered slopes. The best exposures are found in the buttes that rise above the prairie, and in areas of active erosion, such as along rivers and lakes.

The contact between the Sentinel Butte and Golden Valley Formations is exposed in only a few

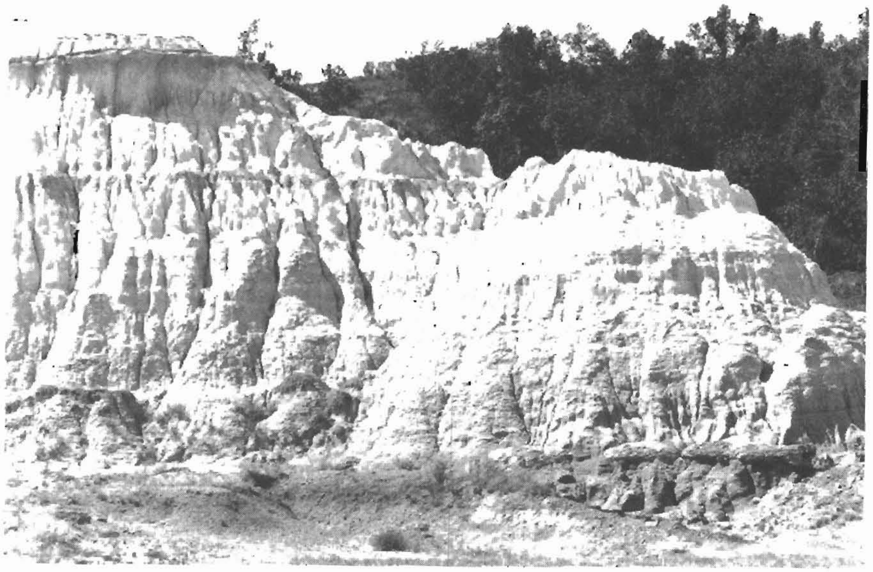


Figure 8. The contact, at the base of the hillside, between the Sentinel Butte Formation and the overlying, white and orange Bear Den Member (141-94-31cca). The Taylor bed forms a thin ledge at the upper left corner of the photo. The contact here is conformable and gradational, and lends credence to the idea that the Bear Den Member is an ancient weathering horizon that developed on top of Sentinel Butte strata.

areas. It is conformable and gradational, indicating that there was no significant change in sediment type or depositional environment across the boundary. In most places, the contact is marked by a prominent color change from brown and dark gray colors typical of the Sentinel Butte Formation to white or light gray colors typical of the Bear Den Member. Bear Den Member strata in particular are normally clayey and feel greasy to the touch.

The Sentinel Butte Formation can be distinguished from the overlying Camels Butte Member of the Golden Valley Formation by: 1) stratigraphic position, with reference to the distinctive Bear Den Member; 2) its more numerous and extensive lignite beds; 3) sandstones that are generally less micaceous than their Camels Butte Member counterparts; 4) generally darker, "somber" grays and browns versus the yellowish browns of the Camels Butte Member; and 5) its Paleocene versus Eocene flora and fauna.

In the greater Dickinson area, the best exposures of Sentinel Butte strata are located along the escarpment in the northeast portion of the Davis Buttes quadrangle (140-95-2, 140-95-3, 141-94-31, 141-95-25, and 141-95-36); along terrace walls of the Green River in 140-95-22dcc, 140-95-22ca, 140-95-26cac; along the valleys of unnamed tributaries to Antelope Creek (138-95-2, 138-95-3, 138-98-10, 138-98-14); and along the valley of the Heart River (139-95-8 to 11). Smaller exposures are common along particularly steep valley walls of the Green and Heart Rivers.

Excellent examples of small- to-medium scale cross-bedding in the Sentinel Butte sandstone can be seen in a railroad cut at Lehigh (139-95-8cba). Contorted bedding, the result of soft sediment deformation, can also be viewed at this locality as well as at a roadcut in the northwest corner of section 35 (139-95).

The contact between the Sentinel Butte and Golden Valley Formations is well exposed north of Dickinson along the escarpment in the northeast portion of the Davis Buttes quadrangle (141-94-31ccd, 141-94-31ccb, and 141-95-36daa) and at Camels Butte (141-96-27dac). South of Dickinson, the contact can be seen near the old clay pits above the Heart River (139-96-8 and 9), along the southern shore of Patterson Lake (139-96-18b), the east valley

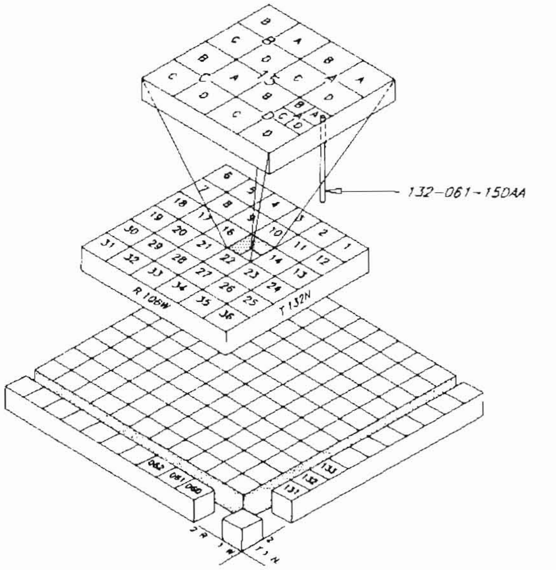


Figure 9. The system used to locate wells, test holes, and outcrop locations in this report.

of Ash Creek (139-97-25 and 36, 139-96-30), and above the east bank of Antelope Creek (138-96-13) (this latter example may be a slump block).

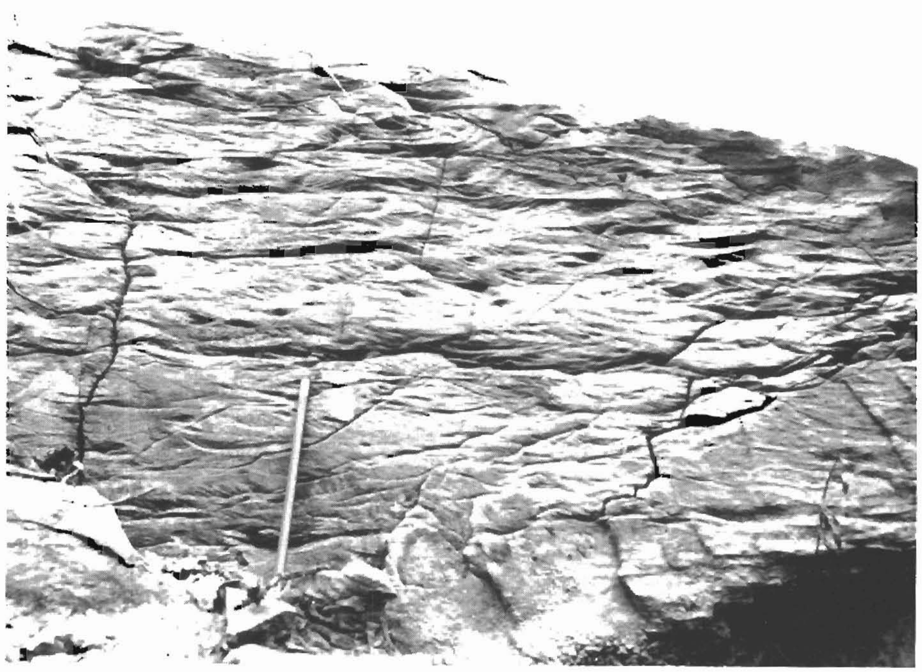
Golden Valley Formation

The Golden Valley Formation was named for a group of beds exposed near the town of Golden Valley, North Dakota (Bensen and Laird, 1947). It consists of two dissimilar members: The lower, bright white, kaolinitic Bear Den Member (Paleocene) and the upper, brown, micaceous Camels Butte Member (Eocene) (Hickey, 1977). Although the members have not been mapped separately, the distinctive Taylor bed silcrete - which commonly marks their contact - has been mapped. Exposures stratigraphically above the silcrete belong to the Camels Butte Member, those below to the Bear Den Member.

Bear Den Member

The Bear Den Member is named for exposures on a tributary to Bear Den Creek about 7.5 miles northwest of Mandaree, McKenzie County. While seldom greater than 25 to 35 feet thick, the bright white color and abundance of the clay mineral kaolinite make this unit an important marker bed in southwestern North Dakota, enabling it to be traced great distances across the countryside. Readily recognized layers such as this are to geologists much like chapter headings in a book, letting them know exactly where they are in the huge thickness of sedimentary rocks of southwestern North Dakota.

Figure 10. Small-scale (ripple) cross-bedding in Sentinel Butte Formation sandstone. Outcrop exposed along railroad cut near Lehigh (139-95-8caa). Pencil for scale.



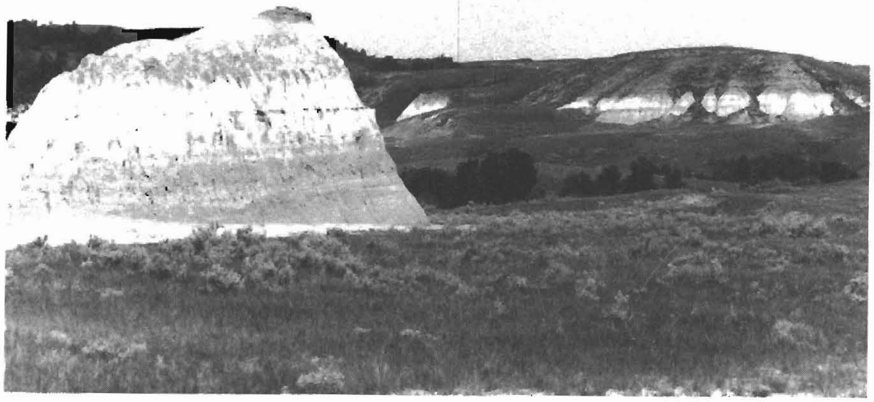


Figure 11. The bright white, mostly barren, steep slopes of the kaolinitic Bear Den Member. These slopes stand in stark contrast to vegetated, more gentle slopes of enclosing units, enabling it to be traced for great distances across the countryside. Note the three units present in the hill in the foreground: a lower gray zone, middle orange zone, and an upper carbonaceous zone. Photo taken looking north into 141-95-36da.

The Bear Den Member is often divisible into three regionally consistent stratigraphic units: basal gray zone, middle orange zone, and a thin upper carbonaceous zone. The contacts between these zones are normally gradational.

Carbonaceous zone - Dark gray to brownish gray, thinly bedded to laminated mudstone, siltstone, and carbonaceous shale. The top of this zone is marked by the Alamo Bluff lignite or its lateral equivalent, the Taylor bed silcrete. Typically less than 2 feet thick.

Orange zone - Light gray to bright white massive clay; locally thin bedded and silty, and locally replaced by a fine- to medium-grained kaolinitic silty sand. Small limonite concretions in the upper part impart characteristic orange stains in weathered exposures. Joints are common and are filled with gypsum and limonite, creating a polygonal pattern on surface exposures. Typically 10 to 15 feet thick.

Gray zone - Light to medium gray siltstone, mudstone, and fine- to medium-grained sandstone. Crossbedded to parallel bedded; locally massive. Typically 3 to 6 feet thick.

The Bear Den Member is typically 15 to 30 feet thick in the Dickinson area. It commonly forms steep, sparsely vegetated slopes that stand in stark contrast to the more gentle, vegetated slopes characteristic of enclosing units. While it has a variety of commercial uses as we shall later see, kaolinite makes a poor medium for plant growth. Where capped by the erosion-resistant Taylor bed silcrete, the Bear Den Member forms characteristically flat uplands or benches. Commonly, however, only small exposures of the Bear Den Member can be seen cropping out through the grass.

On the basis of sedimentary characteristics, paleontologist Leo J. Hickey (1977) demonstrated that the lower gray and middle orange zones of the Bear Den Member were deposited in a fluvial environment rather than a lacustrine setting as suggested by earlier workers. He also noted that the lateral continuity and thinness of the upper gray zone " . . . *together with the presence of standing plant stems in the widespread Taylor bed siltstone seem to*

Figure 12. The middle, orange zone of the Bear Den Member, showing characteristic joints and joint-controlled iron oxide stains (141-94-31cc).

Figure 13. The flat-lying topography northeast of Dickinson. Although only a few inches to 2 feet thick, the Taylor bed silcrete is so hard that it tends to form erosion resistant, planar surfaces, such as this flat area southeast of Simon Butte (140-95-8b). Note the small, bright white exposures of the Bear Den Member.

indicate that deposition took place in a vast swamp with scattered lakes rather than in a single great lake." Bear Den Member strata were thus deposited in a broad, swampy lowland across which meandered sluggish streams. Over 41 species of plants have been reported from the Bear Den Member alone and they indicate a subtropical to warm temperate lowland forest with scattered swamps and small lakes.

The Bear Den Member is believed to be a deep weathering profile - an ancient soil horizon or paleosol - developed on top of the Sentinel Butte Formation (Karner et. al., 1978). The member thus marks a prolonged period of weathering, a hiatus in deposition between the Sentinel Butte Formation and the Camels Butte Member; geologists call this gap in the geologic record an unconformity.

The Bear Den Member marks a distinctive lithologic interval between similar beds of the overlying Camels Butte Member and underlying Sentinel Butte Formation. It is distinguished from these two units by: 1) clay mineralogy, with a predominance of kaolinite over illite and montmorillonite; 2) characteristic three-part color zonation; 3) weathered colors of bright white, light gray, and orange in contrast to the browns and grays of enclosing units; and 4) typically barren, steep slopes.

In the greater Dickinson area, the three-part zonation of the Bear Den Member is best exposed at the northwest end of Camels Butte (141-96-27ddb) and along the escarpment known as the "Fairy Dells" in the northeast corner of the Davis Buttes quadrangle (141-94-31c, 141-95-36a, 141-95-36d).

Other exposures of the Bear Den Member in the Dickinson area are incomplete. They generally lack the distinctive orange staining and instead are characterized by bright white to light gray colors, commonly capped by the Taylor bed silcrete. Locally, as in 140-95-2baa, 140-95-26bba, 140-95-26bdb, 140-96-21, 140-96-27c, 140-96-34bad, 139-96-18bca, and 139-96-25ddb, the Bear Den Member is characterized by bright white, kaolinitic, fine to medium grained silty sand. The three-part color zonation is less well developed in areas where the Bear Den is developed on silty sandstones of the Sentinel Butte Formation as compared to Sentinel Butte siltstone and claystone.

Alamo Bluff lignite - Taylor bed silcrete

The sharp upper boundary of the Bear Den Member is marked by the Alamo Bluff lignite, or its lateral equivalent, the Taylor bed silcrete. The Alamo Bluff lignite is normally less than 3 inches thick, although it reaches up to 5.5 feet thick at its type locality (Hickey, 1977). The Taylor bed is normally from 3 to 10 inches thick, but ranges up to two feet thick in the Dickinson area. Despite the thinness of these units, they form a remarkably persistent marker bed over almost the entire area of the Golden Valley Formation.

The Taylor bed was also named by Leo Hickey for exposures of a silicified siltstone, or silcrete, west of Taylor, North Dakota. Silcrete is a hard, normally gray, quartzite-like rock found scattered across southwestern North Dakota. Like quartzite, it is composed almost entirely of silica, but it has a sedimentary, not metamorphic, origin. In North Dakota, there are two widely recognized thin beds of silcrete. The older of the two silcrete layers, called the Rhame Bed after exposures near Rhame, North Dakota, marks the top of the Slope Formation. The Rhame Bed lies approximately 1,000 feet stratigraphically below the Taylor bed.

Although laterally discontinuous and comparatively thin, the Taylor bed is so distinctive

Figure 14. A typical exposure of the Taylor bed silcrete, here about 18 inches thick, southwest of Dickinson (138-96-30bca).

that it can be traced for miles across the countryside. It is composed of mostly silt-size quartz grains that usually appear to float in a matrix of microcrystalline silica, or chert. The rock is so well cemented that it breaks across individual grains, not around them, thereby producing a conchoidal fracture. Locally, it is pierced by casts of plant stems and roots so well preserved that the imprint of bark, knots, and even insect borings are easily identified. The silcrete is commonly present as a lag deposit of boulders that have been let down as underlying softer sediments are eroded. Where it is still in place, it usually forms a flat-topped surface which stands in stark contrast to the rolling plains of southwestern North Dakota. Exposed surfaces of the silcrete are commonly polished and shaped by the wind, testimony to countless years of natural sandblasting.

Because it is so unusual, silcrete attracted the attention of some of the earliest geologists to work in southwestern North Dakota. It was perhaps first described by N.H. Winchell in 1875 when he recalled a trip from Bismarck to the Black Hills. Former University of North Dakota student Barbara Wehrfritz (1978) described a great many other researchers who recognized these rocks, including R.E. Lloyd (1914) who stated that in places the silcrete is " . . . *strewn so thickly as to make the surface almost impassable for a horse.*" Silcrete in fact has caught the attention of geologists all over the world, particularly in South Africa and Australia where it is especially common. Perhaps it is no surprise that, because so many have been intrigued by its unusual nature, silcrete has been known by many names, including quartzite, pseudoquartzite, siliceous rock, ganister, and several dozen other names. The term silcrete was first used in 1902 to describe rocks near Victoria Falls in central Africa. It is coined from the words *sil*ica and con*crete*. In the more colorful language down under, Australians refer to such material in-place as "billy"; individual cobbles and loose boulders, especially when polished and sculpted by the wind, are called "gibbers."

The Taylor bed formed at the end of the Paleocene time, about 55 million years ago, and it marks the top of the Bear Den Member of the Golden Valley Formation. Exactly how the silcrete itself formed has been the subject of considerable debate. The source of the silica cement and the framework of quartz silt grains is uncertain. The

Figure 15. An unusual, pillow-like or botryoidal upper surface of the Taylor bed silcrete (140-96-12bbc). The origin of these structures is uncertain.

Taylor bed lacks rock fragments other than chert, as well as feldspars and other readily weathered minerals, suggesting that quartz was all that remained after a prolonged period of weathering. It seems that the silt had to have been silicified before the plants died; otherwise, how could the casts be so perfectly preserved? Swampy conditions imply a high water table and the decaying vegetation would have produced acidic, reducing conditions, favorable to the accumulation of peat. A slightly higher pH in the swamps would favor the precipitation of silica over peat.

Because it is resistant to erosion, the Taylor bed silcrete is commonly well exposed. North of Dickinson, it forms prominent, flat surfaces that surround Simon Butte and the northwest side of Davis Buttes. It is widely exposed between these two buttes, and in 140-95-32 and 33, where it forms the flat caprock of a series of low hills. Some of the best exposures that show the Taylor bed and enclosing strata are located in the "Fairy Dells" in 141-94-31ccb and 141-95-36ac. Elsewhere, the Taylor bed is present as a caprock on low hills, and as a lag deposit, as shown on the accompanying geologic map. Good exposures south of Dickinson are located in 139-96-30ba and bc, 139-97-36bac, 139-96-20aaa, and 139-96-28daa. Additional, unusual exposures are described below.

The Taylor bed takes an unusual form where it caps the hilltop in 140-96-12bbc, northeast of Dickinson. There it forms a pavement of large, extremely hard blocks that are 1-2 feet thick and up to 10 feet long. The silcrete is a light gray, massive silicified siltstone that contains comparatively few plant stem molds. No bedding, laminations, or other internal structures were seen in the silcrete. Thin sections show the rock to be composed of very well-sorted, angular, coarse silt to very fine sand size quartz (and rare chert) grains. It is completely cemented by quartz overgrowths, which being optically continuous with adjacent grains, make the grains appear very tightly packed in thin section.

The puzzling thing about this particular outcrop are the pillow-like structures on the upper surfaces of each block. There seems to be no preferred orientation or shape to the structures; no obvious symmetry or asymmetry. They are closely spaced "blobs" up to two feet in length, although most are 3-10 inches long and of comparable width.

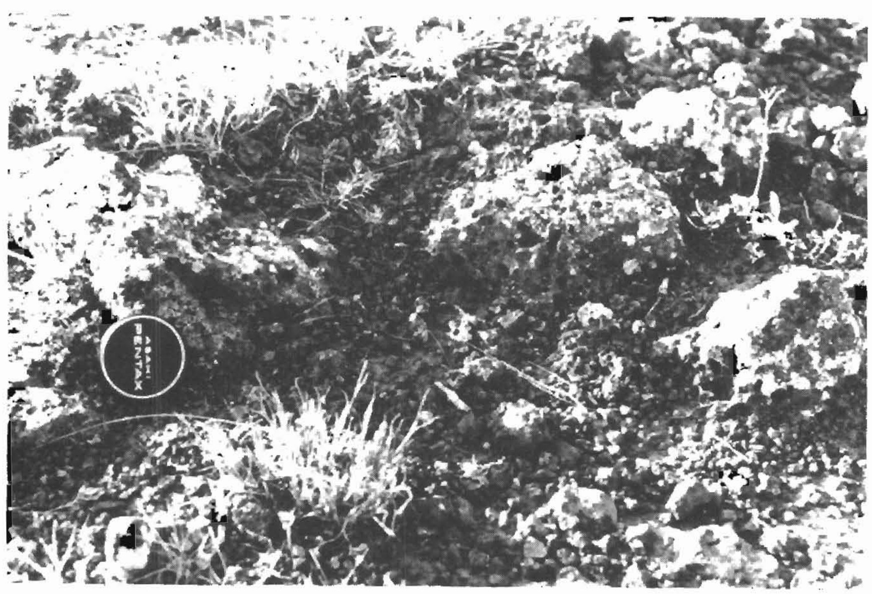
Figure 16. A large, bulbous protrusion which apparently formed as a load cast on the bottom of the Taylor bed (140-96-12bbc). Load casts form in response to settling of sediments of different densities; lava lamps take advantage of the same principle. Note hammer handle for scale.

