National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science

Bighorn Canyon National Recreation Area

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2011/447

ON THE COVER
Exposed rocks within Bighorn Canyon National Recreation Area near Bull Elk Canyon.
Photograph courtesy of David Lopez (geologist/consultant).

THIS PAGE
The sediment-laden Bighorn River winds its way through Bighorn Canyon.
National Park Service photograph by Tim Connors (NPS Geologic Resources Division).

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National Park Service
Geologic Resources Division
PO Box 25287
Denver, CO 80225

September 2011

U.S. Department of the Interior
National Park Service
Natural Resource Stewardship and Science
Fort Collins, Colorado

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Please cite this publication as:

KellerLynn, K. 2011. Bighorn Canyon National Recreation Area: geologic resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2011/447. National Park Service, Fort Collins, Colorado, USA.

NPS 617/110188, September 2011

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Executive Summary

This report accompanies the digital geologic map data for Bighorn Canyon National Recreation Area in Montana and Wyoming, produced by the Geologic Resources Division in collaboration with its partners. It contains information relevant to resource management and scientific research. This document incorporates preexisting geologic information and does not include new data or additional fieldwork by the Geologic Resources Division.

Following the completion of the Yellowtail Dam by the Bureau of Reclamation in 1965, an act of Congress established Bighorn Canyon National Recreation Area on October 15, 1966. The creation of the dam provided hydroelectric power, flood control, irrigation waters, and many opportunities for recreation.

Yellowtail Dam harnessed the waters of the Bighorn River and turned what was a variable stream into a lake that extends approximately 114 km (71 mi) from near Lovell, Wyoming, to Fort Smith, Montana. At full pool, Bighorn Lake covers nearly 7,000 ha (17,300 ac) (U.S. Geological Survey 1993). The entire national recreation area encompasses 48,564 ha (120,296 ac), straddling the Wyoming-Montana border.

The Bighorn River flows north from the Bighorn Mountains, which spread northward from the plains and Great Basin area of Wyoming into south-central Montana. The river meanders across alluvium (basin fill) for much of its length, but occasionally becomes restricted in deep gorges, such as Bighorn Canyon, that were incised into the uplifted northern Bighorn Mountains. The Pryor Mountains rise immediately to the west and north of the national recreation area. The Bighorn and Pryor mountains are the easternmost extension of the Rocky Mountains in this region.

The NPS Geologic Resources Division held a Geologic Resources Evaluation, now Geologic Resources Inventory (GRI), scoping meeting for Bighorn Canyon National Recreation Area on May 18–19, 2005. This GRI report is written for resource managers, to assist in resource management and science-based decision making, but it may also be useful for interpretation. This report expands upon the scoping summary, National Park Service (2005), and ties geologic issues, features, and processes to the digital geologic map for the national recreation area (see "Geologic Map Data" and Attachment 1). In the "Geologic Map Data" section, an overview graphic illustrates the geologic data, and a map unit properties table summarizes the main features, characteristics, and potential management issues for all the rock units on the digital geologic map.

Geologic issues of particular significance for resource management at Bighorn Canyon National Recreation Area include the following:

- Sedimentation. Bighorn Lake is "silting up," most notably at Horseshoe Bend. This is the highest priority geologic issue at the national recreation area.
- Mineral Resources and Mining. Bentonite, uranium, limestone, gravel, and sand are the significant mineral resources within the national recreation area. Dryhead Agate, though not mined commercially, is collected for lapidary purposes in the area.
- Abandoned Mineral Lands (AML). Exploration for uranium in the 1950s resulted in 378 pits within 13 AML sites and features the national recreation area. These sites primarily consist of grooves and mounds of dirt excavated by bulldozers. Ongoing restoration of these sites began in 1983, with the most highly visible reclaimed first.
- Other Disturbed Lands. Abandoned access roads are associated with past land uses, such as mining and ranching activities, and are a significant disturbance on the landscape. Present-day cattle trailing and wild-horse grazing impact vegetation and fragile soil crusts, leaving bare areas susceptible to wind and sheetwash erosion.
- Mass Wasting. Steep slopes, as great as 70%, and fluctuating water levels of Bighorn Lake result in mass-wasting processes and features such as landslides, slumps, and rockfall within the national recreation area. A particular area of concern for mass wasting is Bull Elk Basin.
- Flooding. Flooding, particularly flash flooding in small drainages, results from severe convective storms and causes debris flows at the national recreation area.
- Frost Heaving and Shrink-Swell Potential (of Bentonite). The potential for frost heaving in certain soil types at the national recreation area is a limiting factor for development. Soils at the national recreation area have a moderate shrink-swell potential, which is a limiting factor for the construction of foundations and roads.

This report also provides a geologic history that places the rock units in a geologic context and describes the events leading to the national recreation area's present-day landscape. The geologic features preserved in the national recreation area came about through a series of geologic events that include the following: marine deposition of sediments, in an ocean off the western edge of the North American continent, and later in a sea that stretched north and south across the continent; uplift and deformation during a major period of mountain building; two periods of cave formation; and a long saga of erosion. The "Geologic Features and Processes" section of this report highlights the following:

- Bighorn Lake and Yellowtail Dam. Bighorn Lake is the primary resource at the national recreation area, but its creation as a result of Yellowtail Dam has caused and is causing numerous geomorphic impacts, including the loss of side channels downstream (north) of Yellowtail Dam.
- Fluvial Features and Processes. Segments of both the Bighorn and Shoshone rivers flow within Bighorn Canyon National Recreation Area. In addition, the extreme lower reaches of numerous small streams flow into Bighorn Lake from both the east and the west. The transport of sediment is a significant fluvial process.
- Superimposed, Entrenched, Abandoned Meanders. The stream meanders that cut into the bedrock at Bighorn Canyon National Recreation Area create dramatic scenery that records a history of past erosion during Rocky Mountain uplift.
- Terraces. The well-preserved terraces along the Bighorn, Shoshone, and other rivers in the Bighorn Canyon region provide evidence of the dynamic nature of both fluvial and tectonic processes over the past 2 million years.
- Seeps and Springs. Seeps and springs supply the national recreation area's domestic water. These significant features also have an ecological importance disproportionate to their limited spatial extent. The primary impact to seeps and springs is from livestock.
- Eolian Features and Processes. Strong winds, which can be expected throughout the year, create blowout areas and blowing sand. Eolian processes may impact visitation, for example camping, in open, windy areas. The eolian transport of gypsum is significant for soil formation in the area, and eolian deposits are significant indicators of past climatic conditions.
- Structural and Tectonic Features and Processes. Uplift of thick deposits of marine sedimentary layers creates scenic rock exposures at the national recreation area, including offset strata in faults and a massive anticline.
- Caves and Karst. The National Park Service oversees management of Bighorn Caverns, the largest cave in Montana, which occurs in the limestone of the Madison Group (map unit symbol Mm). Many known caves exist in Madison Group (Mm), which is exposed in the cliffs above Bighorn Lake. Based on the number of caves in the vicinity of the national recreation area, the potential is high for the discovery of additional caves within the national recreation area.
- Paleokarst. Evidence of ancient karst is present in the walls of Bighorn Canyon. The karst surface is marked by sinkholes and caves associated with dissolution of limestone of the Madison Group (Mm). The paleokarst surface is covered and filled by the Amsden Formation (PNMa), which characteristically produces pink staining on the underlying cliffs of the Madison Group.
- Paleontological Resources. The bedrock within Bighorn Canyon National Recreation Area hosts Paleozoic and Mesozoic invertebrate fossils from an extensive record of marine ecosystems that characterize the region. Much younger fossils—mammals from the Quaternary Period—are known from cave sediments and alluvial terrace deposits.

This report also provides a glossary, which contains explanations of technical, geologic terms, including terms on the map unit properties table. Additionally, a geologic timescale shows the chronologic arrangement of major geologic events, with the oldest events and time units at the bottom and the youngest at the top. The timescale is organized using formally accepted geologic-time subdivisions and ages (see fig. 15).

Acknowledgements

The Geologic Resources Inventory (GRI) is one of 12 inventories funded by the National Park Service Inventory and Monitoring Program. The GRI is administered by the Geologic Resources Division of the Natural Resource Stewardship and Science Directorate.

The Geologic Resources Division relies heavily on partnerships with institutions such as the U.S. Geological Survey, Colorado State University, state geologic surveys, local museums, and universities in developing GRI products.

GRI staff would like to thank David Lopez (geologist/independent consultant) for providing text used in the "Superimposed, Entrenched, Abandoned Meanders" section, as well as Dale Pate (Carlsbad Caverns National Park/NPS Geologic Resources Division) and Andrea Croskrey (NPS Geologic Resources Division) for providing feedback on the "Cave and Karst" section of this report. Marith Reheis (U.S. Geological Survey) provided information regarding paleontological resources within the park. Kirk Johnson (Denver Museum of Nature and Science) followed up regarding potential investigation of paleokarst features.

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Introduction

The following section briefly describes the National Park Service Geologic Resources Inventory and the regional geologic setting of Bighorn Canyon National Recreation Area.

Purpose of the Geologic Resources Inventory

The Geologic Resources Inventory (GRI) is one of 12 inventories funded by the National Park Service (NPS) Inventory and Monitoring Program. The GRI, administered by the Geologic Resources Division of the Natural Resource Stewardship and Science Directorate, is designed to provide and enhance baseline information available to park managers. The GRI team relies heavily on partnerships with institutions such as the U.S. Geological Survey, Colorado State University, state geologic surveys, local museums, and universities in developing GRI products.

The goals of the GRI are to increase understanding of the geologic processes at work in parks and to provide sound geologic information for use in park decision making. Sound park stewardship requires an understanding of the natural resources and their role in the ecosystem. Park ecosystems are fundamentally shaped by geology. 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 these goals, the GRI team is systematically conducting a scoping meeting for each of the 270 identified natural area parks and providing a park-specific digital geologic map and geologic report. These products support the stewardship of park resources and are designed for nongeoscientists. Scoping meetings bring together park staff and geologic experts to review available geologic maps and discuss specific geologic issues, features, and processes.

The GRI mapping team converts the geologic maps identified for park use at the scoping meeting into digital geologic data in accordance with their Geographic Information Systems (GIS) Data Model. These digital data sets bring an interactive dimension to traditional paper maps. The digital data sets provide geologic data for use in park GIS and facilitate the incorporation of geologic considerations into a wide range of resource management applications. The newest maps contain interactive help files. This geologic report assists park managers in the use of the map and provides an overview of park geology and geologic resource management issues.

For additional information regarding the content of this report and current GRI contact information please refer to the Geologic Resources Inventory website (http://www.nature.nps.gov/geology/inventory/).

Regional Information

Created by the construction of Yellowtail Dam, Bighorn Lake is the main resource of Bighorn Canyon National Recreation Area (fig. 1). As such, the primary purpose of the national recreation area is recreational, with boating, water skiing, fishing, and swimming as popular activities. Bighorn Lake is situated within a deep canyon surrounded by a landscape of broad valleys and flat uplands. To the east and west, the land rises to the Bighorn and Pryor mountain ranges, respectively. These areas also offer varied recreational opportunities, including hiking, sightseeing, and camping.

Formed by the forces of stream erosion and mountain uplift, much of Bighorn Canyon is narrow, with sheer limestone walls that rise directly above Bighorn Lake. Side canyons branch off from the main canyon. The depth of Bighorn Canyon is approximately 305 m (1,000 ft) at Devil Canyon and 760 m (2,500 ft) on Bull Elk Ridge. Such depths expose a significant section of the area's rock record (figs. 2 and 3). The canyon passes through rocks as old as the Cambrian Period (542 million to 488 million years ago), although exposed rocks from the Mississippian Period (359 million to 318 million year old) are most common. Ancient rocks from the Archean Eon (4 billion to 2.5 billion years ago) are also exposed in the national recreation area, at the base of the Pryor Mountains to the west.

In addition to the 114-km- (71-mi-) long Bighorn Lake, the National Park Service is the steward of 27,718 ha (68,491 ac) of federal land. Geographically situated on the Montana-Wyoming border and adjacent to Crow tribal land, the national recreation area cooperates with two state governments, the Crow tribal government, and many federal entities. For example, the Bureau of Land Management manages the Pryor Mountain Wild Horse Range, which covers a portion of the national recreation area. The State of Wyoming Game and Fish Commission administers the Yellowtail Wildlife Habitat, which overlaps with the management unit in the southern part of the national recreation area. The Bureau of Reclamation manages the operation of the Yellowtail Dam.

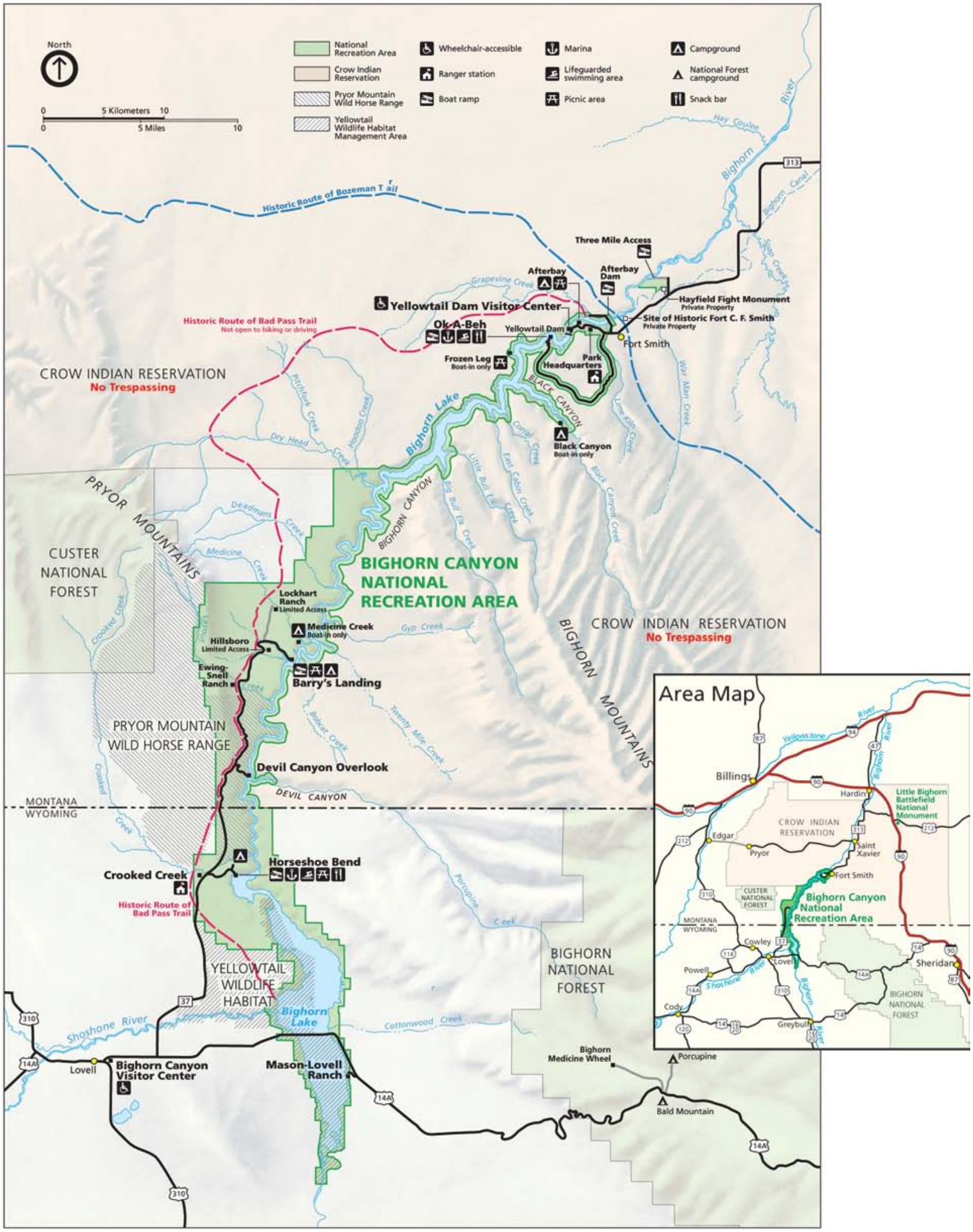


Figure 1. Location map of Bighorn Canyon National Recreation Area. Bighorn Canyon National Recreation Area is in southeastern Montana and north-central Wyoming. It encompasses 48,684 ha (120,296 ac). Bighorn Lake, which is 114 km (71 mi) long, was created by the Yellowtail Dam at the northern end of Bighorn Canyon. National Park Service graphics.

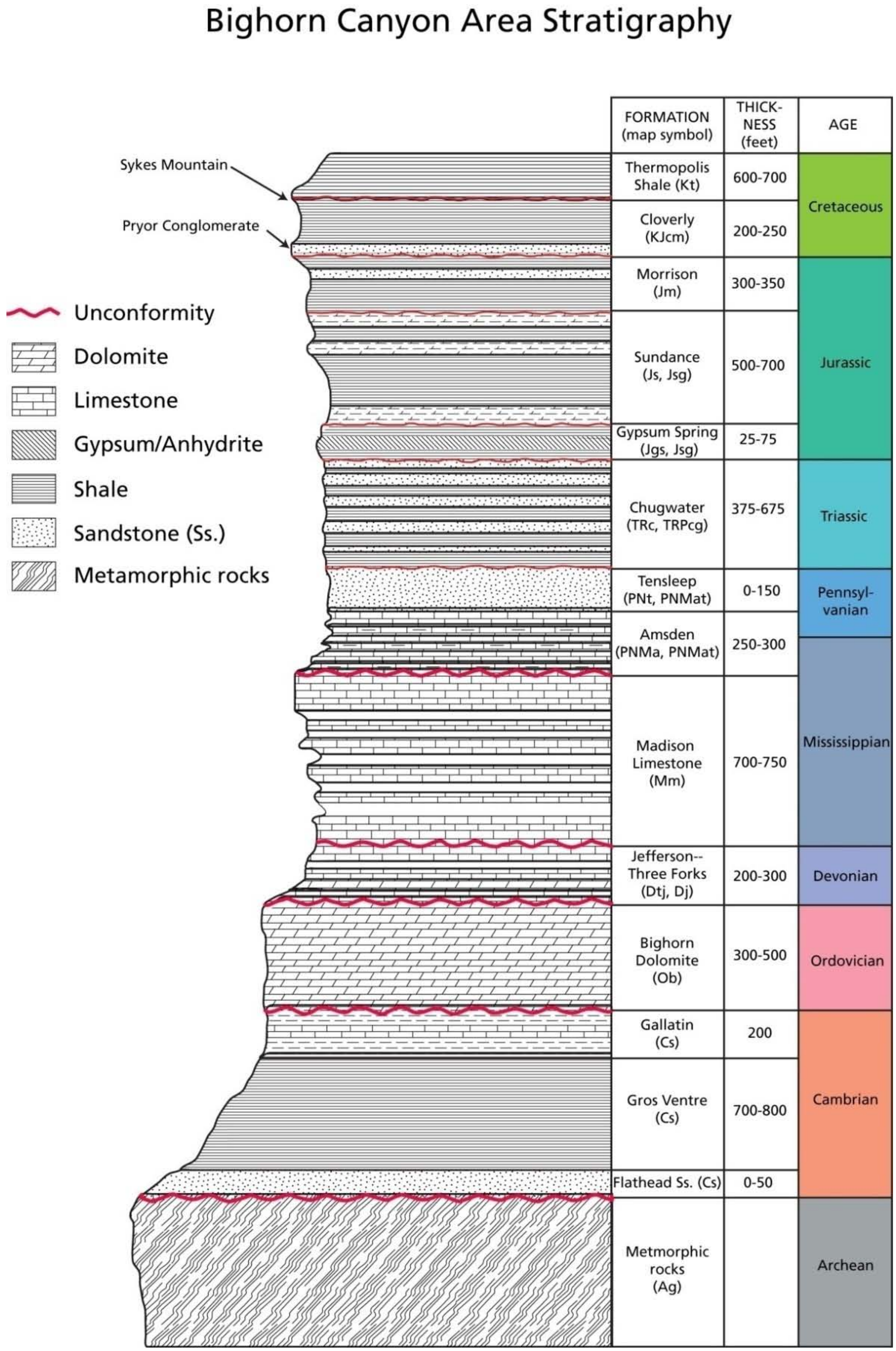


Figure 2. Stratigraphic column for the rocks in the vicinity of Bighorn Canyon. The most prominent rocks exposed in the national recreation area are the Mississippian Madison Group (Mm), which make up the walls of Bighorn Canyon. The Triassic Chugwater Formation (TRc and TRPcg) is also visually prominent. Rock units with a more vertical profile are more erosion resistant, and tend to form cliffs (such as Madison Limestone [Mm]). Map unit symbols are indicated in parentheses for units included in the digital geologic (GIS) data for Bighorn Canyon National Recreation Area. The "Cambrian sedimentary rocks, undivided" unit (Cs) encompasses a variety of units that are separately listed on this column. Standard U.S. Geological Survey timescale colors are used. For more detail, refer to the "Geologic Map Data" section. Graphic drafted by Philip Reiker (NPS Geologic Resources Division) after a stratigraphic column provided by David Lopez (geologist/consultant).

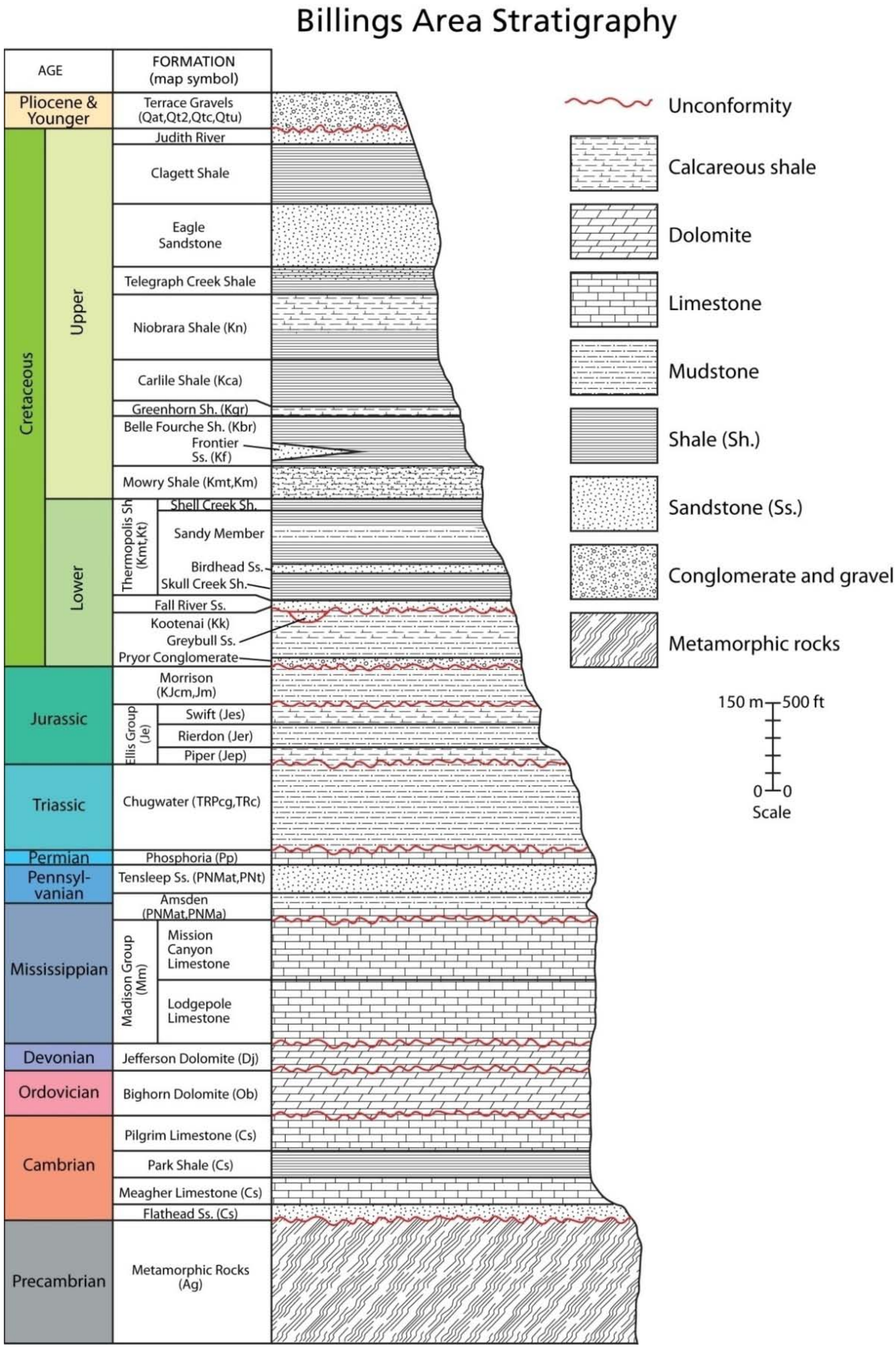


Figure 3. Stratigraphic column for the rocks in the Billings area. Billings is approximately 90 km (56 mi) from the Montana-Wyoming border in Bighorn Canyon National Recreation Area. This stratigraphic column encompasses many of the rock units included within the digital geologic map (GIS) data included for Bighorn Canyon National Recreation Area. The map unit symbols are indicated in parentheses. Not all of these units are exposed within Bighorn Canyon. Rock units with a more vertical profile are more erosion resistant, and tend to form cliffs (such as Madison Group [Mm]) rather than slopes (such as the Thermopolis Shale [Kmt, Kt]). The "Cambrian sedimentary rocks, undivided" unit (Cs) encompasses a variety of units that are separately listed on this column. For more detail, refer to the "Geologic Map Data" section. Standard U.S. Geological Survey timescale colors are used. Graphic drafted by Trista Thornberry-Ehrlich (Colorado State University) after a stratigraphic column provided by David Lopez (geologist/consultant).

