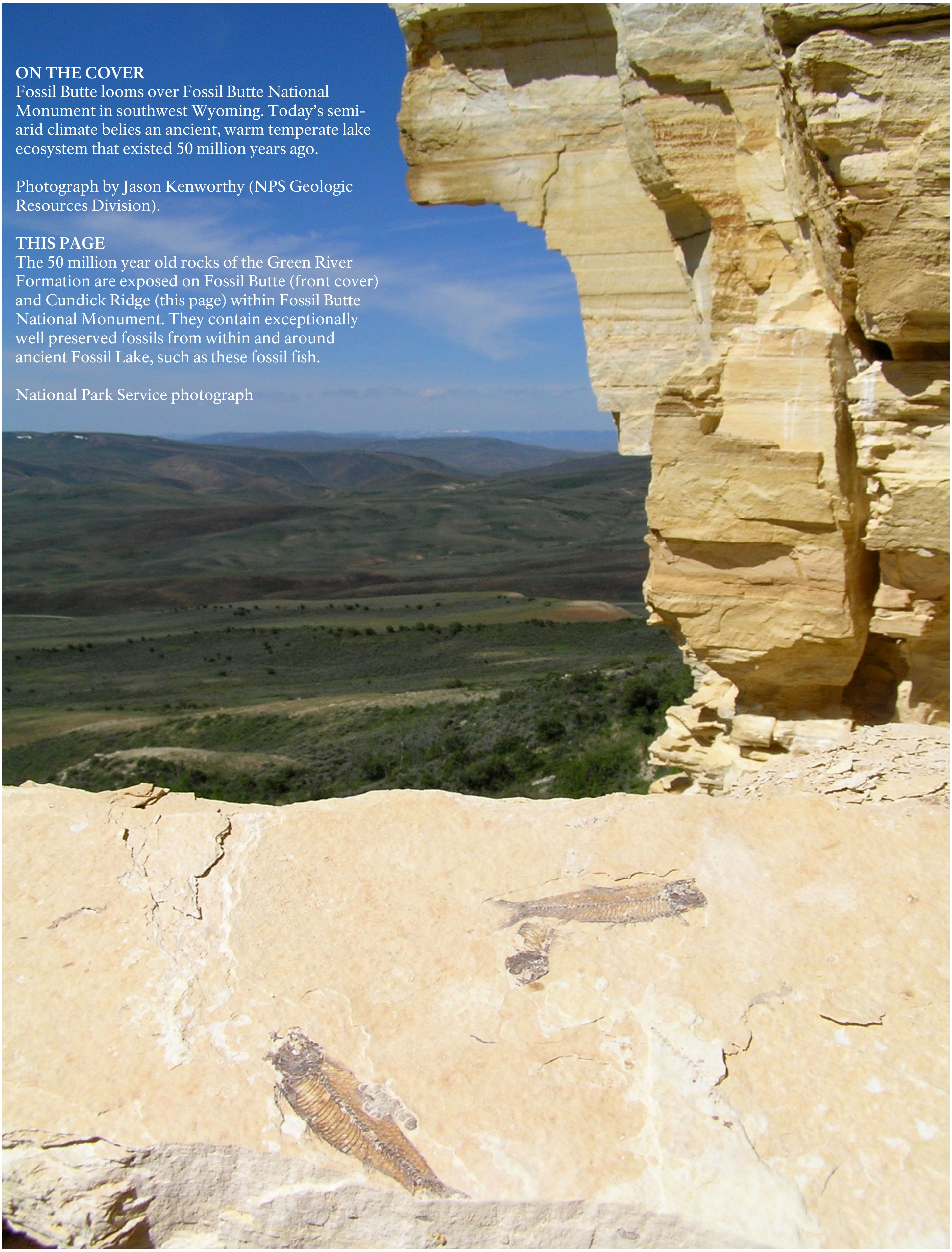
National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science

Fossil Butte National Monument

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2012/587



ON THE COVER
Fossil Butte looms over Fossil Butte National Monument in southwest Wyoming. Today's semi-arid climate belies an ancient, warm temperate lake ecosystem that existed 50 million years ago.

Photograph by Jason Kenworthy (NPS Geologic Resources Division).

THIS PAGE
The 50 million year old rocks of the Green River Formation are exposed on Fossil Butte (front cover) and Cundick Ridge (this page) within Fossil Butte National Monument. They contain exceptionally well preserved fossils from within and around ancient Fossil Lake, such as these fossil fish.

National Park Service photograph

Fossil Butte National Monument

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

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

The National Park Service, Natural Resource Stewardship and Science office in Fort Collins, Colorado publishes a range of reports that address natural resource topics of interest and applicability to a broad audience in the National Park Service and others in natural resource management, including scientists, conservation and environmental constituencies, and the public.

The Natural Resource Report Series is used to disseminate high-priority, current natural resource management information with managerial application. The series targets a general, diverse audience, and may contain NPS policy considerations or address sensitive issues of management applicability.

All manuscripts in the series receive the appropriate level of peer review to ensure that the information is scientifically credible, technically accurate, appropriately written for the intended audience, and designed and published in a professional manner. This report received informal peer review by subject-matter experts who were not directly involved in the collection, analysis, or reporting of the data.

Printed copies of this report are produced in a limited quantity and they are only available as long as the supply lasts. This report is available from the Geologic Resources Inventory website (http://www.nature.nps.gov/geology/inventory/gre_publications.cfm) and the Natural Resource Publications Management website (http://www.nature.nps.gov/publications/nrpm/).

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Executive Summary

This report accompanies the digital geologic map data for Fossil Butte National Monument in Wyoming, produced by the Geologic Resources Division in collaboration with its partners. It contains information relevant to resource management and scientific research. This report was prepared using available published and unpublished geologic information. The Geologic Resources Division did not conduct any new fieldwork in association with this report.

Approximately 50 million years ago, at the beginning of the Eocene Epoch, frigatebirds swooped above the waves of Fossil Lake, a vast, expansive lake that once occupied today's semi-arid, sagebrush and greasewood region of Wyoming's Fossil Basin. At least 15 genera of fish swam in the lake, including paddlefish, stingrays, gar, pike, trout-perch and the abundant herring *Knightia*, Wyoming's state fossil. A cacophony of raucous chatter arose from ancestral parrots, bitterns, goatsuckers, oilbirds, and other bird species. Palm trees grew along the lake shore in what is now the quiet, wind-swept landscape of southwestern Wyoming. Located at approximately the same latitude as it is today, Wyoming was part of a warm-temperate habitat that was home to crocodiles, turtles, snakes, lizards, and a rich variety of insects, birds, and mammals. By preserving this rich, diverse record of fauna and flora, Fossil Butte National Monument not only documents a global greenhouse climate that extended from the equator to the Arctic, but also provides many opportunities to interpret and discuss modern climate change.

Established in 1972, Fossil Butte National Monument today preserves abundant fossil plants and animals from both the Green River Formation and time-equivalent Wasatch Formation. Perhaps the most significant aspect of Fossil Butte National Monument is the remarkable preservation of complete skeletons or rarely preserved organisms that allows for the interpretation of an entire ecosystem. Such rare preservation is called a Lagerstätte. The exceptional quality of preservation, which includes even the delicate skin in some specimens, has propelled the fish fossils from Fossil Basin into museums and rock shops around the globe. The lacustrine sediments and fossils from the Green River Formation and the fluvial and floodplain sediments of the adjacent Wasatch Formation present a relatively detailed record of the complex paleoecology and paleoenvironments in which these organisms lived.

While the strata in Fossil Butte National Monument are Eocene in age, the rocks in the mountain ranges that border Fossil Basin to the east and west record a geologic history that spans roughly the past 500 million years, beginning in the Cambrian Period. This geologic story includes the flooding of the western North American continent by vast shallow seas, the growth of a supercontinent, mountain-building episodes that gave rise to a belt of mountain ranges extending from Alaska to Mexico as well as the present Rocky Mountains, and the formation of an inland seaway that connected the Arctic Ocean with the Gulf of Mexico.

This Geologic Resources Inventory (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. The report discusses geologic issues facing resource managers at Fossil Butte National Monument, distinctive geologic features and processes within the monument, and the geologic history leading to Fossil Butte's present-day landscape.

Based on discussions during a GRI scoping meeting in 2002, a follow-up conference call in 2011, and subsequent communication, as well as new scientific understandings, the following geologic resource management issues were identified and are further discussed in the report:

- Fossil documentation, inventory, monitoring, resource management, and protection
- Mass-wasting events
- Disturbed lands
- Seismic hazards
- Exploration and development of economic resources

Fossil Butte National Monument resource managers continue to catalogue and study the extraordinary fossils found in the monument. Monument staff locate paleontological sites using the global positioning system (GPS) and monitor new and past sites on a site-by-site basis. Visitors are informed of the significance of the monument's paleontological resources to deter potential fossil theft.

Mass wasting, rockfall, slumps, and landslides occur in the national monument. A massive landslide on Fossil Butte destroyed a portion of the Union Pacific railroad bed adjacent to the park. Landslides and slumps in the Wasatch Formation are evaluated for new fossil exposures or the impact on existing sites.

Following the establishment of the Fossil Butte National Monument, the Chicken Creek Ranch site was reclaimed, and little physical evidence remains at the site. In the late 1990s, three stockpond dams were removed from the Chicken Creek watershed and a major restoration project returned the drainage to pre-dam hydrologic conditions. Livestock grazing is no longer permitted in the monument. Today, reclamation of disturbed lands is not a significant issue for Fossil Butte National Monument management.

Although common in Wyoming, earthquakes are rare in the vicinity of Fossil Butte National Monument. Potential for earthquakes exist on the Rock Creek fault system, located northwest and west of the monument. This fault system may generate a maximum magnitude 7.2 earthquake, which is expected to cause only moderate damage, such as broken chimneys, in Kemmerer.

The greatest concerns for resource managers are potential wind farm development and hydrocarbon exploration near the boundaries of the monument, which would affect the monument's viewshed. Currently, the interest in wind farms has decreased and no permit was issued for the area around the monument between 2008 and the completion of this report in 2012.

During the 2002 scoping meeting and 2011 conference call, the following prominent geologic features and processes were identified and are further discussed in the report:

- Eocene paleontological resources
- Quaternary paleontological resources
- Triassic paleontological resources
- Stratigraphic features of the Green River Formation
- Stratigraphic features of the Wasatch Formation

Fossil Butte National Monument offers an opportunity to study an entire ecosystem. Research continues to address the paleoenvironment of Fossil Lake. Research opportunities include a myriad of paleoecological and paleoclimate projects.

This report includes an overview graphic (in pocket) that illustrates the geologic data and a Map Unit Properties Table (in pocket) that summarizes the main features, characteristics, and potential management issues for all rocks and unconsolidated deposits in the immediate area of Fossil Butte National Monument. This report also provides a glossary containing explanations of technical, geologic terms and a geologic time scale showing the chronologic arrangement of major geologic events.

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.

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Introduction

The following section briefly describes the National Park Service Geologic Resources Inventory Program and the regional geologic and historic setting of Fossil Butte National Monument.

Geologic Resources Inventory Program

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

The compilation and use of natural resource information by park managers is called for in the 1998 National Parks Omnibus Management Act (section 204), the 2006 NPS Management Policies, and in the Natural Resources Inventory and Monitoring Guideline (NPS-75). Refer to the "Additional References" section for links to these and other resource management documents.

The objectives of the GRI are to provide geologic map data and pertinent geologic information to support resource management and science-based decision making in more than 270 natural resource parks throughout the National Park System. To realize these objectives, the GRI team undertakes three tasks for each natural resource park: (1) conduct a scoping meeting and provide a scoping summary, (2) provide digital geologic map data in a geographic information system (GIS) format, and (3) provide a GRI report. These products are designed and written for nongeoscientists. Scoping meetings bring together park staff and geologic experts to review available geologic maps, develop a geologic mapping plan, and discuss geologic issues, features, and processes that should be included in the GRI report. Following the scoping meeting, the GRI map team converts the geologic maps identified in the mapping plan into digital geologic map data in accordance with their data model. Refer to the "Geologic Map Data" section for additional map information. After the map is completed, the GRI report team uses these data, as well as the scoping summary and additional research, to prepare the geologic report. This geologic report assists park managers in the use of the map, and provides an overview of the park geology, including geologic resource management issues, geologic features and process, and the geologic history leading to the park's present-day landscape.

For additional information regarding the GRI, including contact information, please refer to the Geologic Resources Inventory website (http://www.nature.nps.gov/geology/inventory/). The current status and projected completion dates for GRI products are available on the GRI status website (http://www.nature.nps.gov/geology/GRI_DB/Scoping/Quick_Status.aspx).

Regional Information and Significance of Fossil Lake

Located about 16 km (10 mi) west of Kemmerer in southwestern Wyoming, Fossil Butte National Monument (fig. 1) encompasses 3,318 ha (8,198 ac) near the geographic center of Fossil Basin. Established in 1972, the monument preserves one of the richest fossil localities in the world. Articulated skeletons, the delicate skin of fossil fish, and feathers are preserved along with amphibians, crocodiles, turtles, birds, and mammals, as well as mollusks, insects, and a variety of plants (fig. 2). The extraordinary quality and completeness of fossil preservation is consistent with a Lagerstätte, where complete skeletons or rarely preserved organisms enable the interpretation of an entire ecosystem. Fossils from Fossil Basin can be seen in museums around the world. New discoveries continue to define an ecosystem that developed during the warmest climate of the past 65 million years.

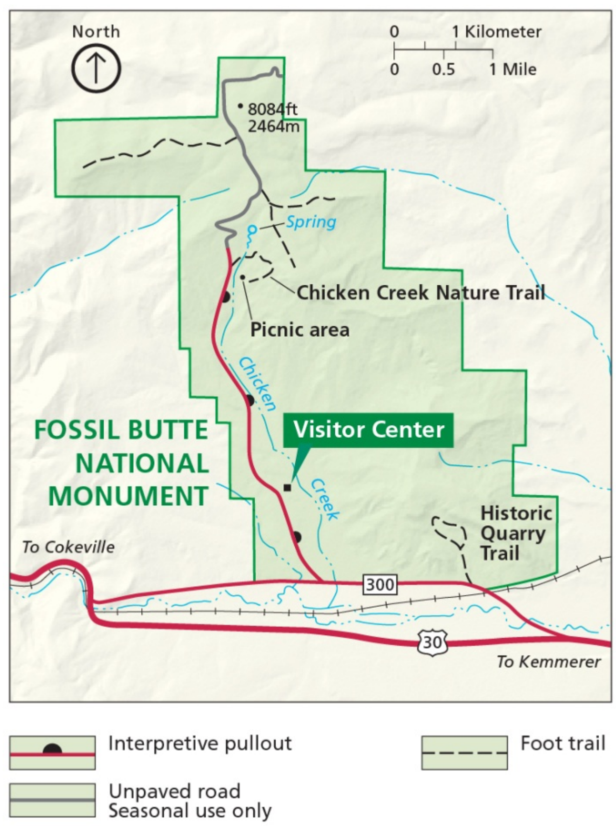


Figure 1. Map of Fossil Butte National Monument. The town of Kemmerer, Wyoming, is located approximately 16 km (10 mi) east of the monument on U.S. Highway 30. National Park Service map, http://www.nps.gov/hfc/cfm/carto.cfm, accessed 12 September 2012.

Figure 2. Fossil fish. Fossil Butte National Monument is known for its exceptionally preserved fossil fish. Here, a *Diplomystus* is caught in the mouth of a *Mioplosus labracoides*, which is about 9 cm (4 in) long. This specimen, referred to as an aspiration, provides evidence of behavior and life in ancient Fossil Lake. National Park Service photograph courtesy of Arvid Aase, Fossil Butte National Monument, http://www.nps.gov/fobu/photosmultimedia/Green-River-Formation-Fossils.htm, accessed 12 September 2012.

Today, Fossil Basin is dry and the surrounding semi-arid region is primarily vegetated by sagebrush and greasewood (fig. 3), but 50 million to 53 million years ago, palm and deciduous trees grew on the shore of Fossil Lake, one of three lakes that formed an extensive great-lakes system in the humid, warm-temperate climate of Wyoming, Utah, and Colorado during the Eocene Epoch (fig. 4). Lake Gosiute, which occupied portions of the Green River Basin to the east, and Lake Uinta, which formed south of the Uinta Mountains, were much larger, but not as deep, as Fossil Lake (Eugster 1982; Smith et al. 2008). At its maximum, Fossil Lake inundated at least 1,500 km^2 (600 mi^2), perhaps as many as 3,900 km^2 (1,500 mi^2) (Arvid Aase, curator, Fossil Butte National Monument, written communication, 11 September 2012) and produced more than 120 m (395 ft) of lake sediments (Buchheim and Eugster 1998; Buchheim et al. 2011).

Fossil Lake teemed with a myriad of fish species, including relatives of today's paddlefish, stingrays, gar, pike, and herring. Occasionally, large-scale fish mortalities occurred, and dead fish settled to the bottom of the lake. Approximately 98% of the fossil-producing beds in Fossil Lake consist of limestone that entered the lake's alkaline waters as dissolved ions and then precipitated (Arvid Aase, curator, Fossil Butte National Monument, written communication, 11 September 2012). The remaining components of silt, volcanic ash, leaves, and other debris were transported into the lake by wind or stream processes and subsequently buried and preserved by overlying sediment.

Before entering Fossil Lake, streams from the surrounding hills and mountains flowed through forests containing more than 250 types of plants including oak, maple, chestnut, and a host of fruit trees. A lush undergrowth of ferns and succulent plants provided habitat for ancestral rodents, dog-sized horses, extinct mammals such as the large *Coryphodon*, carnivorous mammals, bats, a wide variety of insects, snakes, and a host of other animals. Crocodiles and turtles inhabited nearshore environments. Bittern-like birds waded along the shoreline. The forest came alive with the chatter of birds. The hum of insects, squawks of parrots, and chatter from the jungle would have stood in stark contrast to the relatively quiet, wind-swept rolling hills of today's Fossil Basin.

Figure 3. Fossil Butte. Today, the semi-arid region is dry, but 50 million years ago, the sediments that would become Fossil Butte were being deposited in a lake that formed in a warm-temperate climate. National Park Service photograph by Jason Kenworthy (NPS Geologic Resources Division).

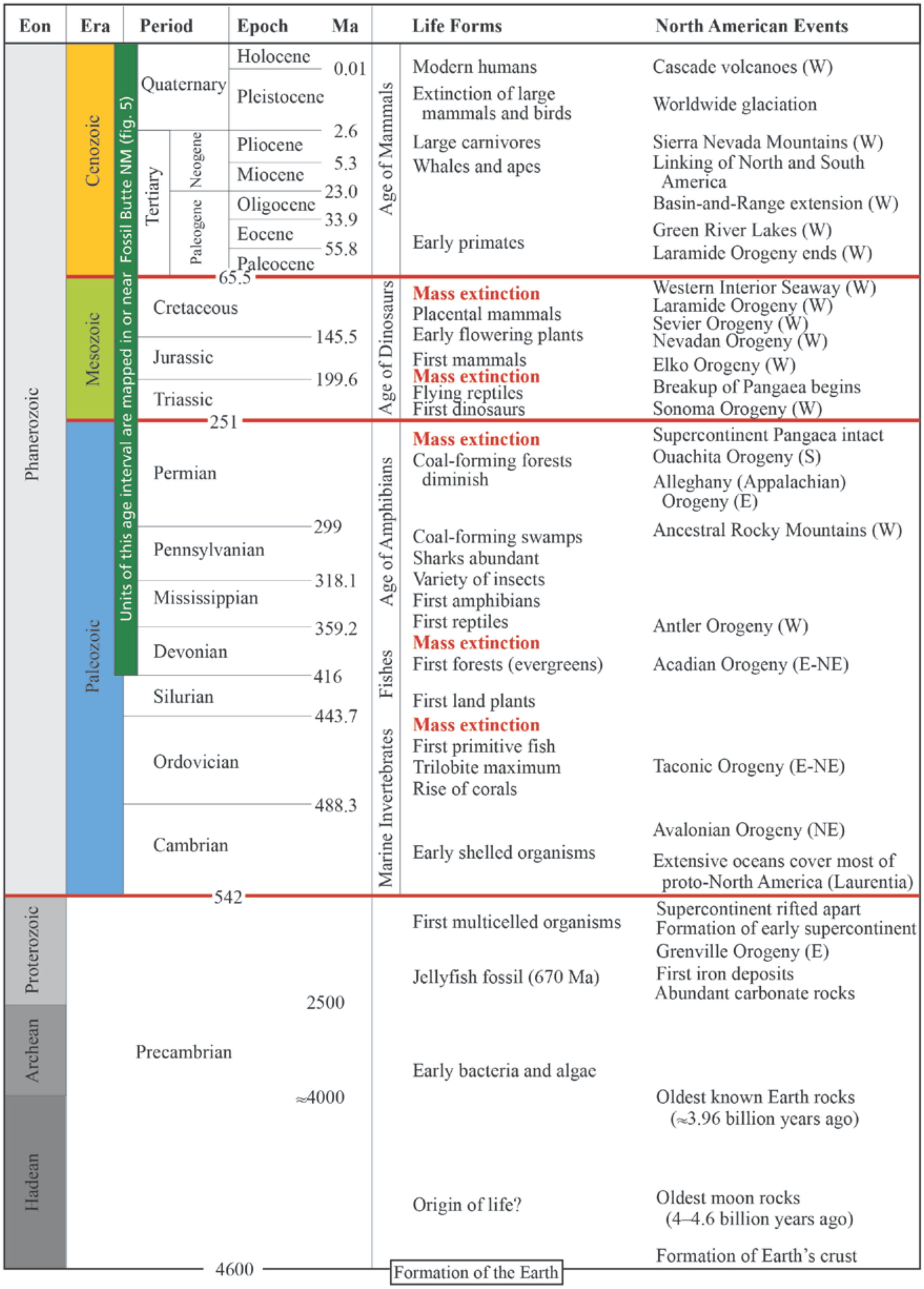


Figure 4. Geologic time scale. The divisions of the geologic time scale are organized chronologically, with the oldest at the bottom and youngest at the top. The green bar indicates the time spanned by rocks mapped in the GRI digital geologic map for Fossil Butte National Monument (see fig. 5 and Map Unit Properties Table for more information). Boundary ages are in millions of years (Ma). Major life history and tectonic events are included. Compass directions in parentheses indicate the regional location of geologic events. Red lines indicate major boundaries between eras. Graphic design by Trista Thornberry-Ehrlich (Colorado State University), adapted from geologic time scales published by the U.S. Geological Survey (http://pubs.usgs.gov/fs/2010/3059/) and the International Commission on Stratigraphy (http://www.stratigraphy.org/ics%20chart/09_2010/StratChart2010.pdf).

Age: Period	Age: Epoch	Formations/Units (map symbol)	General Description
Quaternary	Holocene and Pleistocene	Alluvium (Qal). Secondary-stream alluvium (Qas). Landslide Deposits (Qls). Talus deposits (Qd). Gravel (Qd).	Unconsolidated gravel, sand, silt, and mud. Talus (angular rock debris).
Neogene	Pliocene	Regional Unconformity. Approximately 30 million years of strata are missing in the monument.	
Neogene	Miocene		
Paleogene	Oligocene		
Paleogene	Eocene	Sillem Member of Fowkes Formation (Tfs)	Sandstone, siltstone, and mudstone with limestone and conglomerate layers.
Paleogene	Eocene	Wasatch Formation: Tunp Member (Twt)	Conglomerate.
Paleogene	Eocene	Wasatch Formation: Bullpen Member (Twb)	Green River (Tgr): fish and other fossils are preserved in fine-grained lake deposits. Wasatch (Tw): terrestrial fossils are found in floodplain deposits.
Paleogene	Eocene	Wasatch Formation: Main Body (Tw) / Green River Formation: Angelo Member (Tga)	
Paleogene	Eocene	Wasatch Formation: Main Body (Tw): Mudstone tongue (Twms)	
Paleogene	Eocene	Green River Formation: Angelo Member (Tga)	
Paleogene	Eocene	Green River Formation: Fossil Butte Member (Tgfb)	
Paleogene	Eocene	Wasatch Formation: Main Body (Tw): Sandstone Tongue (Tws)	
Paleogene	Eocene	Green River Formation: Road Hollow Member (Tgrh, Tgul, Tgwm, Tgls)	
Paleogene	Eocene	Wasatch Formation: Lower Member (Twl)	Sandstone and mudstone.
Paleogene	Eocene	Wasatch Formation: Basal Conglomerate Member (Twc)	Conglomerate.
Paleogene	Paleocene	Evanston Formation (Te, Tem, Tec, Tel)	Conglomerate, sandstone, siltstone, mudstone, and coal.
Cretaceous	Upper	Regional Unconformity.	
Cretaceous	Upper	Hams Fork Conglomerate of the Evanston Formation (Keh)	Conglomerate.
Cretaceous	Upper	Adaville Formation (Kav, Kal)	Coal, sandstone, shale.
Cretaceous	Upper	Hilliard Shale (Kh, Khh, Khc)	Shale, sandstone, conglomerate.
Cretaceous	Upper	Frontier Formation (Kf, Kfl, Kfd, Kfdc, Kfo, Kfa, Kfc, Kfcc)	Primarily sandstone with interbeds of coal.
Cretaceous	Lower	Aspen Shale (Ka)	Shale and sandstone with fish scales and mollusks.
Cretaceous	Lower	Bear River Formation (Kbr)	Shale, sandstone, and limestone with gastropod and pelecypod fossils.
Cretaceous	Lower	Thomas Fork Formation (Ktf)	Sandstone and mudstone.
Cretaceous	Lower	Smiths Formation (Ks)	Sandstone and shale.
Cretaceous	Lower	Gannett Group (Kg, Kgc, Ke)	Mudstone, siltstone, sandstone, conglomerate.
Jurassic	Upper	Stump Sandstone and Preuss Red Beds (Jsp)	Sandstone, mudstone, and limestone.
Jurassic	Middle	Twin Creek Limestone (Jt, Jtg)	Limestone.
Jurassic	Lower	Nugget Sandstone (JTRn)	Sandstone.
Triassic	Upper	Ankareh Red Beds (TRa)	Sandstone and mudstone.
Triassic	Middle	Regional Unconformity.	
Triassic	Lower	Thaynes Limestone (TRt)	Silty limestone.
Triassic	Lower	Woodside Red Beds (TRw)	Siltstone and claystone.
Triassic	Lower	Dinwoody Formation (TRd)	Calcareous siltstone, sandy limestone.

NOTE: *Age is in millions of years before present and indicates the time spanned by associated epoch or period. Rock/sediment units associated with those epochs or periods may not encompass the entire age range.

Figure 5. General stratigraphic column for the Fossil Butte National Monument region, Quaternary, Tertiary, and Mesozoic units. Geologic map units are in parentheses. Stratigraphic relationships between the Wasatch and Green River formations are adapted from Buchheim et al. (2011). Terrestrial environments of the Wasatch Formation existed prior to, contemporaneously with, and after Fossil Lake. See the Map Unit Properties Table (in pocket) for more detail. Multiple map symbols represent different members of the same formation. The gray areas represent unconformities, where the stratigraphic succession is missing.

