National Park Service
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Natural Resource Program Center

# Badlands National Park
*Geologic Resource Evaluation Report*

Natural Resource Report NPS/NRPC/GRD/NRR—2008/036

**THIS PAGE:**
**Yellow Mounds Paleosols, Badlands NP**

**ON THE COVER:**
**View from Cedar Pass, Badlands NP**

**NPS Photos by: Dave Krueger and Jim F. Wood**

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Geologic Resources Division
Natural Resource Program Center
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# Executive Summary

*This report accompanies the digital geologic map for Badlands National Park in South Dakota, which the Geologic Resources Division produced in collaboration with its partners. It contains information relevant to resource management and scientific research.*

Badlands National Park encompasses 242,755.94 acres in southwestern South Dakota and is home to striking erosional formations and the world's richest collection of Oligocene- age vertebrate fossils. More than 250 vertebrate species, including both herbivores and carnivores, are represented in the park. Fossil beds in the Eocene and Oligocene formations of the White River Group allow reconstruction of the evolution of these mammal species and their habitat. Paleontological resources were a major reason for establishing Badlands as a National Monument in 1939, for adding acreage in 1976, and for elevating the monument to National Park status in 1978.

Today's landscape is dramatically different from the forests and savannas that covered the area in the Oligocene. Vegetation is sparse and erosion has carved the region into distinctive spires, pinnacles, hoodoos, monuments, buttes, and mesas that are known collectively as the White River Badlands. Badland topography was first recognized and described in South Dakota and the White River Badlands are the type locality for other areas that display similar intricately eroded topography.

Weathering and erosion processes and abundant paleontological resources have given rise to two primary geologic issues facing resource managers at Badlands National Park:

- Mass wasting, and
- Fossil theft.

Erosion is a natural process that is largely responsible for the development of badlands topography and exposure of paleontological resources. Mass wasting, the downslope transport of soil and rock material by gravity, is the primary geologic issue at Badlands National Park. Some of the highest known rates of erosion occur in the South Dakota badlands. Ridges and pinnacles have collapsed overnight as a result of a single thunderstorm. Swelling clay in the poorly consolidated strata creates instability of soil and rock and the potential for mass wasting in the park. Landslides and slumps may bury cultural and fossil sites as well as impact roads and other infrastructure. Landslides may also expose previously undiscovered paleontological sites. The potential rerouting of the Badlands Loop Road, the main road into the park, and the effect it would have on the geological and paleontological resources, viewshed, and historical integrity of Badlands National Park are of concern to park managers.

Fossil theft from poachers and visitors is a continual issue for park management. While thousands of specimens have been collected legitimately over the years, many have also been stolen from the park. In the summer of 2000, Badlands National Park staff began documenting fossil resources in the park in order to gain a better understanding of the stratigraphic position, depositional environment, and degree of preservation of the fossil sites in the park. The goal of a complete paleontological inventory continues with each field season adding valuable information to the fossil database at the park. Easily accessible fossil sites are identified through the inventory, allowing the management team to protect these sites from poachers.

In addition to mass wasting and fossil theft, geohydrology and geologic interpretation are areas that may warrant management attention.

The exceptional paleontological resources and extraordinary badlands landscape, including the prominent Wall, are just two geologic features that welcome visitors to Badlands National Park. Between the Cretaceous and Tertiary strata that form the pinnacles and buttes of the badlands, is a zone of distorted, convoluted bedding that marks the occurrence of some unusual and unexplained Late Cretaceous event. Red and yellow striations that add color to the grayish- green badlands are Tertiary paleosols (ancient soils). Some of these paleosols form marker beds that identify distinct stratigraphic boundaries and a transition from a wet to a dry climate.

The Badlands strata record approximately 75 million years of Earth history. Past marine, near- shore, and terrestrial environments are all reflected in the sedimentary rocks exposed in the park. The same weathering, mass wasting, and erosion processes that formed the landscapes in the past continue to create the distinctive badlands topography and landforms and expose the fossils that are visible today.

# Introduction

*The following section briefly describes the National Park Service Geologic Resource Evaluation Program and the regional geologic setting of Badlands National Park.*

### Purpose of the Geologic Resources 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.

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/).

### Regional Setting

Badlands National Park is located in southwestern South Dakota about 80 km (50 mi) east of the Black Hills (fig. 1) and is home to the world's richest Oligocene- age (33.9-23.03 Ma) vertebrate fossil deposit. These fossils, discovered in the White River Group, are a major reason for the parks existence. Pictures and discussions of these fossil beds are found in nearly every historical geology textbook (Kiver and Harris 1999).

In the mid to late 19$^{th}$ century and early 20$^{th}$ century museums and universities sent numerous fossil-collecting expeditions to the Badlands region. These expeditions competed with private and amateur collectors for the fossil- rich terrestrial deposits (bone beds) of the Tertiary White River Group. In order to preserve the area, individuals in the South Dakota State Legislature petitioned the Federal Government to establish a national park as early as 1909. Norbeck Pass commemorates the efforts of Senator Peter Norbeck who championed the park concept that resulted in the authorization of Badlands National Monument in 1929 and its establishment in 1939. The monument was redesignated as Badlands National Park in 1978. Boundary changes occurred in 1936, 1952, and 1968. In 1976, the Badlands Wilderness Area was created.

Badlands National Park is comprised of three units. The North Unit, also called the Sage Creek Unit, contains 64,250 acres of designated wilderness. Contiguous with the North Unit, the South Unit, or Stronghold Unit, is located within the Pine Ridge Indian Reservation. The Palmer Unit lies to the east of the South Unit and also is within the Pine Ridge Indian Reservation (fig. 2).

Throughout the park erosion has produced distinctive spires, pinnacles, hoodoos, monuments, buttes, and mesas known collectively as the White River Badlands. Badlands National Park contains the largest protected mixed grass prairie in the United States. The park also is the site of the reintroduction of the endangered black-footed ferret.

### Geologic Setting

Badlands National Park is located in the Great Plains Physiographic Province of southwestern South Dakota. Elevations range from 750 m (2,460 ft) along Sage Creek, an ephemeral tributary stream to the Cheyenne River, to 1,000 m (3,280 ft) on Sheep Mountain Table. Rivers draining the higher plateaus east of the Black Hills have dissected the region and contributed to the creation of badlands topography. Badlands National Park is bounded by the Cheyenne River drainage basin to the north and west, the Bad River drainage basin to the east, and the White River drainage basin to the south.

Approximately 75 million years of accumulated sediments and intermittent periods of erosion are recorded in the generally flat- lying (layer- cake) strata of Badlands National Park (fig. 3). The oldest rocks exposed in the park are the Upper Cretaceous marine mudstones of the Pierre Shale. The Fox Hills Formation overlies the Pierre Shale, here recent investigations have revealed previously unrecognized latest Cretaceous fossils.

The Tertiary White River Group (fig. 3) overlies the Fox Hills Formation and contains basal paleosols visible as brilliant red bands of color in the badlands formations. Vast quantities of sediment that eroded from the Black Hills and Rocky Mountain uplifts following the Cretaceous- Tertiary Laramide Orogeny, were carried eastward and southward by streams during late Eocene and Oligocene time forming the fossil rich Chadron and Brule Formations. Volcanoes in the Great Basin and Rocky Mountain areas provided abundant volcanic ash that also became part of the Brule Formation. The 3- 7 m (10- 23 ft) thick Rockyford Ash layer at the base of the Sharps Formation resulted from a catastrophic volcanic eruption in the Great Basin (Larson and Evanoff 1998).

During the Oligocene deposition of the Brule Formation, the region that is now the White River Badlands was lush, wet, and much warmer than today. Many different kinds of animals roamed the floodplain. Fossils discovered in the beds of the White River Group represent over 50 species of herbivores and 14 species of carnivores (Kiver and Harris 1999). The White River beds have been called “the most complete succession of mammal fossils known anywhere in the world” (Wicander and Monroe 1993, p. 541).

Streams draining the Rocky Mountains during the Pliocene deposited coarse- grained sediments (such as the Medicine Root Gravel) in the Badlands area. Sustained erosion of the Badlands began about 500,000 years ago (Kiver and Harris 1999; Rachel Benton, NPS paleontologist, Badlands National Park, written communication, February, 2006). At this time, the Whiter River, now flowing west to east 8- 16 km (5- 10 mi) south of the park, eroded a scarp that through differential erosion has since formed “the Wall,” a prominent geomorphic feature of Badlands National Park.

Today, the Wall acts as a boundary that separates the flat grassy Upper Prairie to the north from the Lower Prairie to the south. The Wall of Badlands National Park towers as much as 46 m (150 ft) above the upper grassland and up to 140 m (460 ft) above the lower grasslands near the Cedar Pass Visitor Center (fig. 4) (Weedon 1990). This geomorphic feature also acts as a water divide. North of the Wall, Sage Creek and Bad River drain the grasslands, northward to the Cheyenne River and northeastward to the Missouri River respectively. Intermittent streams drain the lower grasslands and flow southward to the White River.

Periodically cliffs in the Wall break loose forming slumps. Slumps create holes, pits, and seasonal ponds in the disturbed strata. Faults that displace the colorful horizontal layers are also visible along the Wall as are clastic dikes. The faults are part of the Sage Creek anticline and fault system, called the Sage Creek Arch, which forms one of the more prominent geologic structures in the region (Stoffer 2003). The crest of the southeast- to- northwest- trending Sage Creek anticline parallels the Badlands Loop Road.

### Cultural History

Archaeological evidence records Paleo- Indian use of the area as early as 11,000 years ago. The Arikara who were mammoth hunters were the first known tribe to inhabit the White River area. In the mid- 18th century, the Lakota Sioux, who had been displaced westward by the advance of Euro- American settlers, displaced the Arikara. The Lakota called this area “mako sica,” or “land bad.”

The 18th century French fur traders echoed the Lakota sentiments when they called the area “les mauvaises termes a traverser,” or “bad lands to travel across.” In 1843, fur trader, Alexander Culbertson, collected a large fossilized jaw fragment on one of his trips. The jaw found its way to Dr. Hiram A. Prout, a St. Louis physician, who stated in 1846 that it came from a creature he called a *Paleotherium*. In 1849, Dr. Joseph Leidy renamed Prout’s *Paleotherium*, *Titanotherium prouti* in a paper he published about an Oligocene camel. Leidy went on to publish a series of papers about North American fossils, many of which were from the White River Badlands. From the late 1800s and continuing today, scientists and researchers from institutions from all over the world have studied the renowned fossil resources of the White River Badlands.

Homesteaders didn’t have much impact on the Badlands until well into the 20th century. In this harsh, semi- arid, wind- swept land, the standard 160- acre homestead proved too small to support a family and was increased to 640 acres. In response to homesteading, cattle replaced the bison and wheat fields replaced the prairies on the South Dakota landscape.

During World War II the United States Air Force (USAF) took possession of 341,726 acres of land on the Pine Ridge Indian Reservation for a gunnery range. Included in the gunnery range were 337 acres of then Badlands National Monument. Firing took place primarily within the present- day Stronghold District of the park. In 1968 the USAF returned the land to the Pine Ridge Indian Reservation and in 1970 a Memorandum of Understanding established how the NPS manages this area today.

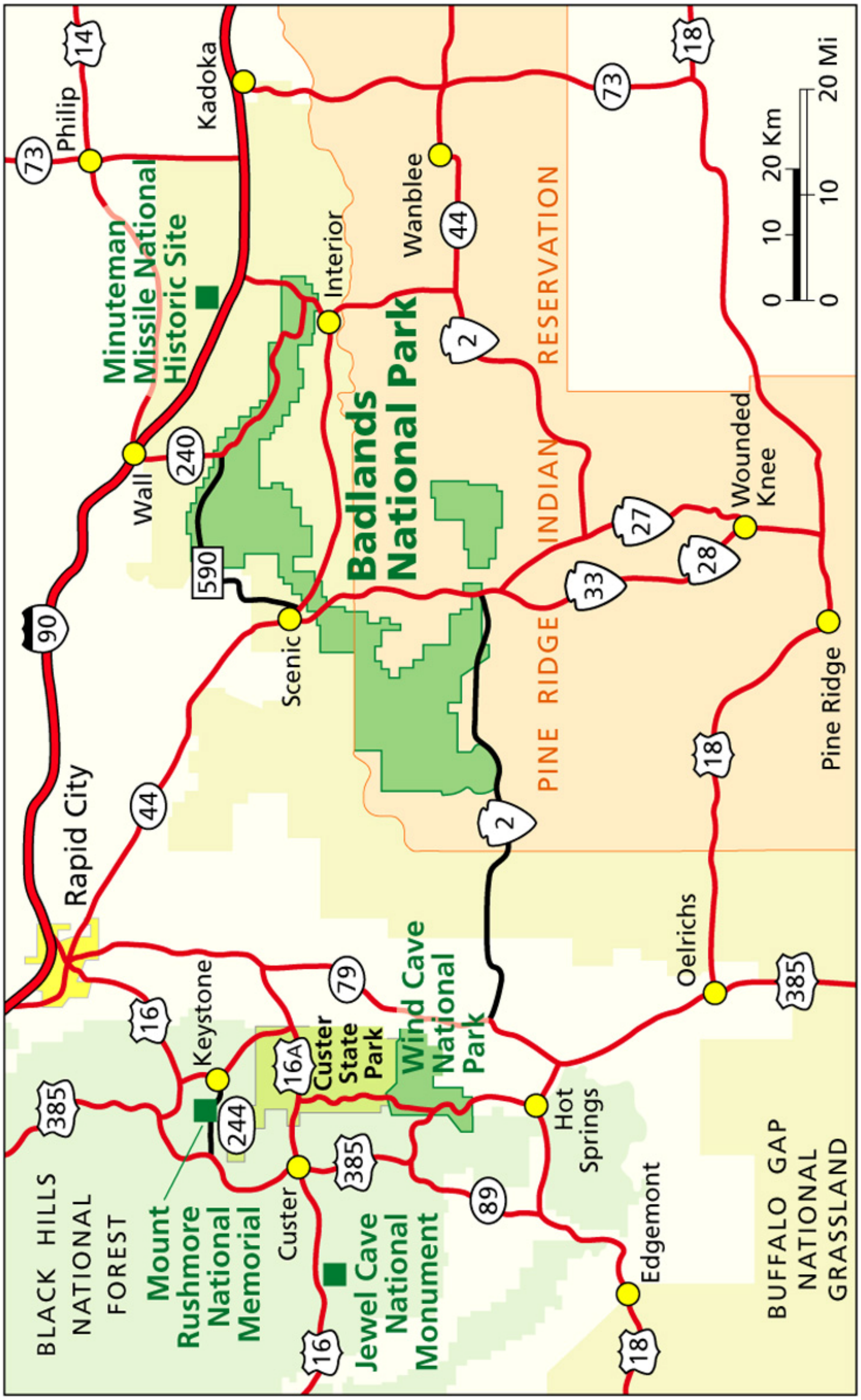


**Figure 1. Regional location map showing the location of Badlands National Park in relation to the Black Hills, Mount Rushmore National Memorial, Jewel Cave National Monument, and Wind Cave National Park.**

