THE GEOLOGY OF THEODORE ROOSEVELT NATIONAL PARK

Billings and McKenzie Counties, North Dakota

By

Robert F. Biek

and

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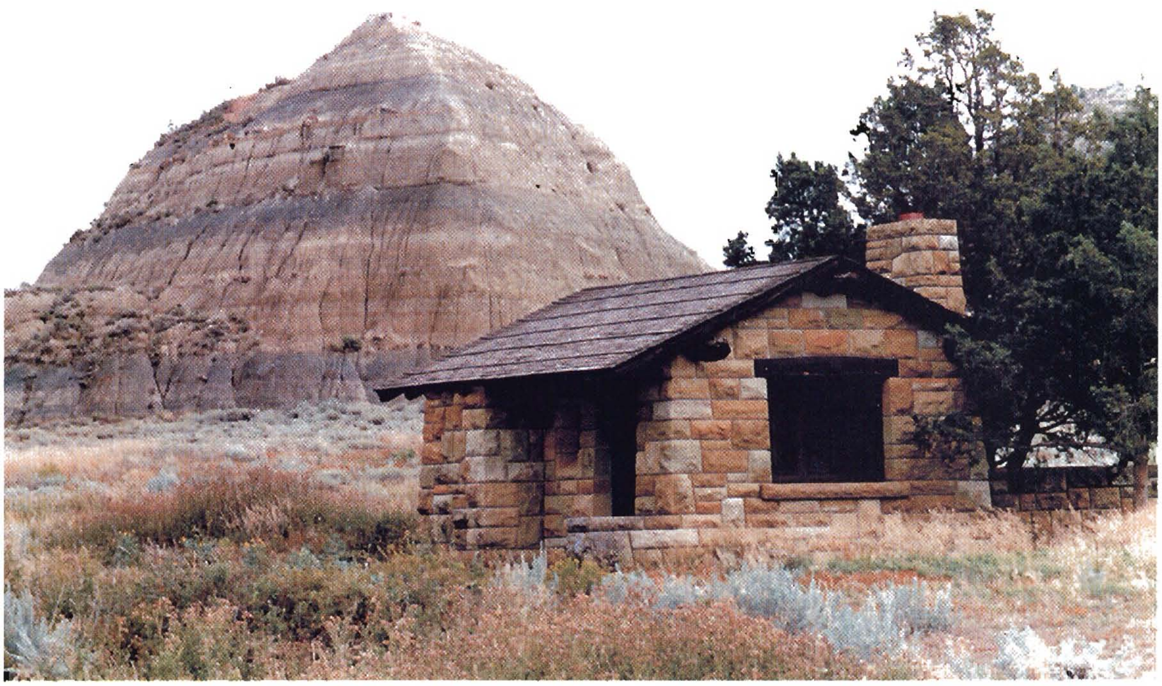

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North Dakota Geological Survey
John P. Bluemle, State Geologist
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R.F. Biek and M.A. Gonzalez North Dakota Geological Survey 2001 M.S. 86

Cover Photo: The old South Unit entrance station, west of Peck Hill, was completed in 1938 by the Emergency Relief Association. The building, and an adjacent stone fence and privy, are built with sandstone blocks probably quarried from nearby Sentinel Butte or Bullion Creek strata. The building lies on a mantled pediment surface. Nearly horizontal lower Sentinel Butte strata are visible in the distant hill.

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Conversions and Equivalents

Measurements were made and are given here in English units, because the topographic base map and the discharge data are given in English units. Metric conversions and equivalents are provided below for those unfamiliar with English units or desiring metric values.

Length	Area	Discharge
1 ft = 0.3048 m	1 ac = 0.4047 ha	1 ft^3/sec = 28.32 liters/sec = 0.0283 m^3/sec
1 mi = 5280 ft = 1.609 km	1 mi^2 = 640 acres = 259 ha = 2.590 km^2	

ACKNOWLEDGMENTS

This mapping project was a cooperative venture between the North Dakota Geological Survey, U.S. Geological Survey, and the National Park Service, and was made possible in part through a USGS-administered National Geologic Mapping Act Statemap grant. Fieldwork was undertaken from July to October 1995 and the resultant maps and report released in June 1996 as NDGS Open-File Report 96-1.

This report was reviewed by North Dakota Geological Survey geologists John Bluemle, Ed Murphy, and John Hoganson, and by Bruce Kaye, Chief Naturalist at Theodore Roosevelt National Park, and is better for their efforts. Former Northern Illinois University colleague Donald L. Clark helped measure the section on the west side of the Petrified Forest Plateau. Special thanks go to the staff at Theodore Roosevelt National Park for providing housing and other logistical support.

ABSTRACT

This report and the accompanying 1:24,000-scale geologic maps of Theodore Roosevelt National Park summarize the surface geology of the Park. The maps show the distribution of Tertiary-age bedrock and unconsolidated deposits of Quaternary age; they emphasize geologic units and sediment types that directly underlie the soil horizon and so complement soil maps of the area.

Strata of the Paleocene Fort Union Group are exposed throughout the North and South Units of Theodore Roosevelt National Park. The Fort Union Group comprises intercalated sandstone, mudstone, shale, bentonite, lignite, and clinker. In the South Unit, the Fort Union strata are divided into the Bullion Creek and the Sentinel Butte Formations (ascending order). In the North Unit, 760 feet of Sentinel Butte strata, representing a nearly complete section of the formation, crop out; neither its lower nor upper contacts are exposed. The Bullion Creek/Sentinel Butte contact plunges beneath the surface just south of the North Unit, between Bennett and Corral Creeks. The upper contact, with the Golden Valley Formation, is also not exposed in the North Unit. There the Achenbach Hills are capped with a lag deposit of large silcrete blocks that clearly belong to the Taylor bed of the Golden Valley Formation, but the underlying, characteristically bright white, poorly vegetated, comparatively thin Bear Den Member is absent.

The most widespread, easily recognizable beds within the Bullion Creek and Sentinel Butte Formations include the HT Butte lignite and HT Butte clinker, the basal sandstone of the Sentinel Butte Formation, the petrified wood horizons, the Sentinel Butte tuff/bentonite (or "blue") bed, and the upper and lower yellow beds. The HT Butte beds mark the contact between the Bullion Creek and Sentinel Butte Formations. A prominent, thick, laterally persistent sandstone marks the base of theSentinel Butte Formation throughout the map area. Above this are two (sometimes only one) horizons containing abundant fossil remains of petrified wood. The Sentinel Butte tuff/bentonite bed is prominent in the North Unit, where it reaches a thickness of 25 feet. The upper and lower yellow beds are each about 15-30 feet thick. They are prominent light yellowish brown, ripple cross-stratified siltstones in the Sentinel Butte Formation.

No faults were found in either the North or South Units during this mapping project. Scores of small offsets are found in basal Sentinel Butte strata throughout the South Unit, but these are invariably related to slumping over burned out portions of the HT Butte and other lignites. Structure contours on the base of the HT Butte clinker and the base of the Sentinel Butte tuff/bentonite demonstrate that these Paleocene units dip gently to the east and northeast at about 100 feet every 2-3 miles (about 0.2°) and are gently warped locally.

Considerations of landscape development and comparisons with clinker development in the Powder River Basin indicate that although the HT Butte clinker forms a continuous surface over much of the South Unit, it likely formed by a number of comparatively small, discrete burns, the latest of which was the Buck Hill burn of 1951 to 1977.

Sand and gravel of local and southwestern affinity and indeterminate late Tertiary-Quaternary age (map unit QTa) have been mapped in both the North and South Units. In the South Unit, these deposits occur as a veneer capping the Petrified Forest Plateau and the unnamed plateau to the south across Knutson Creek. In the North Unit, similar but highly dissected deposits with no distinctive topographic expression are found at Sperati Point. Erratic boulders are found scattered over the sand and gravel at Sperati Point, suggesting that these fluvial deposits pre-date the advance of ice into the area. Quaternary-age sand and gravel deposits (Qt) are inset beneath the QTa deposits and represent alluvium that accumulated below mid- to late Quaternary terrace surfaces formed by the ancestral Little Missouri River.

Holocene alluvial deposits are common along the Little Missouri River and its tributary streams. These deposits are crudely divided into Qoal (older Holocene alluvium), Qal (recent Holocene alluvium), and Qf (fan deposits). Qal encompasses alluvium less than approximately 500 years old, which corresponds to the alluvium of the modern flood plain and the lowest Holocene terrace.

Landslides (Qls) are widespread in both the North and South Units. They range in size from small rotational slumps, debris flows, slumps, and rock falls, to large complex rotational slumps that span areas up to a square mile in size. Most landslides occur in Sentinel Butte strata, perhaps because in the Park these beds tend to form steeper, more barren slopes than underlying Bullion Creek strata. In the North Unit, between the east entrance and Juniper Campground, several landslides are characterized by large coherent blocks with beds dipping into the hillside at 25° to 50°. The presence of undisturbed, horizontal Sentinel Butte strata at the toe of these blocks clearly shows that these blocks were emplaced by rotational slumping, and not by faulting as some have speculated.

INTRODUCTION

Theodore Roosevelt National Park lies in the Little Missouri Badlands physiographic region in southwestern North Dakota *(fig. 1)*. The Park is divided into North (24,070 acres) and South (46,160 acres) Units, between which lies the Elkhorn Ranch (220 acres) site. The geology in all units is characterized by flat-lying to gently warped **sedimentary rocks** of the Fort Union Group (Paleocene) and late **Tertiary-Quaternary** alluvial and **landslide** deposits. Widely scattered **erratic** boulders in the North Unit mark the southwestern limit of **glacial** ice in this part of North Dakota. A lag deposit of large **silcrete** blocks from the Taylor **bed** of the Golden Valley Formation is present in the Achenbach Hills of the North Unit.

The Fort Union Group is divided locally into the Paleocene-**age** Bullion Creek and Sentinel Butte Formations (ascending order) *(fig. 2)*. These **formations** are characterized by poorly **lithified siltstone, claystone, sandstone**, and **lignite** deposited in river, flood-plain, and swamp environments. Both **bedrock** units form **badlands topography**.

In the South Unit, the **contact** between the Bullion Creek and Sentinel Butte Formations is marked by the HT Butte **lignite** or the HT Butte **clinker**, where the **lignite** has burned. A structure contour map on the base of the **clinker** shows that this unit generally dips gently to the east-northeast at about 100 feet every 2-3 miles (about 0.2°). The **contact** plunges beneath the surface just south of the North Unit, between Bennett and Corral Creeks. A structure contour map on the base of the Sentinel Butte **bentonite** in the North Unit reveals a similar very gentle northeast **dip**.

Mineral resources in and around the Park include oil and gas, **lignite**, sand and gravel, **clinker**, **clay**, and stone. **Lignite** was mined at the now abandoned High Grade Coal Mine immediately east of Medora. Several abandoned sand and gravel and **clinker** pits are present in the Park. The North Unit, South Unit, and the Elkhorn Ranch site are surrounded by oil and gas fields; at the South Unit, inclined and horizontal wells in the Fryburg Field underlie the southeastern corner of the Park.

Geologic hazards in Theodore Roosevelt National Park can be grouped into six main categories: 1) **mass-wasting** processes, such as **landslides** and **soil creep**; 2) swelling **soils**; 3) **erosion**, including river-bank erosion, gullying, **sheet wash**, and **piping**; 4) flooding; 5) burning **lignite beds**, and 6) man-made hazards, such as those associated with collapse of underground **lignite** mines.

Methods

The accompanying geologic maps of the North and South Units (Plates I and II) are the result of fieldwork from July to October 1995*. Initial mapping was done directly on 1:20,000-scale black-and-white **aerial photographs** taken in 1958 (North Unit and Elkhorn Ranch site) and 1957 (South Unit); color infrared, 1:63,260-scale **aerial photographs** taken in 1983 were also used. Geologic **contacts** were then transferred to 1:24,000-scale topographic base maps. In all, 41 days were spent in the field, resulting in an average mapping rate of 2.7 square miles per day. Final field checks and revisions were completed in October 2000 and April 2001.

Color descriptions for map units and samples generally follow those of the Geological Society of America's Rock-Color Chart (Goddard et al., 1979), except where less precise descriptions are needed. Grain-size classification follows that of the Udden-Wentworth scale. Figure 3 explains Township, Range, and Section designations.

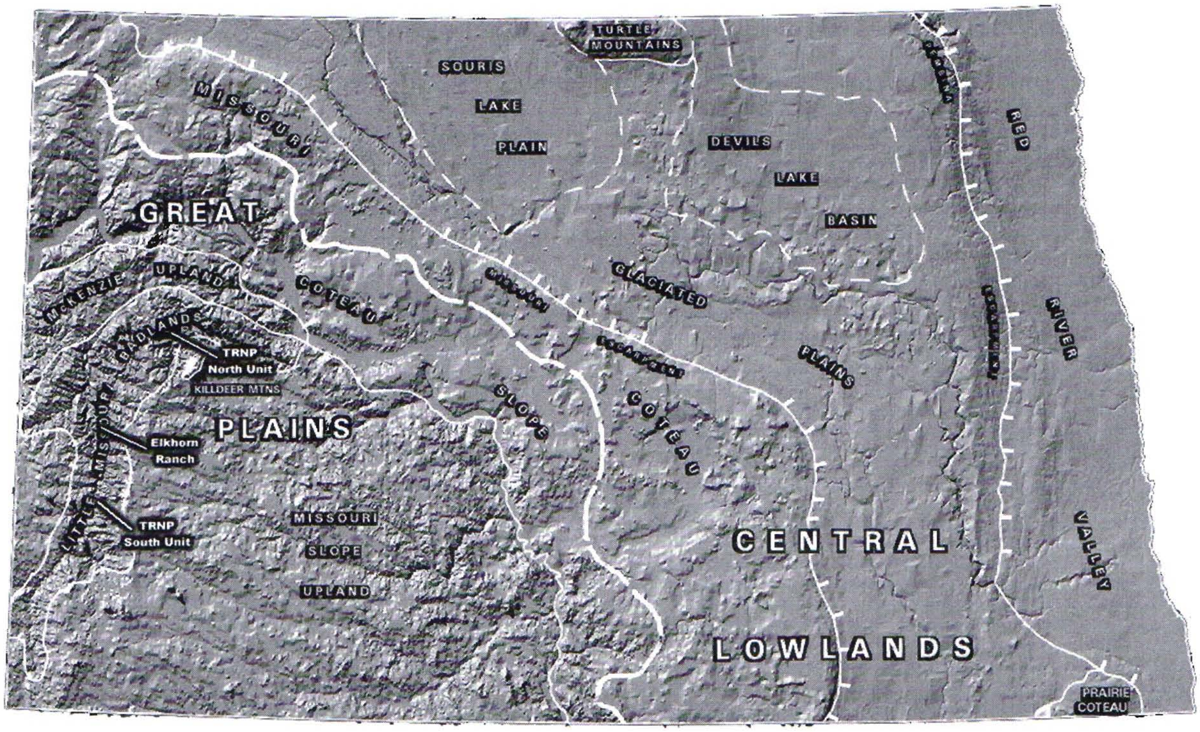
Previous Geologic Investigations

Because the **badlands** offer unparalleled exposures in North Dakota, and also due to the area's scenic beauty, Theodore Roosevelt National Park has been the focus of numerous geological investigations. Other geological reports, whereas they may mention the Park in a cursory manner, are important instead for the regional geological framework that they provide. These investigations are cited under appropriate sections of this report. Geologic maps of the Park are summarized separately below.

Geologic Maps

The geology of the Park is portrayed in several maps. Clayton and others published the 1:500,000-scale state geologic map in 1980. Clarence G. ("Kelly") Carlson provided the first intermediate-scale geologic maps of the South Unit (1983), Elkhorn Ranch Site (1983), and North Unit (1985) in his larger study of Billings, Golden Valley, McKenzie, and Slope counties. Those maps - published at a scale of 1:125,000 on a simplified planimetric base - focused on the distribution of **Tertiary bedrock** units. Aside from their differences in scale, and thus detail, one of the principal differences between these maps is that

* The Elkhorn Ranch site, which borders the west side of the Little Missouri River midway between the North and South Units, was not mapped as a part of this study. Inspection of aerial photographs show that much of the site lies on upper level flood-plain sediments mapped elsewhere as modern alluvium (Qal). Sentinel Butte strata crop out in the bluffs to the west.



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 landscape that resulted from collapse of superglacial sediment.

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 landscape 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.

Figure 1. Map showing major physiographic regions of North Dakota. Even though landforms of considerable variation occur within each region, overall internal similarities make it possible to generalize about the geomorphic processes that operated to shape each region (modified from Bluemle, 2000).

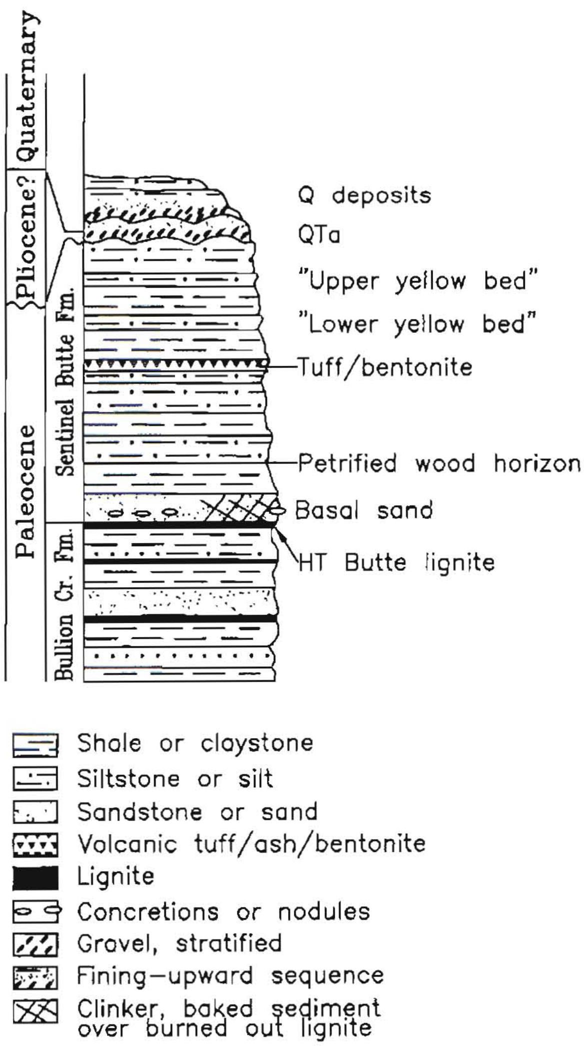


Figure 2. Stratigraphic column showing nomenclature used in this report.

strata of the Golden Valley Formation do appear in the Achenbach Hills on the state geologic map, but not on the county map.

With regard to the Little Missouri Badlands, earlier geologic maps of North Dakota, done at a more generalized scale of 1:1,000,000, reflect the evolution of the Fort Union stratigraphic nomenclature. The first two 1:1,000,000-scale geologic maps of the state (Hansen, 1952 and 1956), show the entire Park to consist of one **formation**, the Tongue River Formation. It was not until 1969, two years after the seminal report of Royse (1967), that Clarence Carlson produced a **bedrock** geologic map of the state that differentiated the Sentinel Butte and Tongue River Formations. Subsequent geologic maps of the state have refined this and other **contacts**, but because of limitations of scale, these maps show only the generalized distribution of map units. On such maps, the Park itself covers less than one square inch; obviously, these mapmakers were constrained as to what they could show.

Leonard (1906) produced a simple, page-size geologic map of the state to accompany North Dakota Geological Survey Biennial Report No. 4, a report about the **clays** of North Dakota. The entire western portion of the state was mapped as Laramie and Fort Union **strata**, including undifferentiated **Tertiary formations**. The map of Leonard (1917) shows Cretaceous and lower **Tertiary** (?) **strata** of the basin margin in southwestern and south-central North Dakota; the Fort Union Formation covers much of the western part of the state, including the Park.

University of North Dakota student, Charles Petter (1956), studied the **badlands** along the north-trending stretch of the Little Missouri River in North Dakota. He, like Laird (1950) and fellow student Schmitz (1955), divided the landscape into a sequence of five "**terraces**," which are discussed in the geomorphology section of this report.

Howard (1960) provided a 1:316,800-scale map of the **glacial** geology of northeastern Montana and northwestern North Dakota, including the North Unit of Theodore Roosevelt National Park, on which he mapped the general extent of early Wisconsinan (?) drift. Other geologic maps (e.g., Clayton et al., 1980; Bluemle, 1988) also show the extent of this drift, evident in the North Unit as widely scattered **glacial erratics**.

University of North Dakota student, Michael Clark (1966), produced a geologic map of the Sperati Point 7.5′ quadrangle, which includes the western part of the North Unit (the map was drawn at 1:12,000-scale on a simplified planimetric base).

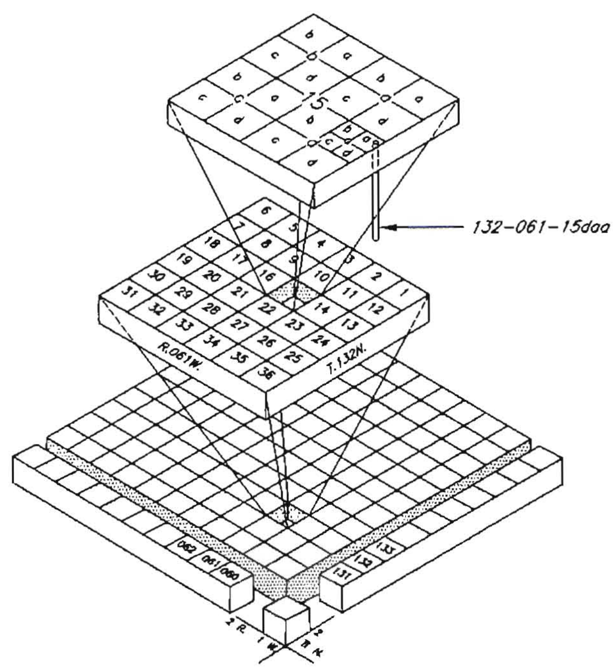


Figure 3. System of numbering outcrop locations.

Whereas earlier workers noticed some of the subtle differences between what are now known as Bullion Creek and Sentinel Butte **strata**, it was University of North Dakota student, Chester Royse (1967), who convincingly argued that these **strata** are deserving of formational status. He mapped the **contact** between the Tongue River [Bullion Creek] and Sentinel Butte Formations in southwestern North Dakota at a scale of about 1:410,000.

Hickey (1977) mapped the distribution of Golden Valley **strata** in western North Dakota at 1:250,000-scale as part of his classic treatise on these Paleocene/Eocene **beds**. He, like others, mapped Golden Valley **beds** atop the Achenbach Hills in the North Unit. The Taylor **bed silcrete**, the upper unit of the Bear Den Member of the Golden Valley Formation, is present as a lag deposit in the hills, but, as described elsewhere in this report, it appears to rest on Sentinel Butte, not Bear Den, **strata**.

In his study of the geochemistry of the Sentinel Butte **tuff/bentonite**, University of North Dakota student, Richard Larsen (1988), mapped the Sentinel Butte **tuff/bentonite** in the North Unit and surrounding area. This marker **bed** was mapped at 1:24,000-scale and recompiled at about 1:42,000-scale on a simplified planimetric base. Larsen mapped the **bed** in sections 148-99-27, -28, and -33 at the east end of the North Unit. The underlying gray **mudstone** is present in this area, but the **bentonite** itself appears to pinch out in section 148-99-32a.

Bluemle and Jacob (1973, 1981) and Murphy et al. (1993) included a simplified, postcard-size geologic map of the South Unit in their guidebooks. Bluemle (1980) provided a generalized geologic map (about 1:500,000) of southwestern North Dakota to accompany his popular guidebook.

Kuehn (1995) mapped **Quaternary landforms** in parts of the South Unit in support of geoarchaeological studies in the Little Missouri Badlands. He included planimetric maps (scales about 1:15,750, 1:23,600, and 1:31,500) of **terraces** in 19 areas in the South Unit and a detailed chronology of the Park's late **Quaternary** geology. Kuehn identified four **Pleistocene** and four **Holocene terrace** levels above modern river-channel deposits and correlated them throughout the Park.

STRATIGRAPHY

Bullion Creek Formation

The Bullion Creek Formation consists of up to 600 feet of **lignite**-bearing, poorly **lithified**, bright yellowish brown **siltstone**, **claystone**, and **sandstone**, deposited in **fluvial**, **lacustrine**, and **paludal** environments of a lower delta plain (Jacob, 1976). These **strata** take their name from Bullion Creek in southern Golden Valley County. Clayton et al. (1977) assigned the name to resolve problems of correlating Paleocene **strata** between North Dakota and adjacent South Dakota and Montana. Clayton et al. (1977, p. 9) succinctly outlined the morass in nomenclature, known as the "Tongue River problem", created by the difficulties of correlation:

> *"The Slope Formation and the Sentinel Butte Formation are both drab-colored units that are separated from each other by a bright-colored unit. Leonard (1908) and Leonard and Smith (1909) were perhaps the first to recognize this bright-colored unit in North Dakota; they referred to this unit as "middle Fort Union." Thom and Dobbin (1924) correlated it with the "Tongue River member" of the "Fort Union Formation" in the Powder River basin for the following reasons: both units are about the same age, both have a similar lithology, both are generally bright colored, both are underlain by drab-colored units, and both were thought to be overlain by Eocene beds. "Tongue River" was the generally accepted name for the bright-colored unit in North Dakota until Brown (1948) showed that the Sentinel Butte Formation is Paleocene, not Eocene. The Sentinel Butte was then reduced in rank, and both it and the unnamed, bright-colored unit were considered to be members of the Tongue River Formation (Hansen, 1956). Later, Royse (1967) argued that the Sentinel Butte is mappable and should be re-elevated to formation rank. He recommended that the "Tongue River Formation" in North Dakota be restricted (again) to the bright-colored beds under the Sentinel Butte Formation."*

Between 1967 and 1977, most North Dakota Geological Survey reports of the Little Missouri Badlands refer to these bright-colored **beds** as Tongue River Formation. Earlier, from about 1948 to 1967, they were considered an unnamed lower subdivision of the Tongue River Formation. Clayton et al. (1977) showed that these bright-colored **beds** appear to be only part of the **strata** mapped as Tongue River Formation in South Dakota or Tongue River member of the Fort Union Formation in Montana. The names Bullion Creek Formation and Slope Formation are now used in North Dakota to avoid using different criteria in defining the Tongue River in different areas.

Jacob (1972) recognized four basic lithologic types in Tongue River (Bullion Creek) **strata**, arranged from top to bottom in an idealized cyclic sequence (*fig. 4*):

1. Sand. Includes linear and tabular sand bodies believed to represent river channel and point-bar deposits;

2. Yellow silt and sand that may be clayey. Ripple

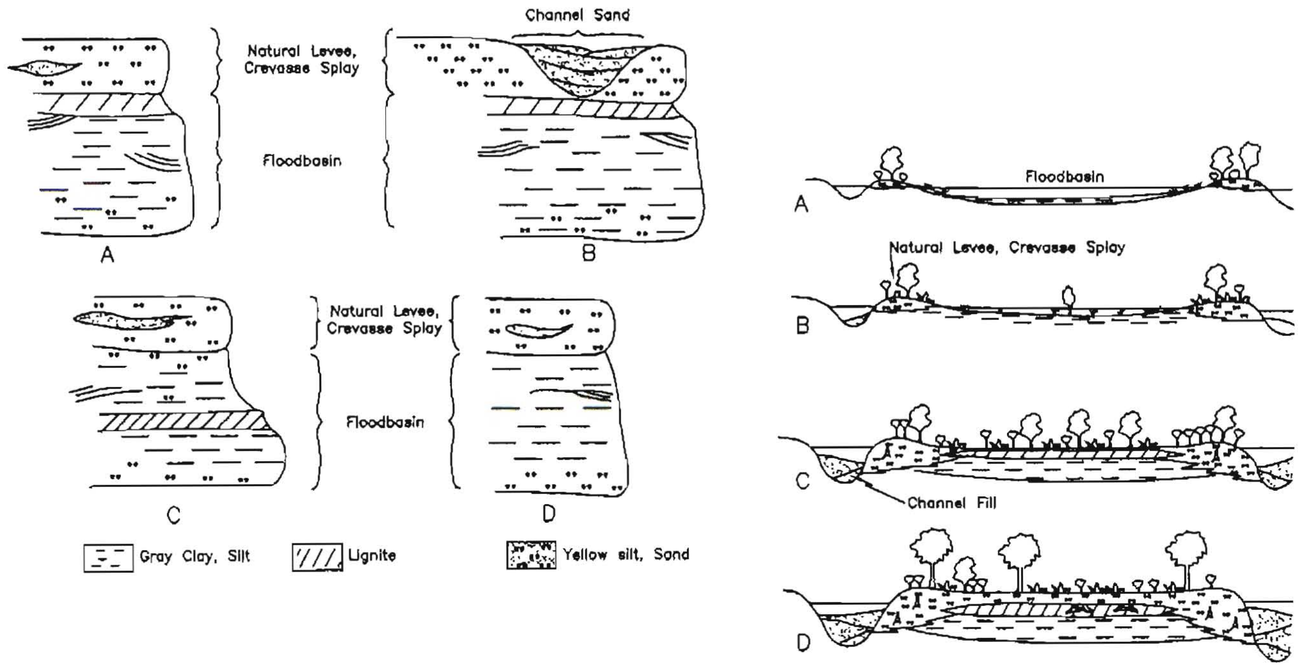


Figure 4. Basic cyclic unit of the Bullion Creek Formation (A, upper left; B-D show variations of basic unit). Also shown at right is a model for the origin of the basic cyclic unit (from Jacob, 1972).

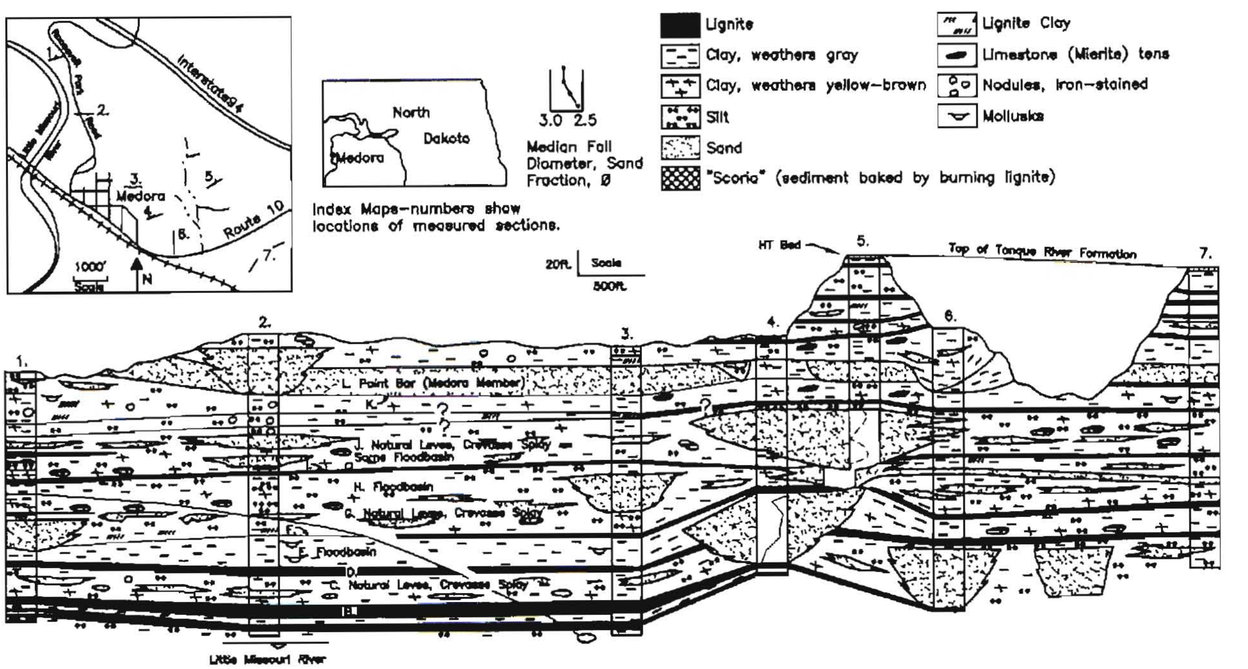


Figure 5. Cross section of Bullion Creek strata exposed in the cliffs near Medora. Horizontal scale distorted between measured sections 4 and 6 (from Jacob, 1972).

stratification and iron **concretions** are common. Thin, isolated lenses of laminated, argillaceous micritic limestone are present. Represents natural levee and crevasse-splay deposits;

3. **Lignite**; and

4. Gray **clay** and silt. Commonly lignitic and fossiliferous. Represents flood-basin deposits.

The thickness and completeness of these cyclic sediment packages are diverse, as suggested by Figure 4.

Jacob (1972) also provided a cross-section of Tongue River (Bullion Creek) **strata** exposed in the cliffs above Medora *(fig. 5)*. He informally named the upper, 15- to 25-foot-thick tabular sand **bed** the Medora member. This moderately well-cemented, cliff-forming **bed** lies about 80 feet below the top of the **formation**; Jacob suggested that it could be traced for tens of miles north and south of Medora.

In the South Unit of Theodore Roosevelt National Park, Bullion Creek **strata** typically form rounded, more vegetated slopes than do **beds** of the overlying Sentinel Butte Formation *(fig. 6)*. Bullion Creek **sandstones** are fine-grained channel and tabular sand bodies. They are typically cemented and so form resistant ledges and caprock; locally they are irregularly cemented so that weathered surfaces have a pitted appearance *(fig. 7a)*. Sedimentary structures - including climbing ripples (*fig. 7b*), trough and planar cross-stratification (*fig. 7c*), burrows, and soft-sediment deformation (*fig. 7d*) - are common in Bullion Creek **sandstones**. Steiner (1978) studied the petrology of Bullion Creek **sandstones**.

Bullion Creek **siltstones, claystones**, and **mudstones** are more common than the **sandstones** described above. **Beds** tend to be thin and laterally continuous over great distances. Carbonaceous horizons, ranging from thin, discontinuous, carbonaceous **shales** to persistent, thick **lignites**, are common. Even the thicker **lignites** contain impurities, including **clay** partings, jarosite (hydrous iron sulfate), selenite, and iron-sulfide **nodules**.

