National Park Service
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Natural Resource Program Center

Agate Fossil Beds National Monument

Geologic Resources Inventory Report

Natural Resource Report NPS/NRPC/GRD/NRR—2009/080

THIS PAGE:
Fossil diorama at Agate Fossil Beds National Monument, an omnivorous entelodont (*Daeodon* or *Dinohyus*) stands over a chalicothere (*Moropus*), Agate Fossil Beds NM.

ON THE COVER:
University Hill on the left and Carnegie Hill on the right, site of the main fossil excavations, Agate Fossil Beds NM.

NPS Photos.

Agate Fossil Beds National Monument

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Geologic Resources Division
Natural Resource Program Center
P.O. Box 25287
Denver, Colorado 80225

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Executive Summary

This report accompanies the digital geologic map for Agate Fossil Beds National Monument in Nebraska, which the Geologic Resources Division produced in collaboration with its partners. It contains information relevant to resource management and scientific research. This document incorporates preexisting geologic information and does not include new data or additional fieldwork.

Formerly a working ranch in sparsely populated northwestern Nebraska, Agate Fossil Beds National Monument is one of the most important paleontological sites in the world for studying Miocene-age mammals and the evolving Miocene world which existed around 20 million years ago. The main bonebeds at Carnegie Hill and University Hill (collectively known as 'Fossil Hills') were the first major concentrated deposits of Tertiary-age mammals discovered in North America. The bonebeds produced the most complete and best-preserved skeletons of *Dinohyus* (now known as *Daeodon*) yet discovered. The corkscrew burrow, *Daemonelix*, is one of the more unusual features discovered in the Monument. The much younger fossils and burrows at Beardog Hill represent the oldest denning community of carnivores known in the fossil record. Furthermore, 100 or more of the tiny camelid, *Stenomylus,* were found mummified and mostly articulated in a quarry east of Fossil Hills.

The fossil birds recovered from Agate Fossil Beds National Monument add to the Monument's faunal diversity and help verify paleoenvironmental interpretations. New genera and species have been identified from the collections, including the first record of a crane, *Gruiformes*. Significantly, the paleoavifauna represents a worldwide fauna that has only recently been recognized at a few other localities.

Protection and preservation of the extraordinary paleontological resources are primary geologic issues at the Monument. The carnivore den site at Beardog Hill and the fossils in the *Stenomylus* Quarry are subject to erosion, weathering, and occasional vandalism. The historic quarries at Fossil Hills are easily accessible to visitors and are not monitored. A comprehensive fossil taxa list for the Fossil Hills, Beardog Hill, and the *Stenomylus* Quarry could prove useful to resource managers.

The fossil collections from Agate Fossil Beds National Monument continue to provide paleontologists with valuable information about the Miocene ecosystem. Further research at the Monument could include testing the east side of Carnegie Hill as well as a significant rock layer in the *Stenomylus* Quarry for mammal fossils.

Agates, which give the park its name, are found in a thin band along ash deposits just above the Miocene bonebeds. Visitors have easy access to the agates, known for their polish and luster. Collecting agates is a legal activity in the U.S. Forest Service Oglalla National Grassland, which is located north of the park, and many visitors come to Agate Fossil Beds National Monument expecting to collect these rocks.

Rockfall areas at University Hill and Carnegie Hill pose a potential hazard to both visitors and researchers. Signs have been posted warning visitors of the hazard.

Exploration wells for oil and gas were drilled just south of the park more than sixty years ago to test the Agate anticline, but no oil or gas was discovered. Minimally productive wells exist about 32 km (20 mi) south of the Monument and potential exploration drilling in the area remains a minor concern for Monument management.

The Miocene landscape was one of broad savannas with vast herds of plant-eating mammals and the carnivores that preyed upon them. Perhaps the Rocky Mountains blocked moisture from reaching the Great Plains of western Nebraska during the Miocene. Drought ensued and the fluctuating climate stressed the habitat of the browsers and grazers. As waterholes evaporated, the animals died, were buried, and became the fossilized deposits so treasured today by paleontologists and visitors to Agate Fossil Beds National Monument.