The undersides of some blocks have what appear to be well-developed load casts, bulbous protrusions that form in response to settling of sediments of different densities.

An unusual reddish brown to blackish red iron-cemented quartz siltstone is present at several localities north of Dickinson. The siltstone has small, generally less than ½ inch diameter, iron oxide nodules that readily weather out, creating voids in the rock and imparting a scoraceous or cinder-like appearance. Angular silt- and fine sand-size chert grains are common in this rock, though much less so than quartz grains. The iron oxide nodules themselves contain angular quartz grains that appear to float in the iron oxide matrix. Impressions of plant material are rare.

That this iron-cemented bed is equivalent to the typical light gray Taylor bed silcrete is demonstrated by exposures that cap the hilltop in the center of 140-96-32, just northwest of Dickinson. The hilltop at the center of the section is capped by iron-cemented siltstone, while the hilltop in 140-96-

Figure 17. An unusual iron-stained variety of the Taylor bed silcrete, exposed atop the hill in 140-96-32dbb, just northwest of Dickinson.



32bdd, 500 feet to the north-northwest, is capped by typical light gray silicified siltstone. The beds lie at the same elevation, both are 1-2 feet thick, and both overlie a light gray, kaolinitic, silty fine sand. A similar relationship is observed in exposures in 140-96-21add. Other exposures of this iron-cemented variety of the Taylor bed are found in 140-96-30dba, 140-96-32bdb, 140-96-34acb, 140-95-11aca, and 140-95-11ccd, and as widely scattered float in nearby areas. The origin of the iron-cemented variety of the Taylor bed is similarly uncertain, especially given its proximity to the typical light gray Taylor bed.

Camels Butte Member

The Camels Butte Member (early Eocene) was named for exposures at the type section on Camels Butte, about six miles north of Dickinson (Hickey, 1977). The Camels Butte Member consists of mostly fluvial sediment as much as 220 feet thick in the Dickinson area. It is characterized by yellowish brown, micaceous, illitic and montmorillonitic siltstone, claystone, and sandstone. It contains several thin, discontinuous lignite beds, some of which have been silicified. Well-indurated sandstone beds increase in thickness and number upsection and cap many of the buttes in the area. These sandstone beds are locally associated with intraformational pebbly sandstone, and local intraformational conglomerate; here, the term "intraformational" refers to mudstone and siltstone clasts derived from adjacent interchannel sediments. An intraformational conglomerate, containing mudstone and siltstone clasts up to two feet long, is present near the top of Camels Butte.

North of Dickinson, good exposures of the Camels Butte Member can be seen on the northwest side of Camels Butte, and at the "Fairy Dells" in 140-94-2b and 3a, 141-94-31c, and 141-95-25c and 36a and 36d. Elsewhere, most Camels Butte Member exposures are restricted to well-cemented sandstones; good examples include the caprock of Davis Buttes and Simon Butte, unnamed buttes in 140-95-23 and 26, and the Youngs Park hilltop just southwest of the I-94/Highway 22 interchange.

Three areas south of Dickinson contain good exposures of well-cemented sandstones in the Camels Butte Member: 1) the top of a small butte southwest of the city where Camels Butte sandstone is quarried for ornamental stone (139-96-20); 2) two

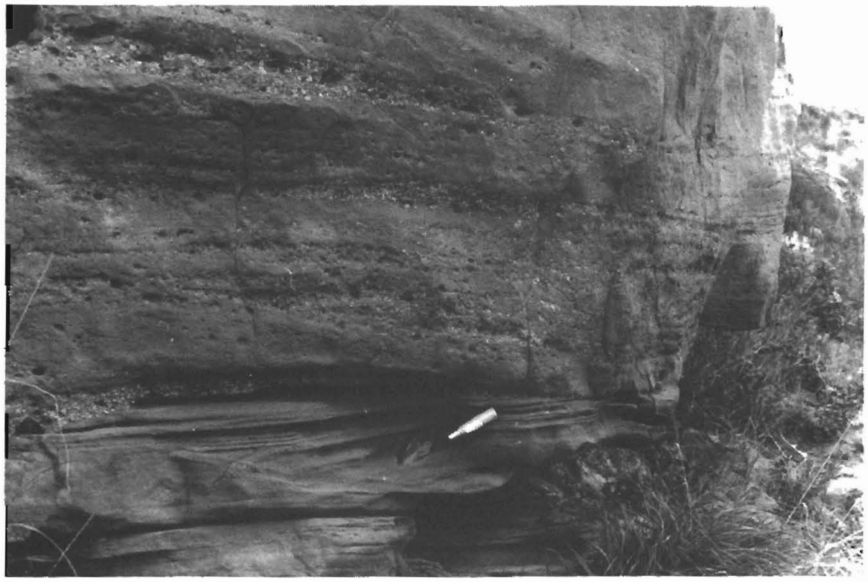


Figure 18. Pebbly sandstone in the Camels Butte Member, at the type section on Camels Butte (141-96-27dda). The pebbles are actually small pieces of mudstone that were eroded from the banks of the river in which the sand was deposited.

Figure 19. Intraformational conglomerate in the Camels Butte Member, at the type section on Camels Butte (141-96-27dda); a crossbedded sandstone is visible at the lower right. The conglomerate, which contains mudstone clasts up to 2 feet long, likely formed as a flood caused the banks of the former river to collapse; the chunks of sediment were then incorporated into the deposits of the river channel itself. Note trowel for scale at upper left.

Figure 20. A channel sandstone in the Camels Butte Member of the Golden Valley Formation (139-96-22ddd). The orientation of the crossbeds indicates that these sands were deposited by a river that, at least here, flowed to the northwest (to the left).

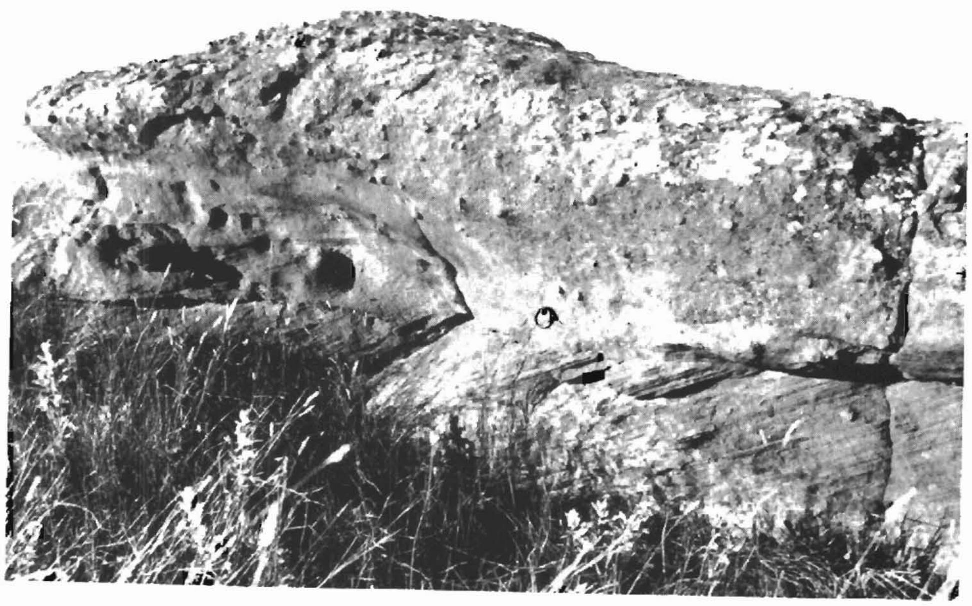


Figure 21. Large-scale crossbedding in a Camels Butte Member sandstone (139-96-26bca).

cross-bedded sandstones exposed at the top of a ridge in sections 26 and 22 (139-96); and 3) the flaggy sandstone caprock of the Dobson Buttes (138-96-1 and 2). The scattered blocks of Camels Butte sandstone in the quarry offer an excellent opportunity to view this fine grained, micaceous, iron-stained, cross-bedded sandstone in three dimensions. The red to purple iron staining outlines bedding planes as well as halos that cross bedding planes. The halos likely formed around a small piece of organic matter that may have changed the chemistry of mineralized groundwaters, leading to the precipitation of iron oxides and hydroxides. Their spherical form indicates that the permeability of the sand was about the same in all directions; enhanced permeability in one direction would have created elongated halos.

Figure 22. Camels Butte Member sandstone capping east Dobson Butte (138-96-1acb). Photo taken looking west to west Dobson Butte.

Figure 23. A lens of chert (one foot thick) overlain by crossbedded sandstone, about 50 feet above the base of the Camels Butte Member at Camels Butte. This chert, formed by the silification of a thin lignite bed, still bears numerous impressions of plant debris.

In a roadcut in 140-96-26ada, the lower Camels Butte Member contains a pale yellowish brown, drusy chert, that is, a chert covered with small crystals. This four- to ten-inch-thick chert occurs about 7 feet above the base of the member, which is there marked by the light gray Taylor bed. The chert is bounded above and below by thin (4-6 inch thick) beds of lignite and carbonaceous shale. This horizon also has several badly splintered silicified stumps still in their upright position. The chert bears numerous impressions and flattened, elongate molds of bark and plant stems, which impart a fine, streaky lamination. The molds and joints are everywhere lined with drusy quartz crystals. Locally, the lignite is only partially replaced by chert. This brown, drusy chert was also seen in outcrops in 140-96-23cbc and 140-96-22abd. The chert is found as a lag deposit in 140-96-33bdb, 140-97-25acb, 140-96-23dcc, and as widely scattered float in nearby areas.

Another chert crops out at an elevation of about 2,710 feet on Camels Butte (about 50 feet above the base of the member), and is present as float atop the hill in 141-95-30cc. Like the brown drusy chert described above, it too has impressions and molds of bark and plant debris. However, this chert is more brittle, is lighter in color, and weathers to a yellowish gray color. It forms discontinuous lenses and pods up to one foot thick with undulatory upper and lower surfaces. Where exposed on Camels Butte, the chert is typically encased in well-indurated channel sands.

In the Dickinson area, the contact of the Camels Butte Member with the underlying Bear Den Member is sharp and marks a change from hard, white kaolinitic strata to comparatively soft, yellowish brown montmorillonitic claystone of the Camels Butte Member. This color and mineralogical change is normally marked by a break in slope, with the steep, barren slopes of the Bear Den Member standing in marked contrast to the gentle, vegetated slopes of the Camels Butte Member.

Chadron Formation

The Chadron Formation of the White River Group was named for exposures in northern Nebraska (Darton, 1899). The formational name was first applied to strata in North Dakota in 1959, and in 1973, three informal members were defined for the Chadron Formation in North Dakota (Moore et. al., 1959; Stone, 1973). In 1993, the NDGS formalized two of these members, the Chalky Buttes and South Heart Members, establishing type sections in the Chalky Buttes near Amidon and in the Little Badlands southwest of Dickinson. Both members are present south of Dickinson. Fossils of the giant titanothere, *Brontotherium*, a large ungulate (hoofed mammal) found in both members, suggest an Eocene age for this strata (Murphy et. al., 1993).

Chalky Buttes Member

Chalky Buttes is the basal member of the Chadron Formation and ranges in lithology from gravel-bearing, cross-bedded sandstone to a sandy, pebbly mudstone. The gravels consist of volcanic porphyry and quartzite, probably derived from the Black Hills and northwestern Wyoming, and locally derived, resistant rock fragments such as petrified wood and chert. Chalky Buttes strata are less than 20 feet thick in the Dickinson area, although elsewhere in the State this member is up to 80 feet thick.

The basal contact of the Chadron Formation is an unconformity that has in excess of 1,000 feet of relief across western North Dakota, thus indicating that significant erosion took place prior to deposition of the formation. As a result, the Chadron Formation unconformably overlies three different formations in North Dakota. In the Dickinson area, the Chadron rests on the Camels Butte Member of the Golden Valley Formation. The contact is well exposed in section 20 (139-96), section 18 (138-96), and section 12 (138-97). A northwest-trending channel of the Chadron Formation appears to have cut into the Golden Valley sandstone near the middle of a butte in section 20. A weathering profile, formed prior to the deposition of the gravels, may explain the bleached and stained nature of the underlying Camels Butte sandstone at this locality.

Based on the vertebrate fossil record, the period of erosion between deposition of the Camels Butte Member of the Golden Valley Formation and the Chalky Buttes Member of the Chadron Formation

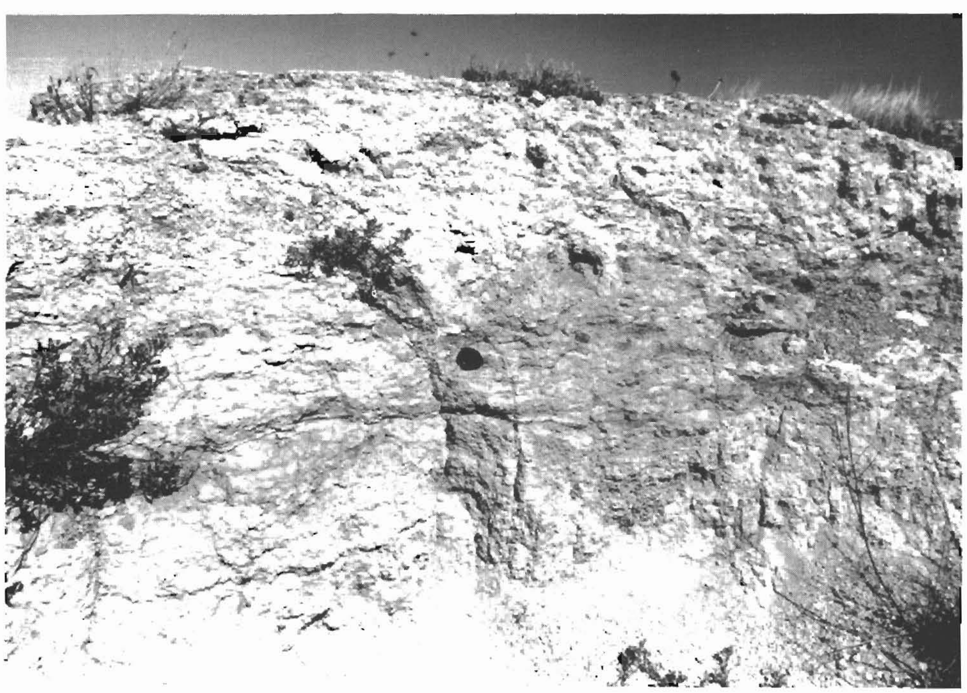
Figure 24. The Golden Valley and Chadron strata southwest of Dickinson (138-96-18ccc). The contact between the Golden Valley and Chadron Formations is present at the midpoint of the photo. The ledge-forming rock at the top of the outcrop is silicified bentonite in the South Heart Member.

Figure 25. The Chalky Buttes and South Heart Members (Chadron Formation) southwest of Dickinson (138-96-18cca). The conglomeratic sandstone in the foreground belongs to the Chalky Buttes Member; South Heart Member strata cap the flat-topped knoll in the background.

may have lasted about 14 million years (Murphy et. al., 1993). In North Dakota, this interval of time marked a change from the humid, subtropical climate of the Paleocene to middle Eocene - with its characteristic floodplains and swamps - to cooler, drier, more seasonal conditions in the late Eocene and Oligocene (Berggren and Prothero, 1992) (Webb, 1977). This climate change resulted in more open, subtropical to warm temperate, woody savanna habitats.

In the Dickinson area, the Chalky Buttes Member is restricted to three isolated exposures in upland settings (139-96-20bdb, 138-97-11 to 14 and 24, 138-96-18 and 19). The Chalky Buttes Member has been quarried at all three of these locations; at the first locality it was disturbed so that the underlying Camels Butte sandstone could be quarried, while the latter two localities were mined for sand and gravel and fill.

Figure 26. Fractured silicified bentonite of the South Heart Member of the Chadron Formation (138-97-13ddd).



South Heart Member

The South Heart Member consists of swelling claystone and lenses of fresh-water carbonates and conformably overlies the Chalky Buttes Member. In this area, the claystone is generally silicified; because it is so hard, it forms vertical, jointed outcrop faces. The South Heart Member reaches a maximum thickness of 96 feet in North Dakota, but is only a few feet thick in the Dickinson area. It is exposed in 138-97-13ddd and 138-96-18ccc.

Quaternary-Late Tertiary Sediments

Sand and gravel of uncertain Quaternary-Late Tertiary age have been mapped north and east of Dickinson. The deposits trend parallel to the modern Green River and occur at elevations ranging from about 20 feet to 210 feet above the modern floodplain. North of Dickinson, these deposits typically occur as linear, esker-like ridges. To the east and south, the deposits occur both as a veneer that caps ridges or promontories along the valley walls and as large, highly dissected deposits with no distinctive topographic expression. Many of the deposits have been mined for their sand and gravel.

These river-channel deposits consist of poorly sorted, iron stained, locally iron-cemented sand and gravel up to about 60 feet thick. They contain pebbles and cobbles of well-cemented, locally derived material (concretions, silicified wood, flint, silcrete, and chalcedony), recycled glacial erratics, and lesser quartzite and porphyry. Small chips and rounded pebbles of lignite are found throughout the deposits, especially near the base of the deposit in 140-95-9c. The lignite is commonly concentrated along bedding planes. Locally, as in the Fisher Sand and Gravel Co. pit located in 140-95-9c, the pebbly sands and gravels are cemented by iron oxides.

These deposits unconformably overlie the Sentinel Butte and Golden Valley Formations and are locally truncated by younger alluvium. The contact with underlying units is seldom exposed and is based in large part on topography and the presence of scattered surficial gravels. The contact with the Sentinel Butte Formation is exposed in 140-95-21dac, 140-95-27bdc, and at the center of 140-95-16dd.

The esker-like form of the deposits north of Dickinson may be a result of differential erosion

Figure 27. A diamicton, a very poorly sorted sedimentary deposit of unknown origin, exposed near the base of a sand and gravel pit northeast of Dickinson (140-95-9ccd). The diamicton may have formed as a mudflow deposit in the ancestral Green River. The clasts have a concretionary rind cemented by gypsum and iron-manganese oxides and give exposures a distinctive, concentric weathering structure.

(Clayton et. al., 1980). The coarse sand and gravel of these channel deposits are more permeable than adjacent finer grained sediments of the Sentinel Butte Formation, allowing precipitation to preferentially infiltrate the sediments rather than erode them. In essence, the banks of the channel have eroded away, leaving behind the coarse sediments of the channel itself.

Two exposures of a diamicton - a very poorly sorted sedimentary deposit of unknown origin - were observed at or near the base of these gravel deposits in 140-95-9ccd and 141-95-33dac. Both are deeply iron stained and are characterized by a wide variety of local lithologies (noted above), and boulders of angular sandstone, mudstone, silicified wood, and lignite. Granitic pebbles are present but uncommon. The matrix is a poorly sorted, silty, coarse sand poorly cemented by iron-manganese oxides. The clasts typically have a concretionary rind cemented by gypsum and iron-manganese oxides and give exposures a distinctive, concentric weathering structure.

The origin of the diamictons is uncertain. They unconformably overlie the Sentinel Butte Formation and are in turn overlain by sand and gravel deposits of indeterminate Quaternary-Late Tertiary age. The deposits are very poorly sorted and the larger, angular, comparatively incompetent mudstone, sandstone, and lignite clasts have apparently not been transported far. The deposits may represent a mudflow deposited in a precursor to the modern Green River channel. Whether they are related to an advance of glacial ice in this part of North Dakota is uncertain. Scattered glacial erratics are present from 1 to 3 miles north of these exposures.

The sand and gravel deposits themselves may have formed as glacial ice blocked rivers that once flowed northeast to Hudson Bay, diverting them to the east and south. The farthest extent of glacial ice in this part of North Dakota, based on the presence of widely scattered erratics, lies just a few miles to the northwest of the modern Green River. These gravels then may have been deposited by a river flowing in front of the ice margin.

Coleharbor Group

Sediments that were deposited during the Pleistocene Epoch - including glacial till, sand and gravel river deposits, and clays and silts of Ice Age lakes - all belong to what geologists call the Coleharbor Group. In the greater Dickinson area, the only evidence of glaciation is widely scattered glacial erratics found north of the Green River. Finer grained sediments and glacial landforms that must have accompanied the ice have presumably been removed by erosion, indicating that the glaciation that affected this area must be comparatively old.

Glacial Erratics

They are known only too well by farmers, who have laboriously piled them in the corners of their fields. Early settlers used them for the foundations of their homes and farm buildings, and today they are much sought after for use in landscaping and as rip rap along the face of dams and shorelines. Some have been split by hand for use in buildings and retaining walls. In addition, some literally have been turned into monuments, whether simply as bases for sculptures or as a source of polished stone. Locally, these boulders are known as field stone, or, perhaps, just plain old damned rock depending on one's point of view. Geologists know them as glacial erratics.