Geologic Issues

The Geologic Resources Division held a Geologic Resources Inventory scoping session for Bighorn Canyon National Recreation Area on May 18–19, 2005, to discuss geologic resources, address the status of geologic mapping, and assess resource management issues and needs. This section synthesizes the scoping results, in particular those issues that may require attention from resource managers. Contact the Geologic Resources Division for technical assistance.

Geologic issues of particular significance for resource management at Bighorn Canyon National Recreation Area are sedimentation, mineral resources and mining, abandoned mineral lands and other disturbed lands, and various geologic hazards. The most critical issue, sedimentation, is discussed first, followed by other issues of management concern.

Sedimentation

In 2005, participants at the Geologic Resources Evaluation (now Geologic Resources Inventory) scoping meeting discussed sedimentation as the primary resource management issue related to the geologic processes operating in the national recreation area. This finding was echoed in 2007, when the Bighorn River System Long Term Issues Working Group (overseen by the Bureau of Reclamation) also specifically identified sedimentation in Bighorn Lake as a concern (U.S. Army Corps of Engineers 2010). A related concern is that sedimentation and the formation of point bars encourage the invasion of nonnative species, such as tamarisk (*Tamarix* L.) and Russian olive (*Elaeagnus angustifolia* L.), which rapidly spread into unvegetated or disturbed areas (National Park Service 2005).

Sedimentation is the process by which sediment, such as silt and sand, is deposited and accumulates, ultimately forming sedimentary layers. More specifically, it is the "silting up" of a reservoir with fine-grained sediment brought in via streams and surface runoff (Neuendorf et al. 2005). When a dam is constructed on a river to store water, sediment transported by water flow is also stored, thereby gradually reducing reservoir capacity by sediment accumulation (Mohammadzadeh-Habili and Heidarpour 2010).

In Bighorn Lake, the most notable sedimentation is occurring in the upper (upstream) reaches, where sediment accumulation is a particular problem at Horseshoe Bend. Horseshoe Bend hosts the major visitor-use facility for the south end of the lake, and the only designated boat launch ramp on Bighorn Lake in Wyoming (National Park Service 1995). Over the years, park employees have observed increasing sandbar development at Horseshoe Bend, and have come to suspect that this encroachment might eventually render the site useless as a water recreation area (National Park Service 1983).

Sediment Sources and Transport

Two major rivers—the Shoshone and Bighorn—flow within Bighorn Canyon National Recreation Area (fig. 1). The Bighorn River, which runs the entire length of the national recreation area, is the major transporter of sediment in the Bighorn Basin. The Shoshone River is one of the large tributaries to the Bighorn River. This tributary flows into Bighorn Lake from the west in the southern part of the national recreation area. On a daily basis, the Bighorn River transports an estimated 3,600 metric tons (4,000 tons) of sediment into the southern end of Bighorn Lake (U.S. Army Corps of Engineers 2010). The Shoshone River contributes approximately 640 metric tons (700 tons) of that amount (Soil Conservation Service 1994).

Sediment is readily washed into rivers as a result of several factors, including the arid climate; erodible quality of the bedrock, particularly the shale, which underlies the uplands adjacent to Bighorn Canyon; sparse vegetation; and steep stream gradients (U.S. Army Corps of Engineers 2010). The makeup of shale (clay, silt, or mud) gives rise to a landscape that is highly erodible. Moreover, steep slopes result in rapid runoff, and sediment is readily carried away on slopes greater than 15% (National Park Service 1981).

Human activities contribute sediment into Bighorn Lake. The major sources of sediment to the Shoshone River are irrigated croplands, rangelands, and stream banks. Specifically, flows returned to the river after cropland irrigation, erosion from croplands due to irrigation practices, and erosion from rangeland supply sediment (Soil Conservation Service 1994). These sources are also present along the Bighorn River and most of its tributaries (Jacobs et al. 1996). Eolian (windblown) processes also contribute sediment to the lake (National Park Service 1978).

Impacts of Sedimentation

A combination of increasing sediment thickness, in excess of 15 m (50 ft) in several areas (U.S. Army Corps of Engineers 2010), and low water levels occasionally prevents boat launching at the national recreation area for weeks at a time (National Park Service 1995). With respect to sediment thickness, the U.S. Army Corps of Engineers surveyed the existing bed elevation at Horseshoe Bend in 2007 and determined an average elevation of 1,100 m (3,608 ft) (U.S. Army Corps of

Engineers 2010). Modeling of base conditions predicted that the level of sediment within Horseshoe Bend will be in the range of elevation 1,103 m (3,620 ft) by as early as 2017 (U.S. Army Corps of Engineers 2010).

Sedimentation buildup at the head of the reservoir has raised the amount of water needed to keep the Horseshoe Bend boat ramp usable. Originally, the ramp could be used down to a water elevation of 1,094 m (3,590 ft). As a result of sedimentation, however, the ramp is no longer usable when the water drops below 1,102 m (3,617 ft) (Bureau of Reclamation 2010).

Managing Lake Levels

The Bureau of Reclamation is responsible for water storage and management within Bighorn Lake; flood-control operations are closely coordinated with the U.S. Army Corps of Engineers. Factors influencing the determination of lake levels include the availability of an adequate water supply, flood control, water storage for hydroelectric power, maintaining flows for river fisheries, maintaining lake levels for lake fisheries, maintaining river flows and lake levels for waterfowl hunting and viewing, and achieving desired lake levels for recreation, in particular launching boats during the summer. Variables that influence water levels are evaporation rates and depth of snowpack in the mountains surrounding the Bighorn Basin drainage. In addition, to meet the needs of water users at dams upstream from Bighorn Lake and to conduct flow and safety evaluations, flow-rate adjustments influence water levels in Bighorn Lake (Jacobs et al. 1996).

In September 2010, the Bureau of Reclamation released the "Draft Bighorn Lake Operating Criteria Evaluation Study & Report." Under this draft plan, the reservoir's water level would be kept between 0.9 m (3 ft) and 2.4 m (8 ft) higher than the previous standard lake level during late winter and early spring. By doing this, the reservoir has a better chance of filling up during spring runoff, and flows can be steadier in the river (Bureau of Reclamation 2010). Under this plan, the reservoir level would be at an elevation of 1,109 m (3,640 ft) during the summer, dropping to 1,106 m (3,630 ft) by the end of November, and, depending on mountain snowpack, would be between 1,099 m (3,605 ft) and 1,102 m (3,614 ft) by the end of March. The benefit of the proposed modification would be that the reservoir would operate about 1.5 m (5 ft) higher on average than in the past, while still maintaining the same level of fall and winter release for the benefit of both power generation and the river fishery (Bureau of Reclamation 2010).

Managing Sedimentation

The draft operating plan addresses the need for increased water levels in the reservoir for launching boats, but does not provide a long-term solution to the problem of sedimentation at Horseshoe Bend. According to the U.S. Army Corps of Engineers (2010), maintaining these higher seasonal reservoir levels will likely provide adequate recreational water depths for 15 to 25 years. However, raising pool elevations will also raise sediment deposition levels, as a new equilibrium elevation is established due to the higher pool (U.S. Army Corps of Engineers 2010).

Ultimately, the National Park Service will need to consider alternatives for further prolonging the life of recreational activities at Horseshoe Bend. In addition to raising pool level during the recreation season, proposed alternatives include trapping sediment before it reaches Horseshoe Bend, flushing sediment through Horseshoe Bend, dredging/removing sediment from Horseshoe Bend, and managing sediment (i.e., preventing excessive erosion) within the uplands of Horseshoe Bend and on the scale of the entire watershed (U.S. Army Corps of Engineers 2008).

Managing the sediment budget in the watershed is a large-scale endeavor involving federal, state, and local stakeholders. The National Park Service can play a role, for example, by encouraging upstream land managers to apply sound land-use practices that minimize erosion. One such opportunity exists when the National Park Service reviews other agencies' planning documents that deal with activities such as grazing or timber harvesting (National Park Service 1995). "In-house," the National Park Service can carefully monitor its road-grading activities, neither grading a road wider than needed nor performing excessive shoulder maintenance (National Park Service 1983).

Mineral Resources and Mining

According to the general management plan, bentonite, uranium, limestone, gravel, and sand are the significant mineral resources both regionally and within Bighorn Canyon National Recreation Area (National Park Service 1981).

Bentonite occurs in shale of the Cretaceous Period (145.5 million to 65.6 million years ago) in beds up to 5 m (16 ft) thick. Units that contain significant beds of bentonite are the Frontier (Kf) and Belle Fourche (Kbf) formations (see "Geologic Map Data").

Uranium exploration occurred in limestone areas of the Madison Group (Mm) and Amsden Formation (PNMa), with some exploration occurring where these formations come in contact with the Chugwater Formation (TRc) (National Park Service 2003a). Although no commercial quantities of uranium were produced from lands within the national recreation area, numerous pits and mounds attest to former exploration activity (see "Abandoned Mineral Lands").

The limestone of the Madison Group (Mm) is very common in the recreation area, and has been quarried in Lime Kiln Creek along the Ok-A-Beh road (National Park Service 1981). This particular quarry yielded building stone for Fort C. F. Smith (National Park Service 2010b). The historic site of Fort C. F. Smith is east of Afterbay Dam, on private property. In the 1860s, troops stationed at the fort guarded the Bozeman Trail,

which crossed the Bighorn River and led to mines in western Montana.
High-grade sand and gravel used for aggregate occur at the southern tip of the recreation area (National Park Service 1981). These deposits are associated with Quaternary alluvium (Qal).

Deposits of "glass sand" occur just north of Horseshoe Bend, on the west side of the canyon (National Park Service 1981). Glass sand is suitable for glassmaking because of its high silica content (93%–99+%) and its low content of colorants such as iron oxide, chromium, or cobalt. The origin of these deposits is eolian deposition of volcanic ash from the Yellowstone caldera (National Park Service 2005) (see "Eolian Features and Processes"). Some of these deposits are as thick as 30 m (100 ft).

In addition, Dryhead Agate from the Phosphoria Formation (Pp), which is collected in the vicinity of the recreation area, may be present within the national recreation area boundaries (National Park Service 2005). Dryhead Agate is characterized by richly colored bands of chalcedony, and is commonly collected by "rockhounds". At one time, many claims for agate mining existed in the area, but no commercial mining operations ever materialized (rocksonline.com 2007). Although not a concern at present, collecting may become a resource-protection issue as visitation increases in the future (National Park Service 2005).

Mining Activity and Impacts

Federal lands within Bighorn Canyon National Recreation Area were closed to mineral entry when it was established. However, the government did not purchase all mineral rights at that time, and private rights remain (National Park Service 1995). There were 77 unpatented mining claims for uranium and bentonite within the boundaries of the national recreation area at the time of its establishment (National Park Service 1978). Today, five unpatented bentonite claims remain. American Colloid Company is the claimant of the five remaining claims (National Park Service 1995). The claimant recently has shown interest in reopening one of the claims (Cassity Bromley, biological science technician, Bighorn Canyon National Recreation Area, written communication, March 29, 2011). These mining claims are situated in a portion of the recreation area away from Bighorn Lake and other water resources, and except for visual intrusion to the viewshed, these claims pose only minor threats to park resources (National Park Service 1983).

Abandoned Mineral Lands

In the 1950s, the Pryor and Bighorn mountains were prospected heavily for uranium, with extensive exploration occurring in what is now Bighorn Canyon National Recreation Area. Rock units of primary interest were the Amsden Formation (PNMa) and the Madison Group (Mm) (see "Geologic Map Data"). As mapped by staff at the national recreation area in the early 1980s, prospectors excavated 378 pits at 13 sites that are now considered abandoned mineral lands (AML) (Cassity Bromley, biological science technician, Bighorn Canyon National Recreation Area, written communication, March 29, 2011). These sites are a significant disturbance in otherwise nearly pristine desert and steppe landscapes.

The AML pits are not deep, subsurface mines; rather they are excavations at the surface created by bulldozers, consisting of 0.3-m- (1-ft-) to 1.2-m- (4-ft-) deep grooves with 0.6-m- (2-ft-) to 1.8-m- (6-ft-) high mounds of excavated dirt at one end (National Park Service 2003a) (fig. 4). The affected areas vary in size from less than 0.004 ha (0.01 ac) to 2.3 ha (5.6 ac), with most sites covering less than 0.008 ha (0.02 ac). However, two-track mining roads used for access are associated with many of the sites (see "Other Disturbed Lands"). Some of these roads are currently being used as trails within the national recreation area (National Park Service 2003a).

The National Park Service initiated restoration work on the 378 pits in 1983, first concentrating on areas highly visible to the public. The sites that were on the two-track mining roads with easy access for backhoes were re-contoured to approximate the original topography as closely as possible. Re-contouring consisted of moving dirt from the mounds back into the grooves, with minimal dirt collected from the sides of the groove (National Park Service 2003a). Sites that did not have access roads or were in sensitive areas, for example, areas with friable soil, were re-contoured by hand using shovels and other hand equipment. The sites were planted with native seed from a local nursery. Native shrubs were also planted on some sites, with water catchment pits around them (National Park Service 2003a).

Most of the work on the AML sites has been done by national recreation area staff members as part of their regular vegetative management duties (National Park Service 2003a). In addition, staff conducts follow-up monitoring on sites that have had restoration treatments. As part of restoration, detailed drawings are made of each site, and botanic and hydrologic conditions are recorded. Each site is photographed and checked for proximity to cultural resources, noxious weeds, and species of special concern. The potential for impact on wetlands or water quality, as well as the potential for socioeconomic or visitor-use impacts, is noted (National Park Service 2003a). In 1999, each site was mapped using global positioning system (GPS) technology.

Beneficial effects of restoration include increases in native plants and forage; fewer disturbed areas for potential weed invasions; improved safety, topography, and viewshed; and improved quality of visitor experience on the trails near the AML sites (National Park Service 2003b).

Mainly as a result of the arid climate, restoration of disturbed sites is a slow process. Rainfall is so sparse at the national recreation area that little or no "natural" erosion of the exploration mounds occurs. In addition, altered slopes and drainage result in slow recovery of vegetation (National Park Service 2003a). With intervention, however, managers at the national recreation area anticipate a marked improvement in appearance (National Park Service 2003a).

Of the 378 pits originally mapped, 141 remain unreclaimed (Cassity Bromley, biological science technician, Bighorn Canyon National Recreation Area, written communication, March 29, 2011). In 2010, previously restored sites were revisited to check the status of recovery, which was generally very good (Cassity Bromley, biological science technician, Bighorn Canyon National Recreation Area, written communication, March 29, 2011).

Other Disturbed Lands

Old, unreclaimed roadbeds are a significant disturbance on the landscape at Bighorn Canyon National Recreation Area. Furthermore, the National Park Service is anticipating the reopening of many access roads in 2012 as a result of the rebuilding of a major power line by the Western Area Power Administration (Cassity Bromley, biological science technician, Bighorn Canyon National Recreation Area, written communication, March 31, 2011).

In the arid environment of Bighorn Canyon, roads remain highly visible, even after years of being abandoned. Restoration work generally is needed to return these roads to natural conditions. To discourage use, the National Park Service has obscured the entrances to many closed roads with native vegetation. In some cases, signage is needed to discourage further use (National Park Service 1983).

In 2001, staff from the NPS Geologic Resources Division inspected eight abandoned ranching/mining roads within Bighorn Canyon National Recreation Area, as well as 100 road cuts along the main road between Crooked Creek and Barry's Landing (Greco 2001). The assessment consisted of photo documentation, onsite discussions of erosional features, and a listing of potential restoration or enhancement options for each of the road cuts. The assessment made two significant points, which managers at the national recreation area need to address to ensure the success of future restoration: first, because the road cuts are primarily an aesthetic issue, staff should evaluate the costs and benefits of restoration before undertaking intensive restoration efforts; second, as long as cattle drives continue, revegetation efforts in these areas will be futile (Greco 2001).

Range cattle first arrived in the Bighorn Canyon area in 1879, creating a legacy of ranching-related impacts, such as stock trails and piles of rusty, barbed wire and other refuse from prior occupation (National Park Service 1983). The tradition of ranching continues today with cattle trailing in the national recreation area, and horse grazing on the Pryor Mountain Wild Horse Range (National Park Service 2004). Cattle and wild horses trample the native vegetation and fragile soil crusts, leaving bare areas susceptible to wind and sheetwash erosion (National Park Service 2004). Livestock trailing requires a permit, which users acquire through the chief ranger at Bighorn Canyon National Recreation Area (National Park Service 2007).

Mass Wasting

Mass wasting refers to the dislodging and downslope movement of soil and rock material, such as during a rockfall, slump, or landslide. Steep slopes—as great as 70% in some areas of the national recreation area—provide conditions for mass-wasting processes, in particular landsliding. Moreover, widely fluctuating lake levels can destabilize slopes. Rockfall, another mass-wasting hazard, is evident throughout the recreation area. Potential rockfall areas exist along the cliffs of the canyon, side canyons, and outcrops.

The digital geologic map for Bighorn Canyon National Recreation Area shows landslide deposits (Qls) mapped at a scale of 1:100,000 by Lopez (2000) and Vuke et al. (2000). These deposits consist of discrete units of rock and soil that have moved down slopes under the influence of gravity. Significantly, at this scale, many small landslides could not be shown (Lopez 2000), for example those in Bull Elk Basin, which is a notable area of mass wasting within the national recreation area (see "Bull Elk Basin"). Modern landslide deposits at the national recreation area are generally between 30 m (100 ft) and 46 m (150 ft) thick (Vuke et al. 2000).

Older landslide deposits (QTls) occur along the base of the Pryor Mountains, some of which are within the national recreation area's boundaries. Lopez (2000) described these deposits as an unconsolidated mixture of soil and blocks of local bedrock along the flanks of the Pryor Mountains uplift. These particular landslides occurred during the Pleistocene Epoch (2.6 million to 11,700 years ago), with some possibly occurring as early as the Pliocene Epoch (5.3 million to 2.6 million years ago). Erosion has obliterated much of the surface form of these older deposits. These older landslide deposits testify to unstable conditions in the past, but most likely have stabilized and pose few hazards today (National Park Service 1981).

Landsliding results in irregular or hummocky surfaces that characteristically have concentric swales and ridges near the downslope limit. Locally, these deposits consist of slumps—internally cohesive, rotated masses of earth.

Factors affecting landsliding include seismic activity, runoff, heavy rains, ground saturation rates, and changing lake levels (National Park Service 1995). For example, mass movement has occurred along the lakeshore west of Horseshoe Bend, southwest of the boat launch ramp (National Park Service 1981). Slumping at Horseshoe Bend adds to the sediment supply (National Park Service 2005) (see "Sedimentation"). This deposit was not mapped at the 1:100,000 scale, and therefore, does not appear on the digital geologic map of the national recreation area.

Wieczorek and Snyder (2009) suggested five methods and "vital signs" for monitoring slope movements: types of landslides, landslide triggers and causes, geologic materials in landslides, measurement of landslide movement, and assessing landslide hazards and risks. The Geologic Resources Division could assist staff at the national recreation area in setting up monitoring protocols.

Bull Elk Basin

Bull Elk Basin has a gently sloping shoreline, which could provide much desired acreage for day use and camping. However, much of the Bull Elk Basin lies within Cambrian sedimentary rocks (Cs) composed of shales and thinly bedded limestone that are prone to mass wasting. Thus, the shoreline is unsuitable for recreational use, particularly as a permanent campground (National Park Service 1983). Major slumps in Bull Elk Basin are located high above the lake, but smaller slumps also occur near the water's edge. The five major slides have a total estimated volume of 145 million m^3 (175 million yd^3) (Taucher 1978). Movement of the slides averages 0.6 m (2 ft) per year (National Park Service 1981). The small slides close to the water exhibit minor creep and sloughing off at the toe (National Park Service 1995).

Mass-wasting processes near the shoreline in Bull Elk Basin could injure a visitor in a boat or at a beach campsite (National Park Service 1981, 1995). As a result, camping in Bull Elk Basin has been prohibited throughout much of the national recreation area's history. Rangers frequently have to remind visitors of the potential danger and enforce the no-camping policy in Bull Elk Basin (National Park Service 1995).

Because camping locations are limited and no major mass-wasting events have occurred in recent years, in 2005 managers at the national recreation area were considering opening Bull Elk Basin for camping (National Park Service 2005). However, at the time of writing, Bull Elk Basin remained closed to camping (Cassity Bromley, biological science technician, Bighorn Canyon National Recreation Area, written communication, March 31, 2011). One option is to allow limited shoreline use after identifying sites with the least risk and greatest stability. Staff at the national recreation area could manage shoreline use of these areas by issuing backcountry use permits (National Park Service 1983).

Flooding

The Bighorn River has three large storage projects, which are managed by the Bureau of Reclamation. The Boysen and Buffalo Bill reservoirs, both in Wyoming, control about 70% of the runoff into the Bighorn Reservoir (Sexton 2011). The Boysen Reservoir, which releases 1,100 million m^3 (892,000 acre feet) to the Bighorn Reservoir, is south of the national recreation area on the Wind River. The Buffalo Bill Reservoir, which releases 800 million m^3 (646,000 acre feet) to the Bighorn Reservoir, is west of the national recreation area on the Shoshone River. The system of dams and reservoirs minimizes flood hazards within the floodplains of these rivers (Jacobs et al. 1996). However, a major failure within these systems, although extremely unlikely, would pose major hazards to residential, industrial, and recreational developments in the floodplains (Jacobs et al. 1996). Moreover, unusually severe rainfall could result in extensive flooding downstream (north) of the Yellowtail Dam (National Park Service 1981).

Smaller drainages in the national recreation area are "classic" locales for flash flooding, consisting of a small contributing area, steep channel and canyon walls, exposed bedrock, and thin soils (Martin 1995). Ground saturation, which leads to extreme runoff, is facilitated by thin soils and can result when heavy rains follow previous precipitation or above normal snowpack (Martin 1995). Under these conditions, sudden, hazardous floods could occur at Bighorn Canyon National Recreation Area (Herschfield 1961).

In high-energy, bedrock canyons such as those in Bighorn Canyon National Recreation Area, flash flooding can be accompanied by extensive mass wasting, in the form of debris flows and bank failures. For example, in June 2006, flash floods resulted from severe convective storms, causing debris flows in Layout Creek, Crooked Creek, and numerous unnamed ephemeral stream channels (fig. 5). These stream channels originate at high elevations on the Pryor Mountains, and have steep gradients before entering the canyon, which can result in highly turbulent and destructive debris flows during flash floods (Cassity Bromley, biological science technician, Bighorn Canyon National Recreation Area, written communication, April 19, 2011). These events may serve to alter the channel bed and banks and possibly raise flood stages dramatically. When flood waters are accompanied by excessive sediment and debris, flows become more viscous, and increased stage (water level) is required to move a given amount of flow. The management implication of this scenario is that areas predicted to be above the elevation of an extreme flood may, in fact, be subject to some degree of flooding, and very few, if any, locations in steep bedrock canyons can be considered absolutely safe (Martin 1995).

Anthropogenic features, such as plugged culverts, can cause flooding above road crossings. In the Trail Creek area, for example, flood waters are likely to overtop roads as a result of an under-engineered culvert, potentially causing extensive erosion and loss of the road crossing. Such an event could leave visitors and staff stranded (Martin 1995; Cassity Bromley, biological science technician, Bighorn Canyon National Recreation Area, written communication, April 19, 2011).

Frost Heaving and Shrink-Swell Potential

According to the soil survey by Parker et al. (1975), frost heaving occurs in soils of the Neville Series—silty clay loam on slopes of 4% to 8%. These soils form on fans and stream terraces in the Bighorn Canyon area. Frost heaving is a severe limiting factor for development, particularly for foundations of low buildings without basements (Parker et al. 1975).

Soils containing bentonite have shrink-swell potential, which is a limiting factor for the construction of foundations and roads. Such soils are less limiting for development of picnic areas, campgrounds, and trails (Parker et al. 1975). Parker et al. (1975) identified soils in the national recreation area to have moderate shrink-swell potential; these are from the Harvey Series—stony loam on 2% to 8% slopes. The NPS Soil Resources Inventory has not yet (September 2011) completed a soils map and database for the park. When completed, such a product could be utilized to identify areas of potential frost heaving or shrink-swell potential.

Figure 4. Abandoned mineral lands. Uranium exploration in the 1950s resulted in extensive disturbances throughout the national recreation area. The disturbed sites are not deep, subsurface mines; rather they are excavations at the surface created by bulldozers, consisting of grooves with mounds of excavated dirt at one end. Of the 378 sites originally mapped, 141 sites remain in need of restoration. National Park Service photograph.

Figure 5. Flash-flooding impacts. In June 2006, as a result of severe convective storms, flash floods caused numerous debris flows at Bighorn Canyon National Recreation Area, including this one at the Hillsboro townsite. National Park Service photograph.

Geologic Features and Processes

This section describes the most prominent and distinctive geologic features and processes in Bighorn Canyon National Recreation Area.