Agate Fossil Beds National Monument is located on an area of the High Plains in the Niobrara Valley that escaped glaciation during the last glacial advance of the Pleistocene Ice Age. Because glaciers did not erode the Pleistocene and Holocene sediments, significant climatic variations during the past 12,000–15,000 years are recorded in the geomorphology, stratigraphy, and paleosols of the Niobrara Valley. The Niobrara River meanders through the park, creating 18 km (11 mi) of riverbank and riparian wetlands.

The rich collection of fauna and associated paleoenvironments at Agate Fossil Beds National Monument provide a rare glimpse into the ecology of the carnivore community during the Early Miocene and significant insight into Tertiary global climate change. Specimens discovered in the fossil quarries continue to help scientists piece together the past. The great bonebed at Agate Fossil Beds National Monument remains one of the most impressive and scientifically interesting paleontological sites in North America.

Introduction

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

Geologic Resources Inventory

The Geologic Resources Inventory (GRI) is one of 12 inventories funded under the National Park Service (NPS) Natural Resource Challenge designed to enhance baseline information available to park managers. The program carries out the geologic component of the inventory effort. The Geologic Resources Division of the Natural Resource Program Center administers this program. The GRI team relies heavily on partnerships with the U.S. Geological Survey, Colorado State University, state surveys, and others in developing GRI products.

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

To realize this goal, the GRI team is systematically conducting a scoping meeting for each of the identified 270 natural area parks and providing a park-specific digital geologic map and geologic report. These products support the stewardship of park resources and are designed for nongeoscientists. Scoping meetings bring together park staff and geologic experts to review available geologic maps and discuss specific geologic issues, features, and processes.

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

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

Regional and Geologic Setting

Fossils discovered at Agate Fossil Beds National Monument were the first major concentrated deposits of Tertiary-age mammals discovered in North America (Kiver and Harris 1999). The first extensive study of Tertiary fossil mammals of the West probably occurred at Badlands National Park, but fossils at Badlands National Park are not found in concentrated bonebeds as they are at Agate (Jason Kenworthy, NPS, written communication, September 2008). Renowned quarries in the upper part of the Harrison Formation at Agate Fossil Beds contain numerous, well-preserved fossils of Miocene mammals. These outstanding specimens, some nearly complete, continue to help scientists piece together mammalian evolution and Tertiary global climate change. Many of the extinct species found at Agate Fossil Beds are distant relatives of modern fauna. The great bonebed at the Monument remains one of the most impressive and scientifically interesting paleontological sites in North America (Hunt 1988).

Agate Fossil Beds National Monument, 3,055.22 acres in size (Federal: 2,737.52 acres; non-federal: 317.70 acres), is located in the sparsely populated ranchland along the Niobrara River of northwest Nebraska (fig. 1). Rocks of the Arikaree Group form an elevated tableland that extends from the Pine Ridge escarpment, a few miles north of Harrison, Nebraska, south to the valley of the North Platte River (Vicars 1979; Hunt 1990). The Monument is about 70 km (43 mi) north of Scottsbluff and 36 km (22 mi) south of Harrison (fig. 2).

All fossil deposits at Agate Fossil Beds National Monument are found in the Miocene-age part of the Arikaree Group, primarily in the Harrison Formation and the informal “Anderson Ranch Formation” (fig. 3). The “Anderson Ranch Formation” was previously called the Upper Harrison beds (Vicars 1979; Hunt 1981; Hunt 1990; LaGarry et al. 2007). The sedimentary rocks in the Arikaree Group include fine-grained sandstone and siltstone that have fluvial, eolian, and volcanic origins (fig. 3).