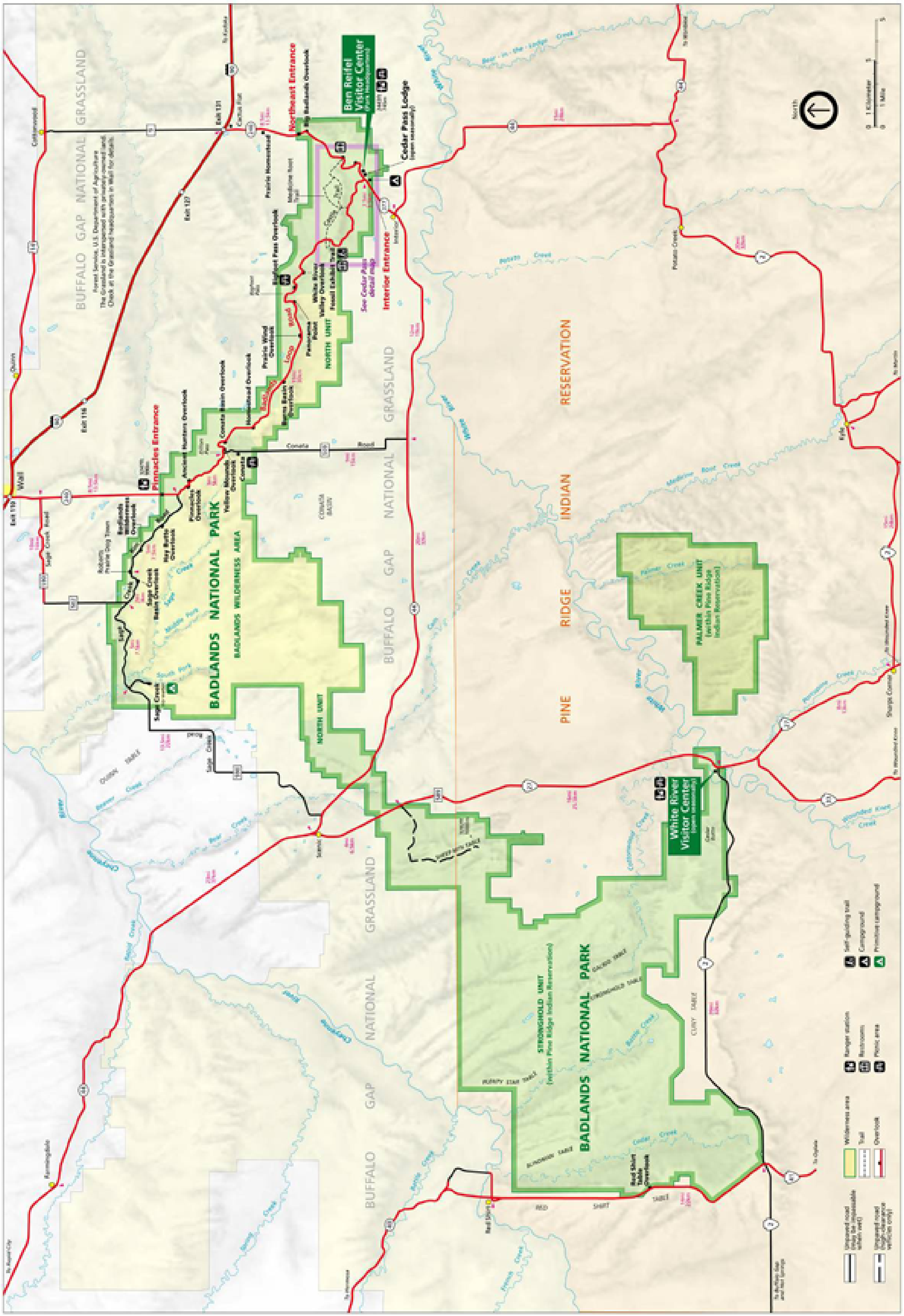


**Figure 2. Park map of Badlands National Park showing the North Unit (Sage Creek Unit), the South Unit (Stronghold Unit), and the Palmer Creek Unit.**

| Period | Epoch | Thickness in meters | Group | Formation | Member or Facies |
|---|---|---|---|---|---|
| Quaternary | | | | | Undivided - stream terraces, landslides, & floodplain deposits |
| Tertiary | Miocene- Pliocene(?) (1.81- 23.03 Ma) | | Medicine Root Gravels | | |
| | Oligocene (23.03- 33.9 Ma) | ~30 | Arikaree Group | Sharps Formation | |
| | | 2- 4 | | Rockyford Ash | |
| | | 100 | White River Group | Brule Formation | Poleslide Member |
| | | | | | Scenic Member |
| | Eocene (33.9- 55.8 Ma) | 10- 15 | | Chadron Fm | Peanut Peak Member |
| | | | | | Crazy Johnson Member |
| | | | | | Ahearn Member |
| | | 0- 4 | | Chamberlain Pass Fm | Interior paleosol |
| | | | | | |
| Cretaceous | Upper Cretaceous (Maastrichtian Age) (65.5- 70.6 Ma) | 0- 16 | | Yellow Mounds paleosol | |
| | | | | Fox Hills Formation | Unnamed marine facies |
| | | 0- 3 | | | (Disturbed Zone) |
| | | 0- 8 | | | Enning facies |
| | | 6- 26 | | | Timber Lake Member |
| | | | | | Trail City Member |
| | | 10- 36 | | Pierre Shale | Elk Butte facies |
| | | 25- 30 | | | Mobridge facies |
| | | | | | Virgin Creek facies |
| | Upper Cretaceous (Campanian Age) (70.6- 83.5 Ma) | 10 | | | Verendrye facies |
| | | | | | Degrey facies |

**Figure 3. Generalized stratigraphic column for Badlands National Park. Members of the Fox Hills Formation are recognized at its type section in the northern Missouri River Valley region but are not differentiated in Badlands National Park. The Fox Hills Formation only occurs sporadically along the northern margins of Badlands National Park. Where the Fox Hills Formation is absent, the Yellow Mounds paleosol developed on and in the Pierre Shale. Age dates are from the International Commission on Stratigraphy (2004) available on at http://www.stratigraphy.org (access July, 2006). The stratigraphic column is modified from Stoffer (2003).**

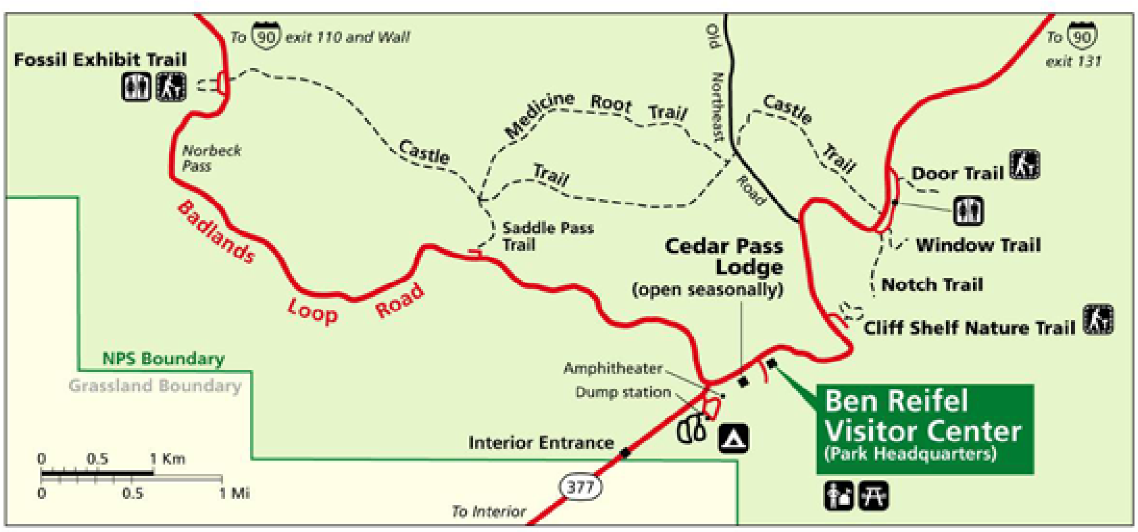


**Figure 4. Detail of the trails in the Cedar Pass area of the North Unit.**

# Geologic Issues

*A Geologic Resource Evaluation scoping session was held for Badlands National Park on June 12, 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 geologic issues section addresses geologic issues as they affect the ecosystem, their importance to park management, and the extent to which they are anthropogenically influenced. The following issues are listed in order of priority as discussed during the scoping workshop at the park.

### Mass Wasting Hazards

Some of the highest known rates of erosion occur in the badlands with some surfaces reduced by 2.54 cm (1 in) every year (Kiver and Harris 1999; Stoffer 2003). Ridges and pinnacles have collapsed overnight as a result of a single thunderstorm. Because most of the White River strata are poorly consolidated and thus, easily eroded, mass wasting processes are the most important geologic issue facing the management of Badlands National Park (fig. 5). Soil and rock stability, structural stability, and the potential for landsliding need to be evaluated prior to any development in the park. An inventory and study of slope stability would help identify potentially hazardous areas.

Landslides have been mapped in the Cedar Pass area, at Norbeck Pass, Sage Creek, and along the Cliff Shelf Trail (fig. 4). The lack of abundant vegetation and steep slopes allow short, intense rainfall events to produce flash floods. Formations associated with the largest number of landslides are the Brule Formation and the Pierre Shale. The Badlands Loop Road (route 240–the main road into Badlands National Park) is built on several active landslides within the Brule Formation. The road requires constant repair and is sometimes a hazard to the public. Major landsliding in the Pierre Shale also impacts the Sage Creek Rim Road.

Landslide deposits in Badlands National Park may be fault related. Higher than average rainfall in 1995 caused the Cedar Pass Slide to move over 0.9 m (3 ft) during a period of 3 months along a trend parallel to the Pass Creek fault. Landslides have been mapped extending 610 m (2,000 ft) from scarps along vertical joints that trend N. 80° W. within the Cedar Pass area. At Norbeck Pass, landslide deposits are mapped along normal faults that trend northwest (Ashworth et al. 1996).

The Cliff Shelf Trail crosses a large slump block that has detached from the cliff behind it and slipped downward, rotating backward. During wetter years, the slump continues to slip and disrupts the Loop Road (Kiver and Harris 1999). Water trapped on the back section of the slump block promotes a luxurious growth of vegetation. Mass wasting contributes sediment directly to some stream channels. An active slump along Sage Creek constantly adds new sedimentary material directly to the stream (Stoffer 2003).

Swelling clays derived from volcanic ash swell when wet and contract when dry, forming a "popcorn- like surface" that makes root establishment difficult and further encourages high rates of erosion. The Tertiary Chadron Formation and the Cretaceous Pierre Shale have high swelling clay contents. Erosion in these areas that lack significant vegetation has produced a karst- like terrain (pseudokarst) in parts of Badlands National Park. Pseudokarst terrains are characterized by closed depressions, sinking streams, and caves produced by processes other than the dissolution of rock.

In Badlands National Park, landslides and slumps may bury cultural and paleontological resource sites while potentially exposing new fossil sites. More studies and research on pseudokarst, rates of erosion, and how fossils are exposed and buried by landslides are needed to define the links between landslide areas and cultural and paleontological resources.

Specific concern was raised during the scoping session regarding potential rerouting of the Badlands Loop Road. The effect any change would have on the geologic and paleontologic resources, the viewshed of the park, and the integrity of the Wall are of great importance to park staff and visitors. Badlands National Park continues to work with Federal Highways personnel and private contractors on these issues.

### Paleontological Resources

The world class fossil beds of the White River Group in Badlands National Park allow detailed study and reconstruction of the evolution of sheep- like and pig- like mammals as well as the horse and rhinoceros. The fossilized remains of more than 250 vertebrate species are found in Badlands National Park.

The park paleontologist coordinates research with universities, colleges, and museums. Research staff prepare fossils, conduct field surveys, and document the fossil condition and history in the Badlands strata. Thousands of fossil specimens have been legally collected from Badlands National Park, however fossil poaching is a major issue. For example, the South Unit contains many historic collecting and research areas, some of which date back to scientific surveys of the late 1800s. On October 26, 1999, a park ranger discovered illegal diggings at the remote Titanothere Bone Bed site in the South Unit. Follow- up surveys documented more than 18 poaching sites. The poachers were never caught, and rangers now patrol the site on a regular basis.

The Big Pig Dig site, a complex assemblage of beautifully preserved mammal bones that serves both research and education, is located adjacent to a moderately traveled gravel road providing easy access for researchers as well as visitors (fig. 6). Ease of access to the Pig Dig site also poses serious vandalism threats. To deter vandalism and poaching, the park has installed a boundary fence around the site, two shelters, and a locking storage shed (Benton 2003). Rangers patrol the area and during the field season paleontology interns are onsite seven days a week.

Fossils illegally collected by park visitors are probably relatively close to roads and trails, whereas amateur and commercial collectors usually collect larger numbers of fossils from more remote sites. The number of cases of illegal fossil collection investigated has increased from one case in 1998 to 32 in 2000, 72 in 2001, 37 in 2006, and 41 in 2007(National Park Service 2005; Rachel Benton, NPS paleontologist, Badlands National Park, written communication, August 21, 2007 and March 24, 2008).

In 2000, a pilot project funded by the National Park Service Natural Resources Preservation Program (NRPP) allowed Badlands National Park to begin documenting the fossils in the lowest horizons of the fossiliferous Scenic Member of the Brule Formation (Benton et al. 2001). Easy access to the lowermost portion of the Scenic Member exposes it to greater threat of poaching and was one reason that the lowermost portion of the Scenic Member was chosen for survey. The NRPP bone- bed mapping project included the following:

- A paleontological site inventory including the identification and taphonomic analysis of each paleontological specimen found,
- A baseline data set including stratigraphic position, depositional environment, and degree of preservation,
- A detailed stratigraphic analysis of the Brule Formation, and,
- The location of easily accessible fossil resources so that the management team at Badlands can protect fossil sites within the park.

Through the NRPP, Badlands staff also is working in partnership with cooperating museums and universities to further document the paleontology, stratigraphy, and sedimentology of the Poleslide Member of the Brule Formation.

After the first summer of fieldwork in 2000, the team had documented and recorded 351 new paleontological sites in the park's Geographic Information System (GIS) (Benton et al. 2001). While hundreds of specimens occur in bone horizons at many of these sites, only 231 specimens were collected during the initial fieldwork. Criteria used to justify collection included threats from erosion or poaching and the overall scientific value of the fossil.

The NRPP bone- bed project marks the first time in the history of Badlands National Park that the extent and location of fossil resources have been documented. Fieldwork continues in the park and each locality is recorded in the park's GIS paleontological database using GPS field data. A report documenting the paleontological surveys completed from 2000 to 2002 is on file at Badlands National Park, and a report documenting the second set of paleontological surveys completed, from 2003 to 2005, will be completed in 2008 (Benton et al. 2006; Benton et al. in progress; Rachel Benton, NPS paleontologist, Badlands National Park, written communication, August 21, 2007).

After six years of surveys, the park continues work toward completing a paleontological inventory. Once complete, the baseline mapping and fossil survey will enable Badlands staff to more efficiently monitor sites that are threatened now or that may become threatened in the future.

Construction activities related to the management alternatives proposed in the General Management Plan (GMP) for Badlands National Park may impact paleontological resources (National Park Service 2005). In the North Unit, ground disturbance from construction of facilities in the park headquarters area, redesigning the Sage Creek Campground, a new Pinnacles visitor contact station, and activities associated with changing the Loop Road could potentially affect fossils. In the South Unit, construction of the Lakota Heritage and Education Center, improvement of the Sheep Mountain Table road, and bombing range cleanup efforts may adversely impact paleontological resources.

However, in both North and South Units, mitigation measures, including surveys and monitoring by paleontologists, should help minimize the extent of negative impacts (National Park Service 2005). In addition, the recommended management alternative presented in the GMP would increase the number visitor contact stations and outdoor classrooms thus, increasing visitor awareness of the significance of fossils in the park. Further, the plan calls for increasing the frequency of ranger patrols and expand the park boundary along SD 44. Boundary expansion would improve access for rangers, researchers, and resource managers into the Badlands Wilderness Area and increase the protection of fossils in the area.

#### Geohydrology Issues

With increased visitation, water supply and water quality continue to be important issues. Scoping workshop participants expressed concerns about water due to extensive herbicide use that has contaminated both surface water and groundwater. The effects of campground development on springs, water use at Sage Creek Campground, as well as potential impacts from any future development are potential research areas that could inform park decision making.

In 1998, the Water Resources Division (WRD) of the National Park Service analyzed the surface water quality in Badlands National Park (National Park Service 1998). Both pH and copper content exceeded Environmental Protection Agency (EPA) screening criteria for freshwater aquatic life, and sulfate, nitrite, and lead were above the EPA criteria for drinking water. Concentrations of fecal bacteria and turbidity exceeded WRD screening limits for freshwater bathing and aquatic life, respectively. Details of the surface- water quality inventory and analysis for Badlands National park are available in Techinical Report NPS/NRWRD/NRTR-98/161 (http://nrdata.nps.gov/BADL/nrdata/water/baseline_wq/docs/BADLWQAA.pdf, accessed August 25, 2007).

Management expressed a need for maps showing natural and man- made ponds. Structural studies of joints and fractures in the rocks would help define the erosional and depositional processes affecting the park's hydrology.

#### Geological Resource Ideas and Interpretive Needs

The following needs were identified at the GRE scoping meeting:

- Publish geologic information for visitors, including brochures or pamphlets for self- guided tours,
- Reprint U.S. Geological Survey geologic map I- 934,
- Provide geologic information to students and faculty of geological field camps when they visit the park,
- Develop interpretive materials for the Pig Dig site,
- Research erosional vs. depositional origins of the clastic dikes in Badlands National Park, and
- Develop a list of research needs for interested researchers.


**Figure 5. Mass wasting potential is high on the unvegetated slopes and relatively unconsolidated strata that form the Wall in Badlands National Park. Note that the more resistant layers are undercut by erosion and will eventually fail.**

**Figure 6. The Big Pig Dig site in Badlands National Park is a significant visitor education and research site. Visitors learn the importance of protecting fossil sites and promoting paleontological research. Park staff and geology students from the South Dakota School of Mines and Technology and other Universities around the United States excavate the site, document the fossils, and interpret the site for visitors. In the background is a cast of an *Archaeotherium* skeleton, the pig-like mammal for which the site was named.**

# Geologic Features and Processes

*This section describes the most prominent and distinctive geologic features and processes in Badlands National Park.*

### Badland Topography

Weathering, mass wasting, and erosion are the physical processes that shape the badlands landscape (fig. 7). Once weathered from bedrock, mass wasting moves the material down an unstable slope and erosion physically removes the sediment to other locations by wind and water. Visitors are amazed by the unusual eroded topography of Badlands National Park. Sparse vegetation and a harsh climate contribute to differential erosion in the park, a process that has exposed fossil sites and stratigraphy allowing visitiors and researchers a glimpse into earth history.

Geomorphic processes at work in Badlands National Park are influenced by the regional climate where presently the average annual rainfall is approximately 43 cm (17 in) with about 77% of it occurring in late spring and summer (April to September) (Stoffer 2003). Rainfall usually occurs as short- duration thunderstorms. Average monthly temperatures range from −5.6°C (22° F) in January to 22°C (72° F) in August with daytime temperatures typically reaching approximately 35°C (95°F) in the afternoon. The combination of high summer temperatures and short rain events, along with dry cold winters, make growing conditions difficult for most plants. Lack of stabilizing vegetation promotes the physical processes that impact the Badlands landscape.

The landforms are controlled by the characteristics of the rocks themselves. The Chadron Formation forms rounded, haystacklike features because it contains mostly clay- rich sediment. The Chadron also has a generally high precipitation infiltration rate due to desiccation cracks. This results in little surface runoff and reduced slope wash deposition (Schumm 1956; Kuehn 2002). The more rugged peaks and canyons in Badlands National Park are found in the Brule and Sharps Formations because their silty, ash- rich sediment is more resistant to erosion than the clay- rich Chadron strata. Because the Brule Formation is harder and less permeable than the Chadron Formation, slopes on the Brule Formation are influenced primarily by surface runoff, whereas sediment transport on Chadron Formation slopes is dominated by soil creep.