Bighorn Lake and Yellowtail Dam

Completed in 1965 by the Bureau of Reclamation, construction of Yellowtail Dam created Bighorn Lake. Yellowtail Dam is a 162-m- (525-ft-) high, concrete-arch dam designed to impound water for power production, municipal and industrial use, irrigation, flood control, sediment retention, recreation, and fish and wildlife enhancement (Bureau of Reclamation 1994) (fig. 6). The dam was named for Robert Yellowtail, a distinguished member of the Crow Tribe and long-time superintendent of the Crow Reservation (Bearss 1970). The Bureau of Reclamation built Yellowtail Dam at the north end of Bighorn Canyon. Yellowtail Dam harnesses the waters of the Bighorn River, and turned the once variable stream into a huge reservoir. Bighorn Lake extends approximately 114 km (71 mi) from near Lovell, Wyoming, to Fort Smith, Montana. Sheer limestone cliffs of the Madison Group (Mm) surround Bighorn Lake.

A second dam—Yellowtail Afterbay Dam—created a small water impoundment with an accessible shoreline at the northern end of Bighorn Canyon National Recreation Area (fig. 7). Yellowtail Afterbay Dam is located 3.5 km (2.2 mi) downstream of Yellowtail Dam. It is a 22-m- (72-ft-) high concrete dam, built to impound water and regulate the water discharge from the power plant at Yellowtail Dam. Coinciding with releases from Yellowtail Dam, water levels fluctuate dramatically in the small Afterbay reservoir. Nevertheless, this reservoir does receive some recreational use, primarily fishing (Jacobs et al. 1996). North of the Afterbay area, the Bighorn River resumes its meandering course through a broad valley on its way to the Yellowstone River.

One of the truly outstanding characteristics of the Bighorn River is the amount of sediment it carries, especially as it nears Bighorn Lake (see inside cover; Soil Conservation Service 1994). With the completion of Yellowtail Dam, large amounts of the Bighorn River's silt load are now trapped within Bighorn Lake (see "Sedimentation"). As a result, the turbidity of the river downstream of Yellowtail Dam is low. As much as a 60-fold decrease in turbidity can occur as the Bighorn River's waters pass through the reservoir (Soltero 1971). Impoundment has transformed the Bighorn River from a naturally silty river upstream of Bighorn Lake, to an unnaturally clear river system downstream of Yellowtail Dam (Jacobs et al. 1996). Furthermore, the temperature of water flowing in the Bighorn River is influenced by residency in the reservoir. Waters flowing into Bighorn Lake are at or near freezing in December, January, and February. Downstream of the dam, however, water temperatures never reach freezing (Jacobs et al. 1996). Minimum temperatures in the river downstream of the dam occur in March and April, followed by a maximum in September (Jacobs et al. 1996).

Geomorphic Impacts

With the creation of Yellowtail Dam and Bighorn Lake, many of Bighorn Canyon's geomorphic features were inundated. River features such as riffles, rapids, and whirlpools made boating on the Bighorn River an adventure. Starting in 1913, commercial boating trips were offered, typically starting at Horseshoe Bend and ending at the Yellowstone River (Bearss 1970). Occasionally these trips covered much greater distances, with some trips reaching New Orleans (Barry 1916). Within Bighorn Canyon, these trips passed through rapids such as Bull Elk Rapids, "the most dangerous white water on the river" (Barry 1916). Bull Elk Rapids was just beyond Dry Head Creek. Boaters also passed "Allen's Rock," named for Dr. Will Allen, who had led a boat expedition through the canyon at the turn of the 20th century. Here, downstream (north) from Bull Elk Rapids, Allen's party had seen their boat shattered and had been compelled to finish their journey on foot (Barry 1916). Additionally, "Homburg Whirlpool"—named for two German boys who lost their lives attempting to pass it—was near the mouth of Black Canyon. These geomorphic/historic features are now gone, submerged under Bighorn Lake. The National Park Service maintains a film record of a trip down the river before construction of the Yellowtail Dam (Jacobs et al. 1996).

Other geomorphic changes include the loss of side channels downstream (north) of Yellowtail Dam. This change has serious implications for the creation and maintenance of aquatic habitat for rainbow and brown trout populations (Godaire 2010). These changes reflect the reduction in peak flows and the sediment supply required to maintain geomorphic complexity (Godaire 2010). As is typical of reservoir operations, regulation of waters through Yellowtail Dam has increased flows during former low-flow periods, and decreased flows during former high-flow periods (Jacobs et al. 1996). Moreover, geomorphic complexity, which is characterized by an active channel area, has been decreasing since 1961 (Godaire 2010). Downstream from Yellowtail Dam, large-scale lateral movement of the channel halted between one and two decades following dam construction (Godaire 2010). The channel positions of the main stem and side channels have been in similar locations since 1980 (Godaire 2010). In an unaltered system, active geomorphic processes would include scouring channels and modifying bars, depositing sediment in new areas, and facilitating the formation of new bars and channels.

Fluvial Features and Processes

Fluvial features at Bighorn Canyon National Recreation Area include segments of the Bighorn and Shoshone rivers, and the extreme lower reaches of numerous small streams that flow into the east and west sides of Bighorn Lake (Jacobs et al. 1996).

Bighorn River

About 16 km (10 mi) of the Bighorn River above the pool of Bighorn Lake flow within Bighorn Canyon National Recreation Area (Jacobs et al. 1996). The Bighorn River is a tributary of the Yellowstone River and is approximately 742 km (461 mi) long. The upper reaches of the Bighorn River, south of the Owl Creek Mountains in Wyoming, are known as the Wind River. The Bighorn River begins where the Wind River emerges from Wind River Canyon, at a point referred to locally as the "Wedding of the Waters" (Judson Finley, assistant professor, University of Memphis, written communication, April 18, 2011). The Bighorn River flows north through central Wyoming toward Montana. Principal tributaries in Wyoming include the Nowood, Greybull, and Shoshone rivers. Near the border with Montana, the river turns northeast, flows past the north end of the Bighorn Mountains and then toward Yellowtail Dam (U.S. Army Corps of Engineers 2010). Beyond Bighorn Canyon, the river flows into the Yellowstone River in Montana (fig. 8).

Shoshone River

A segment of about 6 km (4 mi) of the Shoshone River also flows in the national recreation area. The Shoshone River discharges into Bighorn Lake, after flowing through the Yellowtail Wildlife Habitat area, in the southern part of the national recreation area. The Shoshone River is a major, warm, silt-laden tributary of the Bighorn River and is a primary contributor of sediment (Jacobs et al. 1996) (see "Sedimentation"). Natural flow of the river is affected by power development at the Buffalo Bill Dam, which is located approximately 100 km (62 mi) upstream (south) of the national recreation area; diversions for irrigation of about 57,900 ha (143,000 ac); and return flow from irrigated areas (Jacobs et al. 1996).

Crooked Creek and Other Tributaries

In the vicinity of the national recreation area, tributaries much smaller than the Shoshone River also flow into Bighorn Lake, entering the Bighorn River drainage from the Pryor Mountains to the west and the Bighorn Mountains to the east. Crooked Creek is representative of these smaller tributaries on and adjacent to the national recreation area. Crooked Creek channels drainage from the Pryor Mountains (Jacobs et al. 1996).

As a result of rapid runoff of irrigation water from surrounding agricultural areas, the segment of Crooked Creek flowing through the national recreation area has eroded a deep, narrow channel that has reached bedrock (Department of Range Management, University of Wyoming, site evaluation in park files, cited in Jacobs et al. 1996, p. 34). In some places, the channel has downcut through nearly 6 m (20 ft) of soil and alluvium (Qal) (National Park Service 1996), reaching the Goose Egg Formation (TRpg).

Stabilization and restoration of Crooked Creek is a management objective at Bighorn Canyon National Recreation Area. Mitigation of excessive erosion is difficult: the silt load in Crooked Creek appears to be very low, and major rainstorms periodically scour sediments from the channel bottom. However, beaver dams and the growth of streamside vegetation are helping to restore channel processes (Jacobs et al. 1996). The National Park Service encourages the presence of beaver by aggressively enforcing no-trapping regulations, while protecting from beaver (with wire fencing) the few mature cottonwood trees, which hold the bank in place (National Park Service 1996). Also, the National Park Service has placed fencing along the stream corridor to prevent use by cattle and wild horses (National Park Service 1996).

Superimposed, Entrenched, Abandoned Meanders

Bighorn Canyon is geomorphically distinctive for at least three reasons: first, it formed via superimposition; second, it hosts entrenched meanders; and third, it contains ancient abandoned meanders.

Superimposition

Superimposition is the process by which a stream or drainage system—which originally developed on a cover of easily eroded rocks that has since eroded away—becomes established on a new surface and maintains its course, despite different rock types and structures encountered as it erodes downward. The present-day canyon of the Bighorn River cuts completely through resistant rocks such as the cliff-forming Madison Group (Mm), and structures such as folds of the Bighorn Mountains, without being diverted. Thus, in the process of creating the present-day Bighorn Canyon, the river's course was "superimposed" on the rocks and the structurally uplifted features it encountered (Lopez 2007). Erosion itself occurred as a combination of chemical weathering (dissolution of limestone) and mechanical weathering (breakdown of rock along the riverbed by fluvially transported cobbles, pebbles, and sand grains) (Lopez 2007).

Entrenched Meanders

The ancient Bighorn River meandered across unconsolidated floodplain sediments, which were underlain by rocks that have long since been removed by erosion. As erosion continued, these meanders became entrenched (established via downward erosion) when the river was superimposed on the hard underlying Madison Group (Mm) (fig. 9). Such a deepened meander, which preserves its original pattern with little modification, suggests rejuvenation of a meandering stream under conditions of rapid vertical uplift or lowering of base level (Neuendorf et al. 2005). This was the case for Bighorn Canyon during the Laramide Orogeny—a period of mountain building and uplift starting about 70 million years ago (see "Geologic History").

Abandoned Meanders

In a meandering river system, the highest rate of erosion is on the outside bends of the meanders, called the "cutbanks." At the same time, deposition occurs on the opposite/inside bends of the river, the "point bars." During an earlier stage of entrenchment, the Bighorn River's course was through the Natural Corrals (fig. 10). However, erosion on the two cutbanks of the meandering river cut through a wall separating them, allowing the river to take a new shorter route and in the process abandoning the previous meander. Continued downcutting left the Natural Corrals high and dry (Lopez 2007). This outstanding example of an abandoned meander is across from Devil Canyon Overlook.

Terraces

For decades, the Bighorn Basin has been a classic area for the study of fluvial geomorphology and Quaternary stratigraphy (the study of rock strata) (Reheis 1992). The well-preserved fluvial terraces along major rivers such as the Bighorn, Shoshone, Greybull, Clarks Fork, and Yellowstone have provided evidence of the dynamic nature of fluvial processes and tectonic activity over the past 2.02 million years (Reheis 1984a, 1992).

Three of the five source maps for the digital geologic data for Bighorn Canyon National Recreation Area show terraces along the Bighorn and Shoshone rivers (see "Geologic Map Data"). Lopez (2000) mapped gravels in three levels of terraces of Quaternary age (Qat). These deposits occur along the Bighorn River corridor in the north part of the national recreation area. Pierce (1997) mapped middle level stream terraces (Qt2) west of Bighorn Lake. Rioux (1994) mapped undifferentiated terrace deposits (Qtu) and the Cody terrace (Qtc), located at the southern tip of the national recreation area. No terraces occur in the central, steep–walled canyon portion of the national recreation area.

Generally speaking, the paired nature of terraces on opposite sides of a stream channel is one of the most distinctive characteristic of terrace morphology. The pairs represent the same former floodplain, with higher pairs being older than lower pairs, chronicling the river's downward erosion to the modern floodplain level (fig. 11). Unpaired terraces indicate the removal by erosion or burial by deposition of the terrace on one side of the valley or the other. Tectonics may also disturb terrace forms, shifting terrace elevations along faults.

A distinctive feature of the terraces at Bighorn Canyon National Recreation Area is the sediment that makes up these deposits. Investigators have deduced the histories of the drainages in the Bighorn Canyon area by analyzing and dating these sediments. For example, the sediments in the terraces along the Shoshone River show that this river carries volcanic rocks of the Absaroka Mountains almost exclusively, whereas the Bighorn River carries granitic and sedimentary rocks in addition to volcanic rocks. A substantial increase in the proportion of Absaroka volcanic rocks from one terrace gravel to the next gravel level in the terraces along the Bighorn River reflects the capture (natural diversion) of the Shoshone River by the Bighorn River around 1.45 million to 1.2 million years ago (Reheis 1984a) (see "Geologic History").

Furthermore, in the early 1990s, investigators identified several deposits of tephra (from caldera eruptions in Yellowstone National Park) within the terrace deposits. The tephra allowed investigators to infer the ages of the terrace deposits, based in the timing of the Yellowstone eruption, and permitted them to estimate the ages of older and younger terraces (Reheis 1992). Investigators used this information to calculate stream incision rates, provide insight into drainage histories and Quaternary tectonics, infer the timing of alluvial erosion–deposition cycles, and calibrate rates of soil development (Reheis 1992).

Seeps and Springs

Bighorn Canyon National Recreation Area hosts numerous seeps and springs that emerge from various geologic units (table 1). Spring-bearing units include the Chugwater Formation (TRc), Tensleep Sandstone (PNt), alluvium overlying Mowry Shale (Km), and Bighorn Dolomite (Ob)–Madison Group (Mm). The primary springs are located at the base of the Pryor Mountains in the western part of the national recreation area, and are associated with the Sykes Spring fault zone (see "Structural and Tectonic Features and Processes"). Springs emanating from this zone provide the water supply at the Horseshoe Bend facilities. Springs also occur on the northeast side of Bighorn Lake in the vicinity of Ok-A-Beh, and provide water to the marina there; these springs are on Crow tribal lands. Access by the National Park Service is provided through a memorandum of agreement with the tribe (Jacobs et al. 1996). At the Ewing Snell Science Center, flow from a spring known as Sorenson Spring is stored in a pond and piped out for livestock watering (Jacobs et al. 1996).

In addition to their significance as a domestic water supply, seeps and springs have an ecological importance disproportionate to their limited spatial extent (Schmitz 2007); they are a rare source of water for wildlife in an arid environment. The Greater Yellowstone Network identified seeps and springs in Bighorn Canyon National Recreation Area as an Inventory and Monitoring (I&M) Program vital sign. Together with staff from Montana State University, network staff has conducted a spring inventory at Bighorn Canyon National Recreation Area to characterize the resource and identify management needs (Schmitz 2007). The inventory included a site description of the physical setting and habitat structure, baseline water-quality data, water-age estimation, and recharge-area identification, as well as observed impacts. Investigators assessed water age and recharge with naturally occurring hydrogen isotopes (tritium), and estimated most springs to discharge water with residence times less than 30 years. However, tritium levels from Cass, Cat Track, Lockhart South, Lockhart Springhouse, and Rick's springs indicate water older than 50 years (Schmitz 2007). Significantly, these estimates were made from one-time samples (Schmitz 2007).

Jacobs et al. (1996) noted that extensive land use in the vicinity of Bighorn Canyon National Recreation Area has the potential to alter spring hydrology. At the present time, fencing is necessary to protect the springs from livestock impacts, as a result of cattle trespass and trailing, but old wire fencing is being replaced with buck and rail fencing. Buck and rail fending is preferred because it can be opened outside of trailing season and provides less of an entanglement hazard for wildlife (Cassity Bromley, biological science technician, Bighorn Canyon National Recreation Area, written communication, April 19, 2011).

The National Park Service has identified the following springs as needing protection:

- Lockhart Springs—a series of three or four small seeps along Lockhart Lane. The springs are fenced, but deteriorated fence conditions can occur, allowing access to cattle during trailing each spring and fall. In spring 2011, staff at the national recreation area reconstructed fencing at two of the Lockhart Springs (Cassity Bromley, biological science technician, Bighorn Canyon National Recreation Area, written communication, April 19, 2011).
- Willow Springs—two or three small springs located east of the historic ranch buildings at Mason-Lovell Ranch. Part of the main spring is fenced. It was used by cattle from the adjoining Bureau of Land Management allotment to the east. This spring supplied water for the historic apple orchard. The National Park Service plans to reestablish the orchard and has developed the spring to provide water (Cassity Bromley, biological science technician, Bighorn Canyon National Recreation Area, written communication, April 19, 2011).
- Two small, separate springs in South B pasture of the Dryhead Grazing Allotment. These springs are approximately 0.4 km (0.25 mi) north of the junction of Bad Pass Road with the access road to Barry's Landing. They are fenced for protection from cattle grazing (Jacobs et al. 1996).

Eolian Features and Processes

Strong winds generally can be expected at Bighorn Canyon National Recreation Area during any season of the year (National Park Service 1971). Gusts of 121 km/h (75 mph) have been recorded at Fort Smith, Montana (National Park Service 1971). At present, prevailing winds in the area are westerly.

In 1974, an environmental evaluation identified sand-blowout areas as potential geologic hazards (Wirth Associates 1974), and past project statements have "aimed toward reducing blowing sand" (National Park Service 1995, project management statement BICA-N-202.000). Furthermore, windy conditions and exposure can impact visitation; for example, park managers suspect that visitors avoid the campground at Horseshoe Bend during windy conditions because it sits atop an open, windy knoll (National Park Service 1986). However, during scoping, staff at the national recreation area did not consider ongoing eolian processes such as dust storms to be a significant concern for resource management (National Park Service 2005).

At the scale of geologic mapping, no active eolian deposits are shown on the digital geologic map for the national recreation area. However, eolian sediments from the Holocene Epoch (the last 11,700 years) are present north and east of Crooked Creek. These deposits form sand sheets, wedges, and dunes approximately 3 m (10 ft) to 5 m (16 ft) thick, and have evidence of significant prehistoric human occupations (Judson Finley, assistant professor, University of Memphis, written communication, April 18, 2011). Ancient "paleodunes" preserved in the Tensleep (PNt) and Morrison (Jm) formations are from the Pennsylvanian (318 million to 299 million years ago) and Jurassic (200 million to 146 million years ago) periods respectively.

Scoping participants identified eolian deposits as consisting primarily of volcanic ash (from the Yellowstone caldera) that has been transported and deposited against the mountain front east of the national recreation area (National Park Service 2005). Some of these deposits are as thick as 30 m (100 ft), and in the past have been mined for sand used in glassmaking (see "Mineral Resources and Mining").

Reheis (1987) noted that eolian processes add silicates, calcium carbonate, and gypsum to the soils of Big Horn County, Wyoming. Windblown silt- and sand-sized particles make up a large proportion of the upper parts of the soils that have formed on the Kane alluvial fans, near Lovell, Wyoming. These soils have accumulated gypsum over time, which is added chiefly as eolian dust from both local and distant sources. Sources include the clay and gypsum dunes in the Bighorn Basin, as well as exposed gypsum in the Sheep Mountain anticline to the southwest, on the slopes of the Pryor Mountains to the northwest, and in the Cody area on the west side of the Bighorn Basin (Rehies 1987).

Although eolian deposits are often underrepresented on geologic maps, they are significant indicators of past climatic conditions (Madole 1995; Muhs et al. 1999). According to Reheis (1987), the arid but cool climate has permitted gypsum to accumulate continuously for the past 600,000 years, indicating that the effective moisture in the area has not increased substantially during this time.

Structural and Tectonic Features and Processes

The three primary structural features in the vicinity of Bighorn Canyon National Recreation Area are the Bighorn Mountains, Pryor Mountains, and a structural basin between the two mountain ranges.

The northern end of the Bighorn Mountains is a northward-plunging anticline with steep limbs and a broad top (Richards 1955). A segment of this anticline is exposed in Bighorn Canyon (figs. 7 and 12). For 24 km (15 mi) upstream (south) from the Yellowtail Dam, Bighorn Lake bisects this massive anticline, displaying rocks that span more than 250 million years, including the Pennsylvanian Tensleep Formation (PNt); the Triassic Chugwater and Goose Egg formations, undivided (TRPcg); the Jurassic Piper (Jep), Rierdon (Jer), Swift (Jes), and Morrison (Jm) formations; and the Cretaceous Kootenai Formation (Kk) (see "Geologic Map Data").

East of the recreation area, the sheer cliff face of the Pryor Mountains is the first in a series of major faults that were part of the uplift of the mountain range. The sedimentary rocks of the mountains were broken along nearly vertical planes. The North Pryor fault abruptly terminates the north end of the Pryor Mountains (Mapel et al. 1975). Maximum displacement on this fault is 610 m (2,000 ft). Upthrown on the south, the fault brings the Cretaceous Cloverly Formation (KJcm) on the north against the much older Madison Group (Mm) on the south (Mapel et al. 1975) (see figs. 2 and 3).

Both the Bighorn and Pryor mountains can be characterized as "fault-propagation folds," after the model proposed by McConnell (1994) (David Lopez, geologist/independent consultant, written communication, January 31, 2011). The differences between the two ranges are that in the Pryors, the fault makes it to the surface and cuts the steeply dipping beds along the mountain front. In the Bighorns, the faults do not make it to the surface, and there is a back thrust on the west side that produced the fold in the monocline area (David Lopez, geologist/independent consultant, written communication, January 31, 2011).

Between the Bighorn Mountains and Pryor Mountains is a structural basin, referred to as the Dry Head–Garvin Basin, in which mostly Triassic and lowermost Jurassic rocks are exposed (Mapel et al. 1975).

The combination of originally horizontal rock layers and later deformation has resulted in scenic displays of faulted and folded strata (fig. 12). Structural displays include a near-vertical fault at least 10 km (6 mi) long that strikes eastward across Bighorn Canyon (Richards 1955). This fault is easy to see: the north side of the fault, which includes a pillar of rock called "the Sentinel," is about 60 m (200 ft) higher than the south side of the fault (National Park Service 2010a). Looking across Bighorn Lake from the Sentinel, the layer of Madison Group (Mm) is 60 m (200 ft) lower. North of the Sentinel, just beyond the left-hand bend in the canyon, both canyon walls are suddenly 122-m (400-ft) high above the lake, and the 60-m (200-ft) offset is clearly visible on the east side of the canyon (fig. 13). Hiking from Medicine Creek Campground up the creek (see fig. 1), the same fault is revealed at the mouth of Wassin Canyon (National Park Service 2010a).

The other significant fault in the vicinity of the national recreation area is the Sykes Spring fault zone, which extends 8 km (5 mi) along the foothills east of the Pryor Mountains and west of Horseshoe Bend (National Park Service 1981). This fault zone accounts for a series of springs along the Pryor Mountains (see "Seeps and Springs"). The Sykes Spring fault zone intersects the Madison Group (Mm) in the East Pryor Mountains (Richards 1955). The Madison Group is the major water-bearing unit in the region.

Other faults in the immediate vicinity of Big Horn Canyon are the Dryhead fault on the east side of the Pryor Mountains, Crooked Creek fault that bounds Big Pryor Mountain along the east side, and Sage Creek fault that is the median east–west fault zone bounding Big Pryor Mountain and East Pryor Mountain on the north side (Woodard 1962). The faults in the vicinity of Bighorn Canyon National Recreation Area are not currently active, but Reheis (1984b) documented evidence of Quaternary movement on the North Pryor fault since 1.4 million years ago.

Caves and Karst

Numerous known caves occur within Bighorn Canyon National Recreation Area (National Park Service 2005). The Madison Group (Mm), which makes up the walls of Bighorn Canyon, commonly hosts caves in the area. The most visible caves appear as "big holes" about 23 m (75 ft) down from the top of the cliffs of the canyon walls that surround Bighorn Lake (fig. 14). Many small caves were flooded when Bighorn Lake was created. Other small caves are known to exist in Layout Canyon and along the east-facing cliffs of the Pryor Mountains (National Park Service 1995). Caves also have developed in Bighorn Dolomite (Ob) (Hill et al. 1976).

Various dating methods help to put age constraints on the timing of the development of existing caves in the Bighorn Basin. Aluminum-26/beryllium-10 cosmogenic burial dating for fine eolian sand within the entrance area of Spence Cave (on Sheep Mountain in the Bighorn Basin, Wyoming) yielded a burial age of approximately 310,000 years. Also, a fine, white sediment deposit within Horsethief Cave on the border of Wyoming and Montana is interpreted as being the Lava Creek B fallout ash from the Yellowstone caldera. This ash layer was ejected approximately 640,000 years ago during a major eruption. Because these sediments occur within the caves, that is, the cave would have already formed when these sediments were deposited, these two dates provide minimum estimates for modern cave development in the Bighorn Basin (Stock et al. 2006).

In the past, investigators have documented many of the caves in the vicinity of Bighorn Canyon National Recreation Area (table 2). Two books, *Caves of Wyoming* (Hill et al. 1976) and *Caves of Montana* (Campbell 1978), include brief descriptions of the caves in the area. A thorough survey and inventory of the caves within Bighorn Canyon National Recreation Area has not been completed, and the potential is high for the discovery of unknown caves similar to the ones outside the national recreation area (National Park Service 2005). Such discovery is likely to include "ice caves" similar to Big Ice Cave, located outside the recreation area in the Pryor Mountains. The temperatures of the air and rock in ice caves are at or below 0°C (32°F) for a suitable period of time to accumulate perennial ice, for instance, on the floors of the caves or as ice stalactites.

The National Park Service oversees the management, including public access, of Bighorn Caverns. Based on the length of mapped passageway in Bighorn Caverns, it is deemed the largest cave in Montana (Campbell 1978). Its length suggests that other smaller caves may have greater lengths than their initial inventories show (National Park Service 2005). Bighorn Caverns is located on Crow tribal land, but is managed by the National Park Service under an agreement with the Crow Tribe (National Park Service 2005). A locked gate covers the cave entrance, making it necessary for cavers to make a reservation with park staff to enter the cave. With a 20-m- (66-ft-) deep entrance pit, cavers must rappel into the cave. At least one member of the party must have some prior experience in the cave. In general, public use of the cave is minimal, which has resulted in low management concern (National Park Service 2005).