Abundant agates are found in a thin band along ash deposits just above the Miocene bonebeds. These agates provided the inspiration for the name of the nearby small town as well as the Monument. The most common type of agate at Agate Fossil Beds National Monument is moss agate (Jason Kenworthy, NPS, written communication, June 6, 2008).

The agates range in color from green to amber to light gray and are a variety of quartz called chalcedony. Trace amounts of iron, manganese, chrome, and/or aluminum give the agates their different colors. Moss agate is a semi-precious gemstone that includes trace amounts of green minerals such as chrome or iron embedded in

milky-white quartz. In a moss agate, the inclusions form filaments and other patterns that resemble moss, or in some cases, the coloration resembles blue-cheese.

The complex array of late Pleistocene and Holocene geomorphology, stratigraphy, and paleosols (ancient soils) found in the modern Niobrara Valley at Agate Fossil Beds National Monument reflects significant climate variations over the past 12,000–15,000 years (http://www.nps.gov/agfo/index.htm, accessed April, 2006). Today, the channel of the Niobrara River meanders through the 6 km (4 mi) length of Agate Fossil Beds National Monument, creating 18 km (11 mi) of river bank (fig. 1).

Fossil Record at Agate Fossil Beds National Monument

Oligocene-age fossils are found in the exposed beds of the White River Group at Badlands National Park, about 210 km (130 mi) northeast of Agate Fossil Beds National Monument, and at Scotts Bluff National Monument, about 70 km (43 mi) south of the Monument. However, Arikaree Group rocks of Early Miocene-age (about 24–13 million years old) cover the White River Group at Agate Fossil Beds National Monument (Kiver and Harris 1999).

The Miocene fossils at Agate Fossil Beds National Monument are found in distinct stratigraphic assemblages. A unique, spiral-shaped feature occurs in the lower part of the Harrison Formation, which was deposited approximately 3–4 million years before the upper part of the formation (Jason Kenworthy, NPS, written communication, September 2008; http://www2.nature.nps.gov/geology/parks/agfo, accessed April, 2006). This feature is as tall as a human and mystified early paleontologists (fig. 4). They named the feature *Daemonelix*, or Devil's Corkscrew, thinking that the filled-in cavity was left by some unknown tree that grew a corkscrew-shaped taproot. When bones of *Paleocastor*, an extinct beaver, were found at the bottom of some of these corkscrews, the features were reinterpreted to be filled-in burrows of these ancient dry-land beavers. An overlying ash bed, called the Agate Ash, has been age-dated to be 21.3–22.9 million years ago, making the *Daemonelix* burrows approximately 22–23 million years old (Jason Kenworthy, NPS, written communication, September 2008).

Fossils of the gazelle-camel, *Stenomylus*, are younger than the *Daemonelix* burrows (Hunt 1981). The major sites in Sioux County occur in the *Stenomylus* Quarry, a small detached unit of the Monument located about 2.4 km (1.5 mi) east of University Hill and Carnegie Hill (collectively called the 'Fossil Hills') (fig. 1). *Stenomylus* was extremely diminutive compared to other ancient and modern camelids. The gazelle-like camel stood 0.6 m (2 ft) tall and traveled in herds (fig. 5). The fossils lie beneath a 21-million-year-old ash bed. Unlike the fossils in the main Agate bonebeds, the 100 or more bodies of these ancient camels are mummified and mostly articulated, which suggests a different means of preservation than that in the main bonebeds. The demise of these animals remains a mystery (Kiver and Harris 1999; http://www.cr.nps.gov/history/online_books/berkeley/effinger3/effinger3c3.htm, accessed April 23, 2007).

The main bonebeds at Agate Fossil Beds National Monument consist of an upper and lower bonebed found at the base of the Upper Harrison Beds at Carnegie Hill (fig. 3) (Hunt 1981; Hunt 1990). The beds are separated from each other by units of calcareous tuff and fluvial tuffaceous sandstone and are younger than the strata at the *Stenomylus* Quarry (Hunt 1990). The Eagle Crag Ash, deposited over the upper bonebed, was deposited approximately 19.2 million years ago.