An erratic is a rock that differs in rock type from the bedrock underlying it. The glaciated portion of North Dakota is strewn with erratics from

Figure 28. Glacial erratics in a field north of Dickinson. Erratics, like these granitic and limestone boulders, were carried from Canada to North Dakota by Ice Age glaciers. In the greater Dickinson area, widely scattered erratics are found northeast of the Green River, where they mark the maximum extent of glacial ice in this part of the State.

the Canadian Shield and plains, and they alone are one of the most compelling indications of long-vanished ice sheets. Erratics, in fact, are one of the key pieces of information that, beginning in the late 1830s, led Louis Agassiz and others to document the existence of once vast ice sheets over northern Europe and North America. Previously, such boulders and associated out-of-place finer grained sediments were classified as "drift," a term still used loosely today, in reference to their presumed origin from drifting icebergs during the biblical Deluge. Perhaps the most famous erratic of all is Plymouth Rock, where on December 21, 1620, according to legend, the Pilgrims first set foot in the New World.

Horace Benedict de Saussure, a Swiss physicist and geologist and celebrated traveler of Europe, was apparently the first to use the term "erratic" when in 1779 he described granite boulders lying atop limestone in the Jura Mountains of Switzerland. His term *terrain erratique* is derived from the Latin *erratus*, "to wander," and means, literally, "ground that has wandered". Geologists most commonly use the term erratic as a generic term for cobbles and boulders left behind by glacial ice.

The glaciers left behind a varied suite of igneous, metamorphic, and sedimentary rocks that would not otherwise be found in North Dakota. Granite, gneiss, schist, greenstone, limestone, dolostone, and many other rock types scattered across the glaciated portions of the state may be the bane of farmers, but they are a joy to geologists who savor their diversity. Each has a story to tell, although only a few are sufficiently distinct that geologists can tell where they came from. If you pick up a granitic boulder in the greater Dickinson area, you can be sure it had a Canadian source, although usually it isn't possible to pinpoint just what part of Canada it came from. Boulders composed of carbonate rock can sometimes be characterized as to source area. In the area north of Winnipeg, for example, several Paleozoic carbonate formations are exposed and we can sometimes determine from which formation a boulder was derived. Most boulders of sandstone, on the other hand, were likely moved only a few miles by the glacier from nearby outcrop areas within the state. The sandstone is not well consolidated and any extensive glacial transport of sandstone boulders would normally break them down into much smaller fragments, or simply reduce them to sand.

Farmers and ranchers in the greater Dickinson area are lucky compared to those in more recently glaciated portions of the State, as they have had relatively few glacial erratics to contend with. Erratics don't occur just on the surface where we can see them, but throughout the entire thickness of glacial sediments, which averages between about 150 and 250 feet thick throughout the northern and eastern parts of North Dakota. Seasonal freezing and thawing causes the rocks to work upward from below the plow zone to the land surface, thus ensuring farmers a continual supply of boulders. Every spring a new batch of stones has to be removed from the fields. The smaller rocks can be picked up with rock-picking equipment and carried from the field; larger ones are sometimes blasted with dynamite and the pieces hauled away. Some of the very largest are simply left in place and avoided. In his backroads tour of the perimeter of the contiguous United States, William Least Heat Moon (1982) captured the resignation of farmers to a continual crop of boulders:

> *East of Fortuna, North Dakota, just eight miles south of Saskatchewan, the high moraine wheat fields took up the whole landscape. There was nothing else, except piles of stones like Viking burial mounds at the verges of tracts and big rock pickers running steely fingers through the glacial soil to glean stone that freezes had heaved to the surface; behind the machines, the fields looked vacuumed. At a filling station, a man who long had farmed the moraine said the great ice sheets had gone away only to get more rock. "They'll be back. They always come back. What's to stop them?"*

Granitic and carbonate clasts, as well as cobbles and boulders of local lithologies, were found approximately two miles northeast of Simon Butte in 141-95-26c, 141-95-27d, and 141-95-34a. The erratics have been piled along fencerows and atop a hill in 141-95-27dbc; additional erratics, not shown on the geologic map, are widely scattered throughout 141-95-27c. Such boulders have also been used for landscaping around the Dickinson area.

Oahe Formation

Three groups of alluvial sediment have been mapped in the greater Dickinson area: 1) Quaternary-Late Tertiary sand and gravel (QTa) described above; 2) planar terrace deposits dissected by modern streams (Qa2); and 3) modern alluvial deposits (Qa1).

Colluvial deposits have not been mapped due to problems of scale and their inherent poor topographic expression. Colluvium consists of poorly sorted sand, silt, and clay derived by mass wasting of bedrock units and sediments immediately upslope; it can be similar in appearance to adjacent bedrock units, although it is less compacted and commonly contains scattered organic debris and pebbly gravel. Colluvium is common as a veneer on moderate or steeply sloping hillsides, and in closed depressions or swales.

Alluvial Deposits

High-level terraces (Qa2) are restricted to the Heart River, Green River, and Antelope Creek valleys and their major tributaries. These terraces are level to gently sloping surfaces veneered with sand and gravel. As with the older Quaternary-Late Tertiary sand and gravel deposits, a wide variety of lithologies are present. The terraces formed as these ancestral rivers migrated across their floodplains, planing surfaces smooth and depositing sand and gravel.

The terraces lie at increasingly higher elevations downstream along the Green River. The few terraces present north of Dickinson lie about 10 feet above the modern Green River floodplain. Downstream to the east, major terraces lie at elevations from about 30 to 50 feet above the modern floodplain. The terrace deposits themselves generally range from about 3 to 10 feet thick and have locally been mined for their sand and gravel. They are developed predominantly on the Sentinel Butte Formation, which is locally exposed along the terrace flanks.

South of Dickinson, terraces are especially well developed in and along the valley of Antelope Creek. In the Antelope Creek valley, terrace gravels may be found up to 60 feet above the modern flood plain. In one area, (138-95-7), two sets of terraces, the lower at 10 to 20 feet above the creek and the upper at 30 to 60 feet, can be seen in close proximity. Several small gravel pits have been developed in these terrace deposits.

The terrace deposits were mapped based primarily on their distinctive morphology. Exposures of terrace sediments are few. Some of the best exposures are found in 140-95-22dcc, 140-95-16abb 140-95-7adb, 140-95-26cdb, 138-95-7abb, 138-96-12bbb, and in a railroad cut in 139-95-8bcc.

Modern Alluvial Deposits

Modern alluvial deposits (Qal) have been mapped along the Heart River, Green River, Antelope Creek and their major tributaries. These deposits consist of sand, silt, and clay deposited in modern river channels and floodplains. The deposits locally contain gravel where they have been derived from coarse, older alluvial deposits. These deposits are generally less than 20 feet thick, but local similarity to the sediments of the Sentinel Butte Formation makes thickness determinations difficult.

Modern alluvial deposits are marked by numerous oxbow lakes, truncated meanders, and minor terraces. Oxbows, or meanders, are semicircular curves in a stream that form as a stream erodes the outer bank of a curve, where the current is the strongest, and deposits sediment against the inner bank, where the current is the weakest. The term "meander" is derived from the Maeander River in Turkey, fabled for its circuitous course; "oxbow" alludes to the similarly shaped yoke used to harness an ox. Meanders are characteristic of gently sloping valley floors. As the river channel migrates sideways and downstream, channel segments can be abandoned in favor of shorter, slightly steeper routes, thereby forming oxbow lakes or meander scars.

Landslide Deposits

Most slope failures or landslides in this area are rotational slumps. Slumps are most easily identified on aerial photographs, where their hummocky surface and curved headwall scarp stand in sharp contrast to adjacent undisturbed land. Slope failures normally occur along over-steepened slopes, such as along the banks and steep walls of creek and river valleys. Several large landslides have been mapped on the slopes of the Davis Buttes and Simon Butte. Small, modern landslides are also common along cutbanks of the Green and Heart Rivers and Russian Spring Creek. Landslides are discussed in greater detail under the geologic hazards section of this report.

Artificial Deposits

Fill

Several small areas of artificial fill have been mapped northeast of Dickinson. The fill in 140-96-9cc is used as a retaining pond for stormwater runoff. Fill mapped in 139-96-1 was placed to

Figure 29. An area containing miscellaneous fill just east of Dickinson (139-96-1a). Most such fill, because it contains deleterious materials and is poorly compacted, may be unsuitable for foundations.

provide level areas for building. Fill in this latter area consists of soils and miscellaneous construction and demolition debris. The large area of fill north of the Green River, in 140-96-3a, shows the extent of the J.K. Ranch lignite mine, now reclaimed. Although few areas of fill have been mapped, fill should be anticipated in any area formerly disturbed by construction activities.

Landfills

Three municipal landfills or dumps are shown on the geologic maps that accompany this report. One, located under the present site of the Pioneer Village (140-96-34ca), was operating when aerial photographs were taken of the area in 1957; similar photographs taken in 1965 indicate that the landfill had by then closed. State Health Department records indicate that the northern part of the landfill was uncovered during construction of Interstate 94.

The city of Dickinson operated a dump adjacent to the Heart River from the mid 1960s to the mid 1980s. The operation was located in an old surface lignite mine adjacent to extensive underground workings (139-95-7dd). The site was eventually closed because of its poorly suited location. The present landfill site is located in the large open pit of the Husky lignite mine (139-95-17db), which operated from 1959 to 1988. The landfill began operations in 1986 and currently accepts waste from both Dickinson and the surrounding communities. In addition, numerous, small farm dumps are scattered throughout the greater Dickinson area.

Structure

The Dickinson area lies in the south-central portion of the Williston Basin, a large, bowl-shaped depression filled to the brim with sedimentary rocks. At first glance, these layers of rocks appear essentially horizontal, lying flat for as far as the eye can see. Yet in the North Dakota portion of the basin, there are two major folds - the Cedar Creek and Nesson Anticlines - and innumerable smaller structures revealed by strata that are not quite as flat as we often think. In fact, oil was first found in Montana and North Dakota on the Cedar Creek and Nesson Anticlines, and other discoveries continue to

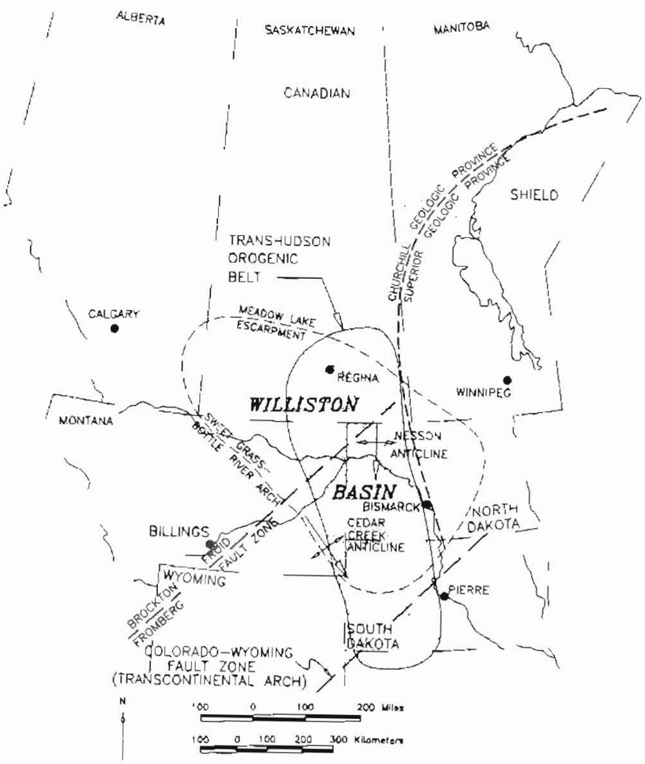


Figure 30. Map of the Williston Basin (Gerhard et. al., 1990).

be made on smaller structures throughout the basin. Many of these structures have their origin in the Precambrian basement, the very old, deeply buried igneous and metamorphic rocks underlying the Williston Basin.

Geologists have divided the Precambrian basement into the Wyoming Craton underlying extreme southwestern North Dakota and the Superior Craton to the east. These two cratons, extremely old and deformed but geologically stable regions, are separated by the Trans-Hudson Orogen (also known as the Western Dakota Mobile Belt), a group of slightly younger rocks that were caught between the two cratons as they collided during the Precambrian (Nelson and others, 1993).

The Trans-Hudson Orogen consists of a mosaic of tectonic blocks or terranes (Shurr, 1995). These blocks include island arcs and microcontinents that were accreted to the craton during the assembly of the North American plate. The block margins are zones of weakness that represent terrane boundaries and faults. Reactivation of these pre-existing zones of crustal weakness is thought to control basin structure and sedimentation patterns, including the location of the oil-producing carbonate mounds around Dickinson. It is this part of the Precambrian basement that underlies the greater Dickinson area, at a depth of about 13,000 feet (10,500 feet below sea level).

This brief summary of the Precambrian basement is offered not only for the sake of completeness (it truly is the foundation on which the story of North Dakota geology rests!), but also to show that the structure that we observe at the surface appears to be related to that underground. Detailed mapping of the Bear Den Member of the Golden Valley Formation - a readily identifiable marker bed - demonstrates that this unit has been warped into a very gently folded, northeast-plunging syncline. The syncline is an extension of the same structure exposed to the southwest in the Little Badlands. This syncline is apparently present in the subsurface as demonstrated by structure contour maps on top of the "Tongue River Formation" (Trapp, Jr. and Croft, 1975), the Ardmore Bentonite Bed (of the Cretaceous Pierre Shale) (Ashworth et. al., 1995), and the Minnekata Formation (Paul Diehl, pers. comm.); it is also apparent on coal cross-sections. The syncline lies within and trends parallel to a major lineament zone identified on Landsat photos (Shurr et. al., 1995). The syncline is absent on the Tyler Formation and deeper units, but both the structure and thickness of these older Paleozoic units do show expression of the block margins (Shurr et. al., 1995).

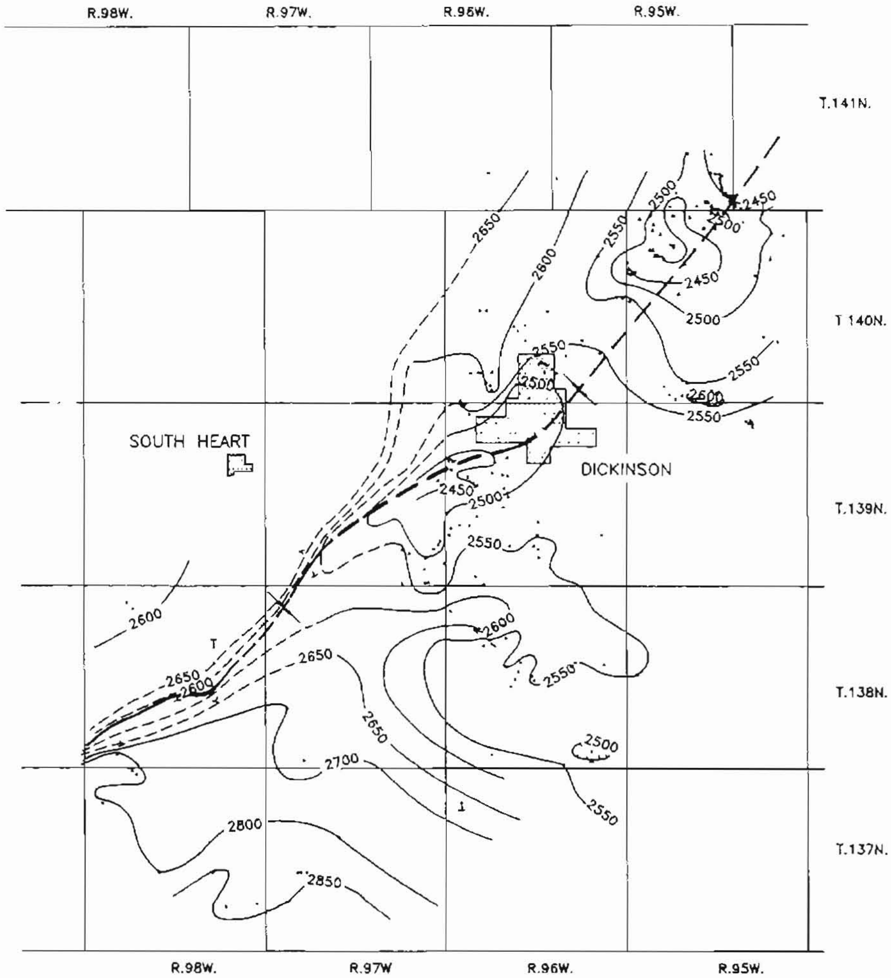


Figure 31. Structure contour map of the Bear Den Member of the Golden Valley Formation. This map shows the altitude and configuration of the member, revealing that it has been deformed into a very gently folded, northeast-trending syncline. The beds generally dip on the order of less than 1° to about 3°. The syncline is modified by equally subtle folds that trend more or less perpendicular to the main axis.

Based on the structure contour map of the Bear Den Member, and scattered exposures of the Taylor bed, strata at the surface are not everywhere horizontal, but dip generally on the order of less than 1^0 to about 3^0. At one small outcrop on the south shore of Patterson Lake (139-96-18bca), the Bear Den Member is dipping to the south at about 10 degrees; these beds do not appear to be part of a slump, although that possibility cannot be ruled out due to the limited size of the outcrop. In two places in the Davis Buttes quadrangle (140-95-6 and 140-95-32), the Taylor bed forms a planar, gently sloping surface - a dip slope of about 3^0. Elsewhere in the Dickinson area, small exposures of the Taylor bed appear to be essentially horizontal.

While no faults have been identified in surface exposures in the mapped area, two small normal faults are visible in the old Husky lignite mine (the present Dickinson landfill). Several small faults were mapped in the underground workings of the

Figure 32. Golden Valley and Sentinel Butte strata along the southern edge of Patterson Lake (139-96-18bca).

The stratigraphic contact is conformable in this area. Beds are dipping to the south at approximately 10 degrees.

Lehigh mine (Northern Pacific Railway, 1947). Kent Hudson (1992), formerly with Royal Oak Enterprises, noted that outcrops along the Heart River at Lehigh reveal a northwest-trending anticline. "*The anticline has local dips to 5 degrees along its northeast flank and 1-2 degrees on its southwest flank. The structure plunges 3 degrees to the northwest and 2.5 degrees to the southeast. Closure on the anticline is located in the NE ¼ NW ¼ of Section 17, T139N, R95W, Stark County. Numerous faults, normal to the anticlinal strike, and accompanied by en echelon relief faults, joints and shears have been encountered throughout the area's mining history. These structures, with displacements ranging from 0.3 to 4.6 meters, created severe problems for the underground mining operations.*" Other normal faults, with displacements ranging from about 1 to 22 feet, are known to occur in the Little Badlands (Ashworth et. al., 1995).

Practical Geology

Despite the simple joy that knowledge brings, a sense of history and of place, most people want more practical information about the geology that can or does affect their lives. It is nice to know where the Bear Den Member of the Golden Valley Formation occurs, yet better, perhaps, to know that it is a good source of pottery clay and that its nutrient-poor, often stony soils are difficult for most plants to grow in. It is nice to know that sand and gravel deposits that lie high above the modern Green River floodplain were likely deposited by an Ice Age river, yet better, perhaps, to know exactly where they can be found. It is nice to know that Paleocene strata in the greater Dickinson area are folded into a northeast-plunging syncline, yet better, perhaps, to know that this structure may be related to the location of the prolific, oil-and gas-producing Lodgepole mounds. The history of lignite mining and oil exploration is interesting, but for construction purposes it is important to know where the abandoned underground tunnels and buried reserve pits are located. And what about landslides - do they really occur out here on the grassy plains? These are but a few of the many questions that the science of geology can answer. By reading and interpreting the landscape about them, geologists provide a unique perspective on the land we live on, including its mineral resources and geologic hazards.

Mineral Resources

The principal mineral resources in the greater Dickinson area are oil and gas, sand and gravel, clay, lignite, and stone. Over 130 wells have been drilled for oil and gas in the four-quadrangle area mapped (and many more in adjacent areas), and the city itself is a major service center for the oil industry. Most sand and gravel pits are located along the Green and Heart Rivers in deposits mapped as QTa and Qa2. Clay, once used locally for the manufacture of bricks and sewer tiles, was mined from the Bear Den Member of the Golden Valley Formation and the Sentinel Butte Formation southwest of Dickinson. Lignite was mined from the 1890s to the 1980s at several locations in the greater Dickinson area. Crushed stone from the Camels Butte Member of the Golden Valley Formation is being quarried just southwest of Dickinson, and field stone has long been used in retaining walls, foundations, and older farm buildings throughout the area.

Oil and Gas

Since 1951, when oil was discovered in Williams County, North Dakota has produced more than 1.2 billion barrels of oil. In 1996, North Dakota production totaled about 32 million barrels, up 9% from the previous year. Most of the increase came

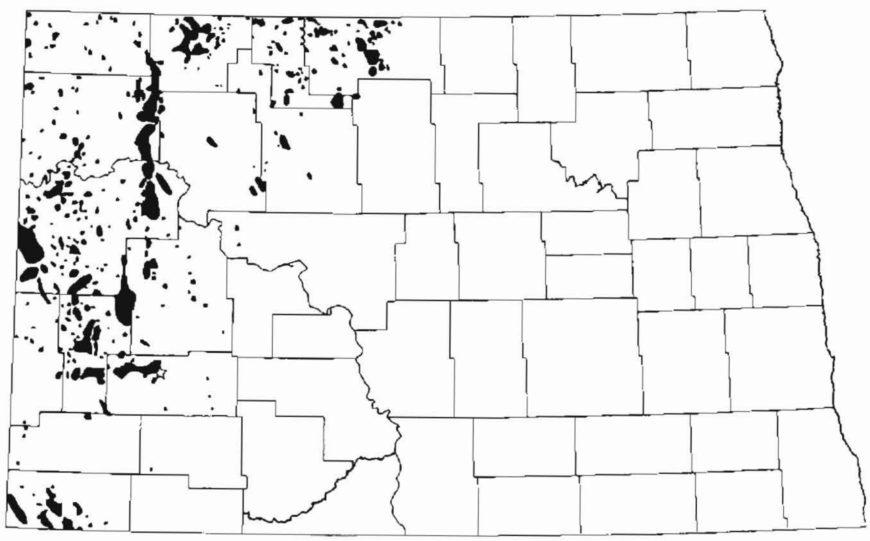


Figure 33. North Dakota oil fields. The location of Dickinson is noted by a star (☆) (modified from Heck, 1995).

from Stark County Lodgepole production and Bowman County Red River production. North Dakota remains the 9th largest petroleum producer in the United States (North Dakota Petroleum Council, 1997).

