National Park Service
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Natural Resource Program Center

Theodore Roosevelt National Park
Geologic Resource Evaluation Report

Natural Resource Report NPS/NRPC/GRD/NRR—2007/006

THIS PAGE:
The Little Missouri River flows near the Juniper Campground in the North Unit of Theodore Roosevelt NP, ND.

ON THE COVER:
View from the Oxbow Overlook Theodore Roosevelt NP, ND.

Photos by: Dave Krueger

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Geologic Resources Division
Natural Resource Program Center
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Executive Summary

This report accompanies the digital geologic map of Theodore Roosevelt National Park produced by staff of the Geologic Resource Evaluation Program. The report contains information relevant to resource management and scientific research.

In addition to memorializing the life, times, and thinking of Theodore Roosevelt, park managers "conserve unimpaired the scenery and natural and cultural resources and facilitate scientific interests in Theodore Roosevelt National Park" (Theodore Roosevelt National Park, Statement for Management, November 1994). Because the park's land management plan identifies oil and gas development adjacent to the park as the single greatest threat to park resources, this issue is discussed first. Other geologic resource issues that may require management attention follow alphabetically.

- Oil and Gas Development—Energy resources in Theodore Roosevelt and the surrounding area include oil, gas, and lignite. While federal oil and gas leasing is prohibited in the park, oil and gas development adjacent to the park has a high potential to impact both cultural and natural resources, including air and water quality; wildlife and plants, particularly threatened and endangered species; natural quiet; scenic views; visitor experience, and dark night skies. Extensive air quality studies have occurred in the area under the auspices of the NPS Air Resources Division in the Natural Resource Program Center.
- Abandoned Mine Lands—In 1999 park staff permanently closed two mine openings in the park. Closure has prevented local residents and visitors from entering the mine and exposing themselves to hazards such as methane, oxygen- deficient conditions, and rockfall. Periodic monitoring of these closures is warranted but no further mitigation is needed. No additional abandoned mine hazards are known in the park.
- Coal Fires—Exposed coal beds are susceptible to ignition via grass fires, lightning strikes, and spontaneous combustion. Once ignited, coal fires may burn for many years. The Coal Vein Trail in the park highlights a fire that burned for 26 years (1951–1977). No coal beds are currently burning in the park. However, fire is a natural element in the regional ecosystem, and resource managers can anticipate future burns.
- Coal Development— Under federal law coal mining is prohibited in Theodore Roosevelt National Park subject to "valid existing rights" (VER). Coal is a leasable commodity and since no coal leases exist in the park there are no VER. Coal resources in the park include lignite and clinker. Lignite is a low- rank coal with thick yet deeply buried beds immediately west of the park; mining these beds is uneconomic with present technologies. However, the potential remains for development of coal- bed methane from these beds outside the park. Burned coal beds—clinker—provide color to the landscape and contribute to the formation of North Dakota badlands.
- Flooding and Fluvial Erosion—The Little Missouri River flows through the three units of the park. Park infrastructure and visitor- use facilities are located in the 100- year floodplain. In addition to flooding, channel migration and bank erosion may adversely affect facilities such as the Juniper, Cottonwood, and Squaw Creek campgrounds.
- Mass Wasting—Primary hazards associated with mass wasting in the park consist of landslides and soil creep. Locally, landslides have been exacerbated by road construction in the park. All existing landslide deposits are capable of renewed activity, and other slopes, especially those in the North Unit containing the Sentinel Butte Formation, may be vulnerable to future movement.
- Paleontological Resources—Petrified wood and freshwater mollusks in the Bullion Creek and Sentinel Butte formations are the most abundant fossils in the park. The increase in popularity of wilderness recreation over the last 20 years has resulted in greater access and concern for protecting fossils. The ability to manage and protect fossil resources is contingent upon an understanding of their geologic and geographic occurrence and distribution. NPS paleontologists have recently developed a monitoring plan for protecting in situ fossil resources, which may be applicable in the park.
- Piping—Percolating water removes soluble or transportable earth materials, creating tunnels and small caves called "pipes." Piping may result from natural or anthropogenic causes and is common in landscapes with rill erosion. In the park, the principal hazard associated with erosional pipes is collapse.
- Bentonite—The characteristic "blue beds" of the Sentinel Butte Formation are composed of bentonite. When wetted, bentonite "swells," expanding up to 16 times in volume. The swelling (and shrinking) of this layer can cause structural damage to buildings, roads, and other infrastructure. Also, wet Sentinel Butte bentonite produces slippery, hazardous conditions cross- country and on roads and trails.

Other distinctive features and processes in the park are concretions and cap rocks, eolian deposits, glacial erratics, oxbows, pediments, sand and gravel, sandstone and silcrete, sheetwash, and terraces. These are discussed in the "Features and Processes" section of this report.

Introduction

This section briefly describes the National Park Service Geologic Resource Evaluation Program and the regional geologic setting of Theodore Roosevelt National Park.

Purpose of the Geologic Resource Evaluation Program

The Geologic Resource Evaluation (GRE) Program is one of 12 inventories funded under the NPS Natural Resource Challenge designed to enhance baseline information available to park managers. The program carries out the geologic component of the inventory effort from the development of digital geologic maps to providing park staff with a geologic report tailored to a park's specific geologic resource issues. The Geologic Resources Division of the Natural Resource Program Center administers this program. The GRE team relies heavily on partnerships with the U.S. Geological Survey, Colorado State University, state surveys, and others in developing GRE products.

The goal of the GRE Program is to increase understanding of the geologic processes at work in parks and provide sound geologic information for use in park decision making. Sound park stewardship relies on understanding natural resources and their role in the ecosystem. Geology is the foundation of park ecosystems. The compilation and use of natural resource information by park managers is called for in section 204 of the National Parks Omnibus Management Act of 1998 and in NPS- 75, Natural Resources Inventory and Monitoring Guideline.

To realize this goal, the GRE team is systematically working towards providing each of the identified 270 natural area parks with a geologic scoping meeting, a digital geologic map, and a geologic report. These products support the stewardship of park resources and are designed for non- geoscientists. During scoping meetings the GRE team brings together park staff and geologic experts to review available geologic maps and discuss specific geologic issues, features, and processes. Scoping meetings are usually held for individual parks and on occasion for an entire Vital Signs Monitoring Network. The GRE mapping team converts the geologic maps identified for park use at the scoping meeting into digital geologic data in accordance with their innovative Geographic Information Systems (GIS) Data Model. These digital data sets bring an exciting interactive dimension to traditional paper maps by providing geologic data for use in park GIS and facilitating the incorporation of geologic considerations into a wide range of resource management applications. The newest maps come complete with interactive help files. As a companion to the digital geologic maps, the GRE team prepares a park- specific geologic report that aids in use of the maps and provides park managers with an overview of park geology and geologic resource management issues.

For additional information regarding the content of this report and up to date GRE contact information please refer to the Geologic Resource Evaluation web site (http://www2.nature.nps.gov/geology/inventory/).

Geologic Setting

Theodore Roosevelt National Park is situated mostly within the confines of the Little Missouri River valley in the remote southwestern corner of North Dakota (figure 1). This part of the Great Plains hosts a landscape that has changed little since 1883 when 24- year- old Theodore Roosevelt came west to hunt buffalo (figure 2). The park commemorates Theodore Roosevelt, the 26th U.S. president, who began to develop his conservation ethic in this place. The setting made a deep impression on the young man and influenced his presidential administrative policy, which promoted access to and sustainable use of public lands.

The Little Missouri River flows northward from Devils Tower and the Black Hills past Theodore Roosevelt National Park and on to the confluence of the Missouri River. The Missouri Plateau section of the Great Plains (figure 3) reflects the thorough dissection of the landscape by the Missouri River and its tributaries. The Little Missouri River flows through the South Unit of the park, past Roosevelt's ranch site, and into the North Unit where it turns abruptly eastward and joins the Missouri River about 80 km (50 miles) away (figure 4).

The Missouri River and its tributaries (e.g., the Little Missouri River in North Dakota and the Yellowstone River in Montana) carved the Missouri Plateau into confined valleys, broad upland surfaces at many levels, and terraces along the rivers. Locally, high buttes rise above the uplands; these are remnants of former interstream divides. Continental ice sheets also dammed many tributary valleys, forming large lakes (Trimble 1993). Recession as a result of badlands development has widened some of the area's larger valleys.

The Little Missouri River valley is part of the Missouri Plateau of the Great Plains, which consists of two distinct sections: glaciated and unglaciated (figure 4). The boundary between the sections occurs in the park and is marked by glacial erratics (boulders) and cobbles. To the north of this glacial limit, much of the Missouri Plateau is a plain of little relief with muted landforms covered by a thick blanket of glacial debris. To the south the unglaciated Missouri Plateau displays the greatest variety of landforms of any section of the Great Plains (e.g., small mountains, plateaus, river valleys, and badlands) (Trimble 1993). Most of Theodore Roosevelt National Park is situated on the unglaciated Missouri Plateau.

Precipitation in the region comes as sudden showers, and storms commonly drop several inches of rain per hour (Opdahl et al. 1975). This sudden influx of precipitation causes runoff and rapid erosion of the poorly consolidated sediments, forming highly dissected badlands topography. In addition, fused then broken beds of burnt coal facilitate erosion during runoff events. Seasonally, small tributaries flow down the steep valley sides along the Little Missouri River, cutting into the strata of the Fort Union Group: shales, clays, sandstones, silts, and lignite of the Bullion Creek and Sentinel Butte formations.

In general, the shales and clays are gray to brown, and the sandstones tend to appear yellowish orange to buff and tan. Blue bentonite in the Sentinel Butte Formation adds another colorful layer to the landscape. Lignite is dark brown to black. Possibly the most noticeable strata in the park are the red beds, locally called "scoria," but more correctly called "clinker." The colorful, interbedded strata on the hillsides of the park add much to the scenic beauty of the badlands.

Figure 1. Location Map of Theodore Roosevelt National Park.

Figure 2. Bison in the South Unit Crossing the Little Missouri River. When Theodore Roosevelt was 24 years old, he came to the region to hunt buffalo. The rugged landscape matched Roosevelt's individualism and influenced his thinking. NPS photo by Dave Krueger.

Figure 3. Physiographic Areas of the Great Plains. Theodore Roosevelt National Park spans the glaciated and unglaciated portions of the Great Plains Physiographic Province. Other National Park System units of the Great Plains include Agate Fossil Beds National Monument (Nebraska), Badlands National Park (South Dakota), Bent's Old Fort National Historical Site (Colorado), Capulin Volcano National Monument (New Mexico), Devils Tower National Monument (Wyoming), Jewel Cave National Monument (South Dakota), Mount Rushmore National Memorial (South Dakota), and Wind Cave National Park (South Dakota).