#### The Wall

The drainage networks of the White River (south of the park), the South Fork of the Cheyenne River (northwest of the park), and the Bad River (north of the park) deposited sediment, including the Medicine Root Gravel, in the Badlands National Park region. The White River cut a narrow valley, and about 500,000 years ago, erosion began to carve the serrated badlands topography. Closely spaced tributaries flowing southward down the steep north valley wall caused the valley side to erode and migrate northward as a line of cliffs that now stretches about 97 km (60 mi) from the town of Kadoka west towards Scenic. This long, narrow spine of buttes is known as the “Badlands Wall,” or “Wall.” In another 500,000 years, the badlands will have migrated north, destroying the Upper Prairie, which is the drainage divide between the White River and the Cheyenne River (Kiver and Harris 1999).

The Wall separates the upper grasslands on the north from the lower grasslands on the south in Badlands National Park (fig. 8). The Wall towers as much as 46 m (150 ft) above the upper grasslands and as much as 137 m (450 ft) above the lower grassland area near the Cedar Pass Visitor Center (Weedon 1990). Separating the flat grassy Upper Prairie from the Lower Prairie, the Wall also acts as a water divide. Intermittent streams in the Lower Prairie flow southward into the White River. The slower, more sluggish streams that characterize the Upper Prairie flow northward to the Cheyenne River and to the Bad River.

#### Other Badland Features

Weakly consolidated, easily eroded fine- grained rock, steep slopes, sparse vegetation, and a semiarid climate combine to produce the stark terrain and classic erosional forms known as badland topography (fig. 8). Castles are large star- or block- shaped features that are the remnants of Tertiary and Cretaceous units. Monuments, or pinnacles, are isolated remnants of sedimentary rock. Both are prevalent throughout the region south of the High Pinnacles Overlook in the North Unit.

Low mesas are scattered in the valley bottoms between the higher castles, walls, and monuments in the badlands. Sod tables are isolated erosional remnants of the once higher plains. Sod has formed a protective cover for the underlying, softer soil materials. The grass- covered surfaces are remnants of an earlier floodplain and record a wetter period when vegetation became established throughout the badlands. Sod tables can be seen in the “Grassy Tables” area and viewed from the High Pinnacles Overlook (Stoffer 2003).

Hoodoos and caprocks are similar features. Harder rocks, such as sandstone, resist erosion and shelter softer, underlying claystone units. The harder sandstone is called a “caprock.” If the claystone erodes, leaving the caprock resting on a pedestal of softer material, the feature is called a “hoodoo.” They are also called “toadstool rocks” because of their form. Hoodoos, which are smaller than castles or monuments, are numerous in the Badlands area.

Yardangs were named for landscape features in the badlands of South Dakota (Baker 1951). These irregular, sharp- crested, undercut ridges are carved by wind erosion into soft but coherent deposits such as clayey sand. They are oriented in the direction of the dominant wind and may be as much as 6 m (20 ft) high and 40 m (130 ft) wide.

Rapid erosion in channels has also formed natural arches and bridges in Badlands National Park. These fragile features, however, are short- lived.

Flash floods remove sediment and often produce rounded, baseball- size clay masses called armored mudballs because their outer surfaces are coated with sand, pebbles and rock fragments.

Globular shaped geodes are discrete nodules that weather out of all the White River Badlands formations, but they are most numerous in the nodular zones of the Brule Formation (Harris et al. 1997; Weedon 1990). The outer layer of the geodes is composed of dense chalcedony. Crystals, commonly calcite or quartz, project into the hollow center of the geode.

### Paleontological Resources

Badlands National Park contains some of the most species- diverse Oligocene fossil beds in the world, contributing greatly to the science of vertebrate paleontology. All sizes of animals, from rodents to the elephant- size Titanotheres, lived on the floodplains that covered the Badlands region during the Oligocene. Golden moles, hedgehogs, and shrews ate Oligocene insects. Recent research on the Oligocene camelid, *Poebrotherium wilsoni*, has shed light on the dietary habits of these camelids as well as Oligocene climate (Wall and Hauptman 2001).

Fossils from the Oligocene strata of the White River Badlands have nearly twice as many mammalian families than are known today for all of North America (Weedon 1990). More than 50 species of herbivores and 14 species of carnivores have been discovered in the Eocene and Oligocene White River Group, primarily in the Oligocene Brule Formation (fig. 3) (Kiver and Harris 1999).

#### Brule Formation

The Brule Formation was originally described as the “turtle and oreodont beds” by the Meek and Hayden Survey in the late 1850s (Stoffer 2003). Oreodonts were primitive ruminants only found in North America. They were about the size of sheep and roamed the plains in large herds (Harris et al. 1997).

Remains of land turtles and oreodonts (especially *Merycoidodon*) are common in some layers of the lower Scenic Member of the Brule Formation. The lower Scenic Member includes the rocks between the underlying Chadron Member and the top of the first marker bed, called marker unit 1. This marker bed is a widespread greenish gray noncalcareous mudstone bed that is characterized by abundant mudstone and claystone rip- up clasts, root traces, and scattered streaks of white limestone (Benton et al. 2001). Channel sand deposits in the Scenic Member were originally called the “*Metamynodon* beds” for bone beds containing an aquatic variety of rhinoceros. Deposited in paleovalleys cut into the Chadron Formation, the lower Scenic Member ranges from 8.7- 25 m (29- 82 ft) in thickness.

Oreodont fossils are abundant in both the Scenic Member and the Poleslide Member of the Brule Formation (Benton et al. 2001; Stoffer 2003; Benton et al. 2004; Mintz et al. 2005).The overlying Poleslide Member of the Brule Formation preserves fossils of a horned sheep- sized herbivore, *Proteroceras*, and also contains oreodonts (genus *Leptauchenia*) (Stoffer 2003).

In 1993, two visitors from Iowa discovered a large backbone near the Conata Picnic Area. This discovery became the Conata Picnic Area Paleontological Site and is one of the more significant paleontological finds in recent years at Badlands National Park (fig. 6) (Benton 2003). The site, discussed above, is better known as the Big Pig Dig, or, simply, the Pig Dig, named for *Archaeotherium,* a large pig- like mammal uncovered there. As many as 100 elements per $m^2$ are preserved at the site, which is biased towards animals of a large body size (Bjork 1994; Ashworth et al. 1996; Benton 2003). Intermixed bones of such animals as *Archaeotherium*, *Subhyracodon* (a hornless rhinoceros), *Mesohippus* (Oligocene horse), and *Leptomeryx* (foot- high deer- like creature) are preserved in a light, olive- gray mudstone layer in the Scenic Member of the Brule Formation. This mudstone layer can reach a thickness of 89 cm (35 in) (Ashworth et al 1996; Benton et al. 2001).

The fossil accumulation at the Pig Dig is unique in the badlands because of the density of bone material and the way in which the fossils were preserved. Vertebrate fossils are most commonly preserved in the badlands either as attritional bone accumulations on ancient land surfaces or bones that have been incorporated into channel sandstone deposits. In contrast, the randomly oriented, semi- articulated to disarticulated bones at the Pig Dig have been preserved in an Oligocene watering hole. The site gives visitors an opportunity to watch paleontologists conducting the arduous, time- consuming task of carefully excavating and preparing fragile fossils for a move to the park’s museum collection.

During a recent NPS survey more than 1000 fossil sites were documented in the Poleslide Member (Benton et al. 2004). Fossils include a horned sheep- size herbivore, *Protoceras*, and oreodonts (Stoffer 2003). The association of vertebrate accumulations with paleosols supports the environmental interpretation of long- term stable land surfaces and periods of rapid eolian deposition when the bones were quickly buried. Stable land surfaces are marked by dense zones of fossil roots, dung balls, and burrows, while times of eolian aggradation are marked by massive volcaniclastic siltstones with sparse paleosol features (Benton et al. 2004; Mintz et al. 2005).

Several fossil sites, also within the lower Scenic Member, have been documented within the Badlands Wilderness Area. One of the more recent discoveries is the Brian Maebius bone bed in Tyree Basin, the first valley west of the Sage Creek Basin in the North Unit (Benton et al. 2001). The site contains a greater diversity of fauna than the Pig Dig site and also contains fossilized wood, pollen, and coprolites.

#### Chadron Formation

The Chadron Formation (uppermost Eocene), which underlies the Brule Formation, is known for Titanotheres (fig. 9). The Titanothere, *Brontothere* ("thunder- beast"), discovered in 1846, was the first Badlands fossil to be described. Titanotheres belong to the genus, Brontotherium , an extinct family of perissodactyls, or odd- toed ungulates, and are considered to be the largest and most impressive of the early mammals preserved at Badlands National Park. About the size of an Indian elephant, Titanotheres looked similar to the modern rhinoceros but were actually more closely related to modern horses. Titaontheres stood about 4 m (12 ft) high and had huge blunt paired horns on their snouts (Harris et al. 1997; Kiver and Harris 1999). These herbivores attained their peak in the Oligocene. The Titanothere Bone Bed is located in the South Unit in strata that represent an Oligocene channel system that originally flowed from the Black Hills.

#### Fox Hills Formation

Whereas Cenozoic fossils preserve terrestrial land animals, Mesozoic fossils from Badlands National Park are mostly marine organisms that represent the last vestige of a sea that inundated the Western Interior of North America. The fossils are found in sedimentary rocks of Late Cretaceous age that are exposed along the lower stream drainages in Badlands. These marine rocks have an impact on the modern environment of the park. They weather relatively slowly compared with the overlying Tertiary strata, yet produce soils that are both rich in nutrients and hold moisture. Consequently, plants well adapted to the high western prairie grow well in areas underlain by Cretaceous bedrock.

Shelled mollusks (mostly clams and ammonites), arthropods, and rare bones, teeth, and scales of fish and swimming reptiles are preserved in Cretaceous marine beds. Both the Cretaceous Pierre Shale and Fox Hills Formation are subdivided into more discrete intervals by using species of ammonites as markers (Stoffer 2003).

At its type locality (the location where a formation is first described and named) in the northern Missouri River Valley region of South Dakota, the Fox Hills Formation has been subdivided into four members, the lowest two being fossiliferous. The Fox Hills Formation in Badlands National Park is unlike the exposures in the type area. Rather than divided into four members, the formation is undifferentiated in the park (Stoffer 2003). Thin ledge-forming sandstone beds of the Fox Hills Formation cap hilltops throughout the southern Sage Creek Wilderness area (especially along the South and Middle Forks of Sage Creek). The coiled ammonite, *Jeletzkeytes nebrascensis*, has been recovered from a red concretion layer in the Fox Hills Formation (Chamberlain, Jr. et al. 2001; Stoffer 2003).Above the zone of concretions, an interval of green- and red- colored fossiliferous marl (a clay- rich limestone) yields ammonites, belemnites (cigar- shaped cephalopods), fish remains, plant material, tiny clams, oyster fragments, and other material. Belemnites, especially *Belemnitella bulbosa*, are perhaps the most common fossils in this interval.

A significant change in fauna is associated with the Disturbed Zone (DZ), a regional zone of intense soft-sediment deformation as much as 5 m (16 ft) thick within the Fox Hills Formation (fig. 3). Two classes of mollusks - bivalves (numerous) and cephalopods (rare) - are the most abundant invertebrate fossils preserved in the DZ (Chamberlain, Jr. et al. 2001). While the bivalve fauna is abundant, it is not diverse. Only nuculid pelecypods occur in significant numbers, and only one species of nuculid has been recovered: *Nucula cancellata* (Chamberlain, Jr. et al. 2001). A poorly preserved specimen of what probably is the inoceramid (clam), *Spyridoceramus (=Tenuipteria) tegulatus,* also has been discovered from the DZ.

Two groups of cephalopods have been found in the disturbed zone fauna: scaphitid ammonites and belemnites. Significantly, baculitid ammonites, which are ammonoids with uncoiled shells rather than the normal (planispiral) form of coiling, are not present. The lack of baculitid ammonites supports the hypothesis that straight- shelled ammonoids dropped out of the fossil record well before the end of the Cretaceous.

Scaphitid ammonites also have an unusual form of coiling. The shell of these ammonoids grows first in a tight coil, then straight, and finally curves back upon the initial coil. Scaphitids are rare and occur as isolated fragments at Badlands. Complete adult specimens are exceedingly rare, thus making identification difficult. The only two species that have been identified are *Discoscaphites gulosus* and *Jeletzkytes nebrascensis*.

Belemnite specimens have been recovered from beds below the DZ in the Wilderness Access Trailhead area. No belemnites have been found higher than about 1 m (3 ft) below the base of the DZ. The specimens appear to be *Belmnitella americana*, common in the Western Interior Seaway (Chamberlain, Jr. et al. 2001).

Although not common, vertebrate remains have been discovered in the Fox Hills Formation in the Badlands area. Osteichthean (bony fish) scales have been found above, below, and within the DZ at Creighton, about 50 km (30 mi) north of the park, and below the DZ at

Wilderness Access Trailhead. Chondrichthian (also spelled “chondrichthyan”) remains and lamniform shark teeth also are present at Creighton and Wilderness Access Trailhead. Chondrichthians are a class of vertebrates that includes fish with skeletons of cartilage rather than bone. Sharks, for example, are chondrichthians. Chondrichthian remains have been recovered from the Timber Lake Member of the Fox Hills Formation and mark the youngest transitional marine chondrichthian assemblages yet recovered from Cretaceous rocks of the Western Interior (Becker et al. 2004).

The 15 surviving species of the order Lamniformes, which includes the great white and mako sharks, are mere remnants of a much greater lamniform lineage that has mostly become extinct. Lamniform sharks first appeared in the fossil record during the early Cretaceous period about 120 million years ago. Lamniform sharks are classified within the infraclass Neoselachii (“new sharks”). Neoselachians are the last common ancestor of living sharks. By the mid- Cretaceous, about 100 million years ago, most modern groups of sharks had appeared. A partial skeleton of what might be a small, neoselachian shark was found at Sage Creek Basin (Chamberlain, Jr. et al. 2001).

Above the DZ` an unnamed marine unit of the Fox Hills Formation contains an abundance of marine trace fossils but very scarce body fossils (Stoffer 2003). Trace fossils (or ichnofossils) are tracks, trails, burrows, borings, fecal pellets and other traces made by organisms. Although difficult to identify, trace fossils can yield valuable information regarding paleoecology and environmental reconstruction. They are potential indicators of bathymetry, currents, food supplies, oxygen supply, rate of deposition, depositional history, substrate stability, and salinity. Ichnofossils have been arranged into nine recurring depositional environments, called ichnofacies, each named for a representative ichnogenus (Pemberton et al. 1992). Fish bone fragments, teeth of a barracuda-like fish, and plant material in the unit above the DZ occur along with trace fossils that represent the *Skolithos* and *Cruziana* ichnofacies. Both *Skolithos and Cruziana* are genus (ichnogenus) names for trace fossil burrows.

*Skolithos* ichnofacies are indicative of relatively high levels of wave or current energy developed in slightly muddy to clean, well- sorted, loose or shifting, sandy substrates. *Cruziana* ichnofacies are characteristic of subtidal, poorly- sorted and unconsolidated substrates in deeper, quieter marine waters (MacEachern and Pemberton 1992; Pemberton et al. 1992). Both varieties of ichnofacies occur within the intertidal or shallow subtidal zone. Trace fossils common to both facies include *Diplacraterion* (U- shaped burrows), *Ophiomorphia* (thick branching burrows with a knobby texture), *Thalassinoides* (burrows with Y- or T- shaped branches), and *Cruziana* (crawling traces with “herringbone,” or chevron- like, tracks) (Stoffer 2003).

#### Pierre Shale

The upper portion of the Pierre Shale is exposed in Badlands National Park along Sage Creek and Sage Creek valley, including the lower drainage basins of East Fork and Middle Fork and most of South Fork, in the North Unit and along Cedar Creek in the South Unit. The giant clam, *Inoceramus sagensis*, occurs in large gray concretions and was named by the Meek and Hayden Survey of the late 1850’s after Sage Creek (Stoffer 2003). Distinctive ammonite species found in the Pierre Shale either within the park or the adjacent area include: *Baculites compressus*, *Baculites cuneatus*, *Baculites reesidei*, *Baculites corrugatus*, *Baculites grandis*, *Baculites baculus*, *Baculites clinolobatus*, *Hoploscaphites melloi*, and *Hoploscaphites birkelundi* (Stoffer 2003). While *Baculites* species are straight shelled ammonites, *Hoploscaphites* species are coiled ammonites.

### Stratigraphic Features

Disturbed Zone of Soft Sediment Deformation: The Disturbed Zone (DZ) at Badlands National Park is part of a regional zone of intense soft sediment deformation that is preserved within the southernmost deposits of the Fox Hills Formation in and around Badlands NP (Stoffer 2003; Chamberlain, Jr. et al. 2001; Terry, Jr. et al. 2004). Previously hypothesized to be the result of the Chicxulub impact that marks the Cretaceous- Tertiary boundary, the DZ has been dated using dinoflagellate biostratigraphic data as late middle to early late Maastrichtian, which is equivalent to the Timber Lake Member of the Fox Hills Formation (Chamberlain, Jr. et al. 2001; Terry, Jr. et al. 2001; Stoffer 2003; Palamarczuk et al. 2003; Terry, Jr. et al. 2004).

The Badlands DZ is the only zone of distorted, convoluted bedding anywhere in the Upper Cretaceous beds of southwestern South Dakota and seems to mark the occurrence of some unusual Late Cretaceous event (Chamberlain, Jr. et al. 2001; Stoffer et al. 2001; Terry, Jr. et al. 2004). The DZ has been documented over 300 $km^2$ (116 $mi^2$) in the badlands area of South Dakota and ranges in thickness between about 0.5 m (1.6 ft) to as much as 5 m (16 ft) where exposed (Chamberlain, Jr. et al. 2001; Stoffer 2003; Terry, Jr. et al. 2004).