Bullion Creek/Sentinel Butte Contact

Leonard and Smith (1909) were among the first to comment on what was later to be known as the Bullion Creek/Sentinel Butte **contact**. They stated (1909, p. 18):

> *"There is a very noticeable difference between the lower Fort Union beds, which outcrop in the bluffs bordering the Little Missouri River, and the upper beds, occurring in the tops of the higher ridges, divides, and buttes, usually some distance back from the river. The lower member is composed of buff and light ash-gray clays and sands in alternate layers. The upper member is formed of strata considerably darker in appearance, mostly dark gray, with many brown, ferruginous, sandy nodules and concretions. The contrast between these members is so well marked and their contact so clearly defined that it can be readily distinguished at a distance and traced without difficulty wherever it is exposed. Over the eastern half of the field a thick bed of lignite or a layer of red clay formed by the burning of the lignite occurs just at the contact of the upper and lower members."*

That explanation is as accurate today as it was more than 90 years ago, and it is surprising, given the prominence of the **contact** in the Little Missouri Badlands, that it wasn't until 1967 that the **contact** was mapped throughout southwestern North Dakota. Royse (1967) provides the

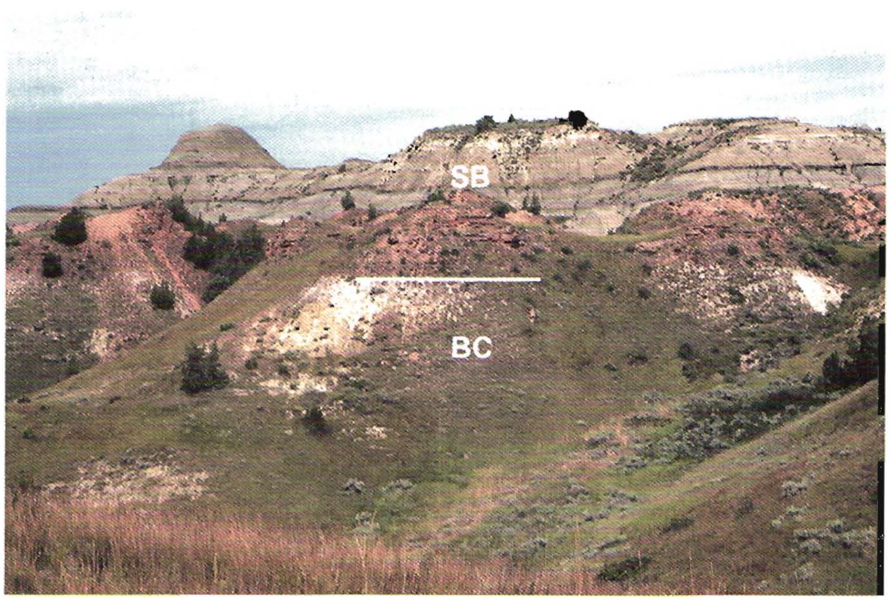


Figure 6. Contact between Bullion Creek and Sentinel Butte strata; here, the HT Butte clinker and underlying Bullion Creek beds are more heavily vegetated than the overlying Sentinel Butte Formation. (Sentinel Butte (SB) above line, Bullion Creek (BC) below line).

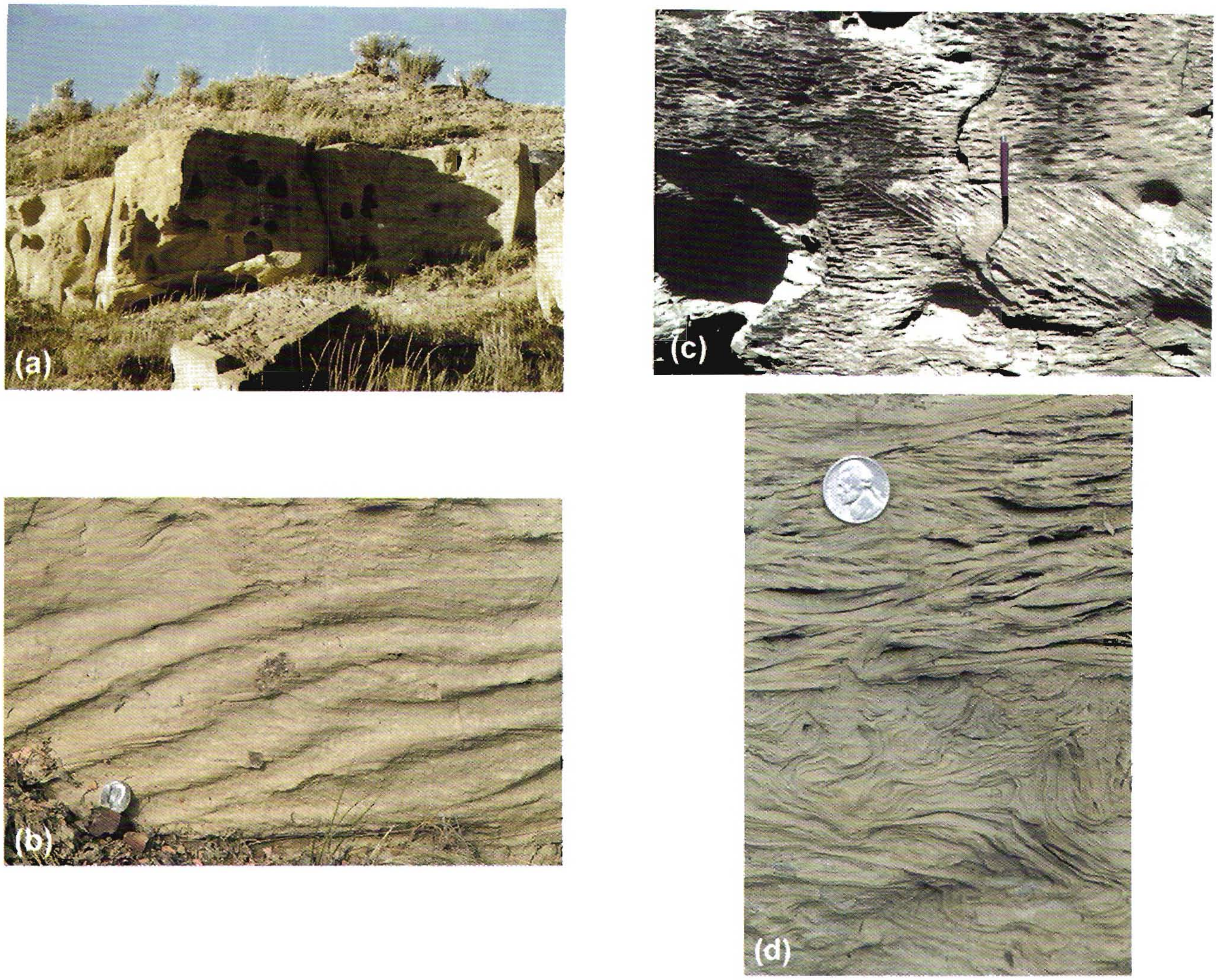


Figure 7. Features of the Bullion Creek sandstone, including (a) pitted weathering, (b) climbing ripples, (c) planar cross-beds, and (d) soft-sediment deformation.

best review to date of the **beds** enclosing the Bullion Creek/ Sentinel Butte **contact** and describes the conflicting interpretations that these similar **strata** have engendered.

The Bullion Creek and Sentinel Butte Formations are differentiated principally by color in weathered exposures. The contrast between the brighter, yellowish brown Bullion Creek **strata** and the darker grayish brown of Sentinel Butte **beds** is, like many aspects of North Dakota geology, perhaps subtle at first glance, but unmistakable once the eye has been trained to see it. The color contrast is especially prominent when seen at a distance. Even though drab-colored, gray and brown **beds** similar to those in the Sentinel Butte Formation occur in the underlying Bullion Creek Formation, and bright yellowish brown **beds** similar to those in the Bullion Creek Formation are found above the basal **sandstone** of the Sentinel Butte Formation, this gross color difference remains the best means of differentiating the two **formations** in weathered exposures. The color contrast between the two **formations** is reduced where drab-colored **beds** occur in upper Bullion Creek **strata**, or where exposures are relatively fresh and unweathered, such as in the headwall of recent **slumps**.

Other differences between the two **formations** are described by Royse (1967, 1970) and Jacob (1973, 1976). There is so much overlap between the two **formations** - in lithology, mineralogy, sedimentary structures, and other features - that no single criterion appears diagnostic. The qualifiers "generally," "usually," "much more," "most," and others sneak into every statement about the differences between the two **formations**. Within the Park, the two principal criteria useful for differentiating the two **formations** in the field are:

1. Stratigraphic position with respect to the HT Butte **lignite** or **clinker**. The HT Butte **lignite**, or more commonly the HT Butte **clinker** produced by its burning, everywhere marks the Bullion Creek/ Sentinel Butte **contact** in the South Unit. The **clinker** is the thickest and most widespread **clinker** in the South Unit.

2. Color. The color contrast between bright yellowish brown Bullion Creek **strata** and grayish brown Sentinel Butte **beds** is most apparent where substantial thicknesses of both **formations** are present. Because **beds** of similar color may appear in both **formations**, color alone may fail locally as a sole means of differentiating the two units.

Other, subtler differences useful for field differentiation of the two **formations** include:

1. Bullion Creek **strata** generally weather to more rounded, smoother, commonly more vegetated surfaces than Sentinel Butte **strata**. Steep, narrow gullies, erosional pipes, and rill **weathering** are rare on Bullion Creek **strata** but are common on Sentinel Butte **beds**.

2. **Petrified wood** is uncommon in the Bullion Creek Formation. It is widespread in Sentinel Butte **strata**, and is especially common near the base of the **formation**.

Hartman and Kihm (1995) showed the Ti4 **age** (middle Tiffanian mammalian biochron, late Paleocene) for the Bullion Creek/Sentinel Butte **contact** in North Dakota in their biostratigraphic study of non-marine molluscan and mammalian fauna of the Fort Union Group.

HT Butte Lignite

Throughout most of southwestern North Dakota, the **contact** between the Bullion Creek and Sentinel Butte Formations is marked by a carbonaceous zone, represented by **lignite**, lignitic **shale**, or both, ranging from several inches to several tens of feet thick. This interval has been known by many names in North Dakota *(Table 1)*. Since 1967, most workers have used the name HT Butte as suggested by Royse (1967).

The HT Butte **lignite** has been variously included in what are now called the Bullion Creek (Tongue River) and Sentinel Butte Formations *(Table 2)*. Royse (1967) considered the HT Butte **bed** a genetic unit of the Tongue River (Bullion Creek) Formation because it appears to represent the culmination of fine clastic sedimentation in which the development of thick **lignites** was fairly common; the thick sequence of basal Sentinel Butte **sandstone** introduced a new episode of sedimentation. Royse (1967) also noted that the thickness of the HT Butte **bed** is highly variable and that thickness alone is not an important factor in correlation of **lignite beds**.

Author	Year	Nomenclature
Leonard	1908	R
Leonard & Smith	1909	F & G
Stebinger	1912	K
Leonard et al.	1925	R
Hares	1928	HT Butte
Fisher	1953, 1954	L
Hanson	1955	L
Meldahl	1956	L
Royse	1967	HT Butte

Table 1. Synonymy of terms applied to the lignitic interval at the Bullion Creek/Sentinel Butte contact. Modified from Royse (1967).

Tongue River (Bullion Creek)		Sentinel Butte	
Royse	1967	Leonard & Smith	1909
Royse	1970	Leonard et al.	1925
Jacob	1973	Sigsby	1966
Moore	1974	Carlson	1983
Steiner	1978	Carlson	1985
Brekke	1979		
Clayton et al.	1980		
Winczewski	1982		
Larsen	1988		

Table 2. Geologic studies, which include Theodore Roosevelt National Park, showing whether the authors considered the HT Butte bed as part of the Bullion Creek (Tongue River) or Sentinel Butte Formations.

The HT Butte **lignite** has burned extensively in the South Unit, most recently from 1951 to 1977 at the "Burning Coal Vein" west of Buck Hill, where Bell and Petter (1956) noted that the **lignite** was about 12 feet thick. Throughout the Park, the HT Butte **lignite** is generally concealed by **clinker** or **colluvium**, and exposures are uncommon. The HT Butte **lignite** can be seen in 140-101-3ca in the gully on the south side of the Park road where it is about 10 feet thick; along the south side of the Petrified Forest Plateau (141-102-35), where Leonard and Smith (1909) noted the **bed** to be about 6 feet thick; in incomplete exposures on the south and west sides of the unnamed **plateau** in 140-102-16 (in 16aaa the HT Butte **bed** appears to be a 5-foot-thick carbonaceous **shale** with **lignite** stringers); and in 140-101-5bcc and 5bca (assuming a standard section, measuring from the township boundary). In a cutbank in 140-101-29daa, the HT Butte **clinker** is underlain by about 7 feet of gray **mudstone** and channel **sandstones** and a 4-foot-thick **lignite**; there the HT Butte **lignite** appears to be parted by a thin clastic wedge *(fig. 8)*. This **lignite** may be equivalent to a 3-foot-thick **lignite** exposed about 4,500 feet to the west along Sheep Creek, which lies about 30 feet below the base of the HT Butte **clinker**; between these two exposures, thick, light brown channel **sandstones** occur between the **lignite** and **clinker**.

Figure 8. Cutbank in 140-101-29daa, showing the HT Butte clinker to be underlain by about seven feet of gray mudstone and channel sandstones and, just above the creek bed, a four-foot-thick lignite. Here the HT Butte lignite appears to be parted by a thin clastic wedge.

In their study of the Sentinel Butte Lignite Field, which includes the western portion of the South Unit, Leonard and Smith (1909, Plate II) mapped the lower **coal** of the Sentinel Butte **group** (obsolete, informal name) (Coal F) in the southeastern part of 141-102, about 250 feet above the Little Missouri River. **Bed** "F" was also mapped underlying the **plateau** in 140-102-9, -10, and -16 at an elevation of about 275 feet above the Little Missouri River, and in 141-101-36. Leonard and Smith (1909, p. 30) noted that *"The lowest member of the group, bed F of the columnar section, has its greatest development in the eastern part of the field, where it is from ten to 16 feet thick. It is found at the contact of the buff sandstone and gray shale with the somber-colored member above. This contact is well marked on account of the abrupt change in the color and character of the material, and can be readily followed throughout the district where it occurs."* They noted that **bed** "F" thins to the north. Clearly, Leonard and Smith (1909) are describing the **contact** between what we now call the Sentinel Butte and Bullion Creek Formations. The "F" **bed** is thus equivalent to the HT Butte **lignite**, although the elevations given by Leonard and Smith (1909) for the "F" **bed** in the **plateau** centered in 140-102-16 are about 75 feet too low (perhaps because elevations were determined by altimeter). They mentioned, but did not map the widespread **clinker**, which lies at the same stratigraphic horizon, east of the Little Missouri River. The only widespread **clinker** in these areas is the HT Butte **clinker**.

Leonard et al. (1925) described the "F" **bed** as Coal R of the Sentinel Butte **group**. They believed it to be one of the most extensive **coal beds** in the state, ranging from 5 to 17 feet thick and covering at least 900 square miles. They noted that the "R" **bed** crops out on the south side of the Petrified Forest Plateau, and in the unnamed **plateau** to the south, across Knutson Creek. From their descriptions, it seems clear that they are referring to the HT Butte **lignite**. However, the **outcrop** elevations given are about 80 to 90 feet too low, perhaps because elevations were determined by altimeter.

Southern Methodist University student, Leonard Moore (1974), studied the palynology of the HT Butte **lignite** and the basal Sentinel Butte Formation. Although no legal descriptions are given, it is clear that at least two of his four samples are not the HT Butte **lignite**, but rather **lignite beds** lower in the section. Sample #423 ("Cottonwood Creek Section") was obtained 40 to 50 feet above the Little Missouri River and from his location map it appears to be located on the divide between Beef Corral Wash and Jones Creek. However, the HT Butte **clinker** is about 240 feet above the river there; the HT Butte **lignite** does not crop out in the bluff southeast of Cottonwood Campground, but there is a seven-foot-thick **lignite** exposed about 50 feet above the valley floor. Moore's sample #424 ("Prominent Bluff Section") supposedly came from 120-140 feet above the Little Missouri River, but based on his location map, in this area just north of the South Unit, the HT Butte **lignite/clinker** is about 240-260 feet above the river. Although he intended to characterize only the HT Butte **lignite**, Moore (1974) mistakenly compared at least three **lignites** in the upper Bullion Creek Formation.

Sentinel Butte Formation

The "Sentinel Butte coal group" was originally defined by Leonard and Smith (1909) for exposures at Sentinel Butte in Golden Valley County, North Dakota. Thom and Dobbin (1924) and Hares (1928) recognized the Sentinel Butte Shale as a member of the Sentinel Butte

Formation. In his study of the Tongue River/Sentinel Butte **contact** in western North Dakota, Royse (1967) elevated the Tongue River (now Bullion Creek) and Sentinel Butte to formational status within the Fort Union Group. He also reviewed the stratigraphic nomenclature of these early **Tertiary** deposits, noting *"Few stratigraphic intervals in the United States have been subject to greater argument, debate, and disagreement than has the late Cretaceous-early Tertiary continental sequence of the western interior"* (Royse, 1967, p. 39). (In the past, the U.S. Geological Survey has conferred formational status upon Fort Union **strata**. More recently, however, they have left the decision of member or formational status to authors.)

Jacob (1976) stated that the Sentinel Butte Formation comprises up to 600 feet of gray to brown **siltstone**, **claystone**, **sandstone**, and **lignite** that was deposited in river, lake, and swamp environments. As in the case of other early **Tertiary** sediments in North Dakota, most individual **beds** are not well cemented. The well-cemented **beds** that are present typically are channel **sandstones** that, because they are harder than enclosing sediments, often form resistant ledges and caprock on buttes.

A nearly complete section of Sentinel Butte **strata** crops out in the North Unit, where it is in excess of 750 feet thick; only about the lower 300 feet crop out in the South Unit. Sentinel Butte **strata** consist of generally poorly **lithified** gray to brown **mudstone**, **siltstone**, **claystone**, **sandstone**, and **lignite**. Isolated, well-cemented, cross-bedded, channel **sandstones** are common. Calcite-cemented **sandstone** and **mudstone concretions**, locally highly jointed and partially filled by drusy calcite, are also common, as are siderite (iron carbonate) **nodules**.

The Sentinel Butte Formation is the most widespread near-surface **Tertiary formation** exposed in North Dakota, and it is the most widespread unit in the Park as well. We mapped several marker **beds** in the Park, including the HT Butte **clinker**, Sentinel Butte **tuff/bentonite**, and the lower yellow **bed** (see *fig. 2*).

HT Butte Clinker

The HT Butte **clinker**, formed by burning of the underlying HT Butte **lignite**, is the most widespread **clinker** in the South Unit. It encircles the Petrified Forest Plateau and the unnamed **plateau** south of Knutson Creek, and crops out on the divides east of the Little Missouri River to points where the HT Butte **lignite** dips below the surface. The HT Butte **clinker** reaches a thickness of 30 to 40 feet along many exposures, but can thin to an eroded, feather edge where it caps small isolated hills and ridges *(figs. 9, 10)*. A thin layer of white **ash**, mostly potash, lime, and other inorganic, incombustible materials, is found at the base of the **clinker**. The **clinker** doubtless formed by a number of comparatively small, discrete burns, the latest of which was the Buck Hill burn of 1951 to 1977. A structure contour map on the base of the **clinker** in the South Unit shows it to **dip** gently to the northeast at about 100 feet every 2-3 miles (0.2°).

Clinker is a collective term for a variety of rock types produced by the burning of **coal beds**. It ranges from only slightly baked sediments, in which original sedimentary textures and structures are still preserved, to a glassy slag *(fig. 11)*. In between, one can see progressively altered baked sediments, or vesicular, frothy, brecciated masses reminiscent of true volcanic **scoria**, or even very hard, fine grained, conchoidal fractured rock known as porcellanite. **Clinker** is normally red in color, but varies from black to the palest pink depending on the characteristics of the original sediment and degree of oxidation or reduction achieved during burning. Because the two rock types can appear similar, **clinker** is known locally as **scoria**; **clinker**, however, is not of volcanic origin.

Clinker is common in all western states where **beds** of **coal** crop out, and it is a major factor in the development of the North Dakota **badlands**. Where **lignite** is exposed by **erosion** it commonly ignites from external sources such as lightning, prairie fires, or human activity, or internally by spontaneous combustion. Many **coal** fires are probably started by spontaneous combustion, as noted by Rodgers (1918). As **lignite** is exposed to the air, it tends to lose moisture and slake or crumble to a fine powder, which can accumulate at the base of the **lignite**. Blain (1955, p. 139) states, *"The powdered coal, having a greatly increased surface area, promotes rapid oxidation. . . . the powdered coal absorbs oxygen in quantities two to three times its own volume. This absorption of oxygen takes place at ordinary temperatures but proceeds more rapidly at higher temperatures, and as the process generates heat, it is self-accelerating. Thus the process generates greater and greater amounts of heat until the lignite begins to burn."* Coates (1980, p. 38) noted that *"The opening of large coal mines in this region (the Powder River Basin) has exposed large amounts of coal to the air, and the abundance of spontaneous mine fires, mostly in finely comminuted coal, is dramatic confirmation of Rodgers' ideas."*

Whatever the cause, once started, the fire burns the seam back into the hillside and fires overlying sediments like brick or even locally into a glassy slag. As the **lignite** burns, overlying sediments **slump** down into the void. Fractures in the **slumped** sediment allow oxygen to reach the fire and combustion gases to escape *(fig. 12)*.

Slumping of overlying **strata** is apparent where **clinker** abuts hillsides *(figs. 9, 13)*. In places, warped **beds**, draped down and over the burned out **lignite**, suggest that the **lignite** had burned sufficiently far into the hillside

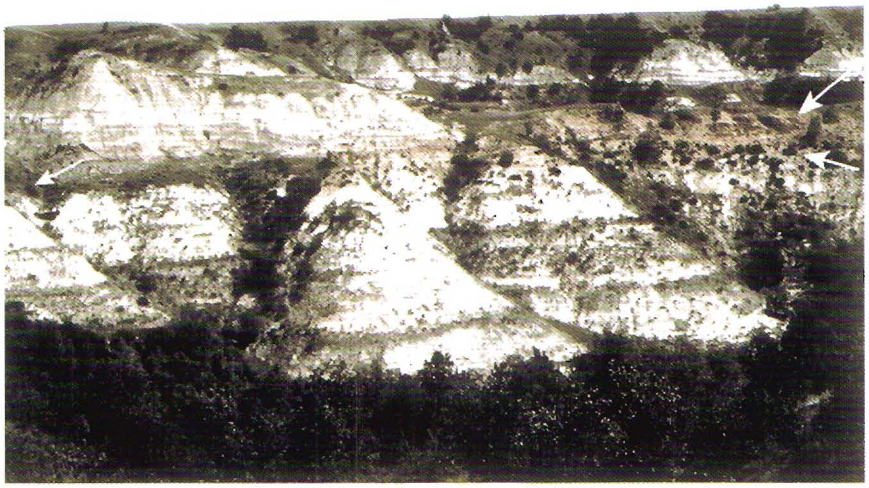


Figure 9. HT Butte clinker (between large arrows). Sentinel Butte Formation is above small arrow, and Bullion Creek Formation is below arrow. Note slumping of overlying Sentinel Butte strata (141-102-36ddc.).

Figure 10. Thin remnant of HT Butte clinker capping conical hill (see arrow) of Bullion Creek strata (view to northwest to 141-102-24acc).

such that **beds** were gently warped downward but did not extensively fracture, thus smothering the fire.

Chimneys mark the locations where hot gases were funneled and vented to the surface; they commonly stand as small, conical hills above a gently rolling HT Butte-capped surface *(fig. 14)*. In chimneys, the rock is thoroughly brecciated and original bedding is destroyed; commonly a vesicular, glassy slag is present that resembles true volcanic **scoria**.

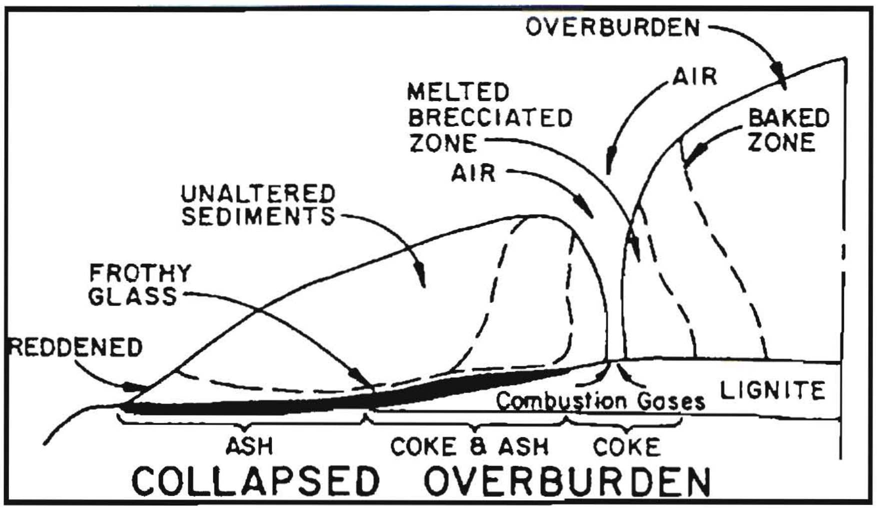
Clinker is harder than the original, poorly cemented **strata** and so resists **erosion**. In many places, the HT Butte **clinker** forms a rolling, grass-covered **plateau** surmounted by only a few outliers of unburned Sentinel Butte **strata** *(fig. 15)*. Locally, the **clinker** surrounds a small depression in unaltered Sentinel Butte **strata**, suggesting that a small **butte**, now since eroded, was there while the HT Butte **lignite** burned. The **clinker** also forms "rings" around many hillsides, again suggesting that **erosion** has removed appreciable amounts of unaltered **strata** after burning ceased *(fig. 16)*.

In places, the **clinker** shows well developed columnar jointing, which many have attributed to thermal contraction during cooling, much as columnar basalts form. But Coates et al. (1987) noted that the conversion of smectite to illite by dehydration occurs at about 150° C, which results in a volume loss in **clay** of about 20 percent. It is this decrease in **clay**-mineral volume that may account for the contraction and joint formation. Coates et al. (1987) also found some sagged and partially molten columns, which suggests that they formed during heating, not cooling.

Each September, from 1951 to 1977, former Bismarck

Figure 11. Close-up view of partly melted, fused mass of vesicular HT Butte clinker (140-102-24baa).

Figure 12. Diagram illustrating some of the processes that occur as a lignite bed burns, thereby baking the overlying materials to clinker. Fractures that develop in the overburden allow oxygen to enter and combustion gases to escape, thereby perpetuating the fire (modified from Sigsby, 1966).



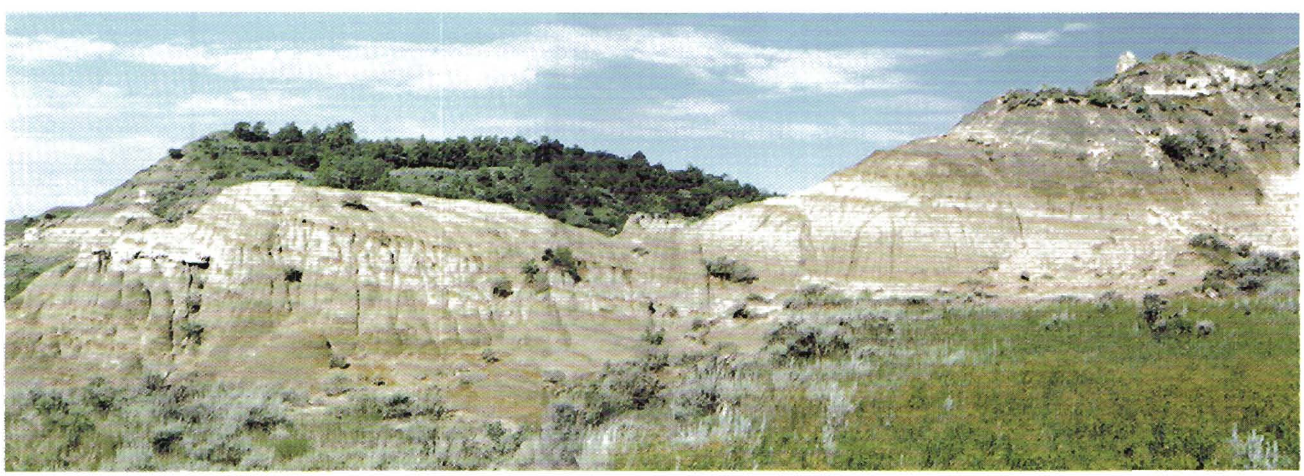


Figure 13. Characteristic slumping and small-scale faulting over burned out portion of the HT Butte clinker (view to the west-northwest to 141-102-26dac).

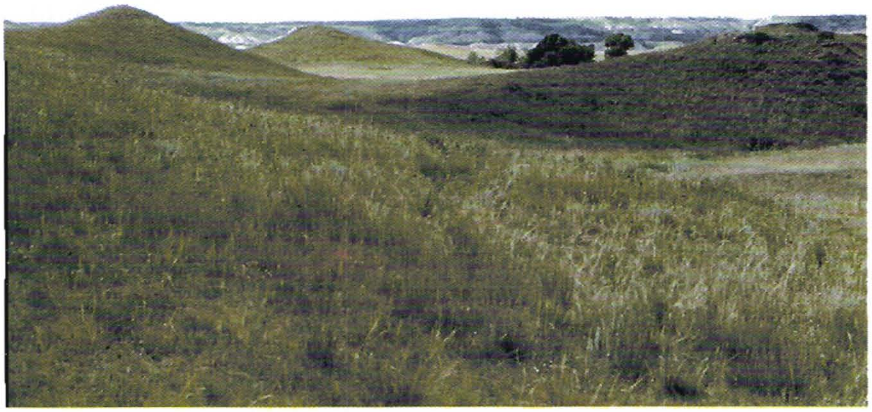
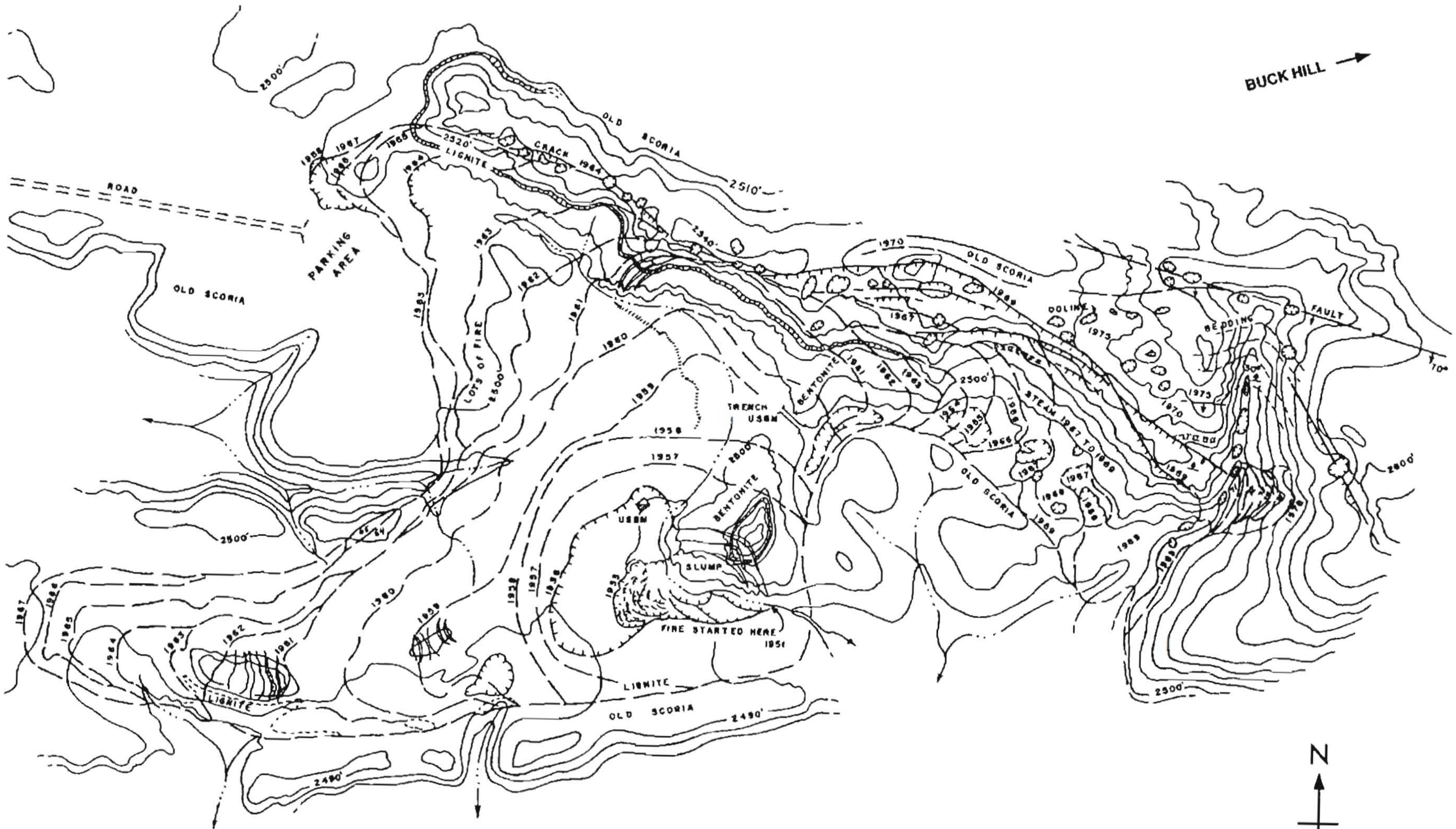


Figure 14. Typical grass-covered expanse of HT Butte clinker. Small hills mark the locations of former chimneys, areas where combustion gases were funneled to the surface, creating a thicker section of partially melted, fused clinker, which is more resistant to erosion than adjacent slightly baked beds (view to the west-southwest to 141-101-28cba).

Figure 15. Gently rolling, grass-covered plain underlain by HT Butte clinker with erosional outlier of unaltered Sentinel Butte strata at center (view to the south-southwest to 140-101-4dda) .

Figure 16. Ring-like ridge of HT Butte clinker (big arrow) surrounding unaltered promontory of Sentinel Butte strata (small arrow). This relation suggests that substantial erosion has taken place since burning of the HT Butte lignite (view to the north to 140-102-24dd).



GEOLOGIC AND TOPOGRAPHIC MAP

HISTORY OF BUCK HILL BURNING COAL BED 1951 TO 1977

THEODORE ROOSEVELT NATIONAL MEMORIAL PARK

GORDON BELL AND STUDENTS
1984

N

SCALE

0 100 FEET

CONTOUR INTERVAL = 10 FEET

EXPLANATION

Crevasses and cracks in the earth due to subsidence and collapse. During and following the burning of the underlying lignite coal bed.