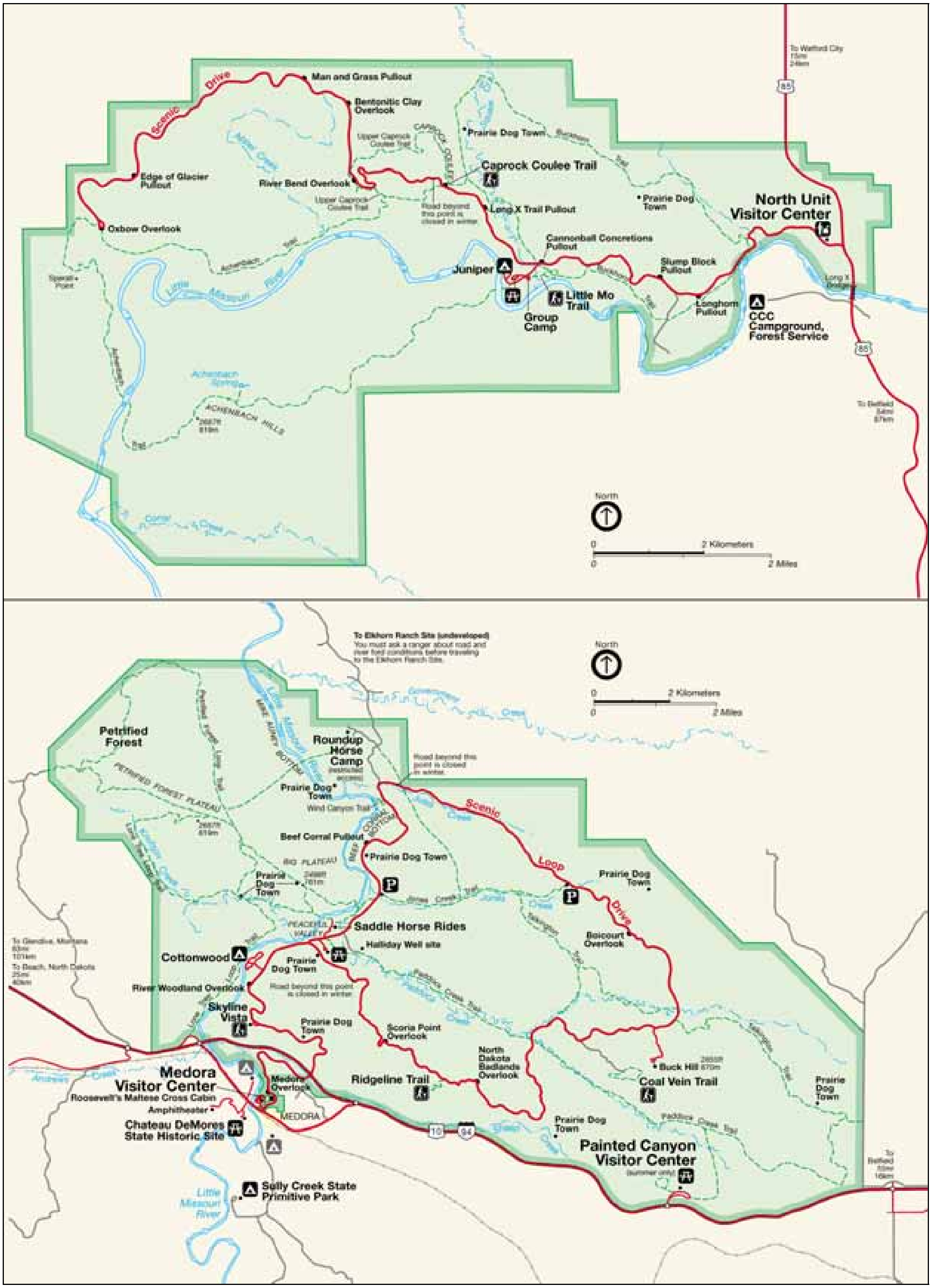

Figure 4. Detailed maps of the North and South Units in Theodore Roosevelt National Park.

Geologic Issues

A Geologic Resource Evaluation scoping session was held for Theodore Roosevelt National Park on June 10, 2002 to discuss geologic resources, address the status of geologic mapping, and assess resource management issues and needs. The following section synthesizes the scoping results, in particular, those issues that may require attention from resource managers.

The land management plan for Theodore Roosevelt National Park identifies oil and gas development in the vicinity of the park as the single greatest concern for resource management; thus, this issue is listed first. Following in alphabetical order are other issues that may require attention from resource managers.

Oil and Gas Development

Under federal statute Theodore Roosevelt National Park is off limits to federal oil and gas development. Nonetheless, at the height of the energy crisis in the 1970's, federal oil and gas leases were issued in the park. No subsequent leases have been issued in the park although periodic interest is expressed in such development. The park lies within the Williston Basin. This structural- sedimentary intracratonic basin—covering portions of North Dakota, Montana, South Dakota, and south- central Canada (Manitoba and Saskatchewan)—is a major producer of oil and gas, lignite, and potash. The deepest portion of the Williston Basin is centered in North Dakota and includes approximately 15,000 feet (4,500 m) of Phanerozoic (table 1) sedimentary rocks. Carbonate sedimentary rocks are the major oil and gas producing units, and clastic sedimentary rocks contain abundant lignite. Energy development on lands adjacent to the park is negatively affecting air and water quality; scenic views; dark night skies; wildlife and plants, including threatened and endangered species; cultural resources; and natural quiet.

Oil and gas were first discovered in the Montana portion of the Williston Basin in 1936, then in Manitoba in 1950, and in North Dakota in 1951. During the last half of the 1970s, development of the United States' portion of the basin was remarkable in its identification of previously unrecognized structures, discovery of new producing zones, and high success rates (Gerhard et al. 1982). In 1970, the entire U.S. portion of the basin averaged 20 active drilling locations; in 1980 the average number had increased to 150 drilling locations (Gerhard et al. 1982). Statistics from the Industrial Commission of North Dakota show that at its peak in 1984 annual production in North Dakota was 52,658,396 barrels of oil produced from 3,546 wells.

North Dakota ranks 9th among U.S. states in production of oil and gas. Most ND production occurs on USDA Forest Service lands in Billings and McKenzie counties. According to statistics from the North Dakota Industrial Commission, Oil and Gas Division, these two counties produce the most oil of the 19 producing counties in the state. Theodore Roosevelt National Park is located in Billings and McKenzie counties. Peak production for Billings County occurred in March 1981 (1,726,136 barrels); McKenzie County peaked in May 1985 with (1,472,169 barrels).

The Little Missouri Grasslands National Forest surrounds Theodore Roosevelt National Park and has the most productive oil fields in the U.S. National Forest System (Hinchman 1993). This national forest lies along the Montana border and has about 600 federally permitted wells. According to the USDA Forest Service, *Dakota Prairie Grasslands/Montana State Office Oil and Gas Leasing Record of Decision* (June 2003), well pads, access roads, and installation of tank batteries, power lines, and pipelines are associated with each well. Well pads are generally about 5 acres (2 ha) and contain the well head, reserve pit, storage tanks, other equipment, and temporary living quarters. Typical production may disturb a site for 40 years. Approximately 100 additional wells occur on lands where surface ownership is federal and subsurface mineral ownership is nonfederal (USDA Forest Service 2001).

In areas with active oil production the potential exists for spills and leaks of drilling fluids, muds, oil, or other waste. Drilling fluids and groundwater encountered in the drilling process are often high in dissolved salt and sometimes contain heavy metals such as barium, cadmium, chromium, lead, strontium and zinc. Spills or leaks of detergents, fuels, machinery fluids, and/or toxic chemicals are also a risk of oil production activities (Iierkley et al. 1998).

The only oil and gas production in the park is on federal leases in the South Unit. In 1975, 12 federal oil and gas tracts totaling 1,316 acres (533 ha) were competitively leased within the South Unit due to concerns with the "drainage" of federal oil and gas from inside the park by external development. Today, such concerns would be addressed through "compensatory royalty agreements" which give the federal government a share in the revenues generated by nonfederal oil and gas development outside the park that drain federal oil and gas in the park. Leases in the South Unit include a "no surface occupancy" stipulation that prohibits drilling and production activities within the park. Seven wells with surface locations south of the park were directionally drilled beneath the park into the federal leases from 1974 through 1995. As of December 2004, one of these wells is producing oil and gas, one is plugged, and five are currently not producing hydrocarbons (statistics from North Dakota Industrial Commission, Oil and Gas Division).

In 2002, the National Park Service completed an Environmental Assessment (EA) that proposed to expand the Elkhorn Ranch Unit to 6,581 acres (2,663 ha) (National Park Service 2002). Elkhorn Ranch, situated between the North and South units, contains both privately held mineral rights and federal oil and gas leases. Since the final EA and a 2003 finding of no significant impact (FONSI), the USDA Forest Service has purchased this property under a "no net gain" procedure. The USDA Forest Service will continue to recognize all rights associated with valid federal leases within the Elkhorn Ranch (Bruce Kaye, Theodore Roosevelt National Park, personal communication, April 24, 2007).

Abandoned Mine Lands

In the early 1990s, staff from the U.S. Department of Interior, Office of Surface Mining, identified hazardous conditions at an abandoned mine land (AML) site in Theodore Roosevelt National Park. As a result of collapse of the overlying strata, the original mine entrances were subsiding. The two openings were not in coal seams but in the weakly consolidated mudstone, siltstone, and sandstone of the overlying cliff face. The weak nature of these bluffs made entry mitigation hazardous (Phil Cloues, NPS Geologic Resources Division, written communication, November 16, 2004).

Coal- bed methane was an additional hazard associated with this abandoned coal mine. As atmospheric pressure conditions fluctuate, methane gas from the underlying coal seam is forced upward through rock fractures. If methane is present at high enough concentrations, explosive conditions can form in mine openings. In addition, suffocation hazards existed due to oxygen-deficient conditions (Dave Shaver, NPS Mining and Minerals Branch, memorandum, June 1, 1992).

Staff from the NPS Mining and Minerals Branch (now the Geologic Resources Division) investigated the site and recommended permanent closure of two openings based on its assessable location behind an NPS maintenance building in Medora, signs of frequent visitation, and unstable conditions. The NPS Geologic Resources Division funded the project using AML Program funds.

Using AML funds park maintenance staff permanently closed the two openings in 1999. The larger of the two openings, referred to as the "east opening," sloped down into the mine and was approximately 25 feet (7 m) above the base of the cliff face. Using long poles so that no one had to enter the unsafe openings, park staff injected 17 bags of polyurethane foam (PUF), which at the time was new technology.

About 200 feet (60 m) west of the larger hole, the smaller opening, referred to as the "west opening," contained a set of mine rails that extended out of the old collapsed portal. Park staff released four bags of PUF in this almost vertical opening and then backfilled it. Park maintenance staff completed the closures in about five hours under very hot conditions. The cost was 10% of the original estimate that would have involved blowing sand up to the hazardous openings (Phil Cloues, NPS Geologic Resources Division, written communication, November 16, 2004). No other AML sites are known in the park and no further mitigation is required at this site but periodic monitoring of the site would be prudent to ensure the continued integrity of the closures.

Coal Fires

Wildfires are a natural element in the ecology of the region. This coupled with abundant exposures of lignite in the Fort Union Group creates a resource management issue for Theodore Roosevelt National Park. When drought or regional downwasting by erosion lowers the groundwater table below the top of a coal bed, the exposed bed has a high probability of burning. Lignite beds, therefore, pose a problem for park planning and management, and the park's prescribed burn program must take into account outcrops of lignite. During the June 10, 2002, scoping meeting, participants suggested that a GeoScientist- in- the- Park (GIP) could identify and map high- potential areas. This data could be added to the park's GIS. Park managers are encouraged to contact the Geologic Resources Division for information about the GIP Program.

No lignite fires are known to be burning in the park at present (Bruce Kaye, THRO, personal communication, April 24, 2007). However, several small fires burned in the northeastern corner of the South Unit in the late 1980s and early 1990s, and resource managers can expect future burns. Grass fires, lightning strikes, and spontaneous combustion may ignite lignite beds. Ranchers have also been known to inadvertently build campfires on coal refuse piles, which have burnt out of control and started coal- bed fires (Heffern et al. 1993). Some of the lignite fires, which started as a result of the lightning- ignited Buck Hill fire in July 1988, appear to be the result of burning juniper roots, which reach down from the surface to underlying coal beds (Bluemle 1988).

Given the right kind of coal, oxygen, and a certain temperature and moisture content, coal will burn by itself (Department of Energy 1993). The "ideal" situation favoring spontaneous combustion is a combination of finely divided coal layers, a slight amount of heat from an outside source (sunlight), and several feet of overburden to retard heat losses by radiation (Bluemle 1988). Absorption of oxygen takes place at ordinary temperatures and because this process generates heat, it is self- generating (Bluemle 1988).