Petroleum (from the Latin *petra* and *oleum* meaning, literally, rock oil) comes from over a hundred oil fields in the Williston Basin. Nearly two thirds of the oil comes from Mississippian-age (about 350 million years old) Madison Group strata, of which the now famous Lodgepole Formation is the lower unit. More than 12,900 wells have been drilled to date in the North Dakota portion of the basin, and about one third of those still produce or are capable of producing oil and gas. Since exploration began, the combined length of all wells drilled is an astonishing 19,070 miles - a distance that would carry one over two thirds of the way around the world (North Dakota Petroleum Council, 1997).

In the Dickinson area, oil and gas are produced from several fields. The Dickinson Field (Dickinson Heath Sand Unit) was discovered in 1958 at a depth of about 7,800 feet below the surface. The Dickinson-Heath-Sand Unit #37, the discovery well for the Dickinson Field, is located in 140-96-31da. Sixty-two holes have been drilled in the field to date, 20 of which are still productive; these 20 wells average 26.5 BOPD (barrels of oil per day) and 1584 MCF (thousand cubic feet) of natural gas. Oil and gas are produced from sandstones of the Tyler Formation, a Pennsylvanian-age (about 330 million year old) complex sequence of varicolored mudstone, shale, sandstone, and carbonate, with local, thin beds of anhydrite and coal. These sediments may have been deposited in nearshore marine environments (Sturm, 1983). Peak production from the field occurred in 1977, four years after a secondary recovery program was initiated (Rygh, 1983). Through December 1996, the Dickinson Heath Sand Unit produced over 25.5 million barrels of oil (this is equivalent to over 300,000 acre-feet, a volume that would cover 300,000 acres - 465 square miles - to a uniform depth of 1 foot).

The Dobson Butte Field was discovered in 1982. Hydrocarbon production there comes from a significantly deeper interval about 11,000 feet below the surface, in Silurian-age strata about 420 million years old. The field was discovered by NRM Petroleum's Kirkwood-Kosteleky #44-29 well (139-96-29dd), which had an initial flowing potential of 383 barrels of oil per day (Anderson and Bluemle, 1985). In 1987, production from deeper, Ordovician-age Red River strata began with the completion of the Kostelecky #32-33 (located in 139-96-33ac). Collectively, the two pools in the Dobson Butte Field have produced over 670,000 barrels of oil (NDIC Oil and Gas Division).

The Davis Buttes Field was discovered in 1985 by the Hrubertz Oil Company Decker 1-31 well (140-95-31ba), which had an initial flowing potential of 122 barrels of oil per day. Like the adjacent Dickinson Field, production comes from Tyler Formation strata about 7,800 feet below the surface (Fischer and Bluemle, 1986). Production through December 1996 totaled over 150,000 barrels of oil; in 1994, the three producing wells in the field averaged only 6.4 BOPD.

By far the most exciting recent discovery, one that caught the attention of oil producers across the country, is the Dickinson Lodgepole play (Burke and Diehl, 1995a). The Conoco, Inc. Dickinson State #74 well, the discovery well for this play, was completed in February 1993 with an initial flowing potential of over 2,000 barrels of oil per day along with 1.2 million cubic feet of natural gas. The discovery of this prolific carbonate mound about 9,800 feet below the surface was made after deeper Silurian and Ordovician objectives proved unproductive. The Dickinson Lodgepole pool was unitized in June, 1994. It consists of two producing wells (the State #74 and Kadrmas #75) and two injection wells using water to maintain reservoir pressure. The wells average about 1,700 barrels of oil per day and 1.5 million cubic feet of natural gas. As of December 1996, just shy of 4 years following its discovery, the Dickinson Lodgepole Unit had cumulative production of over 3.3 million barrels of oil and 1.6 billion cubic feet of natural gas. It is estimated to contain 18 to 19 million barrels of oil; the estimated recovery is 8 million barrels of oil and 4.1 billion cubic feet of natural gas.

Interestingly, in 1957, the Leach Oil Corporation's Kalanek #1 (Dickinson-Heath-Sand Unit #33), located in 140-96-32bc, was completed in upper Madison Group strata only a few hundred feet from the discovery well for the Dickinson Lodgepole Field. At 9,100 feet deep, the well was only about 630 feet above the top of the Dickinson Lodgepole carbonate mound. Although the well had an initial production of about 135 barrels of oil per day, production was poor and totaled only 12,685 barrels of oil; in 1961, the well was re-completed in productive Tyler sands, which had been discovered nearby three years earlier.

Such prolific wells set off a flurry of exploration activity in search of additional Lodgepole carbonate mounds in the Dickinson area. (This is not surprising considering that the average well in North Dakota produces just 23 barrels of oil per day, worth an average of $19.42 per barrel in 1996). The Knopik 1-11, the discovery well for the Eland Field, was completed in December, 1994 with an initial flowing

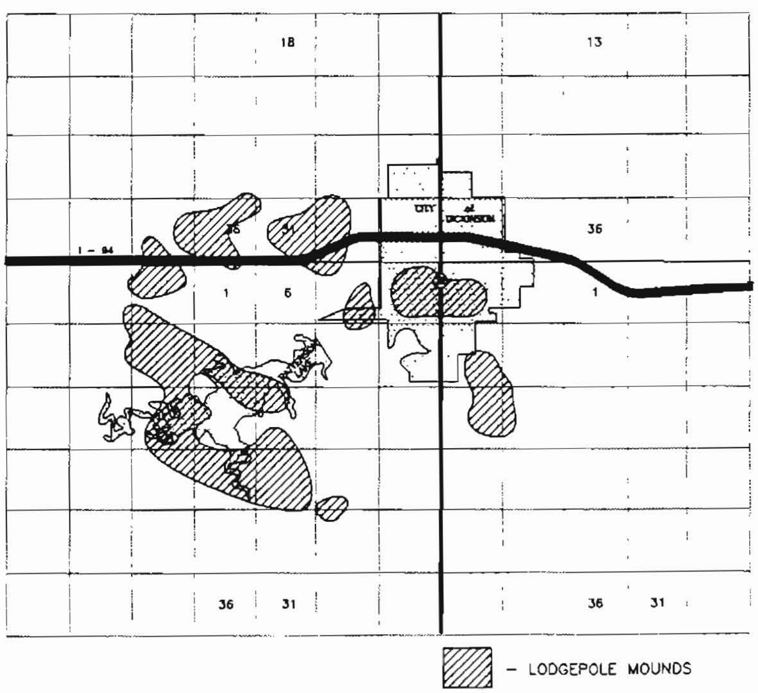


Figure 34. Map of the known Lodgepole mounds in the Dickinson area. (From the files of the NDIC Oil and Gas Division.)

potential of 2,707 barrels of oil per day and 1.55 million cubic feet of natural gas. Eight separate mound pools have been discovered in the Dickinson area.

In the Dickinson area, Lodgepole production comes from carbonate mounds at depths of about 9,500 to 10,000 feet. The mounds are composed primarily of relatively clean (pure) porous limestone that is surrounded by the typical shaley limestone of the Lodgepole Formation. Bryozoan and crinoid fragments are predominant but ostracodes, brachiopods, gastropods, and cephlapods are also found. Bryozoans, or "moss animals", are tiny marine invertebrates that often form very delicate, fan-like colonies that look like netting or screen. Crinoids, marine invertebrate animals known as "sea lilies", used their arms for suspension feeding; they look like miniature palm trees. These and other features of the mounds indicate that they probably formed in deep water, not the turbulent, relatively shallow waters characteristic of coral reefs. Most of the hydrocarbons now present in the mounds probably came from the underlying Bakken Shale, an organic-rich black shale.

The discovery of these mounds sparked leasing and exploration activity throughout the Williston Basin where similar mounds might occur. Prior to the Lodgepole discovery at Dickinson, the Lodgepole Formation was not considered a favorable target for exploration (Burke and Diehl, 1995b).

Aggregate

Aggregate is a collective term for sand and gravel as well as crushed stone. Construction sand and gravel is the leading industrial (non-fuel) mineral commodity produced in North Dakota; after the petroleum and coal industries, it is the third largest mineral industry in the State. Sand and gravel used for construction purposes was valued at $22,000,000 in 1994 and accounted for 84% of the total nonfuel mineral value in North Dakota. In 1996, an average year, 2,706,724 cubic yards (almost 9 million short tons) of sand and gravel were mined - 13.8 short tons for every man, woman, and child in North Dakota (U.S. Bureau of Mines, 1995; N.D. State Soil Conservation Committee, 1997).

That is hard to imagine in that we seldom use aggregate personally, unless perhaps we happen to be building a typical home, which requires about 100 tons of sand and gravel for its construction (Langer and Glanzman, 1993). Regardless, we all make use of the infrastructure in which aggregate is used. In fact, sand and gravel and crushed stone are used primarily in the construction industry, especially in cement concrete for residential and commercial buildings, bridges, and other structures, as well as cement concrete and bituminous mixes (asphalt) for road construction. Aggregate is also used without binder for road bases, road surfacing, snow and ice control, drainage improvements, and a myriad of other uses.

Another thing that may be hard to imagine is that for many uses, ordinary, run-of-the-mill aggregate may not be suitable. General aggregate specifications for cement concrete and bituminous mixes are more stringent than for other construction uses, and both physical and chemical characteristics of the aggregate must be considered. A well-graded aggregate, one that consists of a complete range of particle sizes from sand to gravel, is typically required for such mixes. Weak, easily broken, absorptive, or swelling particles are obviously not suitable. Even aggregate shape is important; too many long or flat pebbles may be harmful to the integrity of the mix. It is these and other physical properties that relate to an aggregate's resistance to freeze-thaw and wet-dry cycles. Furthermore, some minerals chemically react with concrete or bituminous mixes and are therefore undesirable. Because of its chemistry, for example, portland cement produces a highly caustic solution when mixed with water to make concrete. Aggregates that contain excessive amounts of certain silica minerals, such as chert and chalcedony, will react with alkali in cement, swell in size, and damage the concrete. Reactive aggregate such as this can be used, but they require more expensive, low-alkali cements. Thus, while many factors can lead to concrete deterioration - to the cracked, pitted sidewalks and curbs all too often seen - poor quality aggregate can be a major cause.

Aggregate is a low-price, high-volume commodity. Transportation costs alone are often higher than the freight on board (FOB) price. Thus in order to be profitable, aggregate deposits and markets must be relatively close together. Although aggregate operations are usually initially located in rural areas, they are often forced to close as residential land use encroaches upon the operation. This forces quarries to be opened in more distant areas, significantly increasing the cost of aggregate and the products from which it is made.

Perhaps surprisingly, there is more than meets the eye in a typical aggregate operation: 1) Collectively, we require and use much more aggregate than most people realize; 2) All aggregate is not created equally, and it is the physical and chemical characteristics of the material that determine how it can be used; and 3) Aggregate availability, quarry operations, and transportation costs are major industry concerns. Virtually all major metropolitan areas are now faced with shortages of high quality, affordable aggregate due to urban expansion and the literal paving over of aggregate resources. Knowing that, many states and smaller towns are undertaking assessments of aggregate resources and needs, making certain that aggregate supplies are not lost to development.

Sand and Gravel

Sand and gravel has been mined extensively from small pits throughout the greater Dickinson area. Most pits are located in units mapped as QTa and Qa2 and so are found in and near the valleys of the Green and Heart Rivers, Russian Spring Creek, and Antelope Creek. North of Dickinson, along the Green River, deposits of Quaternary-Late Tertiary sand and gravel are up to 60 feet thick. These

Figure 35. A sand and gravel operation in the Dickinson area. Most sand and gravel operations in this area are located in deposits mapped as QTa or Qa2 (this report). Most of these old river deposits are found high above the modern floodplains of the Green and Heart Rivers and Antelope and Russian Spring Creeks.

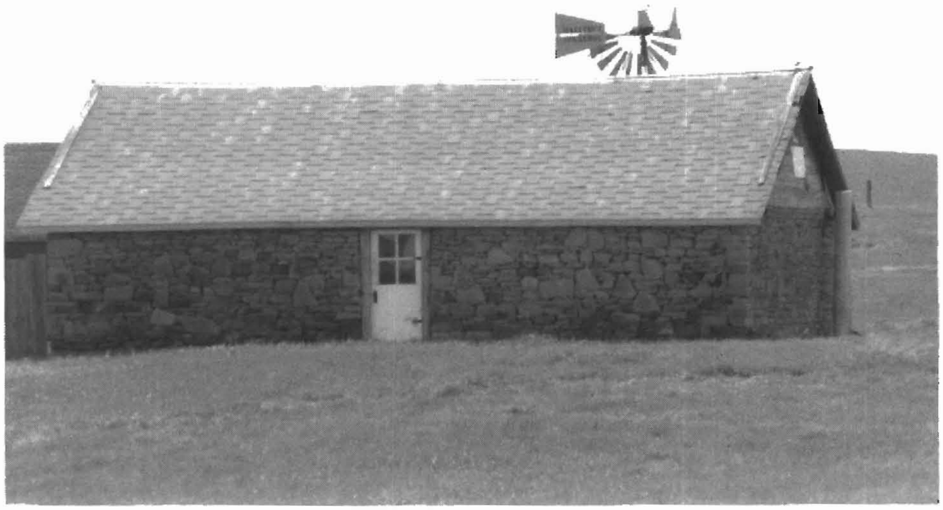


Figure 36. A farm building in the Dickinson area constructed from sandstone quarried from the Golden Valley Formation. Many older buildings and foundations in the Dickinson area are made of local sandstone. Today, sandstone from the Camels Butte Member is quarried south of Dickinson, crushed, and used as decorative stone.

deposits, like most others in the greater Dickinson area, contain significant amounts of chert, chalcedony, and other undesirable minerals. With proper treatment, the sand and gravel is suitable for a wide variety of uses.

Gravel is generally scarce throughout much of southwestern North Dakota, which has led to the widespread use of clinker for road metal. Crushed clinker holds up reasonably well for lightly traveled gravel roads.

Stone

Well-cemented sandstone from the Sentinel Butte and Golden Valley Formations has been used for many retaining walls, foundations, and older farm buildings in the Dickinson area; it has also been crushed and used as aggregate. Flint, found scattered about the surface southwest of Dickinson, has also been used as a building stone. The flint, a silicified lignite, is found as a lag deposit on Golden Valley and older units, indicating that it is Eocene or younger in age. Several small pits on the edge of Davis Buttes (140-96-24dda) suggest that the thinly bedded, flaggy, sandstone caprock there was quarried for similar uses. Micaceous, bleached, iron-stained sandstone in the Camels Butte Member has been mined from a small butte southwest of Dickinson (139-96-20bda) for decorative stone used in landscaping. Small boulders of Taylor bed silcrete, particularly ones that are pierced by hollow plant stem molds, are commonly used as weights to secure fencing. Silicified tree stumps are used in landscaping. Many of these stones can be seen at the Pioneer Village in Dickinson; photos of the stones and a brief geological tour of the village are found at the end of this book.

Clinker, a natural brick-like material formed when lignite beds burn and bake or fuse adjacent sediments, is common in the Sentinel Butte Formation in western North Dakota. However, in the area mapped, only one small outcrop of clinker was found north of Dickinson (on the south side of the Green River in 140-96-6b). Several small exposures are found south of Dickinson although no commercial pits are present in the area.

In addition to locally gathered or quarried stone, many buildings in Dickinson are made with building stones quarried from far away. The Post

Figure 37. Flint, cleared from the adjacent fields, along a fence line southwest of Dickinson. The flint is actually a petrified or silicified lignite that is found as a lag deposit; because it is so hard, it tends to remain behind as poorly cemented strata erode away.

Office at the corner of 1st Street East and Sims Avenue, for example, is trimmed with Indiana Limestone. The Indiana Limestone, or Salem Limestone as it is known to geologists, is composed almost entirely of small fossils and fossil fragments. It was deposited in a warm, shallow, Caribbean-like sea during Mississippian time, about 350 million years ago. Wave action and tidal currents broke and sorted the remains of calcareous shelled organisms, which were then deposited as a uniform-size calcareous sand. *Endothyra baileyi*, a foraminifera, is the most common fossil. Small fragmented crinoid stems, bryozoans, ostracods, tiny gastropods, pelecypods, brachiopods, and other formaninifera are also common. Perhaps the most easily recognizable fossils are small fragments of fenestelloid bryozoans, which form delicate fan-like colonies; they look like netting or screen.

The Post Office itself, built in 1916, is made with a light-colored brick. The steps and base are made with a coarse-grained granite that may have been quarried in Minnesota. Crushed stone - a sandstone from the Camels Butte Member of the Golden Valley Formation - is used for landscaping around the base of the building. Many other buildings in downtown Dickinson incorporate exotic building stones in their design, but in most, brick has been the building material of choice.

Clay

For commercial purposes, clays are divided into six main groups: kaolin, ball clay, fire clay, bentonite, fuller's earth, and common clay. In 1993, the estimated value of all marketable clay produced in the U.S. was about $1.9 billion. Major uses for specific clays are: kaolin - 48% paper, 21% refractories, and 5% glass; ball clay - 20% sanitary ware, 19% floor and wall tile, and 15% dinnerware; fire clay - 67% firebrick; bentonite - 20% foundry sand bond, 23% drilling mud, and 24% iron ore pelletizing; fuller's earth - 77% absorbent uses and 7% insecticide dispersant; and common clay - 97% construction materials (U.S. Bureau of Mines, Mineral Commodity Summaries - Clay, 1993).

As early as 1901, Earle J. Babcock, first State Geologist of North Dakota, discussed the "white fire and earthenware clay" found in the Dickinson area. The Fourth Biennial Report of the North Dakota Geological Survey, published in 1906, is devoted almost entirely to a discussion of North Dakota clays, including those found around the Dickinson

Figure 38. Ranchers have even found a use for the Taylor bed silcrete, especially pieces pierced by plant stem molds - they are used as weights to secure fencing.

area. The stratigraphy, economic geology, value and uses, and manufacturing methods are each described. That report also contains measured sections of the clay pit and bluff southwest of Dickinson (139-96-8) and two other exposures in the Dickinson area (Leonard, 1906).

Pressed brick was first manufactured at Dickinson in 1893 by the Dakota Land and Improvement Co. That plant used Bear Den Member clay from pits in 139-96-8ddd, 9ccc, and 17 aab and acc, and from similar clays north of Dickinson (Clapp and Babcock, 1906). The Dickinson Fire and Pressed Brick Co. developed from this operation sometime after 1898, and ceased operation in the late 1930s. Assistant State Geologist C.H. Clapp (1906) noted that:

> *The Dickinson plant is equipped to make dry-press, stiff-mud and repress brick, but most attention is paid to the production of dry-press brick. Common, face, and fire brick are all manufactured by this process. The clay is obtained from the top of a butte a mile southwest*

Figure 39. The U.S. Post Office in Dickinson. The Post Office was built in 1916 and is trimmed in Indiana Limestone.

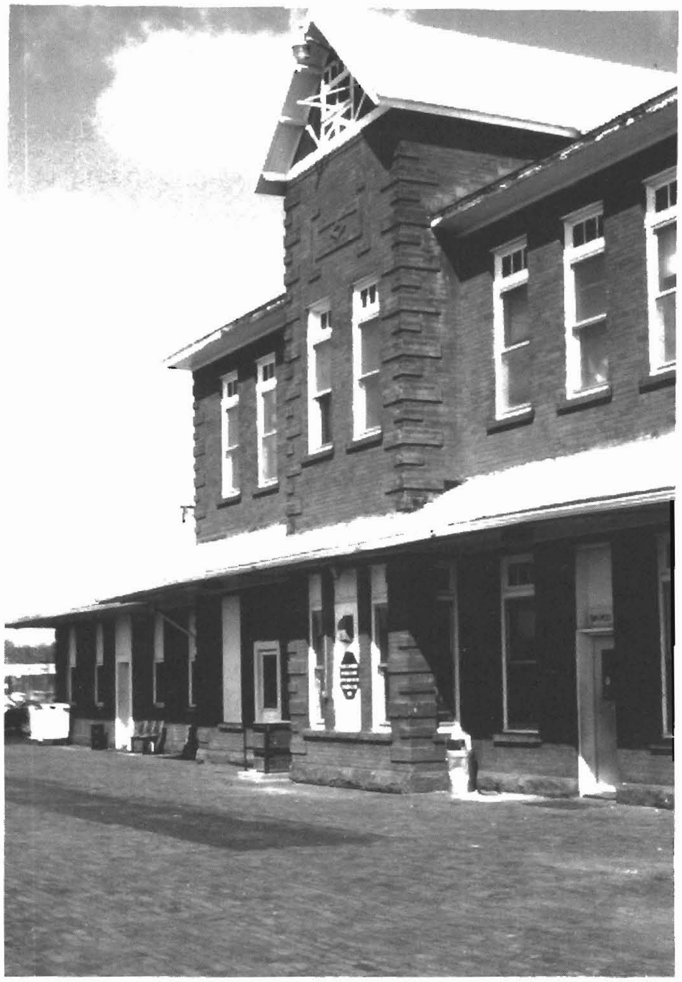


Figure 40. The Dickinson train station on Villard Avenue. The building was constructed from dark red brick that rests on a base of red sandstone blocks; window sills are also trimmed with this red sandstone. Crossbedded strata are readily visible in these partly hand-hewn blocks.

of the town and hauled to the plant in carts. For common brick the clay in a pit just back of the plant and associated with the lignite is mixed with higher grade clay. It is then carried over the Heart river and up to the plant in cars on an inclined railway. The clay goes directly to a pan crusher, and from there to the press. The pressed bricks are set directly in the kilns, the common brick being burned in scove kilns and the front and fire brick in rectangular down-draft kilns. The front and fire brick are burned with lignite at a very high temperature, which is necessary because of the refractory nature of the clay. The common brick is salmon colored, the front brick white, buff, spotted, and flashed. Stiff-mud and represse brick as well as special fire clay shapes are also manufactured.