Although Bighorn Caverns is used infrequently, it is a significant resource. The cave houses exceptional mineral crystals of selenite, aragonite, and gypsum, including rare gypsum flowers (Campbell 1978; National Park Service 2005). Staff members at the national recreation area have set up photo points to monitor theft and damage. Moreover, park staff is confident that the good relationship between the National Park Service and many of the cavers would result in immediate reporting of any damage (National Park Service 2005).

Toomey (2009) suggested "vital signs" and monitoring strategies for caves and karst landscapes, including cave meteorology, airborne sedimentation, direct visitor impacts, permanent or seasonal ice, cave drip and pool water, microbiology, stability, mineral growth, surface expression and processes, groundwater levels and quality, and fluvial processes.

Paleokarst

Another "cave and karst feature" at Bighorn Canyon National Recreation Area is "paleokarst," which formed when limestone of the Madison Group (Mm) was exposed, eroded, and dissolved during the Upper Mississippian and Lower Pennsylvanian periods (345 million to 312 million years ago). The ancient karst surface—which is marked by sinkholes, caves, and other features associated with dissolution of limestone (McCaleb and Wayhan 1969)—formed in the upper 120 m (400 ft) of the Madison Group. The paleokarst surface is filled with sediments of the Amsden Formation (PNMa). As an eastward-transgressive sea covered the area, the Amsden Formation buried the karstic topography.

Evidence of past karst is present throughout the limestone of the Bighorn Basin, including the walls of Bighorn Canyon. Paleokarst features can be distinguished from more recent (Pleistocene and Holocene) solution overprints by infillings of terrestrial sediments that are related to the overlying deposits (Sando 1988). The thick beds of the Madison Group were subjected to erosion, including dissolution of limestone, for 34 million years of exposure. The estimated duration of exposure may be one of the longest known (Sando 1988). Modern karst examples are of much shorter duration, perhaps 5 million years (Sando 1988).

Investigators associate the paleokarst exposed in the Bighorn Basin with the widespread Kaskaskia paleokarst—the most clearly exposed relict karst system in North America (Palmer and Palmer 1995). Paleokarst in Wind Cave National Park, South Dakota, also is associated with the Kaskaskia sequence (Palmer and Palmer 1995; KellerLynn 2009). Kaskaskia paleokarst is typified by sinkholes, fissures, and dissolution caves near the top of the Madison Limestone (Palmer and Palmer 1995). Most of the fissures are narrow, rarely more than 50 m (164 ft) wide and 20 m (66 ft) deep, and are concentrated in areas that were valleys when the caves were forming (Sando 1988). Dissolution caves are abundant below the paleokarst surface (Palmer and Palmer 1995). Many partly filled caves are clustered around 20 m (66 ft) to 30 m (98 ft) below the Amsden-Madison contact in Bighorn Canyon. Most of these voids resemble mixing-zone caves, which form at the freshwater-saltwater interface along seacoasts (Mylroie and Carew 1990). The transition from marine to meteoric conditions that occurred during the late Mississippian Period in this area adds credence to this hypothesis for the origin of these paleocaves (Palmer and Palmer 1995).

According to scoping participants, an investigator from the Denver Museum of Nature and Science completed a PhD dissertation on paleokarst in Bighorn Canyon National Recreation Area (National Park Service 2005), but follow-up correspondence with staff at the museum did not confirm this (Kirk Johnson, vice president of Research & Collections and chief curator, Denver Museum of Nature and Science, e-mail communication, January 1, 2011). Nevertheless, outcrops of paleokarst in the limestone of the Madison Group (Mm) afford an excellent outdoor laboratory for testing models of karst formation and the details of karst processes (Sando 1988).

Another interesting feature of the Kaskaskia paleokarst is that, in the vicinity of the national recreation area, it is a significant archive of late Quaternary environmental change and human occupations (Judson Finley, assistant professor, University of Memphis, written communication, April 18, 2011). Paleokarst features are sinks for eolian and hillslope sediments that date to the last 40,000 years. These sediments record major environmental changes prior to the Last Glacial

Maximum (approximately 18,000 years before present [BP]), the Late Glacial transition (approximately 13,000 BP), and the Pleistocene-Holocene transition (approximately 10,000 BP). The record of paleokarst sediment also tracks variations in Holocene climate, which follow broad trends in the response of biotic systems to millennial- and centennial-scale climatic events (Finley 2008).

Paleontological Resources

Fossils at Bighorn Canyon National Recreation Area are primarily marine invertebrates, which lived in the marine ecosystems that characterized the region for hundreds of millions of years (see "Geologic History"). Santucci et al. (1999) and Koch and Santucci (2003) summarized the paleontological resources at Bighorn Canyon National Recreation Area. These results are included in the map unit properties table (see "Geologic Map Data"). The fossils range in age from the Upper Ordovician Period (approximately 450 million years ago) to the Cretaceous Period (approximately 65 million years ago).

In addition, much younger fossils occur within unconsolidated deposits at the national recreation area. For example, Lucy Piety (Bureau of Reclamation) discovered a vertebra from a musk ox (genus *Ovibos*) near the causeway of Yellowtail Dam. During scoping, participants suggested that the specimen was from a bison (National Park Service 2005), but Marith Reheis (U.S. Geological Survey) confirmed the finding as a musk ox vertebra, and noted documentation of it in Reheis (1987) (Marith Reheis, geologist, U.S. Geological Survey, e-mail communications, October 30 and November 1, 2010). Reheis (1987) used the specimen to constrain the age of the alluvial fan deposit ("fan 3" at the confluence of the Bighorn and Shoshone rivers) in which the fossil was found, and to interpret the climate at the time of deposition—cold, dry arctic steppe/savannah biome on the basin floor. Chuck Repenning (U.S. Geological Survey) identified the specimen (Marith Reheis, geologist, U.S. Geological Survey, e-mail communication, October 30, 2010) and estimated its age to be between 175,000 and 130,000 years old, corresponding to the peak of the Illinoisan glaciation (C. A. Repenning, U.S. Geological Survey, written communication in Reheis 1987, p. C9).

In addition, a highly significant accumulation of Quaternary fossils occurs in the cave sediments of Natural Trap Cave, just outside Bighorn Canyon National Recreation Area, on the western slope of the Bighorn Mountains. Bighorn Caverns, which the National Park Service administers, has a sinkhole-type entrance similar to Natural Trap Cave, suggesting it may preserve fossils like those at Natural Trap Cave (Santucci et al. 2001). Fossils from Natural Trap Cave represent the longest continuous and most extensive record of late Pleistocene biota in the Northern Rocky Mountains (Gilbert and Martin 1984). Natural Trap Cave has been trapping animals at least since the Sangamon interglacial (about 125,000 to 75,000 years ago) (Gilbert and Martin 1984). Numerous animals apparently fell into the sinkhole and, as the name suggests, were trapped and died in the cave. Investigators have collected more than 30,000 specimens from Natural Trap Cave (Gilbert and Martin 1984). Three categories of mammals occur within the cave: (1) mammals that are extinct—for example, short-faced bear (*Arctodus simus*), dire wolf (*Canis diris*), American lion (*Panthera atrox*), American cheetah (*Miracinonyx trumani*), mammoth (*Mammuthus* sp.), American camel (*Camelops* sp.), woodland musk ox (*Symbos cavifrons*), bison (*Bison antiquus*), an extinct species of bighorn sheep (*Ovis catclawensis*), and four species of extinct horses (*Equus* sp.); (2) mammals that are not extinct but that did not occur near the cave at time of the appearance of white settlers in the region—for example, pygmy rabbit (*Brachylagus*), Arctic hare (*Lepus arcticus*), pika (*Ochotona* sp.), collared lemming (*Discrostonyx*), and wolverine (*Gulo gulo*); and (3) mammals that still occur or have occurred nearby in historic times—for example, Merriam's shrew (*Sorex merriami*), bat (*Myotis* sp.), cottontail rabbit (*Sylvilagus* sp.), jackrabbit (*Lepus* sp.), yellow-bellied marmot (*Marmota flaviventris*), ground squirrel (*Spermophilus* sp.), chipmunk (*Eutamias mimimus*), pocket mouse (*Perognathus* sp.), montane vole (*Microtus montanus*), sagebrush vole (*Lagurus curtatus*), prairie vole (*Microtus ochrogaster*), gray wolf (*Canis lupus*), and pronghorn (*Antilocapra americana*).

Furthermore, excavations at numerous caves and rock shelters in the Pryor Mountains and Little Mountain area east of Bighorn Canyon have documented 40,000 years of biotic change in local faunal communities. Significant sites include False Cougar Cave, Bison Pit, Prospects Shelter, and Juniper Cave (Gilbert and Martin 1984; Chomko and Gilbert 1987). Recent work at Last Canyon Cave in the foothills of the Pryor Mountains has documented a significant late Pleistocene fossil assemblage, including extinct forms of Pleistocene horse and caribou (Judson Finley, assistant professor, University of Memphis, written communication, April 18, 2011).

Although much more needs to be known about the size, extent, and condition of paleontological resources at Bighorn Canyon National Recreation Area, managers have set a strategic goal to protect these resources (National Park Service 2001). Santucci et al. (1999) reported two case incidents related to the unauthorized collecting of paleontological resources. Both incidents documented park visitors involved with the illegal collection of invertebrate fossils from Mesozoic rock units, possibly the Sundance Formation (Js), within Bighorn Canyon National Recreation Area. In both cases, the unauthorized fossil collecting occurred in the Sykes Mountain area (Santucci et al. 1999). Unfortunately, neither staff nor funding is presently available to achieve the goal of inventorying or physically protecting these fossils at Bighorn Canyon National Recreation Area (National Park Service 2001).

Santucci et al. (2009) outlined potential threats to in situ paleontological resources, and suggested monitoring "vital signs" to qualitatively and quantitatively assess the potential impacts of these threats. Paleontological vital signs include the following: erosion (geologic factors), erosion (climatic factors), catastrophic geohazards, hydrology/bathymetry, and human access/public use. The authors also presented detailed methodologies for monitoring each vital sign.

Figure 6. Yellowtail Dam. Completed in 1965, Yellowtail Dam created Bighorn Lake and provides a wide variety of recreational uses, production of hydroelectric power, and flood control. The dam is located at the mouth of Bighorn Canyon. National Park Service photograph.

Figure 7. Yellowtail Afterbay Dam. Yellowtail Afterbay Dam created a small water impoundment with an accessible shoreline at the northern end of Bighorn Canyon National Recreation Area. This dam regulates the water discharge from the power plant at Yellowtail Dam to the Bighorn River. Yellowtail Afterbay Dam is located 3.5 km (2.2 mi) downstream of Yellowtail Dam. Note the folded bedrock rising between the two dams and forming the Bighorn Canyon upstream of Yellowtail Dam. National Park Service photograph.

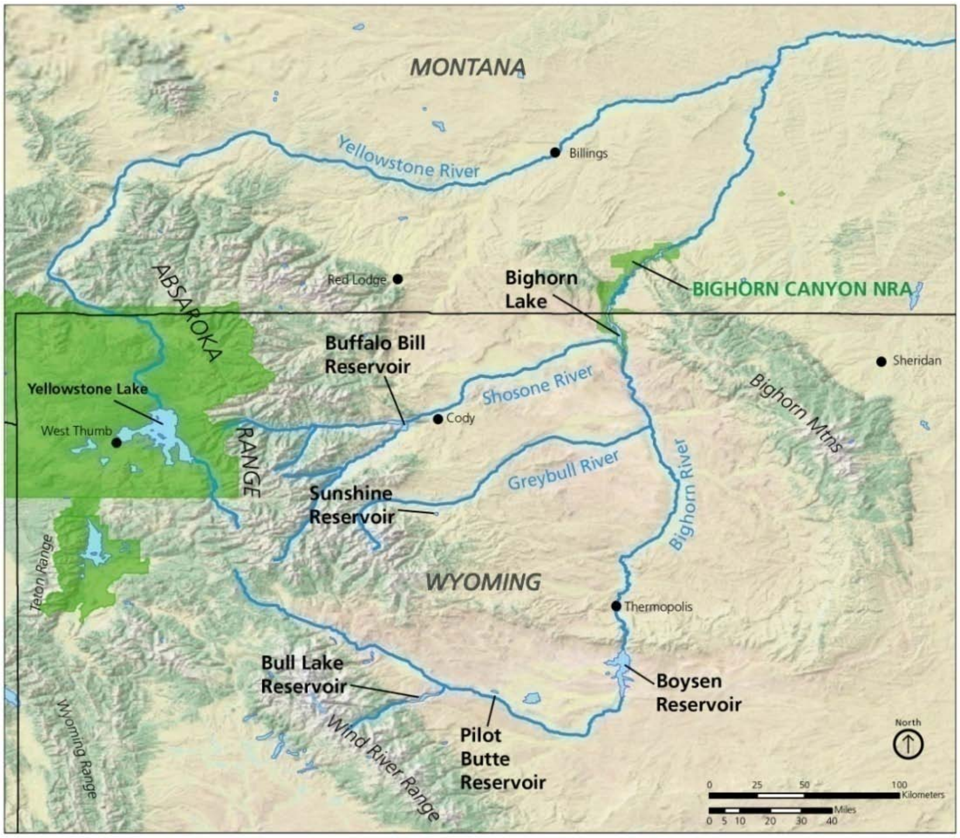


Figure 8. Major rivers and reservoirs in the Bighorn Canyon area. The primary river flowing in Bighorn Canyon National Recreation Area is the Bighorn River, which is a tributary of the Yellowstone River. The Shoshone River, which flows in the national recreation area, is a major tributary of the Bighorn River. The upper reaches of the Bighorn River are known as the Wind River. Green shading on the figure represents the boundaries of National Park Service units. Yellowstone and Grand Teton national parks are to the west of Bighorn Canyon National Recreation Area. Graphic by Philip Reiker (NPS Geologic Resources Division).

Figure 9. Entrenched meanders. A notable geologic and scenic feature at Bighorn Canyon National Recreation Area is the entrenched meanders of the Bighorn River, which cut into bedrock and through uplifted structural features, creating the distinctively sinuous path of Bighorn Canyon. National Park Service photograph.

Figure 10. Abandoned meander. The Bighorn River once flowed through the "Natural Corrals" (marked by arrow on the figure), which it later abandoned. Photograph by David Lopez (geologist/consultant).

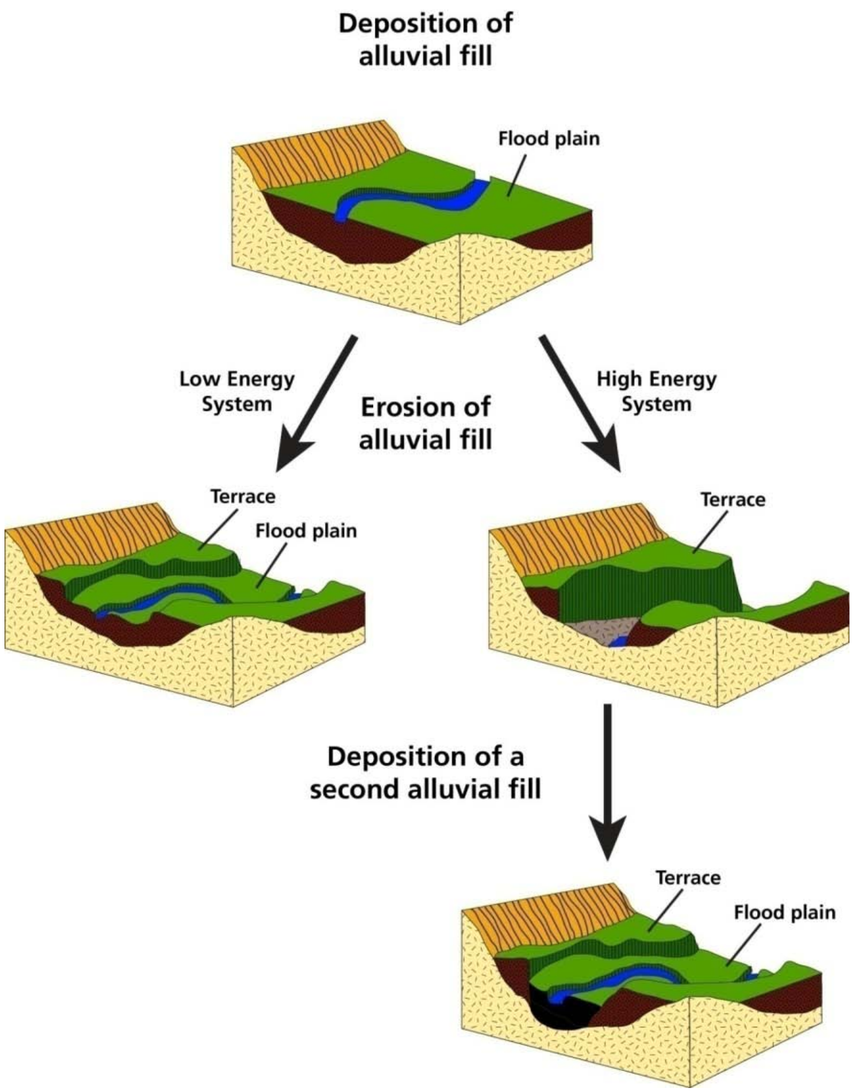


Figure 11. Terraces. The terraces that appear on the digital geologic map of Bighorn Canyon National Recreation Area occur along the Bighorn and Shoshone rivers. These well-preserved deposits provide evidence of the dynamic nature of fluvial processes and tectonic activity over the past 2.02 million years. Graphic by Philip Reiker (NPS Geologic Resources Division).

Table 1. Inventoried seeps and springs at Bighorn Canyon National Recreation Area

Name	Geologic Formation
Bear Spring	Chugwater Formation (TRc)
Cass Spring	Chugwater Formation (TRc)
Cat Track Spring	Chugwater Formation (TRc)
Finley Spring	Undetermined
Hailstorm Spring	Alluvium over Mowry Shale (Km)
Headgate Seep	Near the base of the Bighorn Dolomite (Ob), just uphill from a major fault to the west
Hidden Spring	Tensleep Sandstone
Hillsboro Main Spring	Tensleep Sandstone
Hillsboro Side Spring 1	Tensleep Sandstone
Hillsboro Side Spring 2	Tensleep Sandstone
Layout Spring	Bighorn Dolomite (Ob)–Madison Group (Mm)
North Davis Spring	Chugwater Formation (TRc)
North Trail Creek Spring	Chugwater Formation (TRc)
Last South Spring	Alluvium over Mowry Shale (Km)
Lockhart Springhouse	Tensleep Formation (PNt)
Lockhart South Spring	Chugwater Formation (TRc)
Lockhart Stockpond	Chugwater Formation (TRc)
Mason Lovell	Alluvium over Mowry Shale (Km)
Mason Lovell South	Alluvium over Mowry Shale (Km)
Pentagon	Landslide deposit over Bighorn Dolomite (Ob)–Madison Group (Mm)
Pickett's Wall Seep	Chugwater Formation (TRc)
Rick's Spring	Chugwater Formation (TRc)
Sorenson Spring	Tensleep Formation (PNt)
Trail Creek Campground Spring–Main	Tensleep Formation (PNt)
Trail Creek Campground 2	Tensleep Formation (PNt)
Tyler's Torrent	Tensleep Formation (PNt)

Source: Schmitz (2007).

Figure 12. Deformed rocks. Upheaval during Rocky Mountain uplift deformed the rocks within the Bighorn Canyon area. The folded and faulted strata of ancient marine sediments dramatically rise from Bighorn Lake. Photograph by David Lopez (geologist/consultant).

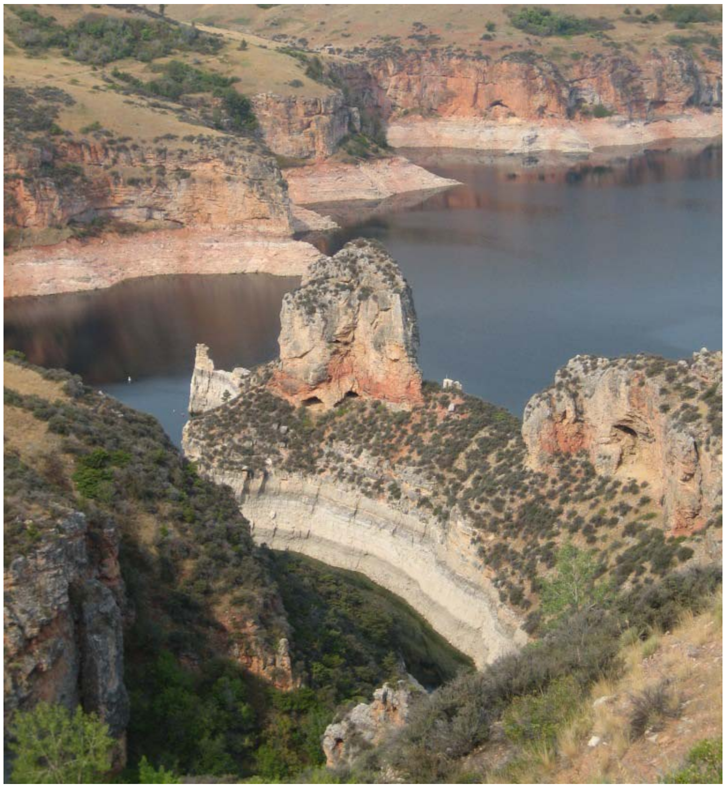


Figure 13. The Sentinel. The north side of a near-vertical fault that cuts across Bighorn Canyon includes a pillar of rock called "the Sentinel." As a result of movement on the fault, the north side of the fault is about 60 m (200 ft) higher than the south side. National Park Service photograph.

Figure 14. Caves. The most visible caves in Bighorn Canyon National Recreation Area appear as "big holes" about 23 m (75 ft) down from the top of the cliffs that surround Bighorn Lake. The caves form in the limestone of the Mississippian Madison Group (Mm). National Park Service photograph.

Geologic History

This section describes the rocks and unconsolidated deposits that appear on the digital geologic map for Bighorn Canyon National Recreation Area, the environment in which those units were deposited, and the timing of geologic events that formed the present landscape.

The geologic history of Bighorn Canyon National Recreation Area started billions of years ago in the Archean Eon and continued as layer upon layer of marine sedimentary strata were deposited in transgressive and regressive seas that advanced and retreated over the continental landmass (figs. 15 and 16). Uplift beneath the essentially horizontal layers of marine sedimentary rocks created the numerous anticlines, synclines, and domes evident in the area. Bighorn Canyon's geologic history also incorporates two periods of cave formation, and a long history of erosion, resulting in the dramatic erosional feature of the canyon itself.

Archean Eon (4 billion to 2.5 billion years ago): Ancient Continental Crust

The rocks of Bighorn Canyon National Recreation Area record a significant portion of Earth's geologic past. Mapped by Vuke et al. (2000) and Lopez (2000), the Archean granitic gneiss and schist (Ag) are the oldest rocks in Bighorn Canyon National Recreation Area and some of the oldest rocks on Earth. An exposure of these rocks crops out at the base of the Pryor Mountains, between Medicine and Layout creeks, on the western edge of the national recreation area. Although the rocks in the Bighorn Canyon area have not yet been radiometrically dated, they are part of the Wyoming Province of Archean rocks—one of only two areas in North America with rocks between 4 billion and 2.5 billion years old (fig. 17). The other area is the Superior Upland of the Great Lakes and Canada, which includes Voyageurs National Park in Minnesota (Graham 2007). These rocks are the ancient continental crust of North America.

Paleozoic Era (542 million to 251 million years ago): Thick Package of Marine Sediments

Although exposure of Archean rocks is limited in the Bighorn Canyon area, rocks from the next geologic era, the Paleozoic Era, are widespread and thick. The Paleozoic Era covers 291 million years and encompasses seven geologic periods: Cambrian, Ordovician, Devonian, Silurian, Mississippian, Pennsylvanian, and Permian, although no Silurian rocks are preserved in the area. Paleozoic rocks are part of a package of sedimentary rocks, 2,700 m (9,000 ft) thick, in the Bighorn Canyon–Hardin area (Richards 1955). These rocks formed at the western edge of North America, which was a passive margin at that time, much like today's East Coast, and in sharp contrast to the active margin along today's West Coast. Shallow seas repeatedly advanced and retreated along the western edge of the continent, depositing sediments. Sand and mud on the continental shelf became sandstone and shale; carbonate-rich sediments, including fragments of marine organisms, became limestone, and, in magnesium-rich seawater, dolomite. Fossils of marine invertebrates such as corals, crinoids, brachiopods, and bryozoans in Cambrian sedimentary rocks (Cs), Bighorn Dolomite (Ob), and the Jefferson and Three Forks formations (Dtj) indicate the presence of warm tropical seas when North America was much closer to the equator (fig. 16; Love et al. 2003).

Also deposited under marine conditions, the Mississippian Madison Group (Mm) makes up the canyon walls along the entire length of Bighorn Lake (fig. 14). The cliff-forming nature of this fossiliferous limestone makes it a particularly notable Paleozoic rock unit in the national recreation area. In addition, this unit is by far the most important cave former in the Bighorn Basin (Campbell 1978). More than 90% of the known caves in Montana formed in these strata (Campbell 1978).

Deposited in a trangressive sea, the overlying Amsden Formation (PNMa) buried (filled in) the caves within the Madison Group. As such, the Amsden Formation marks an earlier erosion cycle and period of widespread cave formation in the rock record between 345 million and 312 million years ago (see "Paleokarst").

Overlying the Amsden Formation is the Tensleep Sandstone (PNt). This formation records both marine and shoreline conditions, including eolian sands that are important oil and gas reservoirs in the surrounding region.