Side- cutting of a stream, a landslide, or rapid erosion can expose fresh coal to the air; mines also penetrate into fresh, unweathered coal. Given sufficient ventilation, a well- oxygenated burning lignite bed can reach temperatures of 3,640°F (2,000°C). This high heat bakes overlying sediments into glassy slag (Biek and Gonzalez 2001). Clinker is the term used to describe the slaggy or vitreous residue of mixed rock and coal ash left after burning. As lignite burns, its volume is significantly reduced creating a void space into which the overlying sediments collapse. Fractures in the slumped sediment allow oxygen to reach the fire and combustion gases to escape. Ultimately an underground coal fire burns all the coal that it can reach before running out of air or fuel. The fire extinguishes naturally where overburden becomes so thick that fractures from the collapse fail to reach the surface to draw more air, or when the fire burns down to the water table (Heffern and Coates 2004). Aside from the obvious fire danger, the principal resource management issue posed by burning lignite beds is the slumping network of fractures that develop (Biek and Gonzalez 2001).

Coal Resources and Mining

Under the Surface Mining Control and Reclamation Act (SMCRA)of 1977, surface coal mining is prohibited in units of the National Park System unless an entity holds "valid existing rights" to mine (see 30 U.S.C. §1272 (e) (1)). No such rights exist in Theodore Roosevelt National Park. The statute covers proposed surface coal mining on federal, state, and private land. Nonetheless, coal rights exist outside the park. SMCRA also prohibits mining external to park boundaries if the proposed development will adversely affect the park. This provision also contains the "valid existing rights" exception (see 30 U.S.C. §1272 (e) (3)).

Lignite, a low- rank coal, is a prominent part of the Fort Union Group (figure 5). Pencil- thin to foot- thick beds of lignite formed in ancient swamps within the Williston Basin (see "Geologic History" section). Long- term stability and slow subsidence of the Williston Basin contributed to the remarkable lateral continuity of these lignite deposits.

The lignite at Theodore Roosevelt National Park is often exposed and frequently burns. This burning produces another interesting rock type, locally called "scoria." The geologic term scoria, however, refers to dark- colored, porous rock associated with basaltic lava flows. No such igneous rocks occur in the park, so the correct term for the material found in the park is "clinker" (figure 6). In some places in the park, clinker melted and flowed like slag from a blast furnace. This flow structure and the porous nature of some clinker may be what caused early settlers to call this rock "scoria" (Laird 1950).

Clinker is the residue formed by burning lignite seams, which have fused and baked overlying sands, shales, and clays. Clinker is generally red due to the presence of iron- rich hematite, but varies from black to pale pink, depending on the characteristics of the original sediment and degree of oxidation or reduction during burning. Heating turns calcium carbonate- rich sediments yellow. As heating continues, the shale and siltstone become intensely fractured, and ochre hues give way to darker, more intense shades of orange and red (Heffern and Coates 2004).

Clinker is used for road base and ornamental lawn and garden material. Clinker has been quarried in at least one location in the South Unit, just east of Johnson's Plateau. The location is labeled as "scoria pit" on the USGS topographic map of the park. The extracted material was used for road construction. Though locally abundant, the material was reportedly of poor quality; therefore, park managers do not foresee any future use of this site (Keith Butler, Theodore Roosevelt National Park, memorandum, December 21, 1992).

Clinker is a major factor in the development of the North Dakota badlands. Natural burning of the lignite beds throughout western North Dakota has resulted in broad areas of hardened clinker- capped landforms. Clinker is more resistant to erosion than nearby unbaked rocks. Differential erosion leaves clinker as a cap on red-topped knobs, ridges, and mesas throughout the park (figure 7). These features rise above the more subdued topography of the less- resistant strata (Bluemle 1988). Clinker also forms an irregular collapsed topography referred to as "thermo- karst." However, this should not be confused with true karst, which forms by dissolution, rather than heating and collapse.

The first European settlers and the Northern Pacific Railroad Company mined lignite near Medora as early as 1884. In the 1950s and early 1960s, uranium- rich lignite was mined both southeast and northeast of the South Unit, at Rocky Ridge and an area south of Fairfield respectively. Under the guidance of the NPS Geologic Resources Division, park maintenance staff permanently closed hazardous mine openings on park land in 1999 (see "Abandoned Mine Land" section). Today, lignite mining is excluded (withdrawn from leasing) inside Theodore Roosevelt National Park. However, North Dakota is the site of the world's largest known lignite deposits (Wiebmer 1977). The thickest lignite beds in North Dakota are just west of the North Unit; however, these particular beds are too deep to mine from the surface in this area (Ed Murphy, North Dakota Geological Survey, oral communication, December 2, 2004). Nevertheless, the potential remains for development of coal- bed methane from the Fort Union Group in the vicinity of the park.

With present technology, the high- moisture content, low- heat content, and potential for spontaneous combustion of the lignite deposits in the vicinity of Theodore Roosevelt National Park makes these deposits uneconomical and difficult to transport over long distances (Russell Dickenson, NPS Director, memorandum to Assistant Secretary, Fish and Wildlife and Parks, January 18, 1983). For these reasons, this particular lignite would need to be processed on site. In the present climate of high energy prices, companies (e.g., Great Northern Properties, the mining enterprise of the Northern Pacific Railroad Company) are reinvestigating the potential for establishing a coal mine and power plant southeast of the South Unit despite these obstacles (Ed Murphy, North Dakota Geological Survey, oral communication, December 2, 2004). Coal industry representatives have discussed gasification as a means to generate electricity in proposed power plants in the region. Gasification refers to the conversion of lignite to gas, in this case for fueling boilers. If high energy prices continue, a coal- fired power plant between Dickinson and Belfield may be forthcoming (Jim Deutsch, North Dakota Public Service Commission, oral communication, December 6, 2004).

While the deposits of lignite are fixed in place, mining activity is dependant on market prices, and economics will provide the driving force for future mining. The North Dakota Geological Survey has produced 1:125,000- scale county maps of the economically recoverable (from the surface) lignite in western North Dakota, which may be of use to resource managers for identifying economically feasible coal mining near the park.

GRD staff recommends that park staff maintain good communication with the Bureau of Land Management, which administers federal leases, to weigh in on leasing decisions and to raise the SMCRA prohibitions designed to protect park resources from surface coal mining. Early involvement in the permitting process near other National Park System units (e.g., New River Gorge National River, West Virginia, and Big South Fork National River and Recreation Area, Tennessee) has proven to be effective in minimizing serious impacts to park resources. Table 2 lists potential major effects of surface mining on park resources.

Flooding and Fluvial Erosion

The Little Missouri River flows through 9 miles (14 km) of the South Unit, 14 miles (23 km) of the North Unit, and across Elkhorn Ranch (figure 8). The river flows undisturbed and is a designated state scenic river (Theodore Roosevelt National Park, Natural Resource Management Plan and Environmental Assessment, July 1984). The river has also been considered for federal wild and scenic river status (Theodore Roosevelt National Park, Land Protection Plan, June 1990). Congress granted a portion of another Little Missouri River in Arkansas “wild and scenic” status in April 1992; authorization is still pending for the North Dakota segment (National Wild and Scenic Rivers System, http://www.rivers.gov/publications/rivers- table.pdf, April 23, 2007). With the exception of the Little Missouri River, the creeks within the park are mostly ephemeral. However, the lower 1.5 miles (2.4 km) of Knutson Creek is permanent, flowing from the west 2.5 miles (4 km) through the South Unit of the park to the Little Missouri (Theodore Roosevelt National Park, Natural Resource Management Plan and Environmental Assessment, July 1984).

The town of Medora, Cottonwood Campground, Squaw Creek Campground, Peaceful Valley Ranch, South Unit park headquarters, and portions of the park road are located within the Little Missouri River 100- year floodplain. These areas are especially prone to inundation during rapid spring thaws with periods of ice jams (Theodore Roosevelt National Park, Natural Resource Management Plan and Environmental Assessment, July 1984). The floodplain and terraces (unit Qal on the geologic map) flanking the Little Missouri River will be inundated during a 100- year flood event (Biek and Gonzalez, 2001). A 100- year flood does not refer to an event that occurs once every hundred years; a 100- year flood can happen any year or a number of years in a row. The term is a statistical designation. Specifically, a 100- year flood has a 1% chance of occurring in any given year. Flood discharges for the Little Missouri River were reported in Emerson and Macek- Rowland (1986) and are presented here in table 3.

Flooding from the Little Missouri River and tributary creeks both cause hazards for persons and property. However, the flood hazard of the Little Missouri River is very different than that of the smaller tributary creeks. The threat of flooding may be known days in advance along the Little Missouri River because it has a relatively large drainage basin. In contrast, intense, localized thunderstorms will most likely cause flash flooding in the smaller tributaries, which may at most be predicted only hours in advance. Storm runoff will fill the floodplain of the relatively narrow tributary valley and flow downslope at high velocity. Once the flood waters of a tributary reach the mouth of the valley, they will flow into the wider floodplain of the Little Missouri River, quickly dispersing, shallowing, and slowing substantially (Emerson and Macek- Rowland 1986).

As the Little Missouri naturally meanders across its floodplain, sediment is eroded from the outside bend of the meander and deposited along the inside bend. This flow causes the channel to migrate laterally across the floodplain, continuously reshaping the surface (Biek and Gonzalez 2001). Abandoned channels and oxbow lakes (see “Oxbow” section) record the geomorphological changes on the valley floor. Because of their proximity to the river, facilities such as Juniper and Cottonwood campgrounds may be adversely affected by channel migration and bank erosion. Additionally, meandering and resulting erosion are threatening Squaw Creek Campground in the North Unit and land adjacent to the Elkhorn Ranch site.

The NPS Water Resources Division briefly addresses floodplain hazard identification and other water related management issues in the Theodore Roosevelt National Park Water Resources Management Plan available online (http://www.nature.nps.gov/water/completedwrmp).

Mass Wasting

According to Biek and Gonzalez (2001), mass wasting in Theodore Roosevelt National Park occurs primarily as landslides and soil creep. The steep, sparsely vegetated slopes in the park are continually reshaped by erosion. Small- scale landslides are a ubiquitous part of this process and most landslides show multiple episodes of slumping (Biek and Gonzalez 2001).

Factors such as lithology, steepness of slopes, and the presence of bentonite influence mass- wasting processes in the park. Most mass wasting occurs in the mixed strata of the Sentinel Butte Formation. Soil creep is also particularly common on steep north- and northeast- facing slopes of the Bullion Creek Formation in the South Unit (Biek and Gonzalez 2001). North- facing slopes that contain layers of Sentinel Butte bentonite tend to retain moisture longer, making them more susceptible to landsliding (GRI workshop, meeting notes, June, 10, 2002).

Road construction activities in the park have locally exacerbated landsliding. Buckled pavement and dips in the road attest to continued movement in several places within the park (Biek and Gonzalez 2001). For instance, in the South Unit, the park road runs over landslide deposits near the trailhead to Ridgeline Trail and along the road to Buck Hill. In the North Unit, the scenic drive regularly intersects landslide deposits between Concretion Pullout and the junction to Highway 85. Ground disturbing activities such as placing fill, regrading, and altering drainage patterns in such deposits may lead to increased instability (Biek and Gonzalez 2001).

The most pronounced landslides are in the North Unit, where two classic types of rotational slumps are present (figure 9). First, large, complex slumps with hummocky surfaces occur along the length of the Little Missouri River valley. The largest of these is on the north flank of Achenback Hills. Achenback Spring flows from the headwall of this landslide.

The second classic type of rotational slump is found north of the Little Missouri River between the east entrance and Juniper Campground. Here, large coherent blocks with beds dipping into the hillside at 25° to 50°, and numerous small displacements within these blocks, collectively accommodate stresses resulting from block rotation (Biek and Gonzalez 2001). The presence of undisturbed, horizontal Sentinel Butte strata at the toe of these rotated blocks shows that these blocks were emplaced by rotational slumping and not faulting (Biek and Gonzalez 2001).