Assistant State Geologist Miller Hansen, in his study of the alumina potential of North Dakota clays, analyzed four Bear Den Member samples (from the Davis Buttes quadrangle, 140-95-32, and from the clay pits southwest of Dickinson, 139-96-8), and found them to average about 18.5% Al_2O_3 (Hansen, 1959). It was determined that it was not economically feasible to establish an alumina processing plant in this area.

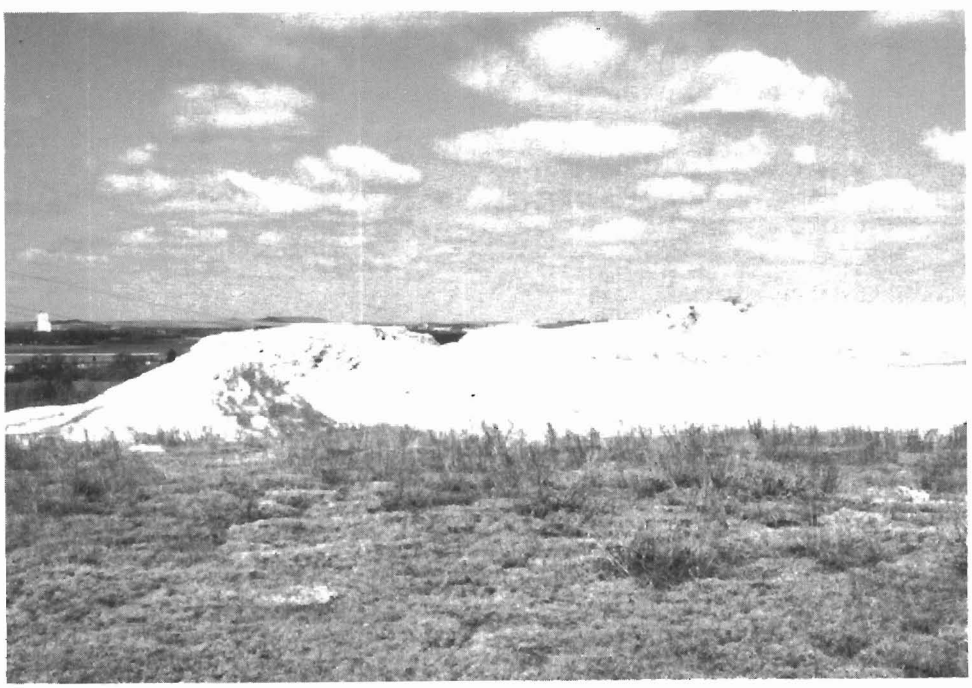


Figure 41. Abandoned clay pits overlooking the Heart River southwest of Dickinson.

Figure 42. The Dickinson Fire and Pressed Brick Company, circa early 1900s. *Photograph by Presthus Studio, Dickinson. Courtesy of the North Dakota State Historical Society.*

In the early 1960s, the Dickinson Clay Products Company began producing ceramic sewer pipe and tile, but closed in 1970 due to competition from plastic sewer pipe products. From 1935 to 1937, the company produced souvenir pottery, such as ash trays, under the names "Dickota," "Dickinson Clay Products," and "Badlands Pottery" (Murphy, 1995).

In 1968, a lightweight aggregate plant opened in Dickinson and by 1973, using clay from the Sentinel Butte Formation, was producing 100 cubic yards of this material per month; the plant closed in the 1970s. Concrete made with lightweight aggregate has a unit weight 40% to 70% less than concrete made with sand and gravel and so is used where weight is a limiting factor, as in tall buildings. Lightweight aggregate is also used to increase the insulation value of concrete, in asphalt overlays to improve traction and reduce breakage of headlights and windows from rock thrown by passing vehicles, as a landscaping material, and in roofing tiles. Lightweight aggregate is made by expanding or bloating clay in a rotary kiln under high temperatures.

Lignite

Most of western North Dakota is underlain by a dozen or more localized beds of lignite, each representing a former swamp deposit, that range from less than one foot to over forty feet in thickness. These lignites, and equivalent strata in adjacent eastern Montana, and northwestern South Dakota, lie in what geologists call the Fort Union Region, the largest coal basin on earth. Estimates of recoverable lignite reserves in North Dakota alone are 16 billion tons from beds greater than 5 feet thick, and an additional 17 billion tons from beds 2.5 to 5 feet thick (Brandt, 1953). A ton of lignite has a heating value roughly equivalent to two barrels of oil. The proven lignite reserves in North Dakota of 35 billion tons are thus equivalent in heating value to 70 billion barrels of petroleum, 58 times the

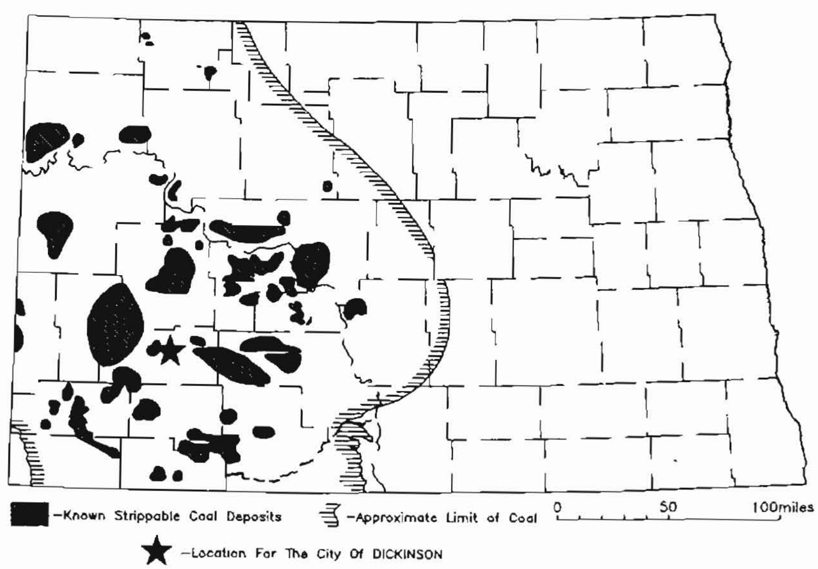


Figure 43. Map of the known coal deposits in North Dakota (Groenewold, 1977). The location for Dickinson is denoted by a (☆).

amount of petroleum produced to date in the North Dakota portion of the Williston Basin. The quantity of lignite in these beds is enormous, and represents about 80% of the recoverable lignite reserves, and 20% of the total coal reserves, in the United States.

Lignite is a "low-rank" coal, meaning that it has been only slightly altered by heat and pressure; subbituminous, bituminous, and anthracite coals have been, respectively, subjected to increasing metamorphism. Because lignite has been subject to the least amount of metamorphic change during the coal forming process, it retains more water and volatile compounds than other coals. It is relatively soft and, compared to other coals, has a lower heat value. Average North Dakota lignite has a heating value of about 6800 Btu/lb; it is composed of about 30% fixed carbon, 26% volatile compounds, 6-7% ash, and 0.6-1% sulfur (Brandt, 1953).

Although it appears as a uniformly black layer when exposed along badlands slopes or mine walls, lignite itself is not a uniform substance. It is composed of physically and chemically distinct organic materials, called macerals (which include woody and waxy materials), and inorganic minerals. After complete combustion of the lignite, the inorganic mineral residue that remains is called ash. Ash consists of compounds of silica, aluminum, iron, calcium, magnesium, and sodium, with lesser potassium, phosphorus, and trace elements. The different materials that make up lignite each contribute to the great variety of products that can be derived from this resource.

The recorded history of lignite mining in North Dakota goes back to 1873, and is recalled in vivid detail by Colleen Oihus (Oihus, 1983). These early mines were small, seasonal wagon mines (so named because farmers and ranchers would bring their own wagons to the mine to be filled with coal) that removed coal from the face of an outcrop. State Geologist Frank A. Wilder and Special Assistant L.H. Wood (1902) noted that:

> *On the Green River, just north of Dickinson, at the Kupper ranch, a fifteen-foot seam of lignite is exposed. It rises from the water's edge and is covered with from ten to thirty feet of clay. Mining by stripping is carried on in winter, six hundred dollars worth being sold last winter, with the selling price being only fifty cents a ton at the mine. The overlying clay is stripped off*

Figure 44. An early lignite mine along Spring Creek in southwestern North Dakota. These mines were generally referred to as wagon mines because farmers and ranchers would bring their own wagons to the mine to be loaded with coal. *Photo courtesy of the North Dakota State Historical Society.*

and dumped into the creek, which removes it during spring floods. The seam is exposed at a number of points along the river for a distance of half a mile, and outcrops a mile and a half back from the river.

In discussing lignite resources of the Dickinson area, State Geologist Arthur G. Leonard noted that "Throughout its course, lignite abounds on Green river. Near its mouth at Gladstone beds of excellent quality, though not exceeding 5 feet in thickness, are found on the Rust and A.B. Powers' farms in Township 140, Range 95, Sections 26 and 27. The exposures are directly on the river and near water level. Two miles farther upstream, in Township 140, Range 95, Section 22, west half, a three-foot bed of good lignite is mined by the owner of the ranch on which it occurs" (Wilder, 1904).

The T.T. Ridl lignite mine, located about 5 miles northwest of Dickinson in 140-97-11aad, was another small surface mine active in the early 1920s. The mine probably operated seasonally, mining lignite exposed along the valley wall.

Wilder and Wood also discussed the early history of lignite mining near Dickinson, an important lignite mining center from the late 1800s through the 1980s. According to their report and North Dakota Public Service Commission records, several mines have operated in the Lehigh area under many names. Two main coal seams were mined, known locally as the 12- to 16-foot-thick Lehigh bed and the thinner, overlying Dickinson bed. Most of the mines were initially operated as underground mines. In the mid-1940s to 1950, those mines still in operation converted to open pit mining methods. At the Husky Briquetting Company mine, the Lehigh and Dickinson beds have an average Btu content of 6520; they average 39% moisture, 9.5% ash, 27% volatiles, 1.8% total sulfur, and 3.5% sodium (Hudson, 1992).

Husky Briquetting, Inc. (Husky Industries, Inc. after 1972) operated a plant at Lehigh from 1927 to 1990, using lignite from the Husky mine and later from the J.K. Ranch mine. The carbonization process involved heating lignite in the absence of air to drive off volatile compounds. The residual solid that remained after carbonization is called coke or char and was formed into briquettes. By-products of the production process included creosote and some heavy tars, used locally as a wood preservative, and pitch (coal tar), used as a binding agent for the briquettes. Initially, the plant produced domestic-heating briquettes, but in 1961, with the advent of rural electrification and natural

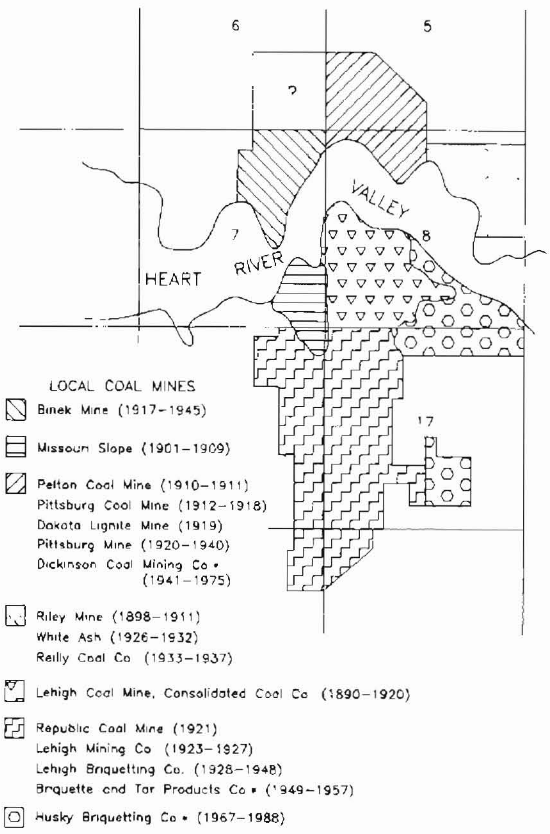


Figure 45. Map showing the approximate limit of lignite mines (primarily underground mines) in the Lehigh area. Two main coal seams were mined, the Lehigh bed (12- to 16-feet-thick) and the thinner, overlying Dickinson bed. Most of the mines were initially operated as underground mines. In the mid-1940s to 1950, those mines still in operation converted to open-pit mining methods.

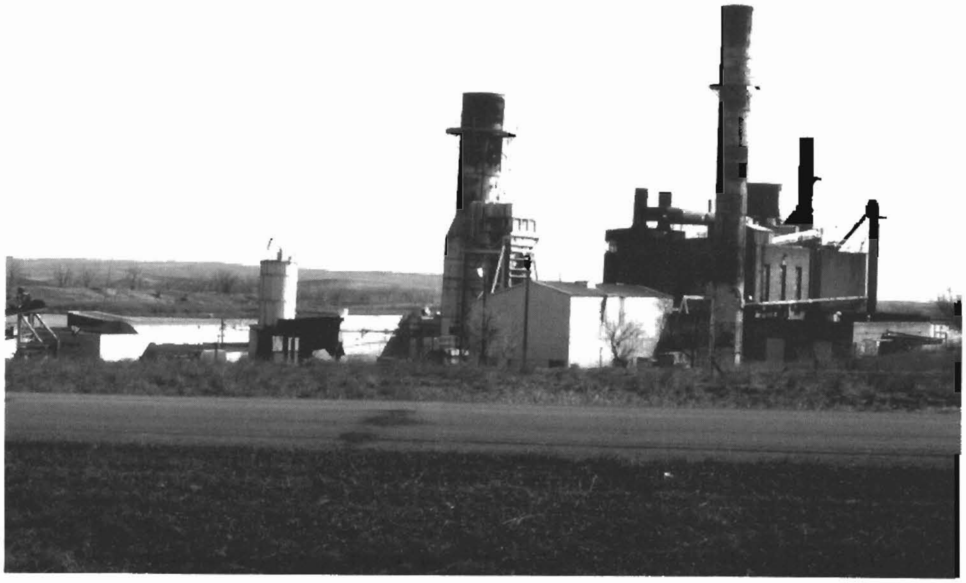


Figure 46. The partially dismantled Husky Briquette Company plant at Lehigh southeast of Dickinson.

For over 60 years, the plant produced charcoal briquettes and the by-products creosote, heavy tars, and pitch.

gas distribution, switched to producing barbecue briquettes. The plant closed in 1990, probably because gas grills had cut sharply into consumer demand for briquettes (Hudson, 1992).

About 5 miles north of Dickinson, in 140-96-3a, Royal Oak Enterprises, Inc. operated the J.K. Ranch lignite mine. Two lignite beds, identified in the mine permit application as the "E" and "F" seams, were mined by open pit methods. The "E" seam ranged from 3.8 to 5.4 feet thick, while the deeper "F" seam varied between 19.0 to 21.3 feet thick. Approximately 80 to 100 feet of overburden was removed to reach the "F" seam (Hudson, 1992).

The J.K. Ranch Mine was active from 1988 to 1990. The lignite was used to produce char for the manufacture of briquettes. The mine produced about 250,000 tons per year by a blade and scraper surface mining operation. Original plans had called for the entire quarter section to be mined, but mining ceased when the plant at Lehigh closed.

In 1994, North Dakota was the 9th largest producer of coal in the U.S., producing 32.2 million tons. Today, lignite is mined at 4 huge strip mines in North Dakota. Gigantic draglines, with booms longer than a football field and 110-cubic-yard buckets (able to fill over 50 pickups with a single scoop), are now used to expose deeply buried coal beds. These draglines, which use as much electricity each day as a city of 5,000 people, are run by three-person crews; they are known by the names such as "Chief Ironsides," "Prairie Rose," "Beulah Belle," and "Gypsie Rose."

Most of the mined lignite is burned at seven coal-fired power plants in southwestern North Dakota. The majority of these are located adjacent to a lignite mine and are thus referred to as mine-mouth plants. Because of its comparatively high moisture content and low Btu value, it is generally not economical to ship lignite to distant power plants. The Great Plains Synfuels Plant, near Beulah, uses about 6 million tons of lignite each year to produce synthetic natural gas and coal by-products. Over two million people in the Upper Midwest now get electricity from North Dakota lignite.

Geologic Hazards

Geologic hazards in the greater Dickinson area can be grouped into five categories: 1) mass wasting processes, such as landslides, soil creep, and swelling soils; 2) erosion, such as that associated with river banks and the shoreline of Patterson Lake; 3) flooding; 4) hazards associated with poor quality groundwater; and 5) man-made hazards such as those associated with abandoned underground lignite mines, abandoned aggregate pits, oil drilling reserve pits, landfills, and artificial fill.

It is not known whether radon is a problem. A 1993 EPA report indicated that Tertiary strata of southwestern North Dakota generally contain higher-than-average amounts of uranium and are known or are likely to cause indoor radon problems in some buildings constructed on these units (Environmental Protection Agency, 1993). Uraniferous lignite was mined and processed in the Belfield area intermittently from 1956 to 1967.

Uranium has also been associated with White River and Arikaree strata. Rocks in close proximity to the unconformity at the base of the Chadron Formation generally show an increase in radioactive minerals. Therefore, because of the proximity of White River strata to this area, it would be prudent to conduct radon tests of structures in T138N R96W and T138N R97W; groundwater in this area should be tested for uranium.

Mass-Wasting Hazards

Landslides

Several large landslides have been mapped in the Davis Buttes quadrangle. Those on the Davis Buttes themselves are developed in the Camels Butte Member of the Golden Valley Formation and in overlying (unmapped) colluvium. They formed as large rotational slumps and are of uncertain age. Each has a characteristic hummocky topography and internal scarps that have been softened or subdued by erosion, suggesting that the slumps may be Pleistocene or early Holocene in age. Recent rotational slumps are present in a similar landslide deposit along the east side of Davis Buttes (140-96-24dd).

Figure 47. A series of large rotational slumps scarring the northeast side of Davis Buttes (140-95-13c).

Note characteristic hummocky topography.

Figure 48. The headwall of a rotational slump on the east side of Davis Buttes (140-95-19ccb).

Two large rotational slumps have also been mapped on Simon Butte. One is developed entirely in the Camels Butte Member of the Golden Valley Formation. Another, the larger of the two, affected strata of the Sentinel Butte Formation and both the Bear Den and Camels Butte Members of the Golden Valley Formation. This slump appears to have been initiated by undercutting of the western side of Simon Butte by the Green River. It has a slightly fresher aspect than the slumps at Davis Buttes, although it too has been subdued by erosion.

Small, modern landslides are also common along cutbanks of the Green and Heart Rivers and Russian Spring Creek. They occur as small rotational slumps on particularly steep slopes, typically where river meanders have undercut adjacent hillsides. Because of limitations of scale, most small landslides have not been mapped; however, steep areas where they can be expected to occur are shown on 1:24,000-scale topographic base maps of the area. The steep valley walls along these rivers, though locally heavily vegetated, are commonly veneered with colluvial and landslide deposits.

Figure 49. A small, modern rotational slump along the Green River (140-95-21dac). Small slumps like this are common along steep valley walls, especially where slopes are undercut by rivers and streams.

Soil Creep

Hillslopes throughout the four-quadrangle area are subject to the process of soil creep. Soil creep, as its name implies, occurs when a thin, coherent plate of soil and weathered bedrock creeps slowly downhill under the influence of gravity and saturated soil conditions. It is apparent as shallow, concentric scars on both steep and moderately sloping hillsides. Such slides affect only near-surface sediments, but can cover entire hillsides. Soil creep is especially common where bedrock is close to the surface. Soil creep can also be recognized as a series of narrow, closely spaced, roughly horizontal ledges, which are often used as trails, and so accentuated, by grazing animals.

These crescentic scars also look similar to seepage steps, erosional scarplets that form where infiltration is impeded by a poorly permeable soil horizon. As water reaches such a layer, it tends to flow downhill where it can emerge at a shallow scar, sapping the soil's strength and facilitating its removal by erosion. Once formed, seepage steps migrate upslope as the seepage face is eroded.

Swelling Soils

Claystone and clayey sandstone of the Chadron Formation commonly contain clay minerals that swell when they become wet. South Heart claystone is generally silicified throughout the map area and therefore not subject to swelling.

Erosion

Patterson Lake

The principal concern with shoreline erosion, aside from reservoir siltation and loss of shoreline property, is that it undercuts adjacent slopes, creating conditions favorable for landslides and rock falls. Rates of shoreline erosion have not been assessed in this study, although casual inspection shows that significant erosion has taken place since the dam was completed in 1950.