A thin remnant of the Permian Phosphoria Formation (Pp) marks the end of the Paleozoic Era in the Bighorn Canyon area. This formation accumulated in a shallow-water zone near deep, upwelling, nutrient-rich water (Love et al. 2003). As a result, the Phosphoria Formation contains deposits of phosphorite (calcium phosphate). In other parts of Montana and Wyoming, as well as Utah and Idaho, the Phosphoria Formation is commercially mined for the manufacture of fertilizer and the production of phosphorus. In the vicinity of Bighorn Canyon National Recreation Area, the Phosphoria Formation hosts Dryhead Agate, known for its stunning multicolored (white to pinkish to reddish-orange) banding and encrustations of crystals such as flourite. Götze et al. (2010) hypothesized that Dryhead Agate developed under hydrothermal conditions in sedimentary host rocks. In most cases worldwide, occurrences of agate are associated with volcanic host rocks such as basalt, andesite, dacite, or rhyolite; occurrences in sedimentary settings are much more rare (Götze et al. 2010).

Spanning the Paleozoic and Mesozoic eras, the Goose Egg Formation (TRPg) was deposited in a shallow lagoon or tidal flat adjacent to the Phosphoria sea.

Mesozoic Era (251 million to 65.5 million years ago): Seas Displaced by Mountain Uplift

The Mesozoic Era incorporates the Triassic, Jurassic, and Cretaceous periods. Deposition of sediments in the relatively shallow seas that covered the region continued throughout this geologic era, creating alternating beds of sandstone, shale, limestone, and dolomite. Bighorn Lake bisects the anticline in which these Mesozoic rocks are distinctively displayed.

Visually prominent on the landscape is the deep red sandstone of the Triassic Chugwater Formation (TRc), which was originally deposited across the shoreline zone of a shallow coastal shelf (figs. 16 and 18; Cavaroc and Flores 1991). Although this formation once covered the entire Bighorn Canyon area, post-uplift erosion has removed much of it. Today notable exposures within the national recreation area occur along the road to Ok-A-Beh, between Barry's Landing and Lockhart Ranch, and prominently at Horseshoe Bend. Holocene alluvium in stream channels from Trail Creek to the Dry Head Creek also contains Chugwater material (Judson Finley, assistant professor, University of Memphis, written communication, April 18, 2011).

Jurassic rocks, such as Piper (Jep), Rierdon (Jer), Swift (Jes), Gypsum Spring (Jgs), and Sundance (Js) formations crop out at the north and south ends of the national recreation area and characterize the ancient marine setting (fig. 16). The Upper Jurassic Morrison Formation, though of minimal exposure within the national recreation area, was important in reconstructing past ecosystems that include terrestrial settings. Turner et al. (2004) showed that the environmental conditions during Morrison time resembled a modern savannah, with both perennial and intermittent streams (Turner et al. 2004). The Morrison Formation is well-known throughout the western United States for its terrestrial dinosaur fossils. The Cloverly Formation (KJcm), which is undivided from the Morrison Formation in the national recreation area, also records nonmarine conditions and contains dinosaur fossils.

An extensive seaway characterizes the subsequent geologic period in the western United States. The Cretaceous Interior Seaway extended from the Arctic to the Tropics, covering the entire west-central part of the North American continent (fig. 16). The Cretaceous sea left thick deposits of shale and sandstone, including the Kootenai Formation (Kk), Thermopolis Shale (Kt), Mowry Shale (Km), Belle Fourche Formation (Kbf), and Frontier Formation (Kf) in the national recreation area. Evidence of marine life includes fish scales and teeth and oyster coquina in some of these formations (see "Geologic Map Data"). Cretaceous rocks are exposed at the northern and southern ends of the national recreation area, in the vicinity of Lime Kiln Creek and Crooked Creek, respectively.

By the end of the Mesozoic Era, the western margin of North America was tectonically active. Oceanic crust was being subducted under North America. Colliding tectonic plates provided the compressional force that caused uplift of the Rocky Mountains during a period of mountain building called the "Laramide Orogeny," which started about 70 million years ago. Mountain building and uplift ultimately displaced the interior seaway (Smith and Siegel 2000). Uplift brought Archean igneous and metamorphic rocks to the surface, notably in the Pryor Mountains west of the national recreation area, and thrusted and folded Paleozoic and Mesozoic sedimentary rocks in the Bighorn Mountains. This basement-involved uplift of originally horizontal beds of Paleozoic and Mesozoic sedimentary rock created the numerous deformed and folded rock structures such as anticlines, synclines, and domes evident in the Bighorn Canyon area.

Cenozoic Era (65.5 million years ago to present day): Creation of Bighorn Canyon

The Cenozoic Era comprises the Paleogene, Neogene, and Quaternary periods, divided into seven epochs (Paleocene, Eocene, Oligocene, Miocene, Pliocene, Pleistocene, and Holocene). With the help of Rocky Mountain uplift, fluvial downcutting and accelerated erosion created the deep Bighorn Canyon. The Bighorn River, which runs through the canyon, flows northward through the Bighorn Basin, meandering across basin fill for much of the distance, but occasionally becoming restricted in deep, narrow gorges. The river incised the canyon at a maximum rate of about 0.4 mm (0.02 in) per year during the late Pleistocene Epoch (Stock et al. 2006). The sharp bends in the canyon today represent past meanders of the river (see "Superimposed, Entrenched, Abandoned Meanders").

Although erosion dominated the late Pliocene and Pleistocene history of the Bighorn Canyon area, episodes of fluvial deposition also occurred, and are represented by stream terraces. Additionally, regional tectonism and glacial–interglacial climatic changes caused numerous major and minor stream captures (fig. 16; Reheis 1984a). For instance, the Shoshone River was captured from its Pryor Gap course by the Bighorn River around 1.45 million to 1.2 million years ago. This capture could have been caused by the reactivation of faults in the Pryor Mountains (Reheis 1984b). Alluvial terraces above modern stream level document these changes in the fluvial system (see "Terraces").

Alluvium deposited by rivers and flowing water across the land surface (i.e., sheetwash), as well as landslide deposits, bring the geologic record to the present day.

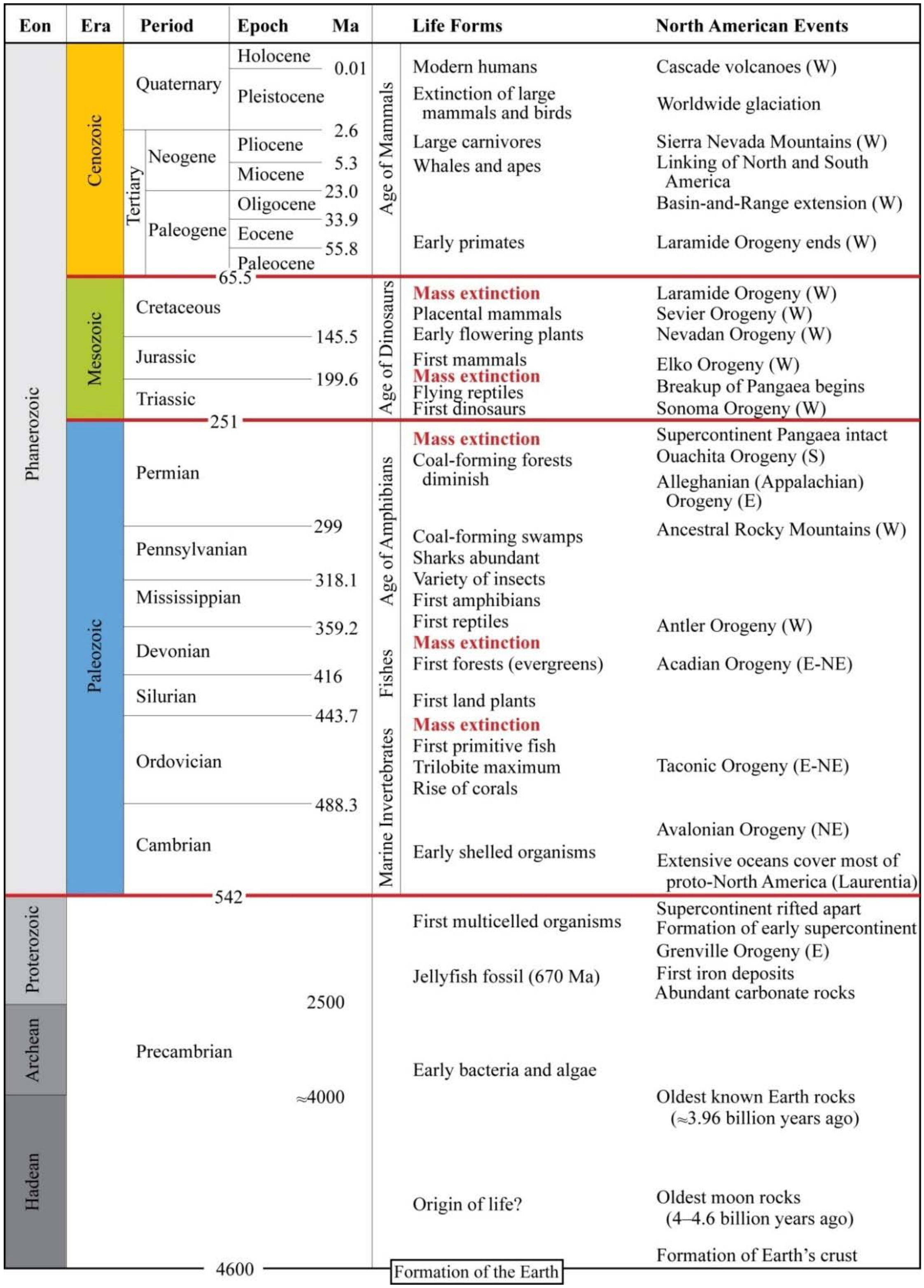


Figure 15. Geologic timescale. Included are major life history and tectonic events occurring on the North American continent. Red lines indicate major unconformities between eras. Radiometric ages shown are in millions of years (Ma). Compass directions in parentheses indicate the regional location of individual geologic events. Drafted by Trista Thornberry-Ehrlich (Colorado State University) with information from the U.S. Geological Survey (http://pubs.usgs.gov/fs/2007/3015) and the International Commission on Stratigraphy (http://www.stratigraphy.org/view/php?id=25).

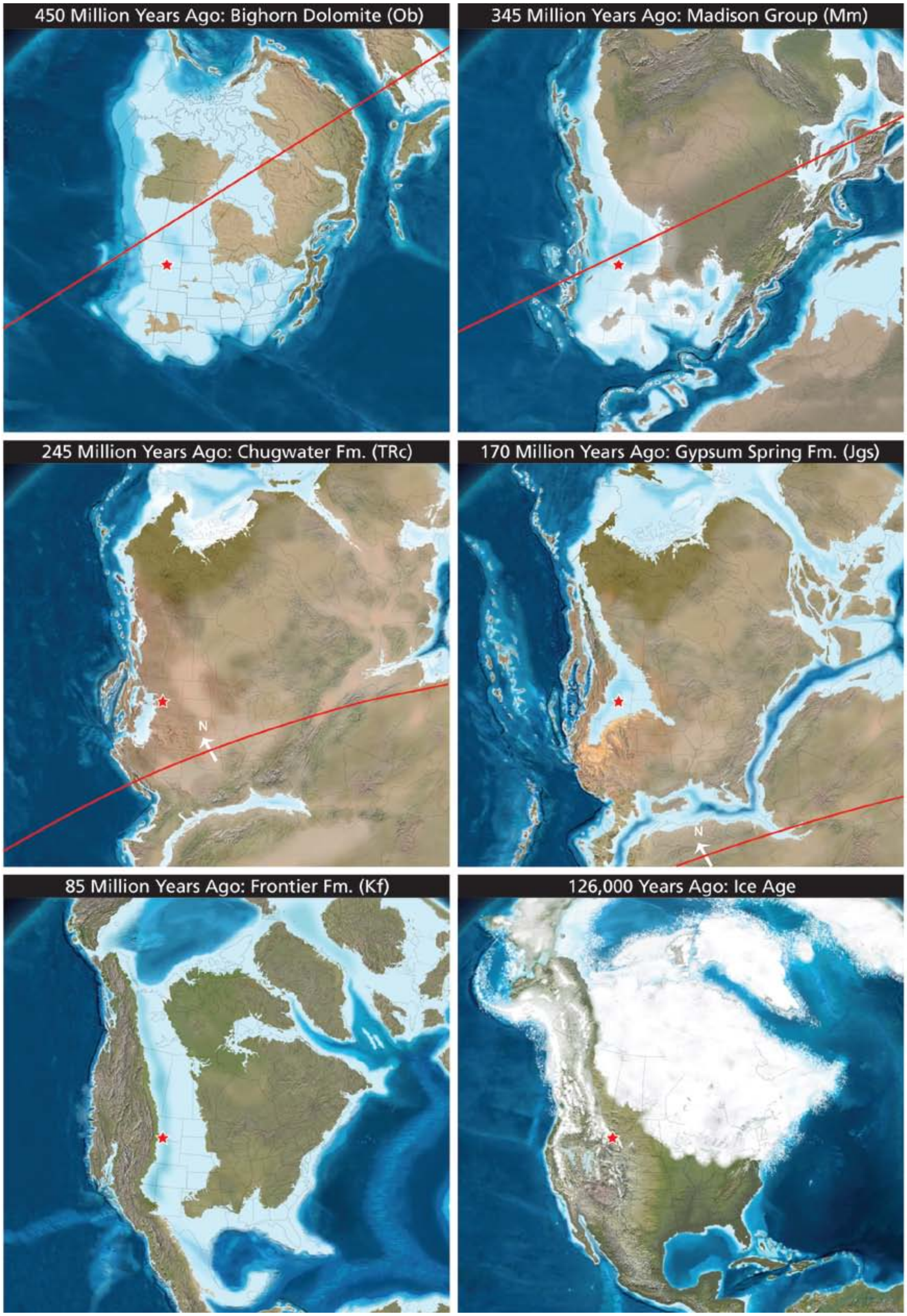


Figure 16. Bighorn Canyon National Recreation Area in the geologic past. Paleogeographic maps are presented for a variety of geologic units mapped within the park. For hundreds of millions of years, the Bighorn Canyon area was submerged beneath shallow seas. The carbonate rocks that make up much of the canyon's walls attest to this watery past. Red line represents the equator; North America was much closer to the equator during the Paleozoic Era. Red star represents the approximate location of Bighorn Canyon National Recreation Area. Fm. = formation. Graphic compiled and annotated by Jason Kenworthy (NPS Geologic Resources Division). Paleogeographic maps by Ron Blakey (Colorado Plateau Geosystems, Inc.) are available online: http://cpgeosystems.com/paleomaps.html.

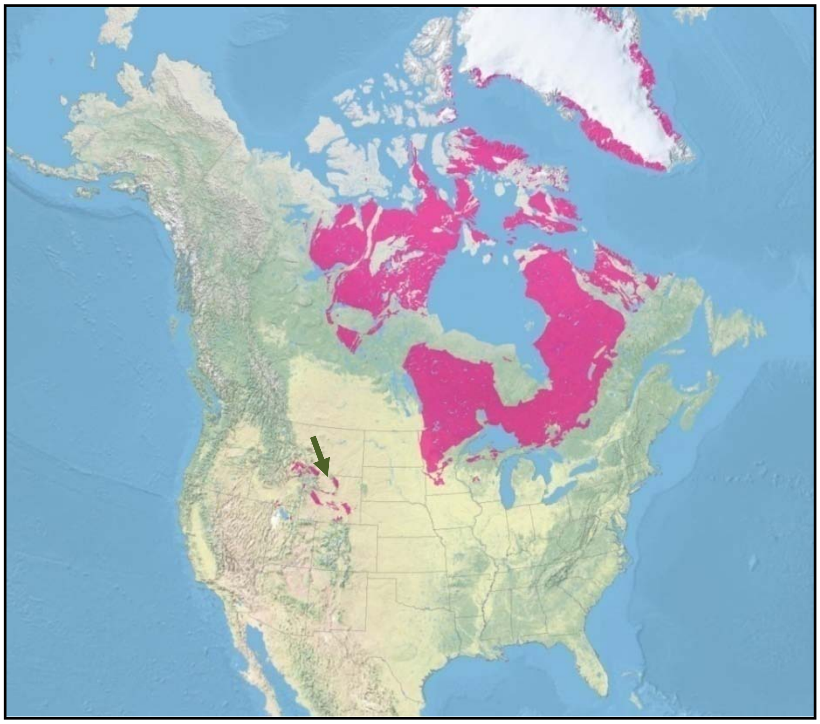


Figure 17. Archean rocks of North America. The Superior Upland (Canada and Lake Superior area) and Wyoming Province host some of the oldest rocks on Earth. Magenta shading highlights these areas on the figure. Bighorn Canyon National Recreation Area is part of the Wyoming Province. Archean rocks span from 4.0 billion to 2.5 billion years ago. Graphic compiled by Jason Kenworthy (NPS Geologic Resources Division) using USGS Digital Geologic Map of North America (Garrity and Soller 2009).

Figure 18. Chugwater Formation. The deep red color of the Chugwater Formation (Triassic sandstone; TRc) is a visually prominent unit at Horseshoe Bend in Bighorn Canyon National Recreation Area. Photograph by Katie KellerLynn (Colorado State University).

Geologic Map Data

This section summarizes the geologic map data available for Bighorn Canyon National Recreation Area. It includes a fold-out geologic map overview and a summary table that lists each map unit displayed on the digital geologic map for the park. Complete GIS data are included on the accompanying CD and are also available at the Geologic Resources Inventory (GRI) publications website: http://www.nature.nps.gov/geology/inventory/gre_publications.cfm.

Geologic Maps

Geologic maps facilitate an understanding of an area's geologic framework and the evolution of its present landscape. Using designated colors and symbols, geologic maps portray the spatial distribution and relationships of rocks and unconsolidated deposits. Geologic maps also may show geomorphic features, structural interpretations, and locations of past geologic hazards that may be prone to future activity. Additionally, anthropogenic features such as mines and quarries may be indicated on geologic maps.

Source Maps

The Geologic Resources Inventory (GRI) team converts digital and/or paper source maps into the GIS formats that conform to the GRI GIS data model. The GRI digital geologic map product also includes essential elements of the source maps including unit descriptions, map legend, map notes, references, and figures. The GRI team used the following source maps to create the digital geologic data for Bighorn Canyon National Recreation Area:

Hallberg, L. L., J. C. Case, C. A. Jessen, and A. L. Kirkaldie. 1999. Preliminary digital surficial geologic map of the Powell 30' × 60' quadrangle, Big Horn and Park counties, Wyoming and southern Montana (scale 1:100,000). Hazards Digital Map HSDM 99-3. Wyoming State Geological Survey, Laramie, Wyoming, USA.

Lopez, D. A. 2000. Geologic map of the Bridger 30' × 60' quadrangle, Montana (scale 1:100,000). Geologic Map GM-58. Montana Bureau of Mines and Geology, Butte, Montana, USA.

Pierce, W. G. 1997. Geologic map of the Cody 1 degree × 2 degree quadrangle, northwestern Wyoming (scale 1:250,000). Miscellaneous Geologic Investigations Map I-2500. U.S. Geological Survey, Washington, D.C., USA.

Rioux, R. L. 1994. Geologic map of the Sheep Mountain–Little Sheep Mountain area, Big Horn County, Wyoming (scale 1:31,680). Open-File Report OF-94-191. U.S. Geological Survey, Washington, D.C., USA.

Vuke, S. M., E. M. Wilde, D. A. Lopez, and R. N. Bergantino. 2000. Geologic map of the Lodge Grass 30' × 60' quadrangle, Montana (scale 1:100,000). Geologic Map GM-56. Montana Bureau of Mines and Geology, Butte, Montana, USA.

These source maps provided information for the "Geologic Issues," "Geologic Features and Processes," and "Geologic History" sections of this report.

Geologic GIS Data

The GRI team implements a GIS data model that standardizes map deliverables. The data model is included on the enclosed CD and is also available online (http://science.nature.nps.gov/im/inventory/geology/GeologyGISDataModel.cfm). This data model dictates GIS data structure including layer architecture, feature attribution, and relationships within ESRI ArcGIS software. The GRI team digitized the data for Bighorn Canyon National Recreation Area using data model version 1.4.

GRI digital geologic data for Bighorn Canyon National Recreation Area are included on the attached CD and are available through the NPS Integrated Resource Management Applications (IRMA) (https://irma.nps.gov/App/Reference/Search?SearchType=Q). Enter "GRI" as the search text and select the park from the unit list. Note that as of September 2011, IRMA is only compatible with the Internet Explorer browser. The following components and geology data layers are part of the data set:

- Data in ESRI geodatabase, shapefile, and coverage GIS formats (compiled map for Bighorn Canyon NRA and vicinity is only available in geodatabase format).
- Layer files with feature symbology
- Federal Geographic Data Committee (FGDC)–compliant metadata
- A help file (.hlp) document that contains all of the ancillary map information and graphics, including geologic unit correlation tables and map unit descriptions, legends, and other information captured from source maps
- An ESRI map document file (.mxd) that displays the digital geologic data.

Table 2. Geology data layers in the Bighorn Canyon National Recreation Area GIS data

Data Layer	Code	On Overview?
Geologic Attitude and Observation Points	atd	No
Geologic Point Features	gpf	No
Mine Point Features	min	No
Fault and Fold Map Symbology	sym	Yes
Folds	fld	Yes
Faults	flt	Yes
Geologic Contacts	glga	Yes
Geologic Units	glg	Yes

Note: All data layers may not be visible on the overview graphic.

Geologic Map Overview

The fold-out geologic map overview displays the GRI digital geologic data draped over a shaded relief image of Bighorn Canyon National Recreation Area and includes basic geographic information. There are five map sheets. One shows the extent of all the digital data. The other four sheets are larger-scale overviews of the park and surrounding area. For graphic clarity and legibility, not all GIS feature classes are visible on the overview. The digital elevation data and geographic information are not included with the GRI digital geologic GIS data for the park, but are available online from a variety of sources.

Map Unit Properties Table

The geologic units listed in the fold-out map unit properties table correspond to the accompanying digital geologic data. Following overall structure of the report, the table highlights the geologic issues, features, and processes associated with each map unit. The units, their relationships, and the series of events the created them are highlighted in the "Geologic History" section. Please refer to the geologic timescale (fig. 15) for the geologic period and age associated with each unit.

Use Constraints

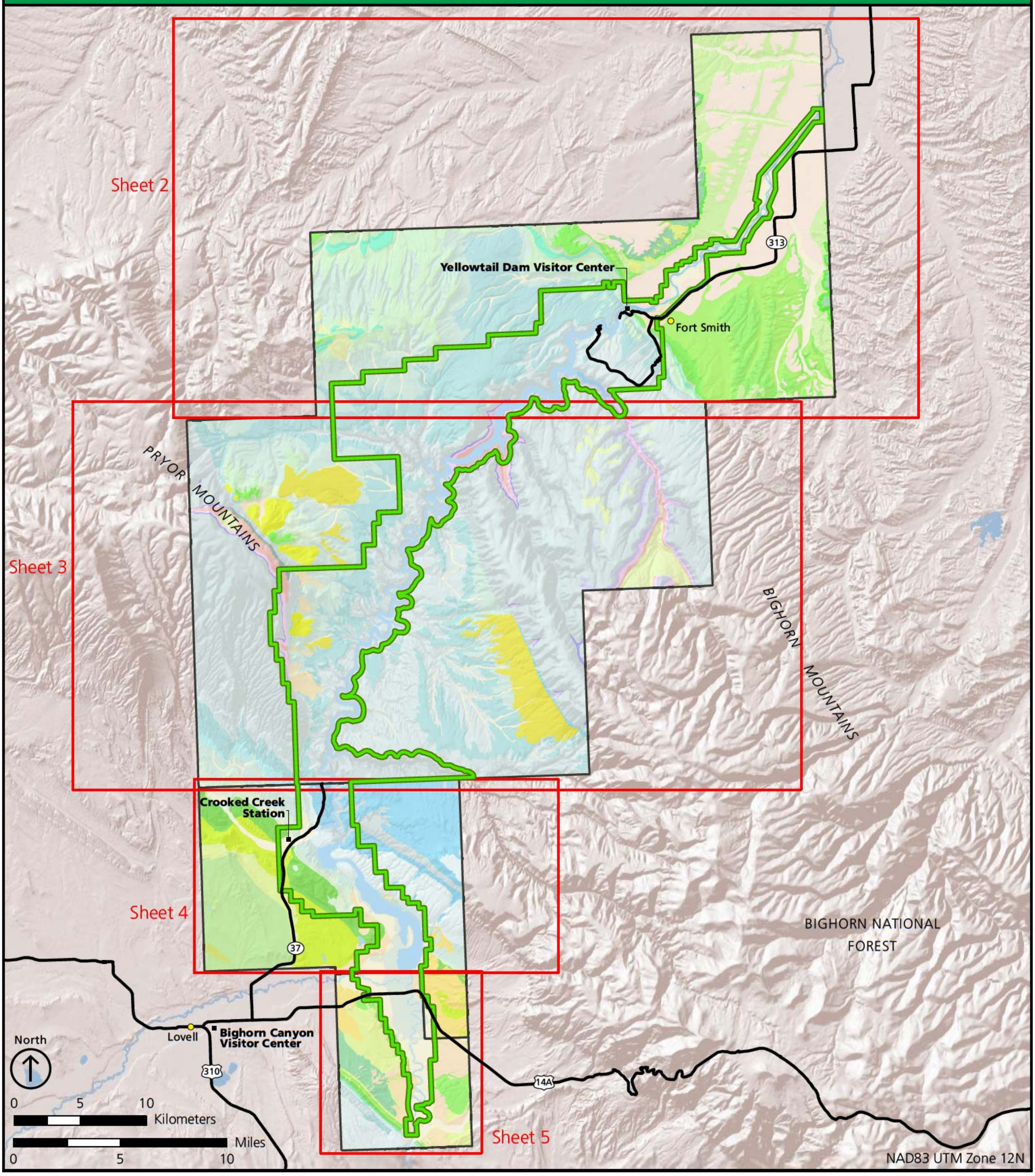
Graphic and written information provided in this section is not a substitute for site-specific investigations, and ground-disturbing activities should neither be permitted nor denied based upon the information provided here. Minor inaccuracies may exist regarding the location of geologic features relative to other geologic or geographic features on the overview graphic. Based on the three source map scales and U.S. National Map Accuracy Standards, geologic features represented here are within the horizontal distances indicated below of their true location.