Paleontological Resources

During a detailed study of 10 square miles (26 km^2) of the park (about 1/10 of the entire area) in 1994, investigation showed that both the Bullion Creek and Sentinel Butte formations are quite fossiliferous (table 4). Investigators mapped 400 fossil sites in the study area. This is an average of 40 fossil sites per square mile. The most common kind of fossil in the park is petrified wood, which occurs sporadically at several stratigraphic levels in the Sentinel Butte and Bullion Creek formations. The abundance of petrified wood and the many upright and intact petrified stumps are evidence of the presence of forests in many areas of the South Unit during deposition of the Sentinel Butte Formation (figure 10). Some of these trees were massive, leaving stumps 7 to 8 feet (2.1 to 2.4 m) in diameter (Hoganson and Campbell 1997). Despite the size of the petrified logs, vestiges of large roots are absent from the petrified stumps and from soil profiles. Though poor preservation has hindered specific identification of the wood types, most of the trees were probably conifers (Hoganson and Campbell 1997). Remains of freshwater mollusks (i.e., snails and small snail opercula, mussels, and pill clams) are also abundant, and ostracodes (small bivalved crustaceans) are present. Shelly remains are so abundant at some localities that they form coquina beds.

In addition to abundant petrified wood and mollusks, many others kinds of plant and animal fossils occur in Theodore Roosevelt National Park. Some of the fossil stumps and logs show evidence of damage (i.e., trace fossils) from Paleocene- age insects and birds. Investigators found only one insect (body) fossil, a beetle (Coleoptera), during the study. Fossils are primarily from the Paleocene but some are as recent as the Quaternary.

According to the park's 1984 natural resource management plan and environmental assessment, few problems with illegal collecting have occurred, despite abundant fossil exposure throughout the park. Fossil localities are monitored through normal patrol activities. However, the Petrified Forest Plateau area is considered a "particularly sensitive area" and this and other backcountry areas are difficult to patrol.

Managing and protecting fossils relies upon an understanding of geologic and geographic abundance, occurrence, and distribution, as well as the factors threatening stability such as weather and climate, rates of erosion, and human activity. In order to quantify fossil loss, NPS paleontologists have established a system of measurable indicators of change to baseline resource conditions (table 5). Paleontological localities at Theodore Roosevelt National Park vary widely in terms of rock types, degree of preservation, geomorphic characteristics, and accessibility. Therefore, a specific indicator may not be useful or appropriate at all fossil sites. Nevertheless, this monitoring strategy provides a multidimensional approach to assessing or measuring impacts to in situ paleontological resources, which may be useful for resource managers at Theodore Roosevelt National Park (see Santucci and Koch 2003; available at http://www2.nature.nps.gov/ParkScience/index.cfm?ArticleID=16 [accessed April 18, 2007]).

Piping

According to the USGS "Water Basins Glossary" at http://capp.water.usgs.gov/GIP/h2o_gloss/, piping is "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." Piping is a major management issue in anthropogenic areas such as earthen dams and raised roads (Pete Biggam, NPS soils scientist, e- mail communication, February 23, 2007).

Piping can also occur in natural settings, typically when sheetwash erosion (see “Sheetwash Erosion” section) starts to concentrate into rill erosion, entering a soil through cracks, animal burrows, fence- post holes, or excavations, and eventually moving through the subsurface to an exit point (Pete Biggam, NPS soils scientist, e- mail communication, February 23, 2007). Pipes are most common on and near the base of steep slopes at Theodore Roosevelt National Park (figure 11). The principal danger associated with erosional pipes is roof collapse (Biek and Gonzalez 2001).

Swelling Soils and Bentonite

Sixty million years ago, volcanoes erupted far to the west of Theodore Roosevelt National Park spewing ash into the atmosphere. Rivers and wind transported and deposited this ash across the northern Great Plains. Chemical weathering altered the ash into bentonite—soft, malleable clay that is composed largely of smectite. As mapped by Biek and Gonzalez (2001) in Theodore Roosevelt National Park, bentonite of the Sentinel Butte Formation appears as bluish colored bands in the badlands. These beds can be traced for miles along the Little Missouri River (figure 12). When wet, bentonite can expand up to 16 times in volume. The inherent swelling and shrinking of bentonite can cause structural damage to buildings, roads, and other infrastructure. Wet bentonite produces slippery, hazardous conditions cross country and on trails and roads. Upon drying the clay contracts and forms the “popcorn” surface characteristic of bentonite.

Bentonite is also an economic resource, though the small deposits in North Dakota are unlikely to be of economic value (Biek and Gonzalez 2001). Bentonite is added to drilling mud to cool cutting tools, remove cuttings, lubricate drill bits, prevent blowouts, and confine underground fluids by creating an impervious coating. Moreover, bentonite is used as a binder for foundry sand and for pelletizing iron ore. It also serves as a sealant or liner for landfills, ponds, and canals. It is an additive used as a filler, stabilizer, or extender in materials such as adhesives, greases, medicines, cosmetics, paint, rubber, and soaps. Most of the bentonite used in the United States comes from Wyoming.

Table 1. Geologic Time Scale

Eon	Era	Period		Epoch	Age (Ma)	Age of
Phanerozoic	Cenozoic	Neogene	Quaternary	Holocene	0.01	Mammals
				Pleistocene	1.81	
			Tertiary	Pliocene	5.33	
				Miocene	23.0	
		Paleogene		Oligocene	33.9	
				Eocene	55.8	
				Paleocene	65.5	
	Mesozoic	Cretaceous			145.5	Reptiles
		Jurassic			199.6	
		Triassic			251.0	
	Paleozoic	Permian			299	Amphibians
		Carboniferous	Pennsylvanian		318	
			Mississippian		359.2	
		Devonian			416.0	Fishes
		Silurian			443.7	
		Ordovician			488.3	Invertebrates
		Cambrian			542.0	
Proterozoic	Also known as Precambrian				2,500	
Archean					3,800?–2,500	
Hadean					4,600?–3,800	

Notes: Dates are in millions of years (Ma) and indicate the beginning of each associated period or epoch. Dates reflect the International Union of Geological Sciences (IUGS), International Stratigraphic Commission (ICS), International Stratigraphic Chart (2004) at http://www.stratigraphy.org/down.htm. The International Stratigraphic Commission does not list the boundary between Archean and Hadean. However, the U.S. Geological Survey lists this boundary at approximately 3,800 Ma and the formation of Earth at approximately 4,600 Ma, which are used here. Mississippian and Pennsylvanian are terms used primarily in North America. Tertiary is no longer used by the International Commission on Stratigraphy (2004) but is listed here because it is still in common use.

Table 2. Potential Impacts of Surface Mining on Park Resources

	Mining operation								
	Exploration	Area dewatering and diversion	Drilling	Blasting	Stripping (overburden removal)	Haulage	Top soil or other soil storage	Maintenance	Beneficiation
Geology and soil									
Soil erosion	*	*				*	*		
Soil organisms		*			*	*	*		
Overburden swelling				*					
Toxic strata				*	*		*		
Soil inversion					*				
Soil stability					*				
Landslides				*					
Spoil piles					*		*		
Oil spills					*	*		*	
Coal spills						*			
Water									
Aquifer effects	*		*	*					
Runoff alteration		*	*	*					
Sediments		*				*	*		
Toxic substances		*							*
Groundwater contamination		*					*		*
Industrial effluents									*
Sludge									*
Air									
Exhaust emissions	*		*		*	*		*	
Dust	*		*	*	*	*	*	*	*
Other (e.g., welding)					*			*	
Blasting fumes				*					
Wildlife and plants									
Vegetation potential							*		
Habitat altered (including migration routes)		*		*	*	*	*		
Species diversity		*							
Aquatic life		*							
Animal essentials		*							
Accidents/Deaths				*		*			
Wildlife disturbed	*	*	*	*		*	*		
Other									
Aesthetic (including wilderness values)				*	*		*	*	*
Noise	*		*	*	*	*		*	*
Dangerous material				*				*	

Source: Ramani and Grim (1978).

Table 3. Flood Discharges for Little Missouri River and Tributaries in Theodore Roosevelt National Park

	Peak recorded discharge	Maximum water-surface elevation	Date	100-year flood discharge	500-year flood discharge
North Unit	110,000 cfs	1,953.03 ft asl	March 25, 1947	78,800 cfs	113,500 cfs
South Unit	65,000 cfs	2,267.25 ft asl	March 23, 1947	65,300 cfs	99,300 cfs
Elkhorn Ranch	No data	No data		69,000 cfs	103,000 cfs
Knutson Creek				31,800 cfs	
Paddock Creek				13,500 cfs	
Squaw Creek				24,600 cfs	

Notes: Discharges are in cubic feet per second (cfs). Maximum water- surface elevations are in feet above sea level (asl). *Source*: Emerson and Macek- Rowland (1986).

Table 4. Fossils at Theodore Roosevelt National Park

Fossil type	Formation
Petrified wood	Bullion Creek and Sentinel Butte
Freshwater mollusks	Bullion Creek and Sentinel Butte
Ostracodes (small bivalved crustaceans)	Sentinel Butte
Coleoptera (beetle)	Sentinel Butte
Leaves (e.g., angiosperms and ferns)	Bullion Creek and Sentinel Butte
Seeds (e.g., *Cercidiphyllum* [katsura tree])	Bullion Creek and Sentinel Butte
Twigs, roots, and branches	Taylor bed of the Golden Valley Formation
Champsosaurs (crocodile- like creature), including common *Champsosaurus* and extremely rare *Simoedosaurus*	Bullion Creek and Sentinel Butte
Crocodiles (probably *Leidyosuchus*)	Bullion Creek and Sentinel Butte
Alligators	Sentinel Butte
Turtles (*Protochelydra*—chelydrid [snapping turtle], and Plastomenus—plastomenid [soft- shelled turtle])	Sentinel Butte
Fish (Amia [bowfin] and *Lepisosteus* gar.)	Bullion Creek and Sentinel Butte
Giant salamander (*Piceoerpeton*)	Sentinel Butte
Plesiadapis (lemur- like mammal)	Sentinel Butte
Bison	Quaternary alluvial and colluvial deposits

Source: Hoganson and Campbell (1997).

Table 5. Factors Affecting the Stability of In Situ Paleontological Resources

SURFACE

Physical	Chemical	Biological	Human
Tectonics • Seismicity • Folding/faulting • Extrusive events (lava flows) *Weathering/Erosion* • Solar radiation • Freeze/thaw • Wind • Water • Fire • Gravity • Mass wasting • Abrasion during transport	• Surface water • Soil/rock pH • Mineral replacement • Oxidation (rust, pyritization)	*Displacement* • Pack rats • Harvester ants *Destruction/Damage* • Burrowing organisms • Trampling ungulates • Vegetation (root and lichen growth)	• Construction (buildings, roads, dams) • Mining • Military activities (construction, vehicles, ballistics) • Theft/vandalism • Poor science and recovery techniques • Livestock • Agriculture • Recreational activities (offroad vehicle travel)

SUBSURFACE

Physical	Chemical	Biological	Human
Tectonics • Seismicity • Folding/faulting • Intrusive events • Metamorphism *Weathering/Erosion* • Freeze/thaw (permafrost) • Water movement (piping, cavern formation) • Gravity • Mass wasting • Compaction • Rockfalls	• Groundwater • Soil/rock pH • Mineral replacement • Metamorphism (partial melt, recrystallization)	*Displacement* • Root growth • Bioturbation *Destruction/Damage* • Burrowing organisms • Root growth	• Construction (buildings, roads, dams) • Mining • Military activities (construction, ballistics) • Theft/vandalism • Poor science and excavation technique (dynamite)

Source: Santucci and Koch (2003).

Figure 5. Lignite. A low-rank variety of coal called lignite is high in sulfur and prominently exposed in Theodore Roosevelt National Park. Burning lignite produces an interesting rock type called clinker, which is generally red in color. NPS photo by Dave Krueger.