In the Badlands area, the DZ is exposed at the following locations: headwaters region of Conata Creek; 5 km (3 mi) directly west of the Pinnacles Ranger Station and south of the Sage Rim Road near the Grassy Tables Overlook; at the Wilderness Access Trailhead; at stream level in the headwaters region of Dry Creek in the Sage Creek Wilderness Area near the park’s southern boundary; and about 1.6 km (1 mi) north of the park boundary in the Buffalo Gap National Grasslands. Physical characteristics of the DZ and adjacent strata include the following (Stoffer 2003):

- Dinoflagellates that record a late middle to early late Maastrichtian age,
- A diverse Late Cretaceous marine fauna below the DZ but not above the DZ,

- Mappable exposures throughout the northern portion of Badlands NP across a region at least 25 km (16 mi) wide and extending north of the park at least 30 km (19 mi),
- As much as 16 m (52 ft) of marine beds above the DZ contain abundant trace fossils but have not yielded Cretaceous fauna – identified fossils and traces in this upper interval all have modern descendents (such as barracuda, sharks, oysters, sand fleas, and others),
- Oriented roll structures in the DZ with sediment layers rolled up like a carpet while they were soft and pliable – these roll structures have an east- to- west orientation in outcrop indicating that sediment movement was toward the south,
- Other soft- sediment features, including clastic dikes, slump glide plane surfaces, and dewatering structures – none of these structures penetrate the beds above or below the DZ,
- Local deposits of charcoal and fragmented plant material, and
- Flat lying and conformable strata along the scoured upper DZ surface.

Similar soft- sediment disruption has been documented after hurricanes or tsunamis along coastal regions. However, the disruption across such a large region within the Western Interior Seaway suggests that something possibly larger than a storm or earthquake formed the DZ (Terry et al. 2004). The origin of the DZ soft- sediment deformation may correspond with some yet unknown late Cretaceous impact or it may simply be the result of a regional geotectonic event. More answers may come from research that continues into the biostratigraphy and magnetostratigraphy of the South Dakota DZ sections (Terry et al. 2004).

#### Paleosols

In Badlands National Park, ancient soil profiles (paleosols) developed on the changing landscape (fig. 7). The Yellow Mounds paleosol formed partly on the Upper Cretaceous Fox Hills Formation and partly on the Upper Cretaceous Pierre Shale where the Fox Hills Formation had been eroded (Retallack 1983; Stoffer 2003). A cut bank along a tributary of Sage Creek in the Grassy Tables Overlook displays the unconformable relations between the green shale of the Fox Hills Formation, the Yellow Mounds paleosol, the reddish flood plain deposits of the Chamberlain Pass Formation, and the gray clay and siltstone of the Chadron Formation (Stoffer 2003).

The Yellow Mounds paleosol is a thick, very strongly developed paleosol with a yellow, sandy horizon that overlies a red, silty- claystone, large clay- filled root channels, and a calcareous layer at depth (Retallack 1983). The Yellow Mounds paleosol was well drained with a low water table. Paleosols in the Yellow Mounds series are complex with considerable relict bedding, possible re- sorted paleosol material, and buried horizons. Located at a major regional unconformity with about 25 m (82 ft) of erosional relief, the Yellow Mounds silty clay loam paleosol developed on a moderately hilly, rolling terrain. The size and deep penetration of root casts in the Yellow Mounds paleosol indicate that forests of large trees grew in the region (Retallack 1983).

The Interior paleosol, part of the Chamberlain Pass Formation, is a red soil that reflects higher oxygenating conditions than were present during weathering of the Yellow Mounds paleosol (Stoffer 2003). The red soil stands out in contrast to the gray floodplain sediments of the overlying Chadron Formation. An abundance of fossil termite nests and other burrows occur locally throughout the Interior paleosol in the Grassy Tables Overlook exposure belt.

The Yellow Mounds and Interior paleosols record sea level fluctuations in the Badlands region. A eustatic sea level fall led to pedogenic modification of the Pierre Shale and the formation of the Yellow Mounds paleosol series. Local subsidence caused a subsequent sea level rise, which backfilled stream channels and deposited the channel sandstone and overbank mudstone facies of the Chamberlain Pass Formation. Lateral changes within Chamberlain Pass paleosols indicate proximal and distal floodplain settings that have distinctive pedological characteristics (Terry, Jr. and Evans 1994).

The paleo- Red River valley incised into the landscape when relative sea level again lowered. Sea level lowering led to intensified pedogenic modification of the Chamberlain Pass Formation and the Interior paleosol series (Retallack 1983; Terry, Jr. and Evans 1994; Ashworth et al. 1996). When sea level rose again, the valley backfilled with the Chadron Formation.

Fossil remains and paleosols in the Eocene Chadron Formation and Oligocene Brule Formation record a change from forested uplands to dryer savannah- like environments in Badlands National Park (Benton et al. 2001; Stoffer 2003). The Eocene and early Oligocene contained widespread woodlands with interspersed streams or marsh areas, but by the end of the Oligocene, cooler and drier conditions prevailed (Retallack 1983; Wall and Hauptman 2001).

#### Other stratigraphic and sedimentary features

The Verendrye Member of the Pierre Shale is a gray shale interval that contains abundant limestone concretions between the underlying Degrey Member and the overlying bentonitic shale beds of the Virgin Creek Member of the Pierre Shale. The Verendrye Member is exposed along Cedar Creek in the South Unit and along Sage Creek in the North Unit. The limestone concretions are septarian (containing an irregular polygonal pattern of internal cracks) and many display fossil debris or preserve the mostly broken shells of a variety of marine invertebrates and an abundance of bioturbation structures (Stoffer 2003).

The concretions may be gutter casts, sedimentary structures that down- bulge the bottom of a sedimentary bed. In cross- section they take the form of a small channel that may be a meter or more in length. Gutter casts are commonly interpreted as features of high-energy events in which storm or wave- generated currents erode bottom surfaces (Duke 1990; Myrow 1992; Graham and Ethridge 1995). Bioturbation data and gutter casts can provide information about water depth, oxygen availability on the seabed, and the orientation of the paleo- shoreline.

An unconformity separates the marine shale of the Fox Hills Formation from the underlying Elk Butte Member of the Pierre Shale. Highlighting this unconformity is an ironstone concretion layer. Large, brown weathered, ironstone concretions in sandy mudstone and shale crop out on the hilltops around the Sage Creek Campground (Stoffer 2003).

The Rockyford Ash defines the base of the Oligocene Sharps Formation. The ash bed forms a white, massive resistant, ledge- forming cap rock. An example of the ash bed can be seen at the Pinnacles Overlook area. The ash is from tremendous pyroclastic flows (ignimbrites) that erupted from volcanoes in the Great Basin region, episodically blanketing the Badlands area with ash (Stoffer 2003).

Gravel deposits on some of the highest tablelands in the park area consist of materials carried by fast- moving streams flowing away from the Black Hills. These deposits are called the Medicine Root Gravel and are about 2 million years old. They were deposited prior to or near the beginning of the Pleistocene Ice Age.

## Structural Features

### Folds and faults

The geologic setting of the Badlands National Park North Unit is controlled partly by the Sage Creek anticline, or Sage Creek Arch, a southeast- to-northwest- trending system of folds and faults that is one of the region's more prominent geological structures. The eastern end of the Sage Creek Arch begins in the eastern end of the North Unit in the vicinity of the Big Badlands. It is partly responsible for the south- facing Badlands escarpment. The crest of the anticline parallels the park's Badlands Loop Road and the Sage Rim Road in the western part of the North Unit. The anticline looses its surficial expression west of Sage Creek. The upper drainages of Conata Creek along the Badlands Loop Road offer the best views of the anticline. In the Grassy Tables Overlook area, small hills in the Yellow Mounds and Interior paleosols mark the crest of the Sage Creek anticline (Stoffer 2003).

Faults in Badlands National Park mainly display offsets in the range of several meters (feet). Northwest of the Conata Basin Overlook, a normal fault that puts Fox Hills adjacent to Chadron Formation has about 10 m (30 ft) of displacement. Along Sage Creek, north of the Sage Rim Road Bridge, a normal fault cuts Pierre Shale beds. Total displacement along this fault is about 50 m (160 ft), but whether the offset is a result of faulting related to the Sage Creek Arch or to a deep- seated slump is not clear. West of the Roberts Prairie Dog Town, a reverse fault with about 20 m (66 ft) of offset juxtaposes Chadron Formation adjacent to strata of the Fox Hills Formation (Stoffer 2003).

The Dillon Pass fault is believed to be part of a series of northwest- trending normal faults as much as 30 km (19 mi) in length that define the northern boundary of a 40 km (25 mi) wide asymmetrical basin (Ashworth et al. 1996). Displacement along this fault can be seen in the misalignment of banding in the Brule Formation. Other northwest- trending normal faults can be seen at Norbeck Pass and along both sides of SD 240 between the Interior Road turnoff and the Cedar Pass Visitor Center (Ashworth et al. 1996).

### Unconformities

Unconformities mark substantial gaps in time between rock units. If the strata beneath an unconformity is tilted at an angle relative to the overlying strata, the unconformity is called an 'angular' unconformity. An angular unconformity between tilted Fox Hills Formation strata and the overlying Chadron Formation is visible along a cut bank of upper Conata Creek (Stoffer 2003). The angular unconformity suggests that the Cretaceous Fox Hills Formation was deformed (tilted) and eroded prior to the deposition of the Eocene Chadron Formation. Deformation was related to the growth of the Sage Creek anticline, and the angular unconformity indicates that the anticline was already developing before late Eocene time.

### Clastic dikes

Prominent clastic dikes, located directly southwest of the SD 240- Old NE Road junction, run nearly perpendicular to the surrounding horizontal layers (fig. 10). Clastic dikes typically form when vertical cracks caused by sediment shrinkage and compaction fill with sediment, which subsequently hardens to form sedimentary rock. The dikes at Badlands, especially in the North Unit, contain a large component of ash, which suggests that the Rockyford Ash may be a potential source of the sediment. However, many of the dikes continue through the Rockyford Ash horizon indicating that additional sediment must also have contributed to the vertical crack (Ashworth et al. 1996).

In the South Unit, near the town of Scenic, groundwater circulating through the dikes has deposited silica cement making the dikes more resistant to erosion than the surrounding strata. The silica is in the form of brown chalcedony. Native Americans used chalcedony, a cryptocrystalline variety of quartz, for spear points, tools and arrowheads since the time of the Paleo- Indians (Weedon 1990; Kiver and Harris 1999).

Because they are relatively resistant to erosion, the dikes often form straight ridges that project above the surrounding sedimentary rocks. These features can be seen at Homestead Overlook and at the Pinnacles

Overlook area (Kiver and Harris 1999; Stoffer 2003). Numerous clastic dikes crosscut the upper Scenic Member of the Brule Formation and the Sharps Formation.

Clastic dikes that have been mapped along two major linear trends suggest that the clastic dikes might occupy fracture sets rather than simple cracks opened by sediment desiccation (Ashworth et al. 1996). More research is needed to explain the origin of these clastic dikes.

### Geoarcheology

In Badlands National Park an active area of research is geoarcheology, the application of earth science techniques to the study of archaeological questions (Kuehn 2002). Researchers who study soil horizons in individual Quaternary stratigraphic sections describe the horizon in detail, age date the minerals, and analyze the horizon for potential cultural sites. A recent study (Kuehn 2002) analyzed eight stratigraphic sections selected from the following land surface categories:

- Upper Prairie surface and the Wall
- Pleistocene (?) Cheyenne River terraces
- Early Pleistocene or late Tertiary surface
- Lower Prairie surface

All three sections from the Upper Prairie surface and from the Wall are associated with sod tables. A Late Prehistoric hearth filled with broken pieces of fire-cracked rock, mammal bone, and abundant fragments of charcoal was dated at 1435 ± 210 years B.P. The oldest archaeological remains are associated with Paleo- Indian traditions and are found at sites located in the South Unit on top of an early Pleistocene- Tertiary plateau surface and from a gravel- covered sod table on the Upper Prairie surface. Sod tables on the Upper Prairie surface also are associated with two of the eight previously recorded Late Plains Archaic and Pelican Lake sites (Kuehn 2002). Data suggest that the Upper Prairie surface near the edge of the Wall has generally good potential for Late Prehistoric, Archaic, and Paleo- Indian sites.

The early Pleistocene or late Tertiary plateau surfaces are most common in the South Unit of Badlands National Park and contain extensive mantles of loess (eolian silt) and sand. Loess unconformably overlies silty loam in a section at Sheep Mountain Table and Pleistocene Medicine Root Gravel in a section at Cuny Table. The eolian deposits have the potential to contain archaeological materials dating from Paleo- Indian through the Late Prehistoric. These upland settings have sediment records that span the late Pleistocene through the Holocene, some of the most complete sediment records of any major landform category in the White River Badlands (Kuehn 2002).

The Lower Prairie surface includes all landforms situated below the Wall such as previously active and currently active floodplains and the channels of today's streams and gullies. The landforms vary considerably in age and elevation. In Sage Creek Basin charcoal dated at 2870 ± 90 yr B.P. has been found in a channel incised into older terrace deposits and into the Pierre Shale. A complete bison vertebra was recovered from planar- laminated sand deposits and yielded an age of 5900 ± 250 yr B.P. In addition, two Late Archaic sites were found in prominent slump block deposits just below the top of the Wall (Kuehn 2002).

Kuehn's study was a preliminary search for relationships between geologic, geomorphic, and landform sequences and the distribution and preservation of archaeological sites in Badlands National Park. The data suggest that additional work is needed to describe the prehistoric and historic use of the badlands, the role of badland environments in the settlement pattern of seasonally mobile hunter- gatherer groups, and other cultural aspects of the culture of the region's oldest inhabitants.

**Figure 7. Badlands topography and paleosols at Badlands National Park. The red bands are paleosols in the Brule Formation. Typical badlands topography of sharply eroded buttes and pinnacles. Photo courtesy of Brian Franzone http://academic.wsc.edu/faculty/raberto1/explorers_club/black_hills_pix/blackhills_photos_page_2.html (access August 20, 2007).**

**Figure 8. The Wall at Badlands National Park. The Wall separates the upper grassland from the lower grassland prairies. Reddish bands are paleosols. Photo courtesy of Brian Franzone http://academic.wsc.edu/faculty/raberto1/explorers_club/black_hills_ pix/blackhills_photos_page_2.html (access August 20, 2007).**

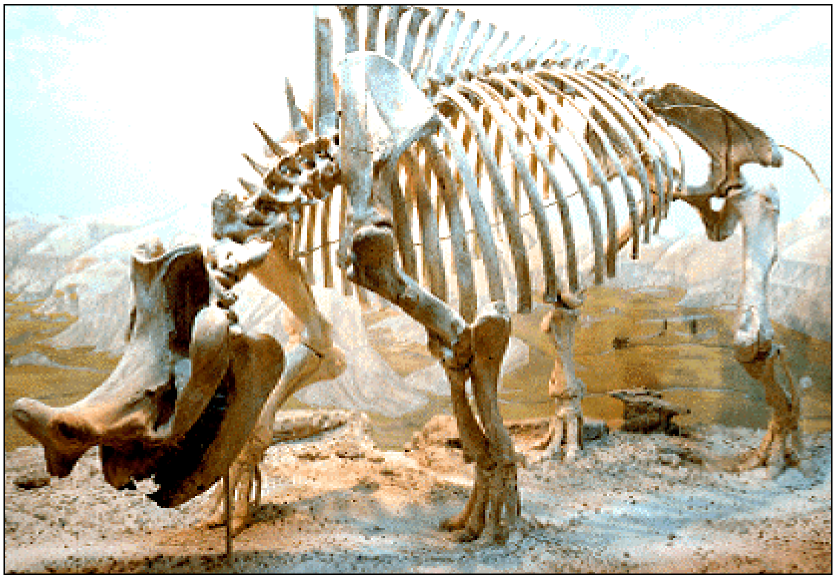

**Figure 9. Titanothere skeleton, South Dakota School of Mines and Technology museum, http://www.sdsmt.edu/services/museum/bronto.gif (accessed August 17, 2007).**

**Figure 10. Clastic dike in Badlands National Park. Note that the dike is composed of material that is more resistant to erosion than the surrounding strata.**

# Map Unit Properties

*This section identifies characteristics of map units that appear on the Geologic Resource Evaluation digital geologic map of Badlands National Park. The accompanying table is highly generalized and is provided for background purposes only. Ground- disturbing activities should not be permitted or denied on the basis of information in this table. More detailed map unit descriptions can be found in the help files that accompany the digital geologic map or by contacting the National Park Service Geologic Resources Division.*

This section explains specific properties associated with different rock units that the park should be aware of when making resource management decisions. Geologic features and processes often occur in or can be restricted to a particular stratigraphic unit (group, formation, or member). The geologic units in the following table and their geologic features and properties correspond to the units found in the accompanying digital geologic data.

Source data for the GRE digital geologic map are from:

Raymond, W.H. and King, R.U., 1976, Geologic map of Badlands National Park and Vicinity, West- Central South Dakota: U.S. Geological Survey Miscellaneous Investigations Map I- 934, scale 1:62,500.

King, R. U., and Raymond, W. H., 1971, Geologic map of the Scenic area, Pennington, Shannon, and Custer Counties, South Dakota: U.S. Geological Survey Miscellaneous Investigations Map I- 662, scale 1:24,000., and

Ellis, M.J., and Adolphson, D.G., 1971, Hydrogeology of the Pine Ridge Indian Reservation, South Dakota: U.S. Geological Survey Hydrologic investigation Atlas HA- 357 , scale 1:125,000.