Coal lens above the burned Buck Hill coal bed or lens.

Sinkhole or doline. Some of these formed along the north ridge during an older burn from the north. Other sinkholes developed from 1967 to 1975 when the fire advanced north under the ridge. Some of the old and new sinkholes contain water, cattails and sedges.

1958

Perimeter of burning. The fire front mapped each September or October.

Vertical shaft by US Bureau of Mines to reach the 4 meter (12ft) thick bed of lignite coal.

Intermittent stream.

"Old [scoria]", produced as part of the sequence of burns that started as soon as the Paleocene coal beds were exposed to the atmosphere. Burning lignite and consequent [scoria] is an important process in the formation of the badlands of North Dakota.

EVENTS

1. The bed of lignite burned progressively as shown by the dated lines. The advance of the fire was followed by a wave of subsidence and collapse with faults, and slumping, like solution karst with "fire karst" features.

2. The coal-bearing strata are Paleocene geologic age and nearly horizontal except near the fault at the east end of the area near Buck Hill.

3. The map was made during active burning of the 12 feet thick coal bed and the consequent burning, baking and fusing of the overlying sedimentary rocks.

4. The ridges collapsed in slices or wedges. The cracks, some 8 feet wide at the surface and the deep fissures conducted air to the subsurface fire.

5. White hot rock-melting temperatures developed in the roaring fire storms in the chimney-like crevasses and fire caves. Molten rock flowed from the cavities to form miniature stalactite and rope-like forms.

6. The resulting [scoria] was enhanced by more tints and shades of pink, yellow, green, red, brown, and tones of black and gray after at least two years of weathering.

7. Fire guards, scraped trailways, were made in advance of the burning coal and tension subsidence cracks.

8. The topography was mapped as part of the project in 1955, 1956, and extended to the east ridge in 1972. Consequently, some original contours cross collapsed areas and misfit geomorphic units. Some ridges settled, as much as 5 feet.

9. All plant life has returned, following the Russian Thistle, to a luxuriant maxima in the grass land. Shrubs and trees are returning slowly in the last burn zone 1976. Juniper trees developed columnar structure during the burning coal and smoke cycle and have returned to normal shape. The animals enjoyed the warm earth and have multiplied.

Figure 17. Geologic and topographic map of the Buck Hill burning coal vein. Because they can appear similar, clinker has long been known locally as "scoria" (from Bell and students, 1984).

Junior College Geology Professor Gordon L. Bell and his students mapped the geology and **topography** of the Buck Hill burning **coal** vein. The unpublished map is dated 1984 and is drawn at a scale of 1:1,200 with a contour interval of ten feet *(fig. 17)*. A south-dipping **fault** and north-dipping **beds** are shown in the northeastern part of the map. **Beds** do indeed **dip** into the hillside, but in a much more chaotic manner than shown. The hillside itself is cut by numerous **slump** scars and blocks that have rotated back into the hillside. Field relations suggest that the "**fault**" shown is simply the main detachment surface of this **slumped** hillside.

In a series of investigations of the **clinker** of the Powder River Basin (Rochelle Hills, Campbell County, Wyoming), Coates et al. (1982) showed that although the **clinker** forms a continuous surface, fission-track dating of detrital zircons indicates that it was produced by a series of small burns rather than a few large burns. Geomorphic considerations suggest that the HT Butte **clinker** also formed by a number of small burns. Generally, older **clinker** is likely to be found on promontory points rather than in canyon heads.

Although the HT Butte **clinker** is the thickest and most widespread **clinker** in the Park, other **lignite beds** have burned in the Park and formed **clinker**, especially along the **escarpment** from Peck Hill, east and north to the area of Sheep Butte Spring (140-101-11a and –12b). Much of that **clinker** appears to come from the burning of a single lignitic horizon, a ten-foot-thick sequence of intercalated thin **lignite beds** and carbonaceous **shales** with widely scattered silicified stumps and logs. It contains excellent impressions of deciduous and coniferous leaves, which are rare in the HT Butte **clinker**.

Basal Sandstone

Throughout much of southwestern North Dakota, the base of the Sentinel Butte Formation is marked by the so-called basal **sandstone**, a generally poorly **lithified**, light gray, silty, cross-bedded **sandstone** ranging from several tens of feet to over 100 feet thick *(fig. 18)*. Royse (1967) was the first to recognize the persistence of this unit. Because of gradational and interfingering relations of its upper **contact**, the basal **sandstone** was not mapped.

In contrast to **sandstones** in the Bullion Creek Formation, rill **erosion** and **castellated weathering** are well developed on exposures of the basal **sandstone** *(figs. 18, 19)*. Isolated, well-cemented **concretions**, including "**cannonballs**," "logs," and lenticular **beds**, commonly

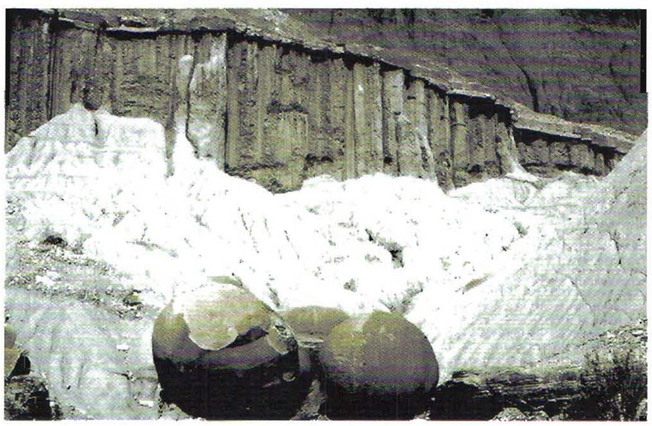


Figure 18. Basal sandstone of the Sentinel Butte Formation at the Concretion Pullout in the North Unit (148-99-32bcc). Castellated and rill weathering, as well as a variety of concretions, characterize this unit.

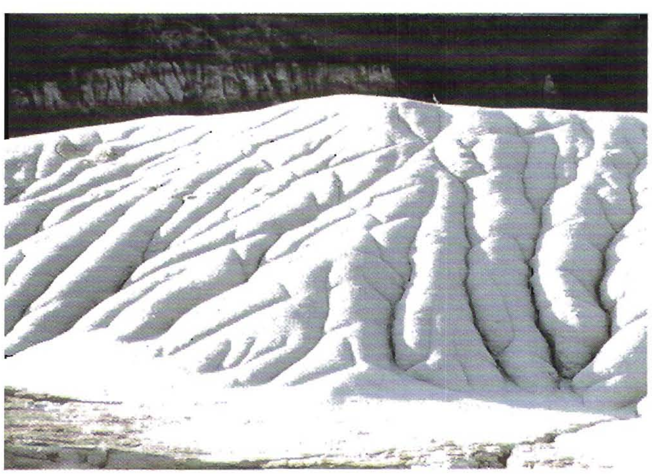


Figure 19. Basal sandstone of the Sentinel Butte Formation showing well-developed rill weathering and miniature fans and pediment (140-101-14ddd).

weather out of the basal **sandstone** (*figs. 18, 20*); many of these **concretions** form the protective caprock of **hoodoos** or pedestals (*fig. 21*). Cross-beds within the basal **sandstone** are locally accentuated by accumulations of **lignite** fragments or iron-oxide **concretions** or stains.

In the South Unit, the basal **sandstone** is found above the HT Butte **lignite** and below the so-called **petrified wood** horizon. The lower part of the basal **sandstone** has been baked into the HT Butte **clinker** where the underlying HT Butte **lignite** has burned. Cross stratification and other sedimentary structures are still visible in much of the resulting **clinker**. Locally the **clinker** surrounds small, shallow depressions that are developed on the sparsely vegetated basal **sandstone**. The mantled **pediment** mapped in the eastern part of the South Unit has developed on the basal **sandstone**. At the western edge of the Petrified Forest Plateau, the basal **sandstone** is less than 20 feet thick; it thickens markedly under the **plateau** and is several tens of feet thick at the eastern edge. The basal **sandstone** is about 60 feet thick east of the Little Missouri River.

In the North Unit, the basal **sandstone** is about 80 to 100 feet thick. It is present along the length of the Little Missouri River and the lower reaches of its tributaries. It is stratigraphically below the **petrified wood** horizon and "blue bed" (of Clark, 1966, and Carlson, 1985). The basal **sandstone** is especially well exposed at the "Concretion Pullout" near Juniper Campground. There it shows rill **erosion** and **castellated weathering** (*fig. 18*).

Petrified Wood Horizons

Horizons of **petrified wood** are found in both units of the Park, and although they are all in the lower Sentinel Butte Formation, it is not known whether the horizons are truly correlative. They do indicate that conditions favorable for the development and preservation of flood-plain forests were more favorable in early Sentinel Butte time than in earlier or later times.

South Unit

Besides the HT Butte **clinker**, the most widespread, easily recognizable horizon in the Sentinel Butte Formation in the South Unit is the so-called **petrified wood** horizon. The horizon can be traced throughout the South Unit and is noted for its large, upright, fluted stumps (*figs. 22, 23*) and, especially in the area south of Paddock Creek, for its silicified **lignite** (*fig. 24*). It ranges from about 20 to 40 feet above the base of the Sentinel Butte Formation along the western side of the Petrified Forest Plateau, and up to about 100 feet above the base of the **formation** in the eastern part of the South Unit.

Hennen (1943) was one of the first to describe this **bed** in his effort to use **Tertiary lignites** and other **beds** to create one of the first structural contour maps of the Williston Basin in North Dakota. He wrote:

"A persistent "marker-bed" for correlation has been recognized in the Fort Union formation by

Figure 20. Oval and log-like sandstone concretions in the basal sandstone of the Sentinel Butte Formation at the Petrified Forest Plateau. Petrified stumps in the foreground and on the ridge in the distance have been let down from erosion of the overlying petrified wood beds (view to the northeast to 141-102-27daa).

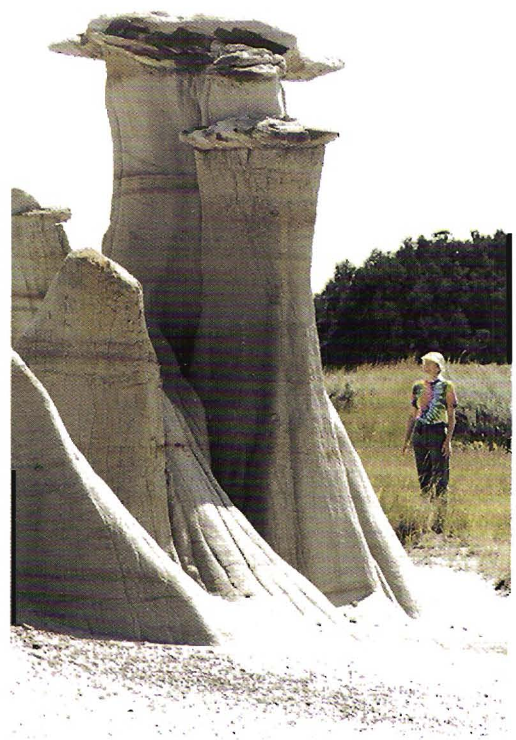


Figure 21. Some of the most spectacular hoodoos (or pedestals) in the Park are formed from the basal sandstone of the Sentinel Butte Formation (view to the south to 140-101-14aba).

Figure 22. Petrified stumps on the Petrified Forest Plateau. Fluted bases and lack of roots are characteristic of these stumps (141-102-27daa).

Figure 23. Large, upright petrified stump on the Petrified Forest Plateau (view to the north to 141-102-26cbb).

the writer. It is a grayish white, flaggy to shaly sandstone, apparently containing a mixture of volcanic ash, with silicified fossil plant stems in abundance, and here and there silicified stumps of trees 3-5 feet in diameter. At points 9-11, inclusive (Fig. 1), it is ordinarily less than 5 feet in thickness, but westward at Sully Springs (Fig. 1, point 3), it is more than 40 feet thick but still is grayish white to ash-gray, with the silicified tree zone at the top. . . . It is in this zone that the "Petrified Forest" occurs on the valley floor of Andrews Creek [Sully Creek], 1.5 miles southwest of Sully Springs railway station. This zone may be observed also, in typical development, at the entrance gate to Roosevelt Park on Highway 10, 5 miles east of Medora." (Hennen, 1943, p. 1569-1570).

Hennen included this silicified zone at the top of his "Sandstone 21." In the Medora area at least, Royse (1967) noted that Hennen's "Sandstone 21" is, at least in part, equivalent to the basal **sandstone** of the Sentinel Butte Formation. (Royse (1967) also discussed problems of correlation that led Hennen to include his "Sandstone 21" in the Tongue River member.) The silicified zone at the top of "Sandstone 21" is the **petrified wood** horizon of this report.

Although we cannot attest to the validity of his correlations outside the Park, we can say that the silicified zone at the top of Hennen's "Sandstone 21" is indeed widespread throughout the South Unit. Correlation of the **bed** is simplified by its proximity to the HT Butte **clinker** and the basal **sandstone**, and by a thin (1- to 2-foot-thick), remarkably persistent **lignite** that lies up to several tens

Figure 24. Silicified lignite of the "petrified wood horizon." This thin, resistant bed forms a protective caprock on small mesas, hills, ridges, and benches in the vicinity of Peck Hill (view to the north to 140-101-27bdb).

of feet below the **petrified wood** horizon *(fig. 25)*. The **petrified wood** horizon clearly encircles the entire Petrified Forest Plateau, but it changes character from one side to the other. Along the western part of the **plateau**, the **petrified wood** horizon appears as two lignitic horizons with numerous upright, silicified stumps and local silicified **lignite** *(fig. 26)*. When traced to the east side of the **plateau**, only a single stump horizon is seen. The dark gray swelling clays above and below the stump horizon on the western side of the **plateau** are lacking in exposures on the eastern side of the **plateau**. To the east, stumps are generally less abundant, although still common. South of the Petrified Forest Plateau, around the unnamed **plateau** in 140-102-9, -10, and -16, the horizon is again represented by a single **bed**.

The **petrified wood** horizon can be traced east across the Little Missouri River, and indeed, in many places is as deserving of the name Petrified Forest as is the Petrified Forest Plateau itself. East of the Little Missouri River, the **petrified wood** horizon is represented by a single stump **bed**, except in the Boicourt Spring and Badlands Overlook areas, where two stump **beds** are present. Stumps, still in their upright growth position, are especially numerous on the drainage divides between Jules, Jones, and Paddock Creeks (140-101-5, -8, and -9); the area surrounding the Painted Canyon Visitor Center (140-101-26, -35, and -36; and 140-100-31); the area west of the old entrance station (140-102-28 and -29); and in the area east of Buck Hill (140-101-24 and 140-100-19c).

The silicified **lignite** south of Paddock Creek commonly caps benches, forming an **erosion** resistant armor. It is generally about 1 foot thick and contains numerous silicified stumps with fluted bases. In many places (e.g., 140-101-26c,d, -28, -29, and 35a,b), the stumps are as common as the most prolific places on the Petrified Forest Plateau, but they are less noticeable because they have the same color as the silicified **lignite**. The **petrified wood** horizon is only locally silicified north of Paddock Creek.

In the northeastern corner of the South Unit, especially in the area around 140-101-3, -4, -11, and -12 and 141-101-36, the **petrified wood** horizon contains comparatively few stumps. Still, it is a lignitic horizon normally more vegetated than enclosing **strata**. The contrast makes it a good marker **bed**, which is generally visible on 1:20,000-scale black-and-white air photos.

The petrified stumps are up to about 6 feet high and 4 feet in diameter at chest height, but most are between 2 to 4 feet tall and 2 to 3 feet wide. Virtually all have fluted bases, and where in place, rest on a thin **lignite** or carbonaceous **shale**; no roots have been observed. Somewhat flattened trunks are less commonly found. The stumps were preserved where buried by flood-plain deposits; the upper parts of the trees simply rotted away. There have been several unpublished studies on the **petrified wood** of Theodore Roosevelt National Park. Indiana University geologist, S. R. Manchester, studied the wood and noted that it *"appears to be a conifer, and my guess is that it belongs to the Taxodiacae (Sequoia family) although the preservation is not good enough to*

Figure 25. The thin, two-foot-thick lignite (at left center) is remarkably persistent throughout the eastern part of the South Unit and facilitates correlation of the overlying "petrified wood horizon" (view to the west-northwest toward hill located in 140-101-4b).

Figure 26. Two petrified wood beds (arrows) on the Petrified Forest Plateau (view to the northeast, 141-102-26cba).

confirm this" (quoted in Fastovsky and McSweeney, 1991, p. 73). Fastovsky and McSweeney (1991, p. 73) also summarized several other unpublished studies conducted on the **petrified wood** of Theodore Roosevelt National Park.

Fastovsky and McSweeney (1991) studied the **paleosols** of the Petrified Forest Plateau in an effort to determine the influence of ancient, exhumed **soils** on the development of modern **soils**. On the western side of the **plateau**, the Petrified Forest consists of two successive coniferous forests that developed on flood-plain sediments *(fig. 27)*. The stump horizons are separated by light to dark gray, laminated **siltstone** and **claystone**, with laterally extensive concretionary and bedding-plane iron stains. They stated that *"The presence of laterally extensive variegated beds is clear evidence of ponded water. This interpretation is reinforced by the unionids, bivalves that perennially live subaqueously, and do not thrive with emergence. Other indicators of flooding are the coal seams, which represent peat (organic matter) accumulated subaqueously in swamps"* (Fastovsky and McSweeney, 1991, p. 74). The trees themselves were probably rooted underwater, like modern bald cypress are today.

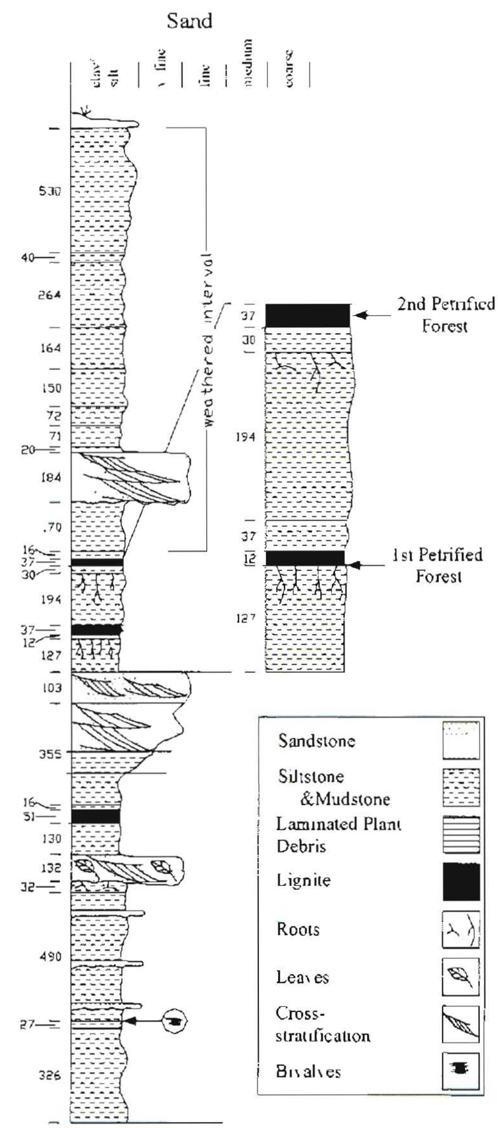


Figure 27. Representative measured section of beds at the Petrified Forest Plateau, 141-102-35bb. Measurements in centimeters (from Fastovsky and McSweeney, 1991).

North Unit

In the North Unit, a stump horizon is present about 300 feet above the base of the Sentinel Butte Formation (about 20 feet below the Sentinel Butte **bentonite**) south of Sperati Point. A similar **bed** is found about 50 feet below the Sentinel Butte **bentonite** at the east end of the Park. Other lignitic horizons in the North Unit also contain **petrified wood**, further reducing the usefulness of this **bed** as a marker.

South of Sperati Point, the horizon is best exposed in 147-100-8bad. There, it consists of two thin **lignite beds**, both locally silicified, separated by about 10 feet of bluish gray swelling **clay**. The lower **lignite**, about 3 feet thick, contains stumps 4-5 feet in diameter still in their upright growth position and flattened logs up to 75 feet long. The upper **lignite** is only 1 foot thick, but it too contains upright stumps; overlying grayish brown, locally iron-stained **mudstone beds** are draped over the stumps and clearly show evidence of compaction *(fig. 28)*.

Sentinel Butte Tuff/Bentonite

The most spectacular **bed** in the North Unit has been variously and informally named the "Blue" by Fisher (1953), the "Big Blue Bed" by Laird (1956) and simply the "blue bed" by Clark (1966) and Carlson (1985). To avoid confusion with other blue-colored **clay** units in the Sentinel Butte Formation, Forsman and Karner (1975) recommended abandoning the term "blue bed" or "big blue bed" in favor of the informal names Sentinel Butte **tuff**, Sentinel Butte **bentonite**, or Sentinel Butte **tuff/bentonite** if both lithologies are present.

These new informal names allude to another significant aspect of this unit, namely that it consists of more than just blue **clay**. In its typical development, the Sentinel Butte **tuff/bentonite** consists of a light gray volcanic **ash** sandwiched between blue **bentonite beds**; collectively the three **beds** are up to 25 feet thick *(fig. 29)*. In many exposures, however, the **ash** is absent. Forsman (1992) traced the Sentinel Butte **tuff** over a nearly 1,500-square-kilometer area in central McKenzie County. The three-part nature of this unit was perhaps first recognized by Royse (1967) and Metzger (1967), but Forsman and Karner (1975) and Forsman (1982, 1985) made the first detailed studies of the **bed**.

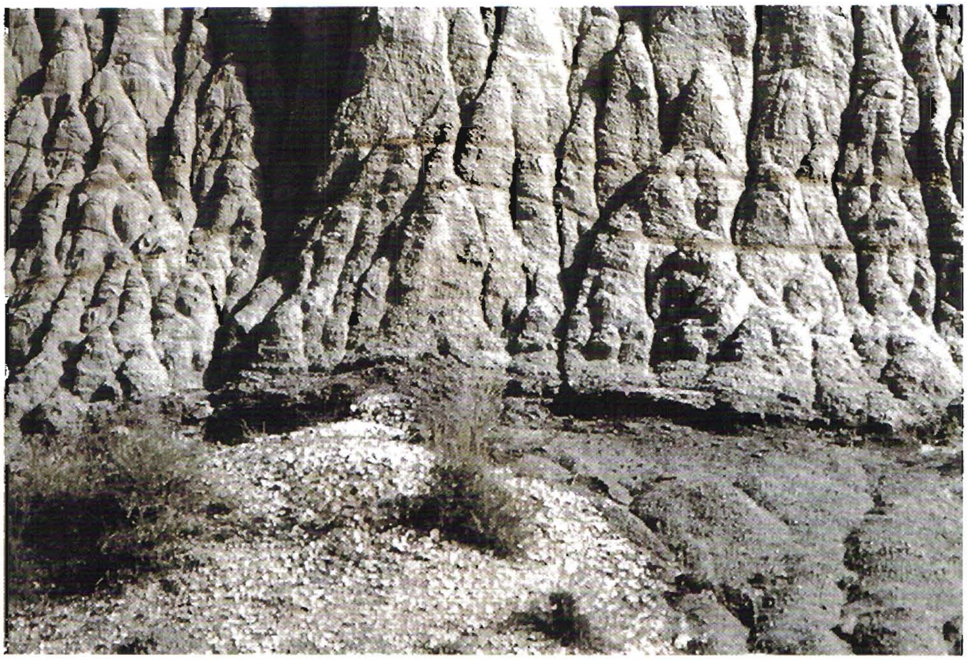


Figure 28. Differential compaction of beds over highly fractured silicified stump (147-100-8bad).

Forsman and Karner (1975) first showed that the "blue bed" contains partially altered volcanic **ash** from a rhyolitic source, a finding later confirmed by Larsen (1988) based on major element concentrations. It is everywhere overlain and underlain by **bentonite**. The **contacts** between the **ash** and enclosing **bentonites** appear sharp but are gradational over a few centimeters. Forsman (1992, p. 269) noted, *"The upper and lower bentonites appear to have formed through progressive alteration of an originally thicker single ash accumulation."*

The Sentinel Butte **tuff** is a conspicuous, laminated, light gray, white-**weathering tuff** or tuffaceous **siltstone** sandwiched between blue bench-forming **bentonite clays**. The **tuff** consists of about 75% silt and 25% **clay**-size particles; about 67% of the silt fraction consists of glass grains of rhyolitic composition, 23% phenocrysts with admixed detrital grains, and 9% authigenic montmorillonite (Forsman, 1982, 1992). The **clay** itself is an iron-rich montmorillonite derived from the alteration of volcanic **ash** (Forsman, 1982). Because of its fine-grained nature, dating the **ash** has been problematic (Forsman, 1982).

Larsen (1988) studied the geochemical fingerprint of the Sentinel Butte **tuff/bentonite** and mapped the **bed** within and near the North Unit of Theodore Roosevelt National Park. He noted that the **tuff** is a chemically distinct unit; microprobe analyses by Forsman (1992) also indicate that the glass grains of the three **beds** have the same major element composition. The Sentinel Butte **tuff/bentonite** is therefore an isochronous marker **bed**.

Widespread lateral continuity and water-formed ripples at the base of the Sentinel Butte **tuff/bentonite** suggest deposition in a **lacustrine** environment. The nearest source of **ash** at the time was over 400 km distant (Forsman, 1992). The **ash** was probably deposited as a thinner layer, later to be concentrated on the floor of a large lake or lakes through normal drainage processes.

Although both bentonites form "popcorn-covered" benches, and both commonly **slump** and flow downhill, the lower **bentonite** is usually more prominent *(figs. 30, 31, 32)*. The **bentonite** itself commonly serves as a detachment plane for larger **slump blocks**; most small **landslides** mapped in the North Unit are found at this horizon *(fig. 33)*.

The distinctive nature of the Sentinel Butte **tuff/bentonite** - dark bluish gray "sandwich" with a white core that contrasts markedly with the grayish browns characteristic of Sentinel Butte **strata** - enables it to be easily traced great distances *(fig. 34)*. It also clearly shows where the unit thins and disappears completely, and where it has been eroded by overlying channels *(fig. 35)*. The Sentinel Butte **bentonite** thins markedly east of Squaw Creek. On the promontory just northwest of the Juniper Campground (148-99-31baa), about 14 feet of **bentonite** are present (the **ash** is missing). To the east of Squaw Creek, the unit thins markedly and is only about 2 feet thick in 148-99-32a, where it appears to pinch out entirely farther east, a fact also noted by Larsen (1988).

The lower **contact** of the Sentinel Butte **tuff/bentonite** is sharp though commonly concealed by **bentonite** clays that have **slumped** and flowed over it. It typically overlies 1-3 feet of thinly bedded to laminated light gray **mudstone** with local iron-stained laminae and **concretions**, which in

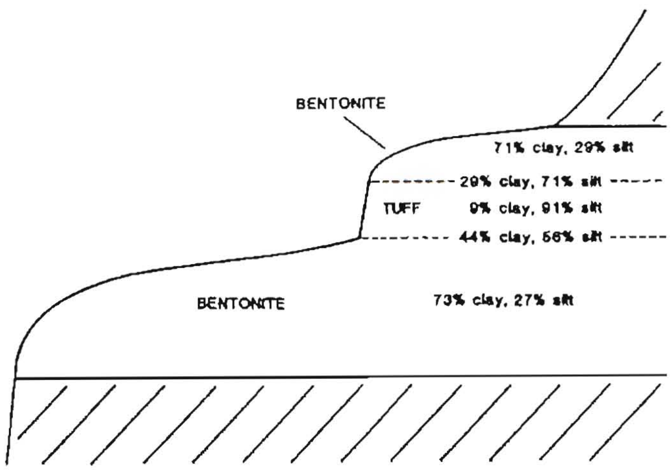


Figure 29. Schematic section of the Sentinel Butte tuff/bentonite (from Forsman, 1992).

turn overlies a brown silty, cross-bedded, ledge-forming **sandstone**.

In the North Unit, the Sentinel Butte **tuff** is best exposed in the area between Oxbow Overlook (148-100-29d) and River Bend Overlook (148-100-26), north of the Little Missouri River. It forms a white, vertical "riser" between the flat, blue, "popcorn-covered" benches of **bentonite**. The **tuff** is commonly laced with a network of joints, along which the **ash** has been altered to **bentonite** *(fig. 36)*. The lower **bentonite** locally contains authigenic barite.

Lower and Upper Yellow Beds

There are several **beds** within the Sentinel Butte Formation that are more reminiscent of the underlying Bullion Creek Formation. The two most prominent of these are found in the North Unit and are known informally as the so-called lower yellow bed and upper yellow bed, each about 15-30 feet thick. Both **beds** are light yellowish brown **siltstones**. Small-scale, ripple cross-stratification is common, as are root traces. Both locally appear white due to an efflorescent crust.

In contrast to the Sentinel Butte **tuff/bentonite**, neither yellow bed has received much study. Cherven (1973, 1978) interpreted the lower yellow bed to be a natural levee and flood-basin deposit *(fig. 37)*; Johnson (1973) ascribed similar depositional environments to the upper yellow bed. Many workers have reported that, in Sentinel Butte **strata**, mollusks are most abundant in the yellow **beds**. Whereas they are indeed common, in our estimation mollusks are most abundant in gray silty **sandstones** and **mudstones** *(fig. 38)*.

The lower yellow bed characteristically forms mostly barren, steep slopes above a dark brown carbonaceous **shale** *(fig. 39)*. It crops out from about 25 to 60 feet above the Sentinel Butte **tuff/bentonite**. Both the upper and lower parts of the unit are typically lighter yellow in color.

The upper yellow bed, which lies about 200 feet above the lower yellow bed, was not mapped due to poor,

Figure 30. View west at bench-forming Sentinel Butte bentonite (148-99-29-ccb).

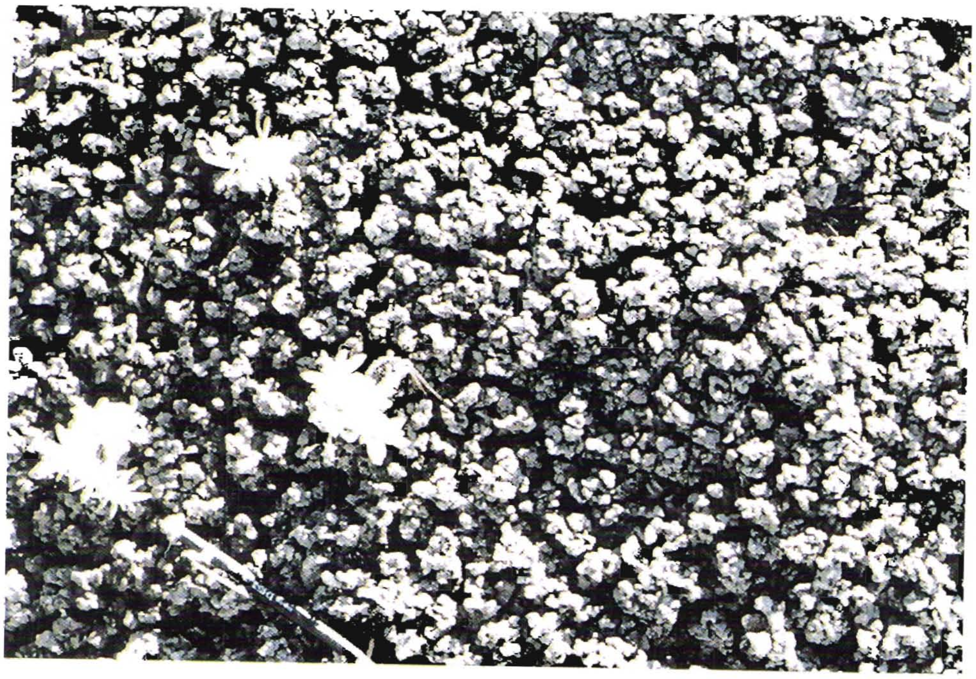


Figure 31. Typical "popcorn" covered surface of the Sentinel Butte bentonite. Note mechanical pencil for scale (148-100-25d).

Figure 32. When saturated, the Sentinel Butte bentonite commonly slumps and flows downhill (view to the northeast to 148-99-30bbc).

Figure 33. Rotational slump with failure plane in the Sentinel Butte bentonite. Note undisturbed horizontal beds (white arrow) beneath the slump block and the tilted beds (black arrow) that dip back into hillside in the slump block (view to the east to 148-100-25cad).

Figure 34. Thin, light-colored Sentinel Butte tuff (black arrow) enclosed in darker colored upper and lower bentonites (white arrows) (view to the north-northeast to 148-100-22dab).

Figure 35. Sentinel Butte bentonite (on ridge crest in foreground) truncated by channel sand (view to the east-southeast to 148-100-34bda).

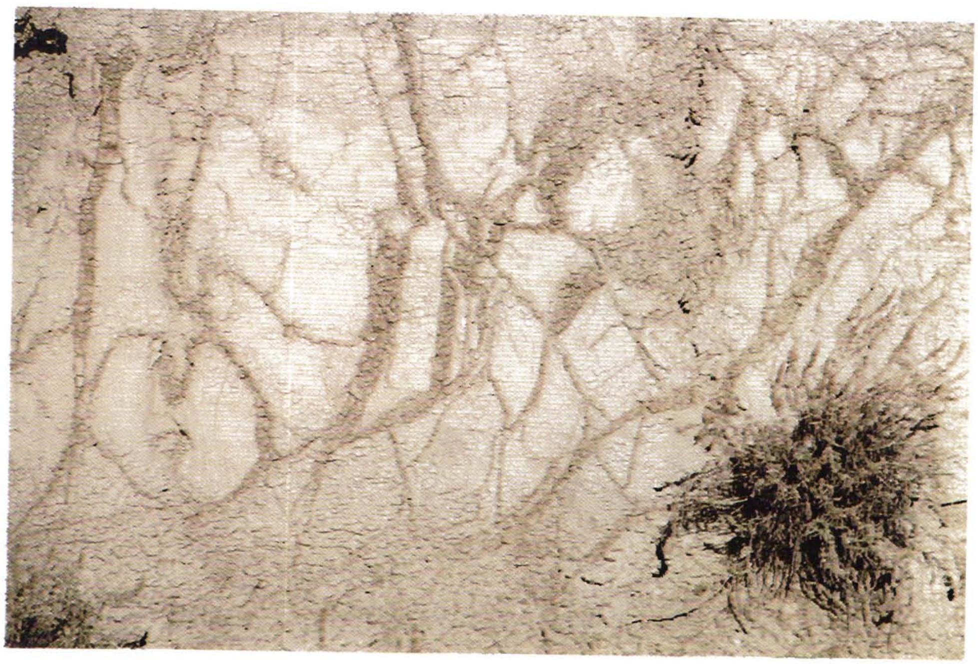


Figure 36. Close-up of Sentinel Butte ash, showing joints along which ash has been altered to bentonite (148-100-22dcc).

widely scattered exposures. It crops out at or near the upland surface in the northeastern part of the North Unit (148-99-26 and -27) at an elevation of about 2,400 feet. It appears to rise in elevation to the southeast, so that it is found at about 2,520 feet in the Achenbach Hills.