The Eocene lakes expanded and contracted in response to fluctuating climatic and geologic conditions. Three major phases of Fossil Lake can be identified from the sedimentary strata exposed at Fossil Butte National Monument. The Road Hollow Member of the Green River Formation (map unit Tgrh) represents the initial phase, which developed on a floodplain in the southern part of the basin (fig. 5; Buchheim 1998; Buchheim et al. 2011). Greater precipitation during the second stage of Fossil Lake resulted in a much larger lake that contained an abundant fish population (Buchheim 1998; Buchheim et al. 2011). Deposition during this phase resulted in the fossiliferous Fossil Butte Member of the Green River Formation (map unit Tgfb). The final phase of Fossil Lake records primarily hypersaline conditions as the basin became closed to outside drainage and filled with

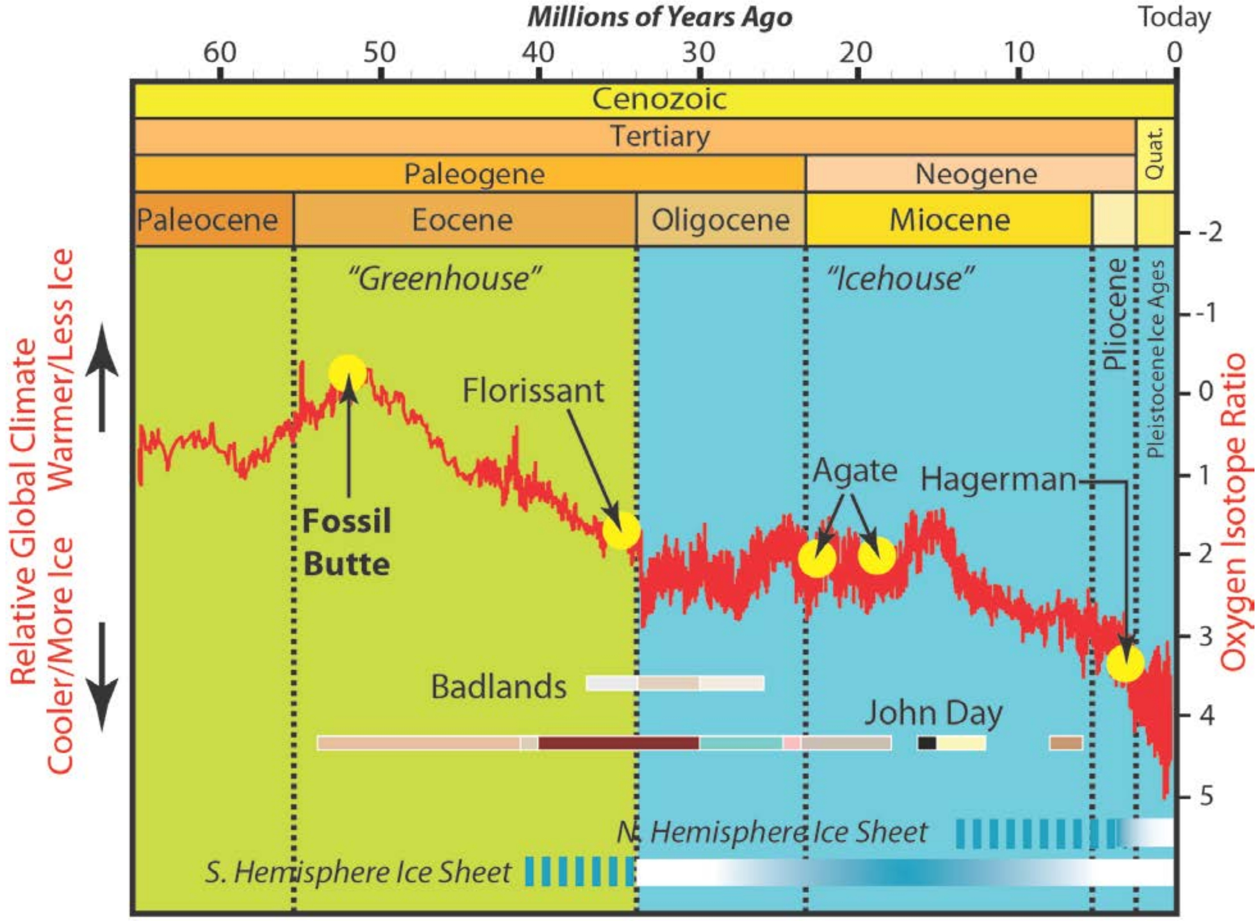


Figure 6. Relative Global Climate during the Paleogene and Neogene Periods. The red line was plotted using ocean temperature data from Zachos et al. (2001, 2008). The yellow dots and horizontal bars indicate the geologic ages or ranges of ages of six NPS units established to preserve scientifically significant Paleogene and Neogene fossils and strata: Fossil Butte National Monument in Wyoming, Florissant Fossil Beds National Monument in Colorado, Agate Fossil Beds National Monument in Nebraska, Hagerman Fossil Beds National Monument in Idaho, Badlands National Park in South Dakota, and John Day Fossil Beds National Monument in Oregon (fig. 7). The transition from global "Greenhouse" conditions with minimal polar ice sheets to "Icehouse" conditions with ice sheets at one or both poles occurred near the Eocene–Oligocene boundary. Graphic adapted from Kenworthy (2010).

river sediments (Loewen and Buchheim 1998). This stage is represented by the Angelo Member of the Green River Formation (map unit Tga; fig. 5; Buchheim et al. 2011).

While the sheer diversity and exceptional preservation of fossils have established Fossil Butte as a premier fossil locality, the record of climate change preserved by the monument is also significant. The fossils and sediments preserve ancient biological communities and environments evolving at a time of maximum Cenozoic global temperatures (Clyde et al. 2001; Wing et al. 2003). Mean annual air temperatures warmed from 15°C to 23°C (60°F to 73°F; Woodburne et al. 2009; Kunzig 2011). The increase in temperature from 53 million to 50 million years ago supported a major increase in floral diversity and habitat complexity (Woodburne et al. 2009; Kunzig 2011).

Past climate change affected plants and animals on a global scale. Fossil Butte National Monument, along with several other NPS units, preserves critical evidence for the reconstruction of Earth's global climate throughout the last 65 million years, when climate transitioned from a "greenhouse" to an "icehouse" (figs. 6 and 7).

Understanding these past climates and climate changes may provide clues to the causes of climate change and suggest ways to predict, monitor, and prepare for future changes.

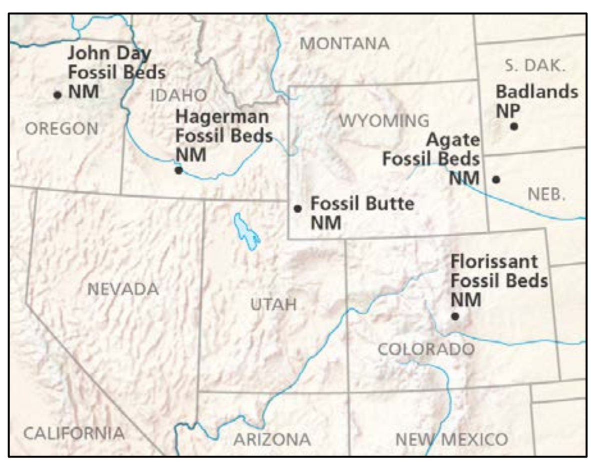


Figure 7. Location of other National Park Service areas established to preserve and interpret fossils from the Cenozoic Era. Fossil ecosystems from these six parks illustrate dramatic global climate change over the past 65 million years. National Park Service map.

In addition to this report, Geologic Resource Inventory reports have been completed or are in preparation for the six NPS areas established to preserve fossils from the Cenozoic Era (fig. 7): Agate Fossil Beds National Monument (Graham 2009a), Badlands National Park (Graham 2008), Florissant Fossil Beds National Monument (KellerLynn 2006), Hagerman Fossil Beds National Monument (Graham 2009b), and John Day Fossil Beds National Monument is in preparation (Graham in prep.).

Regional Landscape

Most of the landscape in Fossil Butte National Monument has been carved from the Eocene Wasatch and Green River formations (fig. 5; Rubey et al. 1975). The reddish, discontinuous, variegated beds of the Wasatch Formation (map unit Tw), deposited in rivers and floodplains (fluvial), contrast sharply with the light-colored, laterally continuous strata deposited in Green River Formation lakes (lacustrine).

Fragmentary terrestrial fossils are found in the main body of the Wasatch Formation (Tw), but the Fossil Butte Member of the Green River Formation (Tgfb) contains the majority of fossils in the monument. The Fossil Butte and Angelo members of the Green River Formation form the crest and slopes of today's Fossil Butte (fig. 3). In the northern part of the basin, the Road Hollow Member is present along with the Fossil Butte and Angelo members. These formations are described in greater detail in the Features and Processes section of this report.

Near the northwestern border of the monument, the Lower Member of the Wasatch Formation (map unit Twl) directly overlies the Early Triassic Thaynes Limestone (map unit TRt), the oldest formation in the monument (fig. 4). This contact represents roughly 200 million years of missing geologic history. Such a gap in the stratigraphic record is known as an "unconformity."

Paleozoic and Mesozoic strata in the Crawford Mountains and Tunp Range border the narrow, north–south-trending Fossil Basin to the west. During the Eocene, the Crawford Mountains formed an island in Fossil Lake while the Tunp Range extended as a peninsula into the lake (Buchheim et al. 2011). The oldest rock unit in the Tunp-Crawford Mountains, immediately west of the monument, consists of Upper Cambrian Gallatin Limestone, but to the east, the oldest rocks exposed on Oyster Ridge are Cretaceous in age (Rubey et al. 1975; M'Gonigle and Dover 1992). The age difference is due to immense thrust faults (fig. 8) that deformed and transported the Paleozoic and Mesozoic strata from west to east during a mountain-building episode (orogeny) that began about 140 million years ago. Evidence of faulting is conspicuous in the surrounding mountain ranges and is present in the subsurface below Fossil Basin. Oyster Ridge separates Fossil Basin from the much larger Green River Basin to the east. The Uinta Mountains form the southern border of Fossil Basin and are cored by Precambrian rocks that were thrust toward the surface on high-angle reverse faults (fig. 8) during a second orogeny beginning approximately 70 million years ago (Gries 1983).

The stratigraphic units in Fossil Basin and adjacent mountain ranges rarely consist of complete sections. Fault displacement, erosion, non-deposition, and other geologic processes have combined to truncate stratigraphic sections throughout the geologic record. In Fossil Butte National Monument, recent fluvial deposits (map units Qal, Qas) and mass-wasting deposits (map units Qls, Qd) record geologic processes that continue to modify the current landscape.

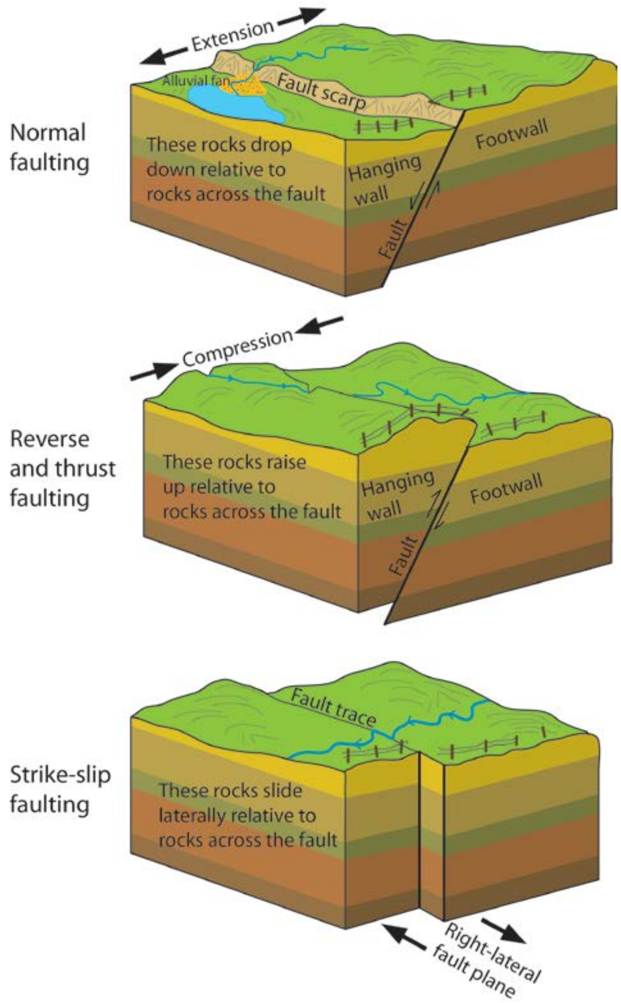


Figure 8. Three general fault types. As a way of orientation, if you walked down a fault plane, your feet would be on the "foot wall," and the rocks over your head would form the "hanging wall." In a normal fault, caused by crustal extension (pulling apart), the hanging wall moves down relative to the footwall. In the Basin and Range Province, the uplifted footwall is called a "horst" and the basin formed by the down-dropped hanging wall is called a "graben." In a reverse fault, caused by crustal compression, the hanging wall moves up relative to the foot wall. A thrust fault is similar to a reverse fault but has a dip angle of less than 45°. In a strike-slip fault, the relative direction of opposing plate movement can be to the right, indicating right-lateral (dextral) movement, or to the left, termed left-lateral (sinistral) movement. A strike-slip fault between two tectonic plate boundaries is called a transform fault. Only normal, reverse, and thrust faults are relevant to the geology of Fossil Butte National Monument. Graphic by Trista Thornberry-Ehrlich (Colorado State University).

Cultural History

In 1856, Dr. John Evans picked up a fossil fish somewhere along Wyoming's Green River and sent the specimen to Dr. Joseph Leidy, an anatomist and paleontologist at the University of Pennsylvania who became the first person to describe a fossil fish from the Green River area. His description of the fossil herring, *Clupea humilis* (now known as *Knightia eocaena*), however, did not draw the attention of scientists. When the Union Pacific Railroad cut into the bluffs 3 km (2 mi) west of the Green River Station in 1868, so many fossil fish were discovered that the right-of-way became known as the "Petrified Fish Cut" (fig. 9; Hesse 1939; McGrew and Casilliano 1975; Kiver and Harris 1999).

Figure 9. Petrified Fish Cut on the main line of the Union Pacific Railroad near Green River, Wyoming. Fossil fish discovered at this location swam in ancient Lake Gosiute, about 150 km (90 mi) southeast of Fossil Butte. Such discoveries prompted the 1871 Hayden survey to explore Fossil Basin in greater detail. U.S. Geological Survey photograph by W.H. Jackson, 1869, available at http://libraryphoto.cr.usgs.gov/htmllib/btch106/btch106j/btch106z/jwh00014.jpg, accessed 14 February 2012.

A. W. Hilliard and L. E. Rickseeker, employees of the Union Pacific Railroad, sent many fossils to Ferdinand V. Hayden, who was in charge of the first federally funded geological survey in the western Wyoming region. Hayden's 1871 report documented features that would be included in Yellowstone National Park, established in 1872, and also included a description of Green River fish fauna by noted vertebrate paleontologist Edward Drinker Cope.

From 1870 to 1877, Cope published a series of papers on the fish fossils in southern and southwestern Wyoming, but locality references were obscure or omitted entirely from his publications. In 1877, he described 25 species of fish from three locations: 1) the Petrified Fish Cut, 2) a site "near the mouth of Labarge Creek," and 3) a locality "near the main line of the Wasatch Mountains" (Cope 1877; Hesse 1939). The third locality may be equivalent to Cope's (1884) Twin Creek locality, which represents the Fossil Butte area (Hesse 1939; Tweet et al. 2012).

Hayden delegated the Green River district to A. C. Peale, a geologist, mineralogist, and paleobotanist with the U.S. Geological Survey. Peale (1879) described the stratigraphy of the region, including the first geologic description of Fossil Butte. Veatch (1907) expanded on Hayden's general stratigraphic description when he mapped the rocks in Fossil Basin. His work established most of the Jurassic to Holocene rock units in the basin (McGrew and Casilliano 1975).

Old references referred to Fossil Butte as the "Fish Cliffs" (Hesse 1939). Commercial fossil collecting began in the late 19th century and has greatly increased since the 1960s. Fossil Butte National Monument cooperates with local commercial quarries to improve exhibits, to raise awareness of the region's geology and paleontology, and to increase the accuracy of information presented to the public (Aase 2009). The park supports a variety of additional research projects, addressing topics that include, but are not limited to, paleobotany, trace fossils, fossil insects, age dating, geologic features, fossil collection and preparation techniques, and data collecting (Arvid Aase, curator, Fossil Butte National Monument, written communication, 11 September 2012). Former commercial sites, including the Haddenhams site and the Larson Fish Quarry, are located within the monument (Tweet et al. 2012).

Throughout the 20th century, comprehensive studies by Bradley (1948), Rubey et al. (1968), Oriel and Tracey (1970), McGrew and Casilliano (1975), Grande (1980), Lamerson (1982), Armstrong and Oriel (1986), Roehler (1993), Buchheim (1994a), Grande and Buchheim (1994), Buchheim et al. (2011), and other researchers contributed greatly to understanding the stratigraphy, geologic structure, and fossil record of the region. Discoveries of hydrocarbons and oil shale in Fossil Basin, improved geophysical techniques, and detailed surface and subsurface research of the faulting in the Rocky Mountains also helped define the deformational and depositional history of southwestern Wyoming.

The fossils of the ancient lake bed within and around Fossil Butte National Monument are nonrenewable resources. The preservation, diversity, and abundance fossils in Fossil Basin are extraordinary. Fossil fish, which document the ancestors of modern freshwater fishes, dominate the Fossil Lake fauna, but they are associated with other aquatic taxa such as turtles, shrimp, crayfish, crocodilians, and plants. Contemporary fossils of terrestrial fauna and flora are found in strata that surround the ancient lake. Established as a National Monument in 1972, Fossil Butte National Monument currently has the potential for nomination as a Geological Heritage Site under the World Heritage Site Program (National Park Service 2006).

Geologic Issues

The Geologic Resources Division held a Geologic Resources Inventory scoping meeting for Fossil Butte National Monument on May 23, 2002, and a follow-up conference call on December 13, 2011, to discuss geologic resources, address the status of geologic mapping, and assess resource management issues and needs. This section synthesizes those discussions and highlights particular issues that may require attention from resource managers. Contact the Geologic Resources Division for technical assistance.

Fossil documentation, inventory, monitoring, and protection are the primary management responsibilities at Fossil Butte National Monument. Additional resource management issues include:

- Mass-wasting events (rockfall, slumps, landslides)
- Disturbed lands
- Energy resource exploration and development
- Seismic hazards

Paleontological Resource Management

The 2009 Paleontological Resources Preservation Act (Public Law 111-11; see the Additional References section) directs the NPS, and other federal land management agencies, to implement comprehensive, science-based paleontological resource management programs. Such programs must include plans for inventory, monitoring, research, and education, as well as the protection of resource and locality information. As of September 2012, regulations associated with the act are being finalized (Julia Brunner, policy and regulatory specialist, NPS Geologic Resources Division, personal communication, 17 September 2012). Refer to the Additional References section for a link to a summary of, and full text for, the Paleontological Resources Preservation Act. Fossil Butte National Monument has maintained an active paleontological resource management program since its establishment in 1972.

Documentation and Inventory

After 100 years of collecting, new fossil species are still being discovered in the Eocene lake sediments of Fossil Basin. Tens-of-thousands to hundreds-of-thousands of fossils are collected each year from commercial fossil quarries located outside of Fossil Butte National Monument (National Park Service 2009). Approximately 200 to 500 fossil specimens are collected from the park's research and interpretation quarry each year. These collections are used for baseline data on Green River fishes and for interpretative opportunities within the park. Fossil Butte National Monument maintains a relationship with the commercial quarries; significant specimens discovered outside the park may be brought to the park for documentation by photography, and/or replica production. Museums and rock shops around the world contain well-preserved fossils from the Eocene Green River Formation. Extraordinary fossil preservation has yielded an unparalleled variety of fossil fish, reptiles, birds, mammals, insects, and plants. Fossil Butte National Monument protects and manages less than 1.5% of the Eocene Fossil Lake deposits in Fossil Basin.

Because of the abundance, diversity, and extraordinary scientific value of the paleontological resources at Fossil Butte National Monument, documentation, inventory, monitoring, and protection of these resources are especially critical. Fossils collected in Fossil Butte National Monument are evaluated, catalogued, and stored by park staff for inclusion in the park's museum or interpretation collections. Because more than half of the fossils found in the research quarry are covered with matrix and are only visible in cross section, they must be x-rayed to collect data on such parameters as size, species, orientation, and articulation. Therefore, specimen cataloguing lags behind collection (Arvid Aase, curator, Fossil Butte National Monument, written communication, 11 September 2012).

The documentation of paleontological resources provides the baseline data necessary to develop an effective inventory and monitoring program for the monument. Paleontological resource inventories typically include data on the scope, significance, and distribution of fossils at each locality, as well as a description of the strata (Santucci et al. 2009). However, because fossil-bearing layers in the Green River Formation extend continuously for miles, these generic approaches need to be modified at Fossil Butte National Monument to address the park's specific fossil deposits (Arvid Aase, curator, Fossil Butte National Monument, written communication, 11 September 2012). In addition, monitoring programs may benefit from identifying environmental and anthropogenic factors, such as those identified in figure 10, that might affect the stability of in situ paleontological resources (Santucci and Koch 2003; Santucci et al. 2009).

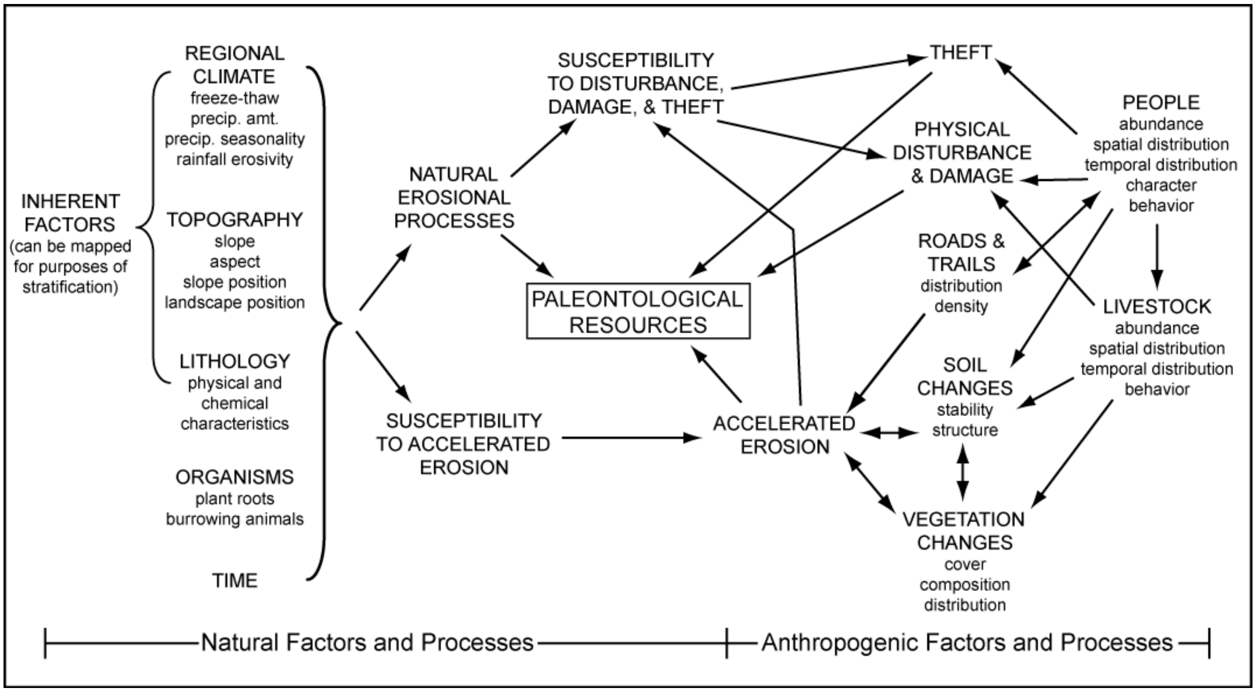


Figure 10. Conceptual diagram illustrating various environmental and anthropogenic factors and processes that might affect the stability of in situ paleontological resources. National Park Service diagram reproduced from Santucci and Koch (2003).

An Inventory and Monitoring Network–based paleontological resource summary was completed for Fossil Butte National Monument and the other parks in the Northern Colorado Plateau Network in 2002 (Koch and Santucci 2002), and a substantially updated, revised, and expanded summary for the Northern Colorado Plateau Network was completed by Tweet et al. (2012). That report provides a summary of the scope and significance of paleontological resources of Fossil Butte National Monument and all other parks in the network. Resource management recommendations were also included.

Monitoring

Once an inventory of paleontological resources has been completed, a monitoring program can be designed. Santucci et al. (2009) have developed a list of five significant properties, or vital signs, to help resource managers monitor the stability of in situ paleontological resources. These vital signs are: 1) rates of natural erosion due to geological variables, 2) rates of natural erosion due to climatic variables, 3) "catastrophic" geologic processes and geohazards, 4) hydrology and bathymetry, and 5) human impacts. They also provide detailed explanations of the needed expertise, specialized equipment, and cost of measuring each vital sign.

In 2002, Fossil Butte National Monument incorporated appropriate vital signs in the initiation of a monitoring program designed to study erosion rates and in situ fossil stability in the highly erosive Wasatch Formation (Santucci et al. 2009). Although erosion exposes fossil material, it also leads to fossil loss. In 2002, the park used a freeze–thaw index, which records temperature fluctuations above and below freezing in a 24-hour periods, to help determine how often fossil sites should be monitored. Such temperature fluctuations can lead to the expansion and contraction of water in rock fractures, which contributes to weathering and erosion. A higher freeze–thaw index suggests higher rates of weathering and erosion than a lower index. Erosion stakes were also installed (fig. 11) and located using the global positioning system (GPS). The monitoring and documentation of any change in the ground surface relative to the stake provides quantitative erosion rate data (Santucci et al. 2009).

Figure 11. Erosion stakes being installed perpendicular to the surface at Fossil Butte National Monument in 2002. Measurement and documentation of movement of the erosion stakes provides information on local erosion rates and the stability of in situ paleontological resources. National Park Service photograph.

Currently, monitoring frequency is determined by repeatedly surveying areas for fossils and overlying GIS data for the repeated surveys. Sites containing paleontological resources become apparent as do those with few or no fossils (Arvid Aase, curator, Fossil Butte

National Monument, written communication, 11 September 2012).

Sites where fossils are eroding from the Wasatch Formation continue to be prospected and located using GPS by Geological Society of America Geocorps interns. Aside from the park's research and interpretation quarry, exposures of the Green River Formation are not subject to systematic fossil prospecting and monitoring. Generally, sites in both formations are evaluated after a mass movement event, such as a rockfall or landslide, when new fossils may be exposed or previous localities damaged. Additional information regarding inventorying and monitoring procedures for paleontological resources is available in Santucci et al. (2009).

Fossil Protection and Theft

An expanding market for vertebrate fossils increases pressure on resource managers to adequately protect the paleontological resources in fossil parks, such as Fossil Butte National Monument. Fossil theft can be difficult to assess and control given the number of exposures and limited park staff, but theft is not thought to be a major issue at the park. The NPS offers training to park staff regarding in the protection of natural resources, including paleontological resources.

A 2002 study of visitors at Fossil Butte National Monument showed that the great majority of visitors agreed with NPS policies that protect fossil resources (Hockett and Roggenbuck 2002). About 87% of on-site visitors felt it was unacceptable to take even a small piece of fossil fish from the monument, and most (81%) visitors also felt it was wrong to remove a fossil from a rock layer. However, about 2% thought that taking a small piece of a fossil fish was acceptable, while about 11% were undecided. In 2011, Fossil Butte National Monument received 16,552 visitors (http://www.nature.nps.gov/stats/index.cfm, accessed 25 April 2012). According to the Hockett and Roggenbuck (2002) study, approximately 330 of these visitors (2%) would not consider the removal of fossils from the monument to be stealing.

Visitor surveys along the Nature Trail (previously the Fossil Lake Trail) yielded similar results (Hockett and Roggenbuck 2003). A majority (86%) of the hikers thought it was wrong to take even a piece of any kind of fossil from Fossil Butte National Monument, and 79% considered chipping fossils out of a rock layer to be wrong. However, about 3% of visitors who responded to the survey believed that taking fossils from the monument was acceptable. About half of the visitors on the trail hiked to the research quarry when it was closed, but most visitors caused no damage to the quarry. In the summer of 2003, only 5 visitors were observed chipping at the layers in the quarry or searching through the waste pile to find fossils. Four of the visitors damaged the quarry layers, but because of the damage, it was not possible to determine whether they stole fossils (Hockett and Roggenbuck 2003).

Santucci (1992) identified three categories of illegal fossil collecting on NPS land: 1) inadvertent casual collecting, 2) intentional casual collecting, and 3) illegal commercial collecting. Research collecting without a permit is also illegal. Commercial quarries operate in Fossil Basin, providing a legal means to obtain Green River fossils. Based on the Hockett and Roggenbuck studies (2002, 2003), any unauthorized fossil collecting at Fossil Butte National Monument would likely fall into the first two categories. Park staff continues to educate the public on the history of Fossil Lake and the NPS mission.

Suggestions from the 2002 survey that might decrease fossil theft and trespass into the park's research and interpretation quarry included: 1) improved trail signage, 2) improved training of Quarry Program interpreters, 3) increased level of interpretive information, and 4) improved self-guided Nature Trail interpretation. In 2004, new waysides were installed along the Nature Trail, and the park is always working on ways to improve the quality of interpretive content and training of interpreters.

Mass Wasting: Rockfall, Landslides, Slumps, and Earthflows

Mudstone in the Wasatch Formation (map unit Tw) contains clay minerals (bentonite) that expand when wet and contract upon drying. This swell–shrink process destabilizes slopes and increases the potential for rockfall, landslides, slumps, and other mass movement. Wasatch Formation clays become saturated and slump, and the more solid Green River Formation limestone (map unit Tgfb) is carried along piggy-back style on top of the collapsing clays. Past landslides are responsible for exposing the cliffs on Fossil Butte.

Landslide deposits mantle the slopes beneath Fossil Butte and Cundick Ridge and are mapped in the park's digital (GIS) geologic data as unit Qls. In 2000, the NPS Geologic Resources Division provided recommendations regarding landslide impacts within the park (Pranger 2000). That report suggested that the most likely trigger for catastrophic landslides of the Green River Formation is warm spring weather following a season of high snowpack.

In 1983, a massive landslide on the southeastern flank of Fossil Butte destroyed a section of the main line of the Union Pacific Railroad (fig. 12). In 2011, a landslide on the eastern border of the park demolished about 180 m (600 ft) of fence. Rockfall also occurred at the northern end of Fossil Butte near the Wasatch saddle. Not all mass wasting events are rapid or catastrophic. Slow-moving earthflows, for example, continue to disturb the Wasatch Formation, particularly south of Cundick Ridge (fig. 13).

Figure 12. Landslide damage. In 1984, a massive landslide on the southeastern flank of Fossil Butte destroyed a portion of the Union Pacific Railroad line immediately adjacent to the park boundary. Left view is to the west, right view is to the east. National Park Service photographs.