The following table presents a list of units exposed in Badlands National Park and features for each map unit. This table includes several properties specific to each unit present in the stratigraphic column including: age, map unit name and symbol, unit description, topographic expression, resistance to erosion, paleontologic and cultural resources, hazards and suitability for development.

# Map Unit Properties Table

| Age | Map Unit (symbol) | Unit Description | Topographic Expression | Erosion Resistance | Paleontological Resources | Cultural Resources | Hazards | Suitability for Development | Other |
|---|---|---|---|---|---|---|---|---|---|
| QUATERNARY | Alluvium (Qa) | Unconsolidated clay to gravel in streambeds, floodplains, and sheetwash. | Low relief | Low | May contain fossils eroded from other formations | Charcoal in channels incised into Kp; Middle Archaic component in alluvial fans | Flash floods | Low | None |
| | Flood- plain alluvium (Qfa) | Light- brown to gray clay, silt, & fine sand; discontinuous sandy & clayey gravel beds in lower part. Composed of sediments deposited during present erosional cycle of streams. Generally thicker along White & Cheyenne Rivers (avg thickness 7.6- 11 m, 25- 35 ft) than along tributaries. Grades laterally into terrace alluvium. Generally water bearing. Yields are adequate for domestic & stock needs, but differ because deposits are not uniform. Along some small tributaries deposits are thin: wells commonly go dry in late summer or early fall. Water levels, especially along rivers, respond rapidly to changes in streamflow. Includes colluvium mapped by the South Dakota Geological Survey (SDGS) on map HA- 357 (Ellis & Adolphson 1971). 0- 12 m (0- 40 ft) thick. | Flatlands adjacent to stream channels | Low | None documented in this report | None documented | None documented in this report | Floodplain | Groundwater quality good where alluvium is underlain by Tertiary deposits & generally poor where underlain by Cretaceous rocks. |
| | Terrace alluvium (Qta) | Light- brown clay, silt, & fine sand; thin discontinuous beds of med to coarse gravel at or near the top. Clayey & sandy gravel common in basal few ft, especially along the White River. As many as 5 terraces present at some locations. Water bearing where deposits extend below the water table of adjacent Qfa, or where water table is perched. Yields & water quality similar to those of Qfa. Not differentiated from flood- plain alluvium in S. Jackson & N. Bennet Counties , S of Badlands National Park, on HA- 357. 0- 18 m (0- 60 ft) thick. | Flat terraces adjacent to, but higher than, present floodplains | Low | None documented in this report | None documented | None documented in this report | Moderate | Groundwater where deposits extend below the water table of Qfa |
| | Landslide deposits (Ql) | Slumped masses consisting predominantly of shale (Kp), clays (Tb), & silt & ash (Ts). Common in areas of high local relief, particularly in Kp, upper part of Brule Fm, Rockyford Ash of Ts, & more frequent on east- facing slopes of map I- 934 (Raymond and King 1976). | Slumps | Low | None documented in this report | Late Archaic sites in prominent slump block deposits just below top of Wall | May destroy paleo and cultural resources | Unstable deposits | None |
| | Eolian sand (Qe) | Sand, predominantly as stabilized sand dunes & yardangs. Includes minor lenticular beds of older alluvial gravel on map I- 934. | Dunes & yardangs | Low | None documented in this report | Bison bone from Sheep Mtn Table; Paleo- Indian to Late Prehistoric material? | None documented in this report | Unstable | None |
| | Windblown sand deposits (Qwd) | Tan unconsolidated very fine to medium quartz sand. Water table generally is near the base of sand. Some deep depressions contain ponds because the water table intersects the land surface. Springs are common along the margins of the deposits. Yields commonly more than adequate for domestic & stock needs. Mapped only where areally extensive or water bearing on HA- 357. 0- 61 m (0- 200 ft) thick. | Dune topo.; small hills to 37 m (120 ft) high,closed depressions; partly stabilized by veg. | Low | None documented in this report | None documented | None documented in this report | Unstable deposits | Groundwater quality good (TDS generally less than 350 Mg/l). |
| | Older alluvium (Qoa) | Generally pediment deposits derived mainly from Tc & Tb & smaller amounts of high- level river gravels. The gravels consist of igneous, metamorphic, & sedimentary rocks characteristic of the Black Hills on I- 934. | Sod tables | Low where sod has been stripped off | None documented in this report | Bison bones, scorched rock from fire rings, worked stones, pottery on eroded toes of dissected sod tables | None documented in this report | Could impact sod tables | None |
| | Old terrace deposits (Qot) | Brown to light- brown silt, clay, sand, & gravel; layers often partly cemented by calcium carbonate; gravel & sand beds commonly interbedded with laminated silty clay. Form terraces generally parallel to the present White & Cheyenne Rivers & slope gently towards the rivers. Generally water bearing in basal few ft. Springs & seeps common along the riverside margins. Yields generally adequate for domestic & stock needs. Mapped where areally extensive or water bearing on HA- 357. 0- 24 m (0- 80 ft) thick. | Nearly flat isolated terraces; 24- 61+ m (80- 200+ ft) above present stream. Gentle slopes to rivers. | Low | None documented in this report | Middle Plains Archaic site; possible sites as old as 2800 to 10,500 years BP in Sage Creek Basin terrace fill | None documented in this report | Moderate | Groundwater quality good (TDS generally less than 500 Mg/l). |
| TERTIARY | Ogallala Formation (To) | Upper unit: Light- tan to light- gray calcareous, massive sandstone; thin discontinuous beds of limestone common near base. Beds of volcanic ash up to 3.4 m (11 ft) thick locally occur near the top. Mapped as the Ash Hollow Fm of the Ogallala Group by the Nebraska Geological Survey (NGS) & SDGS. Relatively impermeable; water bearing only locally because of high topographic position. 0- 46 m (0- 150 ft) thick. Lower unit: Light- gray to light- olive- green fine to medium, unconsolidated or poorly consolidated sand; lower part locally cemented with calcium carbonate. Small blowouts common in sandy areas. Mapped as the Valentine Fm of the Ogallala Group by the NGS & SDGS. Generally water bearing where areally extensive. Springs & seeps common at contact with underlying Arikaree Fm. Yields of most wells adequate for domestic & stock needs. 0- 6 m (0- 20 ft) thick.<br><br>Shown only where mapped by SDGS or described in other published reports. Probably present over large areas in E Shannon, NW Bennet, & SW Jackson Counties (S of Badlands National Park) on HA- 357. **Not exposed in Badlands National Park**. | Upper unit: Thin cap rock on isolated buttes & ridges S of Badlands National Park; erodes to low but prominent bluffs.<br><br>Lower unit: Forms gentle slopes between bluffs of underlying Arikaree Fm. | Upper unit: Forms cap rocks.<br><br>Lower unit: Less resistant to erosion than upper unit. | Not exposed in Badlands National Park | Not exposed in Badlands National Park | Not exposed in Badlands National Park | Not exposed in Badlands National Park | Lower unit: Groundwater quality good (TDS generally less than 250 Mg/l). |

| Age | Map Unit (symbol) | Unit Description | Topographic Expression | Erosion Resistance | Paleontological Resources | Cultural Resources | Hazards | Suitability for Development | Other |
|---|---|---|---|---|---|---|---|---|---|
| TERTIARY | Arikaree Formation (Ta) | Divided into units A, B, C, D, & E on HA- 357; **Not exposed in Badlands National Park.**<br><br>Unit E: Light- tan to brown; interbedded calcareous sand, silt, & clay; contains gray to pinkish- gray tabular concretions & small light- brown & greenish clay balls. Small blowouts & thin, isolated deposits of windblown sand are common. Mapped by SDGS as the Rosebud Fm. 0- 72 m (0- 235 ft) thick.<br>Unit D: Gray, massive, poorly consolidated, fine to very fine sands commonly contains layers of light- gray sandy marl, large concretions & small spherical concretions. Unit difficult to differentiate from underlying units. Mapped by SDGS as the Harrison Fm. 0- 38 m (0- 125 ft) thick.Unit C: Buff siltstone & very fine- grained sandstone. Difficult to distinguish from overlying & underlying units. Mapped as the Monroe Creek Fm by SDGS. 0- 27 m (0- 90 ft) thick.<br>Unit B: Pinkish- tan poorly consolidated silt & very fine- grained sand; gray, 5- 10 cm (2- 4 inches) calcareous concretions are common. Lenses of limestone & channel sand & gravel occur locally throughout the unit in the central & western parts of the Pine Ridge Reservation. Mapped as Ts by SDGS. 0- 114 m(0- 375 ft) thick.<br>Unit A: White, tan buff, & reddish- brown silty volcanic ash; interbedded with thin layers of silt. Caps buttes & tables in NW part of Pine Ridge Reservation. Also called the Rockyford Ash of Ts. 0- 14 m (0- 45 ft) thick. | Unit E: Rolling hills<br>Unit D: Rolling hills except along valleys where it forms steep slopes interrupted by small ledges<br>Unit C: Forms cliffs along major tributaries; rolling, hummocky topo in upland areas.<br>Unit B: Gently rolling grass-covered hills.<br>Unit A: Forms prominent light-colored cliff between the Arikaree & White Rivers; caps buttes & tables in NW part of Pine Ridge Reservation | Units E, D, & B: Erode to gently undulating, rolling hills.<br><br>Unit C: More resistant to erosion than other units in Ta; forms cliffs.<br><br>Unit A: More resistant than units E, D, & B; caps buttes & tables. | Not exposed in Badlands National Park | Not exposed in Badlands National Park | Not exposed in Badlands National Park | Not exposed in Badlands National Park | Most common source of groundwater on Pine Ridge Reservation. Yields vary, probably because of well location & method of completion, but are usually adequate for domestic & stock needs. |
| | Sharps Formation (Ts) | Massive poorly consolidated pinkish- tan silt containing calcareous concretions, local lenses of freshwater limestone, clastic dikes, & chalcedony veinlets. Basal unit, the Rockyford Ash, is a conspicuous white locally silty zeolitic volcanic ash up to 15 m (50 ft) thick. In many places, generally between Cedar Pass & The Pinnacles, the basal unit is a channel fill consisting of pebble conglomerate made up largely of fragments of calcareous nodules derived from ash layers & quartz sand in the upper part of Tb. Lithology is similar to that of the underlying Tb, but the color of Ts above the Rockyford Ash has a more brownish tone than that of Tb. About 100 m (328 ft) thick on map I- 934. | Cap highest levels of the badlands; form flat barren highland studded with sharp spires & near vertical walls formed by clastic dikes. | Low | Leptauchenia, Proscalops, Paleolagus, Palaeocastor, heliscomys, Nimravus | None documented | Fossil theft; mass wasting (slumping & rock fall) | Low | Part of Arikaree Gp. whose type section is in the Pinnacles area of the North Unit |
| | Brule Formation (Tb)<br><br>(White River Group [Twr]) | Interbedded pinkish- & greenish- gray clay, silt, sand, & volcanic ash containing channel sandstones, clastic dikes, & chalcedony veinlets. Contains a conspicuous oreodon & turtle fauna. Due to its high content of fine volcanic ash & calcareous cement, characteristically weathers to very steep slopes & knife- edge ridges. This characteristic alone provides reasonably clear delineation of the Brule- Chadron contact in the badlands. Too impermeable to serve as a groundwater source. Up to 150 m (490 ft) thick.<br><br>Poleslide Mbr.: Reworked eolian volcaniclastics (siltstones) & occasional fluvial channel & overbank deposits; well developed paleosols; rare lacustrine carbonate; 50 m (160 ft) thick in the Cedar Pass Area.<br>Scenic Mbr.: Tuffaceous mudstones & fine- grained sandstones, with minor amounts of claystone, siltstone, & limestone. | Steep fluted cliffs & bluffs; Compose most of the Wall & many of the striking color-banded buttes. | Low | Conspicuous oreodont (Merycoidodon, Leptauchenia) & turtle fauna; horned sheep-sized herbivore (Proteroceras); aquatic rhinoceros (Metamynodon); camel, Poebrotherium wilsoni; coprolites, pollen, fossilized wood<br><br>Pig Dig fossils: Mesohippus,Subhyracodon, Archaeothrium, Leptomeryx | None documented | Fossil theft; mass wasting (slumping & rock fall); Route 240 Loop Road is built on several active landslides in Brule Fm. | Low due to erosion potential | World- class Oligocene fauna; Part of White River Gp. whose type section is in the Pinnacles area of the North Unit |
| | Chadron Formation (Tc)<br><br>(White River Group [Twr]) | Pale- gray- green bentonitic clay alternating with layers of greenish- gray siltstone; basal conglomerate & channel sandstone present in some areas. Contains a conspicuous titanothere fauna. Divisible into an eastern & a western facies. Western facies, SW of Scenic, attains a maximum thickness of about 55 m (180 ft). Includes a thick basal conglomerate & channel sandstone sequence, which has filled stream valleys that were cut into the surface of the underlying Kp in pre- Oligocene time. Eastern facies, near Interior, the conglomeratic channel- fills of the basal Tc are missing, the formation is less than 7 m (23 ft) thick, & in some places it consists only of greenish- gray clay. Generally too impermeable to serve as a groundwater source, but local basal sandstones yield small amounts of water. 0- 34 m (0- 110 ft) thick.<br><br>Peanut Peak Mbr. (youngest): Exposed in North Unit<br>Crazy Johnson Mbr. (middle): Exposed in South Unit<br>Ahearn Mbr. (oldest): Exposed in South Unit<br><br>Interior paleosol: Base of Tc; red weathering profile; | Erodes into low, rounded, barren "haystack" knolls | Low; sandstone & conglomerate more resistant then clay | Conspicuous titanothere fauna (Brontotherium).<br><br>Fossil variety in Tc & Scenic Mbr. of Tb: aquatic turtles (Graptemys); semi- aquatic rhinoceros (Trigonias); cursorial rhinoceros (Hyracodon, Caenopus), titanotheres (Menodus), horses (Mesohippus), creodont carnivores (Hyaenodon), oreodonts (Merycoidodon), pig- like entelodon (Archaeotherium)<br><br>Other fossils: alligator; frog; lizard; birds; opossum; small insectivore; rodent; saber-tooth cat; tapiroid; peccary; camel; squirrel-like, deer- like, rabbit- like, and fox- like animals.<br><br>Interior paleosol: fossil termite nests; other burrows | None documented | High bentonite content; sheet wash; mass wasting (slumping); fossil theft | Low due to bentonite problems | World- class Titanothere fauna; Part of White River Gp. whose type section is in the Pinnacles area of the North Unit; Type section for the Chadron Fm is in the town of Chadron in NW Nebraska.<br><br>Groundwater quality fair (TDS between 600 & 1,000 Mg/l). |