River Erosion

The Heart and Green Rivers, and their larger tributaries, meander across broad floodplains (here mapped as modern alluvium, Qal). The meanders tend to migrate naturally over time, as is evidenced

Figure 50. Shallow, concentric scars which are typical of soil creep (looking south to 140-95-34bad). Soil creep is most visible on land used for grazing. It occurs when a thin, coherent plate of soil and weathered bedrock creeps slowly downhill under the influence of gravity and saturated soil conditions.

Figure 51. Shoreline erosion at Patterson Lake (139-96-7cbd). Such erosion contributes to loss of shoreline property and reservoir siltation and it creates conditions favorable for landslides and rockfalls.

by the maze of abandoned channels and oxbow lakes that are visible in the floodplain. As the rivers and streams meander, they tend to undercut adjacent banks and hillslopes, again creating conditions favorable for landslides.

Flooding

With the construction of the Patterson Lake dam in 1950, flooding along the Heart River south and east of Dickinson has been greatly reduced. However, flooding can and still does occur in low-lying areas adjacent to the Heart River and other rivers and streams in the area. Generally, areas mapped as modern alluvium (Qa1) - that is modern river channel and floodplain sediments - are prone to flooding. Intermediate level terraces (not differentiated from modern alluvium due to problems of scale, but shown on 1:24,000-scale topographic base maps of the area) may be flooded during exceptional events.

Figure 52. Banks undergoing shoreline erosion at the east end of Patterson Lake (139-96-7ddd).

Groundwater Quality

Numerous aquifers in the Fort Union Group and Upper Cretaceous strata underlie the Dickinson area. Groundwater found in strata below the Fox Hills Formation (Upper Cretaceous) is normally too highly mineralized to be of much use. The most productive aquifers in Fort Union strata come from very fine-grained sandstones and lignites with yields generally less than 50 gallons/minute, but occasionally up to 100 gallons/minute. In general, the shallower or younger the strata, the fresher the groundwater; groundwater within the Sentinel Butte Formation, for example, is normally less mineralized than groundwater within the underlying Slope Formation. Groundwater within these units is generally a sodium sulfate type. The total dissolved solids (TDS) within the Sentinel Butte Formation average 1,050 mg/l (Trapp, Jr. and Croft, 1975).

Along the Green and Heart Rivers and Antelope Creek, small unconfined aquifers are present in thin deposits of Quaternary age (Qa1). These aquifers are generally less than 20 feet thick.

Terrace deposits (Qa2) appear to be above the permanent water table but may at times hold perched water. It is unlikely that a well could be sustained in these units for any length of time. The recent availability of Lake Sakakawea water via the Southwest Water Pipeline has vastly improved the quality of drinking water in this area.

Man-Made Hazards

Abandoned Underground Lignite Mines

It is hard to overstate the important role that lignite development has played in the economic development of North Dakota. However, that development has also created environmental problems. The principal concern here, in the Dickinson area, is abandoned underground mines.

North Dakota Public Service Commission records indicate that several underground lignite mines are present in the Lehigh area southwest of Dickinson. As an underground mine was being shut down, the miners often removed coal originally left to support the tunnels during mining; without that

Figure 53. Sinkholes resulting from the collapse of abandoned underground mines in the Binek Mine (139-95-7acc).

support, many areas caved in, creating sinkholes at the surface. The collapse of mine tunnels has created sinkholes above some mined areas of the Binek, Riley, and Lehigh mines. Two similar circular depressions, associated with the Pittsburg mine, are located in 139-95-5c. Mine drawings indicate that the northeastern depression, in 139-95-5cca, may be an abandoned air shaft.

Areas that are known to lie above abandoned underground lignite mines are shown on the geologic map. Approximately 320 acres have been modified by surface mining and an additional 800 acres by underground mining. The extent of these areas is based on mine maps on file at the Public Service Commission and State Historical Society. The maps may not show the full, actual extent of underground workings. The boundary of the mined areas is shown with a dashed line to indicate this uncertainty. Subsurface conditions in the general vicinity of the mines should be investigated prior to any construction activities in such areas.

Abandoned Sand and Gravel Pits

Abandoned sand and gravel and other borrow pits represent a potential hazard not so much from their commonly steep walls, but from the fact that they are often used as waste dumps. Sand and gravel pits in particular may be associated with important groundwater supplies of unconfined, shallow aquifers; waste placed in such pits may adversely affect groundwater quality and future use of the land.

More and more developers are recognizing the value of depleted or abandoned aggregate quarries, especially near larger urban areas. Reclamation is important because no one wants a scarred landscape next door. Further, end uses for such areas are virtually unlimited - recreational areas, housing or other developments, agricultural land. Often, there is more to be gained financially from imaginative reclamation than from simple abandonment.

Figure 54. Waste discarded in an abandoned sand and gravel pit. Because sand and gravel deposits are very permeable and normally associated with shallow aquifers, they make poor waste disposal sites.

Oil and Gas Reserve Pits

During the drilling of an oil and gas well, a reserve pit is constructed to hold the cuttings and spent drilling fluid. In addition, this pit may also receive formation and completion fluids. Upon well completion, the fluids are sucked from the pit and the solids are buried; in rare cases, all of the material may be removed to another site. Drilling fluids in this area are typically salt-based although invert- or diesel-based muds may be encountered. Due to the corrosive nature of the salt, construction in these areas should be avoided. The location of oil and gas wells in the greater Dickinson area, many of which are now plugged and abandoned, may be obtained by contacting the Oil and Gas Division of the North Dakota Industrial Commission.

Landfills

Three municipal landfills are shown on the geologic maps that accompany this report. Waste at the older dumps was routinely burned, which may have helped to destroy some organic pollutants. One landfill, located at the present site of the Pioneer Village (140-96-34ca), was apparently still in use when aerial photographs were taken of the area in 1957; similar photographs taken in 1965 indicate that the landfill had by then apparently closed. State Health Department records indicate that the northern part of the landfill was uncovered during construction of Interstate 94.

Many small farm dumps exist in the greater Dickinson area but have not be mapped as a part of this project. Some may contain discarded agricultural chemical containers. In addition to the potential for contamination of both surface water and groundwater, the decomposition of refuse may create unstable foundation conditions and generate methane gas.

Artificial Fill

Artificial fill may include common borrow material and miscellaneous construction or demolition debris. Most such fill contains deleterious materials and is poorly compacted, and so is unsuitable for foundations. These characteristics also make it more susceptible to slope failure and uneven settlement. Other, engineered fill has been specially designed for foundations or other uses. Although only a few areas of fill have been mapped, fill should be anticipated in all built-up areas.

Potential Avoidance Areas for Excavation and Construction

Flood-Prone Areas

Building construction should be avoided within the 100-year floodplains of the Heart River, Green River, Russian Spring Creek, Ash Creek, and Antelope Creek. Most of the flood-prone areas were mapped as Qal on the accompanying geologic map. Flooding may also occur along intermittent tributaries and ravines associated with these creeks and rivers. These latter areas are too small to be depicted at this map scale.

Areas Prone to Slope Failure

Much of the map area consists of gently rolling topography that is not prone to slope failure. However, oversteepened slopes on the sides of Davis, White, Dobson, and Camels Buttes and hillsides thoughout the area as well as steepened slopes along creeks, rivers, and ravines may be unstable. Slope failure, primarily in the form of rotational slumps, has occurred along the slopes of these buttes. Most of the unstable areas were small and isolated and were not mappable at this scale.

However, several deposits of slumped material at Davis Buttes and along the slopes of Simon Butte were mapped as Qls.

Areas Requiring Additional Foundation Work

In areas where terrace gravels and recent alluvium are at or near the surface, construction foundations or piles would likely need to extend through these unstable units into the underlying bedrock for large structures. These units were mapped as Qa1, Qa2, and QTa.

Avoidance Areas

Approximately 900 acres in the Lehigh area are underlain by underground coal mines. Surface depressions or sinkholes resulting from the collapse of portions of these mines are visible throughout the Lehigh area. No construction should take place in this area without first thoroughly inspecting the subsurface to insure that there are no underlying mine voids. The North Dakota Public Service Commission recently began pumping a concrete mix into the mine voids beneath the county road in sections 8 and 17 in an effort to stabilize the road. The area suspected to be underlain by underground mines is depicted on the map with a cross-hatch pattern.

Three areas of buried waste (two abandoned dumps/landfills) and the present site of the Dickinson landfill were mapped as Qlf. These areas should be avoided both from a health perspective and as potentially unstable ground.

Areas of Difficult Excavation

Areas where either the Taylor bed (as either a red line or a dot) or the Chadron Formation (Tc) were mapped may pose problems during construction or excavation due to the nature of these highly indurated beds. Most of the area underlain by the Sentinel Butte and Golden Valley formations contains easily penetratable or excavatable sandstones, siltstones, and mudstones. Well-cemented sandstones or well-indurated nodules and concretions may be encountered without warning anywhere in the map area.

Summary

We hope to have shown you that the Dickinson area has a varied and very interesting geologic history, one that can be seen in the rocks and landforms exposed at the surface, and in the deeply buried sedimentary rocks and structures that underlie Dickinson and all of western North Dakota. Yet this history is not just for the books. It affects our daily lives. It can tell us what geologic hazards we live among, what mineral resources we can find and produce locally. It can, with luck, tell us where oil is to be found. Geology affects our lives in many ways. Geology makes a difference.

Geology is also fun, and to that end we have included two short fieldtrips, preceded by a geologist's view of the popular Prairie Outpost Park and Pioneer Village. The trips offer you the opportunity to see much of what is presented in the text, to glimpse firsthand selected pages from the book of North Dakota geology.

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Fieldtrip Guide

Dickinson Fieldtrip Guide

The fieldtrip routes outlined below, one for the area north of Dickinson and one for the area to the south, are just two of many possible routes one could take to view the local geology firsthand. The fieldtrip begins at the Dickinson Dinosaur Museum with a tour of the Prairie Outpost Park and Pioneer Village. We have selected features that should remain accessible and well exposed over time, hoping to avoid a frustrating problem common to many such guidebooks, that is the loss of exposures due to revegetation or construction. Having traveled the routes below, you may wish to venture out on your own, map in hand, to explore these and other exposures.

We have made every effort to choose stops that are located on public lands or public right-of-ways, and we ask that you respect the rights of private property owners. If you ask, most property owners are happy to let you look at the rocks on their land.

Dickinson Dinosaur Museum

The Dickinson Dinosaur Museum, which opened in 1994, contains fossils, rocks, and minerals from North Dakota and around the world. It provides an excellent, inspiring look at prehistoric life of the northern Great Plains. The fossils speak vividly about the changes our landscape has undergone over geologic time, and bring to life many of the chapters - the warm, shallow, Caribbean-like seas; coastal swamps and plains; and the deep freeze of the Ice Age - in our book of North Dakota geology. The displays of rocks and minerals give one an understanding of geologic processes and an appreciation of the remarkable diversity of the mineral kingdom.

Prairie Outpost Park and Pioneer Village

A substantial portion of the park has been constructed on an old landfill, which closed in the mid 1960s.

Figure 1. The entrance to the Dickinson Dinosaur Museum.

Petrified tree stumps

These twelve petrified tree stumps were recovered 70 feet below the ground surface at the Binek Coal Mine southeast of Dickinson. This mine was begun in 1918 as an underground mine by Polish immigrant Frank Binek; in 1946, it was converted to an open pit mine. The stumps were donated by Frank's son, Ted, and moved to this site in the fall of 1994. The stumps, the largest of which weighs 12,000 pounds, come from the Sentinel Butte Formation. They likely belong to the genus *Metasequoia* and may have reached over 100 ft tall.

Oil pumping jack

This pumping jack was donated by Chevron USA, Inc. The accompanying display presents the discovery of oil in North Dakota, a summary of production, and the location of petroleum-producing areas. See page 34 for more information on the oil and gas resources of the Dickinson area.

Veteran's Memorial Chapel

This chapel is made from a light grayish brown sandstone and intraformational conglomerate of the Camels Butte Member of the Golden Valley Formation. The term "intraformational" refers to the small mudstone and siltstone clasts in the conglomerate that were derived from interchannel sediments; the clasts were thus derived from the banks of a former river channel, not from some distant source. The rocks were likely quarried from a hill south of the Dickinson golf course.

Scandinavian Stabbur Building

The gardens around this log structure are lined with glacial erratics, petrified wood, and clinker or "scoria". An erratic is a rock that differs in composition from the bedrock underlying it. The glaciated portion of North Dakota is strewn with erratics from the Canadian shield and plains, and they alone are one of the most compelling indications of long-vanished ice sheets. The glaciers brought a varied suite of igneous, metamorphic, and sedimentary rocks that would not otherwise be found in North Dakota. Erratics are commonly seen piled in the corners of farmers' fields; because they are different and more durable than many local rocks, erratics are commonly used for retaining walls, foundations, and landscaping.

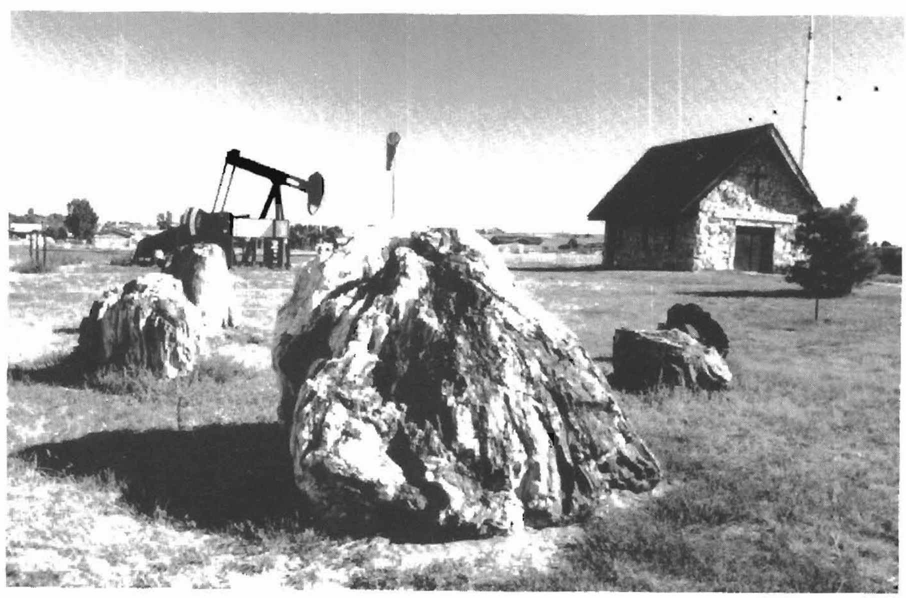


Figure 2. Metasequoia stumps on display at the Pioneer Village.

The erratics here are mostly granitic and were probably gathered northeast of Dickinson, beyond the Green River. It is there where widely scattered erratics can still be seen lying about the countryside. While other evidence of glaciation - the finer glacial sediments and glacial landforms - have long since been removed by erosion, the boulders remain behind, resisting erosion.

Clinker, a natural brick-like material formed when burning lignite beds bake and fuse overlying sediments, is widespread in southwestern North Dakota. In places, temperatures were hot enough to melt the sediments, turning them into a glassy or frothy mass similar to obsidian or true volcanic scoria. Clinker is commonly used as road metal in southwestern North Dakota, and, because of its bright red colors and interesting textures, for landscaping.

D.L. GRHS Memorial Stone House Museum

This stone house was built of local limestone by the Germans from Russia Heritage Society. The stone may have come from the South Heart Member of the Chadron Formation, which forms the caprock of buttes in the Lefor area. These carbonates were investigated by the North Dakota Geological Survey to determine their suitability for the production of a natural cement. The comparatively low calcium carbonate content of the limestones would require benefication before they could be so used. For this and other reasons, a cement plant was never built.

On the south side of the building is a pile of flint, what many early farmers in this area had to laboriously remove from their fields. This flint is actually petrified swamp debris - a silicified lignite bed. This flint formed when silica-enriched groundwater circulated through a layer of lignite, gradually replacing the organic matter with silica. Look closely and you can still see the silicified, flattened remains of plant stems, leaves, and other organic debris.

Flint such as this is common southwest of Dickinson, where it persists as a lag deposit because of its extreme toughness and resistance to erosion. Native Americans used similar flint for arrowheads, scrapers, and other tools. More recently, this flint has been used as a building stone and can be seen in retaining walls and small buildings throughout the greater Dickinson area.

Figure 3. The D.L. GRHS Memorial Stone House Museum

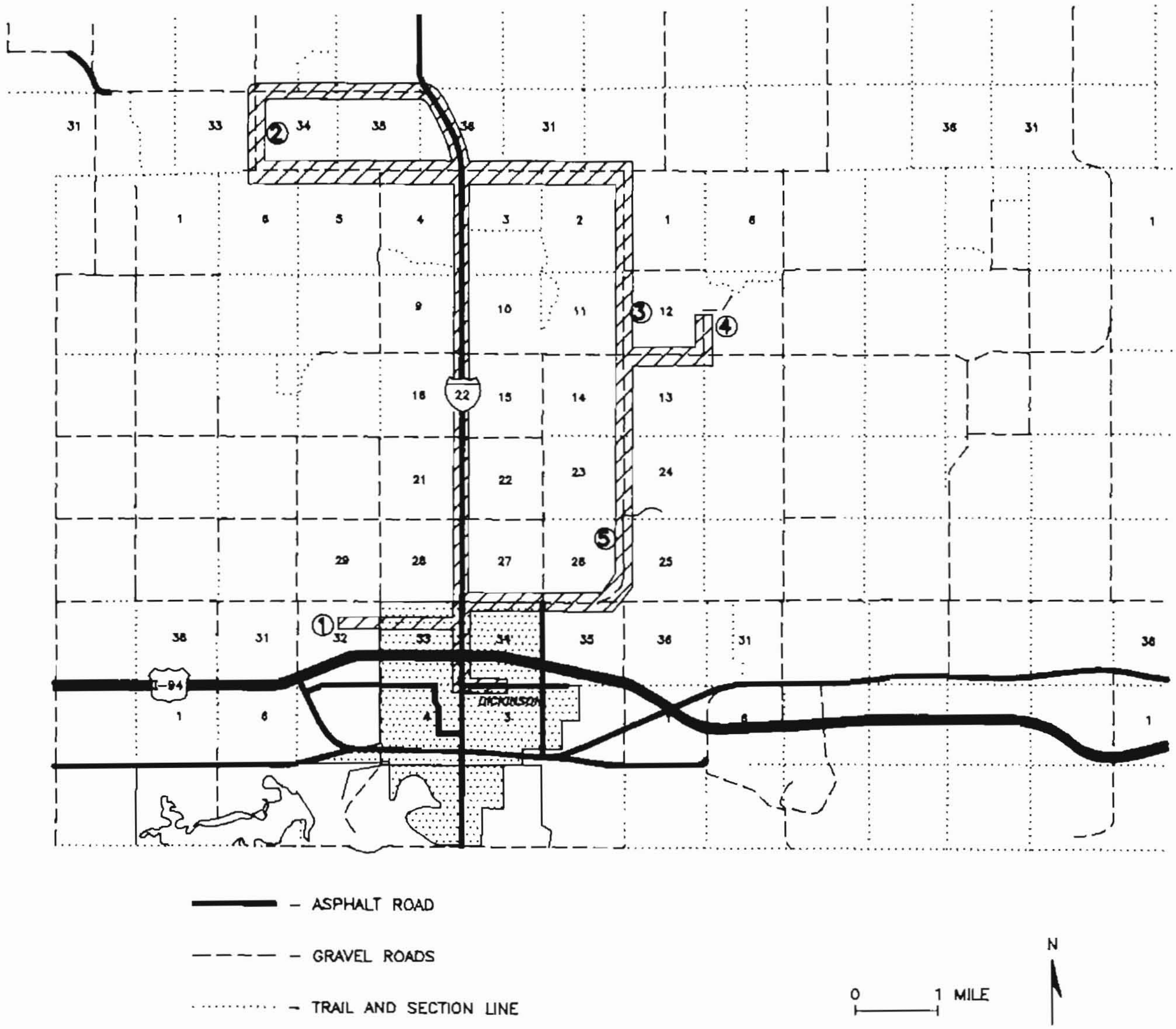


Figure 4. Map of the route of the Dickinson North Roadlog.

Dickinson North Roadlog

Mile

0.0 Begin at the parking lot on the west side of the Dickinson Dinosaur Museum. Turn right out of the parking lot and proceed west on Museum Drive.

0.3 Turn right onto 3rd Avenue W (State Highway 22) and proceed north.

0.6 Turn left (west) onto 15th Street W. Light brown, micaceous, locally iron-stained crushed sandstone from the Camels Butte Member of the Golden Valley Formation is used for landscaping around several of the buildings south of this road.

0.9 Turn left and continue west on 15th Street W.

1.6 Cross State Avenue and continue west on unimproved dirt road to gate.

1.8 *STOP 1.* Park at the gate and walk west approximately 0.3 mile to the top of the hill at the center of Section 32, T140N R96W.

This hill is capped by an unusual, iron-stained variety of the Taylor bed silcrete. The Taylor bed here consists of two contrasting lithologies, a reddish brown, iron-cemented quartz siltstone, and, on the hill just to the northwest, a gray, silicified quartz siltstone (see photo on page 19). The Taylor bed is the uppermost unit of the Bear Den Member of the Golden Valley Formation (Paleocene-Eocene), a 20-30 foot-thick sequence of bright white kaolinitic strata believed to be a weathering horizon. Bright white kaolinitic clay of the Bear Den Member crops out along both sides of freeway to the southwest.