Although mass wasting modifies the landscape at Fossil Butte National Monument, documented impacts to its fossil resources are rare. Except for rockfalls occurring in the Green River Formation, fossils have not been discovered in mass-wasting deposits of the Wasatch and Green River formations, suggesting that landslides have not yet exposed nor buried fossil sites. When rockfalls in the Green River Formation include fossil-bearing layers, fossils are found in the talus (Arvid Aase, curator, Fossil Butte National Monument, written communication, 11 September 2012).

Figure 13. Earthflows in the Wasatch Formation. Whereas the Green River Formation is subject to rapid landslides and rockfall, the Wasatch Formation is subject to slow, nearly continuous, earthflow movement. A large earthflow is visible in the center of the image. Viewpoint is from the park road east toward Cundick Ridge. National Park Service photograph.

The Historic Quarry Trail area (on Fossil Butte) is susceptible to large and small landslides and rockfall, indeed it passes through four large identifiable landslide masses (Pranger 2000). The Nature Trail area (on Cundick Ridge) experiences ground movement (slumping) with less risk for rapid catastrophic landsliding (Pranger 2000). Currently, landslides do not threaten the visitor center or the spring.

The park does not monitor landslides. Should monitoring mass wasting become a priority, park managers may consult Wieczorek and Snyder (2009) for suggestions about how to monitor slope movements. Wieczorek and Snyder (2009) describe various types of slope movement and triggering mechanisms for mass-wasting processes, and suggest five vital signs that can be used to monitor slope movements: 1) type of landslide, 2) landslide triggers and causes, 3) geologic material components, 4) landslide movement, and 5) landslide hazards and risks. They accompany their descriptions of the vital signs with detailed explanations of the needed expertise, specialized equipment, and cost of monitoring.

Disturbed Lands

Reclamation of disturbed lands is not a significant issue for Fossil Butte National Monument management. According to the NPS Geologic Resources Division's Abandoned Mineral Lands (AML) database, the park contains five sand and gravel borrow pits. One additional historic pit is obscured by 2-m- (6-ft-) tall sagebrush and cannot be distinguished from adjacent undisturbed areas (Arvid Aase, curator, Fossil Butte National Monument, conference call, 13 December 2011). Fossil Butte National Monument also contains many historic fossil quarries, which are managed as cultural resources and will not be actively reclaimed.

The Chicken Creek Ranch site was reclaimed in the 1970s following the 1972 establishment of the park. Structures were removed and wells plugged so that no physical evidence remains at the site. Many "two-track" roads are being reclaimed naturally by vegetation after they were abandoned when the park was established. Disturbance from livestock is no longer an issue because livestock grazing is no longer permitted in the monument.

In the 1990s, a major restoration project at the Chicken Creek drainage involved the removal of several stockpond dams, re-engineering and re-contouring of the stream channel and floodplain, planting of native vegetation in the floodplain, and controlling of exotic plants. A long-term monitoring plan was designed to monitor stream stabilization and erosion (Kyte and Santucci 1997; Kyte et al. 1999).

In 2004, the NPS Geologic Resources Division, Water Resources Division, and Intermountain Regional Office assessed two disturbed land sites within the park (Pranger et al. 2004). One site encompasses an abandoned early-20th-century roadbed and culvert immediately north of the current county road, where it crosses secondary-stream alluvium (map unit Qas) in Smallpox Creek. The culvert constricts the channel and diverts it away from its original flow path. Associated gully development in unconsolidated Quaternary gravel (map unit Qg) may threaten a rare stand of thick-leaved peppergrass (*Lepidium integrifolium* var. *integrifolium*). Pranger et al. (2004) recommended restoration of the site if peppergrass habitat would not be negatively impacted. The second site is associated with a remote stock pond dam. Although the dam was removed in 1998, spillway and tributary gullies, up to 5.5 m (18 ft) deep, have not been restored as of September, 2012. Pranger et al. (2004) noted thta the erosion and sedimentation observed at the remote site, while originating from anthropogenic causes, was only marginally more severe than nearby examples of natural erosional processes. Thus, restoration was not an immediate concern.

In 2005, a prescribed fire burned in the monument, but native grasses, sage, and invasive cheat grass have grown in the area. No significant erosion resulted from the fire.

An abandoned oil and gas well and an abandoned water well were not completely plugged and are currently leaking water. Artesian groundwater flow has transformed them into springs. The wells are within 46 to 90 m (150 to 300 ft) of each other. As of December 2011, they are scheduled to be plugged with bentonite pellets in the next few years (Arvid Aase, curator, Fossil Butte National Monument, conference call, 13 December 2011).

Energy Resource Exploration and Development

Although energy resource exploration and development cannot occur on the surface within Fossil Butte National Monument, the NPS does not own subsurface mineral rights. Future technology may make horizontal drilling beneath the park economically viable (Vincent Santucci, geologist, NPS Geologic Resources Division, email communication, 19 April 2012).

Oil Shale

Potential development of oil shale resources adjacent to Fossil Butte National Monument was not mentioned in the conference call as a significant issue for management at the present time. Although oil shale is considered to be present in the Green River Formation, the term is misleading. Kerogen-rich laminated micrite, which is a type of limestone and not a true shale, was deposited in Fossil Lake. More accurately, the Green River Formation contains kerogen-rich deposits that may not prove to be economically feasible to develop using currently-available technology. However, the Bureau of Land Management's (BLM) Draft Oil Shale and Tar sand Programmatic Environmental Impact Statement (2012) indicates that the BLM may deem significant areas of land within 11– to 16 km (7– to 10 mi) of Fossil Butte's eastern and western boundaries as available for oil shale leasing (Kerry Moss, external energy and minerals program coordinator, NPS Geologic Resources Division, written communication, 4 April 2012). Future technological improvements may make this a viable resource.

Oil and Gas

Lincoln County contains 38 oil and gas fields and active exploration continues, but not yet in Lincoln County, township 21 north and range 117 west (T21N, R117W) immediately east of Fossil Butte National Monument. For example, 95 permits to drill for hydrocarbons in Lincoln County were granted between 1 January 2011 and 15 February 2012 (Wyoming Oil and Gas Conservation Commission, http://wogcc.state.wy.us/, accessed 15 February 2012). However, no permit has been granted to drill in T21N, R117W since at least 1 January 2008.

Wind Energy

Leased land to the east, west, and south of Fossil Butte National Monument is being considered for wind energy development. Although outside of the park's boundary, such development would impact the park's viewshed. Wind tower foundations would be 10 m (30 ft) deep and filled with concrete. BLM regulations requiring assessment and mitigation of fossil resources must be addressed prior to and during any construction.

Gypsum, Trona, and Coal

No economic gypsum or bedded trona deposit exists in the park, although such deposits are mined in Green River Formation beds associated with Lake Gosiute. Although coal is an integral part of the current and past Kemmerer-area economies, coal deposits are currently buried too deeply beneath the park to be economic. Approximately 10 km (6 mi) southeast of Fossil Butte National Monument and 6 km (4 mi) west of Kemmerer, the extensive Kemmerer Mine (surface mine) recovers coal from a north–south-trending exposure of Cretaceous Adaville Formation (map unit Kav).

Transmission

A major gas pipeline runs immediately south of Fossil Butte National Monument. Expansion of this pipeline or other energy transmission projects (above or below ground) may become viewshed or resource management issues in the future as the National Energy Grid is assessed (Vincent Santucci, geologist, NPS Geologic Resources Division, email communication, 19 April 2012).

Seismic (Earthquake) Hazards

Earthquakes are common in Wyoming but rare in the vicinity of Fossil Butte National Monument (fig. 14). Most of Wyoming's seismic activity is associated with fault movement along the Teton Range and seismic activity in Yellowstone National Park. Seismic studies and the seismic history of Yellowstone National Park suggest that earthquakes of magnitudes 6.5 to 7.5 are possible in Yellowstone (Case and Green 2000).

The first reported earthquake in Lincoln County occurred near Bedford on 31 March 1915. From 1915 to

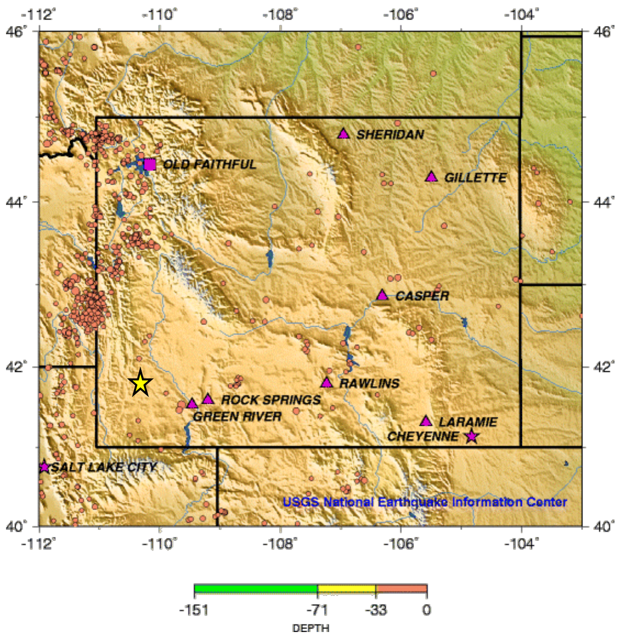


Figure 14. Seismicity map of Wyoming showing earthquakes that occurred between 1990 and 2006. Circles represent earthquakes with color representing the depth, in kilometers, to the epicenter. Note that most earthquakes are associated with the Teton Range and Yellowstone National Park. Few earthquakes have occurred in Fossil Basin. The yellow star represents the approximate location of Fossil Butte National Monument; the purple star is the capital city of Cheyenne; and the purple triangles are cities. Seismicity map available on the Wyoming State Geological Survey website, http://earthquake.usgs.gov/earthquakes/states/wyoming/seismicity.php, accessed 22 February 2012.

23 October 2002, 108 earthquakes occurred in Lincoln County (Case et al. 2002). Three of these were attributed to explosions or seismic line activity related to hydrocarbon exploration. The largest earthquake in the county was an estimated magnitude 5.8 event in 1930. This earthquake, along with the majority of the others, took place west of the Salt River Range in northern Lincoln County. Only 8 earthquakes had magnitudes of more than 4.0 on the Richter scale and were likely noticed by humans. None of the events caused any significant damage. Regional seismic activity outside Lincoln County has been located primarily in Sublette and Teton counties to the north, and has not resulted in significant damage.

From 1915 to 2002, four events occurred between Fossil Butte National Monument and Kemmerer, Wyoming (Case et al. 2002). One of these was the result of an explosion (most likely at the large coal mine west of Kemmerer) and no magnitude was recorded for another. The other two earthquakes were magnitudes 3.7 and 2.5 caused no damage. As of September 2012, no other explosion-caused earthquake has occurred (Arvid Aase, curator, Fossil Butte National Monument, written communication, 11 September 2012).

Potential for earthquakes exists along three active fault systems in Lincoln County: the Rock Creek, Grey's River, and Star Valley fault systems (Case et al. 2002). The north–south-trending Rock Creek fault system, located west and northwest of the monument and approximately 24 km (15 mi) from Kemmerer, is capable of generating a magnitude 6.9 to 7.2 earthquake (Chambers 1988; McCalpin 1993). Case et al. (2002) suggested that a maximum magnitude 7.2 earthquake occurring along the Rock Creek fault would cause only moderate damage, such as broken chimneys, in Kemmerer and Diamondville. However, Fossil Butte National Monument is only about 3 km (2 mi) from the Rock Creek fault, and a magnitude 7.2 earthquake might damage the Visitor Center and museum collections. Neither the Visitor Center nor the museum facility has been assessed for seismic hazards. Although not documented, the museum technician in the mid-1990s claimed that a small earthquake damaged museum specimens in one drawer, although it is not known why only one drawer was affected (Arvid Aase, curator, Fossil Butte National Monument, written communication, 11 September 2012).

Maximum-magnitude earthquake events associated with the other two fault systems are expected to cause no damage to buildings in Kemmerer or at Fossil Butte National Monument (Case et al. 2002).

Geologic Features and Processes

Geologic resources underlie park ecosystems and geologic processes shape the landscape of every park. This section describes the most prominent and distinctive geologic features and processes in Fossil Butte National Monument.

Many NPS units preserve evidence of the dramatic cooling and drying that occurred during the Cenozoic, one of the few times during the past 540 million years when Earth's climate transitioned from a "greenhouse" to an "icehouse" (fig. 6). During greenhouse periods, few or no ice caps are present at either pole and warm–temperate climates exist at relatively high latitudes. During icehouse periods, ice caps are present at one or both poles and warm–temperate climates are not found at high latitudes. Fossils from Fossil Butte National Monument and five other fossil parks (Badlands National Park, Agate Fossil Beds, Florissant Fossil Beds, Hagerman Fossil Beds, and John Day Fossil Beds national monuments) reflect the evolution from greenhouse climates of the Paleocene and Eocene to the icehouse climates that began in the Oligocene and continue today (figs. 6 and 7). In the Eocene, lush warm-temperate forests—containing palm trees, parrots, and flamingos—existed throughout much of western North America. The lakes of the Eocene Green River Formation—Fossil Lake, Lake Gosiute, and Lake Uinta—also existed in that greenhouse setting (Smith et al. 2008).

Fossil Lake was 60–80 km (40–50 mi) long from north to south and about 60 km (40 mi) wide. Fossil Butte National Monument preserves a remarkable collection of fossils and sedimentary features that document the complex ecosystems of Fossil Lake and the surrounding region at a time of maximum global temperatures during the past 65 million years.

This section describes geologic features and processes associated with:

- Paleogene (Eocene) paleontological resources of the Green River and Wasatch formations
- Other paleontological resources
- Stratigraphic features
- Fossils as cultural resources
- Potential and ongoing research projects

Paleogene (Eocene) Paleontological Resources of the Green River and Wasatch Formations

Both the Green River Formation (map unit Tgr) and the Wasatch Formation (map unit Tw) contain fossils that help explain the history of Fossil Lake and the surrounding ecosystems. The Green River Formation contains an exceptional diversity of well-preserved fish fossils, dominated by *Knightia eocaena*, the most abundant, articulated vertebrate fossil in the world and Wyoming's state fossil (fig. 15, table 1). The Wasatch Formation contains primarily fragmentary fossils from a variety of Eocene mammal, reptile, and fish species (table 2).

The fossil collection at Fossil Butte National Monument is extensive. The monument's website provides a list of more than 3,500 fossils from the Green River Formation documented from the monument's research quarry between 1998 and 2011 (http://www.nps.gov/fobu/naturescience/upload/Fossil%20Lake%20Quarry%20data%201998-2007.xls, accessed 27 February 2012). In addition, the monument's collection includes fossils (some of which are replicas) that were collected in other parts of Fossil Basin, including the holotype of the fruit *Lagokarpos lacustris*, the bat *Onychonyctris*, an undescribed snake, the lizard *Saniwa*, and mammals such as the dachshund-shaped *Hyopsodus*, and the dog-sized ancestor of the horse, *Protorohippus* (McMurran and Manchester 2010; Simmons et al. 2008; Tweet et al. 2012). This report presents a summary of the paleontological resources found throughout Fossil Basin, not just those within Fossil Butte National Monument. Unless otherwise cited, the following information was compiled from Tweet et al. (2012) and Arvid Aase, curator at Fossil Butte National Monument.

Green River Formation Paleontological Resources

The Green River Formation is divided into three members, from bottom (oldest) to top (youngest): the Road Hollow, Fossil Butte, and Angelo members.

The Fossil Butte Member (map unit Tgfb) is the middle and most fossiliferous of the three Green River Formation members. It contains not only rays and bony fish fossils, but also algae, spores, pollen, leaves, bivalves, gastropods, ostracods, crayfish, prawns, insects, salamanders, turtles, lizards, snakes, crocodilians, birds, and mammals (table 1). Trace fossils of invertebrates (trails, tracks, burrows) and vertebrates (fish swim traces, coprolites) also occur but are more commonly reported from the other two lakes. Because the fish fossils in the Green River Formation are so well preserved, they have been used to study the evolution of modern groups. The Green River Formation is one of only a few early Cenozoic strata worldwide for which this type of research is possible (Grande 1989, 2001).

Palynomorphs (organic microfossils such as pollen and spores) from the Fossil Butte and lower Angelo members suggest that Fossil Lake was originally surrounded by moist lowlands and floodplains, which transitioned to a dense upland forest of plants that grew under moderate

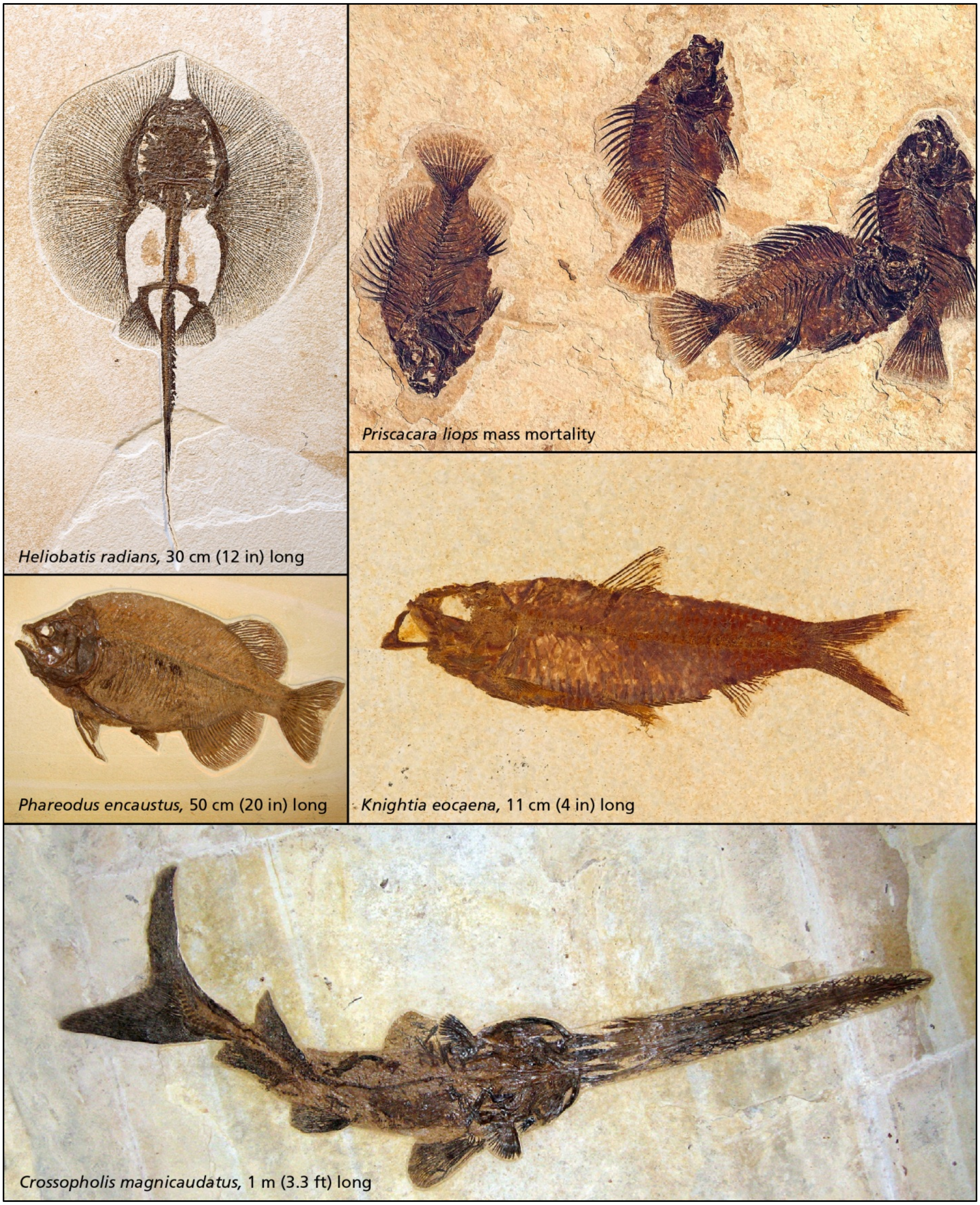


Figure 15. Fossil fish from the Green River Formation. The remarkable state of preservation is consistent with Lagerstätte. Photographs by Arvid Aase, National Park Service, http://www.nps.gov/fobu/photosmultimedia/Green-River-Formation-Fossils.htm, accessed 30 March 2012.

to hot and humid climatic conditions. Low-elevation vegetation eventually displaced the dense upland forest until cooler, drier conditions allowed this forest to expand again.

Road Hollow Member

The Road Hollow Member (map unit Tgrh) remains to be thoroughly investigated, but ostracods, small crustaceans about 1 mm (0.04 in) in length, are very common in Road Hollow limestones and laminated micrite (lithified calcite mud). Fossil fish found in laminated micrites include *Knightia*, *Diplomystus*, *Phareodus*, *Asineops*, and the spiny-finned (percoid) *Priscacara*. Gastropods are common in bioturbated micrites (calcite mud that has been burrowed into by organisms). South of Little Muddy Creek, sandstone beds contain rare crocodile teeth (Buchheim et al. 2011). Abundant fish coprolites litter the surface of some beds. *Presbyornis* feathers and two nesting sites have been found near the base of the Road Hollow Member, and bird, turtle, and mammal bones occur in one sandstone layer. Leaves and plant debris appear in several shale units.

Recently, Buchheim et al. (2011) proposed the division of the Road Hollow Member into three subunits: 1) the lowermost "Lower Shale," 2) a "Lower White Marker Bed," and 3) the "Upper Limestone" subunit. Many of the laminated beds in the Lower Shale unit contain abundant fossils, primarily fish and ostracods. The Lower White Marker Bed contains abundant fossils of fish, ostracods, insects, and plant remains. The Upper Limestone subunit contains abundant gastropods and ostracods.

Fossil Butte Member

Fossils from the Fossil Butte Member (Tgfb) come from fossiliferous layers that may be continuous from nearshore to deep-water localities. Deep-water, fossil-rich sites, located primarily in the center of the basin, include all the sites associated with the famous "18-inch layer." Fossil Butte and several nearby quarries contain deep-water sites. Nearshore environments, located in the northeastern part of Fossil Basin, include "split-fish" layers where the strata split on the bones of the fish and oncolites (algal balls). Mid-lake deposits contain the minifish layer.

Compared with the nearshore sites, the deep-water localities contain more kerogen (insoluble organic material), fewer bottom-dwelling (benthic) animals, and less diverse vertebrates (Grande 1989; Grande and Buchheim 1994; Buchheim and Eugster 1998). The fish are equally well-preserved in shallow- and deep-water sediments, but the extent of fossil completeness differs. Some bones of shallow-water specimens tend to break due to splitting of strata directly on the fossil, whereas deeper-water fossils tend to stay covered due to the higher kerogen content, enabling more precise preparation and, ultimately, more complete fossils. Because the mid-lake minifish layer is relatively low in kerogen, the fish fossils commonly split out along the bones rather than staying covered (Arvid Aase, curator, Fossil Butte National Monument, written communication, 11 September 2012). Fossil collecting has occurred at deep-water sites since the 1850s and at nearshore sites since the 1960s.

Over the years, researchers have identified correlations between fossils and their depositional settings in the Green River Formation. Stingrays, shrimp, crayfish, *Hiodon* and *Amphiplaga*, for example, are more common in nearshore settings. *Notogoneus* are found only in the 18-inch layer rocks. Paddlefish are most common in the minifish deposits, second most common in the nearshore sandwich beds, and rare in other settings (Arvid Aase, curator, Fossil Butte National Monument, written communication, 11 September 2012).

The lake bottom was anoxic (without oxygen) at times, preventing the consumption of organic matter by benthic organisms. Along the lake margin, mollusks, ostracods, and a few fish occupied more restricted settings, and ostracods dominated the dolomitic beds that formed in highly restrictive, hypersaline conditions. Sandstone and siltstone deposited in higher-energy depositional environments, such as those receiving sediments from storm or flood events, primarily contain mollusks and burrows.

Fossil Lake contains a more diverse fish assemblage than do Lake Gosiute and Lake Uinta. At least 15 fish genera are present in the monument, including the abundant *Knightia* and *Diplomystus* (table 1; Buchheim et al. 2011). Cartilaginous fish include two genera and species of rays: *Asterotrygon maloneyi* and *Heliobatis radians*. Twenty-one species of ray-finned fish include paddlefish, gar, bowfins, mooneye, bonytongues, herrings and herring-like fish, gonorynchids (beaked salmon), pike, trout-perch, and several perch-like forms. Two new unnamed perch-like species and an unnamed *Asineops*-like form also have been discovered. The Fossil Butte Member also contains fish mass-death sites, a variety of marks made by fish (called trace fossils), and fish coprolites (fossil feces), which far outnumber the fish body fossils.

Amphibians and reptiles in the Fossil Butte Member include a salamander, an undescribed frog, five species of turtles, one amphiumid, three types of lizards, three snakes, and two crocodilian taxa (table 1). Fossil Lake has also produced one possible lizard skin impression.

The bird assemblage from the Fossil Butte Member continues to grow due to commercial operations. Julia Clark (University of Texas) is currently describing many bird species (Arvid Aase, curator, Fossil Butte National Monument, written communication, 11 September 2012). Weidig (2010) published the most recent list, which includes a lithornithid, frigatebirds, a presbyornithid, landfowl, a bittern-like species, goatsuckers, oilbirds, parrot relatives, and forms with uncertain relationships (table 1). Fossil Butte National Monument's collection includes a fossil feather attributed to the giant ground bird, *Diatryma*. In addition, discovery of scattered bones and a broken egg shell suggests a possible nesting site.

Mammal fossils are rare in the Fossil Butte Member, but the collection includes two specimens of the pantodont *Palaeosinopa*, one specimen tentatively identified as the cat-like *Paroodectes* sp., the arboreal insectivore *Apatemys*, the condylarth *Hyopsodus*, the ungulate *Lambdotherium,* and the fossil horse *Orohippus pumilus* (table 1). Fossil Basin has produced the oldest articulated bat fossils in the world, including two

Table 1. Representative fossils from the Fossil Butte Member, Green River Formation, Fossil Basin.

Fish (23 Genera)	Amphibians and reptiles (19 Genera)	Mammals (26 Genera)
Stingrays *Asterotrygon maloneyi* *Heliobatis radians* (fig. 15) Gar *Lepisosteus bemisi* *Atractosteus simplex* *A. atrox* Bowfin *Amia pattersoni* *Cyclurus gurleyi* Bonytongue *Phareodus encaustus* (fig. 15) *P. testis* Herring and herring-like *Diplomystus dentatus* *Knightia eocaena* (fig. 15) *K. alta* *Gosiutichthys parvus* Perch-like *Mioplosus labracoides* *Priscacara serrata* *P. liops* (fig. 15) *P. hypsacantha* Trout-perch *Amphiplaga brachyptera* *Erismatopterus levatus* Catfish *Hypsidoris farsonensis* *Astephus antizuus* Others *Crossopholis magnicaudatus* (fig. 15) *Eohiodon falcatus* (mooneye) *Notogoneus osculus* (salmon) *Amyzon gosiutensis* (suckerfish) *Esox kronneri* (pickerel) *Asineops squamifrons* (extinct) *Masillosteus janeae* Unnamed *Asineops*-like form	Alligators *Alligator sp.* *Allognathosuchus sp.* *Procaimanoidea sp.* Crocodilian *Borealosuchus wilsoni* *Leidyosuchus wilsoni* *Crocodylus acer* *C. affinis* *Pristichampsus vorax* Turtles (unid., fig. 16) *Baaena arenosa* *Echmatemys septaria* *E. wyomingensis* *Chisternon* *Platypeltis sp.* (soft-shelled) *Trionyx sp.* (soft-shelled) Alcids *Nautilornis avus* *N. proavitus* Lizards *Afairiguana avius* (anole) *Bahndwivici ammoskius* *Saniwa ensidens* (monitor) Others *Boavus idelmani* (boa snake) *Paleoamphiuma tetradactylum* (salamander) *Eopeolobates grandis* (frog)	Bat *Icaronycteris index* *Onychonyctris finneyi* (fig. 16) Condylarths *Hyopsodus minusculus* *H. vicarius* Carnivores *Miacis gracilis* *Vulpavus profectus* *V. australis* *Viverravus minutes* *V. eucristadens* *Mesonyx sp.* (wolf-like) *Metacheiromy sp.* *Sinopa minor* Climbing insectivores *Talpavus nitidus* *Nyctitherium sp.* Arboreal insectivores *Omomys pucillus* *Washakius insignis* Arboreal omnivores *Uintasorex parvulus* *Microsyops elegans* Ground-dwelling herbivores *Pseudotomus robustus* *Paramys delicatus* *Thisbemys sp.* Primates *Notharctus matthewi* (lemur-like) *Tetonius sp.* Others *Orohippus pumilus* (horse) *Hyrachyus sp.* (tapir-like) *Tetrapassaius sp.* *Sciuravis nitidus* *Tellotherium sp.*
Birds (14 Genera)		
Frigatebird *Limnofregata azygosternon* *L. hasegawai* Parrot relative *Cyrilavis colburnorum* *Avolatavis tenens* Ground dwelling bird *P. kistneri* *Pulchrapollia olsoni*	Others *Presbyornis pervetus* (waterbird) *Gallinuloides wyomingensis* (land fowl) *Messelornis nearctica* (bittern-like) *Fluvioviridavis platyrhamphus* (oilbird) *Prefica nivea* (goatsucker) *Primobucco mcgrewi* (perching bird) *Tynskya eocaena* (raptor-like bird) *Cons schucherti* (small, arboreal bird) *Foro panarium* (relationship?) *Diatryma* feather (giant ground bird)	

(Table 1 continued)

Invertebrates (23 Genera)	Insects (30 Genera)	Plants (103 Genera)
Shrimp	Beetles	Representatives include:
Bechleja rostrata	*Eugnamptus sp.* (snout beetle)	Horsetail
	Lebia protospiloptera	*Equisetum winchesteri*
Crayfish	*Sciabregma tenuicornis*	
Procambarus primaevus (fig. 17)	*Adclocera perantiqua*	Palm
	Syntomostylus fortis	*Palmites sp.* (fig. 18)
Clams		*Sabalites sp.*
Plesielliptio priscus	Flies (unid., fig. 17)	
P. n. sp. A	*Eomyza holoptera*	Cattail
Sphaerium sp.	*Sackenia gibbosa*	*Typha lesquereuxi*
	Plecia pealei	
Snails	*Lithophypoderma sp.*	Lillypad
Goniobasis tenera	*Chilosia scudderi*	*Nelumbo sp.*
Hydrobia utaensis	*Cyttaromyia obdurescens*	
H. sp. A	*Pronophlebia rediviva*	Sumac
Valvata subumbilicata		*Rhus mixta*
V. filosa	Mosquito	*R. nigricans*
Viviparus trochiformis	*Culex sp.*	
V. paludinaeformis		Sycamore
Physa bridgerensis	Water strider	*Platanus wyomingensis*
P. longiuscula	*Telmatrechus parallelus*	
P. pleromatis		Tree of heaven
P. sp. A	Planthopper	*Ailanthus lesquereuxi*
Biomphalaria aequalis	*Thaumastocladius simplex*	
B. storchi		Poplar
B. pseudoammonius	Ant	*Populous cinnamomoides*
Drepanotrema sp.	*Archimyrmex sp.*	*P. wilmattae*
Gyraulus militaris	*Liometopum sp.*	
Omalodiscus cirrus	*Eoformica eocenica*	Maple
Lymnaea sp. B	*Protoazteca hendersoni*	*Acer lesquereuxi*
L. similis		
Pleurolimnaea tenuicosta	Wasp	Balloon vine
Oreoconus n. sp. A	*Plectiscidea lanhami*	*Cardiospermum coloradensis*
	Tylocomnus creedensis	
	Tryphoa amasidis	Soapberry
	Pepsis avitula	*Sapindus dentoni*
	Hoplisus archoryctes	
		Pine
	Swallowtail butterfly	*Picea pinifructus*
	Praepapilio colorado	*P. balli*
		P. florissanti
	Moth	
	Hexerites primalis	Fern
		Cladaphlebis septula
	Dragonfly (unid., fig. 17)	*Marsilea sp.*
	Eolestes synthetica	*Regnellidium sp.*
	Stenogomphus scudderi	
	Zacallites balli	
	Cricket	
	Pronemoblus smithii	

Fossil list compiled from Tweet et al. (2012) and Arvid Aase, curator, Fossil Butte National Monument, written communication, 31 August and 4 September, 2012. Note that only fossils identified to genus level are included in the table. A complete list is available at Fossil Butte National Monument. Figure numbers are given for figured fossils. 'Unid." = unidentified.