| Age | Map Unit (symbol) | Unit Description | Topographic Expression | Erosion Resistance | Paleontological Resources | Cultural Resources | Hazards | Suitability for Development | Other |
|---|---|---|---|---|---|---|---|---|---|
| | Chamberlain Pass Formation, White River Grp (mapped as Interior Beds, Kpi) | Conglomerate, sandstone, shale; flood plain deposits (lacking gravel) in Sage Creek Wilderness Area in North Unit; indistinguishable from the Interior paleosol in North Unit. | Conglomeratic beds may cap buttes | Variable | Eocene fossil tooth found in gravel deposits | None documented | Mass wasting (slumping & rock fall) | Variable | Part of White River Gp. Type section about 10 km (6 mi) SW of Kadoka, SD |
| UPPER CRETACEOUS | Yellow Mounds Paleosol (not mapped) | Yellow, sandy A- horizon; red, silty- claystone B- horizon; large clay- filled root channels extending deep into C- horizon; dense calcium carbonate horizon at depth. Parent material is weathered Kp or Fox Hills Fm, where present. | Developed on hilly, rolling terrain | Low | Root casts and other soil formation features | None documented | None documented in this report | Low due to erosion potential | Type section |
| | Fox Hills Formation (mapped as Interior Beds, Kpi) | <u>Unnamed marine facies</u>: Sandstone & shale; interbedded; flat- lying beds; sand sheets are 1- 15 cm (0.4- 6 in) thick; body fossils scarce; abundant marine trace fossils (*Skolithos/Cruziana* ichnofacies); best exposures in Grassy Tables Overlook area; 0- 16 m (0- 52 ft) thick.<br><u>Enning Mbr:</u> Green & red fossiliferous marl; occurs in scattered outcrops along northern park boundary & north of park; 0- 8 m (0- 26 ft) thick.<br><u>Timber Lake Mbr:</u> buff & brown sandstone & shale; large, reddish- brown, fine- sandy textured concretions; Disturbed Zone (DZ) –Interval of soft- sediment deformation throughout park area; E- to- W roll sources; soft- sediment features (roll structures, clastic dikes, slump glide- plane surfaces, dewatering structures) do not penetrate overlying & underlying strata; up to 16 m (52 ft) thick.<br><u>Trail City Mbr:</u> gray sandy mudstone & shale; large, brown weathering, ironstone concretions in hilltops around Sage Creek Campground; Timber Lake and Trail City Members combined thickness of 6- 26 m (20- 85 ft). | Within slopes & cliffs along streams & tributaries (unnamed facies & DZ); ledge- forming sandstone beds cap hilltops; Timber Lake concretion beds form bench- like surfaces | Variable: Sandstone more resistant than shale | <u>Unnamed marine facies:</u> Trace fossils include: *Diplacraterion*, *Ophiomorphia*, *Thalassinoides*, *Cruziana*<br><u>Enning Mbr:</u> Common belemnite, *Belemnitella bulbosa*; also fish remains, plants, tiny clams, oyster frags<br><u>Timber Lake & Enning Mbrs:</u> Ammonite, *Jeletzkeytes nebrascensis*; DZ: Trace fossils; charcoal & fragmented plant material<br><u>Trail City Mbr</u>: Fossilcasts, arthropod parts, fossil wood, rare sharks teeth | None documented | None documented in this report | Variable | Southernmost exposures of Fox Hills Fm; exposed along northern margin of the park. |
| | Pierre Shale (Kp) | Black to dark- gray marine shale & mudstone. Fissile, carbonaceous, poorly resistant to weathering. Layers contain bentonitic beds, large concretions & marine fossils. Channels in the old erosion surface have been mapped SW of Scenic where they form a drainage system about 6 km (4 mi) wide. Upper part of Kp, where it is in contact with the overlying Tc, is deeply weathered, up to 17 m (55 ft) thick, & the dark shale has been altered to red, yellow, & orange claystone. Basal 23- 30 m (75- 100 ft) consists of very dark- gray fissile shale with numerous beds of bentonite. Not a groundwater source. About 610 m (2,000 ft) thick.<br><br>Subdivided into 5 members (from youngest to oldest) (Stoffer 2003):<br><u>Elk Butte Mbr:</u> Noncalcareous, very dark- gray, fissile shale with large, light- gray concretions that lack fossils; exposed along the S side of Sage Creek Anticline in Grassy Table Overlook area & at creek level in the core of the Sage Creek Anticline in Dillon Pass/Conata Creek Basin area; 0- 50 m (0- 164 ft) thick.<br><u>Mobridge Mbr:</u> Calcareous shale with intermittent layers of concretionary limestone; best exposed along upper hillsides along the South Fork & Middle Fork valleys in the Sage Creek Wilderness Area; about 5 m (16 ft) thick.<br><u>Virgin Creek Mbr:</u> Gray to greenish- brown or olive shale with numerous, thin, yellowish bentonite beds; exposed throughout the middle hillside slopes of Sage Creek Valley (North Unit) & most of South Unit; 10- 20 m (32- 66 ft) thick.<br><u>Verendrye Mbr</u>: Gray fissile shale with abundant limestone concretions; exposed along Sage Creek (North Unit) & Cedar Creek (South Unit); concretions are septarian, mostly barren of fossils but with some fossil debris; max 15 m (50 ft) thick<br><u>DeGrey Mbr</u>: Dark, reddish- gray, fissile shale with thin yellow bentonite (jarosite) beds; exposed along Cheyenne River Valley & Indian Creek W of Scenic; scarce fossils; incomplete section. | Generally erodes to rolling topography with deeply incised streams | Low; Mobridge Mbr is more resistant to erosion than the underlying & overlying strata | Elk Butte Mbr: unnamed species of baculites is common; Hoploscaphites melloi; Hoploscaphites birkelundi<br><br>Mobridge Mbr: Baculites clinolobatus<br><br>Virgin Creek Mbr: Baculites grandis<br><br>Verendrye Mbr: Baculites compressus; Baculites cuneatus; Baculites reesidei; Inoceramus sagensis (large clam)<br><br>DeGrey Mbr: Didymoceras cheyennense; Baculites corregatus; Inoceramus sagensis | None documented | Bentonite; Sage Creek Rim Road built on major landslide in Pierre Shale | Low due to bentonite problems | Deposited in the last of the great inland seas to inundate the North American continent. |
| | Niobrara Formation (Kn) | Upper third consists of yellowish- gray to pale- yellow shaly limestone. Where in contact with Tc, the upper 6- 8 m (20- 25 ft) of Kn is deeply weathered to a red, yellow, & orange noncalcareous claystone. Lower two- thirds consist of light- grayish- yellow to brownish- yellow very calcareous shale, with scattered thin interbeds of dark- gray noncalcareous shale. Normally not a groundwater source. Approximately 0- 99m (0- 325 ft) thick. **Not exposed in Badlands National Park.** | Upper third: Steep bluffs with thin limestone ledges.<br>Lower two thirds: Rolling grasslands | Limestone ledges more resistant than shale | Not exposed in Badlands National Park | Not exposed in Badlands National Park | Not exposed in Badlands National Park | Not exposed in Badlands National Park | Not exposed in Badlands National Park |
| | Carlile Shale (Kc) | Dark- gray to brownish- gray marine shale & mudstone. Large septarian concretions common in the upper third. Middle part is sandy & contains thin limestone ledges locally. Not a groundwater source. Approximately 30- 99 m (100- 325 ft) thick. **Not exposed in Badlands National Park.** | Gently rolling grass- covered hills | Low | Not exposed in Badlands National Park | Not exposed in Badlands National Park | Not exposed in Badlands National Park | Not exposed in Badlands National Park | Not exposed in Badlands National Park |

Map units and descriptions for this table and accompanying GIS map are from: Ellis, M.J. and D.G. Adolphson. 1971. Hydrogeology of the Pine Ridge Indian Reservation, South Dakota. U.S. Geological Survey Hydrologic Investigations Atlas, HA- 0357, scale 1:250,000.
* Not mapped on map HA- 0357 but described by Stoffer (2003) in Badlands National Park

# Geologic History

*This section describes the rocks and unconsolidated deposits that appear on the digital geologic map of Badlands National Park, the environment in which those units were deposited, and the timing of geologic events that created the present landscape.*

This section provides a more detailed description of the structure, tectonics, depositional and erosional history, and general stratigraphy of Badlands National Park and the surrounding area. The sedimentary rock layers exposed in the park are only a fraction of the thick sediment package that was deposited in the high Great Plains region. These sedimentary rocks overlie an ancient crust consisting of igneous and metamorphic rocks, similar to those exposed in the core of the Black Hills.

Thee ancient basement rocks are billions of years old and form the North American craton. Wells drilled for water and petroleum show that the thickness of sedimentary rock above the basement varies throughout the region. Over time some areas subsided, forming basins, while others rose forming domes or plateaus. Since the Precambrian (fig. 11), shallow have seas advanced and retreated many times across the region around Badlands National Park. The sedimentary cover in some of these basins, such as the Williston Basin in North Dakota and Montana and the Powder River Basin in Wyoming, is more than 4,000 m (13,000 ft) thick. In the Badlands area, however, the sedimentary cover is only about 980 m (3,200 ft) thick.

The rock record of the Paleozoic Era (251- 542 Ma), is not exposed at Badlands National Park, but in the subsurface it is dominated by limestone formed from calcareous sediments deposited in shallow seas (fig. 12). Uplift of the Ancestral Rocky Mountains in the late Paleozoic generated large quantities of clastic sediments (mostly sand and clay) that filled basins across the region (fig. 13).

Additional sediments were episodically deposited across the badlands area of South Dakota during the Triassic and Jurassic Periods of the Mesozoic Era. By the Early Triassic, the process of plate tectonics had assembled all of the large landmasses around the globe into one large supercontinent, Pangaea. Soon after forming, however, Pangaea began to split apart and the lithospheric plates moved away from one another. Rivers draining westward from the Appalachian region flowed into a low, subdued mid- continent landscape. On the west coast of North America, the Cordilleran mountain belt was actively developing, and ongoing volcanism and mountain building began the events that would lead to the formation of the Western Interior Seaway in the Cretaceous Period.

### Cretaceous Period

As mountain building occurred along the west coast of North America, about 115 Ma (Early Cretaceous), the region east of the mountains gradually subsided and eventually formed a broad, shallow inland sea. At its maximum extent roughly 80 Ma, this Western Interior Seaway extended from the present Wyoming- Idaho border to perhaps the Mississippi Valley region and from the Arctic Ocean to the Gulf of Mexico (fig. 14) (Stoffer 2003). The oldest rocks exposed at the surface in Badlands National Park formed from sediments deposited about 75 Ma in the Western Interior Seaway.

Cretaceous rocks in Badlands National Park preserve a history of gradual changes in sea level and also record the evolution of marine species and environmental changes. Two formations, the Pierre Shale and the lower part of the overlying Fox Hills Formation, represent the Upper Cretaceous in the park.

Pierre Shale: In the Late Cretaceous, between 80 and 60 Ma, the silts and muds of the Pierre Shale were deposited in the Western Interior Seaway (Harris et al. 1997; Stoffer 2003). The fossils and sedimentary features in the Pierre Shale reveal subtle changes in the conditions of the seaway. At times, the seaway supported diverse marine fauna that lived both in and on the seabed, or swam above in the water column. Waves and currents mixed the seawater when sea level was relatively shallow, allowing oxygen- rich water to support a large variety of fauna. Preserved in the sediments that accumulated during periods of low- standing sea level is a mix of shelled mollusks (mostly clams and ammonites); arthropods; and, rare bones, teeth, and scales of fish and swimming reptiles. Traces of burrows and tracks of bottom fauna also are preserved.

At other times, when the seaway was either deeper or stagnant, conditions in the seaway became hypoxic (oxygen- depleted) and inhospitable to many organisms, including invertebrates living in the seabed. In these hypoxic intervals, ammonite shells are relatively scarce, but where they occur they tend to be more complete because they were not subjected to bioturbation. Shell material in some beds provides evidence of massive die- offs. Storms or upwelling events may have mixed the water column, robbing the little available oxygen in the thin oxygenated zone near the surface, and suffocating most of the organisms (Stoffer 2003).

Different species migrated into the seaway from either the Gulf of Mexico or from the Arctic region. Eventually, the new arrivals either died off or adapted and became endemic to the seaway. Cretaceous ammonites in the Pierre Shale and Fox Hills Formation provide excellent documentation of evolution, competition, and environmental change through time. Ammonite species that were abundant, yet short- lived, provide a useful marker bed for mapping and correlating layers of Cretaceous sedimentary rock.

Fox Hills Formation: The lower three units of the Fox Hills Formation (Trail City Member, Timber Lake Member, and Enning Member) record the final Cretaceous deposition in the Badlands National Park region. The Fox Hills Formation is recognized as a complex series of marine, transitional, and terrestrial environments that interfinger across the Western Interior region (Stoffer 2003). In Badlands National Park, however, these lower three units contain ammonites, indicating a marine environment of deposition.

Assemblages of chondrichthian teeth from the Timber Lake Member of the Fox Hills Formation (fig. 3) suggest a diverse, marine and transitional, nearshore ecosystem in the Maastrichtian Stage of South Dakota (Becker et al. 2004). The teeth and other fossils are found in small discontinuous lag deposits in clean, well- sorted, medium to fine quartz sands with hummocky and high- angle tangential cross- stratification. The geometry of the cross- beds and flow directions measured from the cross- beds suggest a complex interaction of storms, wave action, and tides. This type of depositional environment is common in shoreface marine environments. *Ophiomorpha* burrows, coarse- grained vertical burrows common to the *Skolithos* ichnofacies, and wood fragments found in the sand also support an interpretation of a shoreface depositional setting at this time (Becker et al. 2004).

Transitional marine chondrichthian assemblages are the youngest yet recovered from Cretaceous rocks of the Western Interior. The Cretaceous assemblages are so different from chondrichthians recovered from Paleocene deposits in North Dakota that researchers hypothesize that there was a significant turnover among Western Interior chondrichthians during the interval between the deposition of the Upper Cretaceous and Paleocene units (Becker et al. 2004). The cause of this extinction is yet to be explained. The regional Disturbed Zone that contains large- scale slump- roll structures, clastic dikes, flame structures, and massive, homogenized beds supports the notion that a major deformation event occurred in the Late Cretaceous.

Body fossils are scarce in an unnamed marine facies of the upper Fox Hills Formation (fig. 3) but marine trace fossils are common (Stoffer 2003). The types of trace fossils found in this facies represent the lower intertidal zone to shallow subtidal zone of the both *Skolithos* and *Cruziana* ichnofacies (Pemberton et al. 1992; Stoffer 2003).

The Yellow Mounds paleosol developed on an erosional surface on both the Pierre Shale and the Fox Hills Formation (Rachel Benton, NPS paleontologist, Badlands National Park, written communication June 27, 2006). Badlands is at the very southern exposure of the Fox Hills Formation in the region so Fox Hills strata only occur sporadically in the park along the northern margins. The orange “Yellow Mounds” consist of soils and (or) reworked soil that may have been associated with mixed brackish and freshwater environments.

### Tertiary Period

During the early Tertiary, the Badlands area was near sea level and brackish inland seas and lakes still existed throughout the Western Interior region. The Laramide Orogeny that began in the Late Cretaceous and continued through mid- Tertiary resulted in the rise of the Rocky Mountains, including the Black Hills (fig. 15). Forests gave way to savannah or steppes as the climate became drier (Stoffer 2003). Rivers spread sediments over vast expanses of the exposed plains. In a final phase of volcanism at the end of the Laramide Orogeny, white, airborne- volcanic ash rained down upon the region. Sand, silt, and clay, mixed and interbedded with volcanic ash, stacked up thousands of meters thick. Arid conditions existed by the close of the Tertiary.

Chamberlain Pass Formation: The Eocene Chamberlain Pass Formation crops out along an unconformable surface between the top of the Pierre Shale (Yellow Mounds) and the bottom of the Chadron Formation (Terry, Jr. and Evans 1994; Stoffer 2003). The Chamberlain Pass Formation in Badlands National Park consists of floodplain deposits that lack gravel and so is indistinguishable from the Interior paleosol.

The Interior paleosol separates the Chamberlain Pass Formation from the overlying Chadron Formation. In contrast to the Yellow Mounds paleosol, the red Interior paleosol reflects higher oxygenating conditions. The abundant fossil termite nests and other burrows found in the Interior paleosol support this interpretation.

Chadron Formation: The poorly consolidated mudrocks of the Chadron Formation are also Eocene in age (fig. 3). The strata were originally named the “*Titanotherium* beds” for the abundance of bones of *Titanotherium*, large rhinoceros- like mammals found by early investigators. The high bentonitic- clay content becomes sticky, impervious and plastic when wet and dries to a popcorn texture, making the surface an inhospitable environment for most vegetation.

The gravel and sand in the formation consist of chert, granitic rocks, and metamorphic materials that probably derived from streams draining the core and surrounding sedimentary outcrop belts of the Black Hills region. Freshwater limestone beds that occur intermittently in the lower part of the Chadron Formation contain fish and plant remains.

Bones, invertebrate remains, plant material, root traces, animal burrows, coprolites, animal tracks, fossil soils, and sedimentary deposits are typical of stream and floodplain deposits that include shallow, warm water lakes (Stoffer 2003). The fossil remains in the Chadron Formation are consistent with a forested floodplain with scattered sedge meadows, oxbow ponds, and forested upland environments.

Brule Formation: The alternating rusty- red and grayish- white strata of the Brule Formation are derived from stream and floodplain deposits that accumulated during the early part of the Oligocene Epoch. The Scenic Member records a series of reddish paleosols that formed on a broad, aggrading floodplain in which land turtles and oreodonts were common (Stoffer 2003). Tuffaceous mudstones were derived from the alteration of volcanic glass that fell onto the Great Plains as dust (Evanoff and Terry, Jr. 2004). The broadly undulatory contact at the base of the Scenic Member has as much as 24.5 m (80.4 ft) of relief, reflecting an erosional topography cut into the underlying Chadron Formation. During the time that sediment was deposited forming the Scenic Member, paleovalleys filled with light- gray sandstones that coalesced into broad blankets of fluvial deposits. These blankets of sand are capped by thin, very widespread mudstones that extend along the entire length of the Wall and are important marker beds.

The mudstone markers are paleosols and represent a temporary shift from active fluvial deposition to slow accumulation and weathering of volcanic dust. The mudstones are similar to modern Alfisols, mineral soils developed under forests in temperate, humid climates. The paleosols that formed between individual marker beds are thinner, less well developed, and are similar to modern Entisols, and Inceptisols, mineral soils that are not well developed and are characterized by relatively non- distinct layers (Evanoff and Terry, Jr. 2004).

The shift from mudstone beds to thick siltstone beds marks the contact between the Scenic Member and the overlying Poleslide Member. Reworked eolian volcaniclastics and occasional fluvial channel and overbank deposits record a change from wet, subhumid conditions where the volcaniclastic dust was weathered, to drier semiarid conditions where the dust accumulated. (Evanoff and Terry, Jr. 2004; Terry, Jr. and Kosmidis 2004). Retallack (1983) documented 31 paleosols in the Poleslide Member, these define periods of landscape stability during which eolian input was reduced.

Larger stream channels developed as conditions became drier in the mid to late Oligocene. Continuous streams became more ephemeral, and episodic flood events replaced deposition by perennial streams. Many species adapted to open plain environments and became more dependent on water holes for survival.

One of these watering holes may have been a lake that formed in the Badlands region. The lake contained charophytes (green algae), aquatic snails, stromatolites, and fish and covered several hundred square meters (Terry, Jr. and Kosmidis 2004). The paleoclimatic interpretation of associated paleosols suggest that the lake was probably spring fed.

Sharps Formation: The overall change in geologic and environmental conditions that began 28 to 26 Ma is reflected in the Sharps Formation (Stoffer 2003). During the time of deposition of the Sharps Formation, the region became even drier. The Badlands region was episodically blanketed by voluminous ash- fall deposits associated with tremendous ignimbrite- type volcanic eruptions in the Great Basin region. The tuffaceous sandstones, stream channel sands, and floodplain muds are typical of steppe or even desert- like conditions.

The region that is now the White River Badlands supported many kinds of animals during the Oligocene Epoch approximately 34 to 23 million years ago. The land was lush, well watered, and warmer than it is now. Animals roamed the floodplains and were sometimes trapped in floods and quickly buried in river sediments. Preservation was excellent so that the Oligocene beds in Badland National Park are one of the world's most prized vertebrate fossil sites.