Please contact GRI with any questions.

National Map Accuracy Standards		
Map Scale	Meters	Feet
1:250,000	127	417
1:100,000	51	167
1:31,680	16	53

Overview of Digital Geologic Data for Bighorn Canyon NRA

Sheet 1: Full Extent



This figure was prepared as part of the NPS Geologic Resources Division's Geologic Resources Inventory. It is an overview of compiled digital geologic data, and not a substitute for site-specific investigations.

Minor inaccuracies may exist regarding the location of geologic features relative to other geologic or geographic features on the figure. Based on the source map scales (see table at right) and U.S. National Map Accuracy Standards, geologic features represented here will be within certain distances of their true location.

The source maps used in creation of the digital geologic data product include digital Wyoming State Geological Survey and Montana Bureau of Mines and Geology publications and paper U.S. Geological Survey publications. (see literature cited section for specific sources).

Digital geologic data and cross sections for Big Horn Canyon National Recreation Area, and all other digital geologic data prepared as part of the Geologic Resources Inventory, are available online at the NPS Natural Resource Information Portal: https://nrinfo.nps.gov/Reference.mvc/Search. (Enter "GRI" as the search text and select Big Horn Canyon National Recreation Area from the unit list.)

National Map Accuracy Standards
At the map scales below, geologic features are within the indicated distances (horizontally) of their true location.

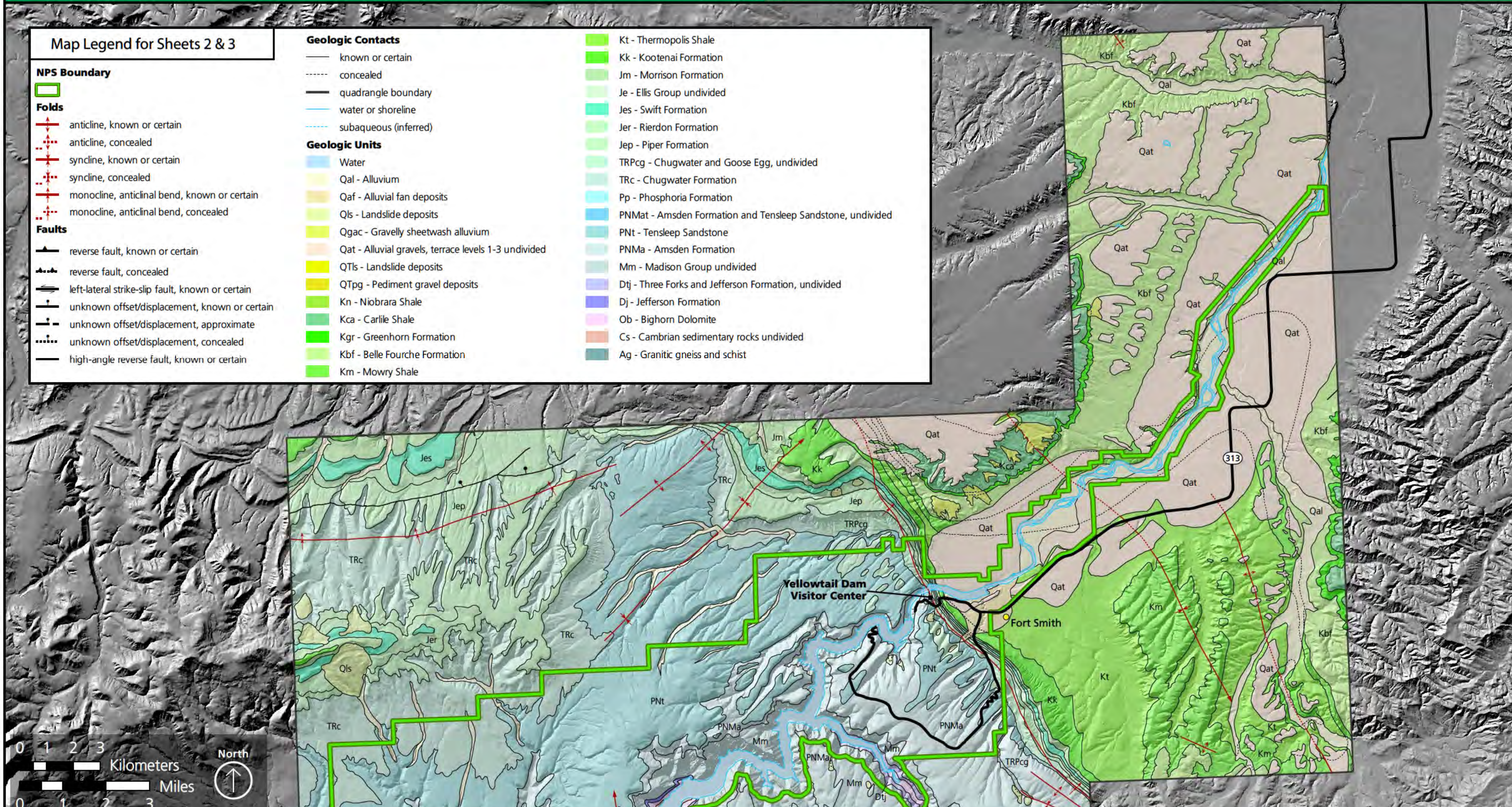
Map Scale	Meters	Feet
1:250,000	127	417
1:100,000	51	167
1:31,680	16	53

Produced by the Geologic Resources Inventory

August 2011

Overview of Digital Geologic Data for Bighorn Canyon NRA

Sheet 2

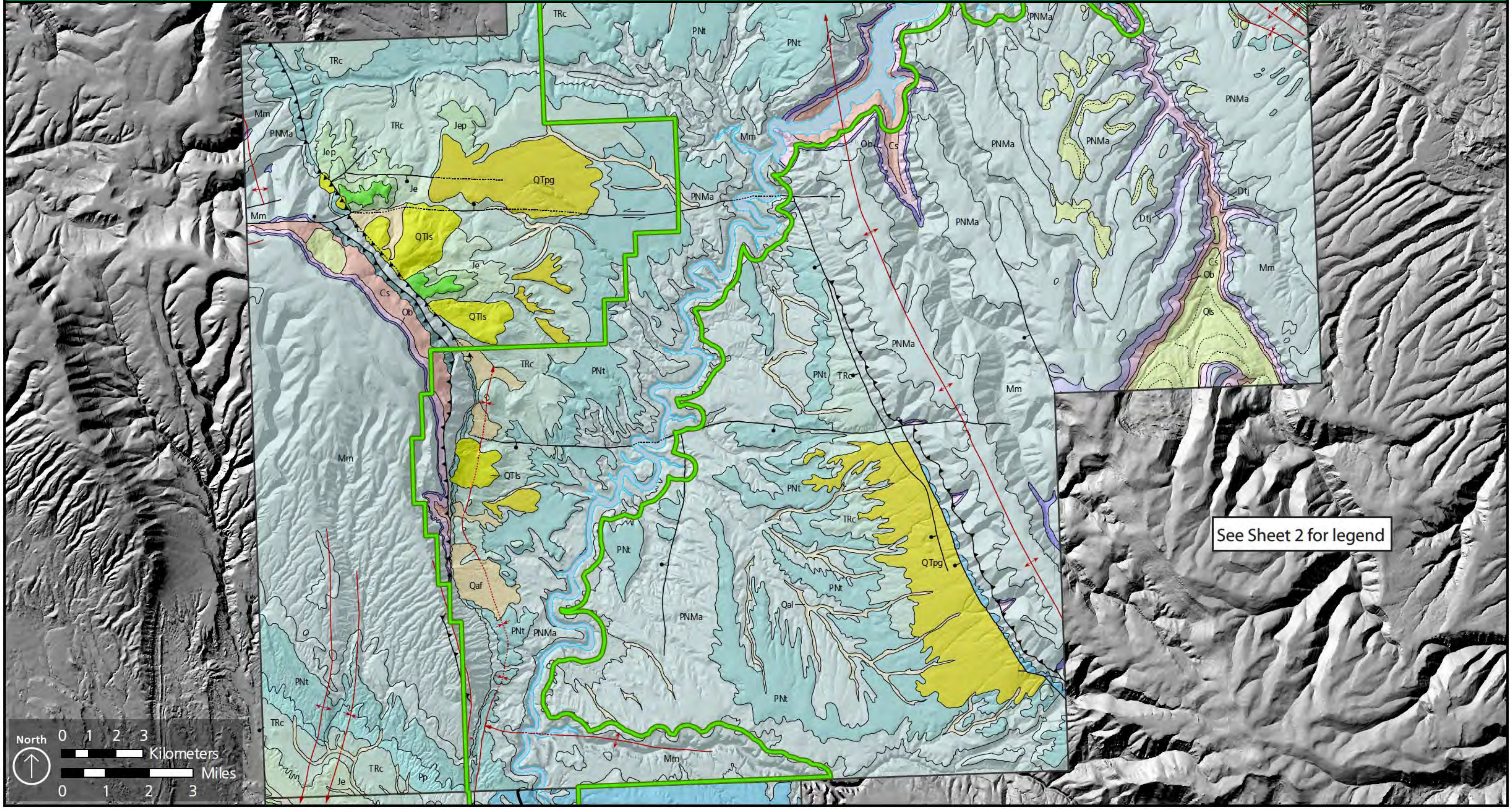


Produced by the Geologic Resources Inventory

August 2011

Overview of Digital Geologic Data for Bighorn Canyon NRA

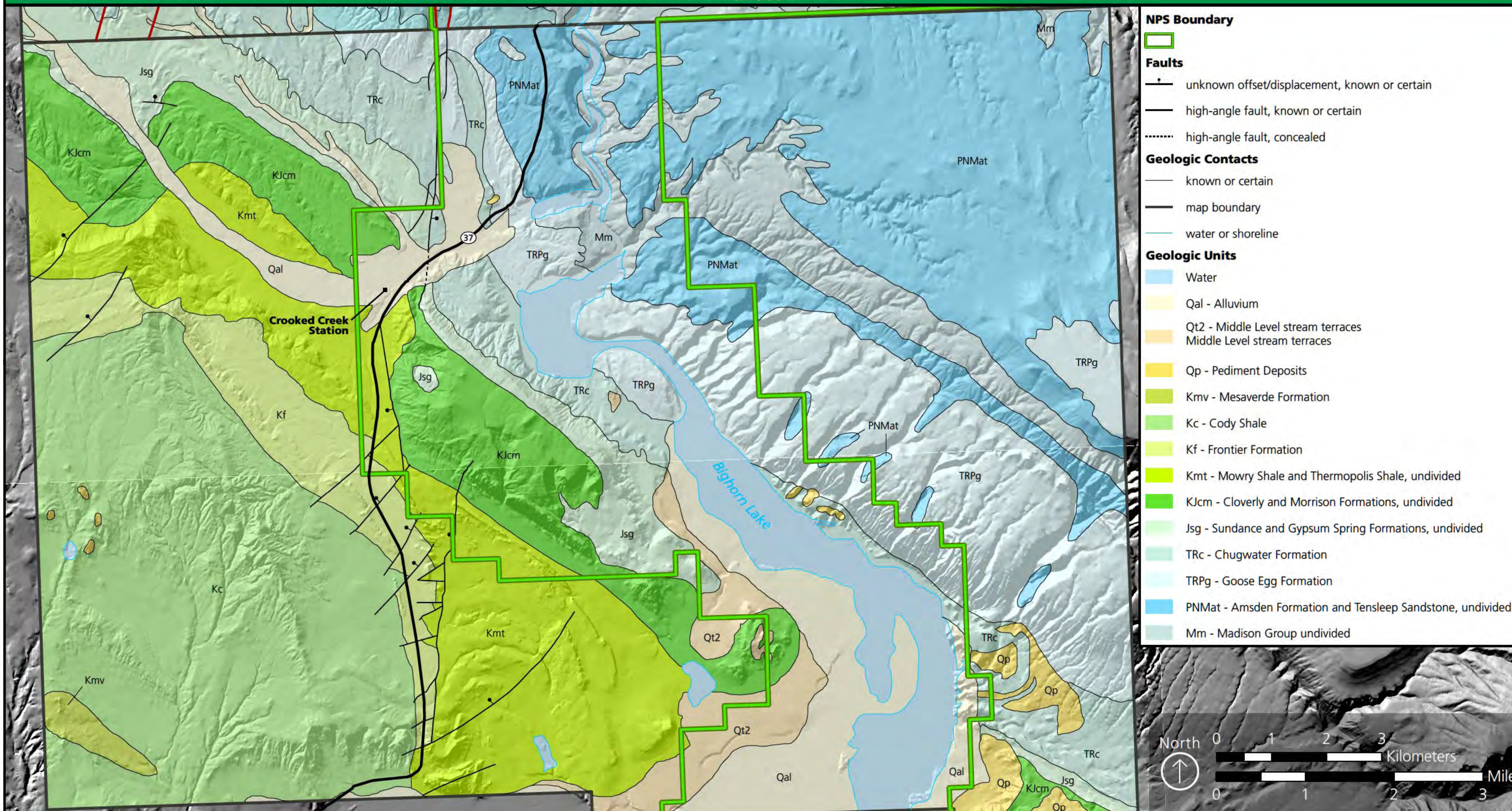
Sheet 3



August 2011

Overview of Digital Geologic Data for Bighorn Canyon NRA

Sheet 4

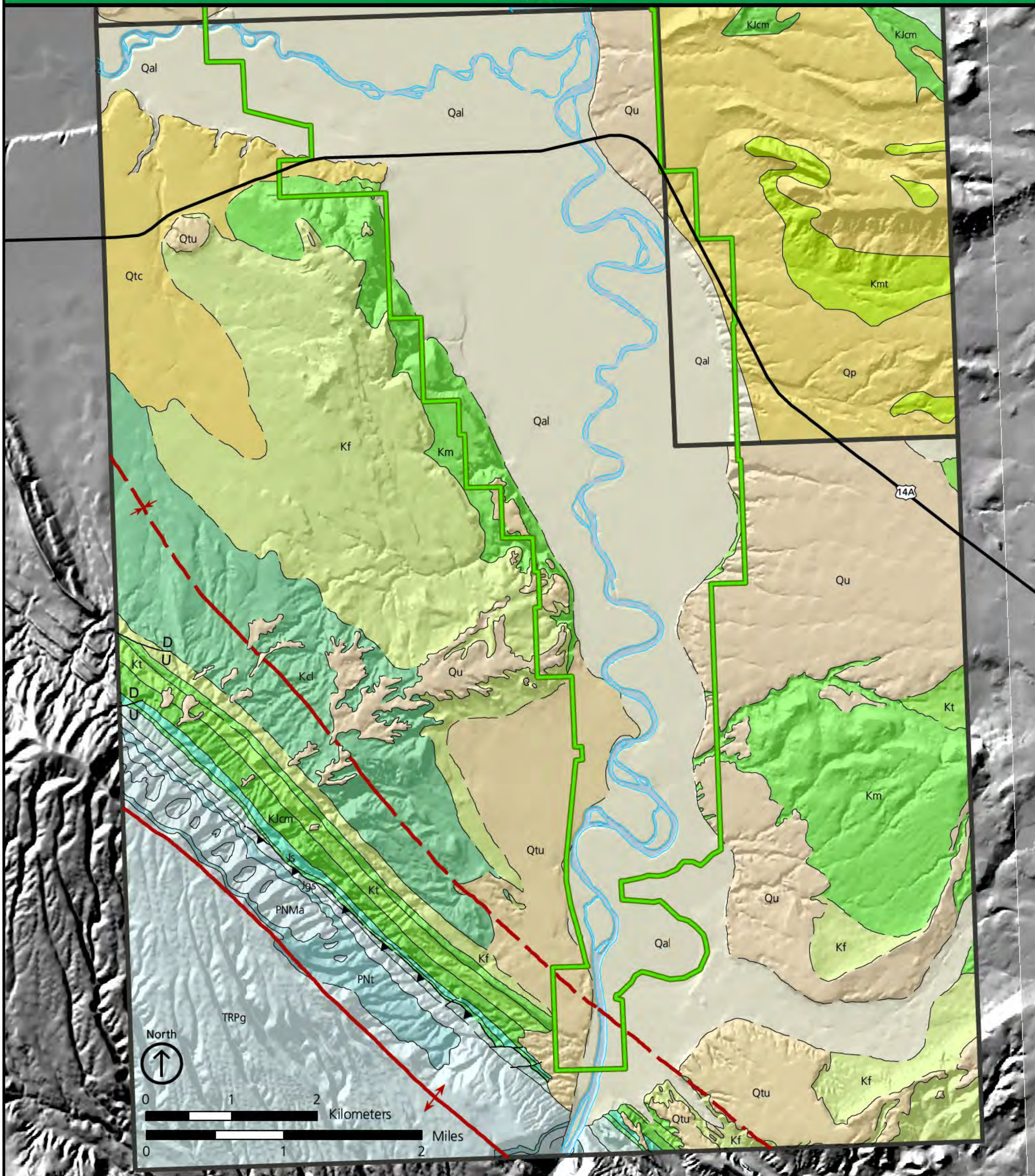


Produced by the Geologic Resources Inventory

August 2011

Overview of Digital Geologic Data for Bighorn Canyon NRA

Sheet 5



NPS Boundary

Folds
- anticline, known or certain
- syncline, known or certain
- syncline, approximate

Faults
- thrust fault, approximate
- D/U unknown offset/displacement, known or certain

Geologic Contacts
- known or certain
- approximate
- map boundary
- water or shoreline
- water or shoreline, approximate
- subaqueous (inferred)
- scratch boundary

Geologic Units
- Water
- Qal - Alluvium
- Qtc - Cody Terrace
- Qtu - Undifferentiated Terrace deposits
- Qu - Undifferentiated pediment and instream beach deposits
- Kcl - Lowermost 1900 feet of the Cody Shale
- Kf - Frontier Formation
- Km - Mowry Shale
- Kt - Thermopolis Shale
- KJcm - Cloverly and Morrison Formations, undivided
- Js - Sundance Formation
- Jgs - Gypsum Spring Formation
- TRc - Chugwater Formation
- TRPg - Goose Egg Formation
- PNt - Tensleep Sandstone
- PNMa - Amsden Formation
- Mm - Madison Group undivided

Produced by the Geologic Resources Inventory

August 2011

Map Unit Properties Table: Bighorn Canyon National Recreation Area

Rows shaded in gray indicate geologic map units that do not occur within Bighorn Canyon National Recreation Area but are included in the digital geologic data (see Attachment 1).

Age	Unit Name (Symbol)	Description	Geologic Issues	Geologic Features and Processes	Geologic History and Park Connections
QUATERNARY (Holocene and Pleistocene)	Alluvium (Qal)	Well to poorly stratified, dominantly clast-supported, and moderately well sorted gravel, sand, silt, and clay along active channels of rivers, streams, and tributaries. Includes alluvial terrace deposits less than 1.8 m (6 ft) above river or stream. Pierce (1997) included alluvial fans and glacial outwash. Thickness as much as 10 m (35 ft). Vuke et al. (2000) described the alluvium of the Big Horn River as mainly pebbles, cobbles, and boulders of limestone and dolomite, andesite and other mafic volcanic rocks, quartzite, granitic rocks, sandstone, and chert, in descending order of abundance. Most sediment in tributaries draining areas underlain by Cretaceous sandstone and shale bedrock is sand, silt, and clay (Lopez 2000).	Flooding—Areas covered by Qal have the potential to flood. Frost Heaving—Terrace soils have frost-heaving potential. Mineral Resources—Placer gold deposits along the Bighorn River prior to inundation behind Yellowtail Dam. Sand and gravel.	Seeps and Springs—**Alluvium (Qal)** over **Mowry Shale (Km)** (and other Cretaceous shales) hosts springs.	May make up terraces, alluvial fans, or glacial outwash, in addition to active stream channels.
	Alluvial fan deposits (Qaf)	Gravel, sand, silt, and clay deposited in fans by modern streams along major valley margins. Display characteristic fan-shaped map pattern and convex upward profile. Typically grade upstream into Qal. Vuke et al. (2000) mapped crudely stratified, gravel-matrix supported fan at mouth of ephemeral stream at base of Big Horn Mountains near Fort Smith. Thicknesses range from very thin at toes to as much as 15 m (50 ft) at heads of fans.	Flooding—Sites of flood-water runoff. Mineral Resources—Sand and gravel.	Seeps and Springs—Source of groundwater.	Characteristic fan-shaped deposits. Contains Lava Creek B ash, 400,000 years old (Reheis et al. 1984).
	Landslide deposits (Qls)	Rock and soil that moved downslope in discrete units, through mass-wasting processes that resulted in irregular or hummocky surfaces, with characteristically concentric swales and ridges near downslope limits. Locally, consist of internally cohesive, rotated slump blocks. Thickness 30 m (100 ft) to 46 m (150 ft).	Mass Wasting—Active landslide potential. Mineral Resources—Sand and gravel	None documented in GRI report.	Landsliding is actively modifying the landscape.
	Gravelly sheetwash alluvium (Qgac)	Poorly to moderately well stratified and well sorted gravel, sand, silt, and clay. Derived from higher level alluvial terrace deposits, and to a lesser extent from bedrock sandstone and shale. Thickness up to 25 m (82 ft).	Mass Wasting—Sheetwash promotes erosion and potentially mass wasting. Mineral Resources—Sand and gravel.	None documented in GRI report.	Sheetwash erosion is actively modifying the landscape.
QUATERNARY (Holocene and Pleistocene?)	Alluvial gravels, terrace levels 1–3, undivided (Qat)	Gravel, sand, silt, and clay underlying terraces 6 m (20 ft) to 61 m (200 ft) above present elevation of modern streams and rivers. Equivalent to Qat1–Qat3, mapped on the Billings quadrangle to the north (Lopez 1996).	Frost Heaving—Terrace soils have frost-heaving potential. Mineral Resources—Sand and gravel.	Paleontological Resources—Musk ox vertebrae (Reheis 1987). Terraces—Provides evidence of dynamic nature of fluvial processes and tectonic activity.	Records fluvial and tectonic activities over the past 2.02 million years.
	Middle level stream terraces (Qt2)	Composed of the Chapman, Powell, Sunshine, and Emblem bench terraces, the no. 2 terrace of Alden (mapped in 1932), and nos. 2, 3, 4, and 5 terraces of Andrews et al. (1947).	Frost Heaving—Terrace soils have frost-heaving potential. Mineral Resources—Sand and gravel.	Terraces—Provides evidence of dynamic nature of fluvial processes and tectonic activity.	Records fluvial and tectonic activities over the past 2.02 million years.
QUATERNARY (Pleistocene)	Pediment deposits (Qp)	Thin veneer of poorly rounded to subangular rock debris, including limestone fragments derived from Heart Mountain detachment fault masses, and surficial material deposited on smooth, gently sloping erosion surfaces cut on bedrock.	Mass Wasting—Rockfall debris.	Structural and Tectonic Features and Processes—Heart Mountain fault is not in the immediate vicinity of Bighorn Canyon National Recreation Area.	Records landscape-scale erosion.
QUATERNARY	Cody terrace (Qtc)	Unconsolidated silt and sand. 30 m (100 ft) to 49 m (160 ft) above the Shoshone River. Commonly capped by pebbles and cobbles.	Frost Heaving—Terrace soils have frost-heaving potential. Mineral Resources—Sand and gravel.	Terraces—Provides evidence of dynamic nature of fluvial processes and tectonic activity.	The most extensive and highest of a series of benches on the Shoshone River.
	Undifferentiated terrace deposits (Qtu)	Fragmentary terrace deposits (silt and sand deposits with gravel caps) along the Bighorn and Shoshone rivers and Little Dry Creek.	Frost Heaving—Terrace soils have frost-heaving potential. Mineral Resources—Sand and gravel.	Terraces—Provides evidence of dynamic nature of fluvial processes and tectonic activity.	Records fluvial and tectonic activities over the past 2.02 million years.

Rows shaded in gray indicate geologic map units that do not occur within Bighorn Canyon National Recreation Area but are included in the digital geologic data (see Attachment 1).