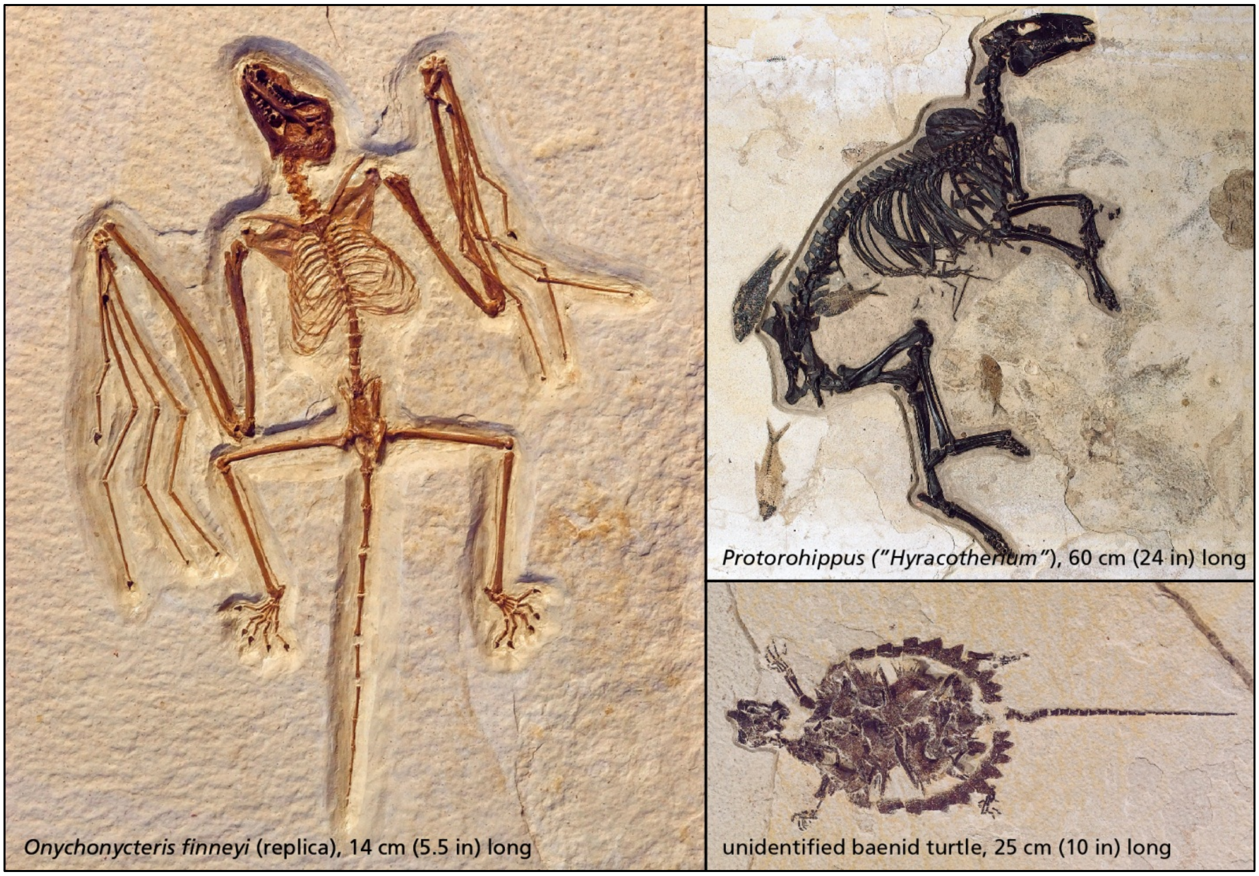


Figure 16. Other vertebrate fossils from the Green River Formation. The bat *Onychonycteris finneyi* is the most primitive bat known. Photographs by Arvid Aase, National Park Service, http://www.nps.gov/fobu/photosmultimedia/Green-River-Formation-Fossils.htm, accessed 30 March 2012.

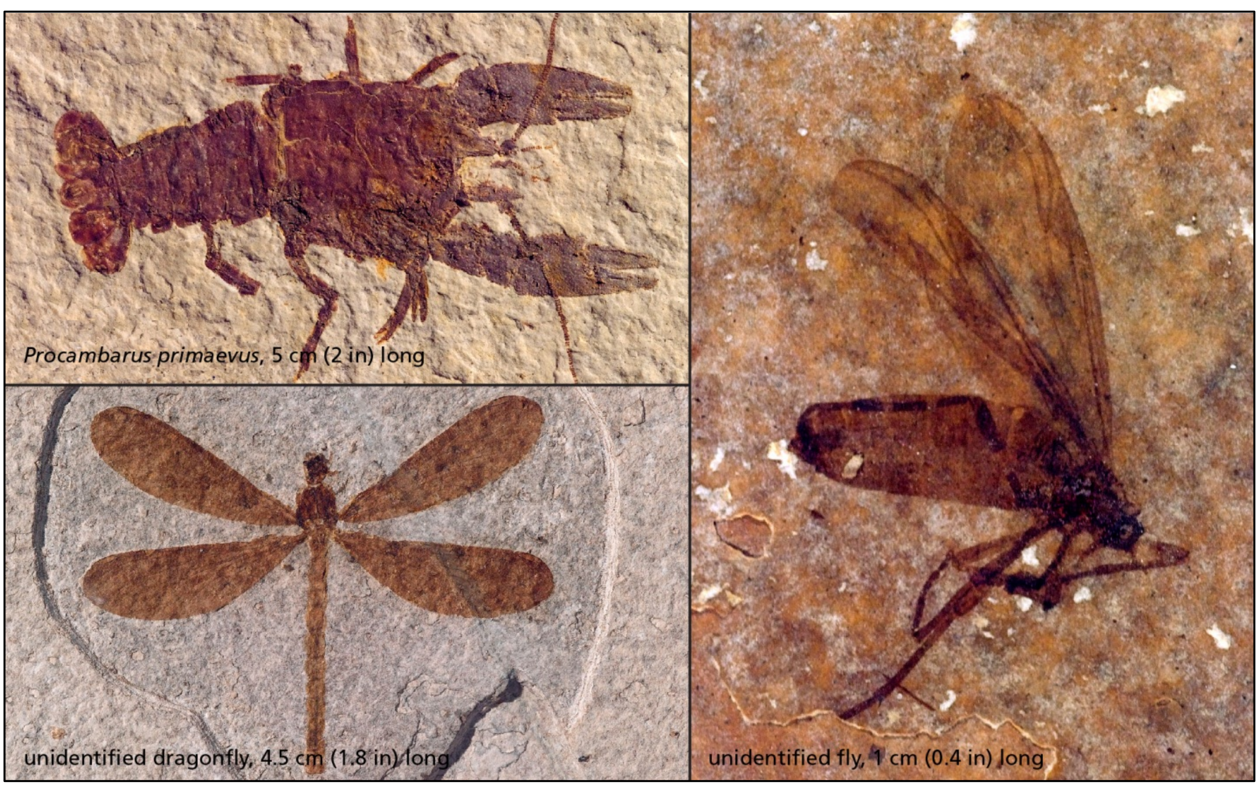


Figure 17. Invertebrate fossils from the Green River Formation. The detail of these delicate fossils illustrates the extraordinary preservation found in the Green River Formation. Photographs by Arvid Aase, National Park Service, http://www.nps.gov/fobu/photosmultimedia/Green-River-Formation-Fossils.htm, accessed 30 March 2012.

specimens of *Onychonycteris* (fig. 16) and more than 30 specimens of *Icaronycteris*. Morphological evidence supports the hypothesis that these bats had echolocation capability (Simmons et al. 2008).

Basin margin limestone layers in the Fossil Butte Member contain primarily stromatolites, gastropods, and ostracods. Most limestone beds rim the basin margin and are exposed between Sillem Ridge and the Absaroka fault (M'Gonigle and Dover 1992, 2004). Fossils of prawns and crayfish (fig. 17) are known from nearshore depositional environments and occasionally from mid-lake deposits.

The plant assemblage from Fossil Lake is diverse, but due to the rarity of these specimens, they are not as well studied or described as those from Lake Gosiute and Lake Uinta (Aase 2009). The paleobotanical collections from Fossil Lake include more than 250 leaf types, such as water lilies, palms, cattails, oaks, sumacs, maples, tropical chestnuts, poplars, roses, Keaki trees, soapberries, trees of heaven, legumes, torchwoods, spurges, verbenas, and at least 12 types of ferns (table 1, fig. 18).

Other fossils in the Fossil Butte Member that help define the Eocene ecosystem include insects (fig. 17), arachnids, and annelid trace fossils. Most insect fossils are of the bibionid fly *Plecia pealei* (march fly), which can account for up to 96% of insect assemblages. Other insects include planthoppers, snout beetles, dragonflies and damselflies, crane flies, bees, wasps, butterflies, and moths (table 1, fig. 17). Fossils of sponges, conchostracans (clam shrimp), and mites have been found in the other lakes, but not at Fossil Lake (Tweet et al. 2012).

Angelo Member

Fossil diversity and abundance decrease in the Angelo Member (map unit Tga), the uppermost (youngest) member of the Green River Formation in Fossil Basin. The quality of preservation also decreases. Stromatolites, formed from cyanobacteria (blue-green algae), became common and reflect shallowing, hypersaline conditions, as do algal-encrusted logs and tufa, limestone that forms from the precipitation of carbonate minerals. Plant fossils include fern spores, gymnosperm and angiosperm pollen, leaf and wood fragments, palm fronds (*Sabalites*), and seed pods. Additional fossils include those of gastropods, ostracods, caddisfly larvae along the lake-shore, dinoflagellates, acritarchs, the turtle *Trionyx*, crocodilians, the duck-flamingo-shorebird *Presbyornis*, mammal bone fragments, large vertebrate coprolites, and bird egg shells. Bird tracks are found in one sandstone unit (Buchheim et al. 2011; Tweet et al. 2012).

Except during freshening events, when the whole lake became hospitable to fish, fish kept primarily to the margins of the lake during this culminating phase of Fossil Lake. The perch "*Priscacara*" *hypsacantha* and *Asineops* dominate the fish assemblage, which also include *Diplomystus*, *Knightia*, *Atractosteus*, and "*Priscacara*" *liops*. One partial amiid (bowfin) has also been discovered in the Angelo Member. The gar *Atractosteus* was the main predator in Fossil Lake at this time.

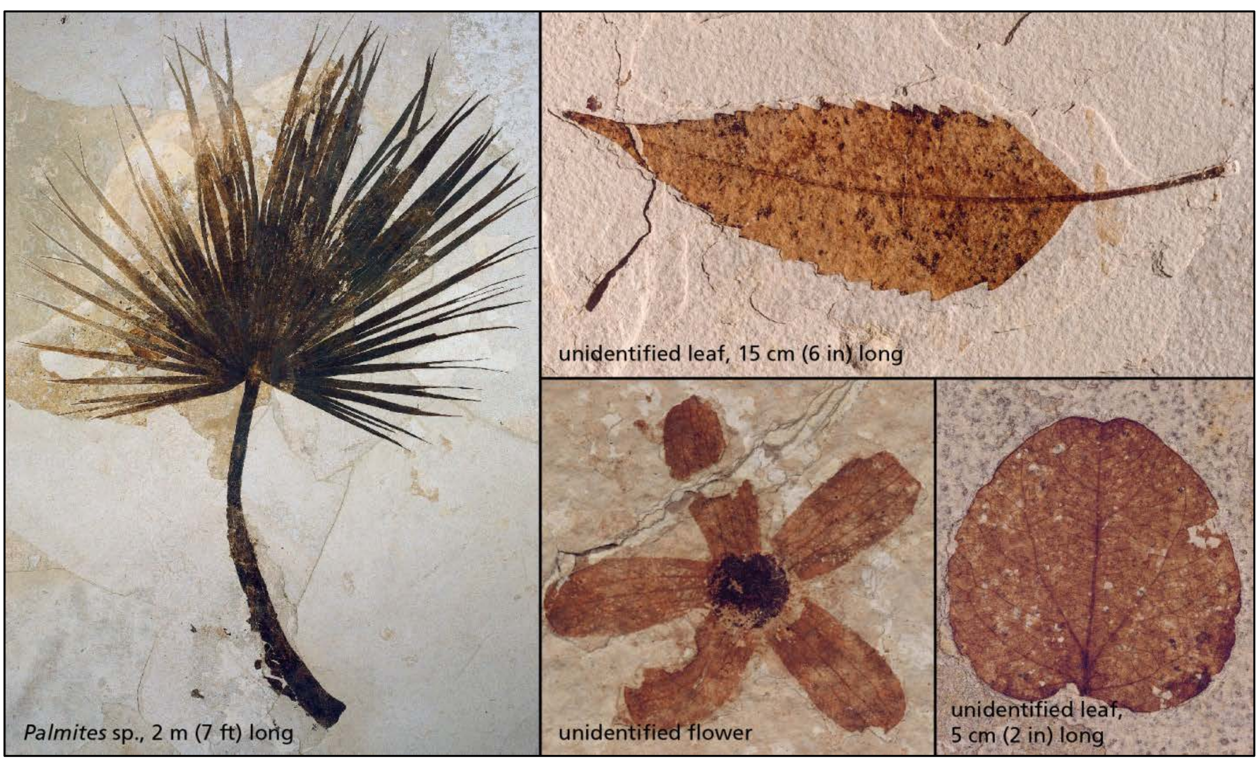


Figure 18. Plant fossils of the Green River Formation. There are more than 250 leaf types, the vast majority of which have not been named. Photographs by Arvid Aase, National Park Service, http://www.nps.gov/fobu/photosmultimedia/Green-River-Formation-Fossils.htm, accessed 30 March 2012.

Wasatch Formation Paleontological Resources

The Main Body of the Wasatch Formation (map unit Tw) is the only member to contain fossils in Fossil Butte National Monument (Tweet et al. 2012). In contrast to the Green River Formation, the Wasatch Formation primarily consists of fragmentary terrestrial fossils (table 2). The primate *Copelemur australotutus* and the artiodactyl *Hexacodus uintensis* were named from specimens collected in the monument. Breithaupt (1990) is the most recently published list and is very similar to that of Gazin (1962) except for the inclusion of the burrowing mammal *Ectoganus* and the early carnivore *Pachyaena*. Arvid Aase, curator at Fossil Butte National Monument, has compiled the most current list of Wasatch Formation fossil mammals and reptiles (table 2).

The monument's collections also include three main assemblages of invertebrate trace fossils representing three different depositional environments. First, flood basin and alluvial plain depositional environments contain *Planolites* and *Skolithos* burrows and possible *Celliforma* (wasp and bee nests). Secondly, an assemblage of vertical, subvertical, and horizontal burrows identifies crevasse splays, fluvial sediments deposited on a floodplain after a stream breaks through a levee. Finally, vertical crayfish burrows identify a fluvial channel assemblage (Zonneveld et al. 2000; Tweet et al. 2012).

Table 2. Fossil mammals and reptiles from the Wasatch Formation, Fossil Butte National Monument.

Mammals (39 Genera)	
Lemur-like primates *Coepelemur australotutus* *Notharctus nunienus* *N. robinsoni* Arboreal omnivores *Microsyops latidens* *M. scottianus* *Cantius frugivorus* *Smilodectes mcgrewi* Arboreal and climbing insectivores *Anemorhysis sp*. (arboreal) *Omomys carteri* (arboreal) *Apheliscus insidiosus* (climbing) *Haplomylus scottianus* (climbing) *Palaeanodon sp.* (climbing) Ground-dwelling herbivores *Ectocion superstes* *Phenacodus trilobatus* *Esthonyx spatularius* Arboreal herbivores *Apatemys chardini* Rodents *Leptotomus parvus* Microparamys *sp*. *Paramys copei* *P. excavates* *Knightomys depressus*	Carnivores *Uintacyon sp*. *Miacis sp*. *Vulpavus canavus* *Viverravus sp*. *Prolimnocyon sp.* (climbing) *Palaeosinopa lutreola* (amphibious fish-eater) Artiodactyls *Hexacodus uintensis* *Bunophorus macroptemus* *Diacodexis metsiacus* *D. secans* *Hyopsodus wortmani* (elongate, dachshund-shaped) Brontotheres *Lambdotherium popoagicum* *Palaeosyops frontinalis* Others *Hyracotherium vasacciense* (horse) *Peratherium marsupium* (possum) *Homogalax protapirinus* (tapir) *Diacodon alticuspis* (leptictid) *Coryphodon sp*. (hippo-like pantodont) *Didymictis protenus* (viverravid) *Meniscotherium chamense* (phenacodontid condylarth) *Ectoganus sp*. (burrowing stylinodontid taeniodont) *Prototomus secundaria*
Reptiles (8 Genera)	
Lizards *Glyptosaurus sylvestris* (armored) *Melanosaurus sp*. *Xestops vagans* *Parasauromalus olseni* Alligator *Procaimanoidea sp*.	Turtles *Baptemys wyomingensis* *Echmatemys cibollensis* *Amyda sp*. (soft-shelled) Crocodile Crocodylid (indeterminate)

Fossil list compiled from Arvid Aase, curator, Fossil Butte National Monument, written communication, 31 August and 4 September, 2012. Note that only those fossils identified to genus level, except crocodylid, are included in the table. A complete list is available at Fossil Butte National Monument.

At Fossil Butte, vertebrate assemblages are recognized in distinct biostratigraphic intervals. The lowermost interval, found within the first 10 m (33 ft) of the Main Body of the Wasatch Formation, contains fossils in siltstone and sandstone beds interpreted as lake-margin and fluvial settings with some paleosol (fossil soil) development (Ambrose et al. 1997). A second interval occurs in the upper 30 m (100 ft), where fluvial mudstones with greater paleosol development contain vertebrate fossils. A third interval occurs just below the contact with the Green River Formation and contains vertebrate fossils in channel and crevasse-splay sandstones interbedded with fluvial mudstones (Ambrose et al. 1997; Gunnell et al. 2002).

These intervals contain nearly three dozen mammal species, including proteutherians (tree shrews and relatives), palaeanodonts (scaly anteater-like animals), taeniodonts, rodents, primates, pantodonts, creodonts, carnivorans, mesonychians, condylarths, perissodactyls (odd-toed ungulates), and artiodactyls (Ambrose et al. 1997; Gunnell et al. 2002). Reptile species are also present and include turtles, lizards, an alligatorid, and a crocodylid (table 2). Gar scales have also been discovered in the unit.

Beyond the borders of the monument, the mudstone tongue of the Wasatch Formation (map unit Twms) encloses logs and branches that fell into water and became encrusted with layers of calcium carbonate–producing algae. The Bullpen Member (map unit Twb) contains gastropods, gars, the extinct fish *Asineops*, and a *Presbyornis* nesting site. Throughout the Green River Basin, the Wasatch Formation includes oncolites, stromatolites, wood fragments, petrified wood, seeds, snakes, *Presbyornis*, other birds, multituberculates (rodent-like mammals), salamander tracks, eggshell fragments, and remains of unknown mammals.

The Wasatch Formation also contains fossils that have been reworked from older Jurassic layers. These include bivalves, Cretaceous-age fish, and dinosaur teeth. Paleozoic fossils may be found in cobbles in Wasatch Formation conglomeratic rocks.

Other Paleontological Resources

In addition to the well documented Paleogene (Eocene) paleontological resources, fossils are known from Quaternary deposits and could potentially be found in Triassic rocks within Fossil Butte National Monument.

Quaternary Paleontological Resources

Fluvial processes and small local landslides (map units Qal, Qas) deposited bison bones in Holocene sediments within Fossil Butte National Monument (McGrew and Casilliano 1975; M'Gonigle and Dover 1992, 2004; Tweet et al. 2012). Bones of large mammals and other fossil material useful for paleoecological and paleoclimatological research have been found throughout the Colorado Plateau and Great Basin, but no large site is present in the monument. About 24 Quaternary fossil sites lie within approximately 100 km (60 mi) of Fossil Butte National Monument in southwestern Wyoming, northeastern Utah, and southeastern Idaho (Benton 1999; Tweet et al. 2012).

Triassic Paleontological Resources

An exposure of Lower Triassic Thaynes Limestone (map unit TRt) has been mapped in a small area within the monument southwest of Rubey Point (McGrew and Casilliano 1975; M'Gonigle and Dover 1992, 2004). Although no fossil has been documented from the Thaynes Limestone within Fossil Butte National Monument, the unit is extensively fossiliferous in the Fossil Basin, containing a variety of shelled marine invertebrates. These invertebrates include foraminifera, sponges, brachiopods (lamp shells), bivalves, cephalopods (ammonites and nautiloids), gastropods, ostracods, lobster-like crustaceans, crinoids (sea lilies), echinoids (sea urchins), ophiuroids (brittle stars), and trace fossils, including resting traces of asteroids (sea stars). Remains of sharks, bony fish, the ichthyosaur *Cymbospondylus*, and bone fragments are also present. The faunal assemblage represents shallow marine environments that once extended from eastern Nevada to southwestern Montana. Tweet et al. (2012) provided a summary of fossils from the Thaynes Limestone.

Stratigraphic Features of the Green River Formation

Stratigraphic features in the Green River and Wasatch formations record the various depositional environments of Fossil Lake and Fossil Basin. The Green River Formation (figs. 5, 19, and 20) grades laterally and vertically into the variegated strata of the Wasatch Formation. All three members of the Green River Formation display a full suite of lake-margin to lake-center lithofacies, which are distinguished from one another on the basis of lithology (table 3; Buchheim and Eugster 1998; Buchheim et al. 2011).

In general, bioturbated micrite forms near the lake margin and kerogen-rich laminated micrite is deposited in the deeper, anoxic central portion of the lake (fig. 19; Buchheim and Eugster 1998). The fossil-rich 18-inch layer (fig. 20) occurs in kerogen-rich laminated micrite, but many fossil-bearing layers across the entire basin are kerogen-poor. The lake bottom was not necessarily oxygenated at the time of deposition of kerogen-poor layers. Further research is needed to understand the origin and preservation of kerogen in Fossil Lake (Arvid Aase, curator, Fossil Butte National Monument, written communication, 11 September 2012).

Road Hollow Member

At least 22 m (70 ft) of interbedded bioturbated and laminated micrites of the Road Hollow Member are exposed at Fossil Butte (location 217 of Buchheim et al. 2011). A 4-m- (13-ft-) thick sequence of interlayered mudstone and laminated micrite caps the member. Radiometric age-dates from volcanic tuffs indicate that this stage of Fossil Lake was dominant from 53.5 million to 52.0 million years ago (Smith et al. 2008).

Table 3. Lithofacies in the Green River Formation, Fossil Basin

Lithofacies	Description	Sedimentary Features	Paleontology
Kerogen-poor bioturbated micrite (KPBM)	Limestone matrix of clay-sized calcite grains supporting sand- to pebble-sized angular clasts; <2% total organic carbon (TOC).	Chaotic mixtures of micrite-supported clasts; abundant horizontal and vertical burrows 0.5–2 cm (0.2–0.8 in) in diameter.	Gastropods, bivalves, ostracods, and fish bones.
Partly-bioturbated laminated micrite (PBLM)	Alternating laminations of clay-sized calcite grains (micrite) and amorphous kerogen; <2% TOC.	Laminated with some burrows similar to KPBM.	Abundant fossil fish.
Kerogen-rich laminated micrite (KRLM)	Alternating calcite (light) and kerogen (dark) laminae; 2–14% TOC.	Laminae average 0.07 mm (0.003 in) thick. Grades laterally and vertically into KPLM.	Abundant fossil fish, leaves, and insects.
Kerogen-poor laminated micrite (KPLM)	Same as KRLM but with lower TOC (<2%).	Same as KRLM but laminae average 0.14 mm (0.006 in) thick.	Abundant fossil fish.
Kerogen-rich laminated dolomicrite (KRLD)	Similar to KRLM but with dominant dolomite content; 2–14% TOC.	Laminations; soft-sediment deformation structures; salt casts.	Ostracods in some layers.
Kerogen-rich chemoturbated dolomicrite (KRCD)	Identical to KRLD except bladed trona crystals disrupt laminae.	Identical to KRLD.	
Kerogen-poor massive dolomicrite (KPMD)	Dolomite; <2% TOC.	Structureless to partly-bioturbated; mudcracks.	
Tuff	Consolidated volcanic ash.	Thin beds; common; 8–25-cm- (3–10-in-) thick k-spar tuff is thickest tuff unit.	No fossils.
Magadi-type chert	Mixture of dolomite, evaporites, and microcrystalline chert.	Similar to recent chert deposits in Lake Magadi of the East African rift system.	
Stromatolites	Sediment trapped by cyanophytes (blue-green algae). Common in the Angelo Member; very rare in the Road Hollow and Fossil Butte members.	Organosedimentary structures (horizontal, domal, subspherical).	Associated with caddisfly larval cases and beetle boring trace fossils at some localities.
Tufa	Variety of travertine. Common in the Angelo Member; very rare in the Road Hollow and Fossil Butte members.	Porous; forms cylinders around logs and twigs.	Wood decays, leaving impressions preserved in tufa covering.
Oncolites	Algal balls.	Dense and very well laminated.	Nuclei include gastropods, bivalves, fossil wood fragments, and flat cobbles.
Sandstone, siltstone, mudstone.	Sand to clay-sized particles; mostly quartz and feldspar.	Trough and ripple cross-bedding; current lineation; slump and other load structures; 4-m- (13-ft-) thick sandstone tongue has top-set, foreset, and bottom set beds.	Gastropods, bivalves, and burrows.

From Buchheim et al. (2011) and Buchheim and Eugster (1998).