Medicine Root Gravel: The Medicine Root Gravel that caps the highest upland areas in the Pinnacles Overlook area is the youngest Tertiary- age sedimentary deposit in Badlands National Park (Stoffer 2003). The gravels are stream terrace deposits that probably were originally derived from fast- flowing streams draining the core of the Black Hills about 2 Ma. During dryer periods of the Pleistocene, eolian dust deposits accumulated on top of the gravel deposits.

### Quaternary Period

Although the Badlands National Park region was not directly impacted by continental glaciation during the Pleistocene, the continental glaciers impacted the landscape because of their influence on regional river systems (fig. 16). Before the Pleistocene Ice Age, western interior rivers flowed north into the Hudson Bay region. As continental ice sheets blocked the north- flowing rivers, large lakes formed along the ice front. Eventually the water breached the divides and modern river systems evolved with the Missouri and Ohio Rivers merging with the Mississippi River system. In general, the Missouri River follows the southwestern boundary of the last major glaciation.

Prior to glaciation, the north- flowing rivers probably had a gentler stream gradient than that of the Missouri River when it formed along the southern ice front. The Missouri River has carved a gorge about 91 m (300 ft) deep for most of its length across the western interior region, and this downcutting has been gradually translating upstream into the headwaters of all its tributaries. This downcutting is producing the relief seen in the badlands region (Stoffer 2003).

The rate of downcutting has not been equal across the region. The Cheyenne River captured all the major streams draining from the Black Hills region, as evidenced by the dry, low divides between the White River and Cheyenne River valleys throughout the western part of the park.

Through the Quaternary, the Cheyenne, White, and Bad Rivers and their tributaries have gradually carved into the plateau that includes Badlands National Park. Stream capture and erosion have created a landscape of mesas and rock pinnacles. Erosion has gradually carved back the bounding escarpments or "walls" of this plateau.

Today's badlands landscape reflects factors and conditions related to the physical character of the rocks as well as climate. The volcanic ash at Badlands National Park is easily eroded and succumbs quickly to erosion as the Wall retreats northward into the upper plain, which is the original land surface (fig. 8). As the ash is eroded, the more durable underlying beds of the Brule Formation are exposed. Slender spires, knife- sharp ridges, and intricately creased slopes of Badlands National Park result from the erosion of the steeper slopes (fig. 8). The softer mudstone of the Chadron Formation forms more rounded ridges and spurs and gentler slopes than the Brule Formation.

Like the character of the bedrock, climate is an important factor with regard to weathering and erosion processes. The combination of high summer temperatures, short intense rain events, and dry, cold winters make growing conditions difficult for most vegetation. The harsh, soil- free conditions around the badlands also limit growth.

Heavy rainfall from thunderstorms flows as sheet wash across the barren land surface, forming rills and rivulets, and eventually flows into stream channels. Sediment, loosened by the heavy rainfall, washes into streams. Mass wasting, such as slumping and rock falls, contributes sediment directly to stream channels. With erosion rates in the barren terrain as much as 2.54 cm (1.00 in) of sediment per year, the landscape of Badlands National Park is constantly changing.

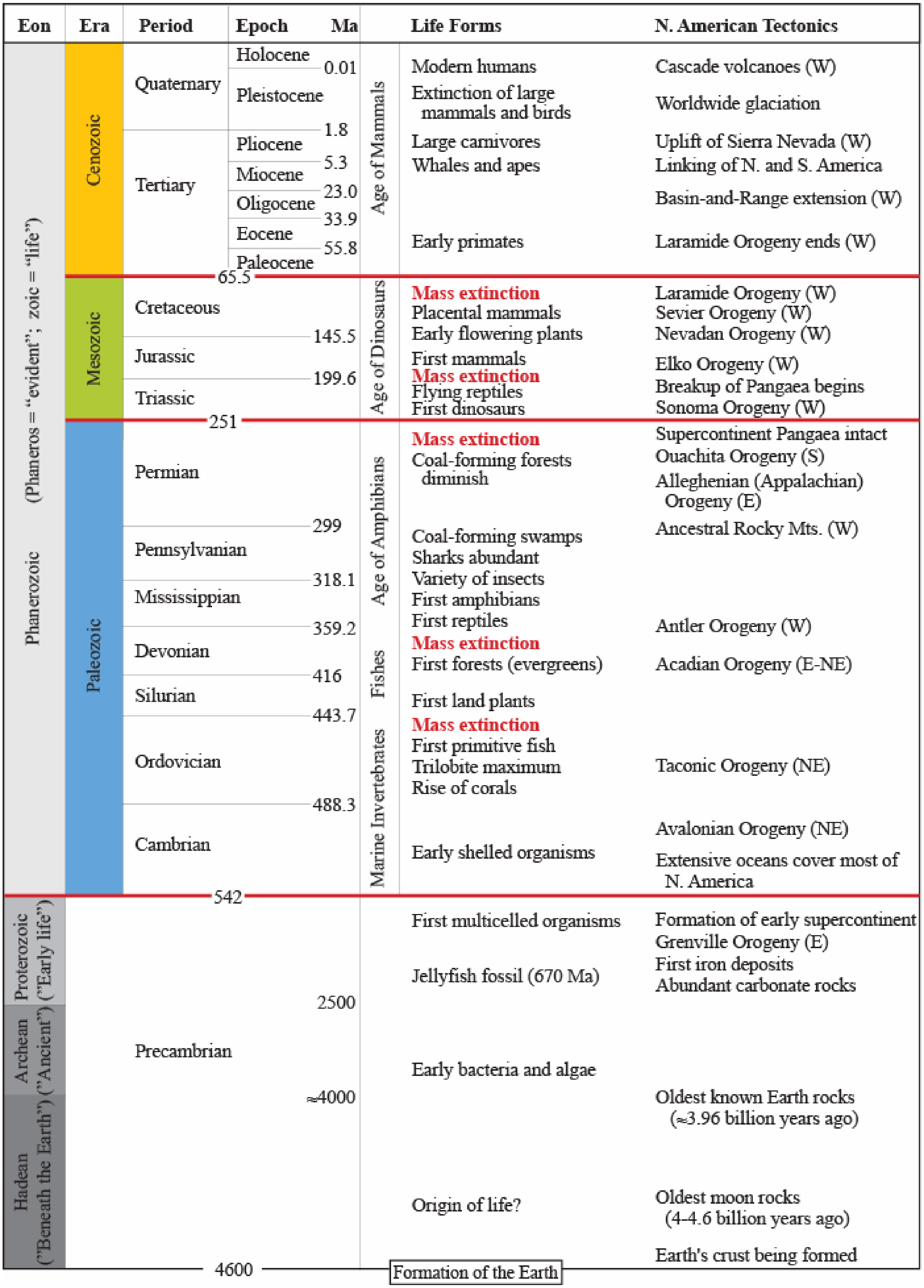


**Figure 11. Geologic time scale adapted from the U.S. Geological Survey and International Commission on Stratigraphy. Absolute ages shown are in millions of years (Ma). Red lines indicate major unconformities between eras. Included are major events in life history and tectonic events occurring on the North American continent. Strata exposed at Badlands National Park include only the latest approximately 75 million years of Earth history.**

**Figure 12. Paleogeographic map of the North American continent during the Late Devonian, approximately 360 Ma. Shallow seas (light blue) cover the Badlands National Park region. Subaerial topography is shown in shades of brown. Map courtesy of Dr. Ron Blakey, Northern Arizona University, available at http://jan.ucc.nau.edu/~rcb7/namD360.jpg (accessed August 21, 2007).**

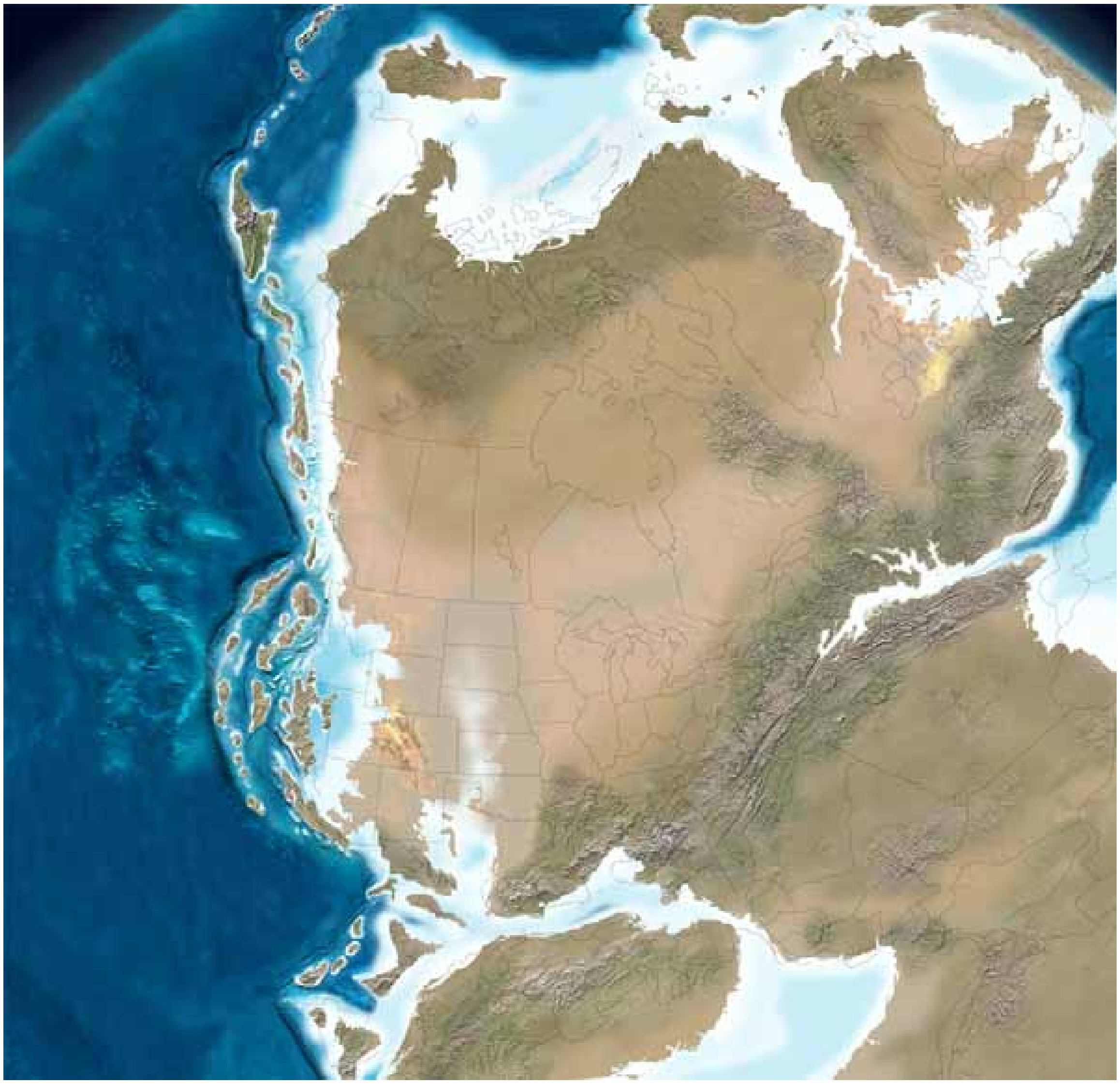

**Figure 13. Paleogeographic map of the North American continent during the Late Permian, approximately 260 Ma. Streams transported sediments eroded from the Ancestral Rocky Mountains in Colorado into the Badlands National Park area where the final remnants of a shallow sea were disappearing. To the east, the plate tectonic collision of the African plate with North America resulted in the Alleghenian Orogeny. Map courtesy of Dr. Ron Blakey, Northern Arizona University, available at http://jan.ucc.nau.edu/~rcb7/namP260.jpg (accessed August 18, 2007).**

**Figure 14. Paleogeographic map of the North American continent during the Late Cretaceous, approximately 85 Ma. The Western Interior Seaway covers the Badlands National Park region. The mountain belt that stretches from Alaska to Mexico is a result of the Sevier Orogeny. Map courtesy of Dr. Ron Blakey, Northern Arizona University, available at http://jan.ucc.nau.edu/~rcb7/namK85.jpg (accessed August 21, 2007).**

**Figure 15. Paleogeographic map of the North American continent during the Eocene Epoch of the Tertiary Period, approximately 40 Ma. Mountains in Colorado and Wyoming are the result of the Laramide Orogeny. Sediments eroded from these mountain ranges were deposited in the Badlands National Park area to form the Chamberlain Pass Formation. Map courtesy of Dr. Ron Blakey, Northern Arizona University, available at http://jan.ucc.nau.edu/~rcb7/namPe40.jpg (accessed August 20, 2007).**

**Figure 16. Paleogeographic map of the North American continent during the Pleistocene Epoch of the Quaternary Period, approximately 0.126 Ma. The continental ice sheet does not impact the Badlands National Park region, but surface water from the Black Hills flows from west to east across western South Dakota. Map courtesy of Dr. Ron Blakey, Northern Arizona University, available at http://jan.ucc.nau.edu/~rcb7/namQ.jpg (accessed August 21, 2007).**

# 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.*

**aggradation (geomorph)**. The building- up of the Earth's surface by deposition, specifically by a stream in order to establish or maintain uniformity of grade or slope.

**alluvium.** Stream deposited sediment that is generally rounded, sorted, and stratified.

**angular unconformity.** An unconformity where the strata above and below are oriented differently; generally caused by structural deformation and erosion of the lower units prior to deposition of the beds above the unconformity.

**anticline.** A fold, generally convex upward, whose core contains the stratigraphically older rocks.

**ash (volcanic).** Fine pyroclastic material ejected from a volcano (also see tuff).

**basement.** The undifferentiated rocks, commonly igneous and metamorphic, that underlie the rocks of interest.

**basin (structural).** A doubly- plunging syncline in which rocks dip inward from all sides (also see dome).

**basin (sedimentary).** Any depression, from continental to local scales, into which sediments are deposited.

**bed.** The smallest sedimentary strata unit, commonly ranging in thickness from one centimeter to a meter or two and distinguishable from beds above.

**bedding.** Depositional layering or stratification of sediments.

**calcareous.** A rock or sediment containing calcium carbonate.

**chalcedony.** A cryptocrystalline variety of quartz.

chondrichthian. Of or relating to vertebrates, especially fish, that have skeletons of cartilage rather than bone.

**clastic.** Rock or sediment made of fragments or pre-existing rocks.

**clastic dike.** A sedimentary dike consisting of a variety of clastic materials derived from underlying or overlying beds.

**clay.** Clay minerals or sedimentary fragments the size of clay minerals (<2 cm).

**craton.** The relatively old and geologically stable interior of a continent (also see continental shield).

**cross-bedding.** Uniform to highly- varied sets of inclined sedimentary beds deposited by wind or water that indicate distinctive flow conditions.

**crust.** The outermost compositional shell of Earth, 10- 40 km (6- 25 mi) thick, consisting predominantly of relatively low- density silicate minerals (also see oceanic crust and continental crust).

**deformation**. A general term for the process of faulting, folding, shearing, extension, or compression of rocks as a result of various Earth forces.

**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.

**eolian.** Formed, eroded, or deposited by or related to the action of the wind.

**epoch.** A geochronologic unit that is longer than a stage but shorter than a period; Paleocene, Eocene, and Oligocene are epochs.

**eustatic.** Relates to simultaneous worldwide rise or fall of sea level in Earth's oceans.

**facies (sedimentary).** The depositional or environmental conditions reflected in the sedimentary structures, textures, mineralogy, fossils, etc. of a sedimentary rock.

**fault.** A subplanar break in rock along which relative movement occurs between the two sides.

**flame structure.** Wave- or flame- shaped plumes of mud preserved in sediment; probably formed by load-casting of mud squeezed upward into an overlying layer.

**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, fault)

**frost wedging.** The breakup of rock due to the expansion of water freezing in fractures.

**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.

**ichnofacies.** A sedimentary facies characterized by a particular type of tracr fossil.

**ichnofossil.** A trace fossil.

**igneous.** Refers to a rock or mineral that originated from molten material; one of the three main classes or rocks: igneous, metamorphic, and sedimentary.

**ignimbrite.** A pyroclastic flow deposit; welded tuff.

**joint.** A semi- planar break in rock without relative movement of rocks on either side of the fracture surface.

**karst topography**. Topography characterized by abundant sinkholes and caverns formed by the dissolution of calcareous rocks.

**Lamniformes.** An order of sharks, also known as mackerel sharks, that includes familiar species of sharks, such as the great white, mako, and thresher sharks.