The fossils in the main bonebeds at Agate Fossil Beds National Monument collected in a waterhole that developed within a wide shallow valley eroded into the semiarid continental interior. The fossils are seldom articulated, but most of the bones from individual skeletons lie near each other. The sedimentation units enclosing the lower and upper Agate bonebeds formed over a prolonged period of time (a number of months to years). Evidence from the units also suggests that the lower and upper bonebeds were the result of a death event that also spanned an interval of time in excess of several months' duration (Hunt 1990). The formation of the upper and lower bonebeds is explained in greater detail in the Features and Processes section and illustrated in a mural and diorama at the visitor center (fig. 6).

The most common mammal fossils in the bonebeds at Agate Fossil Beds National Monument are from the 1 m (3 ft)-high two-horned rhinoceros called *Menoceras*. The stout, blunt horns on a *Menoceras* were arranged side by side on the nose rather than the tandem arrangement of the two horns on the modern African rhinoceroses. A 1.7 m by 2.4 m (1.5ft by 8 ft) block that was removed from the quarry in 1920 contained twenty-two skulls and an uncounted number of skeletons from *Menoceras*. The block is on exhibit at the American Museum of Natural History in New York.

Fossils from the genus *Moropus* are the second most common fossils in the Agate bonebeds. A chalicothere, *Moropus* was a 2 m (7 ft)-tall sloth-like animal with a horse-like head and neck but a short arched back, sloping hips, and rudimentary tail similar to today's tapir (fig. 6). Grinding teeth were like those of the extinct titanothere, while the front teeth resembled those of a ruminant. Remarkably, *Moropus* had toes that were tipped with claws instead of hoofs, an anatomical feature difficult to explain in an ungulate.

Two superb skeletons of the huge entelodont *Dinohyus holland* ("terrible pig") are the most complete and best-preserved skeletons of *Dinohyus* ever found (fig. 6) (Hunt 1988). Although the park and popular literature still refer to these entelodonts as *Dinohyus*, the correct genus name is *Daeodon* ("bloody tooth") (Jason Kenworthy, NPS, written communication, November 20, 2008). The fossils from Agate Fossil Beds National Monument are the best preserved *Daeodon* in North America if not the world (Jason Kenworthy, NPS, written communication, September 8, 2008).

Entelodonts were omnivores with a pig-like lifestyle, although they were not related to the pigs any more closely than the ruminants. *Daeodon* from the park are among the largest entelodonts in the world. Some were the size of a small modern rhinoceros. They are also among the youngest as the family became extinct by middle Miocene.

Fossil bones from camels, oreodonts (sheep-size, cud-chewing plant-eaters), saber-tooth cats, carnivorous beardogs and other animals are mixed in with the *Menoceras*, *Moropus*, and *Daeodon* bones. Specimens of *Parahippus*, one of the last of the "browsing" horses, are also found at Agate Fossil Beds National Monument (Jason Kenworthy, NPS, written communication, September 8, 2008).

In 1981, University of Nebraska paleontologists discovered a concentration of mammalian carnivore dens in the basal Upper Harrison beds exposed in Carnegie Quarry 3, about 150 m (500 ft) from the main Agate bonebed at Carnegie Hill (Hunt 1988; Hunt 1990; Hunt 1999). Radiometrically dated at 19.2 million years old, the dens are burrowed into the sediment fill of the waterhole and therefore postdate the Carnegie Hill death assemblage by some unknown but geologically brief amount of time. The dens contained carnivore remains of two large beardogs (Family Amphicyonidae: *Daphoenodon* and a wolf-sized temnocyonine), two mustelids (Family Mustelidae: *Megalictis* and *Promartes*), and two small fox-sized canids (Family Canidae: *Phlaocyon* and *Tomarctus*) (Hunt 1999).