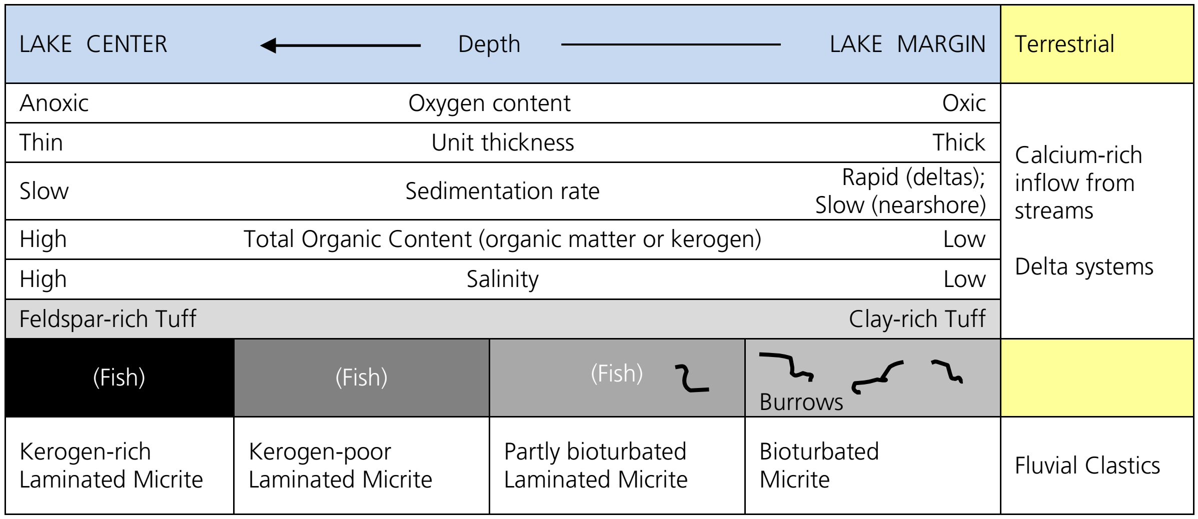


Figure 19. Schematic of Fossil Lake environments and associated rock types. In general, the rock will be composed of either micrite (calcium carbonate mud) or dolomicrite (magnesium-calcium carbonate mud). Descriptive terms indicate the amount of kerogen and the presence of laminations and/or sediment disruption by burrowing organisms. Colors represent land (yellow) and increasing organic matter from the shore to the center of the basin (gray to black). The squiggly lines indicate bioturbation from bottom-dwelling organisms. The rock types reflect the relative distance from the lake margin and the influx of calcium-rich water from river systems. Volcanic tuff that settles through the water column tends to contain more clay toward the lake margin and more feldspar in the center of the lake. Arrow points in the direction of increasing amounts. Fossil fish in the partly bioturbated laminated micrite tend to be disarticulated. Diagram is not to scale. In reality, the lake margin was very narrow immediately adjacent to shore, the partly bioturbated sediment was approximately 0.8–1.6 km (0.5–1 mi) wide, and the kerogen-poor laminated micrite zone was many miles wide and extended across the basin at times. Diagram adapted from Buchheim and Eugster (1998) and comments by Arvid Aase, curator, Fossil Butte National Monument (written communication, 11 September 2012).

In general, kerogen-rich and kerogen-poor laminated micrites deposited in this initial phase of Fossil Lake grade laterally into shallow ostracodal limestone and fluvial to deltaic sandstone and siltstone (Buchheim et al. 2011). As Fossil Lake expanded, Road Hollow mudstone, micrite, and limestone buried the fluvial sandstones and siltstones of the adjacent Wasatch Formation.

Cyclic deposition of the organic-rich Lower Shale subunit of the Road Hollow Member resulted in alternating layers of brown and greenish-gray mudstone, calcimicrite, and siliceous calcimicrite (Buchheim et al. 2011).

The Lower White Marker Bed that overlies the Lower Shale subunit has a distinctive white color due to the presence of weathered layers of kerogen-rich laminated micrite and calcimicrite, which contrast with thin layers of black, kerogen-rich laminated micrite. The subunit represents an episode of lake expansion.

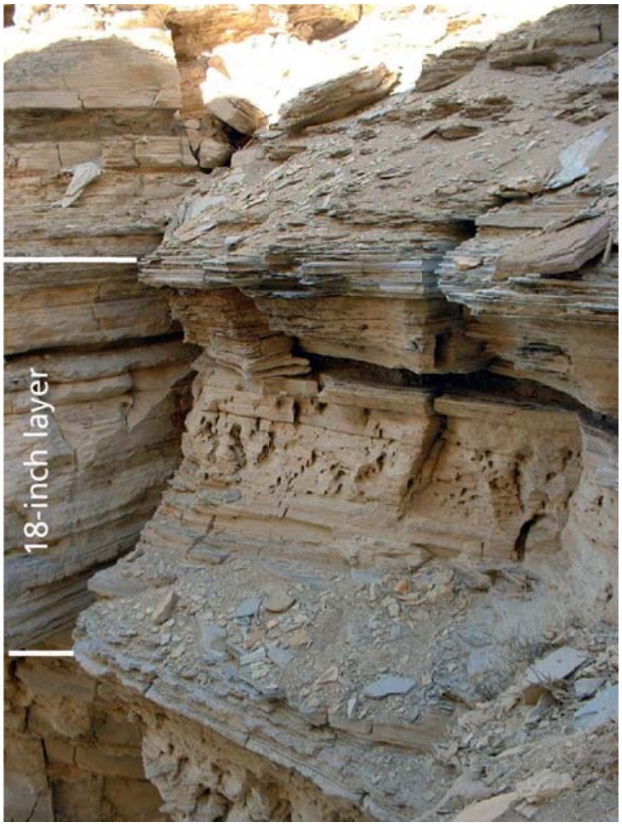
The Upper Limestone subunit of the Road Hollow Member is golden-brown in color and contains alternating layers of limestone, siltstone, and mudstone. The limestone represents continuing, long-term deepening and stabilization of Fossil Lake prior to the progradation of a large delta system into the southern half of the basin (Buchheim et al. 2011).

The Road Hollow Member thins to the north and grades laterally into the Main Body of the Wasatch Formation. The geographic extent of the Road Hollow Member and its sedimentary structures support the interpretation that Fossil Lake began as a floodplain lake in the southern part of Fossil Basin and filled to the north. During the time of Road Hollow Member deposition, Fossil Lake remained relatively shallow and restricted in size compared with the succeeding Fossil Butte Member lacustrine system (Buchheim et al. 2011).

Fossil Butte Member

The Fossil Butte Member was named for an exposed section of rock near the southeastern end of Fossil Butte (known as a 'type locality') in Fossil Butte National Monument (Oriel and Tracey 1970). At the type locality, the Fossil Butte Member consists of 11 m (33 ft) of predominately kerogen-rich and kerogen-poor laminated micrite (locality 217 in Buchheim et al. 2011). These laminated micrites grade laterally into algal, ostracodal, and gastropodal limestones that were deposited near the shore of Fossil Lake (Rubey et al. 1975; Buchheim et al. 2011). Dates obtained from volcanic tuffs in the Fossil Butte Member indicate that this phase of the Eocene freshwater lakes began about 52.0 million years ago (Smith et al. 2008).

South of Fossil Butte National Monument, the Sandstone Tongue of the Wasatch Member (map unit Tws) separates the Fossil Butte Member from the underlying Road Hollow Member. Where the Sandstone Tongue is absent, the contact between the Road Hollow and Fossil Butte members occurs at the base of a 20-30-cm- (8-12-in-) thick kerogen-rich laminated micrite that is pervasive throughout the basin. This lower kerogen-rich laminated micrite bed occurs 2 m (7 ft) below a 15-cm- (6-in-) thick kerogen-rich laminated micrite that is sandwiched between two, 1-3-cm- (0.4-1-in-) thick tuff beds (Buchheim et al. 2011).



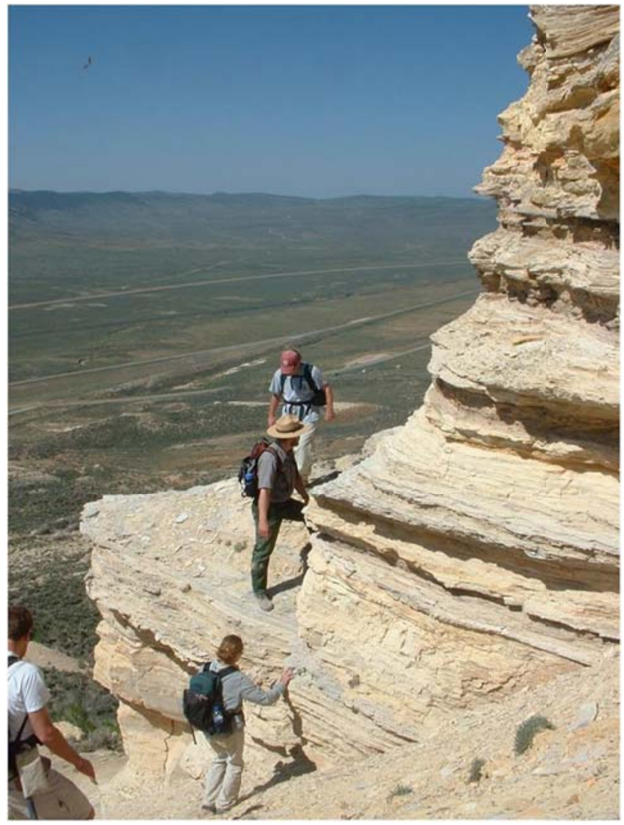


Figure 20. The Green River Formation, Fossil Butte National Monument. The fossiliferous 18-inch layer is in the center of the upper photograph. Note the steepness of the exposure at Fossil Butte and how erosion and weathering affects each layer differently (known as differential erosion). Geologists for scale. National Park Service photographs taken in 2003 courtesy of Jason Kenworthy (Geologic Resources Division).

In addition to the abundant fossil material, strata in the Fossil Butte Member provide information about the evolution and depositional environments of Fossil Lake. The laminated sediments were once thought to represent varves, or layers created by seasonal deposition (Bradley 1929, 1963), but a more recent model has attributed their formation to different mixing ratios between calcium-rich inflow waters and alkaline lake water. These ratios depended on the rates of deposition, distance from shore, and water depth (Buchheim 1994b; Buchheim and Eugster 1998). This interpretation helps explain the association of strata composed of kerogen-rich, kerogen-poor, and bioturbated sediment (fig. 19; table 3).

Deposition of kerogen-rich laminated micrite occurred in the basin center, where lake-generated algae and other organics were left relatively undisturbed by lake-margin, calcium-rich, and clastic fluvial sedimentation. Seasonally anoxic bottom waters enhanced potential preservation of fish and other organisms (Buchheim and Eugster 1998). Shoreward, kerogen content in the sediments decreased and burrowing by organisms increased. A transition occurs from kerogen-rich laminated micrite to kerogen-poor laminated micrite, partly burrowed laminated micrite, and bioturbated micrite near the shore, although this transition varies by 0.8–3 km (0.5–2 mi) along the eastern shore and the bioturbated layers may extend for more than 16 km (10 mi) along the western shore (Buchheim and Eugster 1998; Arvid Aase, curator, Fossil Butte National Monument, written communication, 11 September 2012). The bioturbated, shoreline deposits of the Fossil Butte Member grade landward into fluvial clastics of the Wasatch Formation (fig. 19).

A mudstone tongue (map unit Twms) in the upper part of the Wasatch Formation separates the Fossil Butte and Angelo members in the northern part of the monument (Buchheim and Eugster 1998; Buchheim et al. 2011). At Fossil Butte, however, the mudstone tongue is absent, and the contact is located at the top of an ochre colored tuff bed where the cliffs of the Fossil Butte Member abruptly change to the slopes of the Angelo Member (Buchheim et al. 2011). The ochre colored tuff bed occurs about 3–4 m (9–13 ft) above the thickest tuff bed in the basin. This tuff bed is 8–25 cm (3–10 in) thick and composed primarily of potassium feldspar (the “k-spar tuff” of Buchheim et al. 2011).

Angelo Member

Above the ochre-colored tuff bed at Fossil Butte, the white-weathering Angelo Member (Tga) consists of 27 m (89 ft) of dolomicrite and silty dolomicrite. The unit also contains calcite pseudomorphs, which are calcite crystals that have grown in the voids left by mineral dissolution (Buchheim et al. 2011). The dolomicrite marks a significant change from the fossiliferous micrite of the Fossil Butte Member. This underfilled stage of Fossil Lake is characterized by stromatolites and tufa, which are rare in the Road Hollow and Fossil Butte members.

Stromatolites, desiccation cracks, salt casts and other evaporites, dolomite, tufa-covered logs, and rare fish in the center of the basin indicate a transition to a more hypersaline, inhospitable, arid depositional environment during this latter stage of Fossil Lake. Faunal diversity is low compared with that of the Fossil Butte Member. Ostracods and gastropods dominate the fossil content. *Asineops squamifrons*, which is rare in all Fossil Butte Member strata, dominates the fish fauna in some layers, while in two productive Angelo horizons, *Diplomystus* and *Knightia* are associated with relatively common plants, insects, and feather fossils (Arvid Aase, curator, Fossil Butte National Monument, written communication, 11 September 2012). Eventually, fluvial sediments from the Wasatch Formation filled Fossil Lake.

The strata form the rounded, uppermost slopes of Fossil Butte above the more vertical cliffs of the Fossil Butte Member. In the northern part of the monument, the Angelo Member is overlain by the Bullpen Member of the Wasatch Formation (Twb).

Stratigraphic Features of the Wasatch Formation

The red, purple, brown, yellow, tan, and gray mudstones, claystones, siltstones, sandstones, and conglomerates in the Wasatch Formation represent fluvial and floodplain deposits that rimmed Fossil Lake (fig. 21). A ledge or cliff formed by the Sandstone Tongue (Tws) in the Wasatch Formation provides a useful marker bed in the southern half of the basin (Buchheim and Eugster 1998; Buchheim et al. 2011).

The distinctive red color that occurs in this formation may be the result of the deposition of oxidized organic material in the humid, warm-temperate environment of the Eocene. Lateritic soils that formed in the uplands were likely eroded and deposited on floodplains. Various stages iron oxide reduction caused the bands of purple, gray, orange, and other colors seen in the rocks (McGrew and Casilliano 1975).

Exposures of the Lower Member of the Wasatch Formation (map unit Twl) occur on the flanks of Rubey Point in the far western section of Fossil Butte National Monument (M'Gonigle and Dover 1992). Deposited in floodplains, the tan, brown, pink, red, or gray mudstone forms the primary rock type, but the unit also includes black, carbonaceous siltstones, yellowish-brown sandstone, and thin lenses of stromatolitic and pisolitic limestone (McGrew and Casilliano 1975).

The lower slopes of Fossil Butte display the multicolored Main Body of the Wasatch Formation (Tw), which contrast sharply with the drab, overlying Green River Formation. The bands of bright- to dull-red, pink, purple, yellow, and gray are especially vibrant following a rain. Individual layers range from 0.3– to 3 m (1– to 10 ft) thick and consist predominantly of variegated mudstone with interlayered sandstone, conglomerate, marlstone, siltstone, and claystone (McGrew and Casilliano 1975).

Conglomerates and sandstones, which are more common in the lower part of the Main Body, occur as channel fill deposits. Individual clasts were cemented together by calcium carbonate, which was also responsible for the presence of calcium-rich water along the margin of Fossil Lake. The fine-grained mudstones and siltstones formed in floodplains attached to the streams flowing into the lake.

Figure 21. The Wasatch Formation, Fossil Butte National Monument. The variegated slopes easily erode and vegetation is rare. National Park Service photograph courtesy of Arvid Aase (Fossil Butte National Monument).

The Sandstone Tongue of the Wasatch Formation (Tws), which forms a conspicuous sandstone ledge south of the monument, has been interpreted as a Gilbert-type delta. First described by geologist Grove Karl Gilbert in 1885, a Gilbert delta forms from coarse sediments, rather than fine-grained sediments such as those forming the Mississippi delta. Such deltas are often associated with sediment deposition into freshwater lakes by mountain rivers. In the Eocene, the Sandstone Tongue encroached upon the southern end of Fossil Lake. The brown, cross-bedded sandstone of the Sandstone Tongue forms topset (horizontal), foreset (sloping), and bottomset (horizontal) beds characteristic of Gilbert-type deltas. When Fossil Lake expanded, the delta was covered by lake sediments of the Green River Formation (Oriel and Tracy 1970; Buchheim and Eugster 1998).

In the northern part of the monument, the mudstone tongue of the Wasatch Formation (Twms) separates the Fossil Butte and Angelo members of the Green River Formation (M'Gonigle and Dover 1992, 2004). The dark-red mixture of silt and clay contains cylinders of limestone that formed when logs and branches were transported to the edge of Fossil Lake. Successive layers of algae grew around the logs and resulted in encrustation by calcium carbonate (McGrew and Casilliano 1975).

The Bullpen Member (Twb), the uppermost member of the Wasatch Formation, reflects the gradual transition from the lake environment of the Angelo Member into a swamp and finally a floodplain environment. Similar to the Main Body, the Bullpen Member consists primarily of layers of red, pink, gray, and green mudstone. Sandstone beds and thin, slabby limestones are also present. A few isolated exposures of the Bullpen Member cap low hills in the northern part of Fossil Butte National Monument, but most of the member lies west and south of the monument (M'Gonigle and Dover 1992, 2004).

Fossils as Cultural Resources

At least 237 NPS areas are known to preserve paleontological resources, and some of these fossils are associated with cultural resources (Kenworthy and Santucci 2006). For example, fossils may be associated with archeological sites or ethnographic stories and legends. Body fossils, trace fossils, and petrified wood have been used as building stones in prehistoric and historic structures.

Although fossil–cultural associations have yet to be recognized at Fossil Butte National Monument, archeological investigations in the vicinity have discovered tools made from fossil material, chert projectile points, and artifacts fashioned from algal chert (Tweet et al. 2012). More generally, the fossils of Fossil Butte are part of southwestern Wyoming's culture and have been a source of local pride since their discovery in the 19th century. In fact, Kemmerer bills itself as the "Fossil Fish Capital of the World."

Continued Research Opportunities

Geologic and paleontological resources from Fossil Lake provide the opportunity to study an entire ecosystem, including not only fish species, but also interactions among animals and between animals and plants, turtles and fish, plants and insects, and vertebrates living in and near water. Such research includes a myriad of paleoecological projects, as well as investigations into the changing paleoclimate and its effects on animal and plant species.

Paleoclimate research on the Eocene Green River and Wasatch formations provides opportunities for climate change outreach and the establishment of connections with other parks containing fossils (Kenworthy 2010).

Detailed studies of the Green River Formation continues to address the changing salinity of Fossil Lake. The chemical compositions of the different stratigraphic units helps define the various salinity–alkalinity conditions of Fossil Lake, resulting in a better understanding of the lake's evolution. Questions remain regarding the origin of potassium feldspar in volcanic tuffs, as well as how fish survived in some of the more restricted paleoenvironments of the lake (Buchheim and Eugster 1998).

Fossil Butte National Monument has a variety of other research needs including (Arvid Aase, curator, Fossil Butte National Monument, written communication, 11 September 2012):

- Comprehensive study of fossil insects
- Climate analysis using plant/animal interactions
- Determination of mass mortality causes
- Study of the Road Hollow Member faunal assemblage
- Determination of depositional rates
- Fish growth studies
- Exploration of the mechanisms of lamina deposition.

A summary of past and current research is available in Tweet et al. (2012).

Geologic History

This section describes the rocks and unconsolidated deposits that appear on the digital geologic map of Fossil Butte National Monument, the environment in which those units were deposited, and the timing of geologic events that formed the present landscape.

The geologic history of the area surrounding Fossil Butte National Monument captures the growth of a supercontinent, two mountain-building episodes, the formation of the most extensive inland seaway to bisect North America, the rise of mammals, and the growth of a great lake system in the balmy, warm-temperate Eocene climate of southwestern Wyoming. A wide variety of fish swam in the lakes and dense forests flourished in the surrounding highlands. Eventually, the lakes filled with sediment and the water evaporated. Today, Fossil Butte National Monument preserves the detailed history of the complex Eocene paleoenvironments, ancient organisms, and paleoclimate associated with Fossil Lake.

Ancient Seas: The Paleozoic (542–251 million years ago)

During the Paleozoic, shallow seas advanced and retreated many times across western North America, depositing thick sequences of fossiliferous limestone and dolomite (fig. 22). In the Pennsylvanian (318–299 million years ago), the collision of the southern margin of the North American plate with the northern margin of the South American plate resulted in the Ancestral Rocky Mountains, a northwest-to-southeast trending mountain range extending from central Wyoming through Colorado, New Mexico, and parts of Texas and Oklahoma. The Amsden Formation (map unit PMa), exposed in the mountains west of the monument, consists of limestone and dolomite deposited in shallow, nearshore marine environments and sand, silt, and clay eroded from the Ancestral Rockies (Love et al. 2003).

The Middle- to- Late Permian Phosphoria Formation (map unit Pp), also exposed west of the monument, contains beds of phosphorite, a dark sedimentary rock rich in calcium phosphate. Studies of the formation's invertebrate fauna (brachiopods and conodonts) have indicated that the thin layers of siltstone, limestone, black chert, and phosphate accumulated in shallow water (fig. 22). Cool, upwelling currents swept nutrients onto this shallower shelf from a deeper, offshore environment to the west (Wardlaw 1980; Love et al. 2003). Phosphate-rich hard parts of marine invertebrates and fecal pellets accumulated to form the phosphatic rocks. The Phosphoria Formation records two episodes of sea-level rise (transgression) followed by a major sea-level fall (regression) at the end of the Paleozoic.

Assembling and Dismantling Pangaea: Triassic and Jurassic Periods (251–145 million years ago)

By the Early Triassic (251–246 million years ago), plate tectonic processes had assembled all of the major land masses around the globe into one large supercontinent, Pangaea (fig. 22). Thin beds of calcareous siltstones and sandy limestones of the shallow marine Dinwoody Formation (map unit TRd) interfinger with the bright-red clastic, terrigenous siltstones and shale of the Woodside Red Beds (map unit TRw). The Dinwoody Formation represents an initial transgression of a shallow sea onto the gently westward-sloping Wyoming shelf. Deposition of the Woodside Formation gradually advanced westward over the Wyoming shelf as sea level fell (Dubiel 1994).

The easily eroded siltstone and claystone of the Woodside Red Beds form slopes beneath the cliffs and ledges of the Thaynes Limestone (map unit TRt; Rubey et al. 1975). The gray, silty limestone and calcareous siltstone of the Thaynes Limestone, exposed in the northwestern arm of the monument, indicate another incursion of a shallow sea into the area. The unit thickens westward and northward to as much as 400 m (1,300 ft) northwest of the monument (Rubey et al. 1975).

Middle Triassic (245–228 million years ago) rocks are absent in the Fossil Butte National Monument region (fig. 5). The sandstone, siltstone, and mudstone of the Upper Triassic (228–200 million years ago) Ankareh Formation (map unit TRa) were deposited over the Thaynes Limestone as the sea withdrew from the Wyoming shelf (Dubiel 1994).

By the Early Jurassic (200–176 million years ago), tectonic forces were breaking apart Pangaea. Landmasses began moving to their current positions around the globe. Rising sea level spread the relatively shallow Sundance Sea into Wyoming. The sea advanced from the north and flooded large portions of the Western Interior of North America, a physiographic province bordered to the west by mountains and to the east by the stable North American craton (Brenner 1983; Picard 1993; Brenner and Peterson 1994; Peterson 1994). Wyoming lay within 15° to 20° North latitude, and the eolian, cross-bedded Early Jurassic Nugget Sandstone (map unit JTRn) became part of an extensive erg, or sand sea, in which towering dunes formed from Wyoming to Arizona in the warm, dry climate. Accumulations of fine- to medium-grained, well-sorted dune sand are up to 450 m (1,500 ft) thick.

The Middle Jurassic (176–161 million years ago) mudstone, siltstone, limestone, and rare gypsum in the Gypsum Spring Member (map unit Jtg) of the Twin Creek Limestone (map unit Jt) record deposition in marine to coastal sabkha and tidal flat environments (Peterson 1994). Compression from subduction along the western margin of North America resulted in the rise

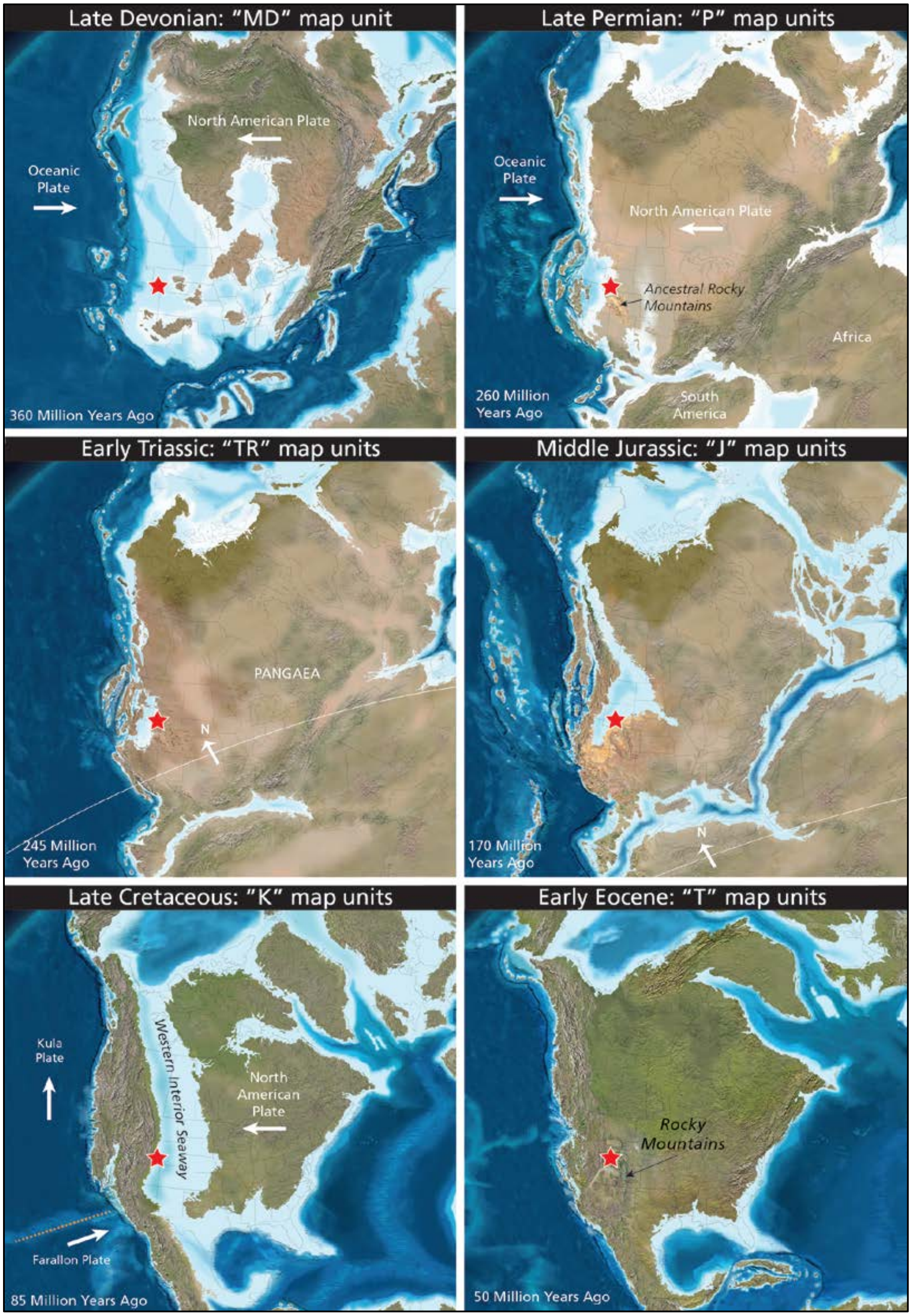


Figure 22. Paleogeographic maps of North America. Approximately 360 million years ago, rising sea level inundated much of the continent with shallow seas, which covered much of western North America throughout the Paleozoic. Approximately 260 million years ago, all of the major land masses were coming together to form the supercontinent Pangaea. The shallow marine Phosphoria Formation (map unit Pp) was deposited adjacent to upwelling, deeper marine water. The collision of South America, Africa, and North America produced the Alleghanian (Appalachian) Orogeny, the Ouachita Orogeny, and the Ancestral Rocky Mountains. Approximately 245 million years ago, the major landmasses had formed the supercontinent Pangaea. Approximately 170 million years ago, Pangaea was breaking apart and a shallow sea encroached into the Fossil Butte National Monument area from the north. A subduction zone had developed along the western margin of North America. In the Late Cretaceous Period, approximately 85 million years ago, the Hams Fork Conglomerate Member of the Evanston Formation (map unit Keh) and the Adaville Formation (map unit Kav) were deposited along the western border of the Western Interior Seaway. The mountain belt that borders the western margin of North America from Alaska to Mexico is a result of the Sevier Orogeny, which in turn is the result of subduction of oceanic crust beneath the North American continental crust. Around 50 million years ago the Rocky Mountains continued to be uplifted along deep-seated reverse faults as a result of the Laramide Orogeny. Fossil Lake, Lake Gosiute, and Lake Uinta form. The red star represents the approximate location of Fossil Butte National Monument. Base paleogeographic maps created by Ron Blakey (Colorado Plateau Geosystems, Inc.), which are available at http://cpgeosystems.com/index.html (accessed 30 March 2012).

of the Western Elko Highlands in Nevada and the subsidence of a north–south-trending trough-like depression in central Idaho and northern Utah (Peterson 1994). Western Wyoming lay on the eastern margin of this encroaching seaway, and the Twin Creek Limestone and Gypsum Spring Member mark the initial incursion of shallow marine waters into the trough (fig. 22).