Figure 6. Clinker. Locally known as "scoria," clinker is the baked residue left from burning coal seams. Outside the park clinker is used for road base and ornamental lawn and garden material. Bruce Heise, GRE Program Manager, is pictured above for scale. Photo by Katie KellerLynn.

Figure 7. Cap Rock. The variation in lithology of the Fort Union Group is displayed as sediments with a wide range of colors and weathering characteristics. The terrain along Caprock Coulee Trail in the park is studded with erosional remnants capped by resistant rock in many forms and sizes. NPS photo by Dave Krueger.

Figure 8. Little Missouri River. The Little Missouri River flows through all three units of Theodore Roosevelt National Park. This photograph was taken near the bend below Juniper Campground in the North Unit. NPS photo by Dave Krueger.

Figure 9. Rotational Slump. A small rotational slump in the Sentinel Butte strata shows the failure plane abruptly merging with a thin bed of lignite. Source: Biek and Gonzalez (2001).

Figure 10. Petrified Stump. The most common kind of fossil in Theodore Roosevelt National Park is petrified wood, which occurs in both the Sentinel Butte and Bullion Creek formations. Photo by Katie KellerLynn.

Figure 11. Piping. Erosional pipes form in the poorly lithified bedrock of Theodore Roosevelt National Park. The principal danger associated with erosional pipes is collapse. NPS photo by Dave Krueger.

Figure12. Bentonitic Clay Overlook of the North Unit. The distinctive “blue bed” (bentonite) of the Sentinel Butte Formation can be traced for miles along the Little Missouri River and for some distance to the north. NPS photo by Dave Krueger.

Geologic Features and Processes

This section provides descriptions of the most prominent and distinctive geologic features and processes in Theodore Roosevelt National Park.

Myriad natural features contribute to the development of badlands topography at Theodore Roosevelt National Park (figure 13). Among these factors are intense seasonal storms; relatively soft, easily erodible rocks; and the absence of dense stabilizing vegetation. Badlands formation is probably the most distinctive geologic process occurring in the park. Badlands topography is discussed in detail in the "Geologic Setting," "Coal Resources and Mining," and "Geologic History" sections. Other features and processes of the landscape at Theodore Roosevelt National Park are presented in alphabetical order here.

Concretions and Cap Rocks

Concretions are hard, compact aggregates of mineral material. They precipitate out of solution from groundwater. Prior to the regional erosion of the Little Missouri badlands, groundwater slowly seeped through the layers of sediments for millions of years. This water contained minerals, which precipitated then cemented around sand grains or other nucleus (e.g., shell or bone fragments). Some concretions are remarkably large, especially in the North Unit. For example, along the scenic drive near Squaw Creek Campground, large, round concretions called "cannonballs" have eroded out of the surrounding rock and accumulated at the base of the cliffs (Murphy et al. 1999). Erosion- resistant concretions preferentially weather out of the basal sandstone of the Sentinel Butte Formation. Many of these concretions form the resistant caprock of pedestals (also known as rain pillars or hoodoos). These cap rocks are flat, hard, sandstone slabs that protect the underlying sediments from erosion. Eventually the slabs will tilt or fall off the pedestals and the remaining soft sediments will quickly erode away (Murphy et al. 1999).

Glacial Erratics

Large boulders once transported by glaciers now rest scattered on bedrock surfaces different from their own compositions, a position which testifies to the effectiveness of glacial erosion and transport. Many erratics have glacial striations or scratches that formed as they were dragged against bedrock during glacial movement. Glacial erratics of granitic and carbonate compositions are the primary evidence of glaciation in Theodore Roosevelt National Park (Biek and Gonzalez 2001). They occur in the North Unit and are thought to mark the maximum extent of glacial ice in this part of the Missouri Plateau. Most of the erratics are 1 to 2 feet (0.3 to 0.6 m) in diameter, but some are almost 5 feet (1.5 m) in diameter (Biek and Gonzalez 2001).

Eolian Deposits

Windblown deposits such as loess and sand cover large areas of the Great Plains. This wide eolian distribution throughout the region was recognized almost as soon as geological exploration began in the late 19th century (Emmons et al. 1896; Gilbert, 1896). Though sporadically mapped and underrepresented on most geologic maps, investigators of Quaternary climate change have renewed scientific interest in loess and eolian sand (Madole 1995). Lengthy loess sequences, such as those present on the northern Great Plains, contain detailed records of Quaternary glacial- interglacial cycles. Scientists consider these to be a terrestrial equivalent to the foraminiferal oxygen isotope record of deep- sea sediments, which document long- term climate change (Muhs et al. 1999). Loess is also a direct record of atmospheric circulation. Information on paleowind from loess in the geologic record can test atmospheric general circulation models (Muhs et al. 1999). In addition, widespread eolian deposits are important sources of information for reconstructing the history of aridification in the interior of North America during the Quaternary (Madole 1995).

In North Dakota, sediments deposited during the Pleistocene Epoch (1.8 million years ago to 11,800 years ago) belong to what geologists call the Coleharbor Group. Sediments deposited during the Holocene Epoch (11,800 years ago to present) belong to the Oahe Formation. Loess is present in both of these units. Although most upland surfaces are veneered with loess, and dune sands are locally present, neither were mapped by Biek and Gonzalez (2001). Loess is difficult to map where it is thin (less than 5 feet [1.5 m]) or overlies rocks that weather to residuum that is texturally similar to loess, as is the case in much of the badlands region (Madole 1995).

Oxbows

The erosion and deposition of sediments associated with active streams constantly change riparian ecosystems. In the valleys at Theodore Roosevelt National Park, streams tend to meander—widening their bends and occasionally short- circuiting them. This leaves the abandoned meanders as oxbow lakes, which slowly fill in with sediment (figure 14). Remnants of these filled lakes record this process as ongoing along the Little Missouri River (Laird 1956). Today, the Little Missouri River makes a wide bend as it turns east in the North Unit. Eventually, the river will abandon the large U- shaped portion of the channel in favor of a more direct route, leaving a stranded oxbow (Murphy et al. 1999).

Pediments

Pediments are broad, erosional, low- angle bedrock surfaces, extending out from highland margins. They are correlative with arid and semiarid conditions and are associated with landscape development over time. However, the connection between pediments and climate is still a subject of debate among geomorphologists (Summerfield 1991).

In Theodore Roosevelt National Park pediments occur at the bases of major escarpments and the heads of major drainages. In the South Unit, the largest pediment surfaces are located at the foot of the eastern escarpment, in the vicinity of Boicourt and Sheep Butte springs, and at the heads of Sheep, Paddock, and Jones creeks. In the North Unit, large pediments occur along Squaw Creek and the Little Missouri River (Biek and Gonzalez 2001). Pediments in the park are complex assemblages in which erosional surfaces have been buried by sheetwash sediment or reworked eolian material (see "Sheetwash Erosion" and "Eolian Deposits" sections). These conditions make interpretation and study of landscape development via pediments difficult in the park.

Sand and Gravel

Sand and gravel are present in alluvial deposits (units QTa and Qt on the geologic map) in the North and South units of Theodore Roosevelt National Park. These deposits occur as a veneer capping high- level plateaus near the Little Missouri River. A thick mantle of Holocene loess often covers these deposits.

Sand and gravel have been mined by private entities from at least two places inside park boundaries. The first location, at the eastern edge of the Petrified Forest Plateau, probably provided sand and gravel for road material (used locally) and the trail leading to the top of Petrified Forest Plateau (Biek and Gonzalez 2001). In 2002 the National Park Service acquired the second location—a 5,510- acre (2,230 ha) land acquisition containing 960 acres (389 ha) of sand and gravel potential. This property was previously owned by Ken and Norma Eberts who periodically sold gravel from the site to Billings County for road improvements. The National Park Service extinguished sand and gravel rights in conjunction with the buyout of the parcel of land (Phil Cloues, NPS Geologic Resources Division, written communication, October 18, 2004).

Sometime before 1957, sand and gravel deposits were also mined from another location atop the plateau immediately east of Medora. This currently unreclaimed pit is located just outside the park's boundary. A large landslide is present on the steep slope just west of the pit (Biek and Gonzalez 2001).

Sandstone and Silcrete

During the 1930s, the Civilian Conservation Corps used medium- grained, cross- bedded sandstone from a quarry near Theodore Roosevelt National Park to construct various structures in the park. For example, rough blocks of what is likely Sentinel Butte sandstone surround the perimeter of the shelter at the Riverbend Overlook in the North Unit (figure 15). Large blocks of the same sandstone and silcrete blocks of the Taylor bed (upper unit of the Bear Den Member of the Golden Valley Formation) line the path down to the shelter. Silcrete is silica- cemented sand and gravel. Investigators are uncertain whether these stones were quarried in the park. A 1937 photo caption implies that the quarry was in the North Unit, but a longtime park employee was certain that the quarry was located 25 miles (40 km) southwest of the park in an area called Flat Top Butte (Biek and Gonzalez 2001). At present, investigators have not seen any evidence of sandstone quarrying within Theodore Roosevelt National Park (Biek and Gonzalez 2001).

In 1938, the Emergency Relief Association built the old South Unit entrance station. This check station, adjacent stone fence, and privy are made from cut and dressed sandstone blocks of unknown origin. A pylon constructed of this same stone upon which the park's name hangs was originally at the check station. It was moved to the Painted Canyon Visitor Center in 1968 (Biek and Gonzalez 2001).

Sheetwash Erosion

In densely vegetated environments, the presence of stabilizing plant roots usually prevents rills from developing. By contrast, in arid and semiarid environments such as Theodore Roosevelt National Park, where precipitation tends to fall in intense bursts, erosional features such as rills and gullies naturally develop. The slopes of many of the buttes in the park are extremely gullied or minutely dissected by running water. Rill- and- gully erosion occurs particularly in the basal sandstone of the Sentinel Butte Formation.

The movement of water across a slope surface is called sheetwash. This is a general term because, unlike a sheet, water flow is never of uniform depth due to microtopography of hillslope surfaces. Sheetwash typically grades into channelized flow as the water movement becomes progressively more concentrated into particular downslope routes. For this reason, the distinction between "sheet flow" and "channelized flow" is sometimes indefinite. Nevertheless, sheetwash flowing from the sides of a butte in the badlands will typically concentrate into tiny rills as a result of irregularities of the slope. Some of these rills break down between rainfall events; others enlarge into gullies that deepen and widen with each rain. As rills develop into gullies, they erode back into the butte until two rivulets meet at their heads. The divide between them becomes very narrow and more succeptible to rapid weathering and erosion. Eventually, the divide between the two rivulets degrades entirely, separating a small portion of the butte side from the main butte. Thus, the butte erodes incrementally by both the action of running water and by this process of segmentation (Laird 1956).

Terraces

Changes in channel gradient, discharge, or sediment load can cause a river to incise its floodplain and form terraces. River terraces also can be cut into previously deposited alluvium or bedrock. Following incision, the original floodplain is abandoned and left as a relatively flat bench (terrace), which is separated from the new floodplain below. River terraces are inclined downstream but not always at the same angle as the active floodplain. The valley wall of an entrenching river may contain a vertical sequence of terraces. The lowest, youngest terrace may retain traces of floodplain morphology, whereas the highest, oldest terrace may be heavily weathered. Terraces can be either paired or unpaired. Paired terraces on opposite sides of the river form when vertical incision occurs more rapidly than the lateral migration of the channel. Unpaired terraces form when rapid lateral shifting of the channel occurs and the river cuts terraces alternately on each side of the valley floor.

In general, geomorphologists differentiate terraces and assign ages based on height above the modern stream level. For example, in the South Unit, alluvial terrace deposits (unit Qt on the geologic map) are subdivided into four mappable units (from youngest to oldest): Qt1, Qt2, Qt3, and Qt4.