In 1991, an older den complex was discovered in Harrison Formation paleosol horizons radiometrically dated at 22 million years old (Hunt 1999). The 5–6 large cylindrical burrows measured up to 10 m (33 ft) in length and 1–2 m (3.3–6.6 ft) in diameter. They were distributed over 450 m^2 (4,800 ft^2). Associated with the burrows were bones of a wolf-sized beardog, a small fox-sized canid, and a rodent.

The two den complexes represent the oldest evidence of denning behavior by large mammalian carnivores known anywhere in the world (Hunt 1999). Such records, which allow insight into the behavior of extinct mammals, are extremely rare. Typically, remains of fossil vertebrates are preserved in stream, lake, or wind-deposited sediments, or unique locations like tar pits or glacial ice so that little information can be gleaned regarding their habitat, community associations, lifestyle, or other ecological relationships. The den communities at Agate Fossil Beds National Monument are an exception in that fossil remains of extinct carnivores were found within and in proximity to their dens.

Fossil birds, although less common than mammals, have also been discovered at the Monument. The paleoavifauna collections in the University of Nebraska State Museum contain representatives from at least six families and four orders, including the first record of a crane, Gruiformes, and additional specimens of the fossil hawk, *Buteo ales* Wetmore (Chandler 1995).

The fossils at Agate Fossil Beds National Monument provide insight into the evolving Miocene world. The bonebeds reveal clues to the life, and death, of now extinct animals that roamed the Great Plains just a few million years prior to the Pleistocene Ice Age. At Agate Fossil Beds, an estimated 75% of all the fossils in the bonebed still remain buried for future generations to study (Kiver and Harris 1999).

Park and Regional History

Humans have been part of the Agate Fossil Beds National Monument landscape for at least 11,000 years (http:// www.nps.gov/agfo/index.htm, accessed April, 2006). Ancient campsites along the Niobrara River record human presence in the park about 2,500 years ago. These campsites are now on terraces 6–8 m (20–25 ft) above the modern river. In the eighteenth and nineteenth centuries, people from 31 of today's American Indian tribes, including the Apache, Arapaho, Arikara, Cheyenne, Comanche, Crow, Dakota Sioux, Kiowa, Lakota Sioux, Nakota Sioux, Omaha, Pawnee, Ponca, and Shoshoni, used the resources of the Niobrara River valley. Several sites and landscapes within the Monument are considered to be sacred traditional Native American places.

The Lakota Sioux called the fossil localities A'bekiyia Wama'kaskan s'e, meaning "Animal Bones Brutally Scattered About" (Mayor 2005). Mayor (2005) states that bones found at Agate Springs were considered "bad medicine" having originated from the malevolent Unktehi monsters. However, fossils of the beaver, *Paleocastor*, along with *Daemonelix* were thought to provide protection from the evil fossils. According to Lakota legend, the beavers sacrificed themselves by becoming stone to counteract the "bad medicine" of the Unktehi bones (Mayor 2005).

In the late nineteenth century, Euro-Americans passed through and then settled in the Niobrara Valley. Agate Fossil Beds National Monument was originally a working cattle ranch owned by James Cook and was known as Agate Springs Ranch. Cook had purchased the ranch from Dr. Elisha B. Graham, his father-in-law, in 1887. Cook was a man of many interests and skills. He was a cowboy, big-game hunter, U.S. Army scout, author, and a close friend of the famous Chief Red Cloud of the Oglala Sioux. When riding past a pair of conical buttes not far from his ranch house, Cook found an animal leg bone protruding from one of the buttes. This bone was the first of a series of discoveries that would greatly influence the lives of the Cook family and the science of paleontology.

In the late nineteenth century, the hunt for fossils in the American West had resulted in a keen competition among paleontologists. Unlike mammalian fossils in most of the rest of the world, mammal fossils in the American West were found to be extremely well-preserved and provided a unique record of mammal evolution in the Cenozoic.