By the late Middle Jurassic, marine waters had spread throughout western Wyoming and eastern Idaho as a sea encroached from the north. The overlying sandstones and limestones of the Middle Jurassic Preuss Red Beds and Middle- to- Upper Jurassic Stump Sandstone were deposited along the southern margin of this shallow sea (Peterson 1994). Although not exposed in Fossil Butte National Monument, the Stump Sandstone in Dinosaur National Monument to the south contains invertebrate fossils, including those of brachiopods, bivalves, belemnite cephalopods, and echinoderms, typical of well-oxygenated marine environments (Graham 2006).

The Great Compression: Cretaceous to Eocene (145–35 million years ago)

Mountain ranges began to develop far to the west of Wyoming as early as the Devonian (416–359 million years ago) as Pacific oceanic plates were subducted beneath the western margin of North America. In the Early Cretaceous (possibly beginning in the latest Jurassic about 150 million years ago), intense compression caused by the subduction of the Farallon oceanic plate beneath North America began to fold thick sequences of Paleozoic and Mesozoic sedimentary strata into extraordinary convex folds (anticlines). These folds reached heights of 1,500–3,000 m (5,000–10,000 ft) and consisted of extensive sheets of rock up to 3 km (2 mi) thick and tens to hundreds of kilometers long. With continued compression, the folds broke along weak layers in the strata, such as beds of shale or gypsum, and the sheets of rock were displaced as much as 80 km (50 mi) to the east along low-angle thrust faults (fig. 8). Eventually, a belt of sedimentary rocks that was originally 320–400 km (200–250 mi) wide was telescoped (compressed) to a final width of about 240 km (150 mi; Armstrong and Oriel 1986; Love et al. 2003).

This Early Cretaceous mountain-building event (orogeny) is commonly referred to as the Sevier Orogeny and may have actively deformed the western margin of North America from approximately 140–50 million years ago. The north–south-trending belt of folds and thrusts (called the Rocky Mountain fold-and-thrust belt) extends from the Brooks Range in Alaska to the Sierra Madre Oriental in Mexico and documents approximately 90 million years of subduction along the entire western margin of North America. The Sevier Orogeny is responsible for the Crawford Mountains and Tunp Range, which bracket Fossil Basin to the west and Oyster Ridge, located east of Kemmerer (fig. 23). It is also responsible for the Caribou, Salt River, Wyoming, and Snake River ranges south of Jackson, Wyoming, and the Wasatch Range in Utah.

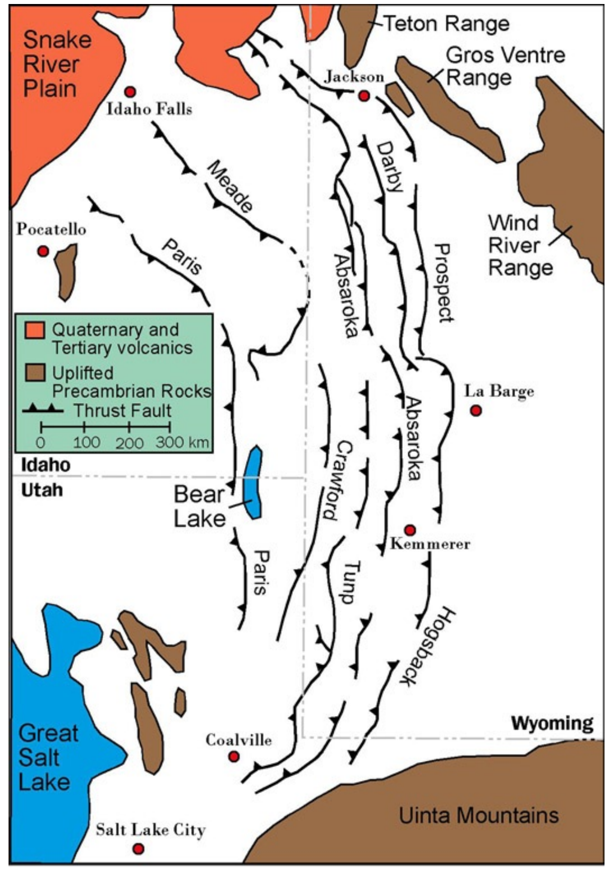


Figure 23. Wyoming-Idaho-Utah portion of the fold-and-thrust belt that extended from Alaska to Mexico. The thrusts are progressively younger from west to east. The yellow star is the approximate location of Fossil Butte National Monument. Modified from Armstrong and Oriel (1986) and available on the Digital Geology of Idaho website: http://geology.isu.edu/Digital_Geology_Idaho/Module5/mod5.htm, accessed 10 February 2011.

Thrust faults in the mountain ranges and beneath Fossil Basin separate thick sequences of sedimentary rock. For example, as much as 3,000–6,000 m (10,000–20,000 ft) of sedimentary strata rest above the fault plane of the Absaroka thrust, the first thrust fault encountered beneath the surface of Fossil Basin (fig. 24; Lamerson 1982; Armstrong and Oriel 1986; Link and DeGrey 2007). Most of the displacement along the gently westward-dipping Absaroka thrust occurred about 84 million to 74 million years ago (Lamerson 1982; Armstrong and Oriel 1986). In the Little Muddy Creek area, about 24 km (15 mi) southwest of Kemmerer, a northwest–southeast-trending bend in the Absaroka thrust divides Fossil Basin into northern and southern sections. Fossil Butte National Monument is located within the northern portion of the basin (Lamerson 1982).

In general, the thrust faults cut progressively younger strata from west to east (Armstrong and Oriel 1986). The Absaroka thrust, for example, originally broke along a weak layer in Cambrian strata and as it progressed from west to east, the fault cut through younger strata until Cambrian strata at the base of the thrust's hanging wall was juxtaposed against Cretaceous strata at the top of its footwall in the Fossil Basin area (fig. 24; Lamerson 1982; Platt and Royse Jr. 1989).

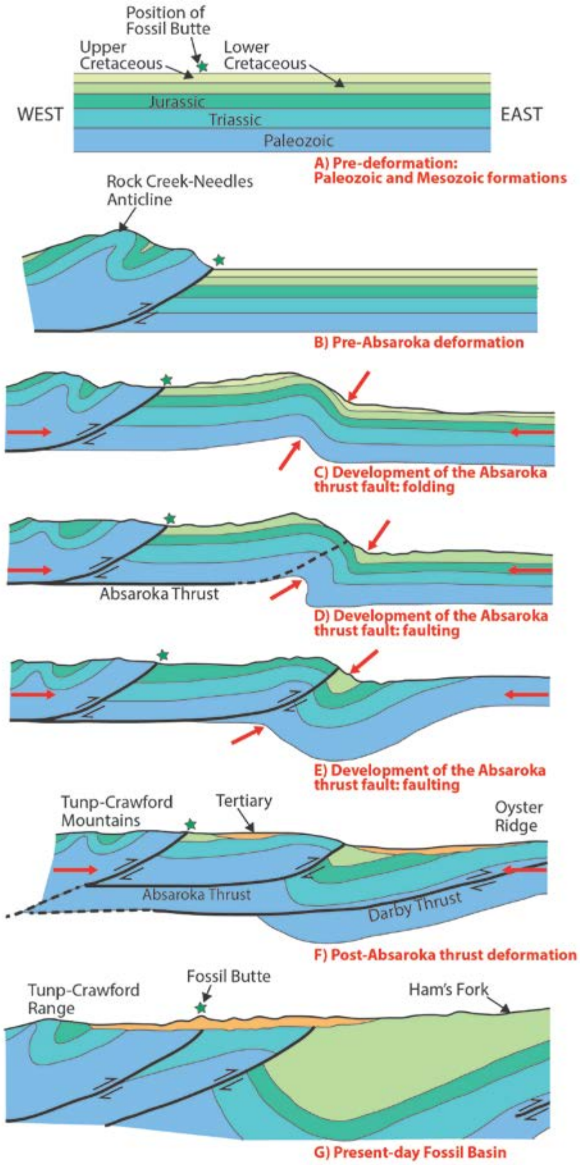


Figure 24. Geologic cross-section and history of Fossil Basin. Initially, horizontal strata were folded into the Rock Creek-Needles anticline (convex fold) above the older, unnamed thrust west of the Absaroka thrust. With continued compression from the west, rocks east of the Rock Creek-Needles anticline were folded and displaced to the east on the Absaroka thrust fault. Erosion and downwarping formed Fossil Basin. Another cycle of folding and thrusting produced the Darby thrust and further downwarping between the Tunp-Crawford Mountains and Oyster Ridge. The Darby thrust is also called the Hogsback thrust in the Fossil Butte area. The arrows indicate direction of movement on the thrust. National Park Service diagram from McGrew and Casilliano (1975) modified by Trista Thornberry-Ehrlich (Colorado State University).

As thrust sheets were stacked atop one another, the crust began to subside to the east, parallel to the fold-and-thrust belt, creating the Western Interior Basin. With subsidence, sea water began to fill the basin from the Arctic region and the Gulf of Mexico. Episodic fluctuations in sea level occurred throughout the Cretaceous, culminating in the formation of the most extensive interior seaway ever to bisect the North American continent (fig. 22). The Western Interior Seaway extended from today's Gulf of Mexico to the Arctic Ocean, a distance of about 4,800 km (3,000 mi; Kauffman 1977; Steidtmann 1993). During periods of maximum sea-level rise, the width of the basin reached 1,600 km (1,000 mi).

During the latest Cretaceous, when the Hams Fork Conglomerate Member of the Evanston Formation (map unit Keh) and the Adaville Formation (map unit Kav) were deposited, the western shoreline of the Western Interior Seaway lay in eastern Wyoming (Cobban et al. 1994). Carbonaceous shale and coal beds in the Adaville Formation suggest deposition in floodplains, marshes, and ponds. Sediments were derived from highlands to the west and northwest (Armstrong and Oriel 1986). Fossil pollen, spores, and leaves in the Hams Fork Conglomerate indicate a warm-temperate climate and abundant woodlands (Oriel and Tracey 1970; McGrew and Casilliano 1975). Since the 1840s, remains of these ancient forests have been mined as coal throughout southwestern Wyoming.As many as nine beds of boulder conglomerate are interlayered with thick beds of conglomeratic sandstone and mudstone in the Hams Fork Conglomerate Member, which may be as much as 300 m (1,000 ft) thick in the Fossil Basin area (Buchheim 2005). Pebbles and boulders in this member are rounded and spherical, suggesting that they were transported by high-energy streams. High-velocity stream-flow knocked the boulders together, rounding their edges, but did not reduce their overall size. Some clasts originally eroded from strata that are now located at least 97 km (60 mi) to the west (Oriel and Tracey 1970). The Hams Fork Conglomerate probably represents the transportation of pebbles and boulders within a large drainage system associated with the Sevier highlands (Oriel and Tracy 1970; Elder and Kirkland 1994).

The gray carbonaceous siltstone and mudstone and tan sandstone of the upper unit of the Evanston Formation (map unit Te) overlie the Hams Fork Conglomerate Member. The drab coloration visually distinguishes the Evanston Formation from the overlying Wasatch Formation. Fossil pollen and leaves in the Evanston Formation confirm a middle or late Paleocene age for the upper unit, and the abundant organic material suggests a very humid, warm-temperate climate (Oriel and Tracey 1970). Because the Hams Fork Conglomerate is latest Cretaceous in age and the overlying upper unit is middle to late Paleocene, the contact between the two units represents an unconformity in which uppermost Cretaceous and lower Paleocene strata are missing.

The Adaville Formation, Hams Fork Conglomerate Member, and the upper unit of the Evanston Formation help determine the timing of the Absaroka thrust. The Absaroka thrust cuts the Adaville Formation, but most of the Hams Fork Conglomerate was deposited above the thrust, indicating that major movement along the thrust occurred in the latest Cretaceous. In the vicinity of Hams Fork, beds of the upper unit of the Evanston Formation are tilted at a different angle than those above the Absaroka thrust. This relationship, called an "angular unconformity," indicates that deformation caused by movement along the Absaroka thrust had stopped prior to deposition of the upper unit of the Evanston

Formation (Oriel and Tracey 1970; Armstrong and Oriel 1986).

The Evanston Formation can also help determine when Fossil Basin began to form. Along the eastern side of Fossil Basin, the lower beds of the Evanston Formation dip, or tilt, about 20° to 40° to the west (Oriel and Tracy 1970). However, the dip of younger beds (those higher in the section) gradually decreases until the uppermost beds are almost horizontal and parallel to the overlying beds of the Wasatch Formation. The change in dip suggests that Fossil Basin began to take shape in the latest Cretaceous and continued to form during the Paleocene.

The Global Greenhouse and Great Lakes of Wyoming: Eocene Epoch (56–34 million years ago)

The Laramide Orogeny occurred between about 70 million and 35 million years ago, resulting in the formation of the Rocky Mountains (fig. 22). Reverse faults associated with the Laramide Orogeny transported much older, Precambrian rocks to the surface. These rocks are now exposed in Grand Teton National Park (Love et al. 2003; KellerLynn 2010), north of Fossil Butte National Monument, and in the nearby Gros Ventre and Wind River ranges. Precambrian rocks also comprise the core of the east–west-trending Uinta Mountains, which form the southern border of Fossil Basin.

Near the end of the Paleocene and beginning of the Eocene, about 56 million years ago, an abrupt increase in global temperatures, which were already much warmer than today, occurred (fig. 6). The event, known as the Paleocene–Eocene Thermal Maximum (PETM) resulted in average annual temperatures in the western United States of 20° to 25°C (68° to 77°F) and Arctic Ocean temperatures of 23°C (74°F; Woodburne et al. 2009; Kunzig 2011). Debate continues about the cause of the PETM, but an estimated 4.5 trillion tons of carbon and an unknown amount of methane entered the atmosphere at that time. This amount of carbon is roughly equivalent to that available in the Earth's present reserves of coal, oil, and natural gas.

The PETM lasted about 170,000 years and coincided with the earliest Eocene mammalian fauna and mammalian immigration in the western United States (Woodburne et al. 2009). It was one of three dramatic climatic episodes that prompted significant mammalian reorganization, floral diversity, and habitat complexity in the Eocene. The great lakes of Wyoming also began to form during the PETM.

The second major climatic episode occurred between 53 million and 50 million years ago, producing a major increase in diversity and extent of vegetation and an average annual temperature of 23 C (74° F) in the continental interior. From 53.5 million to 52.0 million years ago, coincident with this second Eocene episode, Fossil Lake began to form in the floodplain of Fossil Basin. This initial, overfilled stage is represented by the Road Hollow Member (map unit Tgrh).

With increased precipitation and subsequent inflow from surface runoff, the lake expanded and deepened to the balanced-fill stage, represented by the Fossil Butte Member (map unit Tgfb), from 52.0 million to 51.3 million years ago. This period is also coincident with this second episode of global warming. Fossil Lake may have reached depths of 4–5 m (13–16 ft) during this phase (Buchheim 1998). As Fossil Lake expanded, the Crawford Mountains formed an island in the lake, and the Tunp Range became a peninsula that extended into the lake from the north (Buchheim et al. 2011).

The onset of arid conditions led to near-total desiccation of the lake prior to a third episode of global warming, from 50 million to 47 million years ago (Smith et al. 2008; Woodburne et al. 2009). Although renewed expansion of Fossil Lake occurred between 49.6 million and 48.5 million years ago, the lake never fully recovered and the lake water remained brackish to saline throughout the rest of this middle phase (Buchheim 1998).

Plant pollen from the Fossil Butte Member and the lower part of the Angelo Member (map unit Tga) record a humid, warm-temperate climate in transition to a drier, warm temperate climate during this time in southwestern Wyoming (Cushman 1999). The abundant hardwood, riparian and conifer taxa suggest that Fossil Lake was surrounded by moist lowlands and floodplains, and that upland forests covered the adjacent ridges and mountains.

The underfilled stage of Fossil Lake (represented by the Angelo Member) occurred between 51.3 million and 45.1 million years ago, as temperatures began to fall with the onset of global cooling at the end of the early Eocene (Smith et al. 2008). The lack of faunal diversity and the termination of Fossil Lake reflect a decrease in precipitation and surface water inflow. Fossil Lake formed in a closed basin, and disappeared as water resources dried up. The floral and faunal communities of this culminating phase of Fossil Lake reflect a more arid, cooler, and less hospitable climate for living organisms than do communities in the Fossil Butte phase. The lake became shallow and hypersaline, with few fish in the central basin area. Stromatolites, rather than fish, flourished (Loewen and Buchheim 1998). Fluvial sediments and volcanic ash increased the siliciclastic content of the lake and eventually filled in the basin.

The diversity and abundance of organisms, especially fish, and the composition of the sedimentary rock layers in the Green River Formation support a complex history of fluctuating salinity in Eocene Fossil Lake, probably due to fluctuating precipitation caused by global and local climate changes. During times of increased precipitation and surface water inflow, the lake expanded with relatively fresh water. When surface flow decreased, the lake shrank and became more saline. Fresh water dominated the lake's history when the Road Hollow and Fossil Butte members were deposited, whereas extremely saline conditions dominated during the deposition of the Angelo Member. As lake levels changed, the lateral distributions of kerogen-rich deposits, bioturbated micrite, dolomite, sandstone, and mudstone also varied (Buchheim 1994a, 1994b; Buchheim and Eugster 1998; Buchheim et al. 2011). As with modern lakes, the degree of bottom circulation in Fossil Lake determined the extent of anoxic or oxic conditions, which influenced the degree of fossil preservation.

The fluvial, floodplain, deltaic, and shoreline deposits that surrounded Fossil Lake comprise the various members of the Wasatch Formation. Streams flowed into the basin from the surrounding highlands, depositing channel sand and, during flooding, fine-grained silt and mud in floodplains that make up the Main Body of the formation. A Gilbert-style delta advanced into the lake, forming the Sandstone Tongue of the Wasatch Formation (map unit Tws). Debris flows deposited coarse, unsorted material near the margins of the basin, which lithified into the diamictite of the Tunp Member (map unit Twt).

Volcanic tuff beds in the upper part of the Green River Formation record an increase in regional volcanic activity. Between 53 million and 43 million years ago, coincident with the Laramide Orogeny, catastrophic volcanic events erupted thousands of cubic miles of lava, volcanic breccia, and volcanic ash from dozens of volcanoes in the area of today's Absaroka Range (Love et al. 2003; Chandler 2006). In places, the volcanic material is as much as 1,200 m (4,000 ft) thick.

Streams deposited additional sediment, such as the sandstone and siltstone of the Sillem Member of the Fowkes Formation (map unit Tfs), and basins eventually filled with debris eroded from surrounding highlands. The landscape that once consisted of a series of lakes surrounded by highlands became a single vast plateau with only the highest peaks of the Laramide mountain ranges protruding above the relatively flat topography.

The Missing Years: Oligocene to Pleistocene (34–2.6 million years ago)

Oligocene, Miocene, and Pliocene strata have been eroded away from Fossil Basin and the surrounding highlands, although some Oligocene gravels may be present at the top of Elk Mountain, south of the monument (Arvid Aase, curator, Fossil Butte National Monument, written communication, 11 September 2012). However, the changes in faunal and floral diversity and abundance are preserved in several other NPS units (fig. 7). In general, the climate transformed from warm and wet to dry and cool. Fossils from Florissant Fossil Beds National Monument in Colorado record some of the last greenhouse ecosystems documented in parks containing Cenozoic fossils (KellerLynn 2006). Oligocene rocks and fossils, which are abundant at Badlands National Park in South Dakota, record a transition from warm-temperate forests of the Eocene to savannas (scrubby trees and shrubs) and grasslands (Graham 2008).

Miocene volcaniclastic rocks in Idaho's Hagerman Fossil Beds National Monument document the explosive volcanic activity that marked the initial tectonic rifting of the Snake River Plain and the migration of the Yellowstone-Snake River Plain hot spot (Graham 2009b). This volcanic activity eventually culminated in the formation of the Yellowstone caldera, preserved in Yellowstone National Park. During a drying Miocene climate and the growth of savannas and grasslands, mammalian groups underwent major diversification. Agate Fossil Beds National Monument preserves a partial record of the great herds of herbivores and their predators that roamed the expanding midcontinent grasslands just prior to this diversification (Graham 2009a). The diverse fossils and ecosystems of John Day Fossil Beds National Monument in Oregon span more than 40 million of the past 55 million years of the Eocene, Oligocene, and Miocene (Graham in prep.).

Idaho's Hagerman Fossil Beds National Monument preserves a Pliocene ecosystem that evolved just prior to the Pleistocene Ice Ages (Graham 2009b). Fossils of Hagerman horses, camels, pronghorn, mastodon, peccary, saber-toothed cats, and many other animals that roamed the grassland and patches of trees that grew on the ancestral Snake River Plain have been discovered in the steep slopes of the monument.

Approximately 15 million years ago during the Miocene, the tectonic regime along the western margin of North America changed dramatically. Complex rearrangement of the tectonic plates resulted in the stretching of the continental crust to produce the Basin and Range Province of the southwestern United States. Normal faults formed as the crust pulled apart, creating the province's unique landscape of uplifted ranges (horsts) and down-dropped basins (grabens; fig. 8). Extension of the crust about 5 million years ago produced the Teton fault in Grand Teton National Park (KellerLynn 2010). The Grand Tetons continue to rise as normal fault movement continues along this fault (Love et al. 2003).

Shaping the Modern Landscape: Pleistocene to Holocene (2.6 million years ago to present)

The global climate became much colder near the end of the Pliocene (fig. 6). High-latitude icecaps began to expand until large ice sheets spread across much of the northern part of North America (fig. 25). Perhaps as many as 20 major glaciations have occurred in the last 2.5 million years (Love et al. 2003). Alpine glaciers carved canyons in the higher mountain ranges.

Features in Grand Teton National Park provide evidence of the two most recent glaciations, the Pinedale glaciation (110,000 to 10,000 years ago) and the Bull Lake glaciation (200,000 to 130,000 years ago; Love et al. 2003). During the Pinedale glaciation, alpine glaciers also formed in the Wind River Range and Uinta Mountains (Pierce 2004).

The unconsolidated landslide deposits (map unit Qls) in Fossil Butte National Monument and the terrace deposits (map unit Qtg) south of the park along Twin Creek document processes that have been actively modifying the landscape since the Pleistocene Ice Ages.

Figure 25. Pleistocene paleogeographic map of North America. Continental ice sheets advanced from the northern latitudes and alpine glaciers formed at high elevations. The extent of continental ice sheets marks the dramatic change following the warmest global climate of the past 65 million years, represented by the Green River and Wasatch formation deposits within Fossil Butte National Monument. Red star marks the approximate location of Fossil Butte National Monument. Base paleogeographic map created by Ron Blakey (Colorado Plateau Geosystems, Inc.), which are available at http://cpgeosystems.com/index.html (accessed 30 March 2012).

The landslide and terrace deposits are mapped as Holocene and Pleistocene in age. The landslide deposits include slumps, landslides, and mudflows of soil and rock that moved or rotated downslope en masse due to gravity. Terraces, or benches, occur at various levels along present streams and mark previous stream levels. Some terraces represent glacial outwash deposits and others represent redistributed older conglomerate and gravel deposits (M'Gonigle and Dover 1992).

During the Holocene, increased aridity has decreased surface flow, but streams continue to deposit gravel, sand, silt, and clay in floodplains and channels. Alluvial fans form at the mouths of tributary valleys. Susceptible to erosion, the mudstone and siltstone in the Wasatch Formation continue to slump and slide. Landslides in the Green River Formation formed the cliffs of Fossil Butte and Cundick Ridge within Fossil Butte National Monument. Fossil collectors, paleontologists, geologists, and visitors continue to study and marvel at the evidence of long-buried ancient life now found in and around the monument.

Geologic Map Data

This section summarizes the geologic map data available for Fossil Butte National Monument. The Geologic Map Overview Graphics display the geologic map data draped over a shaded relief image of the park and surrounding area. The foldout Map Unit Properties Table summarizes this report's content for each geologic map unit. Complete GIS data are included on the accompanying CD and are also available at the 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. There are two primary types of geologic maps: surficial and bedrock. Surficial geologic maps encompass deposits that are frequently unconsolidated and formed during the past 2.6 million years (the Quaternary Period). Surficial map units are differentiated by geologic process or depositional environment. Bedrock geologic maps encompass older, generally more consolidated sedimentary, metamorphic, and/or igneous rocks. Bedrock map units are differentiated based on age and/or rock type. For reference, a geologic time scale is included as figure 4. Bedrock and surficial geologic map data are provided for Fossil Butte National Monument.

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 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 produce the digital geologic data for Fossil Butte National Monument. These source maps provided information for the "Geologic Issues," "Geologic Features and Processes," and "Geologic History" sections of this report.

Buchheim, P. 2005. Geologic map of Fossil Butte National Monument and vicinity, Wyoming. Unpublished. Loma Linda University, Loma Linda, California, USA (scale 1:24,000).

Lowry, J. 2007. Digital geologic map of Fossil Butte National Monument and vicinity, Wyoming. Unpublished. Utah State University, Logan, Utah, USA (scale 1:24,000).

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 Fossil Butte National Monument using data model version 1.4.

GRI digital geologic data are included on the attached CD and are available through the NPS Integrated Resource Management Applications (IRMA) portal (https://irma.nps.gov/App/Reference/Search?SearchType=Q). Enter "GRI" as the search text and select Fossil Butte National Monument from the unit list.

The following components and geology data layers are part of the data set:

- Data in ESRI geodatabase, shapefile, and coverage GIS formats
- Layer files with feature symbology (see table below)
- 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 4. Geology data layers in the Fossil Butte National Monument GIS data.

Data Layer	Data Layer Code	On Overview Graphic?
Geologic Attitude and Observation Points	ATD	No
Fault and Fold Map Symbology	SYM	Yes
Folds	FLD	Yes
Faults	FLT	Yes
Mine Feature Areas	MAF	No
Mine Feature Area Boundaries	MAFA	No
Geologic Contacts	GLGA	Yes
Geologic Units	GLG	Yes

Geologic Map Overview Graphic

The Geologic Map Overview Graphics (in pocket) display the GRI digital geologic data draped over a shaded relief image of the park and surrounding area. For graphic clarity and legibility, not all GIS feature classes may be visible on the overviews, as indicated in the above table. Cartographic elements and basic geographic information have been added to overviews. Digital elevation data and geographic information, which are part of the overview graphics, 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 (in pocket) correspond to the accompanying digital geologic data. Following the structure of the report, the table summarizes the geologic issues, features, and processes, and geologic history associated with each map unit. The table also lists the geologic time period, map unit symbol, and a simplified geologic description of the unit. Connections between geologic units and park stories are also summarized.

Use Constraints

Graphic and written information provided in this section is not a substitute for site-specific investigations. 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 source map scale (1:24,000) and U.S. National Map Accuracy Standards, geologic features represented in the geologic map data are horizontally within 12 m (40 ft) of their true location.

Please contact GRI with any questions.

Glossary

This glossary contains brief definitions of geologic terms used in this report. Not all geologic terms used are listed. Definitions are based on those in the American Geological Institute Glossary of Geology *(fifth edition; 2005). Additional definitions and terms are available at: http://geomaps.wr.usgs.gov/parks/misc/glossarya.html.*

absolute age. The geologic age of a fossil, rock, feature, or event in years; commonly refers to radiometrically determined ages.
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.
alpine glacier. A glacier occurring in a mountainous region; also called a valley glacier.
angular unconformity. An unconformity where the rock layers above and below are oriented differently. Also see "unconformity."
anhydrite. A mineral consisting of anhydrous calcium sulfate, which is gypsum without the water in its crystal structure. Readily alters to gypsum.
anticline. A convex-upward ("A" shaped) fold. Older rocks are found in the center.
argillaceous. Describes a sedimentary rock composed of a substantial amount of clay.
ash (volcanic). Fine material ejected from a volcano (also see "tuff").
badlands. Eroded topography characterized by steep slopes and surfaces with little or no vegetative cover, composed of unconsolidated or poorly cemented clays or silts.
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.
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.
bioturbation. The reworking of sediment by organisms.
breccia. A coarse-grained, generally unsorted sedimentary rock consisting of cemented angular clasts greater than 2 mm (0.08 in).
breccia (volcanic). A coarse-grained, generally unsorted volcanic rock consisting of partially welded angular fragments of ejected material such as tuff or ash.
calcareous. Describes rock or sediment that contains the mineral calcium carbonate ($CaCO_3$).
calcic. Describes minerals and igneous rocks containing a relatively high proportion of calcium.
caldera. A large bowl- or cone-shaped depression at the summit of a volcano. Formed by explosion or collapse.
carbonaceous. Describes a rock or sediment with considerable carbon content, especially organics, hydrocarbons, or coal.
carbonate. A mineral that has CO_3^{-2} as its essential component (e.g., calcite and aragonite).
carbonate rock. A rock consisting chiefly of carbonate minerals (e.g., limestone, dolomite, or carbonatite).
cementation. Chemical precipitation of material into pores between grains that bind the grains into rock.
chemical sediment. A sediment precipitated directly from solution (also called nonclastic).
chemical weathering. Chemical breakdown of minerals at Earth's surface via reaction with water, air, or dissolved substances; commonly results in a change in chemical composition more stable in the current environment.
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).
colluvium. A general term for any loose, heterogeneous, and incoherent mass of soil material and/or rock fragments deposited through the action of surface runoff (rainwash, sheetwash) or slow continuous downslope creep.
conglomerate. A coarse-grained, generally unsorted, sedimentary rock consisting of cemented, rounded clasts larger than 2 mm (0.08 in).
continental crust. Crustal rocks rich in silica and alumina that underlie the continents; ranging in thickness from 35 km (22 mi) to 60 km (37 mi) under mountain ranges.
continental rifting. Process by which a region of crust undergoes extension (pulling apart), resulting in the formation of many related normal faults, and often associated with volcanic activity.
convergent boundary. A plate boundary where two tectonic plates are colliding.
coprolite. Fossil dung (a trace fossil).