Golden Valley Formation

Several maps (Clark, 1966; Clayton et al., 1980; Hansen, 1952, 1956) show the Achenbach Hills of the North Unit to be capped by the Golden Valley Formation; other maps, including Bluemle (1982, 1988), Carlson (1969, 1985), and Fulton (1976), do not show this relation.

The Achenbach Hills are capped by a lag deposit of large **silcrete** blocks; no **strata** are preserved above this **silcrete** *(fig. 40)*. The blocks are up to 10 feet square and 2 feet thick, but most are somewhat smaller and about 1 foot thick. The **silcrete** is a light gray, massive, silicified quartz **siltstone** with root or stem casts common, some up to several inches in diameter; rarely the roots or stems are silicified as well. Most of the casts pierce the **silcrete** vertically, but many are roughly horizontal.

The **silcrete** blocks form a pavement that has served to protect the Achenbach Hills from **erosion**; the approximate limit of abundant **silcrete** blocks is shown on the accompanying geologic map. Elsewhere in the Achenbach Hills, particularly along their western side, the blocks are concentrated in narrow, steep gullies and on ridge tops; they are not as common in broad swales, where they are presumably covered by slope-wash material. Even at the highest elevation in the hills, about 2,720 feet, the blocks are jumbled and appear to have been let down by **erosion** of underlying **beds**.

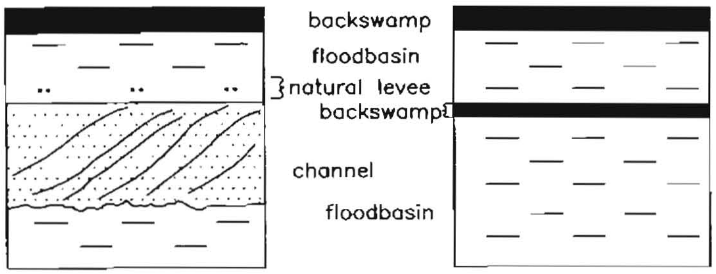
The **silcrete** blocks clearly came from the Taylor bed, the upper unit of the Bear Den Member of the Golden Valley Formation, based on their lithology. The Taylor bed was named by Hickey (1977) for exposures of a silicified **siltstone** west of Taylor, North Dakota. The Bear Den Member is a distinctive, comparatively thin lithologic interval between similar **beds** of the overlying Camels Butte Member of the Golden Valley Formation and underlying Sentinel Butte Formation. It is distinguished from these two units by: 1) its 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. The Bear Den Member is believed to represent a **weathering** horizon developed on top of the Sentinel Butte Formation (Clayton et al., 1980). The **weathering** horizon marks a hiatus in deposition, a **disconformity**, between the Bear Den Member and the overlying Camels Butte Member.

The Achenbach Hills are heavily grassed, and no exposures were found of sediments immediately below the **silcrete**. Still, given that the **silcrete** blocks are lying randomly on the surface, it seems clear that the underlying, characteristically bright white, poorly vegetated, comparatively thin Bear Den Member is absent. Clark (1966) also hinted that the **silcrete** appeared to be a lag deposit, but confused its stratigraphic position. Clark (1966, p. 35) stated *"Removal of a portion of the upper member [Camels Butte Member] may have possibly resulted in the collapse and subsequent accumulation of the "pseudo-quartzite" as a lag gravel(?) on the underlying Sentinel Butte Member [Sentinel Butte Formation]."* He was correct in noting that the **silcrete** lies on the Sentinel Butte Formation, but was incorrect in implying that the **silcrete** belonged to the upper (Camels Butte) member; for unknown reasons, he placed the Sentinel Butte/Golden Valley **contact** in the Achenbach Hills at an elevation of 2,500 feet, 220 feet below the **silcrete**. In fact, except for the lag deposit of **silcrete**, no Golden Valley **strata** crop out in the Achenbach Hills.

The Taylor **bed** developed at the top of the **weathering** profile now marked by the Bear Den Member. The Taylor **bed** lacks lithic 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**. Hickey (1977, p. 25) noted, *"The chemical matrix of the Taylor bed, its open framework of detrital grains, and the appreciable amount of comminuted plant matter that it contains indicates slow deposition with a minimum of clastic input. The numerous standing plant stems in the siltstone are evidence that its deposition took place in areas of shallow water where vegetation was growing, such as a swamp or marsh. A higher pH in the Taylor bed swamps than in those where the Alamo Bluff lignite was accumulating would have favored the precipitation of silica over the accumulation of peat."* The presence of hollow, vertical plant stem molds seems to require that the **silcrete** be silicified prior to decay of the plant material. Leaching of the **soil** profile likely provided the silica necessary for cementation.

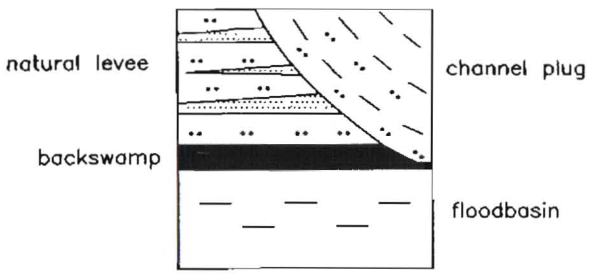
Late Tertiary-Quaternary Sediments

Sand and gravel of indeterminate late **Tertiary-Quaternary age** (QTa) appear in both the North and South Units. In the South Unit, these deposits cap the Petrified Forest Plateau and the unnamed **plateau** south of Knutson Creek and are overlain by a thin, unmapped layer of **loess**. In the North Unit, similar but highly dissected deposits are present at Sperati Point and on three small knolls about 3,000 feet to the south. At each locality, the sand and gravel unconformably overlie the Sentinel Butte Formation. The **contact** with underlying Sentinel Butte **strata** is exposed locally along the perimeter of some of the **plateaus** west of the Little Missouri River in the South Unit. It is

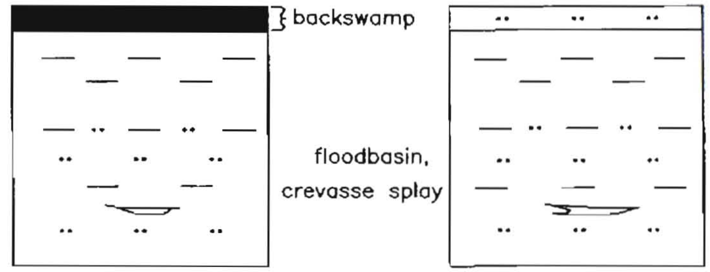


(A) Normal cyclic unit in high–sinuosity stream deposits, formed by lateral accretion in a channel migrating from right to left, followed by overbank (natural levee and flood-basin) deposition.

(B) Cyclic unit formed when a backswamp (lower lignite) is drowned, clay is deposited and then the swamp is re-established.

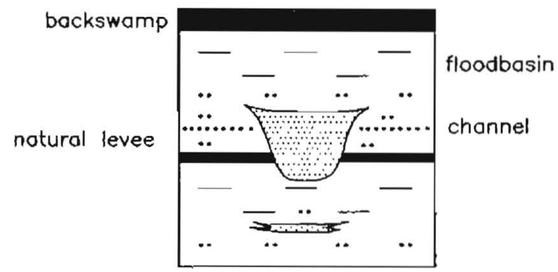


(C) Sequence found when Channel was abandoned and plugged. Thick natural-levee deposits (silt and sand) occur adjacent to cut bank. The channel was migrating from right to left.



(A) Normal cyclic unit in low–sinuosity stream deposits. Silty–clay deposited prior to subsidence below water table and deposition of floodbasin and backswamp clay and lignite.

(B) Backswamp did not form because sedimentation rates were too high. Lignite beds are absent.



(C) Normal cyclic unit truncated by low–sinuosity stream when it was diverted into this area. Erosional base of the channel deposits forms the base of a fining–upward cyclic unit.

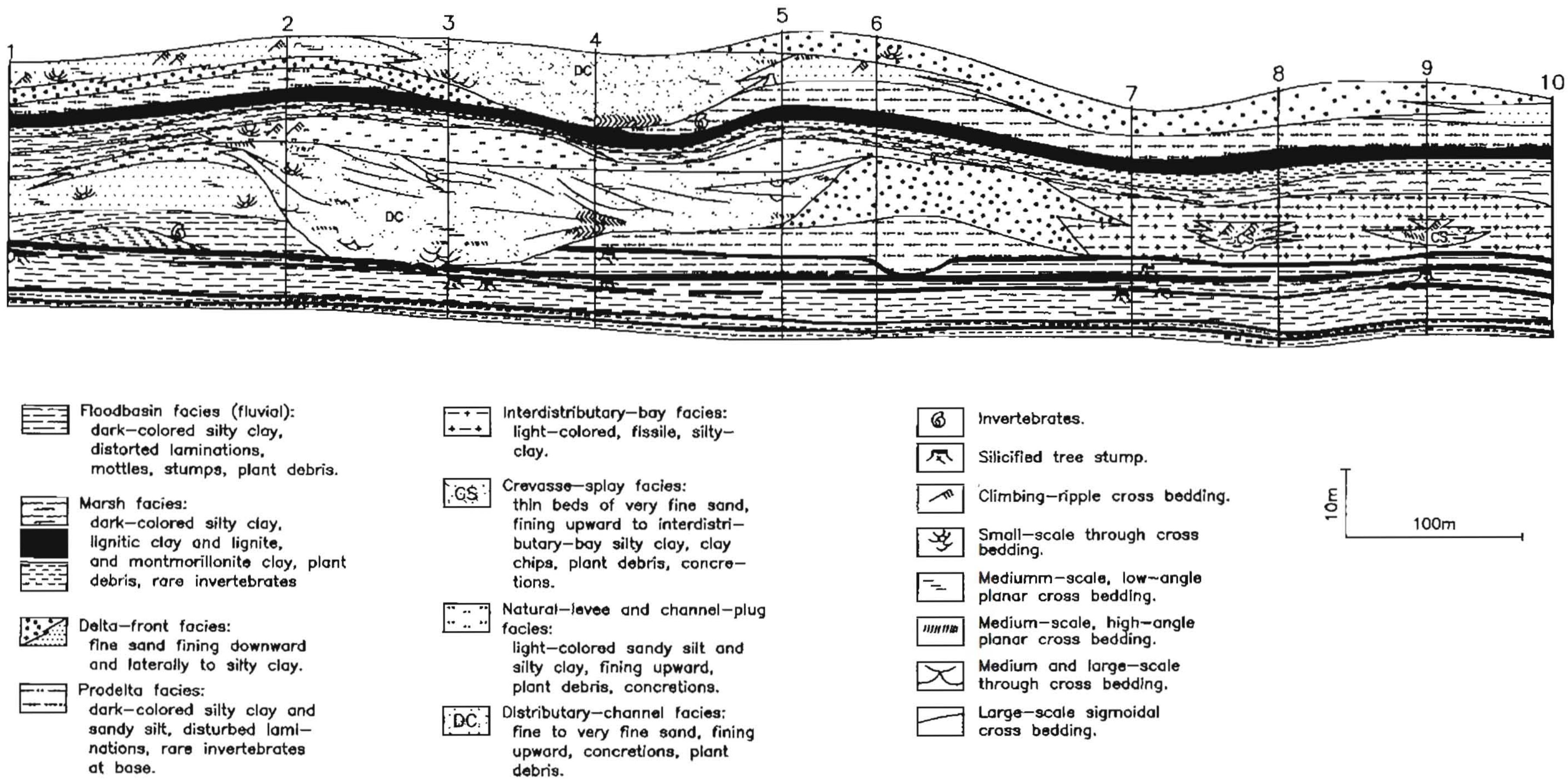


Figure 37. Cross-section of Sentinel Butte strata exposed in the north wall of the Little Missouri River valley. Cyclic units of high-sinuosity (upper left, previous page) and low-sinuosity (upper right, previous page) streams (from Cherven, 1973, 1978).

Figure 38. Cluster of mollusk shells encased in fine-grained Sentinel Butte sandstone (140-101-3bcc)

Figure 39. Lower yellow bed (white arrow) is visible just below the skyline. A similar yellowish siltstone bed caps the knobs on the skyline. Ridge in foreground is capped by landslide deposits, which are apparent by their disturbed and tilted beds (dark arrow; view to the northeast to 148-100-25c).

Figure 40. Lag deposit of large blocks of Taylor bed silicrete. Even at the highest point in the Achenbach Hills, the Taylor bed silcrete appears as a mass of jumbled blocks, indicating that it has been let down by erosion. The underlying, comparatively thin, bright white, poorly vegetated kaolinitic Bear Den Member is apparently not present (view north to the crest of Achenbach Hills, 147-100-10aca).

not exposed in the North Unit.

These sand and gravel deposits consist of moderately sorted, iron-stained, locally iron-cemented material of local and southwestern affinity. They contain pebbles and cobbles of well-cemented, locally-derived material (**mudstone**, **sandstone**, **concretions**, silicified wood, **flint**, **silcrete**, **clinker**, and **chalcedony**), and lesser quantities of quartzite and porphyry. The sand and gravel commonly have a transparent, shiny coating, probably of iron-manganese oxides.

In the South Unit, the QTa deposits are generally less than 5 feet thick and are overlain by a slightly thicker mantle of **Holocene loess**. Generally, these deposits are best exposed along the margins of the **plateaus**, where vegetation cover is sparse and slope-wash processes have removed much of the overlying **soil** and **loess**. At the northern end of the Petrified Forest Plateau, in 141-102-24b, gravel is especially prominent. Several **silcrete** blocks, from 1 to 4 feet long, were also found in this area. A 1-foot-long boulder of gneiss was found in the southwestern corner of 141-102-34aab. Elsewhere, in the interior of the **plateaus**, thick vegetation cover obscures these deposits. In such places, however, the excavated material surrounding animal burrows and ant hills offers a glimpse at the sediments below; the coarse sand brought to the surface by burrowing mammals and ants differs markedly from the finer-grained sands of the Sentinel Butte Formation.

The thickness of these deposits in the North Unit is uncertain because the **contact** between QTa deposits and underlying Sentinel Butte **strata** is covered by **colluvium**. At Sperati Point, QTa deposits may be up to 40 feet in thickness. **Erratic** boulders from about 1 to 4 feet in diameter are scattered over the sand and gravel deposits at Sperati Point, suggesting that these deposits pre-date the advance of ice into the area.

The correlation of sand and gravel deposits in western North Dakota and adjacent Montana remains problematic due to the presence of only widely scattered exposures, poor **age** control, and the inherent lateral variability within a given unit. Definitive correlations have not yet been made. University of North Dakota student Schmitz (1955) mapped these deposits as Flaxville (?) Gravel, indicating an uncertain correlation with similar gravels in eastern Montana first studied in detail by Collier and Thom (1918). Howard (1960, Plate 1) correlated upland deposits (QTa of this report) with the Cartwright and Crane Creek gravels. In contrast, Clark (1966) mapped these deposits as the pre-**glacial** Wiota (?) Gravel, indicating a tentative correlation with the younger Wiota Gravel of Jensen (1951), who worked 120 miles to the west along the Missouri River in eastern Montana. Fulton (1976) incorrectly mapped the deposits as undifferentiated pebble loam, or **till**. Carlson (1985) did not map these sand and gravel deposits, perhaps because he was working at a less detailed scale. These correlations are at best uncertain. Therefore, the deposits are mapped simply as sand and gravel of indeterminate late **Tertiary** to **Quaternary age** following the convention of Clayton et al. (1980).

In the South Unit, Kuehn (1995) mapped deposits across the main part of the Petrified Forest Plateau (141-101-31; 141-102-24, -25, -35, -36) and the unnamed **plateau** south of Knutson Creek as late **Quaternary loess** on a Miocene/Pliocene **fluvial** surface. Perhaps because they are not as well exposed, he did not map similar gravels on the western and northwestern parts of the Petrified Forest Plateau (141-102-26, -27, -34). Petter (1956) correctly equated **terrace** deposits of the Petrified Forest Plateau and the unnamed **plateau** south of Knutson Creek and designated them as his **terrace** level No. 5, Miocene/ Pliocene **age** Flaxville gravels. Carlson (1983) mapped **Quaternary terrace** gravels at Johnson's Plateau and Big Plateau. Whereas he did not map gravels of the Petrified Forest Plateau, he did map gravels on the unnamed **plateau** south of Knutson Creek. He did not differentiate them from topographically lower and younger **Quaternary-age** gravel at Big Plateau and Johnson's Plateau.

Quaternary Sediments: Coleharbor Group and Oahe Formation

In North Dakota, sediments deposited during the **Pleistocene** Epoch – including **till**, **alluvium**, **loess**, and **clays** and silts of **Ice age** lakes – all belong to what geologists call the Coleharbor Group. Sediment deposited during the **Holocene** Epoch belong to the Oahe Formation. Clayton et al. (1976) originally defined the Oahe Formation to include only post-**glacial** silt deposits near Riverdale. Subsequently, Clayton and Moran (1979) redefined the Oahe Formation to include all post-**glacial** (**Holocene**) sediments found throughout the state. The Oahe Formation has been divided into four members. In most places, however, these members are too thin to be mapped separately and their lateral variability is poorly understood. For mapping purposes, Oahe sediments are therefore commonly grouped into informal **lithogenetic** units of **fluvial** (river), **lacustrine** (pond), and **eolian** (wind-blown) sediment. Most **Holocene** sediments in the Park are associated with the **fluvial lithogenetic** subdivision. Although most upland surfaces are veneered with **loess**, and dune sands are locally present, neither was mapped due to problems of scale. **Lacustrine** sediment is rare and none was mapped in the Park.

Unconsolidated deposits of **Quaternary age** are distributed throughout the North and South Units of the Park. These deposits comprise **alluvium** beneath several **Pleistocene terraces** (Qt, subdivided locally into Qt1, Qt2, Qt3, and Qt4), **Holocene terraces** (Qoal), modern **flood plains** (Qal), fans (Qf), undifferentiated **alluvium** and **eolian** deposits overlying **pediment** surfaces (Qmp), **landslide** material (Qls) and **glacial erratics** (Qg). Engineered fill (Qef) has been mapped locally. A thin, widespread mantle of **loess** is distributed over many upland surfaces. It was not mapped but is discussed separately.

Colluvium consists of poorly sorted, **unconsolidated material**, 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 locally contains scattered organic debris and pebbly gravel. **Colluvium** is common as a veneer on moderate or steeply sloping hillsides, at the foot of hillslopes at valley margins, and in closed depressions or swales. **Colluvium** is ubiquitous, but was not mapped because doing so would unduly cover the underlying **bedrock formations**.

Glacial Erratics (Qg)

The only evidence of glaciation comes from widely scattered **erratic** boulders and cobbles of granitic and carbonate composition, which are found north of the Little Missouri River in the North Unit. The **erratics** form a thin, discontinuous, patchy, lag deposit (Qg) on upland surfaces and are most conspicuous along upland margins, where **soil** and vegetation cover are sparse. They are widely scattered, lying atop Sentinel Butte **strata** or poking through a veneer of **Holocene loess**. The **erratics** are believed to mark the maximum extent of **glacial** ice in this part of western North Dakota. Most are 1 to 2 feet in diameter, but some are almost 5 feet in diameter *(fig. 41)*.

The **erratics** are associated locally with lag deposits of gravels of both northern and southwestern affinity. Such gravels are scattered atop the southeast-trending promontory in 148-100-27 and -28 and on the **plateau** in 148-99-20, -28, -29, and -33b. They represent a mixing of sand and gravel of indeterminate late **Tertiary-Quaternary age** and **glacial** sediments, the coarser remains of which persist as a lag deposit. Similar gravel crops out south of Sperati Point on the promontory in 147-100-5, and -8 *(fig. 42)*. Clark (1966) mapped much of the area south and west of the Oxbow Overlook as **outwash**. Fulton (1976) mapped the **erratics** as part of the Medicine Hill Formation; also, he indicated that the southern limit of the Medicine Hill Formation passed through the North Unit, north and west of the Little Missouri River.

The age of the **glacial erratics** is uncertain, primarily because the evidence of glaciation is largely removed and consists only of widely scattered boulders. Fulton (1976) indicated that the **erratics**, part of the Medicine Hill Formation, represent his Glaciation A, the oldest known glaciation in the area. Clayton (1969) and Clayton et al. (1980) described similar **glacial** units in some detail. They argued that these types of **glacial** units are most likely early Wisconsinan or pre-Wisconsinan in **age** for several reasons. First, the **glacial erratics** in the North Unit are beyond the **glacial** maximum of late Wisconsinan **till**, i.e., **till** that has been reliably dated using the **carbon-14** method. Also, the remains of the early Wisconsinan (?) Napolean **till** are found within a few feet to a few tens of feet above the modern drainages. By comparison, all pre-Wisconsinan **glacial** remains are found on drainage divides 200 or more feet above modern drainages, similar to the position of the **glacial erratics** in the North Unit, which are more than 400 feet above the modern drainage. In addition, the late Wisconsinan **glacial** units occur as

Figure 41. Glacial erratics south of Sperati Point (147-100-8abb).

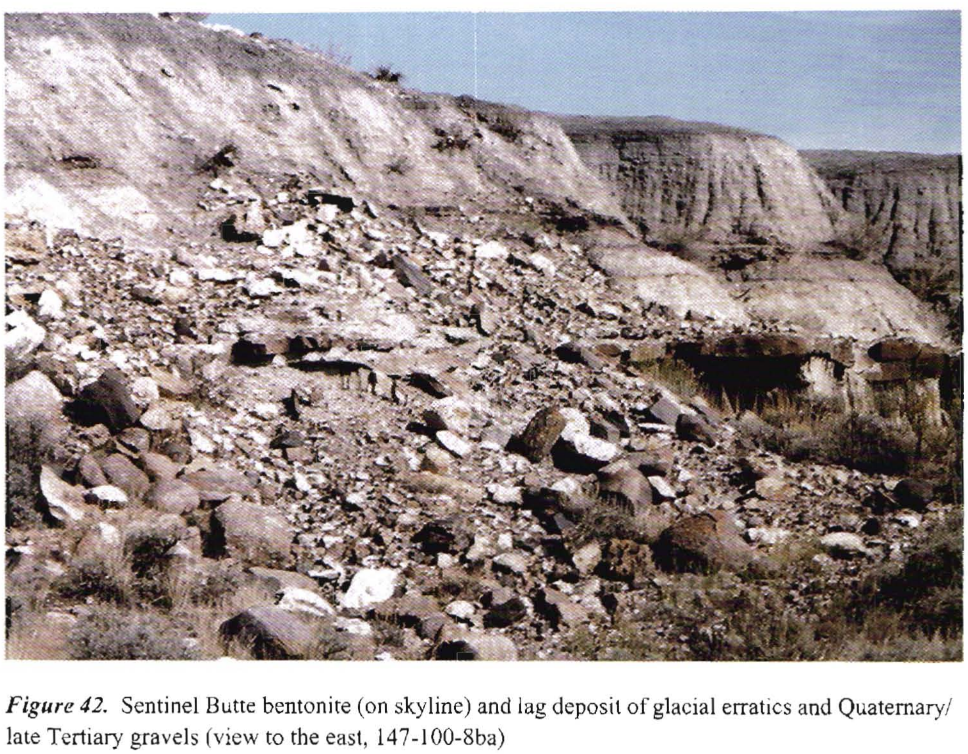


Figure 42. Sentinel Butte bentonite (on skyline) and lag deposit of glacial erratics and Quaternary/ late Tertiary gravels (view to the east, 147-100-8ba)

widespread tills that form constructional **glacial topography**. In contrast, the **glacial erratics** in the North Unit have no constructional **glacial topography**. The **erratics** are believed to be the remnants of **till**. in which all finer material has been removed by **erosion** and/or lost through a long period of **weathering**.

Clayton et al. (1980) described three **glacial** units that are recognized in western and southwestern North Dakota by **erratics**: the Dunn, Verone, and Napolean advances, oldest to youngest. In nearby Dunn County, Clayton (1969) and Clayton et al. (1980) used boulder density to distinguish the **glacial** advances. The Dunn glaciation was identified in areas where the boulder density is 1 boulder per kilometer of roadway, the Verone glaciation has approximately 10 boulders per kilometer, and the Napolean glaciation has approximately 100 boulders per kilometer. Clayton's map (1969, fig. 2 therein) suggested that the **erratics** in the North Unit are related to the Napolean Advance. Subsequent work (Clayton et al., 1980) suggested that the abundance of **erratics** in the North Unit is comparable to the Dunn glaciations in nearby Dunn County. but regional variation in boulder abundance makes this a highly tenuous means of correlation. The preponderance of evidence suggests that the **erratics** of the North Unit are pre-Wisconsinan in **age**; David Fullerton (USGS, Denver, Colorado, personal communications, 2000) has suggested that similar remains of **erratics** in adjacent Montana may even relate to a Pliocene-**age glacial** advance.

Alluvial Deposits beneath Pleistocene Terraces (Qt)

Alluvial deposits of **Pleistocene age** (Qt) are found atop **plateaus**, mesas, buttes, ridges, and benches flanking the valley of the Little Missouri River. These **Pleistocene** deposits lie unconformably on Sentinel Butte or Bullion Creek **strata**. Exposures of **Pleistocene alluvium** are generally restricted to the margins of **plateaus**, especially along south-facing hillslopes where the vegetation cover is sparse. Qt deposits are located 170 to 270 feet below similar sediments (QTa) found atop the Petrified Forest Plateau.

In the South Unit, Qt alluvial deposits are subdivided into four mappable units (Qt1, Qt2, Qt3, and Qt4), which are differentiated by their height above the modern channel of the Little Missouri River. Deposits of Qt4, the highest and oldest **Pleistocene terrace** deposits, are found on the western side of the Big Plateau, the eastern end of Johnson's Plateau, the **plateau** containing the Medora airport (140-102-23c), and similar smaller **plateaus** and ridges along the Little Missouri River. At Johnson's Plateau, the elevation of the basal **contact** of Qt4 is approximately 2500 feet above sea level (asl); which is approximately 260 feet above the channel of the Little Missouri River. The elevation of the **contact** declines by a few feet per mile to the north. The deposits of Qt1, Qt2, and Qt3 are younger and inset beneath deposits of Qt4 (*fig. 43*). At Johnson's Plateau, the elevation of the basal **contact** of the Qt3 **alluvium** is approximately 2480 feet asl or 240 feet above the channel of the Little Missouri River, the basal **contact** of Qt2 **alluvium** is approximately 2460 feet asl (220 feet above modern drainages); and that of Qt1 **alluvium** is approximately 2400 feet asl (160 feet above modern drainages) (*fig. 43*).

The sand and gravel in Qt deposits resemble the older **Tertiary-Quaternary alluvium** (QTa). The gravel contains a wide variety of lithologies of local and southwestern affinity, including **mudstone**, **sandstone**, **concretions**, silicified wood, **flint**, **silcrete**, **clinker**, **chalcedony**, and lesser quantities of quartzite and porphyry. Most clasts are 1 to 3 inches in diameter, but some are up to12 inches. The Qt deposits comprise less than 6 feet of sand and gravel. A comparable thickness of **Holocene loess**, which is not mapped, mantles the **alluvium**.

Isolated, scattered patches of gravel and rare **silcrete** boulders are present atop **plateaus** south of Scoria Point (140-102-24a and -24d), but they have clearly been let down as a lag deposit and so were not mapped.

Geologists have mapped these alluvial deposits in various ways. Some of the distinctions are related to the various scales of mapping, as small-scale maps (low detail) generally have lumped the **Pleistocene** alluvial deposits, and larger-scale maps have divided the **alluvium** into separate units based on height above modern drainages as is done here. Also, the lack of reliable radiometric dates has led to various mapping nomenclatures and styles for these alluvial deposits. For example, Clayton et al. (1980; 1:500,000-scale) mapped the deposits atop Johnson's Plateau and Big Plateau as undivided **Quaternary** and upper **Tertiary** sediment, and so it is unclear whether the surfaces were considered late **Tertiary** or **Quaternary** in **age**. Laird (1950, p. 8) considered these two **plateaus** and the **plateau** containing the Medora airport as his No. 4 **terrace** (numbering up from the modern **flood plain**), a pre-**Pleistocene** surface. He noted that *"The Little Missouri River then was probably a much larger stream than it is now and was flowing in a broad shallow valley which now stands at an elevation some 200 feet above its present level in the present south Roosevelt Park area."* University of North Dakota graduate students (Schmitz, 1955; Petter, 1956) slightly refined Laird's **terraces** in their study of the history of the Little Missouri River. Both mapped sand and gravel deposits at Johnson's and Big Plateaus. Although substantive dates were not available, they considered them a Pliocene/**Pleistocene** surface. Carlson (1983) mapped these deposits simply as **Quaternary terrace alluvium**.

Kuehn (1995) studied this **terrace** level in the South

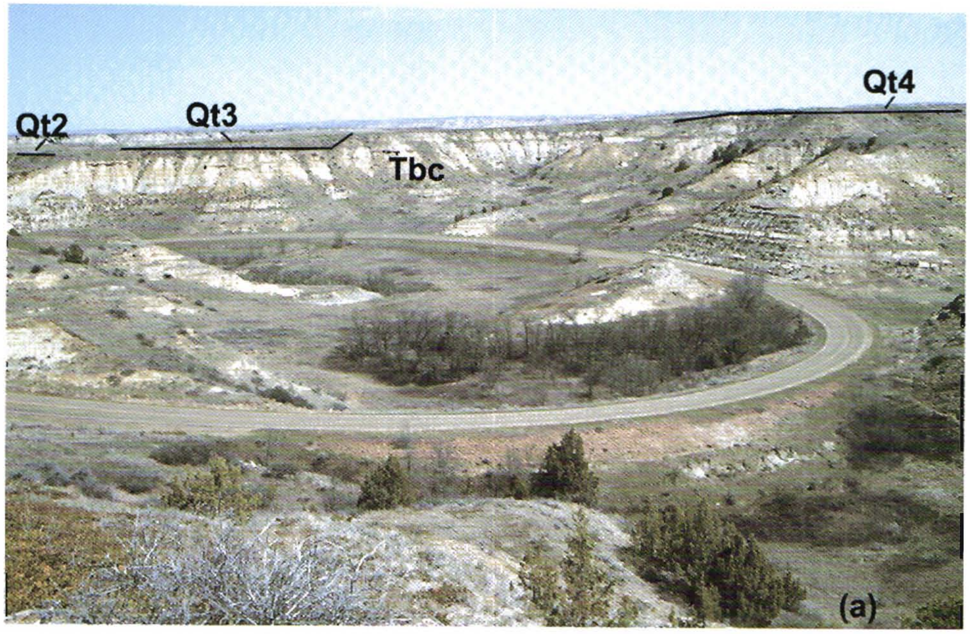


Figure 43. Inset alluvial deposits underlying Quaternary-age terraces on Johnson Plateau. Deposits (Qt1 through Qt4) step up from the modern Little Missouri River. The highest deposit is older than the lower deposits.

Unit in some detail. At Johnson's Plateau, he mapped four cut **terrace** levels delineated by three risers, or sharp breaks in slope. He labeled these Pt1, Pt2, Pt3, and Pt4 (from lowest to highest), which **correlate** to the Qt1, Qt2, Qt3, and Qt4 units respectively, of this report. [Note: Kuehn mapped **landforms**, i.e., **terraces**; we mapped **bedrock** and surface deposits.] Equivalent, but less well-expressed, alluvial deposits are present on Big Plateau.

Kuehn (1995) discovered wood fragments in the **fluvial** gravel at Big Plateau that had a **carbon-14 date** of 24,230 +1510/-1270 yr BP *(Table 3)*. From this date, Kuehn argued that the ancestral Little Missouri River occupied the Pt4 **terrace** level (Qt4 of this report) considerably later than previously thought. Also, Kuehn (1995) argued that the Little Missouri River has downcut 300 vertical feet to the modern channel since 24,000 years BP. Actually, in Kuehn's model, this stream **incision** would have had to have occurred in no more than 17,000 years, because the **Holocene** alluvial deposits, discussed later, show that area streams had downcut to near their modern elevations by 7000 years before present and have since undergone several alternating cut-and-fill cycles of stream **incision** and **aggradation**.

Kuehn's **carbon-14 date** is the only one obtained thus far for the Qt alluvial deposits. For unexplained reasons, Kuehn accepts this controversial date, whereas he rejects two other radiocarbon dates that he obtained. Both rejected samples have **carbon-14 dates** from the Late Wisconsinan (22,290 +/- 310 years BP (Lab # A-6480) and 17,640 +/- 230 year BP (Lab # A-6483) *(Table 3)* (Kuehn, 1995, p. 79)). The samples come from slope-wash deposits situated approximately 200 feet lower in elevation than the Qt4 deposits. By accepting a Late Wisconsinan date for the deposition of Qt4 **alluvium** and by rejecting Late Wisconsinan **carbon-14 dates** for deposits found well below the Qt4 level, Kuehn proposed a much younger and far more rapid formation of the Little Missouri Badlands than ever before imagined. It is much more probable that the wood fragments were found in **colluvium** overlying the **fluvial** gravel and not in Qt4 gravel. Alternatively, roots from a tree could have grown into the Qt4 **alluvium** long after the gravel was deposited.

The **incision** history proposed by Kuehn (1995) conflicts with earlier studies, which related the inception of **incision** to drainage diversion during pre-Wisconsinan time by an early advance of continental glaciers in northwestern North Dakota (e.g., Laird, 1950; Fulton, 1976; Bluemle, 1991 and 2000). Old **glacial till** (Dead Man drift of Bluemle, 1971; and the Medicine Hill Formation of Ulmer, 1973, and Ulmer and Sackreiter, 1973), is in the ancestral channel of the Little Missouri River. This **till** and its associated ice sheet apparently blocked and diverted the Little Missouri River into its present course *(figs. 44a* and *b)*. Regional studies suggested that this **till** is correlative with the Archer **till** of eastern Montana (Fullerton et al., 1995; David Fullerton, USGS, Denver, Colorado, personal communication, 2000), which was overlain by a deposit of volcanic **ash** (the Lava Creek B **ash**; David Fullerton, USGS, Denver, Colorado, personal communication, 2000) approximately 640,000 years ago. These geologic relations suggest that **glacial** diversion of the Little Missouri River occurred well before the Late Wisconsinan and probably by the mid-**Pleistocene**, at least 640,000 years ago.