In 1891, Cook, who had a keen interest in research and preservation of the Fossil Hills, invited Professor Erwin

Barbour of the University of Nebraska to explore the Agate Springs area. Barbour became so fascinated with the spiral-shaped *Daemonelix*, exposed just across the road from the Cook ranch house, that he ignored the bonebeds that one of his students found about 5 km (3 mi) to the east. In 1904, O.A. Peterson from the Carnegie Museum of Pittsburgh began excavations in Carnegie Hill, one of the two conical buttes. He soon realized that he had found a bone bonanza of international significance (NPS 1980; Kiver and Harris 1999). Barbour began excavations in the other hill (University Hill) in 1905.

In 1906, Professor E.B. Loomis and a party from Amherst College excavated a small hill, which Loomis called Amherst Point. This hill is north of University Hill, but it is much less of a "hill" than Carnegie Hill or University Hill (Jason Kenworthy, NPS, written communication, September 8, 2008). In 1908, the Loomis party, working more than 1.6 km (1 mi) away from the Fossil Hills, discovered a quarry of *Stenomylus* skeletons. At least 40 skeletons were removed by the Carnegie Museum in 1909.

The American Museum of Natural History collected specimens at Agate Fossil Beds for about 20 years, beginning in 1910. Other universities and museums conducted major fossil digs up until about 1923. Through the 1960s, many other museums collected large amounts of material from what is now Agate Fossil Beds National Monument. Some of these collections are now housed at Princeton University, the University of Kansas, and the Raymond Alf Museum of Paleontology in southern California.

Cook hosted these groups and, over the years, acquired a rare collection of natural history specimens, fossils, and Indian artifacts. Many of the artifacts were gifts from the Oglala Sioux. Today the Agate Fossil Beds National Monument museum collection contains more than 500 artifacts from the Cook Collection of Plains Indian artifacts.

Harold Cook, James Cook's oldest son, became a geologist and married Eleanor Barbour, the geologist daughter of Professor Barbour. Harold requested that the ranch become part of the National Park System, and through the diligent efforts of the Cook family, Nebraska Senator Roman Hruska, and Representative Dave Martin, Agate Fossil Beds National Monument was authorized June 5, 1965, three years after Harold Cook's death. The Cook Family Board of Directors still owns the ranch and leases it out. They remain active in Monument decision making and planning.

Professor Robert Hunt, Jr., University of Nebraska – Lincoln, conducted significant research into the biostratigraphy, ecosystem, and taphonomy of the Miocene paleofauna throughout the 1980s and 1990s. The first beardog den community was discovered in 1981. Another den community was found in 1991. Professor Hunt's interpretation of the Miocene stratigraphy and the waterhole taphonomy began a new chapter in understanding the Miocene ecosystem. The last excavation in the park was completed in 1990, but research using previously excavated material continues (Jason Kenworthy, NPS, written communication September 8, 2008).