Terraces in Theodore Roosevelt National Park record changes caused by a major climatic cooling event during the Pleistocene Epoch. This cooling caused the advance of large continental ice sheets from northern latitudes. In pre- glacial time, the Little Missouri River flowed north toward Hudson Bay. However, when glaciers advanced southward, local north- flowing streams were blocked; the drainages of the Little Missouri and Yellowstone rivers were diverted along the edge of the ice front. This ice- marginal drainage eventually became the present Missouri River, which the Little Missouri River flows into. The rate of erosion and downcutting of the Little Missouri River was not constant: as erosion and deposition continued, the river cut a series of terraces, remnants of which can be seen in the park (Harris and Tuttle 1990).

Figure13. View of Badlands from Oxbow Overlook. Theodore Roosevelt National Park is an ideal setting for the development of badlands topography. Badlands formation with its high-drainage density is probably the most distinctive geologic process in the park. NPS photo by Dave Krueger.

Figure 14. Oxbow Overlook. The Little Missouri River makes a huge bend as it turns east in the North Unit. Eventually, the river will abandon the large U-shaped portion of the channel and flow in a more direct course, leaving an oxbow. NPS Photo by Dave Krueger.

Figure 15. Shelter at Riverbend Overlook. The Civilian Conservation Corps used medium-grained, cross-bedded sandstone from a local quarry to construct various structures in the park, such as this shelter in the North Unit. NPS photo by Dave Krueger.

Map Unit Properties

This section serves as a critical link between resource managers and the digital geologic map of Theodore Roosevelt National Park. The table is highly generalized and is provided for informational purposes only. Ground disturbing activities should not be permitted or denied on the basis of information contained in this table. More detailed unit descriptions can be found in the help files that accompany the digital geologic map or by contacting the NPS Geologic Resources Division.

The GRE Program created digital geologic data and a helpfile from the map booklet of *The Geology of Theodore Roosevelt National Park* by R. F. Biek and M. A. Gonzalez. Detailed descriptions of the map units and discussions of mineral resources and geologic hazards are provided in the booklet portion of that publication.

The following table summaries the map units of Biek and Gonzalez (2001). It presents an itemized list of features for each map unit: age, unit name and map symbol, location in the park, description, depositional setting, local and global significance, limits for development and recreation, and resource potential (e.g., paleontological, water, and mineral resources).

Map Unit Properties Table

Age	Map Unit (Symbol)	Park Location (unit)	Description	Depositional Setting	Local and Global Significance	Suitability for Development and Recreation	Paleontological Resources
Quaternary (Pleistocene and Holocene)	Engineering fill (Qef)	North and South units	Used in road construction	Roads, bridges, and built up areas (shown on topographic base map)	None	Fill should be anticipated in any area formerly disturbed by construction activities	None
	Modern alluvium (Qal)	North and South units	Sand, silt, clay, & gravel, younger than 500 years old; includes alluvium under modern floodplain & lowest terrace surface; shallow aquifer 25–200 ft (7–61 m)	Modern stream channels, floodplain, and beneath low stream terraces	Part of Oahe Formation—sediments deposited during the Holocene Epoch in North Dakota	100- and 500- year floods, river erosion, channel migration	None
	Older alluvium (Qoal)	North and South units	Sand, silt, clay, and gravel; distinguished from modern alluvium (Qal) by steep, typically vertical, erosion scarp; ≤20 ft (6 m) thick	Stream deposits beneath Holocene terraces	Part of Oahe Formation—sediments deposited during the Holocene Epoch in North Dakota		None
	Alluvial fan deposits (Qf): Alluvial fan deposits (modern) (Qf1); Alluvial fan deposits (older) (Qf2)	North and South units; in South Unit only, differentiated on map into modern and older units	Highly variable sequence—ranging from coarse and poorly sorted sand and gravel to massive or laminated mud; typically consists of locally derived material, except for largest fans of largest tributaries Older fans—deeply incised and no longer receive sediment from their contributory streams	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 (Biek and Gonzalez, 2001)	Part of Oahe Formation—sediments deposited during the Holocene Epoch in North Dakota		Fossil bison
	Mantled pediments (Qmp)	North and South units	Complex assemblage of active and incised alluvial deposits of sand, silt, and clay; mantle ≤3 ft (0.9 m) thick but may exceed 6 ft (1.8 m) in places	Erosional surfaces formed during arid and semiarid conditions; mantled with eolian and sheetwash deposits	Part of Coleharbor Group and Oahe Formation—sediments deposited during the Pleistocene and Holocene epochs in ND		None
	Landslide deposits (Qls)	North and South units	Locally derived sediment; commonly rotational slumps; characterized by hummocky topography, numerous arcuate scarps, and chaotic bedding	Transported principally by gravity (e.g., slump, earth flow, rockfall, and creep) to hillsides and valley floors	None	Active or capable of renewed movement	None documented
	Unconformity						
Quaternary (Pleistocene)	Alluvium beneath Pleistocene terraces (Qt): Qt1	North and South Units; in South Unit differentiated into four map units by height above modern channel	Sand and gravel atop plateaus, mesas, buttes, ridges, and benches flanking Little Missouri River valley; resembles QTa but 170–240 ft (52–73 m) below QTa deposits; ≤6 ft (1.8 m) thick; mantled by Holocene loess (not mapped); Qt4—highest and oldest Pleistocene terrace	Qt1—at 2,400 ft (732 m) above sea level, 160 ft (49 m) above modern drainage	Part of the Coleharbor Group—sediments deposited during the Pleistocene Epoch; sand and gravel (≤5 ft [1.5 m] thick)		24,000- year- old wood fragments; fossil bison
	Qt2			Qt2—at 2,460 ft (750 m) above sea level, 220 ft (67 m) above modern drainage			
	Qt3			Qt3—at 2,480 ft (756 m) above sea level, 240 ft (73 m) above modern drainage			
	Qt4			Qt4—at 2,500 ft (762 m) above sea level, 260–270 ft (79–82 m) above modern drainage			
	Glacial erratics (Qg)	North Unit	Widely scattered granitic and carbonate boulders and cobbles; most are 1–2 ft (0.3–0.6 m) in diameter but some as large as 5 ft (1.5 m)	Deposited at maximum extent of glacial ice	Only evidence of glaciation in park; part of the Coleharbor Group—sediments deposited during the Pleistocene Epoch in North Dakota		None
	Unconformity						
	Upland gravel (QTa)	North and South units	Sand and gravel, underlain by loess; contains pebbles and cobbles of well- cemented, locally derived materials; ≤5 ft (1.5 m) thick	Stream deposits (terraces)	Uncertain correlation with other regional deposits, likely predates advance of ice into the area; Biek and Gonzalez (2001) simply mapped as indeterminate late Tertiary or Quaternary age		Petrified wood
	Unconformity						
Tertiary (Paleocene)	Golden Valley Formation, Bear Den Member, Taylor bed silcrete lag (Tsbsl)	North Unit, Achenbach Hills only	Silcrete (silica- cemented) blocks up to 10 ft (3 m) square and 2 ft (0.6 m) thick, most are about 1 ft (0.3 m) thick; lag deposit; forms a pavement	Swamp or marsh; a weathering horizon indicates hiatus in deposition	None		Trace fossils (i.e., roots and stems)
	Fort Union Group: Sentinel Butte Formation (Tsb)	North and South units	Grayish brown siltstone, claystone, sandstone, and lignite; includes basal sandstone, 1 or 2 petrified wood horizons (depending on location), bentonite (“blue bed”) layer, and siltstone (lower and upper yellow beds); forms hoodoos	River, lake, and swamp environments; ash source from 250 mi (400 km) away; nearly complete section exposed in North Unit (760 ft [232 m]); lower 300 ft (91 m) exposed in South Unit	The most widespread unit in the park and the most widespread near- surface Tertiary formation in North Dakota; clinker (burnt lignite) important to development of badlands topography	Landslides, swelling soils, piping, and rill erosion	Petrified wood, fossil mollusks, concretions
	Fort Union Group: Bullion Creek Formation (Tbc)	South Unit	Bright yellowish brown siltstone, claystone, and sandstone; differentiated from Sentinel Butte Formation by (1) stratigraphic position with respect to the HT Butte lignite or clinker between the two units, and (2) color (brighter = Bullion Creek)	River, lake, and swamp environments	Fort Union Group represents clastic wedge of sediment eroded from Rocky Mountains during Laramide Orogeny	Coal fires and associated slumping in the HT Butte lignite	Petrified wood (uncommon)

Geologic History

This section highlights the map units (i.e., rocks and unconsolidated deposits) that occur in Theodore Roosevelt National Park and puts them in a geologic context in terms of the environment in which they were deposited and the timing of geologic events that ultimately created the present landscape.

Pre-Paleocene

The geologic features displayed in Theodore Roosevelt National Park are primarily Paleocene and younger in age (≤65 million years old). However, the geologic story of the area begins much earlier. The older rocks buried deep beneath the park contain significant natural resources such as oil and gas, which are extracted from Pennsylvanian, Mississippian, Devonian, and Ordovician rocks (see table 1) in the Williston Basin. The Williston Basin is a large, roughly circular depression on the North American craton covering several hundred thousand square miles across parts of North and South Dakota, Montana, and the Canadian provinces of Manitoba and Saskatchewan. The Williston Basin began subsiding during the Ordovician Period. Although the Williston Basin was subsiding, marine sediments were not continuously deposited in it. Nevertheless, the basin contains an unusually complete rock record compared to many basins; some rocks from each Phanerozoic period are preserved there. These strata record several cycles of marine transgressions that filled the basin, followed by marine regressions that drained it. In all, more than 16,000 feet (4,800 m) of sediments, mostly shallow marine but also some terrestrial deposits, settled into the Williston Basin.

The early structural history of the basin is poorly understood (Heck et al. 2002). The earliest rocks are difficult to study because the Lower Phanerozoic and Precambrian (see table 1) rocks are not exposed at the surface in North Dakota and only a few wells have penetrated these rocks. Present understanding of the early geologic history of the basin is pieced together from outcrops in adjacent states and provinces, seismic data, and limited well data (Heck et al. 2002).

During the Cretaceous, an inland sea covered the interior of the continent and more marine sediments collected. The Cretaceous Interior Seaway was hundreds of miles wide and divided North America into two separate land masses. The northwest- southeast oriented epicontinental seaway stretched from the Arctic Ocean to the Gulf of Mexico. The sea retreated from most of the continent by about 65 million years ago. Coincident with this marine regression, the Laramide Orogeny uplifted the Rocky Mountains hundreds of miles west of the park. Uplift produced hundreds of cubic miles of sediment that eroded from the newly formed mountains. Streams carried this sediment eastward and deposited it in great clastic wedges across the Great Plains. A thick sequence of terrestrial sediments, which ranges in age from Late Cretaceous through Oligocene, records this event in many parts of the Dakotas and Montana.

Paleocene

In North Dakota and Theodore Roosevelt National Park, the Fort Union Group represents the Paleocene portion of the clastic wedge, which sloped eastward from the Rocky Mountains. The exact depositional setting of the Fort Union Group has been the subject of some debate. The sediments of the Fort Union Group were deposited on what various investigators have called an “alluvial plain” (Laird 1956), a “meandering fluvial channel system” (Fastovsky and McSweeney 1991), and a “broad sea- level delta” (Theodore Roosevelt National Park Web site, accessed October 25, 2004). Regardless of the specific geomorphic setting, water was apparently ubiquitous in time and space. Thus a reasonable interpretation for the general environment is a low- lying, swampy region in which water- loving trees and other plants grew.

As leaves, branches, and entire dead trees fell into the stagnant waters of the swamps, they eventually became peat as bacteria only partially decomposed them and as additional sediments compressed the organic material. Streams continued to deposit more and more sediment in the area, creating lignite. If more pressure had been applied, bituminous (soft) coal would have eventually formed. A total thickness of about 1,350 feet (410 m) of sediment was deposited during the Paleocene Epoch, forming the 600- foot- (180 m) thick Bullion Creek Formation and the 750- foot- (230 m) thick Sentinel Butte Formation.