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

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-bedding. Uniform to highly varied sets of inclined sedimentary beds deposited by wind or water that indicate flow conditions such as water flow direction and depth.

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.

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

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

crystal structure. The orderly and repeated arrangement of atoms in a crystal.

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).

delta. A sediment wedge deposited where a stream flows into a lake or sea.

detritus. A collective term for lose rock and mineral material that is worn off or removed by mechanical means.

diamictite. Poorly sorted, noncalcareous, sedimentary rock with a wide range of particle sizes.

differential erosion. Erosion that occurs at irregular or varying rates, caused by differences in the resistance and hardness of surface material.

dip. The angle between a bed or other geologic surface and horizontal.

divergent boundary. An active boundary where tectonic plates are moving apart (e.g., a spreading ridge or continental rift zone).

dolomicrite. A sedimentary rock consisting of clay-sized dolomite crystals, interpreted as a lithified dolomite mud (analogous to calcite mud or micrite).

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).

dolomitic. Describes a dolomite-bearing rock, or a rock containing dolomite.

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

dune. A low mound or ridge of sediment, usually sand, deposited by wind. Common dune types include "barchan," "longitudinal," "parabolic," and "transverse" (see respective listings).

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

ephemeral lake. A short-lived lake.

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.

epicenter. The point on Earth's surface that is directly above the focus (location) of an earthquake.

erg. An regionally extensive tract of sandy desert; a "sand sea."

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).

extension. A type of strain resulting from forces "pulling apart." Opposite of compression.

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

feldspar. A group of abundant (more than 60% of Earth's crust), light-colored to translucent silicate minerals found in all types of rocks. Usually white and gray to pink. May contain potassium, sodium, calcium, barium, rubidium, and strontium along with aluminum, silica, and oxygen.

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.

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.

footwall. The mass of rock beneath a fault surface (also see "hanging wall").

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

fracture. Irregular breakage of a mineral. Any break in a rock (e.g., crack, joint, fault).

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

graben. A down-dropped structural block bounded by steeply dipping, normal faults (also see "horst").

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

hanging wall. The mass of rock above a fault surface (also see "footwall").

horst. Areas of relative "up" between grabens, representing the geologic surface left behind as grabens drop. The best example is the Basin-and-Range province of Nevada. The basins are grabens and the ranges are weathered horsts. Grabens become a locus for sedimentary deposition (also see "graben").

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

isotopic age. An age expressed in years and calculated from the quantitative determination of radioactive elements and their decay products; "absolute age" and "radiometric age" are often used in place of isotopic age but are less precise terms.

kerogen. Fossilized insoluble organic material found in sedimentary rocks, usually shales, which can be converted to petroleum products by distillation.

lacustrine. Pertaining to, produced by, or inhabiting a lake or lakes.

lamination. Very thin, parallel layers.

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

lava. Still-molten or solidified magma that has been extruded onto Earth's surface though a volcano or fissure.

left lateral fault. A strike slip fault on which the side opposite the observer has been displaced to the left Synonymous with "sinistral fault."

lens. A sedimentary deposit characterized by converging surfaces, thick in the middle and thinning out toward the edges, resembling a convex lens.

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

lithification. The conversion of sediment into solid rock.

lithify. To change to stone or to petrify; especially to consolidate from a loose sediment to a solid rock through compaction and cementation.

lithofacies. A lateral, mappable subdivision of a designated stratigraphic unit, distinguished from adjacent subdivisions on the basis of rock characteristics (lithology).

lithology. The physical description or classification of a rock or rock unit based on characters such as its color, mineral composition, and grain size.

loess. Windblown silt-sized sediment, generally of glacial origin.

marker bed. A distinctive layer used to trace a geologic unit from one geographic location to another.

marl. An unconsolidated deposit commonly with shell fragments and sometimes glauconite consisting chiefly of clay and calcium carbonate that formed under marine or freshwater conditions.

marlstone. An indurated rock of about the same composition as marl, called an earthy or impure argillaceous limestone.

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

mechanical weathering. The physical breakup of rocks without change in composition. Synonymous with "physical weathering."

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

micrite. Fine-grained carbonate mud.

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

mud cracks. Cracks formed in clay, silt, or mud by shrinkage during dehydration at Earth's surface.

normal fault. A dip-slip fault in which the hanging wall moves down relative to the footwall.

oceanic crust. Earth's crust formed at spreading ridges that underlies the ocean basins. Oceanic crust is 6 to 7 km (3 to 4 miles) thick and generally of basaltic composition.

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

oil shale. A kerogen-bearing, finely laminated brown or black sedimentary rock that will yield liquid or gaseous hydrocarbons on distillation.

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.

ostracod. Any aquatic crustacean belonging to the subclass Ostracoda, characterized by a two-valved (shelled), generally calcified carapace with a hinge along the dorsal margin. Most ostracods are of microscopic size.

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

paleogeography. The study, description, and reconstruction of the physical landscape from past geologic periods.

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

paleosol. A ancient soil layer preserved in the geologic record.

Pangaea. A theoretical, single supercontinent that existed during the Permian and Triassic periods.

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

phosphatic. Pertaining to or containing phosphates; commonly refers to a sedimentary rock containing phosphate minerals.

pisoid. A round or ellipsoidal accretionary body commonly formed of calcium carbonate.

pisolite. A sedimentary rock, usually a limestone, made up chiefly of pisoids cemented together.

plagioclase. An important rock-forming group of feldspar minerals.

plate tectonics. The concept that the lithosphere is broken up into a series of rigid plates that move over Earth's surface above a more fluid asthenosphere.

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

potassium feldspar. A feldspar mineral rich in potassium (e.g., orthoclase, microcline, sanidine, adularia).

prodelta. The part of a delta below the level of wave erosion.

progradation. The seaward building of land area due to sedimentary deposition.

pseudomorph. A mineral whose outward crystal form is that of another mineral species; a pseudomorh replaces a previous mineral.

radioactivity. The spontaneous decay or breakdown of unstable atomic nuclei.

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

red beds. Sedimentary strata composed largely of sandstone, siltstone, and shale that are predominantly red due to the presence of ferric iron oxide (hematite) coating individual grains.

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

relative dating. Determining the chronological placement of rocks, events, or fossils with respect to the geologic time scale and without reference to their numerical age.

reverse fault. A contractional high-angle (greater than 45°) dip-slip fault in which the hanging wall moves up relative to the footwall (also see "thrust fault").

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.

roundness. The relative amount of curvature of the "corners" of a sediment grain.

sabkha. A coastal environment in an arid climate just above high tide. Characterized by evaporate minerals, tidal-flood, and eolian deposits. Common in the Persian Gulf.

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.

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.

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

silicate. A compound whose crystal structure contains the SiO_4 tetrahedra.

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.

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 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).

stromatolite. An organosedimentary structure produced by sediment trapping, binding, and/or precipitation as a result of the growth and metabolic activity of micro-organisms, principally cyanophytes (blue-green algae).

subaerial. Describes conditions and processes that exist or operate in the open air on or immediately adjacent to the land surface.

subduction zone. A convergent plate boundary where oceanic lithosphere descends beneath a continental or oceanic plate and is carried down into the mantle.

subsidence. The gradual sinking or depression of part of Earth's surface.

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.

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

terrestrial. Relating to land, Earth, or its inhabitants.

terrigenous. Derived from the land or a continent.

theory. A hypothesis that has been rigorously tested against further observations or experiments to become a generally accepted tenet of science.

thrust fault. A contractional dip-slip fault with a shallowly dipping fault surface (less than 45°) where the hanging wall moves up and over relative to the footwall.

tongue (stratigraphy). A member of a formation that extends and wedges out away from the main body of a formation.

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.

transform fault. A strike-slip fault that links two other faults or two other plate boundaries (e.g. two segments of a mid-ocean ridge). A type of plate boundary at which lithosphere is neither created nor destroyed, and plates slide past each other on a strike-slip fault.

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

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

tufa. A chemical sedimentary rock composed of calcium carbonate, formed by evaporation as an incrustation around the mouth of a spring, along a stream, or exceptionally as a thick, concretionary deposit in a lake or along its shore. It may also be precipitated by algae or bacteria. A hard, dense variety of travertine.

tuff. Generally fine-grained, igneous rock formed of consolidated volcanic ash.

tuffaceous. A non-volcanic, clastic sedimentary rock that contains mixtures of ash-size pyroclasts.

type locality. The geographic location where a stratigraphic unit (or fossil) is well displayed, formally defined, and derives its name. The place of original description.

unconformity. A substantial break or gap in the geologic record where a rock unit is overlain by another that is not next in stratigraphic succession.

undercutting. The removal of material at the base of a steep slope or cliff or other exposed rock by the erosive action of falling or running water, of sand-laden wind in the desert, or of waves along the coast.

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

volcanic. Describes anything related to volcanoes. Can refer to igneous rock crystallized at or near Earth's surface (e.g., lava).

volcaniclastic. Describes clastic volcanic materials formed by any process of fragmentation, dispersed by any kind of transporting agent, deposited in any environment.

weathering. The physical, chemical, and biological processes by which rock is broken down.

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Additional References

This section lists additional references, resources, and websites that may be of use to resource managers. Web addresses are current as of September 2012.

Geology of National Park Service Areas

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

NPS Views Program (Geology-themed modules are available for Geologic Time, Paleontology, Glaciers, Caves and Karst, Coastal Geology, Volcanoes, and a wide variety of geologic parks): http://www.nature.nps.gov/views/layouts/Main.html#/Views/.

U.S. Geological Survey 3D Geology of National Parks: http://3dparks.wr.usgs.gov/

NPS Resource Management Guidance and Documents

1998 National Parks Omnibus Management Act: http://www.gpo.gov/fdsys/pkg/PLAW-105publ391/pdf/PLAW-105publ391.pdf

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/

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

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State Geological Survey Websites

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

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

Geological Society Resources

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

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

United States Geological Survey (USGS)

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

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; official listing of place names and geographic features): 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 (USGS publications, many available online): http://pubs.er.usgs.gov

U.S. Geological Survey Tapestry of Time and Terrain (descriptions of physiographic provinces): http://tapestry.usgs.gov/Default.html

Appendix: Scoping Session Participants

The following people attended the GRI scoping meeting for Fossil Butte National Monument, held on May 23, 2002, or the follow-up report writing conference call, held on December 13, 2011. Discussions during these meetings supplied a foundation for this GRI report. The scoping summary document is available on the GRI publications website (http://www.nature.nps.gov/geology/inventory/gre_publications.cfm).

2002 Scoping Meeting Participants

Name	Affiliation	Position
Aase, Arvid	NPS, Fossil Butte National Monument	Paleontologist, Curator
Buchheim, Paul	Loma Linda University	Geologist
Connors, Tim	NPS, Geologic Resources Division	Geologist
de Wolfe, Victor	Colorado State University	Geologist
Huss, Joe	Wyoming Geological Survey	GIS Coordinator
Jennings, Debra	NPS, Fossil Butte National Monument	Volunteer
O'Meara, Stephanie	Colorado State University	GIS Specialist
Poole, Anne	Black Canyon of the Gunnison National Park	GIS Specialist
Santucci, Vincent	NPS Geologic Resources Division	Geologist
Thornberry, Trista	Colorado State University	Geologist
Ver Ploeg, Alan	Wyoming Geological Survey	Geologist

2011 Conference Call Participants

Name	Affiliation	Position
Aase, Arvid	NPS, Fossil Butte National Monument	Paleontologist, Curator
Connors, Tim	NPS, Geologic Resources Division	Geologist
Graham, John	Colorado State University	Geologist
Kenworthy, Jason	NPS, Geologic Resources Division	Geologist
Skinner, Nancy	NPS, Fossil Butte National Monument	Superintendent

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NPS 174/117340, October 2012

National Park Service
U.S. Department of the Interior

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www.nature.nps.gov

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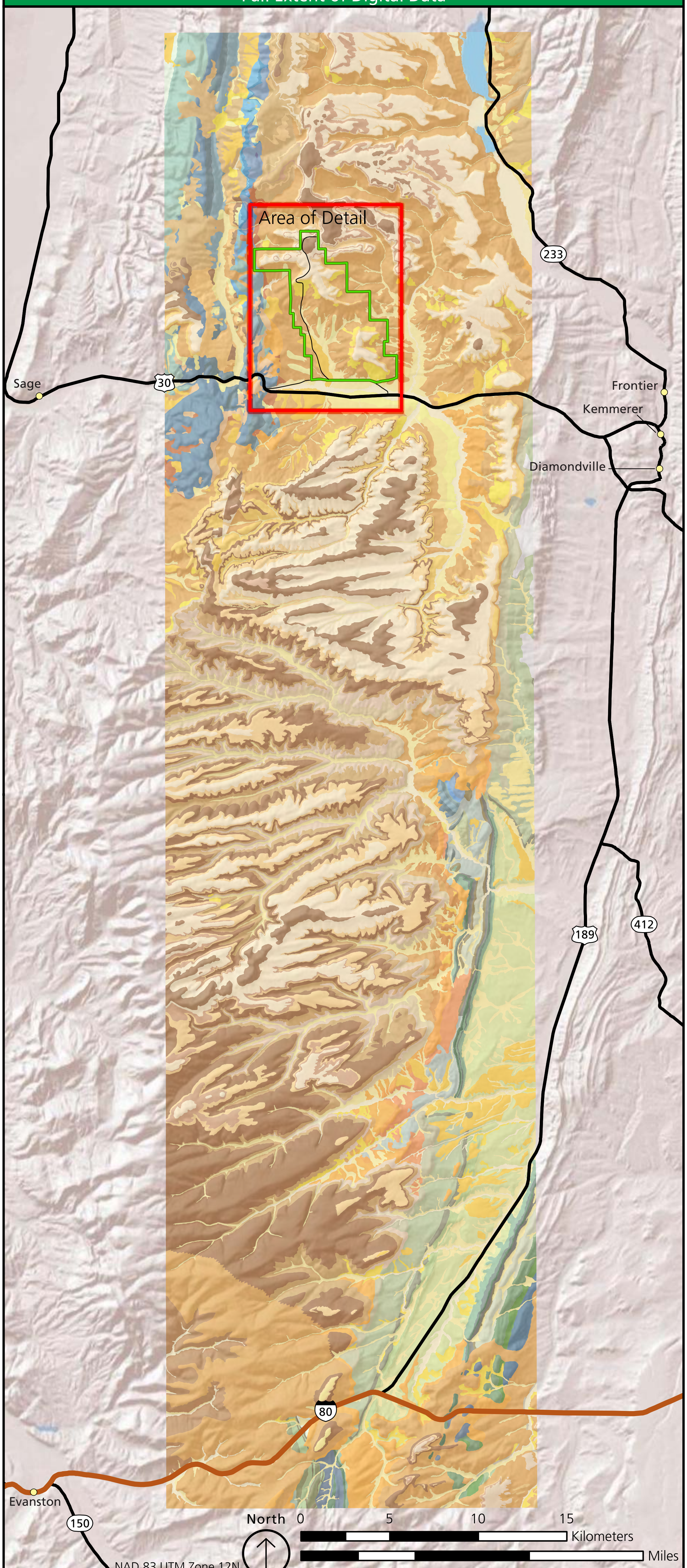
Overview of Digital Geologic Data for Fossil Butte National Monument

Full Extent of Digital Data



NPS Boundary

Folds

- syncline, known or certain
- syncline, concealed
- anticline, known or certain
- anticline, approximate
- anticline, concealed
- overturned anticline, known or certain

Faults

- thrust fault, concealed, teeth on upthrown side
- high-angle fault, known or certain
- high-angle fault, approximate
- high-angle fault, concealed

Geologic Contacts

- known or certain
- approximate

Geologic Units

- Qal - Alluvium
- Qas - Secondary-stream alluvium
- Qls - Landslide deposits
- Qtg - Terrace deposits
- Qty - Younger terrace deposits
- Qd - Talus and rubbly slope deposits
- Qg - Gravel
- Tw - Wasatch Formation main body
- Twt - Tunp Member of the Wasatch Formation
- Twb - Bullpen Member of the Wasatch Formation
- Tgr - Green River Formation, undifferentiated
- Tga - Angelo Member of the Green River Formation
- Tgfb - Fossil Butte Member of the Green River Formation
- Twms - Southern mudstone tongue of the Wasatch Formation
- Tgrh - Road Hollow Member of the Green River Formation
- Twl - Lower Member of the Wasatch Formation
- Twc - Basal Conglomerate Member of the Wasatch Formation
- Te - Upper Unit of the Evanston Formation
- Jt - Twin Creek Limestone
- Jtg - Gypsum Spring Member of the Twin Creek Limestone
- JTRn - Nugget Sandstone
- TRa - Ankareh Red Beds
- TRt - Thaynes Limestone
- TRd - Dinwoody Formation
- Ppu - Phosphoria Formation, Upper Part
- PlPw - Wells Formation
- Pwl - Wells Formation Limestone

This figure is an overview of compiled digital geologic data. It is 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 scale (1:24,000) and U.S. National Map Accuracy Standards, geologic features represented here are within 12 meters / 40 feet (horizontally) of their true location.

This figure was prepared as part of the NPS Geologic Resources Division's Geologic Resources Inventory. The source map used in creation of the digital geologic data product was:

Buchheim, Paul. 2005. Geologic Map of Fossil Butte National Monument and Vicinity, Wyoming (1:24,000 scale). Unpublished. Loma Linda University.

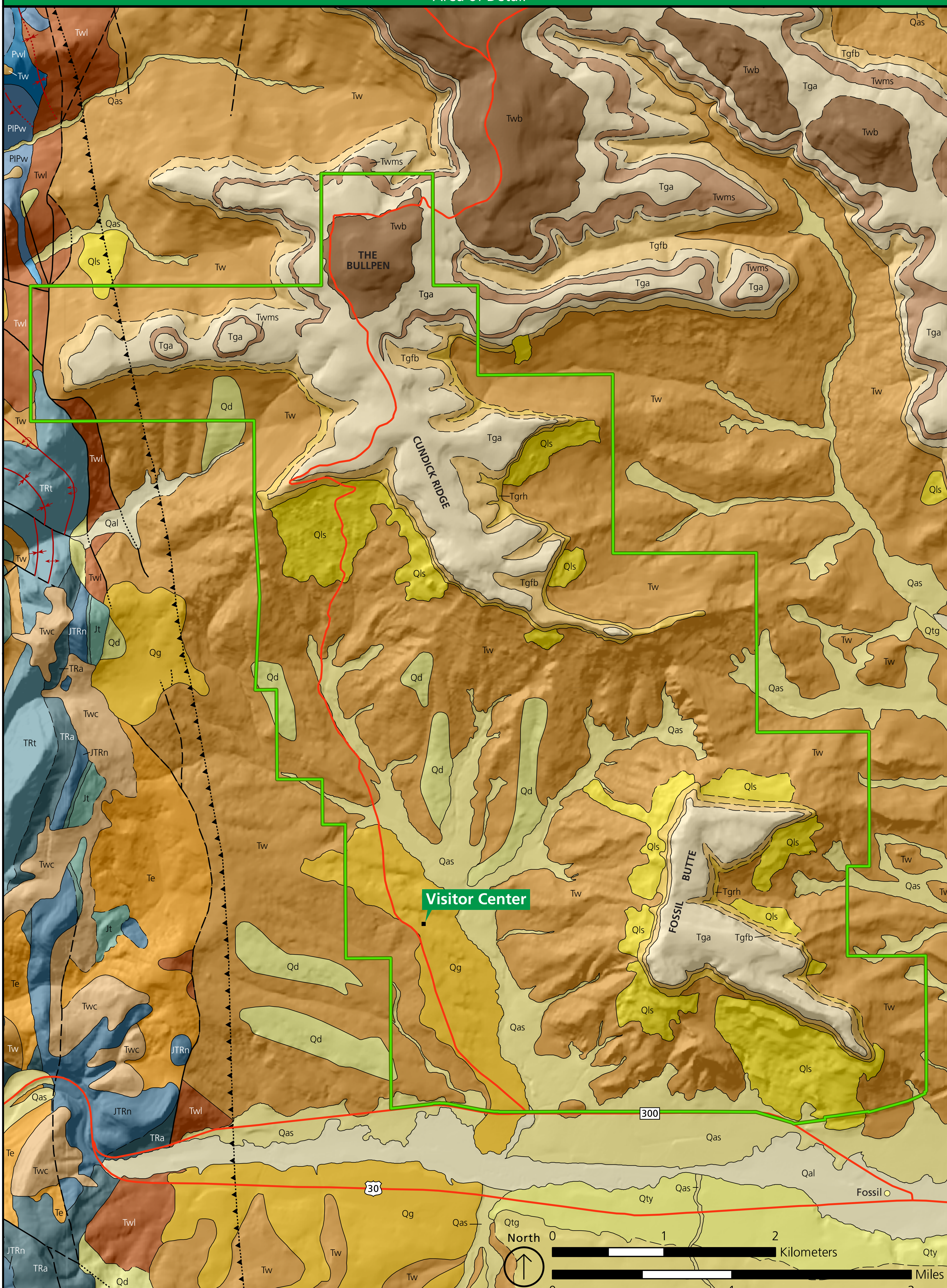
Digital geologic data and cross sections for Fossil Butte National Monument, and all other digital geologic data prepared as part of the Geologic Resources Inventory, are available online at the NPS Integrated Resource Management Applications Portal (IRMA): https://irma.nps.gov/App/Reference/Search. (Enter "GRI" as the search text and select Fossil Butte National Monument from the unit list.)

Produced by the Geologic Resources Inventory

October 2012

Overview of Digital Geologic Data for Fossil Butte National Monument

Area of Detail



NAD 83 UTM Zone 12N

Produced by the Geologic Resources Inventory

October 2012

Map Unit Properties Table: Fossil Butte National Monument

Colored rows indicate units mapped within Fossil Butte National Monument. Italicized text refers to report sections.

Age	Map Unit (Symbol)	Geologic Description	Geologic Issues	Geologic Features and Processes	Geologic History and Park Connections
QUATERNARY (Holocene)	Strip Mine (Qsm)	Strip coal mine operating today. Located southeast of the monument.	*Exploration and Development of Energy Resources*: Surface mining of coal. Not mapped within the monument.	Coal.	*Shaping the Modern Landscape:* Mines are modern anthropogenic alterations to the landscape. *The Great Compression:* Local coal is Cretaceous in age (primarily **Kav**) and represents lush coastal forests near the Cretaceous Interior Seaway.
QUATERNARY (Holocene)	Quarry (Qu)	Operating or abandoned quarry site for the purpose of excavating fossil fish and other fossils from the Green River Formation. Not mapped within the monument because the areal extents of quarries are too limited to be mapped at 1:24,000 scale.	*Paleontological Resource Management:* Monument staff collaborates with outside quarries to document significant fossil discoveries. *Mass Wasting:* Quarry walls may be subject to rockfall.	*Eocene Paleontological Resources:* Fossils are quarried primarily from the Green River Formation.	*Shaping the Modern Landscape:* Quarries are modern anthropogenic alterations to the landscape. *The Global Greenhouse and Great Lakes of Wyoming:* Each year, tens- to hundreds-of-thousands of Eocene fossils, primarily fish, are excavated from Fossil Basin quarries.
QUATERNARY (Holocene and Pleistocene)	Alluvium (Qal)	Unconsolidated gravel, sand, silt and channel flood-plain deposits along present main streams; includes channel fill and flood plain deposits, alluvial fan and terrace deposits.	May be inundated by rare flood events. Mapped along the southernmost border of the monument.	*Quaternary Paleontological Resources:* Bison bones. Alluvial fans, channel fill, flood-plain, and terrace deposits.	*Shaping the Modern Landscape:* Product of fluvial processes.
QUATERNARY (Holocene and Pleistocene)	Secondary-stream alluvium (Qas)	Unconsolidated alluvium, colluvium, and alluvial fan deposits in tributary stream valleys.	*Disturbed Lands:* Although not a primary issue, the abandoned road and culvert in Smallpox Creek may increase gully development. May be inundated by rare flood events.	*Quaternary Paleontological Resources:* Bison bones. Alluvium, colluvium, and alluvial fan deposits in tributary stream valleys.	
QUATERNARY (Holocene and Pleistocene)	Colluvium (Qc)	Unconsolidated debris.	Not mapped within the monument.	Debris covers stream and tributary valley sides and hill slopes.	*Shaping the Modern Landscape:* Results from erosion processes.
QUATERNARY (Holocene and Pleistocene)	Landslide deposits (Qls)	Large hummocky slumps, landslides, and mudflows of unconsolidated rock debris, soil, and slump blocks. Form mainly within the Wasatch Formation (**Tw**).	*Mass Wasting:* Unstable slopes may fail. Individual landslides are mapped within the monument, but to the north, landslides are too numerous to map individually.	*Quaternary Paleontological Resources:* Bison bones may potentially be discovered in **Qls**.	*Shaping the Modern Landscape:* If present, the overlying Green River Formation collapses, slides, or moves when **Tw** is compromised.
QUATERNARY (Holocene and Pleistocene)	Terrace deposits (Qtg)	Unconsolidated boulders, cobbles, pebble gravels, sand and silt.	Not mapped within the monument.	Occur in terraces above present streams.	*Shaping the Modern Landscape:* Some **Qtg** are interpreted as glacial outwash deposits from glacial moraines in the Uinta Mountains; other **Qtg** are composed of redistributed older conglomerate.
QUATERNARY (Holocene and Pleistocene)	Younger terrace deposits (Qty)			Occur in terraces that are younger and topographically lower than older terrace deposits (not mapped in the vicinity).	
QUATERNARY (Holocene and Pleistocene)	Talus and rubbly slope deposits (Qd)	Unconsolidated angular rock debris.	*Mass Wasting:* Results from mass-wasting processes. Potential for further movement.	Talus blocks.	*Shaping the Modern Landscape:* Product of mass-wasting processes.
QUATERNARY (Holocene and Pleistocene)	Loess (Ql)	Unconsolidated fine sand and silt.	Not mapped within the monument.	Well-sorted silt.	*Shaping the Modern Landscape:* Deposited by wind.
QUATERNARY (Holocene and Pleistocene)	Gravel (Qg)	Unconsolidated gravel, pebbles, sand and silt exposed in the southwestern corner of the monument.	*Disturbed Lands:* Gully development along Smallpox Creek may threaten a rare stand of *Lepidium integrifolium* var. *integrifolium* (entire-leaved peppergrass).	Found on pediment surfaces and includes lag concentrates from nearby older formations.	*Shaping the Modern Landscape:* Product of erosion.
PALEOGENE-NEOGENE (Oligocene-Pliocene)	Unconformity				

Colored rows indicate units mapped within Fossil Butte National Monument. Italicized text refers to report sections.