The strata of western North Dakota are typically viewed as essentially horizontal and structureless. However, detailed geologic mapping of the greater Dickinson area has shown that the Bear Den Member - a readily identifiable marker bed - has been warped into a very gently folded, northeast-trending syncline. As calculated from the geologic map, dips are typically on the order of 1-3 degrees. This syncline is apparently an extension of the same structure exposed to the southwest in the Little Badlands, and is apparently present in the subsurface as well (see page 33). Warping of the Bear Den Member in the Dickinson area is certainly post-Paleocene in age and likely post-Eocene; a post-Oligocene/Miocene age is indicated by exposures in the Little Badlands.

The Lodgepole Field discovery well (initial flowing potential of over 2,000 barrels of oil and 1.2 million cubic feet of gas per day) is located about 2,000 feet to the west. Production from this and nearby development and stepout wells comes from a group of carbonate mounds (see page 36). The discovery was made in February, 1993.

1.9 Junction with State Avenue. Cross State Avenue and proceed east on 15th Street W.

2.6 Turn right and continue east on 15th Street W.

3.0 Junction with 3rd Avenue W (State Highway 22). Turn left and proceed north on State Highway 22.

4.9 The high ground on both sides of the road is upheld by rock layers of the Golden Valley Formation that are more resistant to erosion than those of the underlying Sentinel Butte Formation. The low hills to the west are capped by the iron-stained variety of the Taylor bed silcrete, while the hill to the east is capped by sandstone of the Camels Butte Member.

7.1 Cross the Green River.

8.0 This narrow, sandy ridge is one of many that parallel the modern Green River. See *STOP* 2 for explanation.

8.7 Turn left and proceed west on county-line road.

11.0 Crossing another narrow, sandy ridge that lies parallel to the modern Green River.

11.2 Turn right and proceed north on section-line road.

11.3 Crossing yet another narrow, sandy ridge.

11.6 *STOP* 2. Stop at crest of hill. After this stop, continue north along section line road.

This narrow ridge of sand and gravel is one of many that trend parallel to the modern Green River. These river channel deposits contain pebbles and cobbles of resistant, locally derived material (mudstone, sandstone, concretions, silicified wood, flint, silcrete, and chalcedony), recycled glacial erratics from the Canadian Shield, and lesser quartzite and porphyry derived from the ancestral Black Hills or Rocky Mountains. They reach up to 60 feet thick in the greater Dickinson area.

The esker-like form of these deposits are probably a result of differential erosion. The coarse sand and gravel of these channel deposits are more permeable than adjacent finer grained sediments of the Sentinel Butte Formation, which allows precipitation to preferentially infiltrate the sediments rather than erode them. In essence, the banks of the channel have eroded away, leaving behind the coarse sediments of the channel itself.

The age of these deposits is not known. They occur at elevations from about 20 to 210 feet above the modern floodplain of the Green River, indicating that a substantial amount of erosion has occurred since they were deposited. They may be associated with an ice-marginal drainage system that developed in front of glaciers that reached to within a few miles of here, and so are probably early Quaternary in age.

Many of these deposits have been mined for their sand and gravel. Abandoned sand and gravel pits (all located on private land) can be seen throughout the area, and new pits (now generally reclaimed after mining has ceased) continue to be opened.

12.2 Turn right (east) onto section-line road.

13.0 Camels Butte, to the north, is capped by resistant sandstones of the Camels Butte Member of the Golden Valley Formation. Camels Butte is what geologists call the "type section" of the member that bears its name; in essence, it is a reference section, one that geologists refer to in order to learn what typical Camels Butte Member strata look like.

14.3 Turn right (south) onto 3rd Avenue W (State Highway 22).

15.4 Turn left onto 30 R Street SW and proceed east.

16.0 To the south, in the northeast quarter of Section 3, T140N R96W, Royal Oak Enterprises, Inc. operated the J.K. Ranch lignite mine from 1988 to 1990. Two lignite beds, one about 5 feet thick and another about 20 feet thick, were mined by open pit methods. Approximately 80 to 100 feet of overburden was removed to reach the lower, thicker seam. The lignite was used to produce char for the manufacture of briquettes. Mining ceased when the briquette plant at Lehigh closed.

17.4 Turn right onto 109 R Avenue SW and proceed south.

18.6 Cross the Green River.

18.9 *STOP 3.* Stop at crest of hill.

An unusual variety of the Taylor bed silcrete caps the top the hill to the east (which is on private land), but it also occurs as isolated blocks along the roadside to the west. The silcrete occurs as blocks that are about 2 feet thick and up to 10 feet long (see photos on pages 18 and 19). Silicified plant stems or roots and hollow molds can be seen in some of the blocks, and suggest that the silcrete was deposited in shallow water, such as a swamp or marsh. The silcrete itself is a light gray, massive (lacking well developed bedding features), silicified siltstone. This extremely hard rock is composed almost entirely of silica, thus the name silcrete, which derives from the Middle English *concret,* itself derived from the Latin *concrescere,* meaning to grow together or harden.

The puzzling thing about this particular rock are the pillow-like structures on the upper surfaces of each block. Well-developed load structures are present on the undersides of some beds and can be readily explained in terms of settlement, prior to lithification, due to differing sediment densities. However, the botryoidal or pillow-like structures on the upper surface remain a mystery.

19.7 Turn left onto section-line road and proceed east.

20.7 Turn left onto section-line road.

20.9 *STOP 4.*

The bright white clays seen on either side of the roadway belong to the Bear Den Member of the Golden Valley Formation. The Bear Den Member is believed to represent a weathering horizon developed on top of the Sentinel Butte Formation; it marks an unconformity, a hiatus in deposition between Paleocene-age Sentinel Butte strata and Eocene-age strata of the Camels Butte Member of the Golden Valley Formation.

These white clays are mostly kaolinite, a type of clay that forms after prolonged periods of weathering. It feels greasy when rubbed between the fingers; locally it appears orangish due to staining by iron oxides. Areas underlain by these clays often support only sparse vegetation, as many nutrients needed by plants have been leached away. Kaolinite clays are often referred to as china clays, and are widely used in the manufacture of porcelain; kaolinite is also used as a filler and coating material in glossy papers, as a filler in rubber and linoleum, and in various chemical, medicinal, and cosmetic applications. From 1893 to the 1930s, Bear Den Member clays exposed southwest of Dickinson were used in the manufacture of bricks; bricks are still being made by the Hebron Brick Co. from similar deposits near Hebron.

The Taylor bed silcrete caps the kaolinitic Bear Den Member clays. While thinner and much more fractured than the other two silcrete varieties we have seen today, this silcrete is still hard and so resists erosion. It supports the flat, planar topography seen here, and the flat benches that surround Simon Butte to the northeast (see photo on page 15).

A large landslide, with characteristic hummocky topography, can be seen on the west side of Simon Butte.

21.0 Turn around and proceed south.

21.4 Turn right onto section-line road and proceed west.

22.4 Turn left onto 109 R Avenue SW and proceed south.

24.4 Davis Buttes, to the east, rise over 400 feet above the surrounding countryside. They are capped by sandstone of the Camels Butte Member of the Golden Valley Formation.

24.7 *STOP 5.* After this stop, continue south then west back to Dickinson.

Both the Bear Den and Camels Butte Members of the Golden Valley Formation are exposed along the west side of the road. Here, the lower Camels Butte Member is marked by a 4-10 inch-thick chert that lies about seven feet above the base of the member. This drusy chert is bounded above and below by thin beds of lignite and carbonaceous shale. The chert bears numerous impressions and flattened molds of bark and plant stems lined with drusy quartz crystals. This horizon also has several badly splintered, silicified tree stumps still in their upright growth position.

The underlying Bear Den Member can be recognized by the characteristic white kaolinitic clays exposed at the southern end of the roadcut; the Taylor bed silcrete marks the top of the member.

26.7 The white kaolinitic clays at the top of this ridge belong to the Bear Den Member.

27.3 Turn left onto 3rd Avenue W (State Highway 22) and continue south across the freeway.

28.0 Turn left onto Museum Drive

28.3 Dickinson Dinosaur Museum

Figure 5. Photograph of the road ditch at Stop 5.

Figure 6. A closeup photograph of outcrop in background of previous Stop 5.

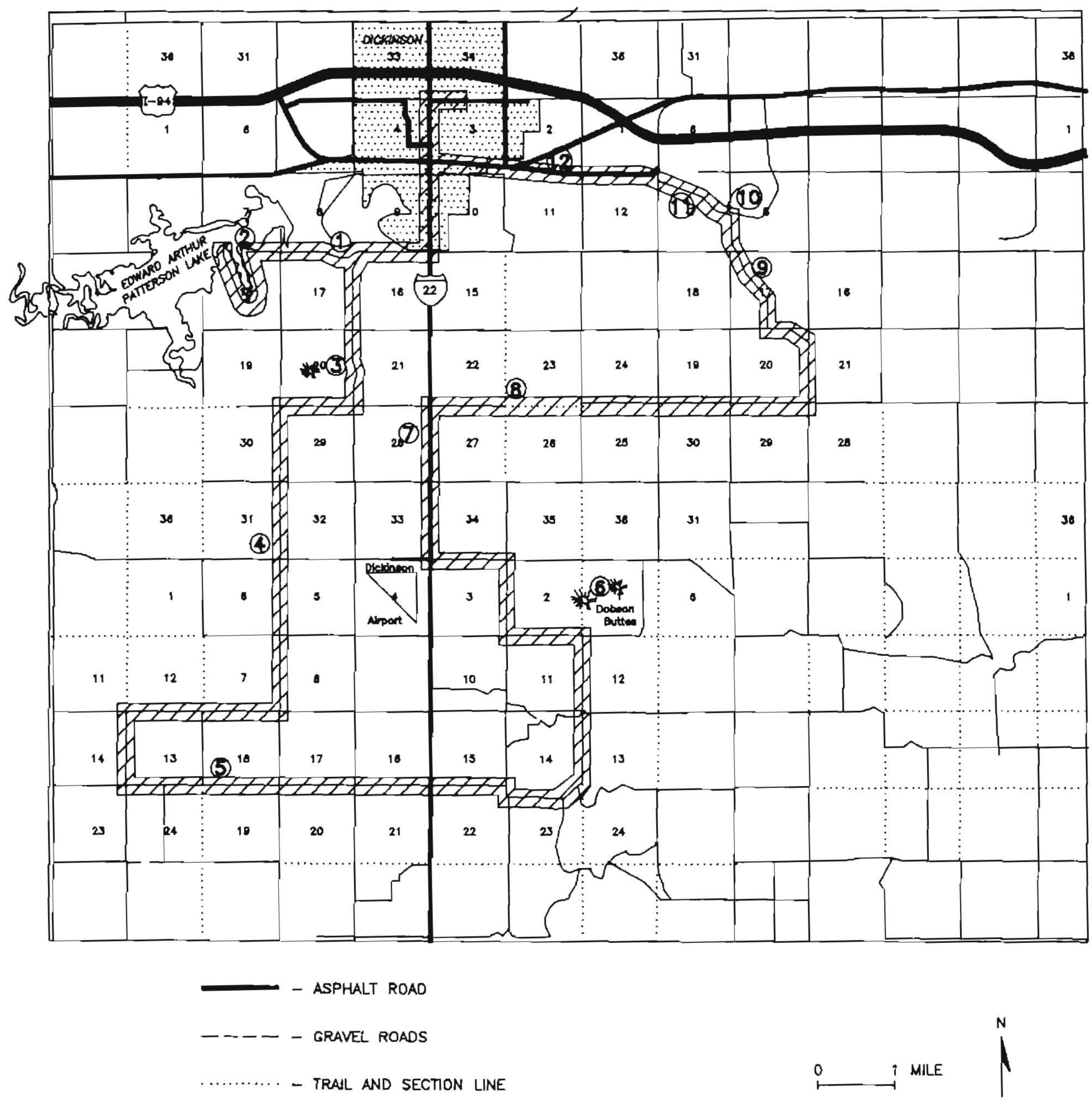


Figure 1. Map of the route of the Dickinson South Roadlog.

Dickinson South Roadlog

Mile

0.0 Begin at the parking lot on the west side of the Dakota Dinosaur Museum. Turn right out of parking lot and proceed west on Museum Drive.

0.3 Turn left on 3rd Avenue W (State Highway 22) and proceed south.

1.9 Cross the Heart River.

2.1 Turn right onto 8th Street SW and proceed west.

3.5 MAP, #1. To the north is the old clay pit used by Dickinson Fire and Pressed Brick Company, which operated from the early 1900s to the late 1930s. Kaolinitic clay (which feels greasy when rubbed between the fingers) was mined from the Bear Den Member of the Golden Valley Formation.

3.8 Another clay pit operated by the Dickinson Fire Pressed Brick Company is present on the south side of the road.

4.1 Road loops south around the golf course.

4.8 Turn left and proceed west on 8th Street SW.

5.3 Turn left onto gravel road and proceed into park.

6.3 MAP, #2. Stop at turnaround overlooking Patterson Lake. Channel sandstones in the Sentinel Butte Formation are exposed along the north shore of Patterson Lake.

Proceed back the way we came in.

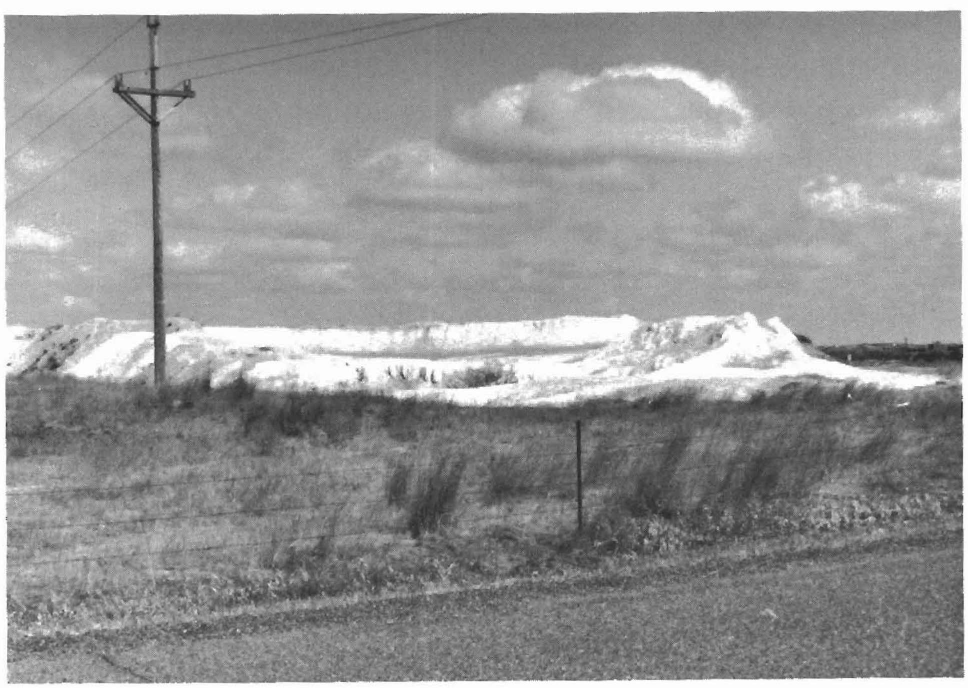


Figure 2. Old clay pit used by Dickinson Fire and Pressed Brick Company.

Figure 3. Looking across Patterson Lake to the sandstones exposed along the north shore.

7.3 Turn right and proceed east on 8th Street SW (paved road).

7.7 Turn right and loop back around golf course.

9.0 Turn right and proceed south on paved road.

9.5 The Bear Den Member of the Golden Valley Formation (bright white claystone) and the Taylor bed (the thin, tan, very hard rock layer) is exposed in the road ditch to the left near the top of the hill.

9.9 Stop sign, proceed straight ahead (south) on 20th Avenue SW. The Taylor bed is exposed in the ditch and fields to the right.

10.0 MAP, #3. Caprock from the hill ½ mile to the west (right) has been quarried for many years for decorative stone. Moderately to well cemented, tan to red-stained, micaceous sandstone in the Camels Butte Member of the Golden Valley Formation is quarried, crushed, and used as landscaping rock around numerous buildings in Dickinson, including the Comfort Inn and Burger King.

10.9 Turn right and proceed west on gravel road.

11.7 Passing tank batteries of producing well drilled into Lodgepole Formation carbonate mounds of the Eland Field. These mounds lie at a depth of about 10,000 feet in the Dickinson area. They were discovered in December 1994, shortly after the Lodgepole discovery well northwest of Dickinson was completed in February, 1993.

11.9 Turn left and proceed south.

13.6 MAP, #4. The Bear Den Member of the Golden Valley Formation is poorly exposed in this area but can be traced through stubble fields due to the brightly colored soils that develop on it.

Figure 4. Two to three-foot blocks of iron-stained sandstone (Camels Butte Member) quarried from the top of a butte in section 20.

15.4 The Bear Den Member and Taylor bed are exposed at hill top to the left.

16.1 Turn right and proceed west.

16.9 Channel sandstone from the Camels Butte Member of the Golden Valley Formation is exposed in roadcut to the left.

17.2 Old building constructed from local stones is present in field to the right.

18.0 Turn left and proceed south on 115 R Avenue SW. The intersection is underlain by the Chadron Formation which is well exposed in the uplands to the north and west.

19.0 Turn left and proceed east on 45 R Street SW.

20.0 The Chadron Formation, which consists of pebbly sandstone and silicified bentonite, is exposed in the ditch and fields along both sides of the road for the next mile.

20.2 MAP, #5. The contact between the Golden Valley and Chadron Formations can be seen just over the hill to the north (left) of the road.

22.2 Bear Den Member visible in banks of Dry Creek south (to the right) of road.

23.0 Proceed straight ahead (east) across Highway 22 staying on 45 R Street SW.

24.1 The flat area to the right (south) is alluvium deposited when the ancestral Antelope Creek flowed at this level before cutting down to its present position.

Figure 5. A typical exposure of the Bear Den Member southwest of Dickinson.

24.9 Turn left and proceed north. The Sentinel Butte Formation is exposed along the banks of Antelope Creek to the right (east).

26.4 Cross bridge over Antelope Creek.

26.6 Thin alluvium (sand and gravel deposited when the ancestral Antelope Creek flowed at a higher elevation than it does today) is draped over the Sentinel Butte Formation.

Figure 6. Strata from the Golden Valley and Chadron formations exposed north of the road at mile 20.2.

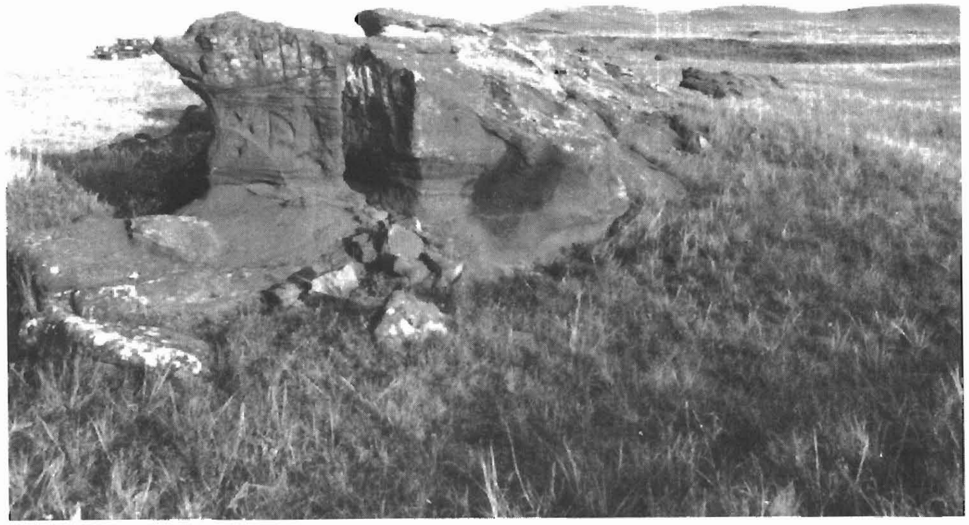
Figure 7. Looking west to West Dobson Butte from the top of East Dobson Butte.

27.3 MAP, #6. Turn left and proceed west onto 43 R Street SW. To the right (north) are the Dobson Buttes. These buttes are capped by moderately cemented sandstones of the Camels Butte Member of the Golden Valley Formation. The buttes remain because the caprock is fairly resistant to erosion, thus protecting the underlying softer strata from erosion.

28.3 Turn right and proceed north on 110 R Avenue SW.

Figure 8. Chunks of flint picked from a field lie along a fence line (camera lens cap for scale).

Figure 9. Sandstone concretions exposed southeast of Dickinson. These types of exposures enable the rocks to be investigated in three dimensions.



29.3 Turn left and proceed west on 42 R Street SW. The flat area to the right (north) formed as a result of runoff depositing sediment eroded from the surrounding hills. Geologists call this sediment slopewash or colluvium.

29.7 Flint in the rock pile to the north used to litter these fields. Resistant rocks such as these are called "float" or a lag deposit by geologists. The flint was originally deposited hundreds of feet higher than this level, but was "let down" or "floated" downward as the surrounding soft sedimentary rock was eroded and washed away.

30.4 Turn right and proceed north on Highway 22.

31.4 MAP, #7. The Bear Den Member and Taylor bed are exposed at the surface throughout the development to the left (west) of road.