Also, during this time, volcanoes punctuated the landscape of the western United States. Rivers and winds transported the erupted ash into North Dakota. Along with other sediments and organic material, this ash accumulated in standing water. Silica (quartz) from these ash deposits played a major role in the petrifaction of cypress, sequoia, and other deciduous and cone- bearing trees that grew in the low- lying, subtropical environment. Few representative fossil- leaf locales are in the park, so investigators have interpreted the existence of various species from a fossil site called Wannagan Creek. This site is in the Bullion Creek Formation and is located just to the west of the South Unit (John Hoganson, North Dakota Geological Survey, written communication, December 7, 2004). Groundwater moving through the silica- rich volcanic ash dissolved the silica. When this silica- saturated water soaked into the trees, microcrystalline material replaced the organic compounds in the wood. In some cases, the internal structures of the trees including growth rings were preserved in stone. In addition to allowing petrifaction of wood, the Paleocene ash layers formed the bentonite "blue beds," which now contribute to the scenic badlands topography in the park.

Post-Paleocene

Scattered remnants of post- Paleocene sediments are present throughout western North Dakota as isolated caps on buttes. These units, including the Golden Valley Formation and the White River Group, were deposited during the Eocene and Oligocene epochs (56–23 million years ago). In the park, a lag deposit composed of silcrete called the Taylor bed (the upper portion of the Bear Den Member of the Golden Valley Formation), caps the Archenbach Hills of the North Unit. Geologists interpret this lag deposit as a weathering horizon developed on top of the Sentinel Butte Formation (Clayton et al. 1980). The weathering horizon marks a hiatus in deposition, called an unconformity, between the Bear Den Member and the overlying Camels Butte Member (Biek and Gonzalez 2001). This silcrete lag contains only silica- rich chert and lacks lithic fragments such as feldspar and other readily weathered minerals. This composition suggests that resistant quartz was all that remained after a prolonged period of weathering (Hickey 1977).

As a result of intense long- term weathering and erosion, no bedrock units in western North Dakota are younger than Oligocene in age. Accumulations of gravel and sand (e.g., unit *QTa* on the geologic map) are difficult to date but provide the only evidence of deposition subsequent to Oligocene time. Post- Laramide regional uplift at the end of the Paleocene Epoch caused a change in regional base level, forcing streams to incise their channels. For millions of years, streams had been depositing sediment nearly continuously on the Great Plains. In western North Dakota the uplift caused the rivers ancestral to the modern Little Missouri River system to dissect the plains, incising and eroding away much of the poorly consolidated upper rock layers. Huge volumes of sediment from the northern Great Plains were carried towards Hudson Bay.

Pleistocene

After much incision, river channel courses were firmly established at the beginning of the Pleistocene Epoch (1.8 million years ago). At the same time global climate changes triggered the advance of great ice sheets from the north. These continental glaciers formed, advanced, and retreated many times during the Pleistocene Epoch. Glacial erratics in the North Unit record the farthest local extent of glacial advance onto the Missouri Plateau. The glacial effects in this area are not particularly pronounced; classic glacial features such as moraines do not appear in this landscape. However, glacial effects were significant with respect to the changes made to regional drainage patterns. These changes strongly influenced the recent geology of Theodore Roosevelt National Park (Laird 1956).

Before the initial advance of continental ice sheets, the Missouri River flowed northeastward into Canada and to Hudson Bay (figure 16). Its major tributaries, the Yellowstone and Little Missouri rivers, joined the Missouri in northwestern North Dakota. The east-flowing Knife, Heart, and Cannonball rivers in North Dakota also joined a stream that flowed northward to Hudson Bay (Trimble 1993). When continental ice sheets advanced southward from Canada and reached as far as the upper North Unit in the park, the ice blocked the courses of these north- flowing rivers. This forced them to create new routes eastward and southward, thereby emptying into the Mississippi River instead of Hudson Bay.

According to Biek and Gonzalez (2001), glacial diversion of the Little Missouri River occurred by mid- Pleistocene time, at least 640,000 years ago, though the exact timing is uncertain. Nevertheless, by the time the ice sheet retreated, the northern portions of both the Little Missouri and Missouri rivers were entrenched into new channels. The new route of the northern Little Missouri River followed a steeper course, causing the whole river to flow faster and begin downcutting rapidly into the layered sediments. Because the elevation of the mouth of the Little Missouri was now considerably lower than it had been before joining the Yellowstone River (just east of present- day Williston), it eroded quickly through the soft sedimentary rocks. As the river began rapid incision, its tributaries also began cutting gullies on a grand scale, carving the fantastically broken topography of the badlands. In addition, as streams eroded the poorly consolidated sediments, many valley walls became over-steepened and unstable. The presence of bentonite exacerbated this situation. These slopes often failed causing landslides. The most spectacular landslides are those in the North Unit, where two classic types of rotational slumps are present (see "Mass Wasting" section).

The rate of erosion and incision of the Little Missouri River was not constant. As intermittent erosion and deposition continued, the stream cut a series of four terraces, the remnants of which can still be seen in the park (Harris and Tuttle 1990). The complicated story recorded in these terraces is still unclear, and the lack of reliable radiometric dates has lead to various mapping styles and nomenclature for these deposits (Biek and Gonzalez 2001). Correct geomorphic interpretation of these terraces is significant for completely understanding (1) when the ancestral Little Missouri River occupied the highest terrace level, (2) the exact timing of drainage diversion of the ancestral Little Missouri River, (3) the timing of inception of incision of badlands erosion, and (4) the rate of formation of badlands topography.

Holocene

In the past 11,800 years, various geologic processes that began during the Pleistocene have continued. This includes the formation of badlands topography, mass wasting, and the formation and mantling of pediments (see "Mass Wasting" and "Pediments" sections).

However, three types of deposits in the park are exclusively Holocene in age: alluvial fans, various alluvium (units Qoal and Qal on the geologic map), and engineered fill. Alluvial fans are present at the mouths of nearly every small valley in the park where they mingle with stream deposits. The upstream portion of alluvial fans is gradational, interfingering with sheetwash and colluvial deposits that mantle valley margins. Other alluvial deposits of Holocene age are found along stream channels show that most streams have been aggrading for the past 150 years or more, but the upper reaches have incised during this same period (Biek and Gonzalez 2001). Finally, some areas of engineered fill occur in the park: along U.S. Route 85 in the North Unit and along I-94 in the South Unit. These mappable units show that humans are agents of landscape change.

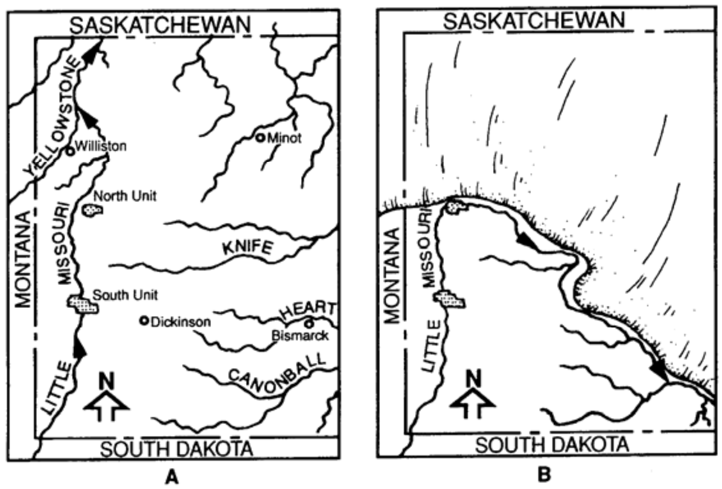

Figure 16. Pre- and Post-Glacial Drainages of North Dakota. A. Rivers flowed north into Canada and northeast to Hudson Bay before glaciers diverted them. B. Glacial diversion caused the rivers to change direction. Source: Murphy et al. (1999).

Glossary

This glossary contains brief definitions of technical geologic terms used in this report. Not all geologic terms used are referenced. For more detailed definitions or to find terms not listed here please visit http://wrgis.wr.usgs.gov/docs/parks/misc/glossarya.html.

alluvial fan. A fan- shaped deposit of sediment that accumulates where a high- gradient stream flows out of a mountain front into an area of lesser gradient such as a valley.
alluvium. Stream- deposited sediment that is generally rounded, sorted, and stratified.
aquifer. Rock or sediment that is sufficiently porous, permeable, and saturated to be useful as a source of water.
ash (volcanic). Fine pyroclastic material ejected from a volcano.
base level. The lowest level to which a stream can erode its channel. The ultimate base level for the land surface is sea level, but temporary base levels may exist locally.
basin (structural). A doubly plunging syncline in which rocks dip inward from all sides.
basin (sedimentary). Any depression, from continental to local scales, into which sediments are deposited.
bed. A "unit" of sedimentary strata commonly ranging in thickness from one centimeter to a meter or two and distinguishable from beds above and below.
bedding. Depositional layering or stratification of sediments.
block (fault). A crustal unit bounded by faults, either completely or in part.
cementation. Chemical precipitation of material into pores between grains that bind the grains into rock.
chemical weathering. The dissolution or chemical breakdown of minerals at Earth's surface via reaction with water, air, or dissolved substances.
clastic. Rock or sediment made of fragments or preexisting rocks.
clay. Clay minerals or sedimentary fragments the size of clay minerals (<1/256 mm).
craton. The relatively old and geologically stable interior of a continent.
crystalline. A regular, orderly, repeating geometric arrangement of atoms.
dip. The angle between a structural surface and a horizontal reference plane measured normal to their line of intersection.
drainage basin. The total area from which a stream system receives or drains precipitation runoff.
dune. A low mound or ridge of sediment, usually sand, deposited by wind. Common dune types include the barchan dune, longitudinal dune, parabolic dune, and transverse dune.
eolian. Formed, eroded, or deposited by or related to the action of wind.
ephemeral stream. A stream that flows only in direct response to precipitation.
fault. A subplanar break in rock along which relative movement occurs between the two sides.
feldspar. A group of abundant rock- forming minerals. Feldspars are the most widespread of any mineral group and constitute 60% of Earth's crust. They occur in all types of rocks. Feldspars are white and gray to pink, have a hardness of 6, are commonly twinned.
formation. Fundamental rock- stratigraphic unit that is mappable and lithologically distinct from adjoining strata and has definable upper and lower contacts.
fracture. Irregular breakage of a mineral; also any break in a rock (e.g., crack, joint, or fault)
hoodoo. Pillars developed by erosion of horizontal strata of varying hardness. Typically found in climatic zones where most rainfall is concentrated during a short period of the year.
igneous. Refers to a rock or mineral that originated from molten material; one of the three main classes or rocks: igneous, metamorphic, and sedimentary.
karst topography. A landscape characterized by abundant sinkholes and caverns formed by the dissolution of calcareous rocks.
landslide. Any process or landform resulting from rapid mass movement under relatively dry conditions.
lava. Magma that has been extruded onto Earth's surface, both molten and solidified.
lithification. The conversion of sediment into solid rock.
lithology. The description of a rock or rock unit, especially the texture, composition, and structure of sedimentary rocks.
loess. Silt- sized sediment deposited by wind.
meanders. Sinuous lateral curves or bends in a stream channel.
mechanical weathering. The physical breakup of rocks without change in composition (syn: physical weathering).
member. A lithostratigraphic unit with definable contacts that subdivides a formation.
mesa. A broad, flat- topped erosional hill or mountain that is bounded by steeply sloping sides or cliffs.
metamorphism. Literally "change in form." Metamorphism occurs in rocks with mineral alteration, genesis, or recrystallization from increased heat and pressure.
mineral. A naturally occurring, inorganic crystalline solid with a definite chemical composition or compositional range.
orogeny. A mountain- building event, particularly a well-recognized event in the geological past (e.g., the Laramide Orogeny).
outcrop. Any part of a rock mass or formation that is exposed or "crops out" at Earth's surface.
overburden. Non- economic, often unconsolidated, rock and sediment overlying an ore, fuel, or sedimentary deposit.