Age	Unit Name (Symbol)	Description	Geologic Issues	Geologic Features and Processes	Geologic History and Park Connections
QUATERNARY	Undifferentiated pediment and in stream beach deposits (Qu)	Sloping surfaces cut on bedrock and usually mantled with rock fragments.	Mass Wasting—Rockfall debris.	None documented in GRI report.	Records landscape-scale erosion.
QUATERNARY–TERTIARY (Pleistocene and Pliocene?)	Landslide deposits (QTls)	Unconsolidated mixture of soil and blocks of local bedrock along the flanks of the Pryor Mountains uplift. Surface form obliterated by later erosion.	Mass Wasting—Older (likely inactive) landslide deposits occurring at the base of the Pryor Mountains.	None documented in GRI report.	Records occurrences of past landsliding.
	Pediment gravel deposits (QTpg)	Angular and subangular, coarse gravel derived from local bedrock, mostly limestone. Pediment surface is slightly dissected. Thickness 3 m (10 ft) to 9 m (30 ft).	Mineral Resources—Gravel.	None documented in GRI report.	Forms smooth surfaces sloping away from the Pryor and Bighorn mountains.
UPPER CRETACEOUS	Mesaverde Formation (Kmv)	Upper part: Interbedded light-gray sandstone and gray shale. Lower part: Massive, light-buff, ledge-forming sandstone containing thin, lenticular coal beds. Thickness 200 m (656 ft) to 400 m (1,312 ft).	Mass Wasting—Shale may cause erosion and mass movement. Lower part forms ledges. Mineral Resources—Coal.	None documented in GRI report.	Regressive marine sequence deposited in Cretaceous Interior Seaway.
	Cody Shale (Kc)	Shale, light to dark gray, calcareous in lower half. Uppermost beds consist of sandstone, shale, and thin bentonite beds. Thickness about 680 m (2,230 ft).	Shrink-Swell Potential—Bentonite may cause shrink and swell. Mass Wasting—Shale may cause erosion and mass movement. Mineral Resources—Bentonite. Moderate oil and gas potential in shale units.	Paleontological Resources—Abundant mollusks, fish scales, and some reptile bones (Santucci et al. 1999).	Transgressive marine sequence deposited in Cretaceous Interior Seaway.
	Lowermost 580 m (1,900 ft) of the Cody Shale (Kcl)	Mainly gray shale, calcareous in lower part. Changed from Kca on source map due to symbol conflict with Carlile Shale (Rioux 1994).	Mass Wasting—Shale may cause erosion and mass movement.	Paleontological Resources—Abundant mollusks, fish scales, and some reptile bones in **Cody Shale (Kc)** (Santucci et al. 1999).	Deposited in Cretaceous Interior Seaway.
	Niobrara Shale (Kn)	Olive-gray and dark brownish-gray fissile shale with abundant, thin bentonite beds. Contains thin beds of very calcareous, laminated sandstone, siltstone, and sandy limestone near the top. Medium light-gray to pale yellowish-brown concretions up to 0.6 m (2 ft) in diameter commonly present. Contains a 3-m- (9-ft-) thick bed of calcareous shale 23 m (75 ft) above the base of the formation. Thickness 125 m (410 ft) to 213 m (700 ft). Lopez (2000) placed upper contact at change from calcareous shales to non-calcareous shales of Telegraph Creek, and basal contact below ledge-forming zone of closely spaced, fossiliferous, gray septarian concretions with veins of brown calcite.	Shrink-Swell Potential—Bentonite may cause shrink and swell. Mass Wasting—Shale may cause erosion and mass movement. Mineral Resources—Bentonite.	Paleontological Resources—Bivalves (*Anomia* sp., *Inoceramus deformis*, *Pteria nebrascana*, and *Veniella* sp.), cephalopods (*Baculites codyensis*, *Baculites mariasensis*, *Baculites sweetgrassensis*, and *Scaphites impendicostatus*), oysters (*Ostrea congesta*), ammonites (*Clioscaphites vermiformis*), and indeterminate nautiloids, gastropods, pelecypods, echinoid spines, and fish scales.	Deposited in Cretaceous Interior Seaway.
	Carlile Shale (Kca)	Very dark-gray to dark bluish-gray fissile shale, with dark-gray sandy shale at the base and in the middle. Interval about mid-section contains laminae and thin beds of argillaceous, platy, light brownish-gray to light olive-gray sandstone. The lower sandy shale contains two bentonite beds 0.6 m (2 ft) to 0.9 m (3 ft) thick. The uppermost part contains closely spaced, medium-gray calcareous septarian concretions, with thick veins of dark-brown calcite. Lopez (2000) identified septarian concretions and nodules, ranging from light-gray to dark-yellowish-orange. Thickness 76 m (250 ft) to 91 m (300 ft). Basal contact placed above last calcareous shale in the underlying Greenhorn Formation (Lopez 2000).	Shrink-Swell Potential—Bentonite may cause shrink and swell. Mass Wasting—Shale may cause erosion and mass movement. Mineral Resources—Bentonite. Septarian concretions and nodules.	Paleontological Resources—Cephalopods (*Baculites besairiei*, *Scaphites corvensis*, and *Scaphites nigricollensis*), bivalves (*Crassatellites reesidei*, *Inoceramus altus*, *Inoceramus flaccidus*, and *Veniella goniophora*), bryozoans (*Membraniporina* sp.), clams (*Nucula* sp.), oysters (*Ostrea congesta*), ammonites (*Placenticeras stantoni* and *Prionocyclus wyomingensis*), and gastropods (*Tritonium kanabense*).	Sandstone beds locally support growth of pine trees, but otherwise surface exposures are nearly bare of soil and vegetation. Deposited in Cretaceous Interior Seaway.

Rows shaded in gray indicate geologic map units that do not occur within Bighorn Canyon National Recreation Area but are included in the digital geologic data (see Attachment 1).

Age	Unit Name (Symbol)	Description	Geologic Issues	Geologic Features and Processes	Geologic History and Park Connections
UPPER CRETACEOUS	Greenhorn Formation (Kgr)	Dark bluish-gray calcareous, poorly resistant shale that weathers very light brownish-gray. Typically poorly exposed. Locally, contains numerous light-gray calcareous septarian concretions, and a thick zone of bentonitic shale or bentonite at the base. Upper contact marked by change to non-calcareous shale. Thickness 23 m (75 ft) to 35 m (115 ft).	Shrink-Swell Potential—Bentonite may cause shrink and swell. Mass Wasting—Shale may cause erosion and mass movement. Mineral Resources—Bentonite.	Paleontological Resources—Ammonites (*Allocrioceras annulatum* and *Vascoceras catinus*), bivalves (*Mytiloides labiatus* and *Plicatula* sp.), oysters (*Ostrea* sp.), cephalopods (*Scaphites delicatulus*, *Watinoceras reesidei*, *Pseudaspidoceras* sp., and *Quitmaniceras* sp.), and fish bones.	Deposited in Cretaceous Interior Seaway.
UPPER CRETACEOUS	Frontier Formation (Kf)	Thick, lenticular, gray sandstone, gray shale, brown carbonaceous shale, and bentonite. Contains large sandstone concretions. Hosts <u>Torchlight Sandstone Member</u> at top and <u>Peay Sandstone Member</u> in lower part. Interfingers with the upper part of the **Belle Fourche Formation (Kbf)**. Thickness 106 m (348 ft) to 182 m (600 ft).	Shrink-Swell Potential—Bentonite may cause shrink and swell. Mass Wasting—Shale may cause erosion and mass movement. Mineral Resources—Stucco bentonite bed mined in the area, about 60 m (200 ft) above the base, thickness 2 m (7 ft). Moderate oil and gas potential.	None documented in GRI report.	Deposited in Cretaceous Interior Seaway.
UPPER CRETACEOUS	Belle Fourche Formation (Kbf)	Dark-gray, fissile shale, containing ferruginous concretions and bentonite beds. In upper part, light-gray and brownish-gray calcareous concretions about 15 cm (6 in) to 30 cm (1 ft) in diameter, and light-brown to dark yellowish-orange concretions up to 1.2 m (4 ft) in diameter. Thickness up to 145 m (475 ft).	Shrink-Swell Potential—Bentonite may cause shrink and swell. Mass Wasting—Shale may cause erosion and mass movement. Mineral Resources—Bentonite: 1.8-m- to 2.1-m- (6- to 7-ft-) thick bentonite bed in lower part; the Soap Creek bentonite bed in the middle part, which is 60 m (197 ft) thick; and a 1.8-m- to 2.1-m- (6- to 7-ft-) thick bentonite bed in the upper part.	None documented in GRI report.	Deposited in Cretaceous Interior Seaway.
UPPER CRETACEOUS	Mowry Shale (Km)	Light-gray to medium-gray siliceous, very fine- to fine-grained sandstone and siltstone, with silvery sheen interbedded with medium dark-gray fissile shale. Shale weathers to bluish white. Locally, some sandstone beds are highly silicified, resulting in very hard quartzite. Thickness 76 m (250 ft) to 120 m (395 ft).	Shrink-Swell Potential—Bentonite may cause shrink and swell. Mass Wasting—Shale may cause erosion and mass movement. Mineral Resources—Contains several bentonite beds, typically 0.3 m (1 ft) to 1.2 m (4 ft) thick, including Clay Spur bentonite, which is 3 m (10 ft) thick and lies about 15 m (50 ft) below top. Chert pebbles.	Paleontological Resources—Fish scale impressions are common in many beds (Richards 1955).	Deposited in Cretaceous Interior Seaway.
UPPER AND LOWER CRETACEOUS	Mowry Shale and Thermopolis Shale, undivided (Kmt)	<u>Upper sequence</u>: Gray and brown shale, in part siliceous, containing numerous bentonite beds. Thickness 100 m (328 ft) to 135 m (443 ft). <u>Lower sequence</u>: Soft, black shale containing numerous bentonite beds. Thickness 120 m (394 ft) to180 m (591 ft). <u>Muddy Sandstone Member of Thermopolis Shale</u> about 60 m (197 ft) above base.	Shrink-Swell Potential—Bentonite may cause shrink and swell. Mass Wasting—Shale may cause erosion and mass movement. Mineral Resources—Bentonite. Oil and gas.	Paleontological Resources—See individual unit descriptions.	Deposited in Cretaceous Interior Seaway.
LOWER CRETACEOUS	Thermopolis Shale (Kt)	<u>Upper part</u>: Dark-gray fissile shale. <u>Lower part</u>: Dark-gray to olive-gray fissile shale with interbeds and laminae of olive-gray and light olive-gray, argillaceous sandstone. Contains thin bentonite beds and zones of iridescent, very dusky-purple to grayish-black ferruginous concretions ("ironstones"). Rioux (1994) noted round dahllite concretions at base. Lopez (2000) and Vuke et al. (2000) included the <u>Fall River Sandstone</u> with the Thermopolis Shale. The Fall River Sandstone underlies the Thermopolis Shale and is an upward-coarsening sequence of interbedded, medium dark-gray, fissile shale and fine-grained, quartzose, light brownish-gray to moderate yellowish-brown sandstone. Sandstone coarsens and beds thicken slightly up section, commonly rippled, burrowed to bioturbated, and moderately to heavily limonite and hematite stained. Combined thickness 183 m (600 ft) to 213 m (700 ft).	Shrink-Swell Potential—Bentonite may cause shrink and swell. Mass Wasting—Shale may cause erosion and mass movement. Mineral Resources—Bentonite.	Paleontological Resources—Mollusks, fish bones, sharks teeth, and marine reptile bones (David Lopez, geologist/independent consultant, written communication, January 31, 2011). Trace fossils (burrows and bioturbation).	Deposited in Cretaceous Interior Seaway.

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Age	Unit Name (Symbol)	Description	Geologic Issues	Geologic Features and Processes	Geologic History and Park Connections
LOWER CRETACEOUS	Kootenai Formation (Kk)	Reddish-brown, olive-gray, and dusky-purple bentonitic mudstone interbedded with lenticular, fine- to coarse-grained sandstone. Thin zones of light-gray nodular limestone common in upper part. Greybull Sandstone Member (thick, lenticular, fine-grained sandstone) locally present at top. Pryor Conglomerate Member at base is brown conglomerate and pebbly coarse-grained sandstone, 6 m (20 ft) to 18 m (60 ft) thick. Total thickness 59 m (195 ft) to 75 m (245 ft).	Mass Wasting—Landslides and slumps common. Mineral Resources—Bentonite.	Structural and Tectonic Features and Processes—Exposed in massive anticline. Pryor Conglomerate Member forms hogbacks.	Deposited in Cretaceous Interior Seaway. Equivalent to Clovery Formation (Wyoming terminology).
LOWER CRETACEOUS AND UPPER JURASSIC	Cloverly Formation and Morrison Formation, undivided (KJcm)	Cloverly Formation: "Rusty beds" with thin ironstone beds, sandstone, and dark-gray shale overlying lenticular channel sandstones of the Greybull Sandstone Member in the upper 49 m (160 ft). Remainder is varicolored shale and gray sandstone not easily separated from underlying Morrison Formation. Morrison Formation: Pale green and varicolored shale, mudstone, and white, lenticular, ledge-forming sandstone beds, locally cross-bedded. Combined thickness 189 m (620 ft).	Mass Wasting—Shale may cause erosion and mass movement. Sandstone beds in Morrison Formation form resistant ledges. Mineral Resources—Clay and shale. Coal. Moderate oil and gas potential.	None documented in GRI report.	Cloverly Formation named from Cloverly Post Office on eastern side of the Bighorn Basin. Nonmarine setting.
UPPER JURASSIC	Morrison Formation (Jm)	Variegated, mainly greenish-gray and pale reddish-brown mudstone. Very fine to fine-grained, quartzose, calcareous, cross-bedded sandstones are commonly present at about midsection, 1.5 m (5 ft) to 3 m (10 ft) thick but locally can be as much as 9 m (30 ft) thick. Total thickness 91 m (300 ft) to 107 m (350 ft).	Mineral Resources—Low oil and gas potential.	Paleontological Resources—Contains fragmentary dinosaur bones in the nonmarine sediments (Santucci et al. 1999). *Allosaurus* remains were discovered in the Morrison Formation on Bureau of Land Management property about 32 km (20 mi) south of the national recreation area (Santucci et al. 1999). A sauropod track locality was identified on the west side of Sykes Mountain in the upper portion of the Salt Wash Member (Engelmann and Hasiotis 1999). Contains tetrapod swim tracks (Harris and Lacovara 2004; Mickelson 2005). Turner et al. (2004) reconstructed the ancient ecosystem of the Morrison Formation. Structural and Tectonic Features and Processes—Exposed in massive anticline.	Perhaps the most well-known dinosaur-bearing formation in the western United States. Upper contact at the base of the Pryor Conglomerate Member of the **Kootenai Formation (Kk)**. Basal contact at the top of fossiliferous limy sandstone and coquina of the underlying **Swift Formation (Jes)**. Marine, freshwater, and terrestrial settings.
	Swift Formation (Jes)	Greenish-gray to yellowish-gray fine- to coarse-grained, plane-bedded or cross-bedded, glauconitic, fossiliferous sandstone or very sandy limestone coquina at the top. Medium-gray poorly resistant claystone interbedded with silty to sandy moderately resistant, greenish-gray claystone in the lower part. Greenish-gray to yellowish-gray, poorly resistant, glauconitic, fossiliferous sandstone at the base and one or more similar thin glauconitic sandstones higher in the unit. Thickness about 35 m (115 ft).	Mass Wasting—Poorly to moderately resistant to erosion. Forms resistant ledges and hogbacks. Mineral Resources—Low oil and gas potential.	Paleontological Resources—Coquina. Structural and Tectonic Features and Processes—Exposed in massive anticline.	Upper formation of **Ellis Group**. Marine depositional setting.
	Rierdon Formation (Jer)	Light-gray limestone, brownish-gray, sandy oolitic limestone, and light yellowish-gray, fine-grained calcareous sandstone. Greenish-gray to light-brown calcareous shale in lower part. Thickness about 55 m (180 ft).	Mass Wasting—Shale may cause erosion and mass movement. Sandstone forms resistant ridge; limestone forms smooth slopes. Mineral Resources—Building stone (oolitic limestone).	Structural and Tectonic Features and Processes—Exposed in massive anticline.	Middle formation of **Ellis Group**. Marine depositional setting.
	Sundance Formation (Js)	Gray-green sandstone, siltstone, and shale with thin fossiliferous limestone. Resistant glauconitic, cross-bedded sandstone at top. Thickness about 113 m (370 ft).	Mass Wasting—Top (sandstone) resistant to erosion. Shale may cause erosion and mass movement.	Paleontological Resources—Cephalopods (*Belemnites* sp.), bivalves (*Gryphaea* sp.), and star-shaped crinoid columnals (*Pentacrinus* sp.) (Richards, 1955). In the Crooked Creek area, the Rierdon Formation (part of Sundance Formation of Wyoming terminology) contains fossil fish (David Lopez, geologist/independent consultant, written communication, January 31, 2011).	Extensive, covering parts of Montana, Wyoming, Colorado, and South Dakota. Largely marine with abundant fauna.

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Age	Unit Name (Symbol)	Description	Geologic Issues	Geologic Features and Processes	Geologic History and Park Connections
UPPER AND MIDDLE JURASSIC	Sundance Formation and Gypsum Spring Formation, undivided (Jsg)	Sundance Formation (Upper and Middle Jurassic): Green and gray shale, greenish-gray, glauconitic, limy sandstone, and thin beds of gray, fossiliferous limestone. Thickness 110 m (360 ft) to 140 m (374 ft). Gypsum Spring Formation (Middle Jurassic): Red and gray shale, fossiliferous limestone, and gypsum. Gypsum bed at base up to 30 m (98 ft) thick. Total thickness 20 m (65 ft) to 70 m (230 ft).	Mass Wasting—Poorly to moderately resistant to erosion. Mineral Resources—Gypsum.	Caves and Karst—Dissolution possible in gypsum beds. Paleontological Resources—See individual unit descriptions.	See individual unit descriptions.
MIDDLE JURASSIC	Gypsum Spring Formation (Jgs)	Red-brown silty shale with interbedded gypsum, limestone, and dolomite. Thickness about 61 m (200 ft).	Mass Wasting—Poorly consolidated and readily eroded. Mineral Resources—Massive, white gypsum bed at base.	Caves and Karst—Dissolution possible in gypsum beds.	Occurs in Yellowstone province, Snake River basin, Greater Green River basin, Wasatch uplift, Uinta basin, and Uinta uplift. Represents basal deposits of transgressive sea.
MIDDLE JURASSIC	Piper Formation (Jep)	Upper part: Brownish-red claystone, with scattered streaks of green claystone interbedded with brownish-red siltstone. Middle part: White dolomitic limestone bed and gray-to-lavender chalcedony nodules. Medium-gray limestone and white dolomitic limestone interbedded with red claystone and white gypsum. Lower part: Dark brownish-red claystone, with lenses of white gypsum underlain by massive white gypsum, interbedded with some brownish-red claystone, siltstone, and medium-gray limestone. Thickness 23 m (75 ft) to 46 m (150 ft).	Mass Wasting—Forms resistant ledge below smooth slopes of the **Rierdon shales (Jer)**. Mineral Resources—Gypsum. Chalcedony nodules.	Caves and Karst—Dissolution possible in gypsum beds. Structural and Tectonic Features and Processes—Exposed in massive anticline.	Includes distinctive "red beds." Named for town of Piper, Montana. Lower formation of **Ellis Group**. Marine depositional setting.
JURASSIC	Ellis Group, undivided (Je)	Consists of the **Swift Formation (Jes)**, **Rierdon Formation (Jer)**, and **Piper Formation (Jep)**. See descriptions of individual units.	Mass Wasting—Poorly to moderately resistant to erosion. **Swift Formation (Jes)** forms ledges. Mineral Resources—Oil and gas. Gypsum.	Structural and Tectonic Features and Processes—Forms hogbacks. Part of Montana folded belt province.	Marine depositional setting. Equivalent to Sundance Formation of Wyoming terminology.
TRIASSIC	Chugwater Formation (TRc)	Interbedded moderate reddish-brown, fine-grained sandstone, siltstone, and mudstone. Thin light-gray limestone bed is present near the top. Rioux (1994) noted thin sandstone beds near the top and dolomite lenses. Gypsum beds are common in lower part. Typically, strike valleys develop at the base of the Chugwater Formation above resistant rocks of the **Phosphoria (Pp)** and **Tensleep (PNt)** formations. Thickness 137 m (450 ft) to 250 m (820 ft).	Mass Wasting—Poorly to moderately resistant to erosion. Parent material for highly erodible soils. Mineral Resources—Gypsum thickens to about 3 m (10 ft) locally.	Seeps and Springs—Produces groundwater high in sulfates (attributed to gypsum). Hosts springs. Paleontological Resources—The only fossils from this unit occur in the gray chert pebbles within the basal conglomerate, which Richards (1955) reported as Pennsylvanian fauna eroded from the **Tensleep Formation (PNt)** or **Amsden Formation (PNMa)**. Structural and Tectonic Features and Processes—Exposed in massive anticline.	Very scenic, brick-red color. Deposited across the shoreline zone of a shallow coastal shelf.
LOWER TRIASSIC AND PERMIAN	Chugwater Formation and Goose Egg Formation, undivided (TRPcg)	Chugwater Formation: Red to dark reddish-brown, generally thin-bedded, locally cross-bedded, calcareous or gypsiferous, fine-grained and very fine-grained sandstone and siltstone. Goose Egg Formation: Light-gray, very light-gray or pink, finely crystalline gypsum, interbedded with red, fine-grained sandstone and siltstone. Occurs only locally. Combined thickness about 150 m (492 ft).	Mass Wasting—Potential for erosion. Mineral Resources—Gypsum.	Caves and Karst—Dissolution possible in gypsum beds. Structural and Tectonic Features and Processes—Exposed in massive anticline.	Prominent, resistant 1.5-m- (5-ft-) thick, light-gray limestone ledge about 35 m (115 ft) below the top of the **Chugwater Formation (TRc)**.
LOWER TRIASSIC AND PERMIAN	Goose Egg Formation (TRPg)	Upper unit: Greenish-gray shale, some dolomite and gypsum. Thickness 15 m (50 ft). Middle unit: Gray, resistant cherty dolomitic limestone and dolomite. Thickness 27 m (90 ft). Lower unit: Mostly red shale with some gypsum, dolomite; thin phosphorite and blue gray chert at top, probably equivalent to the **Phosphoria Formation (Pp)** to the west. Thickness 40 m (130 ft). Total thickness about 82 m (270 ft). Pierce (1997) described the formation as follows: Red sandstone and siltstone, white gypsum, and a few thin beds of dolomite. Thickness about 50 m (164 ft).	Mass Wasting—Shale may cause erosion and mass movement. Mineral Resources—Gypsum. Phosphorite.	Caves and Karst—Dissolution possible in gypsum beds.	Deposited in a shallow lagoon or tidal flat adjacent to the Phosphoria sea. The hematitic rocks suggest marginal marine, high humidity, and warm arid climate. Chemically deposited rocks suggest submergence of detrital source area or increased evaporation rate.

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Age	Unit Name (Symbol)	Description	Geologic Issues	Geologic Features and Processes	Geologic History and Park Connections
PERMIAN	Phosphoria Formation (Pp)	Light-gray limestone, sandstone and quartzite, commonly grayish-pink, cherty. Lopez (2000) noted that because the formation is a very thin remnant, it was mapped separately only where scale allowed, but otherwise included with the **Tensleep Formation (PNt)**. Thickness 3 m (10 ft) to 15 m (50 ft).	Mineral Resources—Radioactive layers (uranium). Locally, a reddish-brown variety of chert, known as Dryhead Agate, mined and collected for lapidary purposes. Phosphorite. Hydrocarbon source rock.	None documented in GRI report.	Cyclic marine deposit (upwelling and geothermal conditions).
PENNSYLVANIAN	Tensleep Sandstone (PNt)	Very light-brown to light yellowish-brown, very fine-grained to medium-grained, well-sorted, well-rounded, cross-bedded, porous-to-tightly cemented sandstone. Locally, contains some thin limestone beds, nodular chert, dolomite, or silty green shale. Also, locally silicified to form quartzite (Lopez 2000). Thickness up to 61 m (200 ft).	Mass Wasting—Shale may cause erosion and mass movement. Mineral Resources—High oil and gas potential. Nodular chert.	Seeps and Springs—Source of groundwater. Hosts springs. Paleontological Resources—Foraminifera (*Bradyina* sp.) and fusulinids (*Climacammina* sp., *Fusulina rockymontana*, *Pseudostaffella* sp., *Wedekindellina euthysepta*, and *W. excentrica*) (Richards 1955). Structural and Tectonic Features and Processes—Exposed in massive anticline.	Named for extensive exposures in walls of lower canyon of Tensleep Creek in Bighorn and Powder River basins, Big Horn County, Wyoming. Extends along flanks of Bighorn Range. Marine and shoreline setting.
UPPER AND MIDDLE PENNSYLVANIAN, MIDDLE PENNSYLVANIAN TO UPPER MISSISSIPPIAN	Amsden Formation and Tensleep Sandstone, undivided (PNMat)	<u>Tensleep Sandstone (Upper and Middle Pennsylvanian)</u>: Light-gray, well-sorted, cross-bedded and massive sandstone. Thin beds of gray limestone and dolomite in lower part. Thickness 40 m (131 ft) to 75 m (246 ft). <u>Amsden Formation (Middle Pennsylvanian to Upper Mississippian)</u>: Red shale contains some gray, dolomitic limestone and chert and hematite nodules. Basal part commonly red siltstone or sandstone. Thickness 45 m (147 ft) to 90 m (295 ft).	Mass Wasting—Shale may cause erosion and mass movement. Mineral Resources—Uranium. Oil and gas. Chert and hematite nodules.	See individual unit descriptions.	See individual unit descriptions.
LOWER PENNSYLVANIAN AND UPPER MISSISSIPPIAN	Amsden Formation (PNMa)	Light-red to red, purple, green, or light-brown shale, siltstone, and sandstone, interbedded with very light-gray to gray limestone and dolomite that locally contains chert. Lopez (2000) also included mudstone in description. Thickness ranges from 43 m (140 ft) to 91 m (300 ft). Locally, tectonically thinned to only a few feet along the margins of Pryor Mountains uplift (Lopez 2000).	Mass Wasting—Shale may cause erosion and mass movement. Mineral Resources—Uranium. Low oil and gas potential.	Paleokarst—Unconformably overlies karst surface developed on limestone of the **Madison Group (Mm)**. Paleontological Resources—Marine invertebrates, including sponge spicules, fusulinids (*Climacammina* sp., *Pseudostaffella* sp., and *Profusulinella* sp.), and foraminifera (*Calcitornellids*, *Bradyina* sp., and *Tetrataxis* sp.) (Richards 1955).	Represents widespread Kaskaskia paleokarst surface. Characteristically produces pink staining on underlying cliffs of **Madison Group (Mm)**. Deposited in a transgressive sea.
MIDDLE MISSISSIPPIAN	Madison Group, undivided (Mm)	Light-gray to light brownish-gray limestone and dolomitic limestone. Thick-bedded to massive in the upper part (<u>Mission Canyon Limestone</u>) and thin-bedded to thick-bedded in the lower part (<u>Lodgepole Limestone</u>). Also contains thin, interbedded gray shales. Locally, at base, is <u>Cottonwood Canyon Member</u> (Lower Mississippian and Upper Devonian), which consists of gray dolomite, dolomitic siltstone, and sandstone about 5 m (16 ft) thick. Total thickness 149 m (490 ft) to 305 m (1,000 ft).	Mass Wasting—Shale may cause erosion and mass movement. Mineral Resources—Upper massive beds of very pure limestone are quarried in the southwest part of the Pryor Mountains for industrial uses and lime production. Oil and gas potential; geologic and production zones A–D developed by oil exploration (McCaleb and Wayhan 1969). Collapse features may host low-grade uranium deposits.	Seeps and Springs—Major water-bearing unit in the region. Hosts springs. Caves and Karst—Fractures. Collapse features and caves are common at the upper karst surface, which is infilled with shale from the overlying **Amsden Formation (PNMa)**. Provides evidence of past cave formation and hosts present-day caves. Caves within Madison Group may preserve Quaternary fossils. Paleontological Resources—Highly fossiliferous formation within the national recreation area. Produces abundant marine invertebrates, including bryozoans, corals, brachiopods, and crinoids (Santucci et al. 1999). Crushing teeth of the cochliodont (fish) *Hybodus* also occur.	Historical lime production at Lime Kiln Creek along the Ok-A-Beh road. Forms the walls of Bighorn Canyon. Widespread across Idaho, Montana, North Dakota, South Dakota, and Wyoming. Marine depositional setting.