Alluvial Deposits of Holocene Age (Qoal and Qal)

Alluvial deposits of **Holocene age** are found within a height of 35 feet above stream channels, although some deposits are up to 50 feet above stream channels. Along tributary streams, there are five distinct **fluvial** surfaces: four **Holocene** cut-and-fill **terraces** and the modern **flood plain** *(fig. 45)*. It is impractical to map all five of these surfaces along tributaries at a scale of 1;24,000, although Kuehn (1995) attempted to do this. **Terrace** correlations are complex, because: 1) the height of fill **terraces** is not constant up drainage ways; the **relief** among **terraces** increases where valleys narrow, and diminishes where valleys widen, 2) fill **terraces** of lower reaches gradually change to **strath terraces** along upper reaches, and 3) the lower reaches of most streams have been aggrading for the past 150 years or more, whereas the upper reaches have incised during this period. In this work, the **fluvial** deposits of **Holocene age** are simplified into two mappable units, Qoal and Qal. Qal designates **alluvium** that is younger than about 500 years age, whereas, Qoal designates older **alluvium**. Qoal includes all deposits underlying the three highest **Holocene terraces** (Qt1, Qt2, and Qt3 surfaces of Gonzalez, 1987a, 1987b, 1996, 2001a or the T4, T3, and T2 surfaces of Kuehn, 1995). Qal includes all **alluvium** underlying the modern **flood plain** as well as the lowest **terrace** surface (Qal and Qt4 surfaces of Gonzalez, 1987a, 1987b, 1996, 2001a, 2001b; or the T0 and T1 surfaces of Kuehn, 1995).

Qoal deposits are distinguished from modern alluvial deposits (Qal) by a steep, typically vertical, erosional scarp *(fig. 46)*. Qoal deposits are less than 20 feet thick, comprising a vertical sequence of coarse gravel and sand deposited by **lateral-accretion** processes, overlain by sand, silt, and **clay** deposited by **vertical-accretion** processes on **flood plains**, commonly capped by silt-rich sediment, and interrupted by buried **soil** profiles with varying degrees of development *(figs. 47a, 47b, 47c)*. At valley margins, Qoal deposits interfinger with and are locally overlain by slope-wash sediments, valley-margin **alluvium** and **colluvium**, and **alluvial fans**.

Thomas Hamilton (1967a, 1967b) undertook the first study of recent **alluvium** in the Park as part of his Master's thesis at the University of North Dakota. His work concentrated on young alluvial deposits of the Jones Creek

Table 3. Summary of Carbon-14 dates from Late Wisconsinan and Holocene alluvial fills

Map unit (this report)	Carbon-14 date (years before present[a])	Lab number	Material	Landform/fill	Source
Qt4	24,230+1150/-1270	A-7114	Wood	Pt4	Kuehn, 1995
---	22,290+/-310[c]	A-6480	Bulk soil	Colluvium	Kuehn, 1995
---	17,640+/-230[c]	A-6483	Bulk soil	Colluvium	Kuehn, 1995
Qoal	6660+/-45	A-6481	Charcoal	T4	Kuehn, 1995
	6115+145/-140	A-7113	Charcoal	T4	Kuehn, 1995
	5000+130/-125	A-78137	Bulk soil	T3	Kuehn, 1995
	3860+/-70	WIS-1907	Bulk soil	Qt2[b]	Gonzalez, 1987a
	3830+/-70	WIS-1908	Bulk soil	Qt2[b]	Gonzalez, 1987a
	3240+/-80	WIS-1906	Bulk soil	Qt2	Gonzalez, 1987a
	2960+/-70	WIS-1909	Bulk soil	Qt2	Gonzalez, 1987a
	2475+/-60	A-7110	Charcoal	T2	Kuehn, 1995
	2400+/-60	Beta-38736	Bulk soil	T2	Kuehn, 1995
	2280+/-70	WIS-1910	Bulk soil	Qt3	Gonzalez, 1987a
	2190+/-130	Beta-27718	Charcoal	T2	Kuehn, 1995
	880+/-25[d]	A-6482	Charcoal	T2	Kuehn, 1995[d]
Qal	380+/-120	Beta-32261	Charcoal	T1	Kuehn, 1995
	300+/-65	Beta-31477	Bone	T1	Kuehn, 1995
	290+/-80	Beta-31937	Bone	T1	Kuehn, 1995
	<185	I-2325	Wood	Paleosol B	Hamilton, 1967a
	150+/-60	Beta-31786	Charcoal	T1	Kuehn, 1995
	100+/-0.8% modern	Beta-32164	Bone	T1	Kuehn, 1995

[a] By convention, radiocarbon years BP (before present) use A.D. 1950 as the reference year.
[b] Samples WIS-1907 and -1908 were originally thought to be from the Qt1 fill, but subsequent field work in this study indicates they were misidentified and properly belong to Qt2 fill.
[c] Kuehn (1995, pp. 78-79) rejected dates, although they do make stratigraphic sense.
[d] Kuehn (1995, p.78) rejected the date, although it does make stratigraphic sense and elsewhere in his thesis (pp. 144-145) the date is used.

basin; these coincide with the Qal deposits of this report. Mark Gonzalez (1987a, 1987b, 1987c) undertook the first study of older **Holocene** alluvial deposits in the Park as part of his Master's thesis at the University of Wisconsin-Madison. His study was restricted to the **fluvial** deposits along Paddock Creek. David Kuehn's (1995) doctoral dissertation at the University of Texas A & M is the most detailed study of the **Holocene alluvium** in the Park to date. Kuehn studied the **alluvium** along all the major drainages in the Park. He, like Gonzalez (1987a, 1987b, 1987c, 1996), identified four **Holocene age terraces** and a modern **flood plain** along the major ephemeral streams.

Gonzalez (1987a) and Kuehn (1995) provided 12 **carbon-14 dates** from Qoal equivalent deposits (Table 3). Four dates are reported from the oldest **Holocene** fill (Qt1 of Gonzalez, 1987a; and T4 of Kuehn, 1995) although subsequent field work suggests that Gonzalez misidentified a Qt2 as a Qt1 fill. Kuehn's (1995, p. 78) samples provided **carbon-14 dates** of 6115+145/-140 years BP and 6660+/-45 years for T4. Dates for the next younger fill (Qt2 of Gonzalez, 1987a; T3 of Kuehn, 1995) include 3860+/-70 years BP, 3830+/-70 years BP, 3240+/-80 years BP, 2960+/-70 years BP (Gonzalez, 1987, p. 56), and 5000+130/-125 years BP (Kuehn, 1995, p. 78). Six radiocarbon dates have been obtained from the youngest fill included in the Qoal map unit (Qt3 of Gonzalez, 1987a; T2 of Kuehn, 1995). These include dates of 2280+/-70 years BP (Gonzalez, 1987a, p. 56), 2190+/-130 years BP, 2475+/-60 years BP, 2400+/-60 years BP, and 880+/-25 years BP (Kuehn, 1995, p.78). These are all in close agreement, except for sample A-6482, which Kuehn rejected. He does not explain why it was rejected.

Hamilton (1967a) and Kuehn (1995) provided six radiocarbon dates for **alluvium** mapped here as Qal. This includes the **alluvium** beneath the modern **flood plain** and the youngest **terrace**. All six dates indicate that the Qal **alluvium** is less than 500 years old (Table 3). Everitt (1968) and Gonzalez (1987a, 1996, 2001a, 2001b) provided

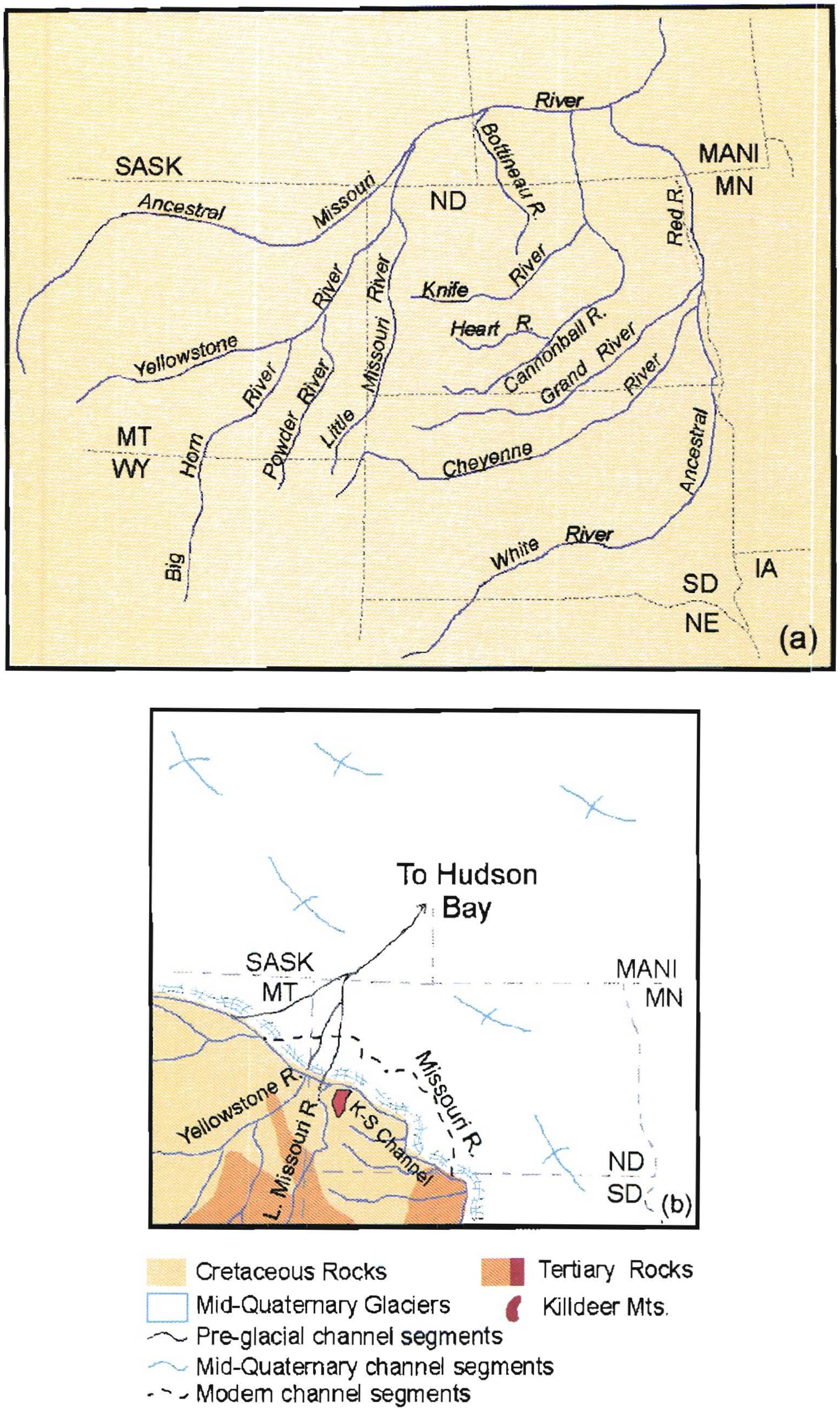


Figure 44. (a) Rivers of the northern Great Plains flowed north to Hudson Bay prior to the formation of large continental ice sheets during the Quaternary. (b) When ice sheets developed in Canada west of Hudson Bay and advanced into North Dakota, drainages to Hudson's Bay were blocked and diverted into ice-marginal positions. The diverted channel of the Little Missouri River had a shorter, steeper course, which increased the erosive powers of the river and initiated the downcutting that created the badlands topography along the Little Missouri River.

Figure 45. Four Holocene terraces and the modern flood plain commonly occur along the small tributary streams of the Little Missouri River. Individual remnants of the four terraces are too small and patchy to be mapped separately at a scale of 1:24,000. The alluvium below the three oldest and highest terrace surfaces are collectively mapped as Qoal (older alluvium), and the alluvium below the lowest terrace and the modern flood plain is mapped as Qal (recent alluvium).

Figure 46. Erosional scarp (or riser) between Qoal and Qal alluvium (view to the southeast up Paddock Creek, 140-101-17d).

dendrochronologic data to show that the Qal deposits formed primarily in the past 250 years. Gonzalez (1996, 2001a, 2001b) demonstrated that many of the small tributaries that feed the Little Missouri River incised along their upper reaches in the mid-19th Century, and filled in their lower reaches during the past 230 or more years. Gonzalez (1987a, 1987b. 1987c) and Kuehn (1995) did not have these **dendrochronologic** data to illustrate these processes, and hence some of their detailed **terrace** correlations are incorrect.

Gonzalez (1987a, 1987c) noted that the radiocarbon dates obtained from buried **paleosols** correspond to **soil**-forming episodes reported in **loess** deposits of the Missouri River Valley in North Dakota, the Nebraska Sandhills, and the dune fields of northeastern Colorado. That these geomorphic events appear to be in phase throughout a large area suggests that climate may be responsible for their occurrence. Kuehn (1995) noted that in valley-margin settings, **fluvial** deposits commonly interfinger with or are capped by **slope-wash** sediments, and that at the mouths of tributary streams, they interfinger with **alluvial fans**. The **terraces** are locally mantled with **loess**.

Modern alluvial deposits (Qal) are mapped along the Little Missouri River and its major tributaries. These deposits consist of sand, silt, and **clay** deposited in modern

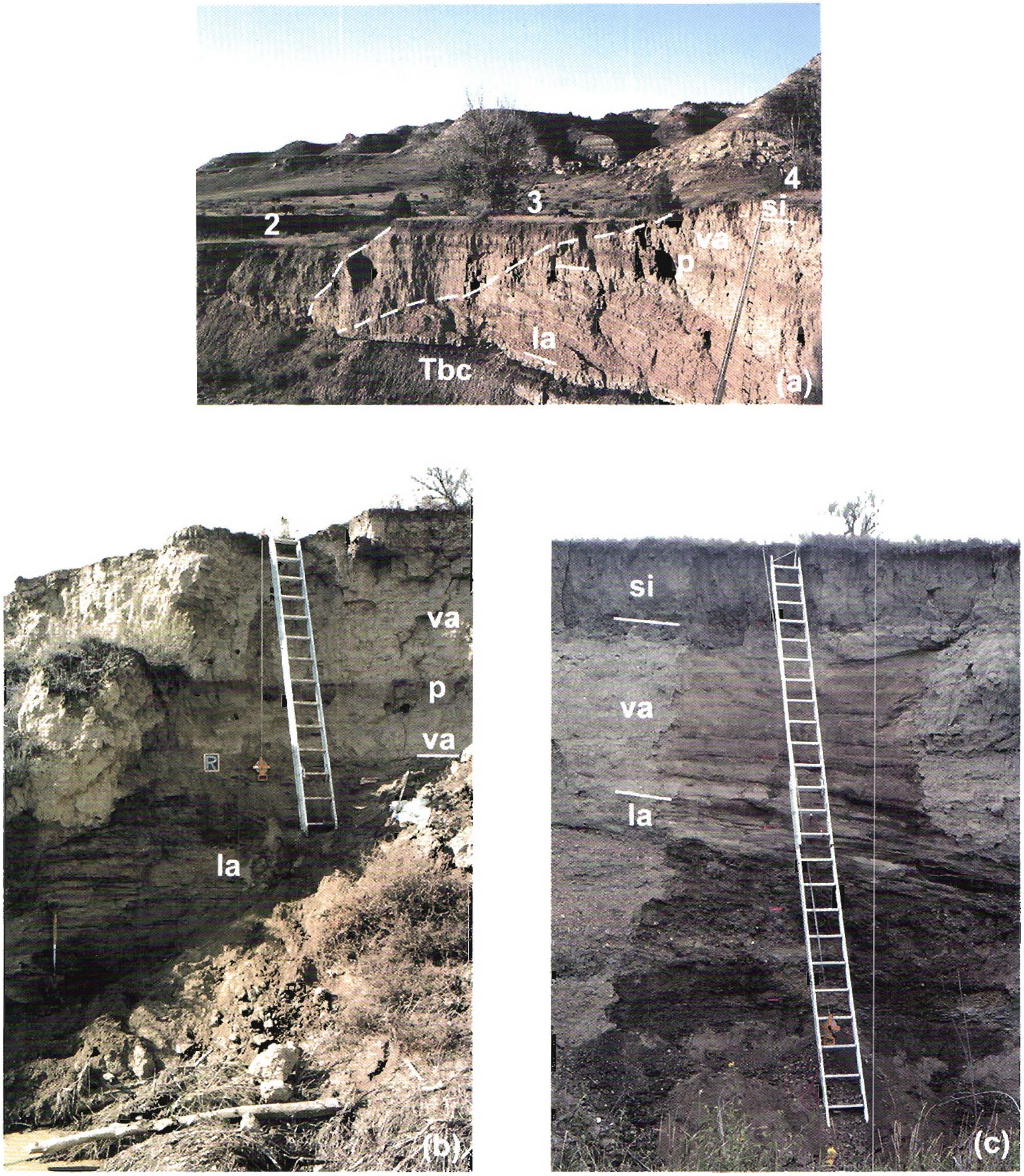


Figure 47. Stratigraphy of the Qoal alluvium comprises a lateral-accretion (la) deposit of sand and gravel overlain by a vertical-accretion (va) deposit of sand, silt, and clay. Buried paleosols (p) of varying degrees of development interrupt the vertical sequence of alluvium, and silt-rich caps (si) of in situ and reworked loess cap many of the alluvial deposits. (a) Alluvium and windblown silt exposed beneath three Holocene terraces (2, 3, and 4 numbered younger to older) along Paddock Creek (140-101-17dbc). The alluvium beneath terrace #4 is deposited directly on bedrock, the Bullion Creek Formation (Tbc). (b) Alluvium exposed beneath Holocene terrace #2 along Paddock Creek with a well developed buried soil profile (140-101-17ccd). (c) Alluvium mantled by windblown silt beneath the #4 Holocene terrace along Paddock Creek (140-102-13aab).

Figure 48. Note narrow, arcuate bands of cottonwoods that parallel the river channel. Each band marks the location of a former point-bar or natural levee deposit (view to the east-southeast to the Little Missouri River, 148-100-36b).

river channels and **flood plains**. Prominent features of the Little Missouri River **flood plain** are arcuate bands of uniform-age cottonwood trees (Everitt, 1968); each band corresponds to a former point-bar deposit *(fig. 48)*. Studies by Everitt (1968) and Kuehn (1995) have shown that sediments older than about 400 years are not present on the floor of the Little Missouri River valley.

The thickness of these deposits is uncertain. Based on three test borings, Croft (1985a,b) provided a cross-section of the Little Missouri aquifer just south of the North Unit, indicating that the **alluvium** there is at least 176 feet thick. These values appear to be anomalous in comparison to other well data in the area. In the South Unit, at Mike Auney Bottom (141-101-32a), Kuehn (1995) noted that T1 sediments overlie **lignite**, and that this same **lignite** was exposed, during a period of very low flow, at the bottom of the current river channel, thereby precluding the presence of deeply buried **alluvium**. The driller's log from the National Park Service's headquarters well (140-102-26b) at Medora shows only 33 to 34 feet of alluvial deposits over **bedrock**.

Everitt (1968) investigated the recent history of the Little Missouri River **flood plain** in the North Unit by examining the growth of flood-plain forests. Tree-ring analyses showed that the cottonwood forest comprises a series of uniform-aged stands of trees that increase in age away from the channel *(fig. 49)*. Each stand formed from a cottonwood thicket on a point-bar deposit and, thus, records recent migration of the channel. (Mature cottonwood forests do not reseed themselves and so there are no saplings in the understory.) Everett showed that most of the modern flood-plain sediments were deposited within the past 300 years.

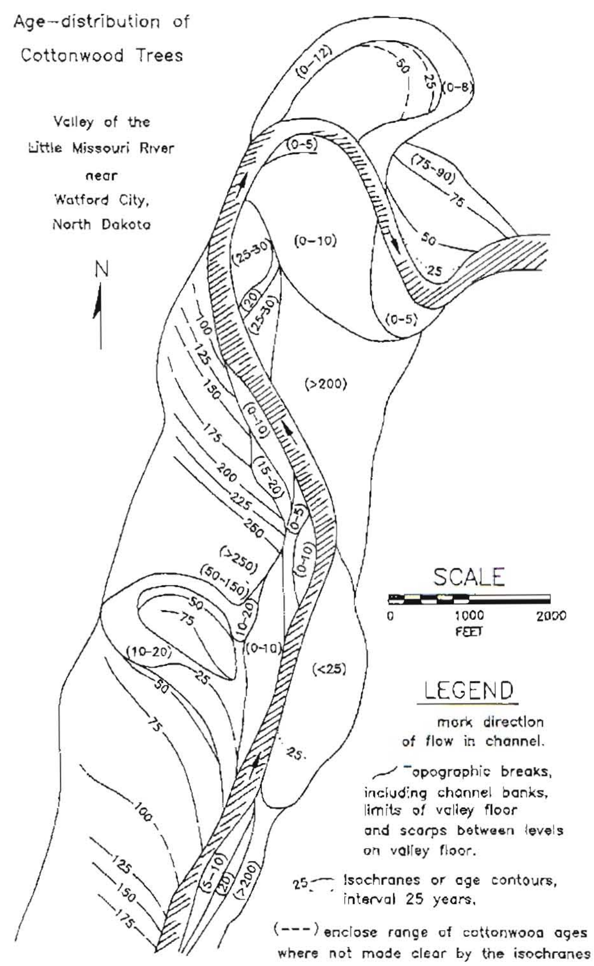


Figure 49. Age map of the valley floor along a reach (147-100-4, 148-100-33) of the Little Missouri River based on the distribution of cottonwood trees (from Everitt, 1968).

Along the Little Missouri River, there are two low surfaces, separated by a 10- to 15-foot-high erosional scarp. These surfaces were described as the No. 1 and No. 2 **terrace** surfaces by Laird (1950), Schmitz (1955), and Petter (1956). Everitt (1968) examined a series of **aerial photographs** that showed that the flood of March 1947, considerably widened the channel, pushing the riverbanks back to the scarp that now separates the upper and lower surfaces. Thus, Everitt classified the **flood plain** as split-level, containing both high and low **flood plains**. The **terrace**-like **topography** formed simply as a result of channel expansion during unusual flood events. (The classification of this surface as a **terrace** or a **flood plain** is really one of semantics, depending in large measure on the frequency of flooding.)

Alluvial Fans (Qf)

Alluvial fans are present at the mouths of nearly every small valley, but only the larger fans along the Little Missouri River and its major tributaries were mapped. Where adjacent fans coalesce or where **alluvium** accumulates at the base of hillslopes along the valley margin, the resulting deposits are referred to as valley-margin **alluvium**, which is stored in alluvial aprons, alluvial slopes, or bajadas. Generally, the valley-margin **alluvium** is not mapped unless the deposits appear to be more than 6 feet thick and cover areas greater than 10 acres (a quarter-quarter-quarter section). Fans consist of a highly variable sequence ranging from coarse and poorly sorted sand and gravel to massive or laminated mud. All but the largest fans of the larger tributaries consist of locally derived materials eroded from adjacent hillsides.

Fans interfinger with stream deposits at their downstream end. The upstream portion of **alluvial fans** is gradational, interfingering with slope-wash and colluvial deposits that mantle the margin of valleys. Older **Holocene** fans are distinct from more modern fans in two respects. First, the older fans are invariably deeply incised by their contributing streams. Second, the older fans may still receive slope wash from adjacent hillsides, but they no longer receive sediment from their contributing streams, because these incised streams bypass the old **fan** surface and transport sediment to younger, inset **fan** surfaces or **fluvial** channels.

Mantled Pediments (Qmp)

Pediments are eroded or planated **bedrock** surfaces that form at the base of steep slopes. **Pediments** typically form wherever steep, poorly vegetated hillsides undergo rapid **erosion** *(fig. 50)*. In the South Unit, the largest **pediment** surfaces are found at the base of the eastern **escarpment**, in the vicinity of Boicourt and Sheep Butte Springs, at the heads of Sheep, Paddock, and Jones Creeks *(figs. 51, 52)*. In the North Unit, large **pediments** are found along Squaw Creek and the Little Missouri River.

Strictly speaking, **pediments** are erosional surfaces; however, the **pediments** in the Park are complex assemblages in which the erosional surface has been buried by **slope-wash** sediment and/or reworked **eolian** material. Some of the mantled **pediments** are zones of active alluviation, whereas others are deeply incised, marking an end to deposition and the resumption of erosional processes. The mantle of fine-grained material burying **pediments** is mapped here as Qmp. The mantle is generally less than 3 feet thick *(fig. 53)* but exceeds 6 feet in places.

The distinction between alluvial deposits and some mantled **pediment** deposits is somewhat arbitrary. Indeed, Kuehn (1995), who undertook a detailed study of the **Quaternary stratigraphy** of the South Unit, mapped many of the upper **pediments** as **slope wash** and the remainder as one of two older **terraces** (his T3 or T4). Unlike **terraces** in downstream reaches, **terraces** in the headwater reaches are **strath terraces**, that is they are **bedrock**-cut surfaces that are mantled by relatively thin deposits of **fluvial** sediment. Because both **straths** and **pediments** are **bedrock**-cut surfaces, they can be easily confused. The true distinction between stream and **pediment** deposits is the geometry of the **bedrock**-cut surface. A **strath terrace** is level perpendicular to the channel and dips downstream nearly parallel to the gradient of the modern **flood plain**. A **pediment** surface generally dips away from hillslopes towards channels. Because both **strath** and **pediment** surfaces are mantled with alluvial and reworked **eolian** materials, the diagnostic geometry of the **bedrock** surface is hidden from view. **Pediment alluvium** was mapped only at the foot of major **escarpments** and the heads of major drainages.

Mass-Wasting Deposits

Mass-wasting deposits are widespread in both the North and South Units. They include materials deposited by **creep**, slide, flow, **slump**, and rock-fall on hillsides and valley floors. They range in size from small, individual block falls, to large, complex, rotational **slumps** that cover up to 1 square mile in area.

Landslides (Qls)

Mass-movement deposits more than a few acres in area and formed by **slump**, **earth flow**, and rock falls have been collectively mapped as **landslide** (Qls) deposits. Smaller **landslides** and individual hillslopes affected by **creep** are shown on the geologic map with a symbol, rather than as a map unit (see map legend). **Creep** is particularly common on north- and northeast-facing slopes of the Bullion Creek Formation in the South Unit. These hillslopes are recognized by a series of roughly horizontal, nearly parallel fractures and hummocks. Landslides are discussed

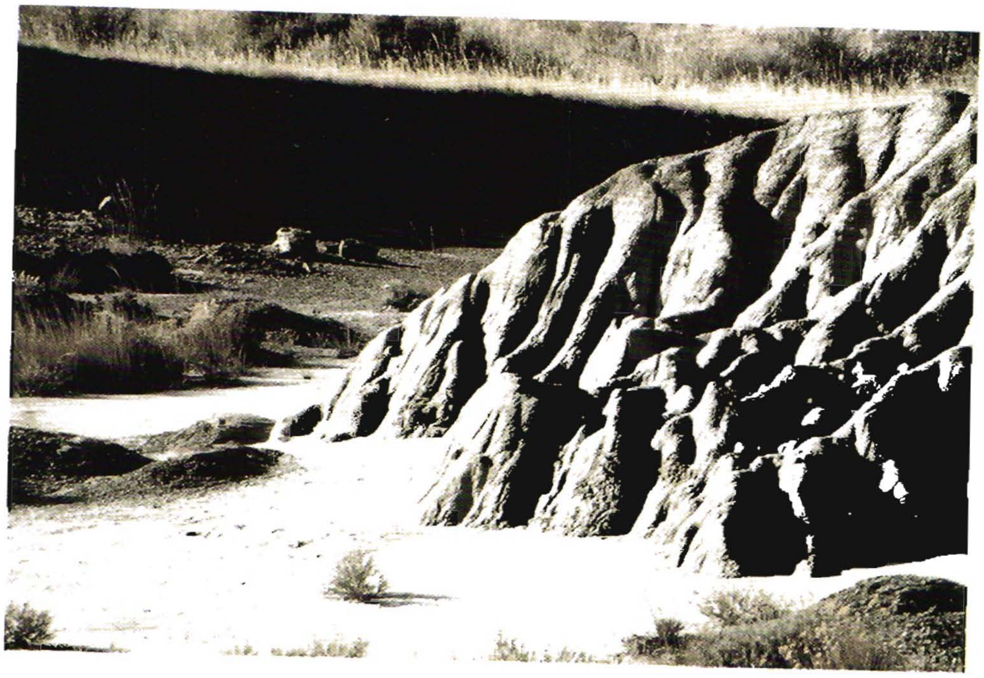


Figure 50. Miniature pediment. Pediments are planated bedrock surfaces, covered with a veneer of slope-wash sediment, that form at the base of steep slopes (140-101-13d).

Figure 51. Gently sloping, grass-covered pediment and an outlying, residual knob, or inselberg, of Sentinel Butte strata (view to the east-southeast from 140-100-19bc).

Figure 52. Whereas most pediment surfaces in the Park abut steep hillsides, in many places, the pediments are eroded around their margins and have become separated from adjacent hillsides by an erosional gap (view to the southeast at 140-101-11cad).

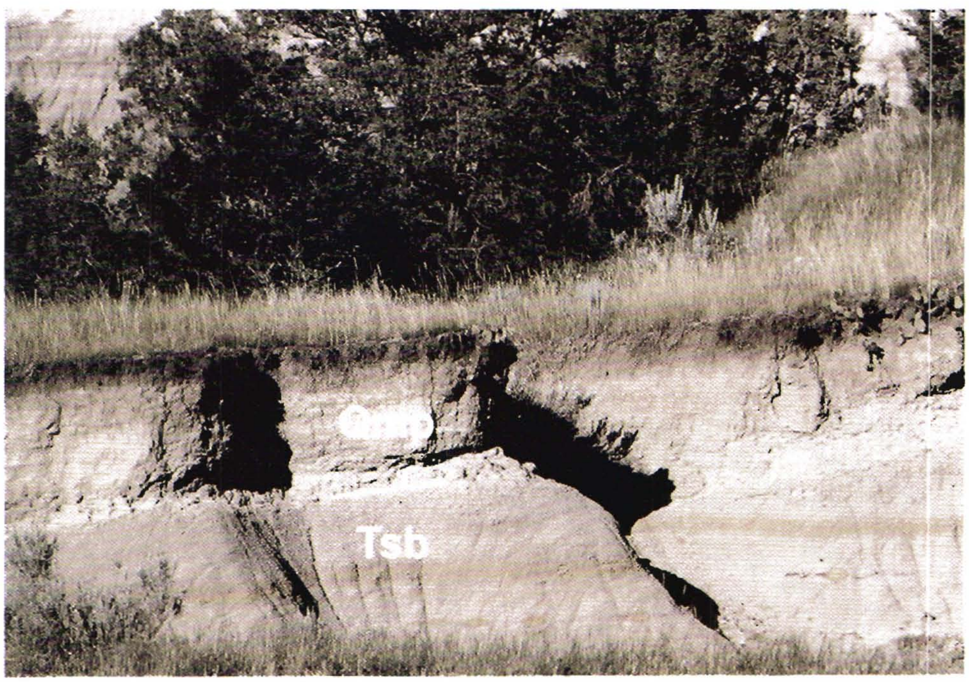


Figure 53. Veneer of alluvium and wind-transported silt mantles many pediment surfaces. In this view, the unconsolidated mantle (Qmp) overlies the Sentinel Butte Formation (Tsb) (140-101-11dac).

in more detail under the *Geologic Hazards* section of this report. Most **landslides** involve **strata** of the Sentinel Butte Formation. Large rotational **slumps** are characterized by their hummocky **topography**, numerous arcuate scarps, and greatly disturbed, randomly oriented bedding *(fig. 54)*. Smaller slope failures are ubiquitous and appear to be more prevalent on Sentinel Butte **strata** *(fig. 55)*. They also occur along over-steepened slopes, such as along the banks and steep walls of creek and river valleys.

In the South Unit, the largest **landslides** are along the eastern **escarpment**, along the eastern flank of the Petrified Forest Plateau, and surrounding Buck Hill. The influence that **lignite beds** can have on **landslide formation** is also clearly shown in the South Unit. In 140-101-13ddc, the failure plane of a small rotational **slump** dips steeply until it intersects and merges with a thin **bed** of **lignite** *(fig. 56)*. A similar example is found in 140-101-14bbb.

The most spectacular **landslides** are those in the North Unit, where two classic types of rotational **slumps** are present. Large, complex **slumps** with a characteristically hummocky surface are present along the length of the Little Missouri River valley. The largest of these is on the north flank of Achenbach Hills; Achenbach Spring flows from the headwall of this **landslide**.

The second classic type of rotational **slump** is found

Figure 54. Looking northwest towards large, complex rotational slump below Oxbow Overlook (at upper left), 148-100-33b. The hummocky topography of such slumps contrasts sharply with adjacent undisturbed strata.

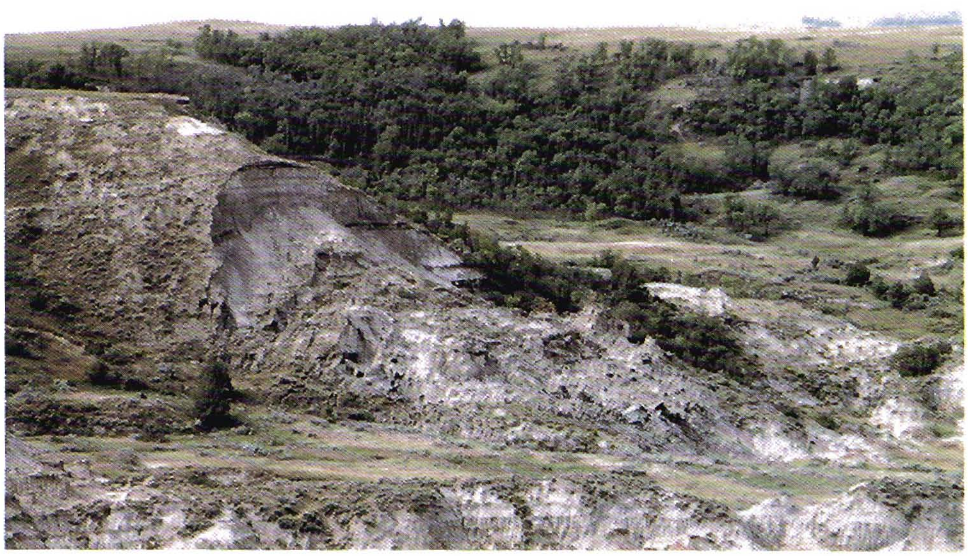


Figure 55. Small landslide in Sentinel Butte strata (view to the southwest to 140-100-32bca).