Age	Map Unit (Symbol)	Geologic Description	Geologic Issues	Geologic Features and Processes	Geologic History and Park Connections
PALEOGENE – Eocene	Fowkes Formation: Sillem Member (Tfs)	Gray, pale-pink siltstone, sandstone, and tuffaceous mudstone with lenses of conglomerate and interbeds of marlstone, ostracodal limestone, and stromatolitic limestone. Preserved in isolated, erosional remnants in the western part of Fossil Basin. 30–120 m (100–390 ft) thick.	Not mapped within the monument.	Gradational with the underlying Wasatch Formation.	*The Global Greenhouse and Great Lakes of Wyoming:* The youngest consolidated formation in Fossil Basin, the Fowkes Formation is an alluvial deposit, similar to **Tw**.
PALEOGENE – Eocene – Green River Formation	Green River Formation undifferentiated (Tgr)	Buff to brown, kerogen-rich laminated micrite (fine-grained limestone), gray to tan limestone, marlstone, and tuff beds. Light-brown to gray sandstone, siltstone, and gray to green mudstones become abundant toward the basin margins; 100–250 m (330–820 ft) thick; thins toward the west.	Not mapped within the monument. Within the monument, the Green River Formation is divided into the three members listed below. See descriptions of geologic issues for individual members.	*Eocene Paleontological Resources:* Abundant fossils. See members below and Table 1.	*The Global Greenhouse and Great Lakes of Wyoming:* Represents deposits of Fossil Lake.
PALEOGENE – Eocene – Green River Formation	Angelo Member (Tga)	White, buff, and brown dolomite and silty dolomicrite. Quartz and feldspar form a high percentage of most dolomicrite beds. Tufa coated sticks and logs mark the contact with **Tgfb**. Grades margin-ward into **Tw**. Up to 40 m (130 ft) thick.	*Paleontological Resource Management:* Documentation, inventory, monitoring, and protection. *Mass Wasting:* Forms steep slopes in the northern half of Fossil Basin, including the slopes that cap Fossil Butte. Potential rockfall and cliff collapse.	*Eocene Paleontological Resources:* Ostracods, plant fragments, bird bones in one limestone unit; bird tracks in one sandstone unit; stromatolites and caddisfly larval cases; avian egg-shell fragments. Fossil fish are mostly absent except in a few laminated micrite beds. *Stratigraphic Features:* Calcite psuedomorphs after saline minerals; salt casts; tufa; desiccation cracks.	*The Global Greenhouse and Great Lakes of Wyoming:* Represents the culminating, underfilled stage of Fossil Lake between 51.3 million and 45.1 million years ago.
PALEOGENE – Eocene – Green River Formation	Fossil Butte Member (Tgfb)	Buff to brown kerogen-rich laminated micrite, gray to tan limestone (micritic, gastropodal, ostracodal), gray to brown laminated micrite, marlstone, and abundant tuff beds. Buff to gray-green siltstone and mudstone become abundant toward the basin margins. Contact with **Tga** is marked by an ochre tuff bed that is 3–4 m (10–13 ft) above the "kspar tuff." Contact with **Tgrh** is marked by the "lower oil shale" 1–2 m (3–7 ft) below the "lower sandwich bed" (see text). In central and southern Fossil Basin, the lower contact is the top of **Tws**. Thickness is 70 m (230 ft) at Fossil Butte; thins toward the west and grades into and interfingers with **Tw** toward the basin margins.	*Paleontological Resource Management:* Documentation, inventory, monitoring, and protection. Monument's research and interpretation quarry is located in **Tgfb**. Historic quarries are also in this unit. Potential fossil theft. *Energy Resource Exploration and Development:* Areas east and west of the monument that contain "oil shale" (kerogen-rich laminated micrite) may be leased for future development. *Mass Wasting:* Forms cliffs and bluff exposures at Fossil Butte. Potential rockfall or cliff collapse.	*Eocene Paleontological Resources:* Two groups of fossil localities: nearshore and deep-water. Deep-water sites include the "18-inch layer," which includes Fossil Butte. As of this report, fossils in **Tgfb** include 23 genera of fish, 19 genera of amphibians and reptiles, 26 genera of mammals, 14 genera of birds, 23 genera of invertebrates, 30 genera of insects, and 103 genera of plants (table 1). *Stratigraphic Features:* Predominantly kerogen-rich laminated micrite; burrows.	*The Global Greenhouse and Great Lakes of Wyoming:* Represents the balanced-fill phase of Fossil Lake between 52.0 million and 51.3 million years ago. As with the other two members, the lateral changes in rock type reflect the transition from lake-margin to lake-central depositional environments (see text). About 200–500 fossils are collected annually from the research and interpretation quarry within the monument. The Haddenham and Larson fish quarries, former commercial sites, are located within the monument.
PALEOGENE – Eocene – Green River Formation	Road Hollow Member (Tgrh)	Laminated limestones, kerogen-rich laminated micrites, and ostracodal, gastropodal, and bioturbated limestone interbedded with red and brown sandstones, siltstone, mudstone, and gray to green claystone; some tuff beds; fossils in laminated units are similar to **Tgfb**. Grades to the west and south into **Tw**. **Tgul**: Upper Limestone bed. Golden-brown layers of alternating limestone, siltstone and mudstone; limestones contain invertebrate fossils; a thin unit of kerogen-rich laminated micrite occurs at the base and grades upward into siltstone and mudstone; grades laterally into **Tw**. **Tgwm**: Lower White Marker bed. Distinctive white color due to weathering of kerogen-rich laminated micrite and calcimicrite; beds may be quite chalky and form long benches; grades into **Tw** towards the lake margin. **Tgls**: Lower Shale bed. Brown and greenish-gray units of alternating mudstone, laminated calcimicrite, and siliceous calcimicrite; grades southward and westward into **Tw**. Grades into **Tw** towards the lake margin.	*Paleontological Resource Management:* Documentation, inventory, monitoring, and protection. *Energy Resource Exploration and Development:* Areas east and west of the monument that contain "oil shale" (kerogen-rich laminated micrite) may be leased for future development. *Mass Wasting:* Forms lower slopes beneath **Tgfb**. No significant geologic issues. **Tgul**, **Tgwm**, and **Tgls** are not mapped as individual units within the monument at the scale of 1:24,000.	*Eocene Paleontological Resources:* Fish in laminated micrites: *Knightia*, *Diplomystus*, *Asineops*, *Priscacara*, *Phareodus*. Abundant fish coprolites. Gastropods in biotrubated micrites. Some bivalves. Ostracods common in limestones and laminated micrites. Rare crocodile teeth (south of Little Muddy Creek). Bird, turtle, mammal bones in one sandstone unit. Plant leaves and fragments in several units. **Tgul**: Abundant gastropods and ostracods, and pelecypods. **Tgwm**: Kerogen-rich laminated micrite units appear almost black due to their high organic content at Chicken Creek; abundant fossils (fish, ostracods, insects and plant remains). **Tgls**: Abundant fossils of fish and ostracods. *Stratigraphic Features:* The best-developed lacustrine sequence is in the vicinity of Road Hollow (type section) and Chicken Creek in the central part of Fossil Basin. Kerogen-rich and kerogen-poor laminated micrites.	*The Global Greenhouse and Great Lakes of Wyoming:* Represents the initial, overfilled phase of Fossil Lake between approximately 53.5 million and 52.0 million years ago. This is a new member described by Buchheim et al. (2011), who also propose formal recognition of the stratigraphic units: **Tgul**, **Tgwm**, and **Tgls**. **Tgwm**: Predominance of kerogen-rich laminated micrites interbedded with a few siliciclastic units suggests a deeper stage of the lake and corresponds to major transgressions that deposited thinner, kerogen-rich layers as far south as Sheep Creek.

Colored rows indicate units mapped within Fossil Butte National Monument. Italicized text refers to report sections.

Age			Map Unit (Symbol)	Geologic Description	Geologic Issues	Geologic Features and Processes	Geologic History and Park Connections
PALEOGENE	Eocene	Wasatch Formation	Tunp Member (Twt)	Diamictite (rock with a variety of particle sizes); red mudstone matrix with large angular blocks up to 6+ m (20+ ft) slumped and shed off local terrain. Thickness: 30–152 m (100–500 ft) thick.	Not mapped within the monument. Deposited along the periphery of Fossil Basin, associated with thrust faults.	*Stratigraphic Features:* Marginal unit of the Wasatch Formation restricted to the northwestern margin of Fossil Basin.	*The Global Greenhouse and Great Lakes of Wyoming:* Probably originated from mudflows and gravity sliding that resulted in the coarse, unsorted debris deposit.
PALEOGENE	Eocene	Wasatch Formation	Bullpen Member (Twb)	Variegated red, gray, and green mudstone; interbeds of gray and tan sandstone, brown laminated limestone, and light-gray shale; grades into lacustrine interbedded mudstone and limestones toward the east in the area of the South Fork of Twin Creek; up to 120 m (390 ft) thick. Forms low hills mostly west and south of the monument.	*Paleontological Resource Management:* Fossils have not been documented in **Twb** within the monument. *Mass Wasting:* Bentonite, a clay mineral that swells when wet and shrinks upon drying, is present in some claystone beds and may cause slumping.	*Eocene Paleontological Resources:* No fossils in the monument, but gastropods, gars, and the extinct fish *Asineops*, are known from the member. *Presbyornis* nesting site. *Stratigraphic Features:* Transition from lake environment (**Tga**) to a swamp and floodplain environment.	*The Global Greenhouse and Great Lakes of Wyoming:* Deposited across the entire Fossil Basin after Fossil Lake ceased to exist. Deposition of this uppermost member of the Wasatch Formation ends before 50 million years ago (Early Eocene).
PALEOGENE	Eocene	Wasatch Formation	Main body (Tw)	Primarily red, maroon, yellow, and gray variegated mudstone and claystone with beds of brown, yellow, and gray fine to coarse grained sandstone and conglomerate; other lithologies include diamictite, marlstone, and pisolitic limestone; coarsens toward the west. Up to 450 m (1,500 ft) thick in the northern part and 320 m (1,000 ft) thick in the southern part of Fossil Basin.	*Paleontological Resource Management:* Documentation, inventory, monitoring, and protection. *Mass Wasting:* Unstable slopes due to bentonitic claystones. Potential for landslides, which undercut the more resistant, blocky limestone of the Green River Formation and may cause rockfall.	*Eocene Paleontological Resources:* Only fossiliferous member of the Wasatch Formation within the monument. Includes 39 genera of mammals and 8 reptile genera (table 2). *Stratigraphic Features:* Spectacular red-colored badlands are particularly well-exposed at the saddle between Fossil Butte and Cundick Ridge. Channel-fill and floodplain deposits.	*The Global Greenhouse and Great Lakes of Wyoming:* Deposited in floodplains and stream channels. Locally, may overlap the Evanston Formation or may rest directly on Mesozoic or Paleozoic strata. The Wasatch Formation begins in Fossil Basin about 53.5 million years ago (Early Eocene).
PALEOGENE	Eocene	Wasatch Formation	Southern Mudstone Tongue (Twms)	Red mudstone, shale and sandstone derived from the Wasatch Formation in the northern part of the monument. Pinches out toward the south (basinward). Up to 40 m (130 ft) thick.	*Paleontological Resource Management:* Fossils have not yet been documented in **Twms** within the monument. No significant issues.	*Eocene Paleontological Resources:* Beyond the monument boundaries, **Twms** contains algal logs (logs encrusted by layers of calcium carbonate–producing algae.	*The Global Greenhouse and Great Lakes of Wyoming:* Represents the northern shoreline of Fossil Lake. Possibly deposited in a large delta. Merges with **Twt** to the north and west.
PALEOGENE	Eocene	Wasatch Formation	Sandstone Tongue (Tws)	Brown- weathering gray cross-bedded sandstone and interbedded mudstone; interlayered with **Tgr**, separates **Tgfb** from **Tgrh**. Up to 25 m (82 ft) thick. Limited in distribution to south of the monument. Thins and pinches out before reaching the monument.	Not mapped within the monument.	**Stratigraphic Features**: Forms a conspicuous ledge south of the monument. Cross-bedded, deltaic sandstone. Thickens significantly toward the south.	*The Global Greenhouse and Great Lakes of Wyoming:* Interpreted as a lacustrine Gilbert-type delta with topset, foreset, and bottomset sandstone beds that prograded into the southern part of Fossil Lake until lake level rose.
PALEOGENE	Eocene	Wasatch Formation	Lower Member (Twl)	Gray, brown, and red sandstone and mudstone, carbonaceous claystone, and stromatolitic and pisolitic limestone; locally unconformable with **Tw**. Up to 100 m (330 ft) thick. Exposed in the far western section of the monument just below Prow Point.	*Paleontological Resource Management:* Fossils have not yet been documented in **Twl** within the monument. *Mass Wasting:* No significant issues.	*Eocene Paleontological Resources:* Stromatolites. *Stratigraphic Features:* Intermediate in color and composition between the overlying **Tw** and underlying **Te**.	*The Global Greenhouse and Great Lakes of Wyoming:* Represents floodplain and stream channel deposits and a gradual change in climatic and/or sedimentary conditions in Fossil Basin.
PALEOGENE	Eocene	Wasatch Formation	Basal Conglomerate Member (Twc)	Conglomeratic sandstone composed of Nugget Sandstone clasts; 1–100 meters (3.3–330 ft) thick.	Not mapped within the monument. Only locally exposed in Fossil Basin.	Lenticular conglomerate beds.	*The Global Greenhouse and Great Lakes of Wyoming:* Represents channel sediments that filled stream beds cut into Mesozoic rocks.
PALEOGENE	Paleocene	Evanston Formation	Upper unit (Te)	Gray claystone and siltstone; interbeds of tan sandstone, carbonaceous claystone, coal, and boulder conglomerate. Up to 300 m (1,000 ft) thick. Not as colorful as **Tw**.	Not mapped within the monument. Exposed in a belt along the eastern and western borders of Fossil Basin.	Paleocene fossil vertebrate fauna, pollen, and leaves.	*The Great Compression:* Overlies a major pre-Tertiary unconformity. Depositional environments include streams, marshes, and ponds. Not involved in main Absaroka thrusting, suggesting that the thrust was Late Cretaceous and Fossil Basin began forming in the Late Cretaceous and continued in the Paleocene.
		Evanston Formation	Unconformity				
CRETACEOUS	Upper	Evanston Formation	Hams Fork Conglomerate Member (Keh)	Boulder to pebble conglomerate of well-rounded quartzite, chert, and limestone; contains beds of gray and brown cross-bedded sandstone and gray mudstone; poorly exposed; 300 m (1,000 ft) thick.	Not mapped within the monument. Exposed east of the monument and west of Cumberland Flats.	Late Cretaceous fossils include: *Triceratops* jaw, gastropods, leaves, pollen, and spores. As many as nine beds of boulder conglomerate interstratified with thick beds of conglomeratic sandstone and mudstone.	*The Great Compression:* Excellent rounding and sphericity of pebbles and boulders suggest moderate transport of the material in a large drainage system. **Keh** is mapped above and below the Absaroka thrust.

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Age		Map Unit (Symbol)	Geologic Description	Geologic Issues	Geologic Features and Processes	Geologic History and Park Connections
CRETACEOUS, Upper	Adaville Formation	Adaville Formation (Kav)	Gray brown and tan shale and siltstone; gray platy to cross-bedded, bioturbated sandstone; carbonaceous shale; numerous coal beds. Up to 880 m (2,900 ft) thick. Basal part forms ledges and cliffs.	*Energy Resource Exploration and Development:* Source of coal for local mines (i.e., Kemmerer Mine). Not mapped within the monument. Exposed east of the monument and west of Cumberland Flats.	Coal beds up to 35 m (115 ft) thick in the middle and lower parts of the formation. Fossil leaves have been dated to the latest Cretaceous. Bedding is more uniform bedding than in **Keh**.	*The Great Compression:* These units are in the footwall (east) of the Absaroka thrust. Helps date movement on the Absaroka thrust as latest Cretaceous. Bedding structures and marine fossils suggest that the Lazeart Sandstone was a prograding beach sequence.
		Lazeart Sandstone Member (Kal)	Light gray to white, yellow-brown to tan, fine- to medium-grained sandstone exposed as thick cliffs with intervening slopes of brownish-gray shale and coal beds; 180 m (590 ft) thick.			
	Hilliard Shale	Hilliard Shale (Kh)	Dark gray to tan claystone, siltstone, and sandy shale; thin interbeds of light-gray sandstone and bentonite.	Not mapped within the monument. Forms the surface of Cumberland Flats, east of the monument.	Abundant marine mollusks, a few ammonites, and palynomorphs.	Interbedded marine shale, siltstone, and sandstone in the footwall (east) of the Absaroka thrust. Deposits associated with the Cretaceous Western Interior Seaway.
		Hinshaw Member (Khh)	Interbedded shale and gray to tan, fine-grained sandstone units 0.3–10 m (1–33 ft) thick. Grades upward into the overlying **Kal**. Overall thickness about 260–305 m (850–1,000 ft).	Exposed in a thin strip along the western margin of Cumberland Flats, east of the monument.	Hummocky bedding, large-scale ball and pillow sedimentary structures, trough cross-bedding. Burrows.	
		Conglomerate of Little Muddy Creek (Khc)	Conglomerate and sandstone; conglomerate primarily well rounded Mesozoic and Paleozoic boulders derived from the upper plate of the Absaroka thrust. Maximum thickness about 610 m (2,000 ft).	Exposed along Little Muddy Creek, southeast of the monument on Cumberland Flats.	Boulders up to 2 m (7 ft) in diameter.	
	Frontier Formation	Frontier Formation (Kf)	Sandstone, siltstone, and carbonaceous shale with thick interbeds of coal; porcellanite (white volcanic ash) and conglomerate interbeds; up to 670 m (2,200 ft) thick.	Not mapped within the monument. The Frontier Formation and its members are exposed along the western slope of the north–south-trending Oyster Ridge, east of Kemmerer and Cumberland Flats.	Coal. Porcellanite. Palynomorphs.	Nonmarine and marine units record nearshore depositional environments associated with the Cretaceous Western Interior Seaway. Formation is in the footwall (east) of the Absaroka thrust.
		Lower Unit (Kfl)	White sandstone interbedded with siltstone, carbonaceous shale, coal beds, porcellanite, and conglomerate.		Coal. Porcellanite.	
		Dry Hollow Member (Kfd)	Gray, greenish-gray, and tan nonmarine shale and siltstone; interbeds of tan and brown coal and fine- to medium-grained sandstone; approximately 100–130 m (330–430 ft) thick.		Kemmerer coal bed near the top under a 3-m- (10-ft-) thick sandstone that contains a marine fauna. Sandstone is platy to cross-bedded; locally bioturbated.	
		Conglomerate Member (Kfdc)	Not an official member. Conglomerate that locally forms channels that cut into **Kfo**.		Channel-shaped deposits of conglomerate.	
		Oyster Ridge Sandstone Member (Kfo)	Light tan to white sandstone, medium-grained, planar to cross bedded, with interbeds of brown shale; forms cliffs; 24–35 m (79–115 ft) thick.	Not mapped within the monument. The Frontier Formation and its members are exposed along the western slope of the north–south-trending Oyster Ridge, east of Kemmerer and Cumberland Flats.	Sandstone is parallel-bedded to cross-bedded and contains marine fauna indicative of a marine shoreline environment.	Nonmarine and marine units record nearshore depositional environments associated with the Cretaceous Western Interior Seaway. The formation is primarily in the footwall (east) of the Absaroka thrust and in the hanging wall of the Darby thrust that formed Oyster Ridge, but it is also in the hanging wall (west) of the Absaroka thrust south of Muddy Creek where a kink is present in the north–south-trending thrust fault.
		Allen Hollow Member (Kfa)	Dark-gray to greenish-brown shale, siltstone and sandstone; covered slopes; approximately 92 m (300 ft) thick.		*Collignoniceras woolgari* fauna.	
		Coalville Member (Kfc)	Dark greenish-gray shale interbedded with tan sandstone that is fine-grained, cross-bedded, ripple-marked, and bioturbated; 24–46 m (70–150 ft) thick.		Flaggy to cross-bedded, ripple-marked, bioturbated sandstone with brackish-water to marine fauna.	
		Chalk Creek Member (Kfcc)	Greenish-gray to brown, nonmarine shale, bentonitic shale, tuff and tuffaceous sandstone; platy to cross-bedded, locally bioturbated; approximately 300–400 m (1,000–1,300 ft) thick.		Platy to cross-bedded sandstone, coal, nonmarine shale, and molluscan fauna represent nearshore depositional environments.	
CRETACEOUS, Lower		Aspen Shale (Ka)	Light to dark gray shale and quartzite sandstone; porcellanite forms prominent ridges; unit contains fish scales, palynomorphs, and mollusks; 245–370 m (809–1,220 ft) thick.	Not mapped within the monument. Exposed on Oyster Ridge, east of Kemmerer and Cumberland Flats.	Fish scales, palynomorphs, and molluscan fauna.	Represents deposition associated with the developing Cretaceous Western Interior Seaway. These units are in the footwall (east) of the Absaroka thrust. The Darby thrust, also a product of the Sevier Orogeny, formed Oyster Ridge.
		Bear River Formation (Kbr)	Dark gray carbonaceous shale, olive-tan sandstone, and limestone containing the abundant gastropod (*Pyrgulifera*) and pelecypod fauna that frequently blankets the weathered slopes; poorly exposed, forms slopes; 200–400 m (660–1,300 ft) thick.		Gastropod (*Pyrgulifera*) and pelecypods fossils. Palynomorphs.	
		Thomas Fork Formation (Ktf)	Interbedded buff sandstone and reddish-brown mudstone containing gray limestone nodules averaging 2–3 cm across; thickens southward from 100–400 m (330–1,300 ft) thick.	Not mapped within the monument. Located in the upper plate (hanging wall) of thrust faults and broken into fault slices by normal faults in the highlands west of the monument.	Limestone nodules. Merges to the south, and is lithologically indistinguishable from, the upper part of the Kelvin Formation (Lower Cretaceous) in northeastern Utah.	Displaced and deformed by thrust faults and normal faults associated with the Sevier Orogeny. Located above (west of) the Absaroka thrust fault.

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Age		Map Unit (Symbol)	Geologic Description	Geologic Issues	Geologic Features and Processes	Geologic History and Park Connections
CRETACEOUS	Lower	Smiths Formation (Ks)	Tan quartzite or fine grained sandstone with black carbonaceous shale at its base; up to 120 m (400 ft) thick.	Not mapped within the monument. Located in the upper plate (hanging wall) of thrust faults and broken into fault slices by normal faults in the highlands west of the monument.	Black, carbonaceous shale at the base of the unit.	Displaced and deformed by thrust faults and normal faults associated with the Sevier Orogeny. Located above (west of) the Absaroka thrust fault.
CRETACEOUS	Lower	Gannett Group (Kg, Kgc, Ke)	**Kg**: Gannett Group. Brick-red and orange-brown to maroon mudstone, siltstone, and sandstone with a few interbeds of limestone and conglomerate; 640 m (2,100 ft) thick. **Kgc**: Chert pebble conglomerate beds; approximately 1 m (3.3 ft) thick. **Ke**: Ephraim Conglomerate. Red to tan cross-bedded sandstone, and massively bedded conglomerate with abundant black chert pebbles; up to 200 m (660 ft) thick.	Not mapped within the monument. Located in the upper plate (hanging wall) of thrust faults and broken into fault slices by normal faults in the highlands west of the monument and on the eastern side of Oyster Ridge.	Interbedded limestone, mudstone, siltstone, sandstone, and conglomerate beds. Cross-bedded to massive.	
JURASSIC	Upper	Stump Sandstone and Preuss Red Beds (Jsp)	**Stump Sandstone**: Greenish-gray sandstone and limestone. **Preuss Red Beds**: Red to purplish-gray sandstone and silty claystone with thin beds of red to tan sandstone. Unit thickens to 520 m (1,700 ft) west of the Crawford fault.	Not mapped within the monument. Exposed in the upper plate of the Tunp thrust, west of the monument, and on the eastern slope of Oyster Ridge, east of the monument.	Because the unit is thin, the Stump Sandstone has been mapped with the Preuss Red Beds in the area.	*Assembling and Dismantling Pangaea:* Deposited along the southern margin of a shallow sea that encroached into southwestern Wyoming during the Middle Jurassic as Pangaea separated.
JURASSIC	Middle	Twin Creek Limestone (Jt, Jtg)	**Jt**: Sandy argillaceous thin bedded limestone and red calcareous siltstone in the lower part. Forms conspicuously bare slopes; massive oolitic limestone beds. Up to 880 m (2,600 ft) thick west of the monument and 240–300 m (790–1,000 ft) thick east of the monument. **Jtg**: Gypsum Spring Member. Red calcareous mudstone and siltstone and gray limestone breccia. Up to 30 m (100 ft) thick.	Not mapped within the monument. Exposed in the upper plate of the Tunp thrust, west of the monument, and on the eastern slope of Oyster Ridge, east of the monument.	**Jt**: Limestone contains the distinctive crinoid fossil, *Pentacrinus*. In cross-section, the crinoid stem is pentagonal or star-shaped. **Jtg**: Breccia believed to be formed by solution, or leaching, of anhydrite and subsequent collapse of overlying limestone.	*Assembling and Dismantling Pangaea:* **Jt**: Abundant crinoids suggest that the limestone formed in a marine environment with well-circulating bottom currents. **Jtg**: Represents deposition in marine to hypersaline marine or coastal sabkha and tidal flat environments.
JURASSIC	Lower	Nugget Sandstone (JTRn)	Buff, pink, and white quartzite and sandstone; massive to cross-bedded; fine to medium grained, well sorted; up to 450 m (1,500 ft) thick in the Tunp Range and 200 m (700 ft) thick east of the monument.	Not mapped within the monument. Exposed on Rock Creek Ridge (upper plate of the Tunp thrust), west of the monument, and east of Oyster Ridge, east of the monument.	Forms prominent ridges and cliffs with blocky talus slopes. Massive to eolian cross-bedded sandstone.	*Assembling and Dismantling Pangaea:* Part of an extensive sand sea (erg). Early Jurassic in age according to the U.S. Geological Survey.
TRIASSIC	Upper	Ankareh Red Beds (TRa)	Red and maroon calcareous sandstone or quartzite; siltstone, sandy calcareous mudstone, and some local beds of red to green-gray limestone near the middle of the formation; 225 m (740 ft) thick.	Not mapped within the monument. Exposed west of the monument.	Greater proportion of sandstone than Woodside Red Beds (**TRw**).	*Assembling and Dismantling Pangaea:* Deposited over the Thaynes Limestone as the shallow sea withdrew from southwestern Wyoming.
TRIASSIC	Mid.	Unconformity				
TRIASSIC	Lower	Thaynes Limestone (TRt)	Gray, silty erosion-resistant limestone and calcareous siltstone; thickness increases to the north and west from 215–400 m (710–1,300 ft) thick. Mapped near the northwestern corner of the monument.	**Paleontological Resource Management**: Documentation, inventory, monitoring, and protection.	*Triassic Paleontological Resources:* Contains a varied assemblage of marine invertebrate fossils, mostly oysters and clams. Fossils not yet discovered within the monument.	*Assembling and Dismantling Pangaea:* Represents another incursion of a shallow sea into the area.
TRIASSIC	Lower	Woodside Red Beds (TRw)	Red siltstone and claystone with thin interbeds of red sandstone and gray limestone. Up to 200 m (660 ft) thick. Forms slopes.	Not mapped within the monument. Exposed in the Tunp Range, west of the monument.	Nonresistant sequence of siltstone and claystone forms slopes.	*Assembling and Dismantling Pangaea:* Deposited over the Wyoming shelf as sea level fell.
TRIASSIC	Lower	Dinwoody Formation (TRd)	Greenish-gray calcareous siltstone, claystone, and argillaceous sandy limestone; thin bedded. Thickness: 30–150 m (100–490 ft).		Weathers tan to buff-gray. Distinctive thin layers of siltstone and claystone above the Phosphoria Formation (**Pp**).	*Assembling and Dismantling Pangaea:* Represents initial incursion of a shallow sea onto the gently westward-sloping Wyoming shelf.
PERMIAN	Middle-Upper	Unconformity				
PERMIAN	Lower	Phosphoria Formation (Pp)	Dark-gray siltstone, thin-bedded limestone, dolomitic limestone, and black chert. Thickness: 130 m (430 ft).	*Energy Resource Exploration and Development:* Source of phosphate rock and associated vanadium, gypsum, and oil and gas in the subsurface. Not mapped within the monument. Exposed to the west in the Tunp Range.	Invertebrate marine fossils (brachiopods and conodonts).	*Ancient Seas:* Represents deposition in shallow marine water that received nutrients from upwelling currents, which provided phosphorus for the hard parts of marine invertebrates and fecal pellets.
PERMIAN	Lower	Phosphoria Formation: Upper Part (Ppu)	Dark-gray siltstone, thin-bedded limestone and black chert. Several chert beds.		Resistant ledges of red to gray dolomitic limestone and chert.	
PERMIAN	Lower	Phosphoria Formation: Lower Part (Ppl)	Dark phosphatic siltstone, gray dolomite, and thin-bedded black chert and limestone.		Phosphatic rock and vandiferous carbonaceous siltstone that has vanadinite, a mineral containing vanadium and lead.	

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PENNSYLVANIAN		Wells Formation (PlPw, Pwl)	**PlPw**: Wells Formation. Light-gray, fine-grained sandstone and quartzite with beds of dolomite and limestone. Total thickness is 185–305 m (610–1,000 ft). **Pwl:** Wells Formation limestone. Gray limestone, 80 m (260 ft) thick.	*Energy Resource Exploration and Development:* Source of silica sand, limestone for road aggregate, and oil and gas in the subsurface. Not mapped within the monument. Well exposed along the crest of Dempsey Ridge and near the base of the Absaroka thrust sheet on Commissary Ridge.	Invertebrate marine fossils in the limestone.	*Ancient Seas:* Represents deposition in marine environments.
MISSISSIPPIAN	Upper	Amsden Formation (PMa)	Reddish-gray to black cherty limestone and limestone breccia with interbeds of yellowish-red sandstone and quartzite and red to yellow siltstone and claystone. Thickens west to east from 45 to 120 m (150 to 390 ft).	In the subsurface, **PMa** may act as a confining unit (low porosity and permeability) to underlying groundwater aquifers. Not mapped within the monument. The upper part of the formation is exposed where Little Beaver Creek crosses Dempsey Ridge in the Tunp Range.	Invertebrate marine fossils.	*Ancient Seas:* Contains limestone and dolomite deposited in shallow, near-shore marine environments as well as terrigenous sediment eroded from the Ancestral Rocky Mountains.
MISSISSIPPIAN	Mid.	Unconformity				
MISSISSIPPIAN / DEVONIAN	Lower / Upper	Darby Formation (MDd)	Dark gray or brown fetid (malodorous) dolomite, massive to medium bedded with interbeds of black, yellow and red sandy calcareous siltstone in upper part; approximately 270 m (890 ft) thick.	Not mapped within the monument. Exposure with limited areal extent located west of Sillem Ridge, west of the monument.	Fetid odor commonly results from decaying organic matter.	Shallow, peritidal deposition on the eastern coast of the inland sea that spread into Wyoming as a result of the Antler Orogeny.

Reference maps: Buchheim, H. P. 2005. Geologic map of Fossil Butte National Monument and vicinity, Wyoming. Unpublished. Loma Linda University, Loma Linda, California, USA (scale 1:24000); and Lowry, J. 2007. Digital geologic map of Fossil Butte National Monument and vicinity, Wyoming. Unpublished. Utah State University, Logan, Utah, USA (scale 1:24000).