paleontology. The study of the life and chronology of Earth's geologic past based on the phylogeny of fossil organisms.

pediment. A gently sloping, erosional bedrock surface at the foot of mountains or plateau escarpments.

plateau. A broad, flat- topped topographic high of great extent and elevation above the surrounding plains, canyons, or valleys (both land and marine landforms).

potash. An impure form of potassium carbonate (K_2CO_3) mixed with other potassium salts. Potash has been used since antiquity in the manufacture of glass and soap, and as a fertilizer.

regression. A long- term seaward retreat of the shoreline or relative fall of sea level.

rill. One of the first and smallest channels formed by runoff.

rock. A solid, cohesive aggregate of one or more minerals.

sandstone. Clastic sedimentary rock of predominantly sand- sized grains.

scarp (or escarpment). A steep cliff or topographic step resulting from vertical displacement on a fault or by mass movement.

sediment. An eroded and deposited, unconsolidated accumulation of lithic and mineral fragments.

sedimentary rock. A consolidated and lithified rock consisting of detrital or chemical sediment(s).

shale. A clastic sedimentary rock made of clay- sized particles that exhibit parallel splitting properties.

silt. Clastic sedimentary material intermediate in size between fine- grained sand and coarse clay (1/256–1/16 mm).

siltstone. A variable lithified sedimentary rock with silt- sized grains.

slope. The inclined surface of any geomorphic feature or rational measurement thereof (syn: gradient).

slump. A generally large, coherent mass movement with a concave- up failure surface and subsequent backward rotation relative to the slope.

soil. Surface accumulation of weathered rock and organic matter capable of supporting plant growth and often overlying the parent rock from which it formed.

spring. A site where water flows out at the surface as a result of the water table intersecting the ground surface.

strata. Tabular or sheet- like masses or distinct layers of rock.

stratigraphy. The geologic study of the origin, occurrence, distribution, classification, correlation, and age of rock layers, especially sedimentary rocks.

stream. Any body of water moving under gravity flow and confined within a channel.

subsidence. Sinking or depression of part of Earth's surface.

tectonic. Relating to large- scale movement and deformation of Earth's crust.

terraces (stream). Step- like benches surrounding the present floodplain of a stream due to dissection of previous floodplain(s), streambed(s), or valley floor(s).

terrestrial. Relating to Earth or Earth's dry land.

topography. The general morphology of Earth's surface including relief and location of natural and anthropogenic features.

trace fossils. Evidence of organisms' life activities, rather than the organisms themselves, such as tracks, root casts, nests, chew marks on fossil leaves, and fossilized dung.

transgression. Landward migration of the sea due to a relative rise in sea level.

trend. The direction or azimuth of elongation or a linear geological feature.

unconformity. A surface within sedimentary strata that marks a prolonged period of erosion or no deposition.

uplift. A structurally high area in Earth's crust, produced by tectonic movement that raises the rocks.

volcanic. Related to volcanoes; describes igneous rock crystallized at or near Earth's surface (e.g., lava).

water table. The upper surface of the saturated (phreatic) zone.

weathering. The set of physical, chemical, and biological processes by which rock is broken down in place.

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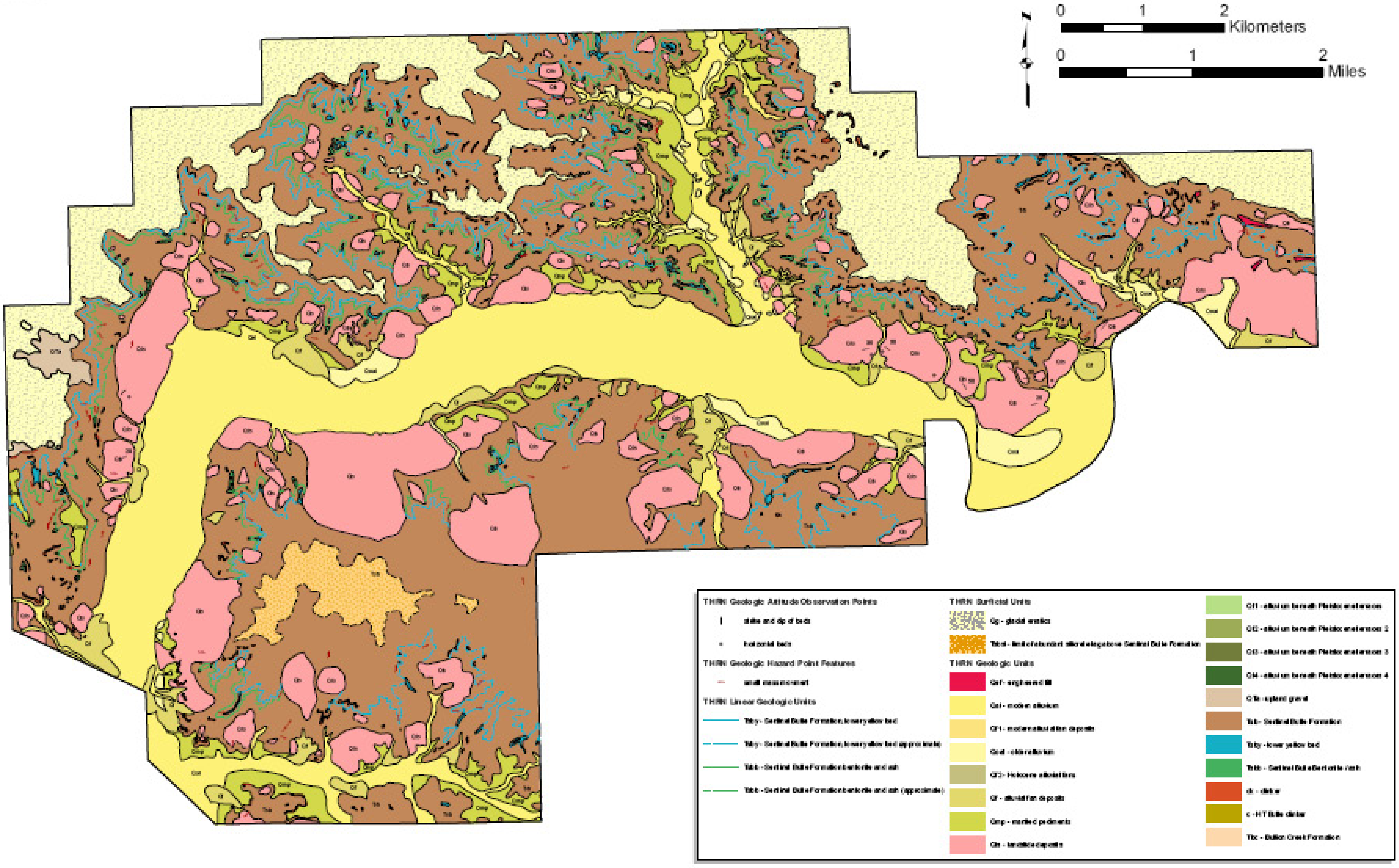
Appendix A: Geologic Map Graphic

The following page provides a preview or "snapshot" of the geologic map for Theodore Roosevelt National Park. For a poster size PDF of this map or for digital geologic map data, please see the included CD or visit the GRE publications webpage: http://www2.nature.nps.gov/geology/inventory/gre_publications.cfm

Geologic Map of Theodore Roosevelt National Park, North Dakota

North Unit

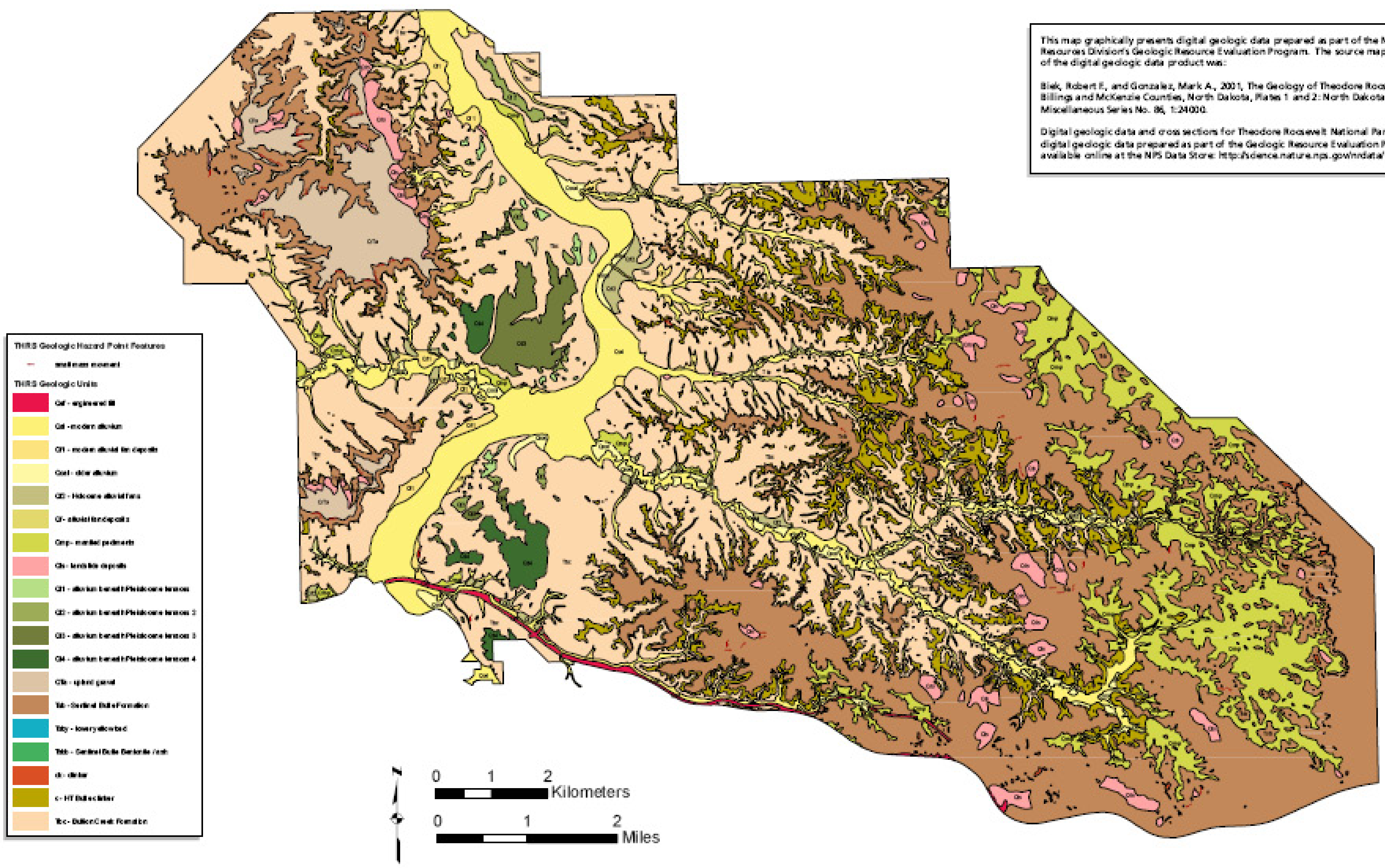


South Unit

This map graphically presents digital geologic data prepared as part of the NPS Geologic Resources Division's Geologic Resource Evaluation Program. The source map used in creation of the digital geologic data product was:

Biek, Robert F., and Gonzalez, Mark A., 2001, The Geology of Theodore Roosevelt National Park, Billings and McKenzie Counties, North Dakota, Plates 1 and 2: North Dakota Geological Survey, Miscellaneous Series No. 86, 1:24000.

Digital geologic data and cross sections for Theodore Roosevelt National Park and all other digital geologic data prepared as part of the Geologic Resource Evaluation Program, are available online at the NPS Data Store: http://science.nature.nps.gov/nrdata/



Theodore Roosevelt National Park

Geologic Resource Evaluation Report

Natural Resource Report NPS/NRPC/GRD/NRR—2007/006
NPS D-133, June 2007

National Park Service

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