Figure 56. Small rotational slump in Sentinel Butte strata. Note rotation of beds and how the failure plane abruptly merges with a thin bed of lignite (view to the south, 140-101-13ddc).

Figure 57. Large rotational slump block in the North Unit. Displaced strata indicate that these blocks have moved downslope about 120 vertical feet. The presence of undisturbed, horizontal Sentinel Butte strata at the base of these blocks indicate that these blocks were emplaced by rotational slumping, and not faulting as some have speculated (view to the east-southeast to 148-99-33db).

north of the Little Missouri River between the east entrance and Juniper Campground; there, **landslides** are characterized by large coherent blocks with **beds** dipping into the hillside at 25° to 50° *(fig. 57)*. Numerous small displacements are found within the blocks and collectively have served to accommodate stresses resulting from block rotation *(fig. 58)*. Matching the lower yellow **bed** in the **slump block** in 148-99-33db with the same undisturbed **bed** in the valley wall above shows that this block has moved down about 120 feet in elevation. The presence of undisturbed, horizontal Sentinel Butte **strata** at the base of these blocks clearly shows that these blocks were emplaced by rotational **slumping** and not by faulting, as some have speculated. A greenish gray **clay**, present in undisturbed **strata** at the "Concretion Pullout" and in the Caprock Coulee area at an elevation of about 2,020 feet, is also present at the center of 148-99-32 and shows that the **strata** at the toe of the slide have not been displaced.

Substantial **erosion** has occurred since emplacement of the **slump blocks**, so that the upper part of the detachment surface along which the blocks moved has been almost entirely eroded away. Two small parts of this surface are exposed, however, in 148-99-32b *(fig. 59)*. There the surface dips to the south (at 60°) and southeast (at 35°). A dark bluish gray **bentonite**, apparently the

Sentinel Butte **bentonite**, blankets the surface, suggesting that the **bentonite** itself may have at least locally served to "lubricate" the detachment surface.

In the North Unit, many small rotational **slumps** have developed over the Sentinel Butte **bentonite** (see *fig. 33*). The **bentonite** has served as a detachment surface, and overlying **beds** have rotated down and into the hillside to create a miniature version of the much larger **landslide** blocks described above.

Artificial Deposits

Engineered Fill (Qef)

Several small areas of engineered fill were mapped in both units of the Park. Fill in the North Unit has been mapped along U.S. Route 85 and in the South Unit along Interstate 94.

Although few areas of fill are mapped, fill should be anticipated in any areas formerly disturbed by construction activities. Many such areas - roads, bridges, and built up areas - are shown on the topographic base map.

Figure 58. Numerous small displacements are found within the large slump blocks of the North Unit and collectively have served to accommodate stresses resulting from block rotation (view to the northeast at 148-99-33dd).

Figure 59. Failure plane (arrow) dips to the south at 60°. A dark bluish gray bentonite, apparently the Sentinel Butte bentonite, blankets the surface, suggesting that the bentonite itself may have at least locally served to "lubricate" the detachment surface (view to the west at remnant of failure plane in 148-99-32b).

STRUCTURE

Theodore Roosevelt National Park lies near the center of the Williston Basin, a broad, structural depression filled with **sedimentary rocks** *(fig. 60)*. The regional **dip** of surface **beds** is generally 155-194 ft/mi toward the center of the basin (Hickey, 1977), with gradually increasing dips for older **strata**. Regional dips are interrupted in many areas by small structures and by the Cedar Creek and Nesson Anticlines. See Gerhard et al. (1982) for a review of the structural development of the Williston basin.

Although the **strata** of western North Dakota are typically viewed as essentially horizontal and structureless, detailed mapping of the HT Butte **clinker** in the South Unit and of the Sentinel Butte **tuff/bentonite** in the North Unit demonstrates that these **beds dip** gently to the northeast at about 100 feet every 2-3 miles. Given three widely spaced points on each of these **beds**, dips are determined to be about 0.2° to the east and northeast, imperceptible to the naked eye. Structure contour maps show that these **beds** are gently warped as well, which is typical of such flat-lying **strata**. Elsewhere in southwestern North Dakota, structural contour maps, such as those of Meldahl (1956) and Fisher (1953), show that surface **strata** are not truly horizontal, but **dip** gently toward the center of the basin.

No **faults** were found in either the North or South Units during this mapping project. The apparent lack of tectonic deformation, other than gentle tilting of **beds** towards the center of the basin, fits, at least in part, with the model of "lineament-block tectonics" developed by Shurr et al. (1994). In their model, southwestern North Dakota and adjacent areas are broken into a mosaic of tectonic blocks by what are known as "Landsat lineament zones," comparatively narrow zones a few tens of miles wide that are mapped using linear features visible on satellite images in conjunction with subsurface structure contour maps. These zones are the sites of numerous structural and stratigraphic anomalies and are believed to reflect zones of **basement** weakness; they bound relatively large (hundreds of square miles) blocks that show little evidence of internal deformation. The Precambrian **basement** is thus thought to consist of a collage of blocks and bounding zones of weakness, representing accreted island arc and microcontinent terranes, that have been reactivated throughout Phanerozoic time, thereby influencing depositional patterns.

The South Unit lies in the southwestern corner of one such block *(fig. 61)*. The North Unit lies near the northwestern corner of the same block and appears to overlap or lie close to a subsidiary lineament zone that parallels the northeastern margin of the block. Detailed mapping of key marker **beds** in both units revealed no evidence of faulting. In particular, the anomalously straight trend of Paddock Creek, aligned as it is with the mouth of Knutson Creek (140-102-3, -11, and -12), suggests some underlying structural control. However, the base of the HT Butte **clinker** is accordant across Paddock Creek and no evidence of displacement was found.

Whereas there are no **faults** indicative of deep-seated tectonic activity in the Park, late **Tertiary** tectonic features of these lineament zones - including normal **faults**, gentle folds, and angular **unconformities** - are known in and near the Little Badlands southwest of Dickinson, where Arikaree (Oligocene to Miocene) and older **strata** are **faulted** and warped into a northeast-trending **syncline** (Shurr et al., 1996). Near Dickinson, the **strata** of the Bear Den Member (latest Paleocene) are warped, reflecting a continuation of the Little Badlands **syncline**. Also, normal **faults** offset Paleocene-**age** Sentinel Butte **lignites** (Biek and Murphy, 1995). In addition, White River Group (Eocene to Oligocene) **strata** are extensively **faulted** and capped in angular **unconformity** by undisturbed Arikaree **strata** at Slim Buttes in northwestern South Dakota (Shurr et al., 1996).

Scores of small offsets are present in basal Sentinel Butte **strata** throughout the South Unit, but these are invariably related to **slumping** over burned-out portions of the HT Butte and other **lignites**. Perhaps the most spectacular example is found in the hill in 140-101-4, about 3,300 feet from the north section line and 1,000 feet from the east section line *(fig. 62)*. These small, intersecting offsets, with displacements from about 1 to 10 feet, were first noted by Lee Jefferis, geologist with the Bureau of Land Management. The geometry of these offsets is complicated by a 16-inch-thick **lignite** into which several of the failure planes abruptly terminate. The offsets cannot be traced beyond the hill in question, nor can they be traced into the adjacent **clinker** itself. Geomorphic considerations suggest that the hill has eroded considerably since burning of the HT Butte **lignite**, so that what remains were once buried failure planes. A small rotational **slump** in 140-101-13ddc clearly shows that offsets such as these commonly flatten or sole into **lignites** (see *fig. 56*).

MINERAL RESOURCES

The principal mineral resources in Theodore Roosevelt National Park include oil, gas, **lignite**, sand, gravel, smectite **clay** (or **bentonite**), and stone. A detailed review of these commodities is beyond the scope of this report; nevertheless, a few salient points are outlined below.

Oil and Gas

The North Unit, South Unit, and Elkhorn Ranch site are surrounded by oil fields that produce either from Tyler

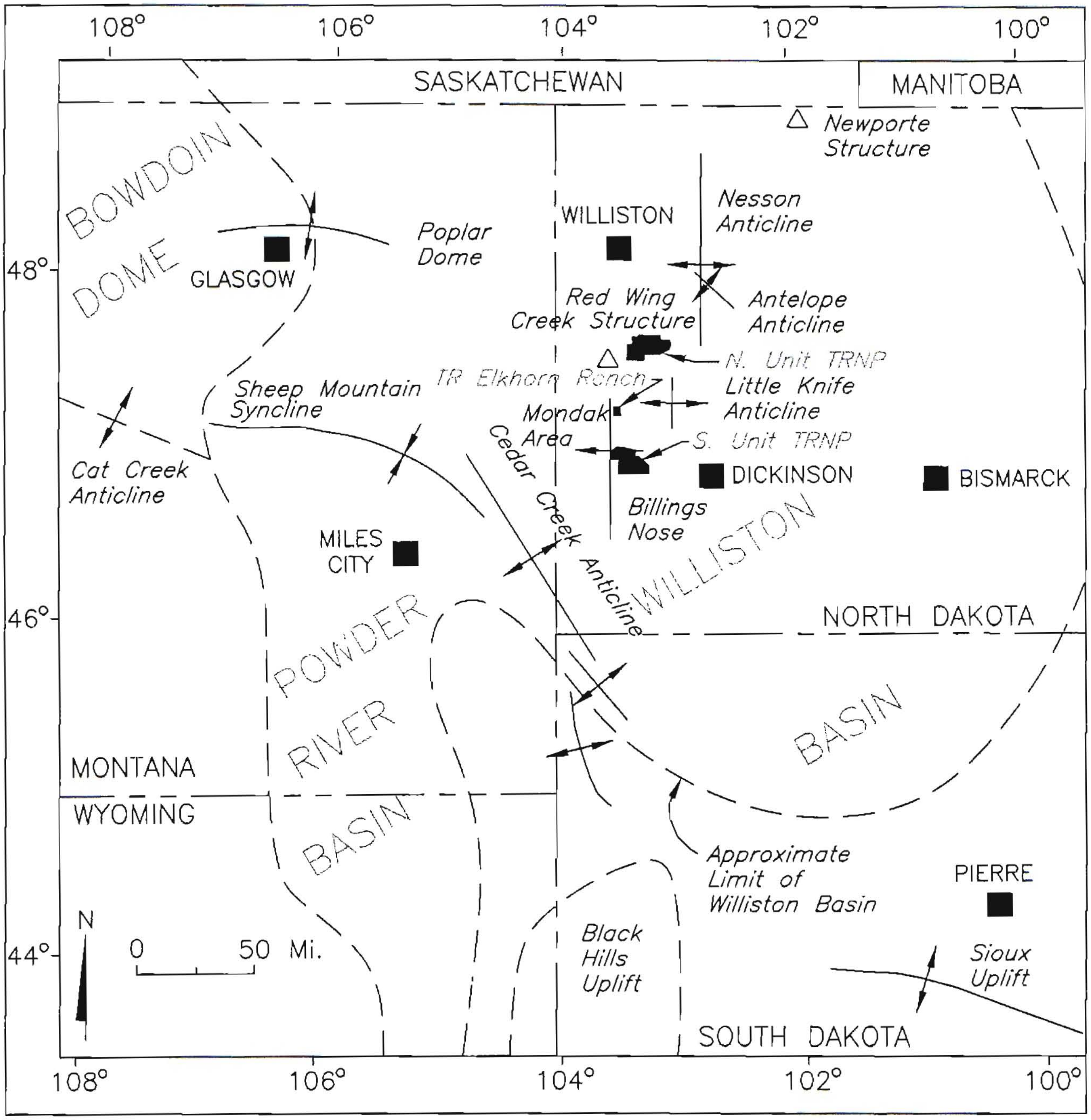


Figure 60. Map of the Williston Basin. The North, South, and Elkhorn Ranch units of Theodore Roosevelt National Park are shaded (modified from Bluemle, 2000).

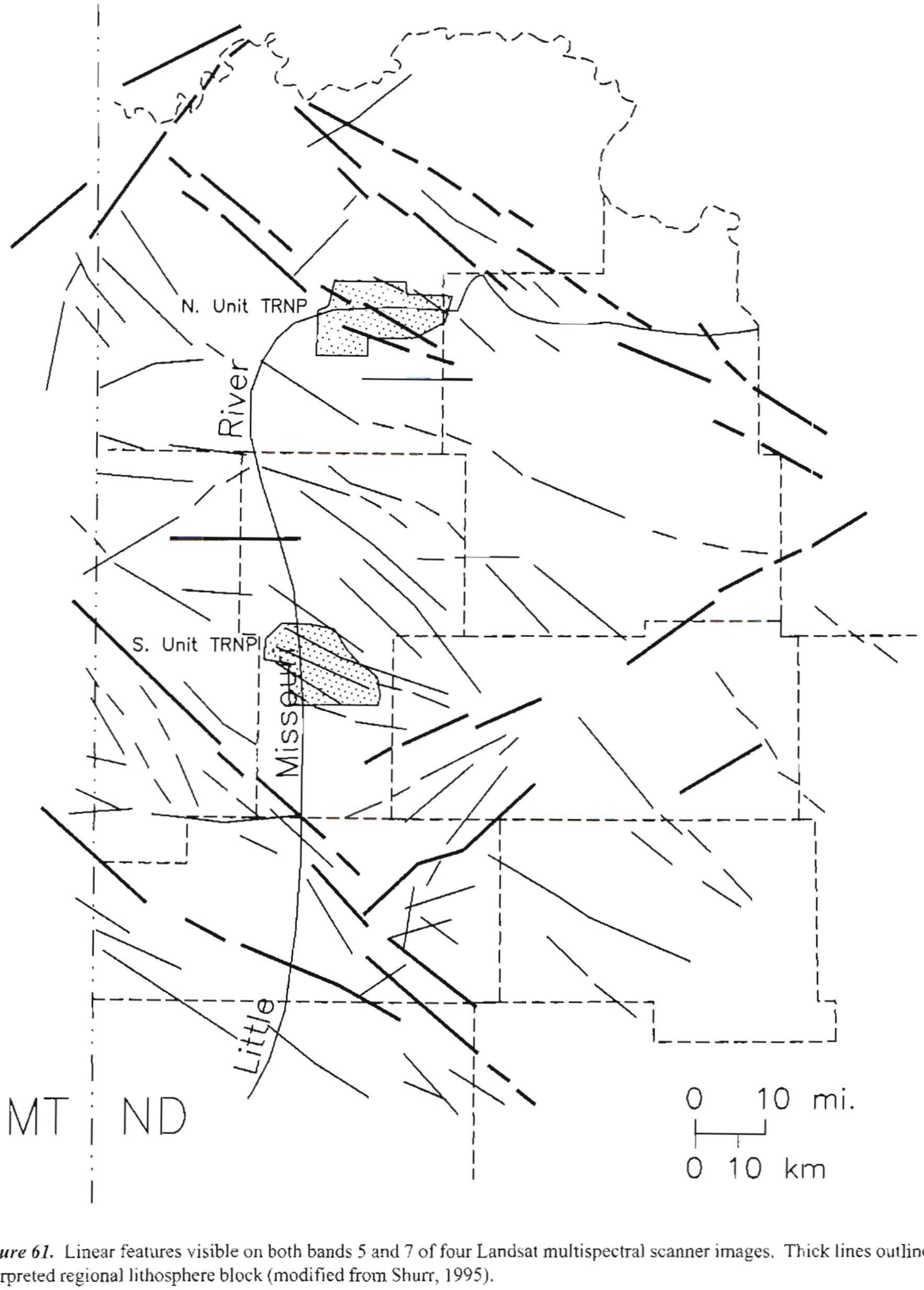


Figure 61. Linear features visible on both bands 5 and 7 of four Landsat multispectral scanner images. Thick lines outline interpreted regional lithosphere block (modified from Shurr, 1995).

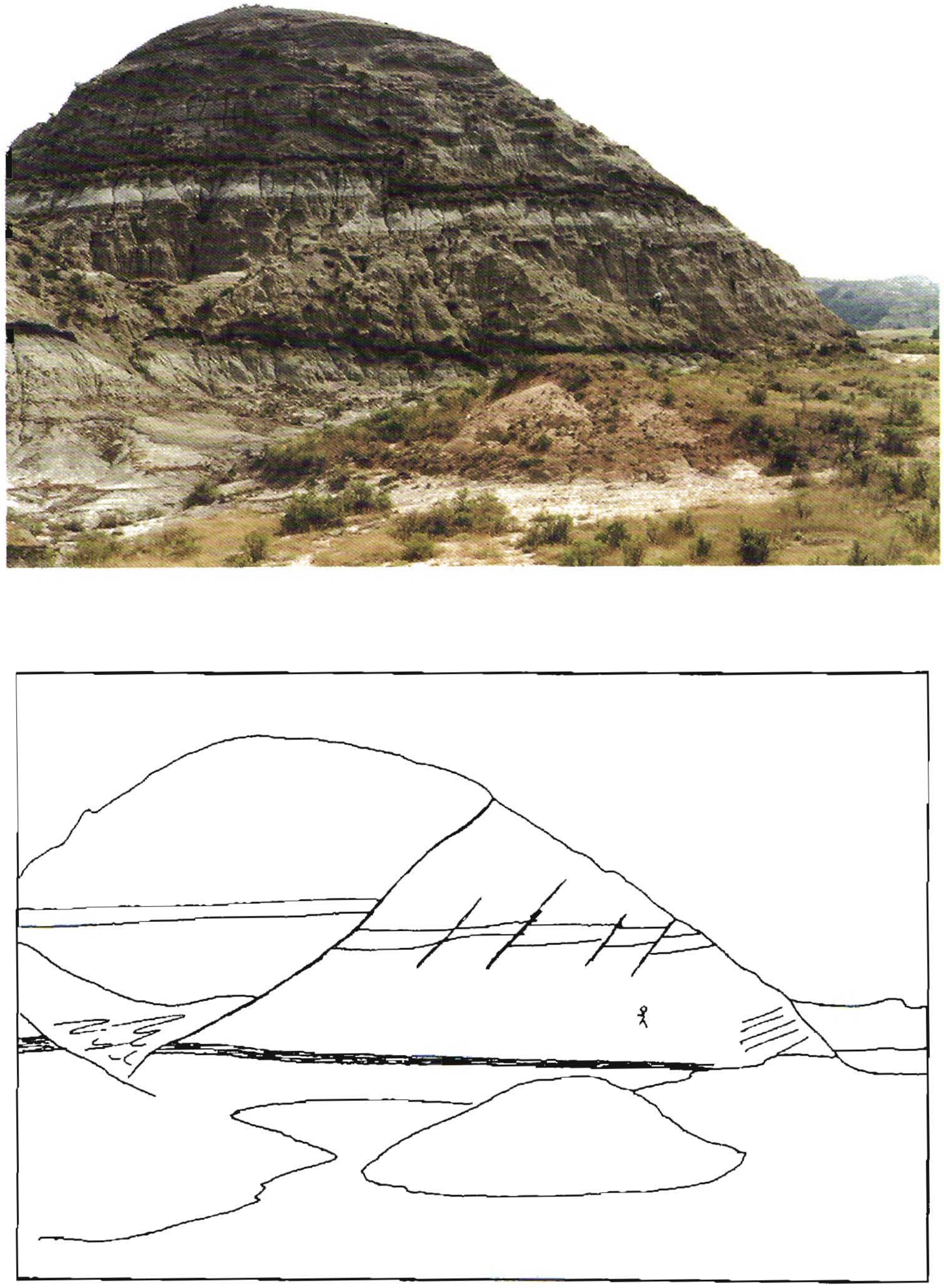


Figure 62. Complex slump in basal Sentinel Butte strata. This hill is sliced by numerous small, intersecting offsets with displacements from about one to ten feet which are believed to have resulted from slumping over burned out portions of the HT Butte lignite. View to the south at hill in 140-101-4, about 3300 feet from the north section line and 1000 feet from the east section line.

(Pennsylvanian), Madison (Mississippian), Bakken (Devonian-Pennsyvanian), Birdbear, Duperow (Devonian), or Red River (Ordovician) **strata,** or some combination of these units.

The first **petroleum** production from the general vicinity of the Park came in 1953 when the Fryburg Field was discovered immediately south of the South Unit. Production from this field comes from **strata** in the Tyler Formation and Madison Group. Peak production occurred in 1968, but the Fryburg Field continues to be important with 77 producing wells thus far. In 1993, six of seven new wells in the Fryburg Field were successful. These wells had an average Initial Potential (IP) of 120 barrels of oil per day (BOPD). The Fryburg Field extends one mile into the southeastern part of the South Unit, where six inclined wells, some temporarily abandoned, and one horizontal well extract **petroleum** from Tyler and Madison **beds**.

One of the more unusual oil and gas producing fields is the Red Wing Creek Field, located just a few miles west of the North Unit. The discovery, in 1972, caused a good deal of excitement in the industry because of the relatively high production rates from an anomalously thick section of Mississippian **strata**. Oil is produced from a six-mile diameter, roughly circular structure that was apparently formed by a meteorite impact *(fig. 63)* (Gerhard et al., 1982). About 6,000 vertical feet of **strata** were disturbed by the impact.

The Late Devonian- to Early Mississippian-**age** Bakken Shale has long been considered a "source rock," an organic-rich **formation** that has generated large amounts of oil. With the advent of horizontal drilling technology in the late 1980s, the comparatively thin Bakken itself became a major target for explorationists. The Bakken Shale consists of two organic-rich **shales** separated by a middle unit of variable lithology; collectively these units are less than 100 feet thick. Most horizontal wells are completed in the upper **shale**, which is generally less than ten feet thick. Typically, the horizontal portion of a Bakken well is 2,000 to 3,500 feet long, oriented to intersect as many fractures as possible. The Bakken play peaked in 1990 when 65 successful horizontal wells were drilled.

Both the South Unit and the Elkhorn Ranch site lie in what **petroleum** geologists call the "Bakken Fairway." The southwestern margin of the fairway marks the depositional limit of the Bakken, while the northeastern margin is defined on the basis of water resistivity in the middle member. Schurr (1995) noted that the northwest and southeast margins terminate at northeast-trending lineament zones. Initial potentials for wells in the Bakken Fairway were as high as 1,912 BOPD, but averaged around 300 BOPD.

The TR Field and Whiskey Joe Field are located on the Billings Anticline, a long, north-trending structure developed in lower and middle Paleozoic **strata.**

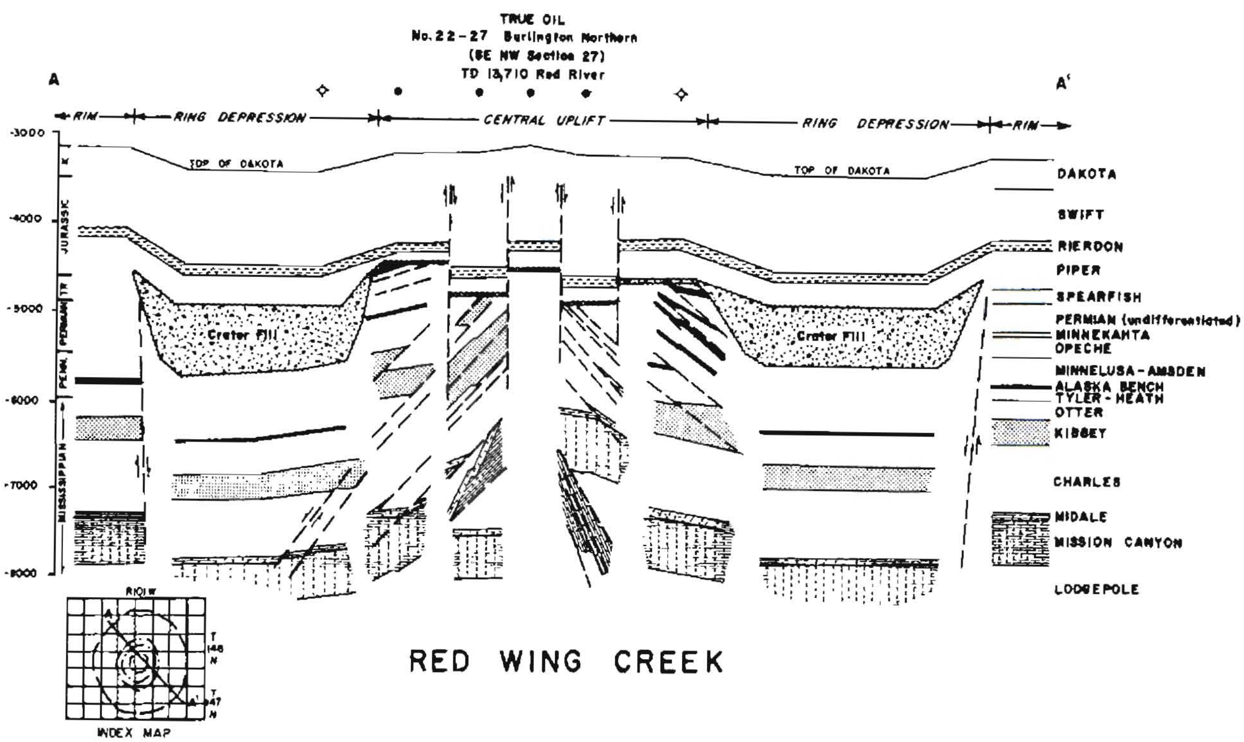


Figure 63. Cross section through the Red Wing Creek structure, interpreted to have been formed by a meteorite impact (from Gerhard et al., 1982).

Production in these fields comes almost entirely from Madison Group **strata**.

Lignite

Lignite was mined near Medora by the first European settlers and by the Northern Pacific Railroad Co. as early as 1884 about 1/4 mile west of the railroad station at Medora. North Dakota Public Service Commission records indicate that, sometime prior to 1912, two underground mines, the De Mores Coal Mine and the High Grade Coal Mine, opened in 140-102-26b. The entrance to the abandoned High Grade mine can still be seen in a hillside just east of Medora.

North Dakota Public Service Commission records reveal discrepancies in the legal location of the High Grade mine. SEBR records indicate the mine is in 140-102-26c. However, surveyor Donald C. Fauss prepared a map of the Hygrade (High Grade) Lignite Coal Company underground workings (1:360 and 1:2,400) dated June 29, 1940 *(fig. 64)*. The mine entrance is located in 140-102-26bbd, and, as noted, can still be seen in the hillside just east of Medora. An air shaft, located about 180 feet northeast of the entrance, is also shown on the map. It is possible that **lignite** was originally mined in the southwest quarter of section 26 and the mine later moved. The mine probably closed about 1946.

The **lignite** was mined from the "C" **bed** of Leonard and Smith (1909), the "K" **bed** of Leonard et al. (1925, p. 37-38), and unit "B" on the cross section of Jacob (1973). This **lignite** belongs to what Leonard et al. (1925) called the Medora Group of **coal beds**. This **bed** has been mined elsewhere in the Medora area. Leonard and Smith (1909, Plate II) traced this **bed** in the Medora area and northward where it plunges beneath the surface in 140-102-1.

Records of the North Dakota Public Service Commission indicate that the De Mores Coal Mine, an underground, single-entry mine, was also located in 140-102-26b. The mine opened sometime prior to 1909 and closed in 1930. The exact location of the DeMores mine is uncertain.

Sand and Gravel

Sand and gravel are present in alluvial deposits mapped as QTa and Qt in both the North and South Units. These deposits occur as a veneer capping high-level **plateaus** near the Little Missouri River. They consist of poorly sorted, iron-stained, locally iron-cemented sand and gravel of local and southwestern affinity. They contain pebbles and cobbles of well-cemented, locally derived material (**mudstone**, **sandstone**, **concretions**, silicified wood, **flint**, **silcrete**, **clinker**, and **chalcedony**), and lesser amounts of quartzite and porphyry. The sand and gravel are generally less than about 5 feet thick and are overlain by a slightly thicker mantle of **Holocene loess**. In the North Unit at Sperati Point, the thickness of these deposits is uncertain, but they may reach up to about 40 feet thick.

Sand and gravel have been mined from at least two localities in the South Unit. One such locality, in 141-101-

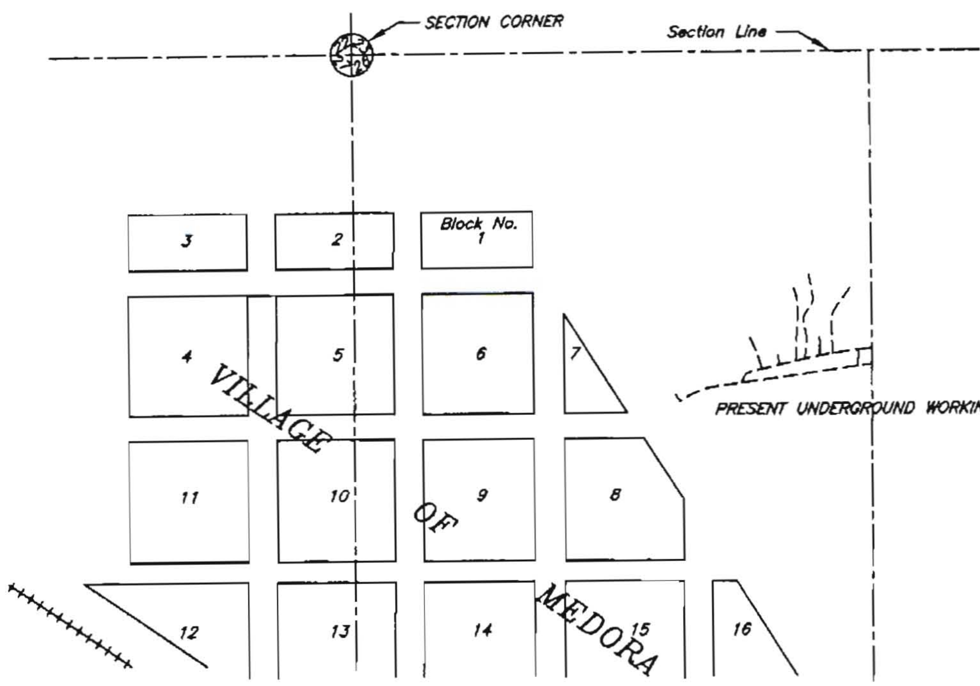


Figure 64. Map of the High Grade Coal Mine, Medora (140-102-26bbd) (from Fauss, 1940).

29bad, is incorrectly labeled a **scoria** pit on the topographic base map of the Park. There, 3 feet of sand and gravel are overlain by up to 7 feet of **loess**. Sand and gravel have also been mined at the eastern edge of the Petrified Forest Plateau (141-101-31cca and 31cdb). The sand and gravel were probably used locally as road metal for the trail leading up onto the Petrified Forest Plateau.

Sand and gravel were also mined atop the **plateau** immediately east of Medora beginning sometime before 1957. The unreclaimed pit lies just outside the Park's boundary. A large **landslide** is present on the steep slope just west of the pit.

Smectite Clay

Bentonite, a smectite **clay** that is composed principally of the **clay** mineral montmorillonite, is derived from the alteration of volcanic **ash**. Bentonites with sodium as an exchangeable ion swell conspicuously when wet; calcium bentonites are only slightly swelling or non-swelling. The Sentinel Butte **bentonite**, an iron-rich montmorillonite that swells conspicuously when wet, is one of only three bentonites in North Dakota shown to have been derived from volcanic **ash**, although other volcanic tuffs are known to occur in the state (Forsman, 1992). The Sentinel Butte **bentonite** forms prominent benches in the North Unit and adjacent areas.

Swelling **bentonite** is used in drilling mud to keep cutting tools cool, to remove cuttings, to lubricate the drill bit, to confine underground fluids by creating an impervious coating on the hole wall, and to prevent blowouts. In addition, **bentonite** is used as a binder for foundry sand, as a binder for pelletizing iron ore, as a sealant or liner for landfills, ponds, and canals, and as a filler, stabilizer, and extender in materials such as adhesives, greases, medicines, cosmetics, paint, rubber, and soaps. Much of the **bentonite** used in the United States comes from Wyoming, the nation's largest supplier of **bentonite**, and it is unlikely that the small deposits in North Dakota will be of economic value.

Stone

In 1937, the Civilian Conservation Corps built a shelter of partly dressed, medium-grained, cross-bedded **sandstone** at the Riverbend Overlook in the North Unit *(fig. 65)*. **Sandstone** from a local quarry was used for the construction of these structures, but it is uncertain whether the quarry was in the Park or some miles outside. A 1937 photograph caption implies that the quarry was in the North Unit, but a longtime employee of the Park was certain that the quarry was some 25 miles southwest of the Park in an area called Flat Top Butte. We have not seen any evidence of **sandstone** quarrying in the Park, and so concur that the stone probably came from the Sentinel Butte Formation outside the Park's boundary. Unhewn blocks of what is likely Sentinel Butte **sandstone** are used around the perimeter of the shelter. Large blocks of the same **sandstone** and Taylor **bed silcrete** line the path down to the shelter.

The old South Unit entrance station (140-101-28dbd) was completed in 1938 by the Emergency Relief Association *(fig. 66)*. This 15- x 20-foot check station and adjacent stone fence and privy are made from cut and dressed blocks of **sandstone**. A pylon (upon which the Park's name is hung) originally at the check station was moved to the Painted Canyon Visitor Center in 1968. The source of the stone is uncertain, but it is likely from either local Sentinel Butte or Bullion Creek **strata**.

Clinker has been quarried in at least one location in the South Unit, just east of Johnson's Plateau in 140-102-13cdd and 24baa. This **clinker** formed from the burning of the underlying HT Butte **lignite**.

The North Unit entrance station and visitors center, built in 1993, are made from a Minnesota stone known as Kasota Marble. The Kasota Marble comes from the Kasota area of southeastern Minnesota where it has been quarried since 1868.

GEOLOGIC HAZARDS

Geologic hazards in Theodore Roosevelt National Park can be grouped into six main categories: 1) **mass-wasting** processes, such as **landslides** and **soil creep**; 2) swelling **soils**; 3) **erosion**, such as that associated with river banks, **piping**, and **sheet wash**; 4) flooding; 5) burning **lignite beds**; and 6) man-made hazards such as those associated with collapse of underground **lignite** mines.