**landslide.** Any process or landform resulting from rapid mass movement under relatively dry conditions.

**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, generally of glacial origin.
**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.
**metamorphic.** Pertaining to the process of metamorphism or to its results.
**normal fault.** A dip- slip fault in which the hanging wall moves down relative to the footwall.
**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.
**overbank deposits.** Alluvium deposited outside a stream channel during flooding.
**paleogeography**. The study, description, and reconstruction of the physical geography from past geologic periods.
**paleontology.** The study of the life and chronology of Earth's geologic past based on the phylogeny of fossil organisms.
**Pangaea (also spelled Pangea).** A theoretical, single supercontinent that existed during the Permian and Triassic Periods (see Laurasia and Gondwana).
**pebble.** Generally, small, rounded, rock particles from 4 to 64 mm in diameter.
**pedogenic.** Pertaining to soil formation.
**plateau.** A broad, flat- topped topographic high of great extent and elevation above the surrounding plains, canyons, or valleys (both land and marine landforms).
**plate tectonics.** The theory that the lithosphere is broken up into a series of rigid plates that move over Earth's surface above a more fluid asthenosphere.
**pseudokarst:** A karst- like terrain having closed depressions, sinking streams, and caves, but produced by a process other than the dissolving of rock.
**reverse fault.** A contractional, high angle (>45°), dip- slip fault in which the hanging wall moves up relative to the footwall (also see thrust fault).
**sandstone**. Clastic sedimentary rock of predominantly sand- sized grains.
**scarp.** A steep cliff or topographic step resulting from vertical displacement on a fault or by mass movement.
**scaphitid ammonite.** An ammonite with an unusual coiling pattern that begins in a tight coil, then straightens out, and finally coils back towards the initial coil.
**sediment.** An eroded and deposited, unconsolidated accumulation of lithic and mineral fragments.
**sedimentary rock.** A consolidated and lithified rock consisting of detrital and/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.
**strata.** Tabular or sheet- like masses or distinct layers (e.g., of rock).
**stratigraphy.** The geologic study of the origin, occurrence, distribution, classification, correlation, age, etc. of rock layers, especially sedimentary rocks.
**stream piracy.** The process by which active headward stream erosion breaches a drainage divide and intercepts part of an adjacent drainage basin.
**strike.** The compass direction of the line of intersection that an inclined surface makes with a horizontal plane.
**subsidence.** The gradual sinking or depression of part of Earth's surface.
**taphonomy.** The branch of paleoecology dealing with all processes that occur after the death of an organism until its discovery.
**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 flood plain(s), stream bed(s), and/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 fossil.** Sedimentary structure, such as tracks, trails, burrows, etc., that preserve evidence of an organism's life activities, rather than the organism itself.
**trend.** The direction or azimuth of elongation or a linear geological feature.
**tuff.** Generally fine- grained, igneous rock formed of consolidated volcanic ash.
**type locality.** The geographic location where a stratigraphic unit is well displayed, is formally defined as a typical section, and derives its name.
**unconformity.** A surface within sedimentary strata that marks a prolonged period of nondeposition or erosion.
**uplift.** A structurally high area in the crust, produced by 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.
**yardang**. A long, irregular, sharp- crested, undercut ridge between two round- bottomed troughs, carved on a plateau or unsheltered plain in a desert region by wind erosion, and consisting of soft but coherent deposits.

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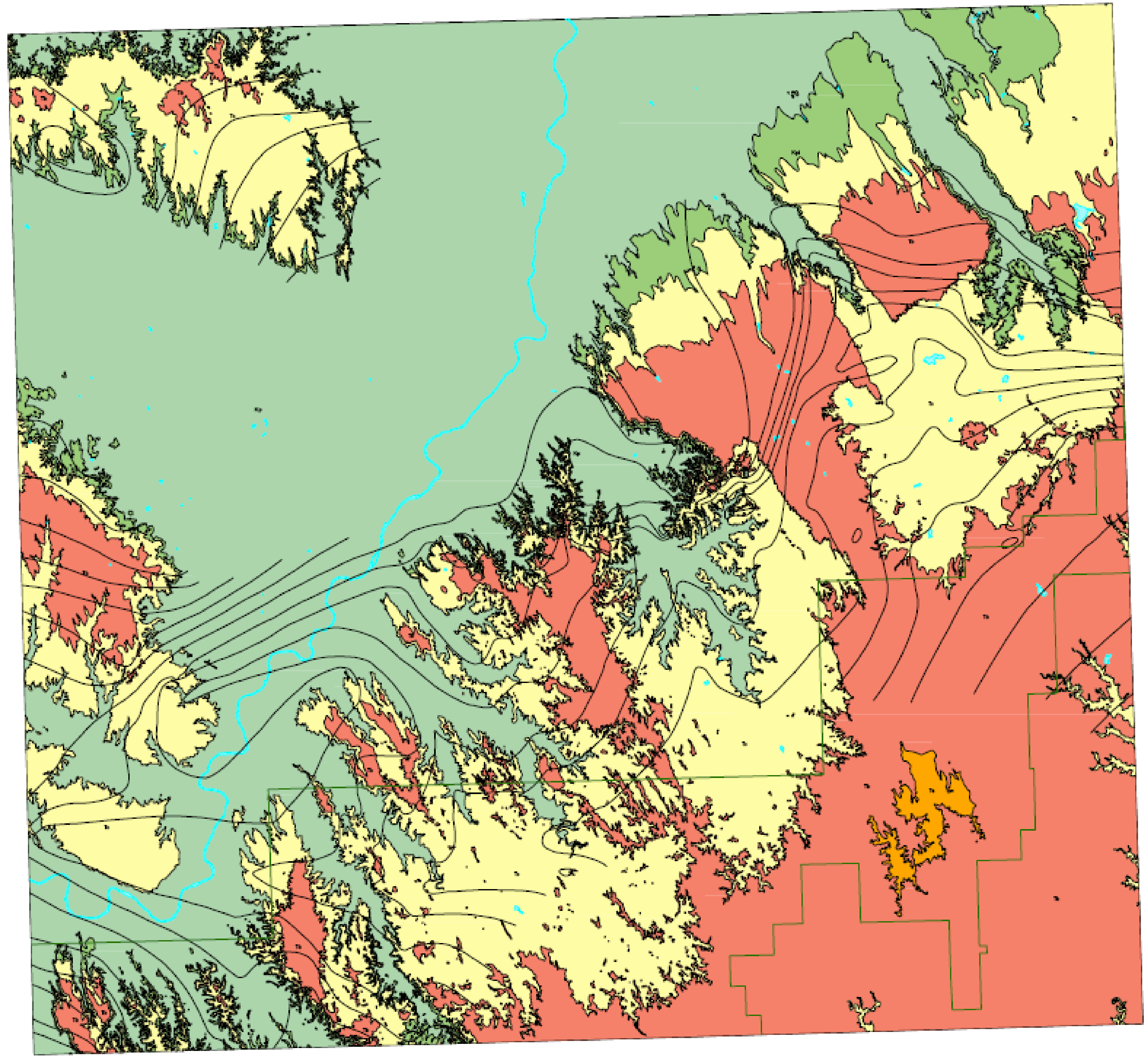
# Appendix A: Geologic Map Graphic

*The following pages are a preview or snapshot of the geologic maps for Badlands National Park. For poster- size PDFs of these maps or for digital geologic map data, please see the included CD or visit the Geologic Resource Evaluation publications Web page (http://www2.nature.nps.gov/geology/inventory/gre_publications).*

# Geologic Map of Badlands National Park - Scenic Area



**Badlands National Park Boundary**

**Structure Contour Lines**

- base of Chadron Formation (Tc), known or certain

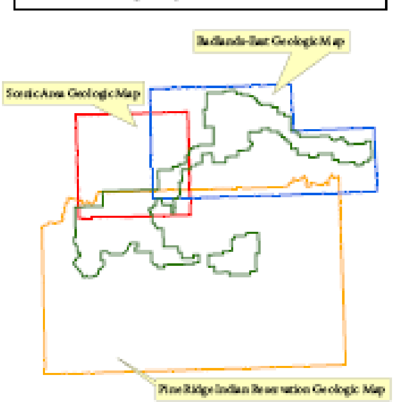
**Geologic Contacts**

- known or certain
- quadrangle/map boundary
- shoreline

**Geologic Units**

- Ts - Sharps Formation of Harksen
- Tb - Brule Formation
- Tc - Chadron Formation
- Kpi - Pierre Shale, Interior Beds
- Kp - Pierre Shale
- Water

**Index of Geologic Maps for Badlands National Park**




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:

King, R. U., and Raymond, W. H., 1971, Geologic map of the Scenic area, Pennington, Shannon, and Custer Counties, South Dakota: U.S. Geological Survey Miscellaneous Investigations Map I-662, scale 1:24,000.

Digital geologic data and cross sections for Badlands 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/

0 2 4 8 Kilometers

0 1 2 4 Miles

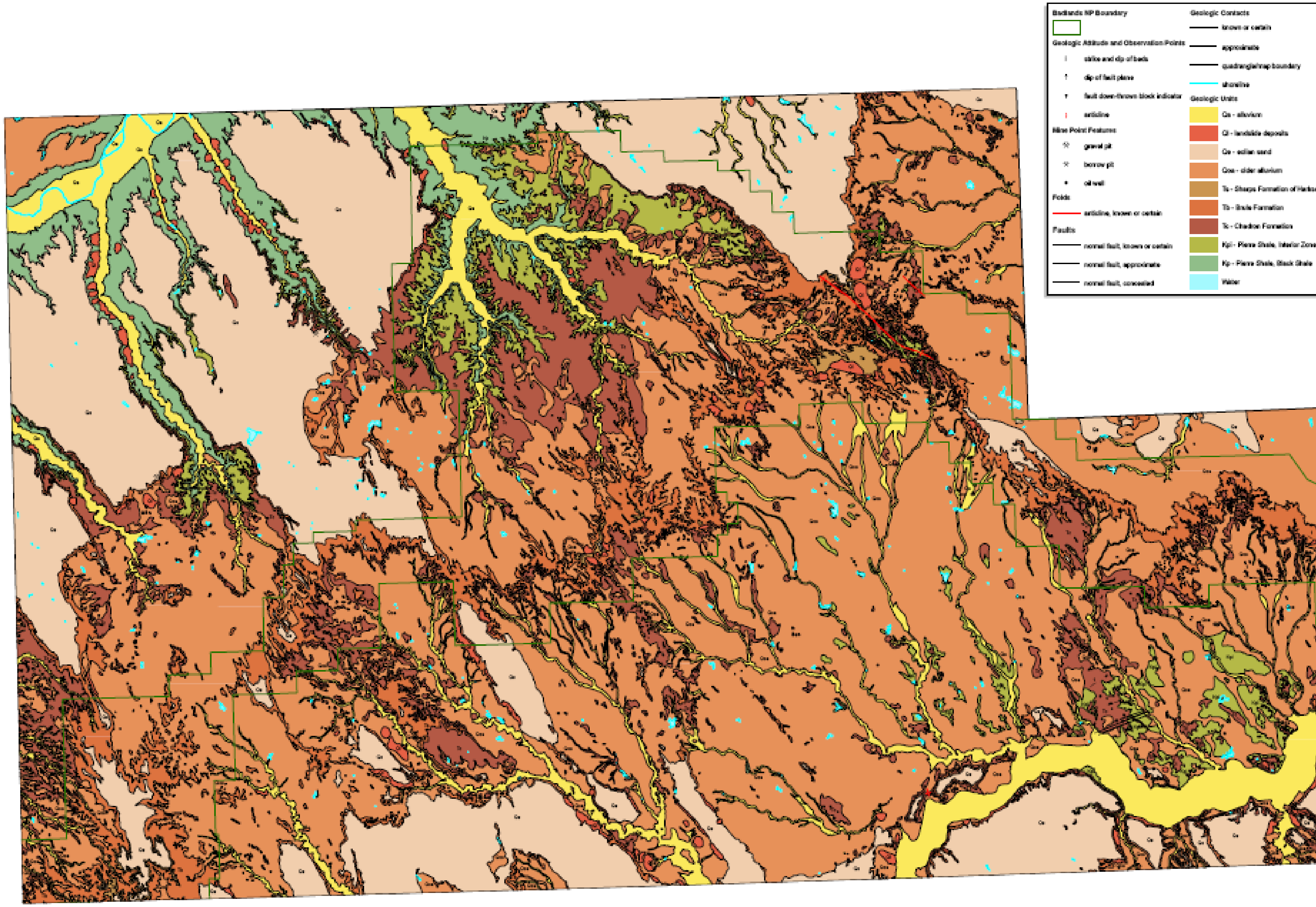
Produced by Geologic Resources Division

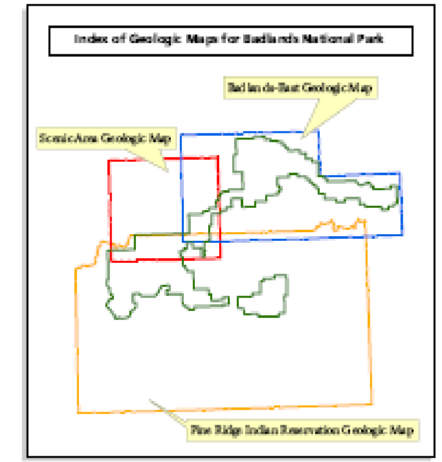
June 2008

Badlands National Park
South Dakota

National Park Service
U.S. Department of the Interior

# Geologic Map of Badlands National Park - East




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:

Raymond, W.H. and King, R.U., 1976, Geologic map of Badlands National Park and Vicinity, West-Central South Dakota U.S. Geological Survey Miscellaneous Investigations Map I-934, scale 1:62,500.

Digital geologic data and cross sections for Badlands 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/

0 4 8 16 Kilometers

0 2 4 8 Miles

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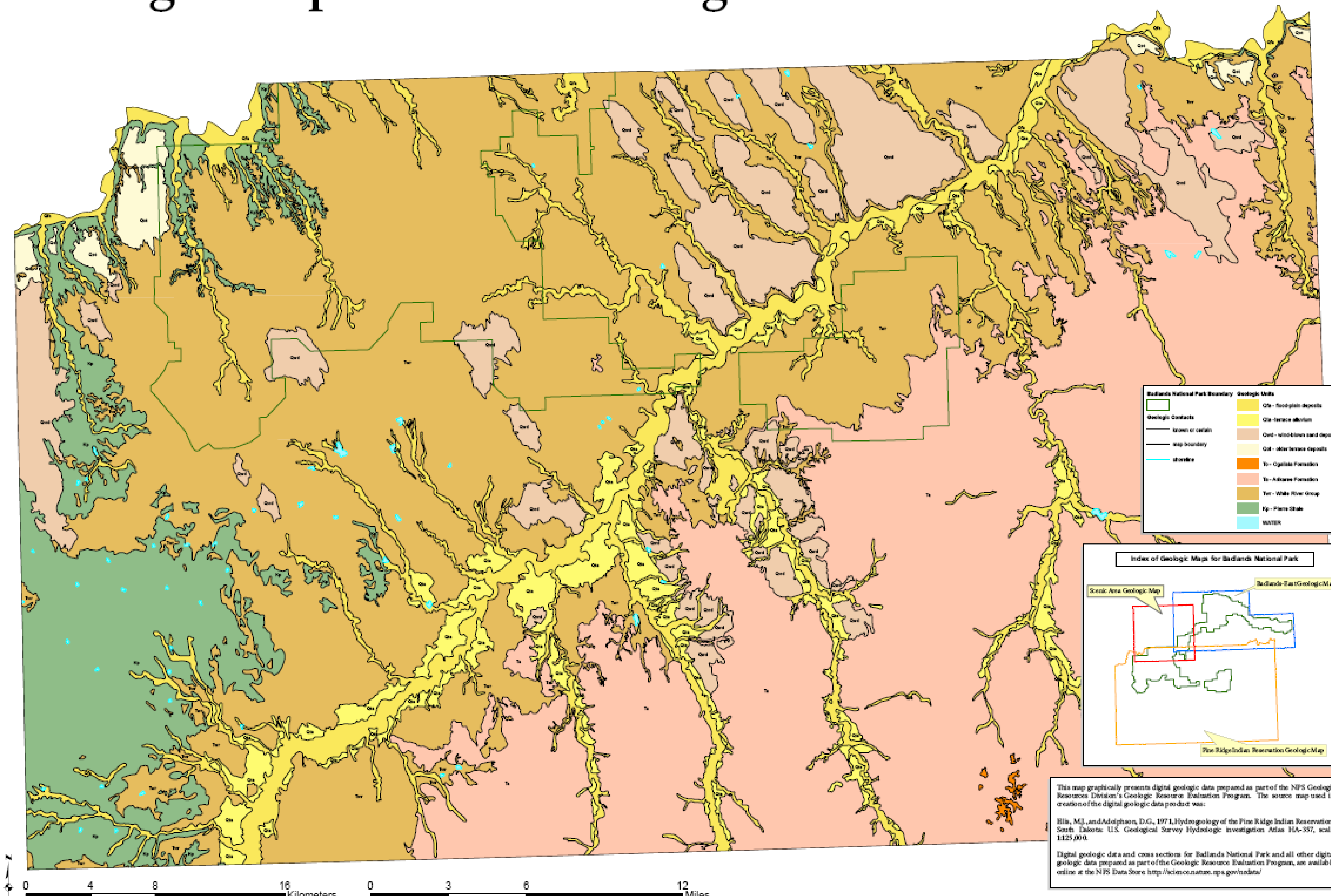
National Park Service
U.S. Department of the Interior

# Geologic Map of the Pine Ridge Indian Reservation

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Digital geologic data and cross sections for Badlands 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/

Produced by Geologic Resources Division

June 2008

# Badlands National Park

*Geologic Resource Evaluation Report*

Natural Resource Report NPS/NRPC/GRD/NRR—2008/036
NPS D-155, June 2008

## National Park Service

*Director* • Mary A. Bomar

## Natural Resource Stewardship and Science

*Acting Associate Director* • Mary Foley, Chief Scientist of the Northeast Region

## Natural Resource Program Center

The Natural Resource Program Center (NRPC) is the core of the NPS Natural Resource Stewardship and Science Directorate. The Center Director is located in Fort Collins, with staff located principally in Lakewood and Fort Collins, Colorado and in Washington, D.C. The NRPC has five divisions: Air Resources Division, Biological Resource Management Division, Environmental Quality Division, Geologic Resources Division, and Water Resources Division. NRPC also includes three offices: The Office of Education and Outreach, the Office of Inventory, Monitoring and Evaluation, and the Office of Natural Resource Information Systems. In addition, Natural Resource Web Management and Partnership Coordination are cross- cutting disciplines under the Center Director. The multidisciplinary staff of NRPC is dedicated to resolving park resource management challenges originating in and outside units of the national park system.

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