32.0 The Bear Den Member and Taylor bed are exposed to the left in west road cut.

32.5 Turn right and proceed east along trail (only if it is dry).

33.5 MAP, #8. Elongated sandstone concretions are present on both sides of the trail. The orientation of crossbeds in the concretions show that the river that deposited this sand was flowing to the northwest. Proceed straight (east) along trail.

34.5 Proceed straight (east) onto 40 R Street SW.

35.6 Building to the right (south) was constructed from locally quarried sandstone of the Camels Butte Member of the Golden Valley Formation.

37.5 Turn left and proceed north on 106 R Avenue SW.

37.7 Sentinel Butte Formation in east roadcut.

Figure 10. The Husky Briquetting, Inc. plant at Lehigh in January, 1929. *Photo courtesy of the Special Collections at the Chester Fritz Library at the University of North Dakota.*

38.3 Clinker or "scoria" pit to the right (northeast). Clinker is rock baked and fused by the intense heat given off from the burning of underlying coal. This resistent rock is used in this area as road metal.

39.2 MAP, #9. The Dickinson landfill is located in the large open pit created during the mining of the Lehigh coal bed by Husky Briquetting, Inc. Sedimentary rock, including several thin coals, from the Sentinel Butte Formation are well exposed along the south pit wall. Several small normal faults are also visible in this cut.

Figure 11. Miners removing coal at the Lehgih Briquetting Company's underground mine at Lehigh circa 1920s. *Photo by the Osborn Studio, Dickinson, courtesy of Special Collections in the Chester Fritz Library at the University of North Dakota.*

Figure 12. Sinkholes have formed on this hillside as a result of the collapse of shallow underground coal mines.

39.7 Site of old briquette plant that operated from 1927 to 1990. The plant pulverized lignite, mixed it with a binding agent, and fused it into briquettes that were used for domestic heating and barbecues.

40.2 The old Dickinson landfill is located to the left (west) of the road in the area south of the Heart River. The landfill operated from the mid-1960s to the mid-1980s. The road in this area is surrounded and underlain by an underground coal mine. This area underwent underground mining from the early 1900s into the late 1940s. The underground workings cover an area of approximately 800 acres in the Lehigh area. The surface sinkholes formed when the underground rooms collapsed can be seen throughout this area but are most prominent north of the briquette plant.

40.6 Cross railroad tracks. An alluvial terrace (dark brown sand and gravel) is exposed near the top of the railroad cut to the right (east).

40.7 MAP, #10. The machinery in this area is from the old Binek Mine. The large *Metasequoia* stumps were excavated while the Lehigh coal was being mined. The *Metasequoia* trees grew in the swamps that formed the Lehigh coal.

40.9 MAP, #11. Collapse features (sinkholes) from underground mines are visible on both sides of the road.

41.0 The Sentinel Butte Formation is poorly exposed in a roadcut to the right.

42.6 MAP, #12. Turn left on Villard (I-94 Business Loop) and proceed west into Dickinson.

44.3 Most of downtown Dickinson is situated on a flat terrace of the Green River.

44.6 Many of the buildings in downtown Dickinson were constructed with bricks that were produced at the old Dickinson Fire and Pressed Brick plant.

45.2 Turn left and proceed north on 3rd Avenue W.

45.9 Turn left and proceed west on 9th Street SW.

46.1 Turn right into Youngs Park. Sandstones of the Camels Butte Member of the Golden Valley Formation are exposed at the top of the hill.

46.7 Turn left out of park back onto 9th Street SW and proceed east.

46.9 Turn left onto 3rd Avenue W and proceed north.

47.5 Turn right and proceed east on Museum Drive.

47.8 Turn left into Museum parking lot.

Figure 13. Examples of brick buildings located in downtown Dickinson.

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Richard A. Baker, *Drafting Technician*
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North Dakota Geological Survey
600 East Boulevard Avenue, Bismarck ND 58505-0840 1997

Geology of the Dickinson Area, North Dakota

by Robert F. Biek and Edward C. Murphy

North Dakota Geological Survey

Map Unit Descriptions

Qf Artificial deposits: Fill used to create level building sites, reclaim mined land, and to build dams, retaining ponds, and other structures. Consists of engineered fill, construction and demolition debris, and general borrow material. Although only selected deposits have been mapped, fill should be anticipated in all built-up areas.

Qlf Landfill deposits: Engineered landfill deposits and common dumps.

Qls Mass-movement deposits: Locally derived sediments redeposited by rotational slumping. Characterized by a subdued, anastomosing network of internal scarps. Mapped on the steep slopes of Davis and Simon Buttes. Probably late Pleistocene to early Holocene in age, although some have been subject to recent movement.

Qa1 Modern alluvial deposits: Sand, silt, and clay deposited by modern streams and rivers. Gravelly where derived from coarse, older alluvial deposits. Includes river channel and floodplain sediments. Contains numerous truncated meanders and minor terraces. Local similarity to the Sentinel Butte Formation makes thickness determinations difficult; generally less than 20 feet thick.

Qa2 Alluvial deposits: Poorly sorted sand, silt, clay, and gravel. Forms planar terrace deposits, elevated relative to modern streams, that are dissected by modern alluvial deposits. Fluvial (channel and floodplain) sediment generally less than 10 feet thick.

QTa Sand and gravel: Poorly sorted, iron stained, locally iron cemented sand and gravel. Contains pebbles and cobbles of locally derived material (mudstone, sandstone, concretions, silicified wood, flint, silcrete, chalcedony), recycled glacial erratics, and lesser quartzite and porphyry (derived from the Black Hills or Rocky Mountains). Occasional small to medium boulders of local sandstone and mudstone. Occurs as esker-like ridges, a veneer that caps hilltops, and deeply eroded deposits with no distinctive topographic expression. Fluvial (channel) sediment up to 60 feet thick.

Tc Chadron Formation: The Chadron Formation consists of two members a lower light-colored sand with quartzite and porphyry (Chalky Buttes Member) and an upper, dark-colored smectitic clay (South Heart Member).

Chalky Buttes Member – White to yellowish gray conglomeratic sandstone. The sandstone varies from a conglomeratic sandstone to a sandy, pebbly mudstone. Pebbles are predominantly quartz but also include volcanic porphyry. Exposures limited to topographic highs in the map area. Unconformably overlies the Golden Valley Formation. Fluvial sediment less than 25 feet thick.

South Heart Member –Grayish tan to gray, swelling claystone and mudstone. Generally silicified within the map area and locally pebbly. The silicified unit is well indurated, highy fractured, typically forms vertical faces in outcrops, and is only a few feet thick in this area.

Tgv Golden Valley Formation: The Golden Valley Formation consists of two dissimilar members, described below. Although not mapped separately, the distinctive Taylor Bed silcrete –which often marks their contact– has been mapped. Exposures stratigraphically above the silcrete belong to the Camels Butte Member, those below to the Bear Den Member.

Camels Butte Member – Yellowish brown, micaceous, illitic and montmorillonitic siltstone, claystone, and sandstone. Well-indurated sandstone beds increase in thickness and number upsection, and are associated with local intraformational conglomerate and intraformational pebbly sandstone. Contains several, thin, discontinuous lignite beds, some of which have been silicified. Mostly fluvial sediment as much as 200 feet thick.

Bear Den Member – Light gray to bright white kaolinitic strata often divisible into 3 stratigraphic units: basal gray zone, middle orange zone, and a thin upper carbonaceous zone. The contacts between these zones are normally gradational. This tripartite division is locally replaced by a bright white, kaolinitic, fine to medium grained silty sand. Often forms steep, sparsely vegetated slopes. Mostly fluvial sediment, which is 15 to 30 feet thick in the Dickinson area. Formed as a weathering horizon on the Sentinel Butte Formation.

Carbonaceous Zone –Dark gray to brownish gray, thinly bedded to laminated mudstone, siltstone, and carbonaceous shale. The top of this zone is marked by the Alamo Bluff lignite or its lateral equivalent, the Taylor Bed silcrete. Typically less than 3 feet thick.

Orange Zone –Light gray to bright white massive clay; locally thin bedded and silty. Small limonite concretions in the upper part impart characteristic orange stains. Joints are common and are filled with gypsum and limonite, creating a polygonal pattern on surface exposures. Locally replaced by a bright white, kaolinitic, fine to medium grained silty sand. Typically 10 to 15 feet thick.

Gray Zone –Light to medium gray siltstone, mudstone, and fine to medium grained sandstone. Crossbedded to parallel bedded; locally massive. Typically 3 to 6 feet thick.

Tsb Sentinel Butte Formation: Gray to brown, variably lithified siltstone, mudstone, claystone, sandstone, and lignite. Calcite-cemented sandstone and mudstone concretions are common, as are siderite nodules. In this area, the contact with the Golden Valley Formation appears conformable and gradational. Fluvial, lacustrine, and swamp sediment that forms gentle, vegetated slopes. Only the upper 200 feet of the formation are exposed.

Geological Symbols

- Contact. Exposed or visible on 1:20,000 scale aerial photographs
- Approximate contact. Based on scattered exposures of the Bear Den Member or Taylor Bed, or where the contact with Quaternary units shows poor topographic expression
- Very approximate contact. Poorly constrained by very widely scattered exposures
- Taylor Bed
- Taylor Bed: Solid dot indicates small exposure
- Taylor Bed: Open circle indicates lag deposit of Taylor Bed silcrete let down by erosion of underlying beds
- Glacial erratics
- Collapse hole
- Area known to overlie abandoned underground lignite mine

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0 2 4
Miles

0 2 4
Kilometers

SCALE 1:62,500

1 inch represents approximately 1 mile
Lambert Conformal Conic Projection
Standard Parallels at 46°57'30" and 46°47'30"

N W E S

Cartographic Compilation by:
Ryan P. Waldkirch
North Dakota Geological Survey
Geologic Investigation No. 1
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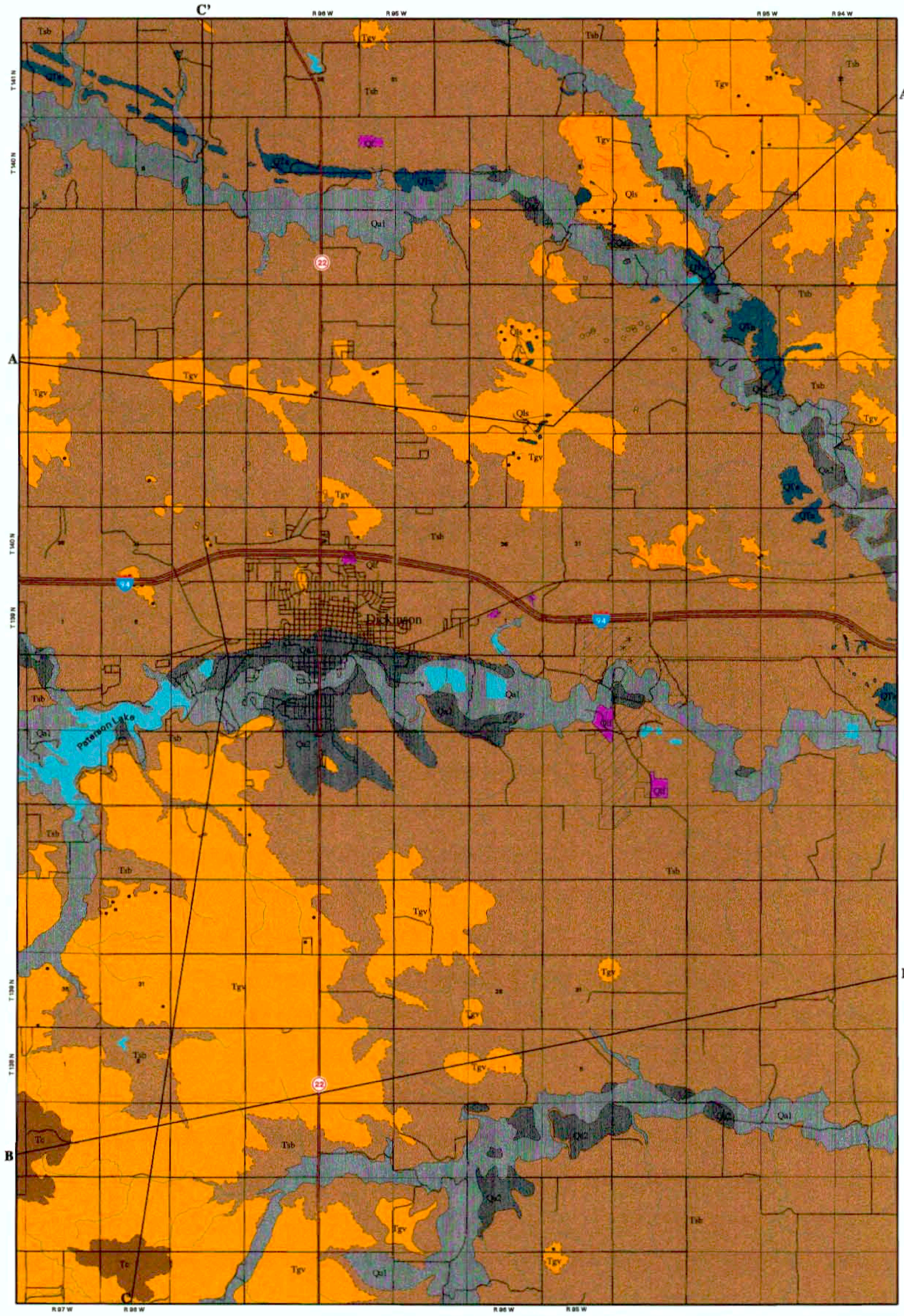

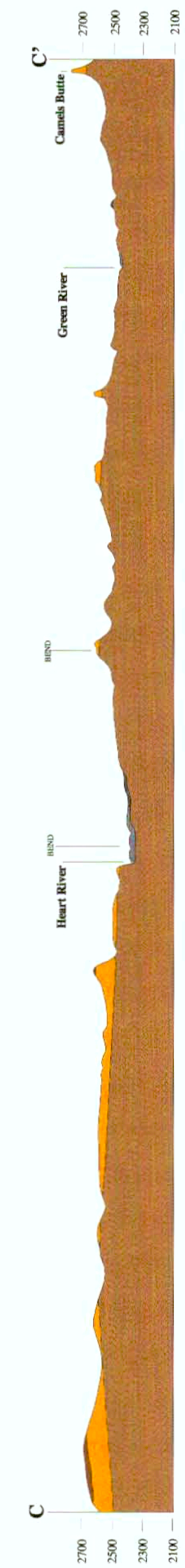

Dickinson Area, North Dakota

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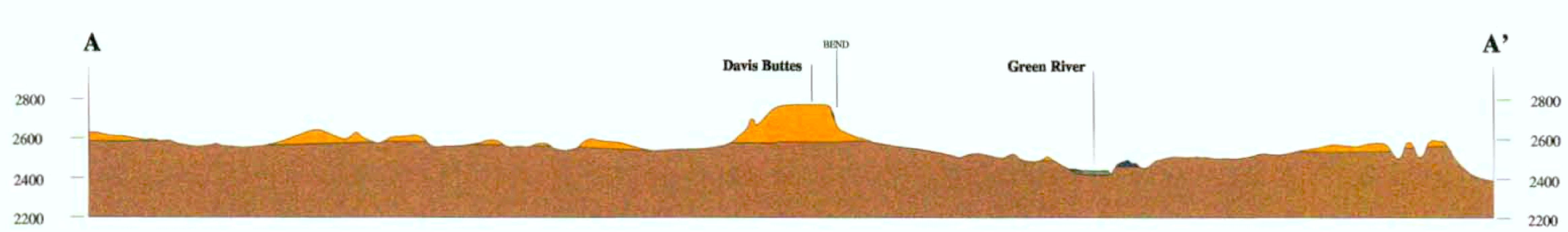
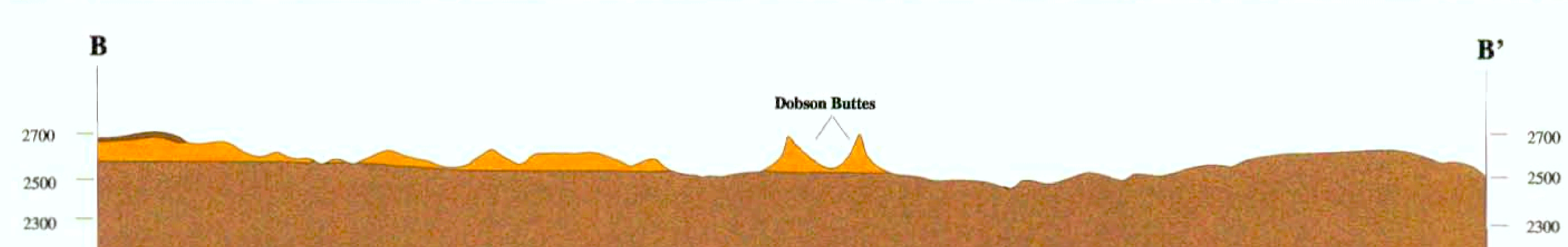




Map Explanation

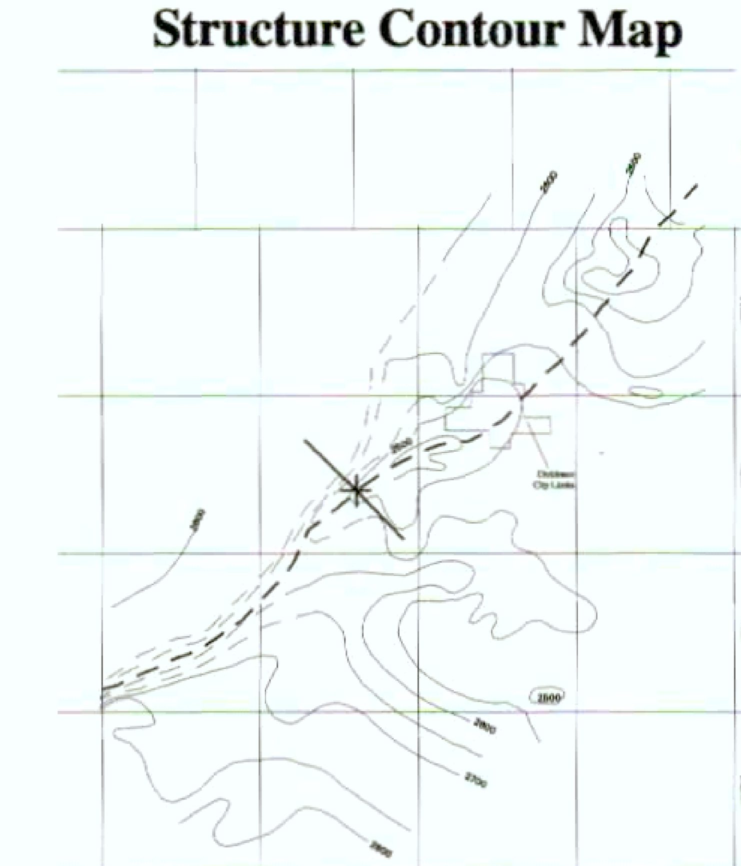
This map displays the surface geology of the greater Dickinson area. The map portrays both Tertiary–age bedrock units and unconsolidated deposits of Quaternary age; it emphasizes geologic units that directly underlie the soil horizon, and so complements existing soil maps. Dickinson lies in the Missouri Slope Uplands physiographic region of southwestern North Dakota. The surface geology of this region is characterized by flat lying to very gently folded Fort Union, White River, and Arikaree strata (Paleocene to Miocene) and Pleistocene to Holocene alluvial and landslide deposits. Widely scattered erratic boulders are believed to mark the southwestern limit of glacial ice in this part of North Dakota.

The Sentinel Butte Formation (Paleocene) is the oldest bedrock unit exposed in the mapped area. It, as well as the overlying Golden Valley Formation (Paleocene to Eocene), is characterized by siltstone, claystone, and sandstone deposited in river, floodplain, and swamp environments. The Sentinel Butte Formation in particular contains numerous lignite beds, at least two of which have been mined in the area. The Chadron Formation (Eocene) unconformably overlies the Golden Valley Formation in the southwest portion of the map area. It consists of pebbly conglomerate and sandy mudstone deposited in river and floodplain environments, and swelling claystone deposited in lacustrine settings.

Geologic hazards in the greater Dickinson area can be grouped into five main categories: 1) mass wasting processes, such as landslides, soil creep, and swelling soils; 2) erosion, such as that associated with river banks and the shoreline of Patterson Lake; 3) flooding; 4) hazards associated with poor quality groundwater; and 5) man–made hazards such as those associated with landfills, oil drilling reserve pits, abandoned sand and gravel pits, and underground mines. The principal near–surface mineral resources in the greater Dickinson area are sand and gravel, clay, and lignite. While significant clay and lignite resources remain, only sand and gravel is now being mined. Most sand and gravel pits are located along the Green and Heart Rivers in deposits mapped as QTa and Qa2.

This map is the result of fieldwork during the summer of 1994. Mapping was done on 1:24,000 scale topographic base maps with the aid of aerial photographs taken in 1965 (1:20,000) and 1991 (1:41,000). The map is compiled and reduced from the original 1:24,000 scale geologic maps of the Davis Buttes, Dickinson North, Dickinson South, and Lehigh 7.5 minute quadrangles. These more detailed maps (reproduced as blueline copies with a 1:24,000 scale topographic base) and accompanying technical geologic report are available as NDGS Open–File Report 95–1.

Structure Contour Map



This map shows the altitude and structure of the Bear Den Member of the Golden Valley Formation. The contours reveal a gently folded Northeast trending syncline. Contour interval 50 feet. See NDGS Open File Report 95-1 for 1:24,000 scale version and control points.

Correlation of Map Units