Tertiary strata of southwestern North Dakota contain above average amounts of uranium and are known or are likely to cause indoor radon problems in some buildings. In a study conducted by the EPA (1993, p. IV-15), 78% of the residential homes tested in Billings County (area surrounding the South Unit) and 50% of the homes in McKenzie County (North Unit) had levels of indoor radon exceeding the EPA-recommended limit of 4 pico-Curies per liter. The geology indicates that the potential exists for buildings in the Park to have high levels of indoor radon.

Mass-Wasting Hazards

Landslides

Several dozen large **landslides** and countless smaller **landslides** have been mapped in Theodore Roosevelt National Park. Most occur in **strata** of the Sentinel Butte Formation. Most large **landslides** in the Park form as

Figure 65. The structure at the River Bend Overlook was built in 1937 by the Civilian Conservation Corps. It is made of a partly dressed, medium-grained, cross-bedded sandstone likely from the Sentinel Butte Formation at Flat Top Butte. Unhewn blocks of what is likely Sentinel Butte sandstone are used around the perimeter of the shelter. Large blocks of the same sandstone and Taylor bed silcrete line the path down to the shelter (view to the southeast at the River Bend Overlook, 148-100-26daa).

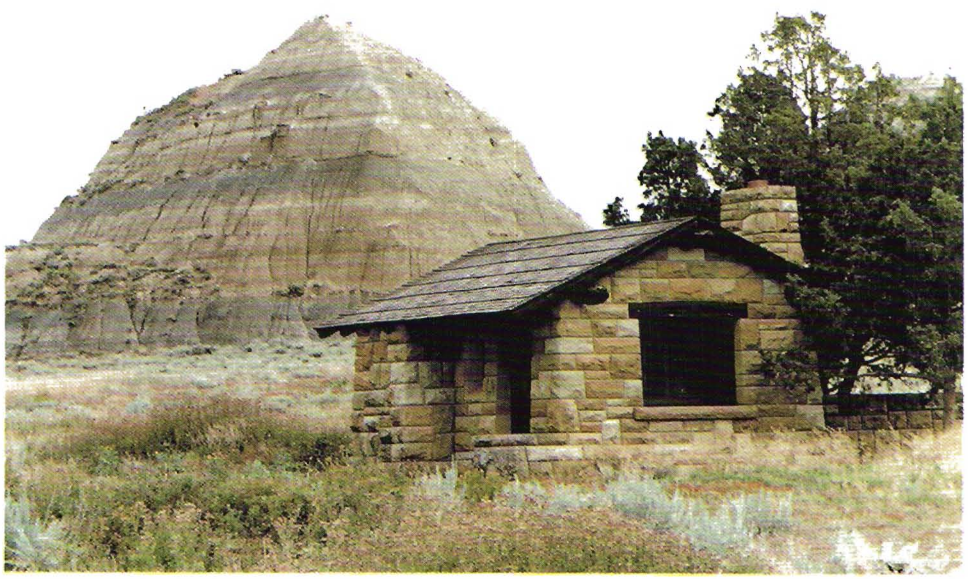


Figure 66. The old South Unit entrance station (140-101-28dbd) was completed in 1938 by the Emergency Relief Association. The source of the stone is uncertain, but it is likely from either local Sentinel Butte or Bullion Creek strata.

complex rotational **slumps** and are characterized by hummocky **topography**, **beds** that **dip** back into the hillside, and numerous, arcuate, internal scarps. Some **landslides** in the Park with completely disaggregated **beds** are properly classified as debris or **earth flows**. Large slides tend to be more densely vegetated than adjacent slopes, probably because the hummocky **topography** allows more precipitation to infiltrate rather than run off the slope.

The age of many of these **landslides** is uncertain. Most likely the **landslides** formed during the late **Pleistocene** and **Holocene** Epochs. Near the entrance to the North Unit (148-99-35b), **landslide** deposits have been partly truncated by Qoal **alluvium**. The **landslide** deposit has been subdued by **erosion** and the headwall area is highly dissected, both evidence that this slide is comparatively old. In contrast, the headwall of the large **landslide** across the river to the southwest, in 147-99-5b, has been modified only slightly by subsequent **erosion**.

With the possible exception of the coherent, steeply dipping parts of the large **slump blocks** in the North Unit (148-99-32, -33, and -34), all **landslides** should be considered active or capable of renewed movement; most **landslides** in fact do show multiple episodes of **slumping**, including recent (within the last few years) **slumping**. Buckled pavement and dips in the road attest to continued movement in several places within the Park.

The comparatively steep, often sparsely vegetated **badlands** slopes are continually being reshaped by **erosion**. Small, shallow **landslides** are a ubiquitous part of this process. Because of limitations of scale, such small features have not been mapped; however, steep areas where **landslides** can be expected to occur are shown on the topographic base map.

In the North Unit, the Sentinel Butte **bentonite** is especially susceptible to flowing downhill under the influence of gravity. In fact, most small **slumps** in the North Unit are associated with the Sentinel Butte **bentonite**. Failure planes of these small **slumps** invariably merge into the **bentonite**, with the overlying **beds** often rotated such that they **dip** back into the hillside (see *fig. 33*).

Soil Creep

Hillslopes throughout the Park are also subject to the process of **soil creep** (**soil** slide of Trimble, 1979). **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. **Soil creep** affects only **soil** and near-surface sediments, but can cover entire hillsides. **Soil creep** is especially common on north- and northeast-facing slopes underlain by weathered Bullion Creek Formation in the South Unit.

Soil creep can also be recognized as a series of narrow, closely spaced, roughly parallel and horizontal ledges, which are used commonly as game trails, and so accentuated, by grazing animals.

Swelling Soils

Swelling **soils** can cause structural damage to buildings, roads, and other infrastructure. In Theodore Roosevelt National Park, the classic example of swelling sediments is the Sentinel Butte **bentonite**. The **bentonite** expands up to about 16 times when wet, creating a characteristic "popcorn" surface typical of expanding clays. A sequence of similar "blue" clays is found in the South Unit along the western edge of the Petrified Forest Plateau.

Erosion

River Erosion

Erosion is the primary geological process responsible for shaping the Little Missouri Badlands. Though **erosion** may be hard to visualize as a **geologic hazard**, its incessant action can eventually undermine roads, buildings, and other infrastructure.

Everitt (1968) and Kuehn (1995) have shown that the modern **flood plain** of the Little Missouri River (here mapped as Qal) is less than a few hundred years old. As the river naturally meanders across its **flood plain**, sediment is eroded from the outside bend of the **meander** and deposited along the inside bend. The result is that the channel migrates across the **flood plain** and continuously reshapes the surface. Abandoned channels and oxbow lakes bear vivid testimony to the natural changes that occur on the valley floor. Eventually, facilities such as Juniper and Cottonwood Campgrounds may be adversely affected by channel migration and bank **erosion**.

Piping

Piping is common in poorly **lithified bedrock** as well as overlying alluvial, colluvial, and **landslide** deposits. It produces a system of tunnels, small caves, and pseudo-karst **topography** that collectively serves to channel runoff underground *(fig. 67)*. Pipes form when surface runoff erodes vertically downward through poorly **lithified** sediments. **Piping** is often initiated at small cracks and joints, which can be enlarged through **erosion** to the size of small rooms. The principal danger associated with erosional pipes is roof collapse. Although erosional pipes have not been mapped, they are very common on and near the base of steep **badlands** slopes.

Figure 67. Erosional pipe (arrow) in the Sentinel Butte Formation (140-101-10ab).

Flooding

In 1986, U.S. Geological Survey hydrologists estimated the water-surface elevations for the 100- and 500-year flood **discharges** along the Little Missouri River. The water-surface elevations for the 100-year flood **discharge** were also estimated for the areas near the mouths of Knutson, Paddock, and Squaw Creeks. The report was based on U.S. Geological Survey streamflow data at Medora, which spanned the periods May 1903 to September 1934 and October 1945 to September 1976 and included 50 annual peak **discharges** and elevations. The station at the downstream end of the North Unit had a continuous record from September 1934 to 1986 and included 48 annual peak **discharges** and elevations. **Discharge** data were not available for the Elkhorn Ranch Site, nor for Knutson, Paddock, or Squaw Creeks. There, the 100-year flood **discharges** were estimated using standard hydrologic methods.

From these data, Emerson and Macek-Rowland (1986) developed a series of cross-sections that show areas expected to be inundated by the 100- and 500-year flood events. These profiles show that much of the areas herein mapped as Qal, including the broad **terraces** flanking the Little Missouri River, will be flooded during a 100-year flood event. The Park's 1987 General Management Plan contains detailed planimetric maps that show the 100-year **flood plain** for selected portions of the Little Missouri River.

The highest recorded peak elevation on the Little Missouri River at Medora occurred on March 23, 1947, when the river crested at an elevation of 2,267.25 feet with a peak **discharge** of 65,000 cubic feet per second (cfs). The second highest elevation, 2,265.10 feet, was recorded on April 1, 1952. In the North Unit, the highest recorded level of the Little Missouri River occurred on March 25, 1947, when the river crested at an elevation of 1,953.03 feet with a peak **discharge** of 110,000 cfs.

Emerson and Macek-Rowland (1986) estimated that the March 23, 1947, flood in the South Unit approximates the 100-year flood event for that stretch of the Little Missouri River. The 100-year flood **discharge** determined for the North Unit is 78,800 cfs, considerably less than the peak **discharge** of 110,000 cfs recorded on March 25, 1947.

Emerson and Macek-Rowland (1986) noted that because of its large drainage basin, the threat of floods on the Little Missouri River may be known days in advance. In contrast, flooding along tributary creeks will most likely be caused by local, intense thunderstorms, and the threat of a flood may be known only hours in advance.

Burning Lignite Beds

Although **lignite beds** are not burning now in Theodore Roosevelt National Park, several small fires were burning in the northeastern corner of the South Unit in the late 1980s and early 1990s; future burns should be expected. **Lignite beds** may catch fire by a number of natural or man-made causes. Once ignited, **lignite** tends to burn back into the hillside, causing **slumping** of overlying **beds**. A well-oxygenated burning **lignite bed** can reach temperatures of 2,000°C, hot enough to turn overlying sediments into a glassy slag. Aside from the obvious danger of the fire itself, the principal danger posed by burning **lignite beds** is the **slumping** and network of fractures that develop above burned out portions of the **lignite**.

Man-Made Hazards

Abandoned Underground Lignite Mines

North Dakota Public Service Commission records indicate that two underground **lignite** mines are present in 140-102-26b. The entrance to one of these, the High Grade Coal Mine, is located on National Park land just east of Medora, about 1,000 feet from both the west and north section lines (see *fig. 64*). An air shaft is located about 180 feet northeast of the mine entrance, possibly in or near a northwest-trending ravine. The mine extends eastward to at least the quarter section line. Because the eastern part of the mine was not surveyed, the maps may not show the full, actual extent of underground workings. Subsurface conditions in the general vicinity of the mine should be investigated prior to any construction activities in this area.

Except where tunnels may be close to the edge of the **plateau**, overburden at the High Grade mine is up to about 200 feet thick. Thus there appears to be little danger of sinkhole development above the mine. However, the mine entry itself, though fenced, remains open.

The location of the De Mores Coal Mine, reported to be in 140-102-26b, is unknown. The mine apparently operated from sometime before 1909 until 1930.

Mass Movements

Landslides are a natural and important process in the formation of the **badlands**. However, landsliding has locally been exacerbated due to road construction activities. Most **landslide** deposits are inherently unstable. Regrading, placing fill, and altering drainage patterns in such deposits may lead to further instability.

In the South Unit, the Park road had to be rerouted around Buck Hill. The road was originally built on **landslide** deposits on the north side of Buck Hill; the spur that leads to a parking area near the top of the hill is still beset by **landslide** problems. In 140-101-3d. the Park road, as it descends down to Jones Creek, crosses a pre-existing **landslide** deposit that also shows signs of renewed movement. Elsewhere along the South Unit road, minor **creep** of steep hillsides is apparent as small cracks in the asphalt, oriented parallel to the hillside.

In 140-101-34d, a 1,500-foot-long segment of Interstate 94 was built over a pre-existing **landslide**. When investigated in August 1995, there were numerous seeps at the toe of the **landslide** and areas where cattails and other marsh vegetation flourished. The slide is dissected by a network of anastomosing scarps, and the toe of the slide had undergone recent (within the last year or two) small-scale **slumping**. Engineered fill was placed over the **landslide** in 140-101-34ddb; a drainpipe emerges from the base of the fill and directs runoff into a tributary of Paddock Creek. Smaller amounts of fill were placed along the freeway to the northwest.

In the North Unit, the Park road crosses a small **landslide** deposit in Cedar Canyon, although there is no evidence of recent movement. East of Juniper Campground, the Park road threads its way through several old **landslide** deposits, none of which showed signs of recent movement that may affect the road.

Summary

Principal findings of this mapping project include:

1. The **bedrock** geology comprises the Bullion Creek and Sentinel Butte Formations (ascending order) of Paleocene **age**. Plateaus, stream valleys, and valley margins contain alluvial deposits of late **Tertiary** through **Holocene age**.

2. In the South Unit, the **contact** between the Bullion Creek and Sentinel Butte Formations is marked by the top of the HT Butte **lignite**, and where the **lignite** has burned, by the base of the HT Butte **clinker**.

3. In the North Unit, the Sentinel Butte Formation reaches a thickness of greater than 750 feet, representing a nearly complete section of the **formation**. Neither the lower nor upper **contacts** of the **formation** are exposed in the North Unit. The bottom **contact** plunges beneath the surface just south of the North Unit, between Bennett and Corral Creeks. The upper **contact**, with the Golden Valley Formation, is also not exposed in the North Unit, but a **silcrete** lag deposit atop Achenbach Hills attests to its "proximity."

4. The Achenbach Hills are capped with a lag deposit of large **silcrete** blocks that based on lithology and stratigraphic position clearly came from the Taylor **bed**, the upper unit of the Bear Den Member of the Golden Valley Formation. The Achenbach Hills are heavily vegetated, and no exposures of sediments immediately below the **silcrete** were found. Still, given that the **silcrete** blocks are lying randomly at the surface, it seems clear that the underlying, characteristically bright white, poorly vegetated, comparatively thin Bear Den Member is absent.

5. Two principal criteria are useful for differentiating the Bullion Creek and Sentinel Butte Formations in the field:

   a) Stratigraphic position with respect to the HT Butte **lignite** or **clinker**. The HT Butte **lignite**, or more often the **clinker** produced by its burning, everywhere marks the Bullion Creek/Sentinel Butte **contact** in the South Unit. The **clinker** is the thickest and most widespread **clinker** in the South Unit.

b) Color. The color contrast between bright yellowish brown Bullion Creek **strata** and grayish brown Sentinel Butte **beds** is most apparent where substantial, weathered thicknesses of both **formations** crop out. Because **beds** of similar color may appear in both **formations**, color alone may fail locally as a sole means of differentiating the two units.

Other, more subtle differences useful for field differentiation of the two **formations** include:

c) Bullion Creek **strata** generally weather to more rounded, smoother, commonly more vegetated surfaces than Sentinel Butte **strata.** Steep, narrow gullies, erosional pipes, and rill **weathering** are rare on Bullion Creek **strata** but are common on Sentinel Butte **beds.**

d) **Petrified wood** is uncommon in the Bullion Creek Formation. It is widespread in Sentinel Butte **strata,** and is especially common near the base of the **formation.**

6. In its typical development, the Sentinel Butte **tuff/ bentonite** consists of a light gray volcanic **ash** sandwiched between bluish gray **bentonite beds**; collectively the three **beds** are up to 25 feet thick in the North Unit and form prominent "popcorn-covered" benches. The distinctive contrast of the Sentinel Butte **tuff/bentonite** with enclosing **strata** enables it to be traced easily over great distances. It also shows clearly where the unit thins and disappears completely, and where overlying channels have eroded it. To the east of Squaw Creek, the unit thins markedly and appears to pinch out entirely. It is only about 2 feet thick in 148-99-32a.

7. Considerations of landscape development, and comparisons with **clinker** development in the Powder River Basin, indicate that although the HT Butte **clinker** forms a continuous surface over much of the South Unit, it likely formed by a number of comparatively small, discrete burns, the latest of which was the Buck Hill burn of 1951 to 1977. Generally, older **clinker** is apt to be found on promontories high above modern streams, while younger **clinker** is generally found at the heads of modern drainages.

8. Next to the HT Butte **clinker**, the "**petrified wood** horizon" is the most widespread, easily recognizable **bed** in the Sentinel Butte Formation in the South Unit. The horizon can be traced throughout the South Unit, and is noted for its large, upright, fluted stumps and for its silicified **lignite**, especially in the area south of Paddock Creek. The horizon occurs from about 20 to 40 feet above the base of the Sentinel Butte Formation along the western side of the Petrified Forest Plateau, and up to about 100 feet above the base of the **formation** to the east. Along the western part of the Petrified Forest Plateau, the horizon appears as two lignitic horizons with numerous upright, silicified stumps and local silicified **lignite**. When traced eastward, to the east side of the **plateau**, only a single stump horizon is seen. East of the Little Missouri River the horizon is represented by a single stump **bed**, except in the Boicourt Spring and Badlands Overlook areas where two stump **beds** are present.

9. In the North Unit, a stump horizon is found about 300 feet above the base of the **formation** (about 20 feet below the Sentinel Butte **bentonite**) south of Sperati Point; a similar **bed**, about 50 feet below the Sentinel Butte **bentonite**, has been mapped at the east end of the Park. South of Sperati Point the horizon is best exposed in 147-100-8bad. There, it consists of two thin, stump-bearing **lignite beds**, both locally silicified, separated by about ten feet of bluish gray swelling **clay**.

10. Other stump-bearing **beds** in the Park are of only local extent.

11. Sand and gravel of local and southwestern affinity and indeterminate late **Tertiary-Quaternary age** are present in both the North and South Units. In the South Unit, these deposits form a veneer capping the Petrified Forest Plateau and the unnamed **plateau** to the south across Knutson Creek. In the North Unit, similar but highly dissected deposits, are present at Sperati Point and on three small knolls about 3,000 feet to the south. In the South Unit, the sand and gravel are generally less than 5 feet thick and are overlain by a slightly thicker mantle of **Holocene loess**. The thickness of these deposits in the North Unit is uncertain. At Sperati Point, they may reach up to about 40 feet thick. **Erratic** boulders from about 1-4 feet in diameter are found scattered over the sand and gravel at Sperati Point, suggesting that the deposits pre-date the advance of ice into the area.

12. Numerous remnants of old river deposits are found throughout the Park, though they are most distinctive in the South Unit. The oldest and highest surface is mapped as QTa, **fluvial** sand and gravel of indeterminate late **Tertiary-Quaternary age**. The basal **contact** of this unit is around 2660 to 2670 feet above sea level (asl). The **contact** declines a few feet per mile to the north in the South Unit. **Quaternary-age fluvial** deposits are evident on Big Plateau, Johnson's Plateau, and a few unnamed **plateaus** that border the broad Little Missouri River valley. These deposits are labeled Qt1, Qt2, Qt3, and Qt4, youngest to oldest. The basal **contact** of Qt4 is at an elevation of 2520 feet asl at the **plateau** containing the Medora airport (140-102-23c) (declining gradually to the north to about 2500 feet on Johnson's Plateau and even lower farther north). The basal **contact** of Qt3 has an elevation around 2480 feet; that of Qt2 is around 2460 feet (asl) and that of Qt1 is around 2400 feet (asl) at Johnson's

Plateau. All contacts decline a few feet per mile to the north.

Five distinct **Holocene-age** alluvial deposits (four **terrace** and the modern flood-plain deposits) are found on the valley floor and valley margin along the Little Missouri River and its tributaries. It is impractical to map these deposits at 1:24,000-scale along the tributaries, where they are most apparent. Therefore, the deposits of the three oldest **terraces** are collectively mapped as Qoal (older **alluvium**) and the youngest **terrace** and modern flood-plain deposits are mapped as Qal (modern **alluvium**). Qoal represents deposits approximately 500 to 8000 years old; and Qal represents deposits less than 500 years old. Accordant levels of Qoal and Qal **terraces** argue for their correlation between the units of the Park.

13. Structure contours on the base of the HT Butte **clinker** and the base of the Sentinel Butte **bentonite** demonstrate that these Paleocene units **dip** gently to the east and northeast at about 100 feet every 2-3 miles. Dips were determined to be about 0.2°, based on three widely spaced points on these **beds**. Structure contour maps show that these **beds** are gently warped as well, which is typical of such flat-lying **strata**.

14. Detailed mapping uncovered no **faults** in either the North or South Units. The apparent lack of tectonic deformation, other than gentle tilting of **beds** towards the basin center, fits, at least in part, with the model of "lineament-block tectonics" outlined by Shurr et al. (1994).

15. Scores of small offsets are present in basal Sentinel Butte **strata** throughout the South Unit, but these are invariably related to **slumping** over burned out portions of the HT Butte **lignite**. Perhaps the most spectacular example is found in the hill in 140-101-4, about 3,300 feet from the north section line and 1,000 feet from the east section line. The geometry of these small, intersecting offsets, with displacements from about 1-10 feet, is complicated by a 16-inch-thick **lignite** into which several of the failure planes abruptly terminate. The offsets cannot be traced beyond the hill in question, nor can they be traced into the adjacent **clinker**. A small rotational **slump** in 140-101-13ddc shows that offsets such as these locally flatten or sole into **beds** of **lignite**.

16. **Geologic hazards** in Theodore Roosevelt National Park can be grouped into six main categories: 1) **mass-wasting** processes, such as **landslides** and **soil creep**; 2) swelling **soils**; 3) **erosion**, such as that associated with river banks, **piping**, and **sheet wash**; 4) flooding; 5) burning **lignite beds**; and 6) man-made hazards such as those associated with underground **lignite** mines.

17. North Dakota Public Service Commission records indicate that sometime prior to 1912, two underground mines, the High Grade and De Mores Coal Mines, opened in 140-102-26b. The entrance to the abandoned High Grade mine can still be seen in the Park in the hillside just east of Medora. The location of the De Mores mine is uncertain.

18. **Landslides** are widespread in both the North and South Units. They range in size and type from small rotational **slumps**, debris flows, and rock falls, to large complex rotational **slumps** that span areas up to a square mile in size. Most **landslides** involve Sentinel Butte **strata**.

19. In the North Unit, between the east entrance and Squaw Creek campground, several **landslides** are characterized by large coherent blocks with **beds** dipping into the hillside at 25° to 50°. The presence of undisturbed, horizontal Sentinel Butte **strata** at the toe of these blocks clearly show that these blocks were emplaced by rotational **slumping** and not by faulting as some have speculated. Substantial **erosion** has occurred since emplacement of the **slump blocks**, so that the upper part of the detachment surface along which the blocks moved has been almost entirely eroded away. However, two small parts of this detachment surface are exposed in 148-99-32b. There the surface dips to the south (at 60°) and southeast (at 35°); a dark bluish gray **bentonite**, apparently the Sentinel Butte **bentonite**, blankets the surface, suggesting that the **bentonite** itself may have at least locally served to "lubricate" the detachment plane.

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GLOSSARY

The definitions below are based in part on the Glossary of Geology, third edition, published by the American Geological Institute. The definitions provided here are restricted to those meanings intended in this document.

aerial photograph Any photograph taken from the air, such as a photograph of a part of the Earth's surface taken by a camera mounted in an aircraft.

age (a) A term used informally to designate a length of geologic time during which the rocks of any stratigraphic unit were formed. (b) The position of anything in the geologic time scale; e.g. ''the rocks of Miocene age". It is often expressed in years.

aggradation The building-up of the Earth's surface by deposition; specifically the upbuilding performed by a stream to establish or maintain uniformity of grade or slope.

alluvium Unconsolidated sediment of comparatively recent geologic time deposited by running water generally in and along rivers and streams, but also on fans or at the base of a hillslope.

ash Fine (under 2.0mm diameter) material expelled during a volcanic eruption. The term usually refers to unconsolidated material but is sometimes used for its consolidated counterpart, tuff.

badlands Intricately stream-dissected topography, characterized by a very fine drainage network with high drainage densities and short steep slopes. Badlands develop on surfaces with little or no vegetative cover overlying unconsolidated or poorly cemented clay, silt, or sand.

basement The undifferentiated complex of rocks that underlies the rocks of interest in an area. In many places the rocks of the complex are igneous and metamorphic and of Precambrian age, but in some places they are Paleozoic, Mesozoic, or even Cenozoic.

bed A bed (or beds) is the smallest formal lithostratigraphic unit of sedimentary rocks.

bedrock A general term for the rock, usually solid, that underlies soil or other unconsolidated, surficial material.

bentonite A soft, plastic, porous, light-colored rock composed essentially of clay minerals of the montmorillonite (smectite) group plus colloidal silica, and produced by chemical alteration of a glassy igneous material, usually a tuff or volcanic ash. Its color ranges from white to light green and light blue when fresh, becoming light cream on exposure and gradually changing to yellow, red, or brown. The rock is greasy and soaplike to the touch (without gritty feeling), and commonly has the ability to absorb large quantities of water accompanied by an increase in volume of about 8 times.

butte A conspicuous, usually isolated, generally flat-topped hill or small mountain with relatively steep slopes or precipitous cliffs, capped by a resistant layer of rock and bordered by talus that represents an erosional remnant carved from flat-lying rocks; the summit is smaller in extent than that of a mesa.

cannonball A large, spherical concretion as much as 10 feet in diameter; resembles a cannonball, as in the Cannonball Member (Paleocene) of the fort Union Formation in North Dakota; cannonball concretions are also found in other Fort Union Group formations.

carbon-14 dating A method of determining an age in years by measuring the concentration of carbon-14 remaining in organic material, usually formerly living matter, but also water bicarbonate, etc. The method is based on the fact that assimilation of carbon-14 ceases on removal of the material from the Earth's carbon cycle (i.e. on the death of an organism). Most carbon-14 ages are calculated using a half-life of 5730±40 years or 5568±30 years. Thus the method is useful in determining ages in the range of 500 to 40, 000 years, although it may be extended to 70, 000 years by using special techniques. Synonym: radiocarbon dating; carbon dating.

castellated Said of a physiographic feature, such as a cliff, peak, or iceberg, that displays a towering or battlementlike structure.

chalcedony A cryptocrystalline variety of quartz. It is commonly microscopically fibrous, may be translucent or semitransparent, and has a nearly waxlike luster, a uniform tint, and a white, pale-blue, gray, brown, or black color and commonly fills or lines cavities in rocks.

clay (a) A rock or mineral fragment or a detrital particle of any composition (often a crystalline fragment of a clay mineral), smaller than a very fine silt grain, having a diameter less than 1/256 mm (4 microns or 0.00016 in.). (b) A loose, earthy, extremely fine-grained, natural sediment or soft rock composed primarily of clay-size or colloidal particles and characterized by high plasticity and by a considerable content of clay minerals and subordinate amounts of finely divided quartz, decomposed feldspar, carbonates, ferruginous matter, and other impurities; it forms a plastic, moldable mass when finely ground and mixed with water, retains its shape on drying, and becomes firm, rocklike, and permanently hard on heating or firing. Some clays are nonplastic.

clay mineral One of a complex and loosely defined group of finely crystalline or amorphous hydrous silicates, essentially of aluminum (and sometimes of magnesium and iron). Clay minerals are formed chiefly by alteration or weathering of primary silicate minerals such as feldspars, pyroxenes, and amphiboles, and are found in clay deposits, soils, shales, alteration zones of ore deposits, and other rocks, in flakelike particles or in dense, feathery aggregates of varying types. They are characterized by small particle size and ability to adsorb substantial amounts of water and ions on the surfaces of the particles. The most common clay minerals belong to the kaolin, montmorillonite, and illite groups.

claystone An indurated clay having the texture and composition of shale but lacking its fine lamination or fissility; a massive mudstone in which clay predominates over silt; a nonfissile clay shale.

clinker Sediment that has been baked to a degree by heat from buried, burning coal (lignite in North Dakota). Clinker may range from rock that has completely melted, to material with a glassy texture, to brick, to slightly colored and hardened material. Commonly and erroneously called "scoria" in North Dakota.

coal A readily combustible rock containing more than 50% by weight and more than 70% by volume of carbonaceous material including inherent moisture, formed from compaction and induration of variously altered plant remains similar to those in peat. Differences in the kinds of plant materials (type), in degree of metamorphism (rank), and in the range of impurity (grade) are characteristic of coal and are used in classification.

colluvium A general term applied to any loose, heterogeneous, and incoherent mass of soil material and/or rock fragments deposited by rainwash, sheetwash, or slow continuous downslope creep, usually collecting at the base of gentle slopes or hillsides.

concretion A hard, compact mass or aggregate of mineral matter, normally subspherical, but commonly oblate, disk-shaped, or irregular; formed by precipitation from aqueous solution about a nucleus or center, such as a leaf, shell, bone, or fossil, in the pores of a sedimentary rock. Most concretions were formed shortly after sediment deposition.

contact The surface between two types or ages of rock.

correlate To show correspondence in character and stratigraphic position between geologic formations in two or more separate areas.

creep The slow, downslope movement of mineral, rock, and soil particles under gravitational stress. Many types of creep have been described on the basis of material properties, stress level, stage and rate of deformation, mechanics of failure, geometric patterns, and cause of deformation.

dendrochronology The study of annual growth rings of trees for dating of the recent past. Adjective: **dendrochronologic**.

dip The angle that a structural surface, e.g. a bedding or fault plane, makes with the horizontal.

discharge The rate of flow at a given moment, expressed as volume per unit of time (typically cubic feet per second, cfs).

disconformity An unconformity in which the bedding planes above and below the break are essentially parallel, indicating a significant interruption in the orderly sequence of sedimentary rocks, generally by a considerable interval of erosion (or sometimes of nondeposition), and usually marked by a visible and irregular or uneven erosion surface, weathering zone, or soil horizon.

earthflow A mass-movement landform and process characterized by downslope translation of soil and weathered rock over a discrete basal shear surface (landslide) within well defined lateral boundaries. The basal shear surface is more or less parallel with the ground surface in the downslope portion of the flow, which terminates in lobe-like forms. Overall, little or no rotation of the slide mass occurs during displacement, although, in the vicinity of the crown scarp, minor initial rotation is usually observed in a series of slump blocks. Earthflows grade into mudflows through a continuous range in morphology associated with increasing fluidity.

eolian Pertaining to the wind; deposits as loess and wind-blown dune sand.

erosion The general process or the group of processes whereby the materials of the Earth's crust are loosened, dissolved, or worn away, and simultaneously moved from one place to another by natural agencies, including weathering, solution, corrasion, and transportation; the mechanical destruction of the land and the removal of material (such as soil) by running water (including rainfall), waves and currents, moving ice, or wind.

escarpment A long, more or less continuous cliff or relatively steep slope facing in one general direction, breaking the continuity of the land by separating two level or gently sloping surfaces, and produced by erosion or by faulting. The term is often used synonymously with scarp, although escarpment is more often applied to a cliff formed by differential erosion.

erratic Boulders and other rock fragments transported by glacial ice from their place of origin typically to an area where the bedrock is different.

fan (alluvial) A low, outspread, relatively flat to gently sloping mass of loose rock material, shaped like an open fan or a segment of a cone, deposited by a stream (esp. in a semiarid region) at the place where it issues from a narrow valley upon a plain or broad valley, or where a tributary stream is near or at its junction with the main stream.

fault A fracture or a zone of fractures along which there has been displacement of the sides relative to one another parallel to the fracture.

flint A variety of chert (quartz) that was used as artifacts (spear points, arrowheads, etc.); example in North Dakota is Knife River Flint.

flood plain The surface or strip of relatively smooth land adjacent to a river channel, constructed by the present river in its existing regimen and covered with water when the river overflows its banks. It is built of alluvium carried by the river during floods and deposited in the sluggish water beyond the influence of the swiftest current. Used in this report for surfaces inundated on a frequent and nearly annual basis following the conventions of Wolman and Leopold (1957).

fluvial (a) Pertaining to a river or rivers. (b) Produced by the action of a stream or river.

formation The basic geological unit in lithostratigraphic (rock-strata) classification. A formation must be identifiable on the basis of easily recognized physical properties and be widespread enough to be mapped at a regional scale. Formations may be combined into groups or subdivided into members where these, too are recognizable and mappable.

geologic hazard A naturally occurring or man-made geologic condition or phenomenon that presents a risk or is a potential danger to life and property. Examples include landsliding, flooding, earthquakes, ground subsidence, faulting, dam leakage and failure, mining disasters, pollution, and waste disposal.

glacial (a) Of or relating to the presence and activities of ice or glaciers, as glacial erosion. (b) Pertaining to distinctive features and materials produced by or derived from glaciers and ice sheets, as glacial lakes. (c) Pertaining to an ice age or region of glaciation.

group The major lithostratigraphic unit next higher in rank than a formation; a group consists of two or more associated and adjoining formations having significant lithologic features in common.