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Age	Unit Name (Symbol)	Description	Geologic Issues	Geologic Features and Processes	Geologic History and Park Connections
UPPER DEVONIAN	Three Forks Formation and Jefferson Formation, undivided (Dtj)	Three Forks Formation: Light gray to brownish-gray thin- to medium-bedded, silty to shaly limestone and dolomite interbedded with greenish-gray shale, siltstone, and sandstone. Jefferson Formation: Dark brownish-gray, dolomitic, partly granular limestone. Combined thickness about 60 m (198 ft).	Mass Wasting—Shale may cause erosion and mass movement. Mineral Resources—Low oil and gas potential. Has fetid smell of petroleum.	Paleontological Resources—See individual unit descriptions.	Occurs in central Montana uplift; Montana folded belt and Yellowstone provinces; and Bighorn, Wind River, and Greater Green River basins. Maine depositional setting.
UPPER DEVONIAN	Jefferson Formation (Dj)	Dolomitic limestone, light brownish-gray, fetid, poorly exposed, typically occurs as float above **Bighorn Dolomite (Ob)**. Total thickness about 76 m (250 ft).	Mineral Resources—Dark-colored dolomites have fetid smell of petroleum.	Paleontological Resources—Marine invertebrates. Brachiopods (*Atrypa* sp.) and coral (*Amplexiphyllum* sp.) (Richards 1955).	Marine deposit, probably deposited in shallow water.
MIDDLE ORDOVICIAN	Bighorn Dolomite (Ob)	Very light-gray to very pale-orange micritic dolomite and dolomitic limestone. Has characteristic pock-marked surface due to differential weathering. Thickness 120 m (394 ft) to 152 m (500 ft).	Mass Wasting—Upper part thin- to thick-bedded; lower part massive and resistant. Forms resistant cliffs in lower reaches of deep canyons. Mineral Resources—Moderate oil and gas potential. Chert.	Caves and Karst—Potential for caves. Cavities have connection to local legends of “Little People” who reside in the Pryor Mountains (Lopez 1995). Seeps and Springs—Hosts springs. Paleontological Resources—An archaeogastropoda was discovered at Bighorn Canyon (Santucci et al. 1999).	Named for Bighorn Mountains. Marine depositional setting.
MIDDLE AND UPPER CAMBRIAN	Cambrian sedimentary rocks, undivided (Cs)	Light-red sandstone and quartzite, greenish-gray shale and sandy shale, gray thin-bedded limestone and greenish-gray flat-pebble limestone conglomerate. Thickness 213 m (700 ft) to 244 (800 ft).	Mass Wasting—Slumping possible, notably in Bull Elk Basin. Erosion potential.	None documented in GRI report.	Equivalent to the Flathead, Gros Ventre, and Gallatin formations of Wyoming, or the Flathead, Wolsey, Meagher, Park, and Pilgrim formations of Montana.
ARCHEAN	Granitic gneiss and schist (Ag)	Pale- to moderate-red granitic gneiss, medium dark-gray, quartzofeldspathic gneiss, biotite-hornblende schist, quartzite, and aplite. Contains mafic dikes and quartz veins.	None documented in GRI report.	None documented in GRI report.	Oldest rocks in the national recreation area and some of the oldest on Earth. Part of the Wyoming Province of Archean rocks.

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://geomaps.wr.usgs.gov/parks/misc/glossarya.html. Definitions are based on those in the American Geological Institute Glossary of Geology (fifth edition; 2005).

absolute age. The geologic age of a fossil, rock, feature, or event in years; commonly refers to radiometrically determined ages.

aggradation. The building-up of Earth's surface by depositional processes, specifically the upbuilding performed by a stream in order to establish or maintain uniformity of grade or slope.

alluvial fan. A fan-shaped deposit of sediment that accumulates where a hydraulically confined stream flows to a hydraulically unconfined area. Commonly out of a mountainous area into an area such as a valley or plain.

alluvium. Stream-deposited sediment.

anticline. A convex-upward ("A" shaped) fold. Older rocks are found in the center.

aplite. A light-colored intrusive igneous rock characterized by a fine-grained texture. Emplaced at a relatively shallow depth beneath Earth's surface.

aquifer. A rock or sedimentary unit that is sufficiently porous that it has a capacity to hold water, sufficiently permeable to allow water to move through it, and currently saturated to some level.

Archaeogastropoda. A taxonomic order of sea snails used in older classifications of gastropods (i.e., snails and slugs). Also known as Aspidobranchia.

argillaceous. Describes a sedimentary rock composed of a substantial amount of clay.

ash (volcanic). Fine material ejected from a volcano.

back thrusting. Thrust faulting toward the interior of an organic belt, with the direction of displacement contrary to tectonic transport.

base level. The lowest level to which a stream can erode its channel. The ultimate base level for the land surface is sea level, but temporary base levels may exist locally.

basin (structural). A doubly plunging syncline in which rocks dip inward from all sides.

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

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

bedding. Depositional layering or stratification of sediments.

bed load. The part of the total stream load that is moved on or immediately above the stream bed, such as the larger or heavier particles (boulders, pebbles, and gravel) transported by traction or saltation along the bottom; the part of the load that is not continuously in suspension or solution.

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

bentonite. A soft clay or greasy claystone composed largely of smectite. Formed by the chemical alteration of glassy volcanic ash in contact with water.

block (fault). A crustal unit bounded by faults, either completely or in part.

blowout (geomorphology). A general term for a small saucer-, cup-, our trough-shaped hollow or depression, formed by wind erosion on a preexisting dune or other sand deposit, especially in an area of shifting sand or loose soil, or where protective vegetation is disturbed or destroyed; the adjoining accumulation of sand derived from the depression, where recognized, is commonly included. Some blowouts may be many kilometers in diameter.;

brachiopod. Any marine invertebrate belonging to the phylum Brachiopoda, characterized by two bilaterally symmetrical valves that are commonly attached to a substratum but may also be free. Range—Lower Cambrian to the present.

breakdown (cave). The collapse of the ceiling or walls of a cave; also, the accumulation of debris thus formed.

bryozoan. Any invertebrate belonging to the phylum Bryozoa and characterized by colonial growth, a calcareous skeleton, or, less commonly, a chitinous membrane, and a U-shaped alimentary canal, with mouth and anus. Range: Ordovician to Holocene, with possible downward extension into the Upper Cambrian.

calcite. A common rock-forming mineral: $CaCO_3$ (calcium carbonate).

calcitornellids. A type of encrusting foraminifera.

chalcedony. A variety of quartz that is commonly fibrous on a microscopic level, may be translucent or semitransparent, and has a nearly wax-like luster.

chert. A extremely hard sedimentary rock with conchoidal (smooth curved surface) fracturing. It consists chiefly of interlocking crystals of quartz. Also called "flint."

clast. An individual grain or rock fragment in a sedimentary rock, produced by the physical disintegration of a larger rock mass.

clastic. Describes rock or sediment made of fragments of pre-existing rocks (clasts).

clay. Can be used to refer to clay minerals or as a sedimentary fragment size classification (less than 1/256 mm [0.00015 in]).

claystone. Lithified clay having the texture and composition of shale but lacking shale's fine layering and fissility (characteristic splitting into thin layers).

concretion. A hard, compact aggregate of mineral matter, subspherical to irregular in shape; formed by precipitation from water solution around a nucleus such as shell or bone in a sedimentary or pyroclastic rock. Concretions are generally different in composition from the rocks in which they occur.

conodont. One of a small number of small, disjunct fossil elements assigned to the order Conodontophorida, phosphatic in composition, and commonly toothlike in form but not in function; produced in bilaterally paired, serial arrangement by small marine animals of uncertain affinity. Range—Cambrian (possibly Late Precambrian) to Upper Triassic.

continental shelf. The shallowly submerged part of a continental margin extending from the shoreline to the continental slope with water depths less than 200 m (660 ft).

coquina. Limestone composed of cemented shell fragments.

coralloid. A term describing a variety of nodular, globular, botryoidal, or coral-like speleothems with concentric crystal growth.

cosmogenic dating. The method of determining the absolute age of near-surface rocks and landforms such as landslides, recent lava flows, moraines, alluvial fans, and fluvial terraces using cosmic rays emanating from space. These rays interact with Earth's geomagnetic field, atmosphere, and lithosphere, whereby they attenuate according to the density of the matter through which they pass. By measuring the daughter products produced by collisions of cosmic rays with terrestrial matter (cosmogenic nuclides), it is possible to obtain absolute ages of surface exposures.

creep. The slow, imperceptible downslope movement of mineral, rock, and soil particles under gravity.

crinoid. A marine invertebrate (echinoderm) that uses a stalk to attach itself to a substrate. "Arms" are used to capture food. Rare today, they were very common in the Paleozoic. Crinoids are also called "sea lilies."

cross section. A graphical interpretation of geology, structure, and/or stratigraphy in the third (vertical) dimension based on mapped and measured geological extents and attitudes depicted in a vertically oriented plane.

crystalline. Describes a regular, orderly, repeating geometric structural arrangement of atoms.

dahllite. A resinous, yellowish-white carbonate-apatite mineral, sometimes appearing in concretionary spherulites.

debris flow. A moving mass of rock fragments, soil, and mud, in which more than half the particles of which are larger than sand size.

deformation. A general term for the processes of faulting, folding, and shearing of rocks as a result of various Earth forces such as compression (pushing together) and extension (pulling apart).

dike. A narrow igneous intrusion that cuts across bedding planes or other geologic structures.

dolomite. A carbonate sedimentary rock of which more than 50% by weight or by areal percentages under the microscope consists of the mineral dolomite (calcium-magnesium carbonate).

dome. General term for any smoothly rounded landform or rock mass. More specifically refers to an elliptical uplift in which rocks dip gently away in all directions.

downcutting. Stream erosion process in which the cutting is directed in primarily downward, as opposed to lateral erosion.

drainage basin. The total area from which a stream system receives or drains precipitation runoff.

eolian. Formed, eroded, deposited by, or related to the action of the wind. Also spelled "Aeolian."

ephemeral stream. A stream that flows briefly only in direct response to precipitation in the immediate locality and whose channel is at all times above the water table.

evaporite. A sedimentary rock composed primarily of minerals produced from a saline solution as a result of extensive or total evaporation of the solvent (usually water).

fault. A break in rock along which relative movement has occurred between the two sides.

fault-propagation fold. A fold that forms just in front of the tip of an actively propagating fault.

floodplain. The surface or strip of relatively smooth land adjacent to a river channel and formed by the river. Covered with water when the river overflows its banks.

flowers (cave). Speleothems with crystal petals that radiate out from a common center.

flowstone. A general term for any deposit of calcium carbonate or other mineral formed by flowing water on the walls or floor of a cave.

fold. A curve or bend of an originally flat or planar structure such as rock strata, bedding planes, or foliation that is usually a product of deformation.

foliation. A preferred arrangement of crystal planes in minerals. In metamorphic rocks, the term commonly refers to a parallel orientation of planar minerals such as micas.

formation. Fundamental rock-stratigraphic unit that is mappable, lithologically distinct from adjoining strata, and has definable upper and lower contacts.

frost heaving. The uneven lifting or upward movement, and general distortion, of surface soils, rocks, vegetation, and structures such as pavements, due to subsurface freezing and growth of ice masses (especially ice lenses); any upheaval of ground caused by freezing.

geode. A hollow, more or less globular body, up to 30 cm (12 in) or more in diameter, found in certain limestones and volcanic rocks, and rarely in shales. Significant features include a thin outer layer of dense chalcedony, partial filling by inward-projecting crystals, and evidence of growth by expansion. A geode is separable from the rock in which it occurs and its crystals are not of the same minerals as those of the enclosing rock.

geology. The study of Earth including its origin, history, physical processes, components, and morphology.

gneiss. A foliated rock formed by regional metamorphism with alternating bands of dark and light minerals.

granite. An intrusive igneous (plutonic) rock composed primarily of quartz and feldspar. Mica and amphibole minerals are also common. Intrusive equivalent of rhyolite.

gypsum. The most common sulfate mineral (calcium sulfate). Frequently associated with halite and anhydrite in evaporites.

hogback. Any ridge with a sharp summit and steep slopes of nearly equal inclination on both flanks, resembling in outline the back of a hog.

horn coral. Rugose or solitary corals abundant in the Paleozoic Era but now extinct.

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

interglacial stage. A subdivision of a glacial epoch separating two glaciations, characterized by a relatively long period of warm or mild climate during which temperature rose to at least that of the present day; especially an interval of the Pleistocene Epoch, as the "Sangamon Interglacial Stage."

ironstone. Any rock containing a substantial proportion of an iron compound, or any iron ore from which the metal may be smelted commercially, specifically an iron-rich sedimentary rock, either deposited directly as a ferruginuos sediment or resulting from chemical replacement.

island arc. A line or arc of volcanic islands formed over and parallel to a subduction zone.

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

lamination (sedimentary). The thinnest recognizable unit layer of original deposition in a sediment or sedimentary rock, differing from other layers in color, composition, or particle size; specifically, such a sedimentary layer less than 1 cm in thickness (commonly 0.05–1.00 mm thick). Also, the formation of such a layer.

landslide. Any process or landform resulting from rapid, gravity-driven mass movement.

limb. Either side of a structural fold.

limestone. A sedimentary rock consisting chiefly of calcium carbonate, primarily in the form of the mineral calcite.

loam. A rich, permeable soil composed of a friable mixture of relatively equal and moderate proportions of clay, silt, and sand particles, specifically a soil consisting of 7%–27% clay, 28%–50% silt, and 23%–52% sand.

mafic. Describes dark-colored rock, magma, or minerals rich in magnesium and iron.

mass wasting. A general term for the downslope movement of soil and rock material under the direct influence of gravity.

meander. Sinuous lateral curve or bend in a stream channel. An entrenched meander is incised, or carved downward into the surface of the valley in which a meander originally formed. The meander preserves its original pattern with little modification.

member. A lithostratigraphic unit with definable contacts; a member subdivides a formation.

meteoric (water). Pertaining to water of recent atmospheric origin.

mineral. A naturally occurring, inorganic crystalline solid with a definite chemical composition or compositional range.

moonmilk. A soft white, initially plastic deposit that occurs on the walls of caves. It may consist of calcite, hydromagnesite, nesquehonite, hunite, aragonite, magnesite, dolomite, or other minerals.

oil field. A geographic region rich in petroleum resources and containing one or more wells that produce, or have produced, oil and/or gas.

oolite. A sedimentary rock, usually limestone, made of ooliths—round or oval grains formed by accretion around a nucleus of shell fragment, algal pellet, or sand grain. These laminated grains can reach diameters of 2 mm (0.08 in), but 0.5–1 mm (0.02–0.04 in) is common.

orogeny. A mountain-building event.

outcrop. Any part of a rock mass or formation that is exposed or "crops out" at Earth's surface.

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

parent material. Geologic material from which soils form.

pebble. Generally, small rounded rock particles from 4 to 64 mm (0.16 to 2.52 in) in diameter.

phreatic zone. The zone of saturation. Phreatic water is groundwater.

pisolitic (sedimentary). Pertaining to pisolite—a sedimentary rock, usually limestone, made up chiefly of cemented pisoids (round or ellipsoidal accretionary bodies commonly formed of calcium carbonate).

placer. A surficial mineral deposit formed by mechanical concentration of mineral particles from weathered debris. The common types are beach placers and alluvial placers.

point bar. A low ridge of sand and gravel deposited in a stream channel on the inside of a meander where flow velocity slows.

popcorn. In speleology, a colloquial name for coralloids.

radiometric age. An age expressed in years and calculated from the quantitative determination of radioactive elements and their decay products.

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

rockfall. Mass wasting process where rocks are dislodged and move downslope rapidly; it is the fastest mass wasting process.

sand. A clastic particle smaller than a granule and larger than a silt grain, having a diameter in the range of 1/16 mm (0.0025 in) to 2 mm (0.08 in).

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

schist. A strongly foliated metamorphic rock that can be readily be split into thick flakes or slabs. Micas are arranged in parallel, imparting a distinctive sheen, or "schistosity" to the rock.

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

sedimentary rock. A consolidated and lithified rock consisting of clastic and/or chemical sediment(s). One of the three main classes of rocks—igneous, metamorphic, and sedimentary.

selenite crystals. The clear, colorless variety of gypsum, occurring (especially in clays) in distinct, transparent monoclinic crystals, or in large crystalline masses that easily cleave into broad folia.

septarian. Describes the irregular, polygonal pattern of internal cracks developed in a sepatrium, closely resembling the desiccation structure of mud cracks; also said of the epibenetic mineral deposits that may occur as fillings of these cracks.

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

sheetwash/sheet erosion. The removal of thin layers of surface material more or less evenly from an extensive area of gently sloping land by broad continuous sheets of running water rather than by streams flowing in well-defined channels.

silt. Clastic sedimentary material intermediate in size between fine-grained sand and coarse clay (1/256 to 1/16 mm [0.00015 to 0.002 in]).

siltstone. A variably lithified sedimentary rock composed of silt-sized grains.

slope. The inclined surface of any geomorphic feature or measurement thereof. Synonymous with "gradient."

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

soda straw. A tubular stalactite that maintains the diameter of a drop of water and resembles a drinking straw in appearance.

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

speleothem. Any secondary mineral deposit that forms in a cave.

spring. A site where water issues from the surface due to the intersection of the water table with the ground surface.

stage (hydrology). The height of a water surface above an arbitrarily established datum plane.

stalactite (speleology). A conical or cylindrical speleothem that hangs from the ceiling or wall of a cave. It is deposited from drops of water and is usually composed of calcite but may be formed of other minerals.

stalagmite (speleology). A conical or cylindrical speleothem that is developed upward from the floor of a cave by the action of dripping water. It is usually formed of calcite but may be formed of other minerals.

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

stratification. The accumulation, or layering of sedimentary rocks in strata. Tabular, or planar, stratification refers to essentially parallel surfaces. Cross-stratification refers to strata inclined at an angle to the main stratification.

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

stream. Any body of water moving under gravity flow in a clearly confined channel.

stream capture. The natural diversion of the headwaters of one stream into the channel of another stream having greater erosional activity and flowing at a lower level, especially diversion effected by a stream eroding headward at a rapid rate so as to tap and lead off the water of another stream.

stream channel. A long, narrow depression shaped by the concentrated flow of a stream and covered continuously or periodically by water.

stream terrace. 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).

structural geology. The branch of geology that deals with the description, representation, and analysis of structures, chiefly on a moderate to small scale. The subject is similar to tectonics, but the latter is generally used for the broader regional or historical phases.

structure. The attitude and relative positions of the rock masses of an area resulting from such processes as faulting, folding, and igneous intrusions.

syncline. A downward curving (concave up) fold with layers that dip inward; the core of the syncline contains the stratigraphically younger rocks.

talus. Rock fragments, usually coarse and angular, lying at the base of a cliff or steep slope from which they have been derived.

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

tectonics. The geologic study of the broad structural architecture and deformational processes of the lithosphere and asthenosphere.

tephra. A collective term used for all pyroclastic material, regardless of size, shape, or origin, ejected during an explosive volcanic eruption.

tephrochronology. The collection, preparation, petrographic description, and approximate dating of tephra. Also, the chronological and correlation studies using tephra layers.

terrace. A relatively level bench or step-like surface breaking the continuity of a slope (also see "stream terrace").

terrigenous. Derived from the land or a continent.

toe (slope). The lowest part of a slope or cliff; the downslope end of an alluvial fan.

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

trace fossil. Tracks, trails, burrows, coprolites (dung), etc., that preserve evidence of organisms' life activities, rather than the organisms themselves.

transgression. Landward migration of the sea as a result of a relative rise in sea level.

trilobite. Any marine arthropod belonging to the class Trilobi6ta, characterized by a three-lobed ovoid outer skeleton, divided lengthwise into axial and side regions and transversely into cephalon ("head"), thorax (middle), and pygidium ("tail"). Range—Lower Cambrian to Permian.

tritium. A radioactive isotope of hydrogen having two neutrons and one proton in the nucleus.

turbidity. A measure of the opaqueness or reduced clarity of a fluid (usually water) due to the presence of suspended material.

unconformity. An erosional or non-depositional surface bounded on one or both sides by sedimentary strata that marks a period of missing time.

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

vadose water. Water of the unsaturated zone or zone of aeration.

water table. The upper surface of the saturated zone; the zone of rock in an aquifer saturated with water.

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Additional References

This section lists additional references, resources, and web sites that may be of use to resource managers. Web addresses are current as of September 2011.

Geology of National Park Service Areas

National Park Service Geologic Resources Division (Lakewood, Colorado). http://nature.nps.gov/geology/

NPS Geologic Resources Inventory publications. http://www.nature.nps.gov/geology/inventory/gre_publications.cfm

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NPS Geoscientist-in-the-parks (GIP) internship and guest scientist program. http://www.nature.nps.gov/geology/gip/index.cfm

Resource Management/Legislation Documents

NPS 2006 Management Policies (Chapter 4; Natural Resource Management): http://www.nps.gov/policy/mp/policies.html#_Toc157232681

NPS-75: Natural Resource Inventory and Monitoring Guideline: http://www.nature.nps.gov/nps75/nps75.pdf

NPS Natural Resource Management Reference Manual #77: http://www.nature.nps.gov/Rm77/

Geologic Monitoring Manual
R. Young and L. Norby, editors. Geological Monitoring. Geological Society of America, Boulder, Colorado. http://nature.nps.gov/geology/monitoring/index.cfm

NPS Technical Information Center (Denver, repository for technical (TIC) documents): http://etic.nps.gov/

Geological Survey Websites

Montana Bureau of Mines and Geology: http://www.mbmg.mtech.edu/

Wyoming State Geological Survey: http://www.wsgs.uwyo.edu/

U.S. Geological Survey: http://www.usgs.gov/

Geological Society of America: http://www.geosociety.org/

American Geological Institute: http://www.agiweb.org/

Association of American State Geologists: http://www.stategeologists.org/

Other Geology/Resource Management Tools

Bates, R. L. and J. A. Jackson, editors. American Geological Institute dictionary of geological terms (3rd Edition). Bantam Doubleday Dell Publishing Group, New York.

U.S. Geological Survey National Geologic Map Database (NGMDB): http://ngmdb.usgs.gov/

U.S. Geological Survey Geologic Names Lexicon (GEOLEX; geologic unit nomenclature and summary): http://ngmdb.usgs.gov/Geolex/geolex_home.html

U.S. Geological Survey Geographic Names Information System (GNIS; search for place names and geographic features, and plot them on topographic maps or aerial photos): http://gnis.usgs.gov/

U.S. Geological Survey GeoPDFs (download searchable PDFs of any topographic map in the United States): http://store.usgs.gov (click on "Map Locator").

U.S. Geological Survey Publications Warehouse (many USGS publications are available online): http://pubs.er.usgs.gov

U.S. Geological Survey, description of physiographic provinces: http://tapestry.usgs.gov/Default.html

Appendix: Scoping Session Participants

The following is a list of participants from the GRI scoping session for Bighorn Canyon National Recreation Area, held on May 18–19, 2005. The contact information and email addresses in this appendix may be outdated; please contact the Geologic Resources Division for current information. The scoping meeting summary was used as the foundation for this GRI report. The original scoping summary document is available on the GRI publications website: http://www.nature.nps.gov/geology/inventory/gre_publications.cfm.

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NPS 617/110188, September 2011

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