Holocene An epoch of the **Quaternary** period, from the end of the **Pleistocene**, approximately 10, 000 years ago, to the present time; also, the corresponding series of rocks and deposits.

hoodoo A fantastic column, pinnacle, or pillar of rock produced in a region of sporadic heavy rainfall by differential weathering or erosion of horizontal strata, facilitated by joints and by layers of varying hardness, and occurring in varied and often eccentric or grotesque forms. Found mainly in areas of badlands topography. Synonym: rock pillar, pedestal.

ice age A loosely used synonym of glacial epoch, or time of extensive glacial activity; specifically the latest of the glacial epochs, also known as the **Pleistocene** Epoch.

incision The process whereby a downward-eroding stream deepens its channel or produces a narrow, steep-walled valley. Synonym: **downcutting**.

lacustrine Pertaining to, produced by, or formed in a lake or lakes; e.g. ''lacustrine sands" deposited on the bottom of a lake, or a ''lacustrine terrace" formed along its margin.

landform Any form or feature of the Earth's surface produced by natural causes; it includes major forms such as plain, plateau, and mountain, and minor forms such as hill, valley, slope, terrace, fan, and dune. Taken together, the landforms make up the surface configuration of the Earth.

landslide A general term covering a wide variety of mass-movement landforms and processes involving the downslope transport, under gravitational influence, of soil and rock material en masse. Terminology designating landslide types generally refers to the landform as well as the process responsible for it, e.g. rockfall, translational slide, block glide, avalanche, mudflow, liquefaction slide, and slump.

lateral accretion Outward or horizontal sedimentation; e.g., digging away of the outer bank of a stream meander and building up of the inner bank to water level by deposition of material brought there by rolling or pushing along the bottom. Cf: **vertical accretion**.

lignite A brownish-black coal that is intermediate in coalification between peat and subbituminous coal; consolidated coal with a calorific value less than 8300 BTU/lb, on a moist, mineral-matter-free basis. Also known as brown coal.

lithify To change to stone, or to petrify; esp. to consolidate from a loose sediment to a solid rock

lithogenesis Dealing with the processes that produce sedimentary deposits; the origin and formation of rocks, esp. of sedimentary rocks. Adjective: **lithogenetic**.

lithostratigraphic unit A defined body of sedimentary, extrusive igneous, metasedimentary, or metavolcanic strata that is distinguished and delimited on the basis of lithic characteristics and stratigraphic position. It generally conforms to the Law of Superposition and commonly is stratified and tabular in form. Boundaries of lithostratigraphic units are placed at positions of lithic change.

loess Windblown dust; a widespread, homogeneous, massive, unconsolidated, but slightly coherent, fine grained (predominantly silt with subordinate clay- to fine sand-sized particles) deposit that blankets much of today's North Dakota landscape.

mass wasting A general term for the dislodgement and downslope transport of soil and rock material under the direct application of gravity. In contrast to other erosion processes, the debris removed by mass wasting is not carried within, on, or under another medium. The mass properties of the material being transported depend on the interaction of the soil and rock particles and on the moisture content. Mass wasting includes slow displacements, such as creep and solifluction, and rapid movements such as rockfalls, rockslides, and debris flows.

meander One of a series of regular sinuous curves, bends, loops, turns, or windings in the course of a stream. It is produced by a mature stream swinging from side to side as it flows across its flood plain or shifts its course laterally toward the convex side of an original curve. v. To wind or turn in a sinuous or intricate course; to form a meander.

mudstone (a) An indurated mud having the texture and composition of shale, but lacking its fine lamination or fissility; a blocky or massive, fine-grained sedimentary rock in which the proportions of clay and silt are approximately equal; a nonfissile mud shale. (b) A general term that includes clay, silt, claystone, siltstone, shale, and argillite, and that should be used only when the amounts of clay and silt are not known or specified or cannot be precisely identified; or ''when a deposit consists of an indefinite mixture of clay, silt, and sand particles, the proportions varying from place to place, so that a more precise term is not possible.

nodule A small, irregularly rounded knot, mass, or lump of a mineral or mineral aggregate, commonly having a warty or knobby surface and no internal structure, exhibiting a contrasting composition from the enclosing sediment or rock matrix in which it is embedded; e.g. a chert nodule in limestone. Most nodules are secondary structures; in sedimentary rocks they are primarily the result of postdepositional replacement of the host rock and are commonly elongated parallel to the bedding.

outcrop That part of a geologic formation or structure that appears at the surface of the Earth.

outwash Stratified sand and gravel that was washed out from a glacier by meltwater streams and deposited in front of or beyond the end moraine or the margin of an active glacier.

paleosol A buried soil horizon. When uncovered, it is said to be exhumed. Synonym: buried soil.

paludal Pertaining to a marsh.

pediment A broad, gently sloping, erosion surface or plain of low relief, typically developed by subaerial agents (including running water) in an arid or semiarid region at the base of an abrupt and receding mountain front or plateau escarpment; underlain by bedrock (occasionally by older alluvial deposits) that may be bare but are more often partly mantled with a discontinuous veneer of alluvium derived from the upland masses.

petrified wood A rock formed by permineralization of wood by silica in such a manner that the original form and structure of the wood is preserved. The silica is generally in the form of opal or chalcedony.

petroleum (a) A naturally occurring complex liquid hydrocarbon, which after distillation and removal of impurities yields a range of combustible fuels, petrochemicals, and lubricants. Crude oil. (b) A general term for all naturally occurring hydrocarbons, whether gaseous, liquid, or solid.

piping Erosion by percolating water in a layer of subsoil, resulting in caving and in the formation of narrow conduits, tunnels, or ''pipes" through which soluble or granular soil material is removed; esp. the movement of material by the flow or seepage of water along underground passages.

plateau Broadly, any comparatively flat area of great extent and elevation generally underlain by horizontal strata or characterized by horizontal structure; an extensive land region considerably elevated above the adjacent country; it is commonly limited on at least one side by an abrupt descent, has a flat or nearly smooth surface but is often dissected by deep valleys and has a large part of its total surface at or near the summit level.

Pleistocene An epoch of the **Quaternary** period, after the Pliocene of the **Tertiary** and before the **Holocene**; also, the corresponding worldwide series of rocks. It began 1.6 million years ago and lasted until the start of the **Holocene** some 10, 000 years ago. Synonym: Ice Age; Great Ice Age; glacial epoch.

point bar One of a series of low, arcuate ridges of sand and gravel developed on the inside of a growing meander by the slow addition of individual accretions accompanying migration of the channel toward the outer bank.

Quaternary The second period of the Cenozoic era, following the **Tertiary**; also, the corresponding system of rocks. It began 1.6 million years ago and extends to the present. It consists of two epochs of unequal length: the **Pleistocene**, up to about 10, 000 years ago, and the **Holocene** since that time.

relief (a) A term used loosely for the physical shape, configuration, or general unevenness of a part of the Earth's surface, considered with reference to variations of height and slope or to irregularities of the land surface; the elevations or differences in elevation, considered collectively, of a land surface. The term is frequently confused with topography. Syn: topographic relief. (b) The vertical difference in elevation between the hilltops or mountain summits and the lowlands or valleys of a given region.

sandstone (a) A medium-grained clastic sedimentary rock composed of abundant rounded or angular fragments of sand size set in a fine-grained matrix (silt or clay) and more or less firmly united by a cementing material (commonly silica, iron oxide, or calcium carbonate); the consolidated equivalent of sand, intermediate in texture between conglomerate and shale. (b) A field term for any clastic rock containing individual particles that are visible to the unaided eye or slightly larger.

scoria A vesicular, cindery crust on the surface of andesitic or basaltic lava; this term is commonly misused in North Dakota to refer to clinker. *See* **clinker**.

shale A fine-grained detrital sedimentary rock, formed by the consolidation, especially by compression, of clay, silt, or mud. It is characterized by finely laminated structure, which imparts a fissility typically parallel to the bedding.

sheet wash Sediment transported and deposited by the thin sheets of water flowing across the surface of the ground.

silcrete (a) Soil, sand, or gravel cemented into a hard mass by silica. (b) A siliceous duricrust.

siltstone An indurated silt having the texture and composition of shale but lacking its fine lamination or fissility; a massive mudstone in which the silt predominates over clay; a nonfissile silt shale. Siltstone has a composition intermediate between that of sandstone and shale and consists of at least two-thirds silt.

slope wash Soil and rock material transported down a slope by mass wasting assisted by running water not confined to channels. Cf: colluvium.

slump A landslide characterized by a shearing and rotary movement of a generally independent mass of rock or earth along a curved slip surface (concave upward) and about an axis parallel to the slope from which it descends, and by backward tilting of the mass with respect to that slope so that the slump surface often exhibits a reversed slope facing uphill.

slump block The mass of material torn away as a coherent unit during slumping. It may be more than 1 mile long and as thick as 300 feet in the Little Missouri Badlands.

soil All unconsolidated materials above bedrock, particularly the material that supports plant life and has been altered by biological processes, in addition to chemical and physical processes.

strath A broad, flat valley bottom formed in bedrock and resulting from degradation,'first by lateral stream cutting and later by whatever additional processes of degradation may be involved; a level valley floor, representing a local base level, usually covered by a veneer of alluvium.

stratigraphy The science of rock strata. It is concerned not only with the original succession and age relations of rock strata but also with their form, distribution, lithologic composition, fossil content, geophysical and geochemical properties; and their interpretation in terms of environment or mode of origin, and geologic history.

stratum (plural **strata**) A tabular or sheetlike body or layer of sedimentary rock, visually separable from other layers above and below; a bed. Stratigraphic unit that may be composed of a number of beds.

syncline A concave upward fold of which the core contains the stratigraphically younger rocks.

terrace A relatively level or gently inclined surface, which commonly occurs along the margin and above the level of a body of water, marking a former water level; e.g., a stream terrace. The term commonly but incorrectly is applied to the deposit underlying the tread and riser of a terrace, esp. the alluvium of a stream terrace; ''this deposit ... should more properly be referred to as a fill, alluvial fill, or alluvial deposit, in order to differentiate it from the topographic form" (Leopold et al., 1964, p. 460).

Tertiary The first period of the Cenozoic era (after the Cretaceous of the Mesozoic era and before the **Quaternary**), thought to have covered the span of time between 65 and 1.6 million years ago. It is divided into five epochs: the Paleocene, Eocene, Oligocene, Miocene, and Pliocene.

till Unsorted and unstratified rock debris composed of a wide range of particle sizes that was deposited directly by a glacier.

topography The general configuration of a land surface or any part of the Earth's surface, including its relief and the position of its natural and man-made features.

tuff A general term for all consolidated pyroclastic rocks.

unconformity (a) A substantial break or gap in the geologic record where a rock unit is overlain by another that is not normally next in stratigraphic succession, such as an interruption in the continuity of a depositional sequence of sedimentary rocks or a break between eroded igneous rocks and younger sedimentary strata. It results from a change that caused deposition to cease for a considerable span of time, and it normally implies uplift and erosion with loss of the previously formed record. (b) The structural relationship between rock strata in contact, characterized by a lack of continuity in deposition, and corresponding to a period of nondeposition, weathering, or esp. erosion (either subaerial or subaqueous) prior to the deposition of the younger beds, and often (but not always) marked by absence of parallelism between the strata. Common types of unconformities recognized in U.S.: nonconformity; angular unconformity; disconformity; paraconformity.

unconsolidated material A sediment whose particles are not cemented together, occurring either at the surface or at depth.

vertical accretion Upward growth of a sedimentary deposit; e.g., settling of sediment from suspension in a stream subject to overflow. Cf: **lateral accretion**.

weathering The destructive process or group of processes by which earthy and rocky materials on exposure to atmospheric agents at or near the Earth's surface are changed in color, texture, composition, firmness, or form, with little or no transport of the loosened or altered material; specifically the physical disintegration and chemical decomposition of rock that produces an in-situ mantle of waste.

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Industrial Commission of North Dakota

John Hoeven
GOVERNOR

Wayne Stenehjem
ATTORNEY GENERAL

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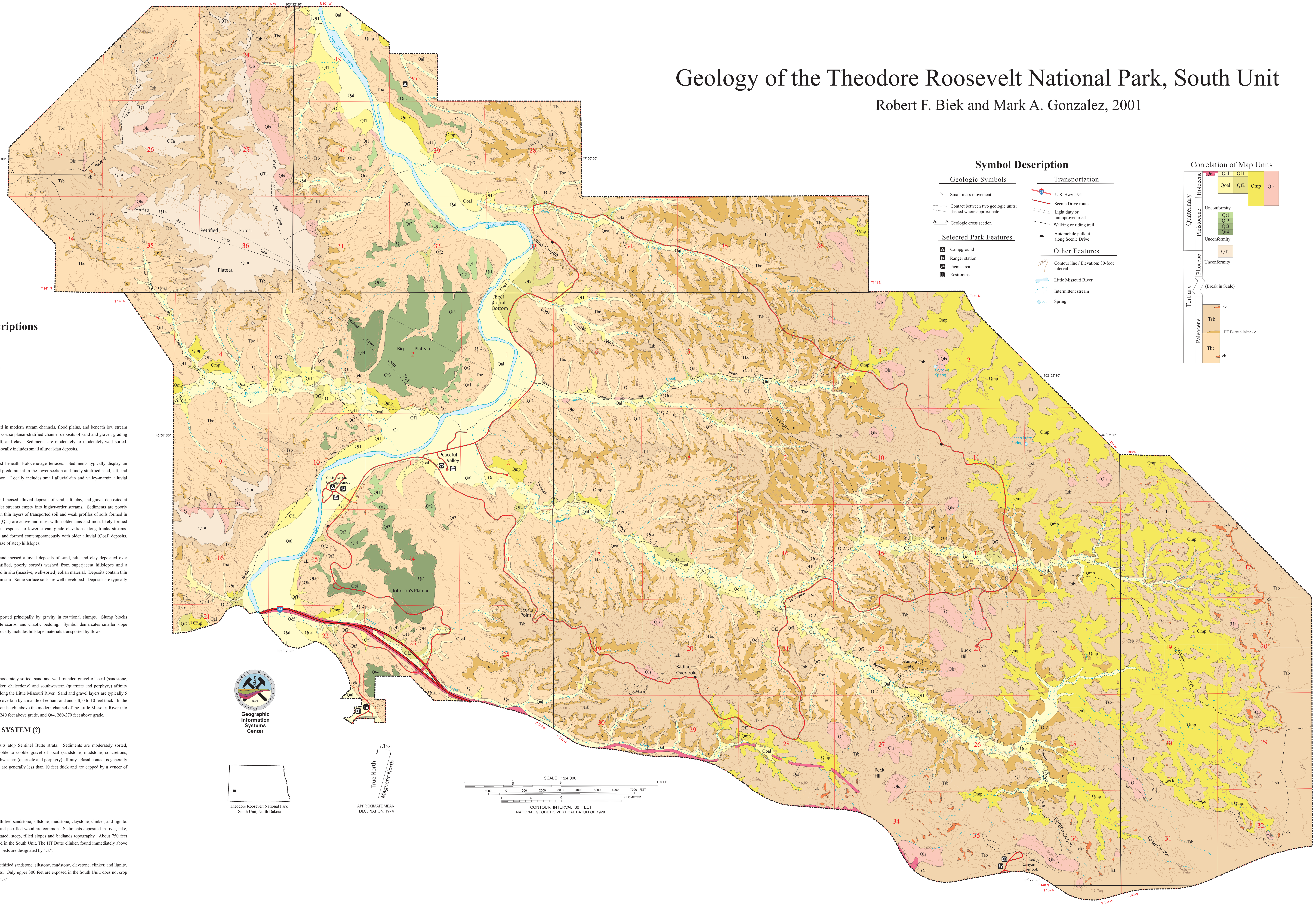
2001

Miscellaneous Series 86
Plate I

North Dakota Geological Survey
John P. Bluemle, State Geologist

Geology of the Theodore Roosevelt National Park, South Unit

Robert F. Biek and Mark A. Gonzalez, 2001



Symbol Description

Geologic Symbols

- Small mass movement
- Contact between two geologic units; dashed where approximate
- A — A' Geologic cross section

Selected Park Features

- Campground
- Ranger station
- Picnic area
- Restrooms

Transportation

- U.S. Hwy I-94
- Scenic Drive route
- Light duty or unimproved road
- Walking or riding trail
- Automobile pullout along Scenic Drive

Other Features

- Contour line / Elevation; 80-foot interval
- Little Missouri River
- Intermittent stream
- Spring

Correlation of Map Units

Quaternary
Holocene
Pleistocene
Tertiary
Pliocene
Paleocene
Qef
Qal
Qf1
Qoal
Qf2
Qmp
Qls
Unconformity
Qt1
Qt2
Qt3
Qt4
Unconformity
QTa
Unconformity
(Break in Scale)
ck
Tsb
HT Butte clinker - c
Tbc
ck

Unit Descriptions

ARTIFICIAL DEPOSITS

Qef

Engineered fill Fill used in the construction of roadways.

QUATERNARY SYSTEM

RECENT

OAHE FORMATION

Qal

Modern alluvium Sand, silt, clay, and gravel deposited in modern stream channels, flood plains, and beneath low stream terraces. Sediments typically comprise cross-stratified and coarse planar-stratified channel deposits of sand and gravel, grading upward to finely stratified overbank deposits of sand, silt, and clay. Sediments are moderately to moderately-well sorted. Sediments have been deposited within the past 500 years. Locally includes small alluvial-fan deposits.

Qoal

Older alluvium Sand, silt, clay, and gravel deposited beneath Holocene-age terraces. Sediments typically display an upward-fining sequence: crudely stratified gravel and sand predominant in the lower section and finely stratified sand, silt, and clay in the upper section. Buried soil profiles are common. Locally includes small alluvial-fan and valley-margin alluvial deposits.

Qf1
Qf2

Alluvial fan deposits Complex assemblage of active and incised alluvial deposits of sand, silt, clay, and gravel deposited at the mouths of canyons and at confluences where low-order streams empty into higher-order streams. Sediments are poorly stratified and poorly to moderately sorted. Deposits contain thin layers of transported soil and weak profiles of soils formed in situ. Subdivided by age into Qf1 and Qf2. Modern fans (Qf1) are active and inset within older fans and most likely formed contemporaneously with modern alluvial (Qal) deposits in response to lower stream-grade elevations along trunks streams. Holocene-age fans (Qf2) are typically inactive and incised and formed contemporaneously with older alluvial (Qoal) deposits. Locally includes colluvium deposited by slopewash at the base of steep hillslopes.

Qmp

Mantled pediments Complex assemblage of active and incised alluvial deposits of sand, silt, and clay deposited over pediments. Sediments represent alluvium (weakly stratified, poorly sorted) washed from superjacent hillslopes and a combination of reworked (weakly stratified, well-sorted) and in situ (massive, well-sorted) eolian material. Deposits contain thin layers of transported soil and weak profiles of soils formed in situ. Some surface soils are well developed. Deposits are typically less than 3 feet thick, locally more than 6 feet thick.

RECENT/PLEISTOCENE

Qls

Landslide deposits Locally derived sediment transported principally by gravity in rotational slumps. Slump blocks characterized by hummocky topography, numerous arcuate scarps, and chaotic bedding. Symbol demarcates smaller slope failures and hillslopes affected strongly by heave (creep). Locally includes hillslope materials transported by flows.

PLEISTOCENE

COLEHARBOR GROUP

Qt1
Qt2
Qt3
Qt4

Alluvium beneath Pleistocene terraces Poorly to moderately sorted, sand and well-rounded gravel of local (sandstone, mudstone, concretions, silicified wood, flint, silcrete, clinker, chalcedony) and southwestern (quartzite and porphyry) affinity beneath broad, flat to gently sloping axial-stream terraces along the Little Missouri River. Sand and gravel layers are typically 5 to 10 feet thick, range from 2 to 20 feet in thickness, and are overlain by a mantle of eolian sand and silt, 0 to 10 feet thick. In the South Unit, deposits of Qt are subdivided on the basis of their height above the modern channel of the Little Missouri River into Qt1, 160 feet above grade, Qt2, 220 feet above grade, Qt3, 240 feet above grade, and Qt4, 260-270 feet above grade.

LATE TERTIARY/QUATERNARY SYSTEM (?)

QTa

Upland gravel Sand and well-rounded gravel deposits atop Sentinel Butte strata. Sediments are moderately sorted, iron-stained, locally iron-cemented sand and polished pebble to cobble gravel of local (sandstone, mudstone, concretions, silicified wood, flint, silcrete, clinker, chalcedony) and southwestern (quartzite and porphyry) affinity. Basal contact is generally more than 400 feet above modern stream grade. Deposits are generally less than 10 feet thick and are capped by a veneer of loess.

TERTIARY SYSTEM

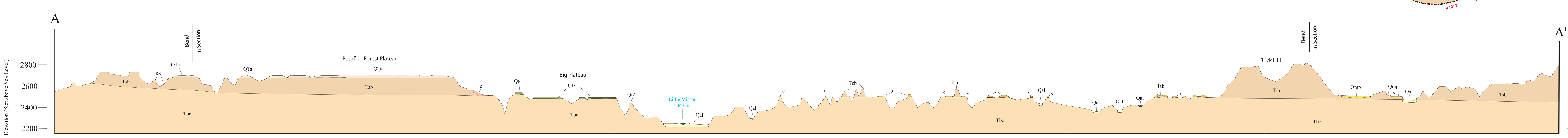
PALEOCENE

Tsb (ck, c)

Sentinel Butte Formation Gray to brown, variably lithified sandstone, siltstone, mudstone, claystone, clinker, and lignite. Calcite-cemented sandstone concretions, siderite nodules, and petrified wood are common. Sediments deposited in river, lake, and swamp environments. Typically forms sparsely vegetated, steep, rilled slopes and badlands topography. About 750 feet thick in the North Unit; only the lower 300 feet are exposed in the South Unit. The HT Butte clinker, found immediately above the contact with Tbc, is designated by "c". Unnamed clinker beds are designated by "ck".

Tbc (ck)

Bullion Creek Formation Yellowish-brown, variably lithified sandstone, siltstone, mudstone, claystone, clinker, and lignite. Sediments deposited in river, lake, and swamp environments. Only upper 300 feet are exposed in the South Unit; does not crop out in North Unit. Unnamed clinker beds are designated by "ck".



The North Dakota Geological Survey compiled this map according to conventional cartographic standards, using what is thought to be the most reliable information available. The North Dakota Geological Survey does not guarantee freedom from errors or inaccuracies and disclaims any legal responsibility or liability for interpretations made from the map, or decisions based thereon.

This map is Plate I from North Dakota Geological Survey Miscellaneous Series 86 (MS-86). The field work required to produce this map was conducted by Robert F. Biek and Mark A. Gonzalez, with additional work done by Edward C. Murphy. This project was carried out under Assistance Award 1434-95-A-1374, from the USGS, Department of the Interior.

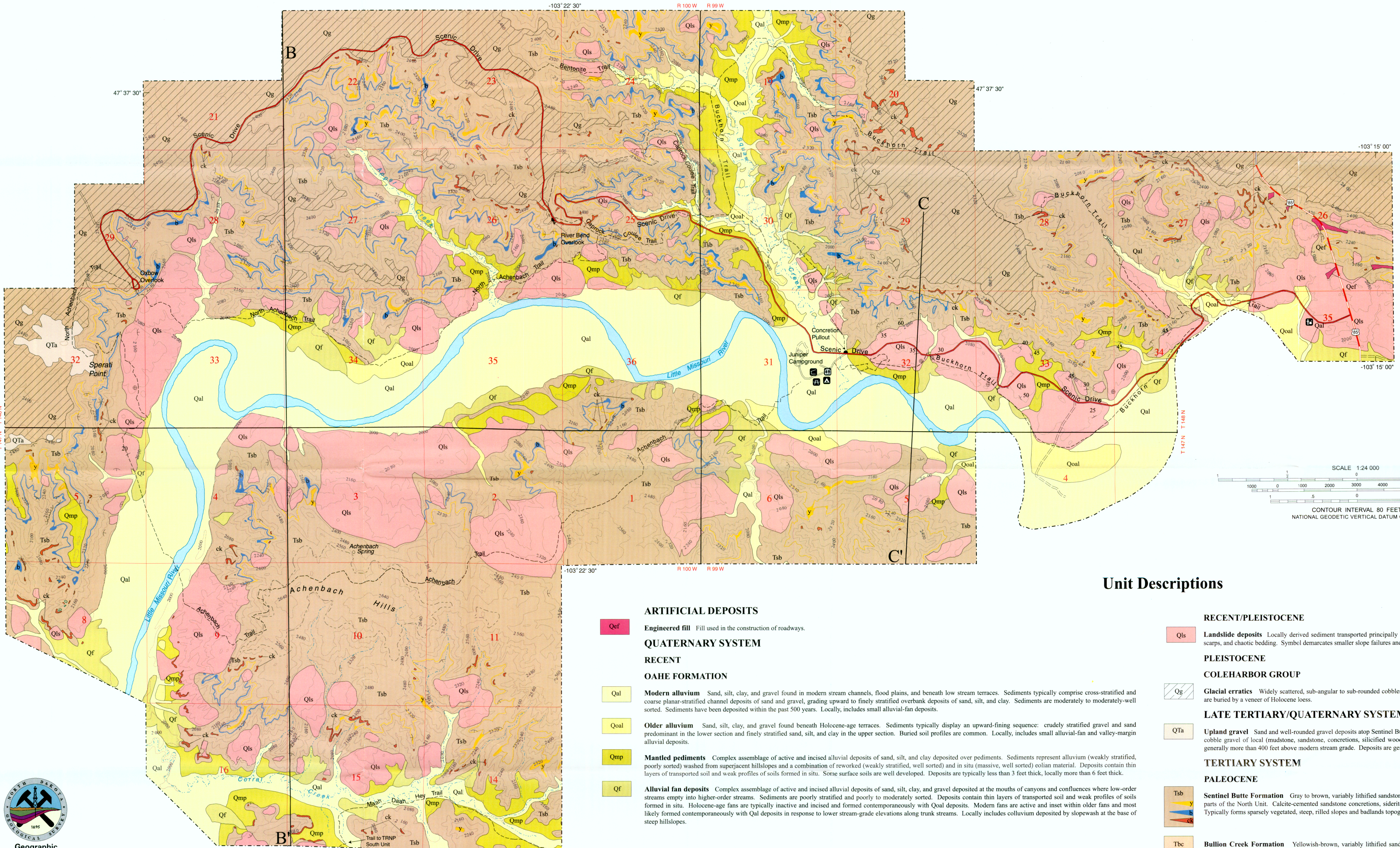
Cartographic Compilation: Kadrmas, E.L., and Waldkirch, R.P.

Miscellaneous Series 86
Plate II

North Dakota Geological Survey
John P. Bluemle, State Geologist

Geology of the Theodore Roosevelt National Park, North Unit

Robert F. Biek and Mark A. Gonzalez, 2001



Symbol Description

Geologic Symbols

- Strike and dip of bedding; approximate where dashed
- Horizontal Bedding ; used only near areas of large landslides
- Small mass movement
- Contact between two geologic units; dashed where approximate
- Limit of abundant silcrete lag above Sentinel Butte Formation

Other Features

- Contour Line / Elevation; 80-foot interval
- Little Missouri River
- Intermittent stream

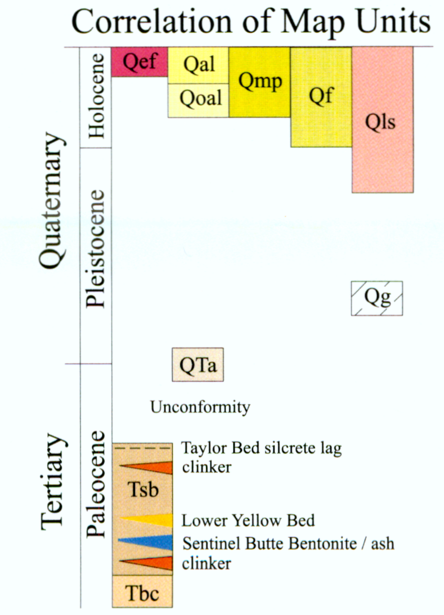
Transportation

- U.S. Hwy 85
- Scenic Drive route
- Light duty or unimproved road
- Walking or riding trail
- Automobile Pullout along Scenic Drive

Park Features

- Group Camping
- Ranger Station
- Picnic Area
- Shelter
- Restrooms

Correlation of Map Units



SCALE 1:24 000

CONTOUR INTERVAL 80 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

Unit Descriptions

ARTIFICIAL DEPOSITS

Qef — **Engineered fill** Fill used in the construction of roadways.

QUATERNARY SYSTEM

RECENT

OAHE FORMATION

Qal — **Modern alluvium** Sand, silt, clay, and gravel found in modern stream channels, flood plains, and beneath low stream terraces. Sediments typically comprise cross-stratified and coarse planar-stratified channel deposits of sand and gravel, grading upward to finely stratified overbank deposits of sand, silt, and clay. Sediments are moderately to moderately-well sorted. Sediments have been deposited within the past 500 years. Locally, includes small alluvial-fan deposits.

Qoal — **Older alluvium** Sand, silt, clay, and gravel found beneath Holocene-age terraces. Sediments typically display an upward-fining sequence: crudely stratified gravel and sand predominant in the lower section and finely stratified sand, silt, and clay in the upper section. Buried soil profiles are common. Locally, includes small alluvial-fan and valley-margin alluvial deposits.

Qmp — **Mantled pediments** Complex assemblage of active and incised alluvial deposits of sand, silt, and clay deposited over pediments. Sediments represent alluvium (weakly stratified, poorly sorted) washed from superjacent hillslopes and a combination of reworked (weakly stratified, well sorted) and in situ (massive, well sorted) eolian material. Deposits contain thin layers of transported soil and weak profiles of soils formed in situ. Some surface soils are well developed. Deposits are typically less than 3 feet thick, locally more than 6 feet thick.

Qf — **Alluvial fan deposits** Complex assemblage of active and incised alluvial deposits of sand, silt, clay, and gravel deposited at the mouths of canyons and confluences where low-order streams empty into higher-order streams. Sediments are poorly stratified and poorly to moderately sorted. Deposits contain thin layers of transported soil and weak profiles of soils formed in situ. Holocene-age fans are typically inactive and incised and formed contemporaneously with Qoal deposits. Modern fans are active and inset within older fans and most likely formed contemporaneously with Qal deposits in response to lower stream-grade elevations along trunk streams. Locally includes colluvium deposited by slopewash at the base of steep hillslopes.

RECENT/PLEISTOCENE

Qls — **Landslide deposits** Locally derived sediment transported principally by gravity in rotational slumps. Slump blocks characterized by hummocky topography, numerous arcuate scarps, and chaotic bedding. Symbol demarcates smaller slope failures and hillslopes affected strongly by heave (creep). Locally, includes hillslope materials transported by flows.

PLEISTOCENE

COLEHARBOR GROUP

Qg — **Glacial erratics** Widely scattered, sub-angular to sub-rounded cobbles and boulders of granitic and carbonate composition that lie atop Sentinel Butte strata and poke through or are buried by a veneer of Holocene loess.

LATE TERTIARY/QUATERNARY SYSTEM (?)

QTa — **Upland gravel** Sand and well-rounded gravel deposits atop Sentinel Butte strata. Sediments are moderately sorted, iron-stained, locally iron-cemented sand and polished pebble to cobble gravel of local (mudstone, sandstone, concretions, silicified wood, flint, silcrete, clinker, chalcedony) and southwestern (quartzite and porphyry) affinity. Basal contact is generally more than 400 feet above modern stream grade. Deposits are generally less than 10 feet thick, but may be up to 40 feet thick at Sperati Point; capped by a veneer of loess.

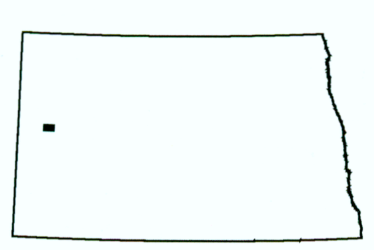
TERTIARY SYSTEM

PALEOCENE

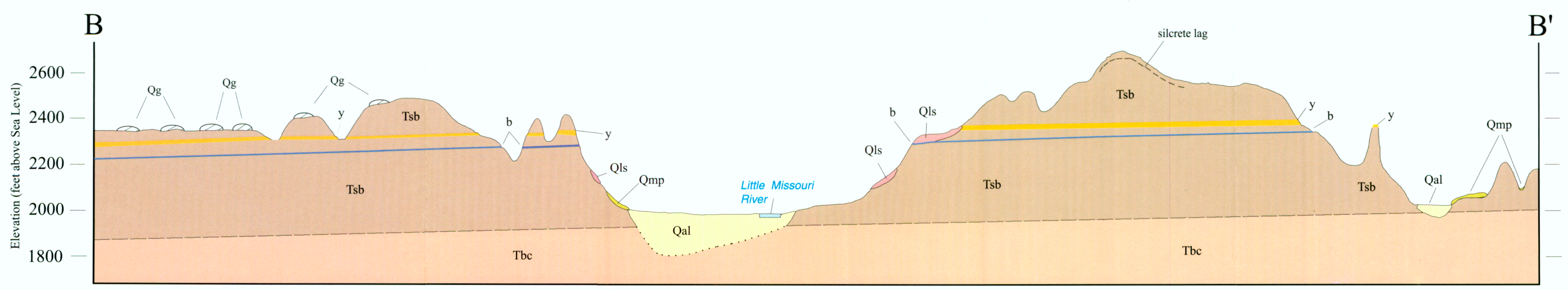
Tsb (y, b, ck) — **Sentinel Butte Formation** Gray to brown, variably lithified sandstone, siltstone, mudstone, claystone, clinker, and lignite. A bed of tuff/bentonite up to 20 feet thick is found in parts of the North Unit. Calcite-cemented sandstone concretions, siderite nodules, and petrified wood are common. Sediments deposited in river, lake, and swamp environments. Typically forms sparsely vegetated, steep, rilled slopes and badlands topography. About 750 feet thick in the North Unit; only the lower 300 feet are exposed in the South Unit.

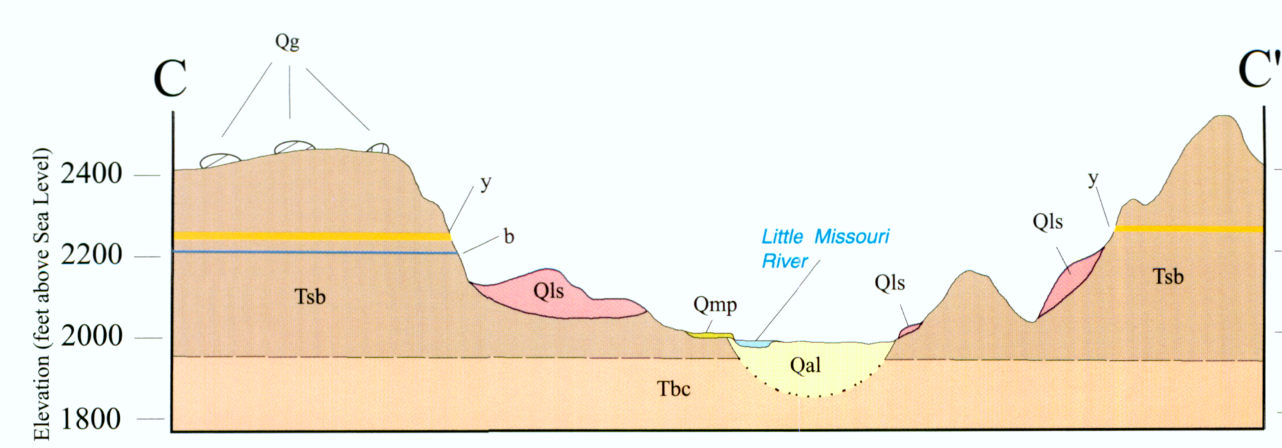
Tbc — **Bullion Creek Formation** Yellowish-brown, variably lithified sandstone, siltstone, mudstone, claystone, clinker, and lignite. Sediments deposited in river, lake, and swamp environments. Only upper 300 feet are exposed in the South Unit; does not crop out in North Unit.

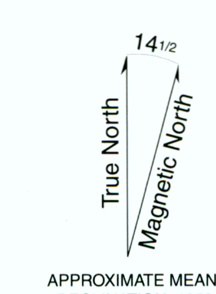
Geographic Information Systems Center



Theodore Roosevelt National Park
North Unit, North Dakota







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Cartographic Compilation: Waldkirch, R.P.