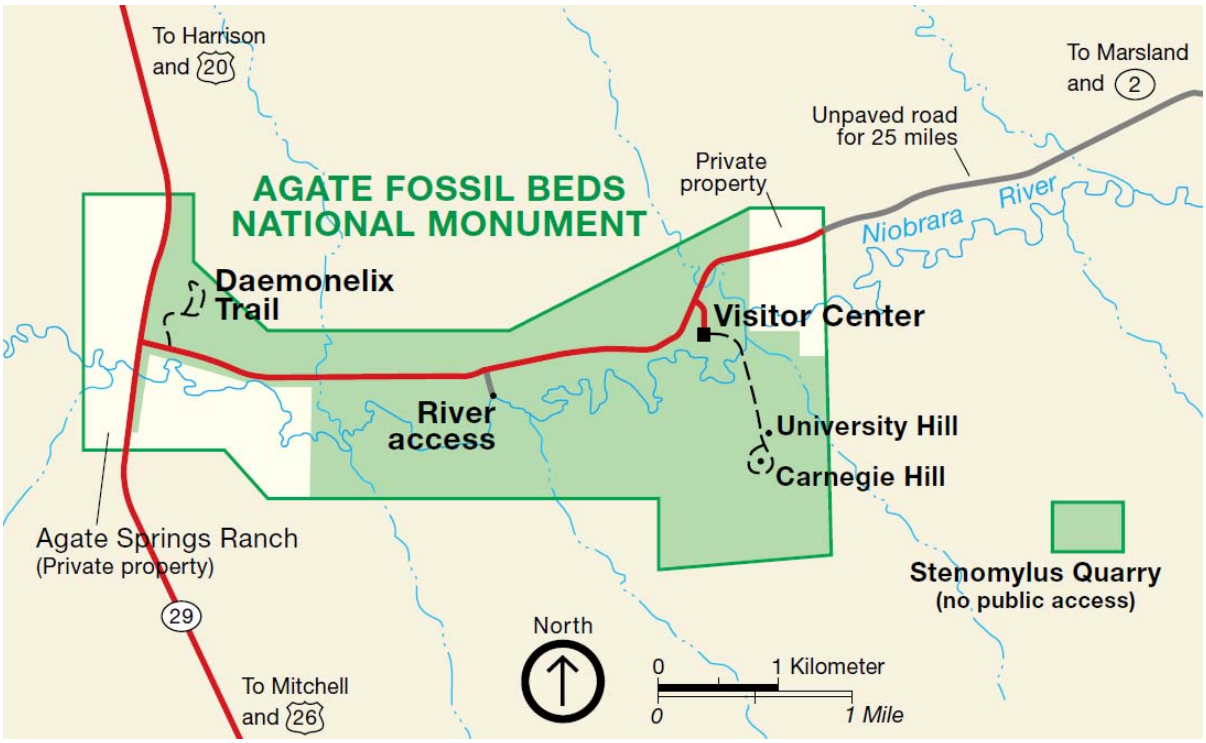


Figure 1. Map of Agate Fossil Beds National Monument.

Figure 2. Regional location map of Agate Fossil Beds National Monument. Map courtesy of http://maps.nationalgeographic.com.

Epoch	Group	Formation	Lithology	Interpretation
EARLY MIOCENE	Arikaree	Upper Harrison Beds "Anderson Ranch Fm"	Dense, micritic limestone	Shallow holomictic lake
			Massive, bioturbated very fine silty sandstone	Eolian pyroclastic dust mantling interchannel plains
			Cross-stratified, fine sandstone Thin-bedded fine to very fine sandstone with cross & horizontal stratification	Flood plain & channel deposits of wide sandy braided stream
			Paleosol	Prominent soil
			Limy tuff & sandstone (Agate bonebed & beardog dens)	Waterhole within a wide shallow valley
		Harrison	Fine, cross-stratified, horizontally stratified & massive sandstones (*Stenomylus* fossils) (*Daemonelix* burrows)	Undifferentiated stream & eolian deposits

Figure 3. Lithology and paleoenvironments of the Upper Harrison Beds and Harrison Formation at Carnegie Hill, Agate Fossil Beds National Monument, Sioux County, Nebraska. The Agate bonebed occurs at the base of the Upper Harrison Beds (now referred to as the "Anderson Ranch Formation") in a unit composed of intertongued calcareous tuff and tuffaceous fluvial sandstone that represents a waterhole environment. The Early Miocene is an epoch within the Tertiary Period (fig. 12). Figure modified from Hunt (1990).

Figure 4. Vertical plexiglass display case encompasses the corkscrew burrow, *Daemonelix*. Photograph courtesy of Jason Kenworthy, NPS.

Figure 5. *Stenomylus* display at Agate Fossil Beds National Monument on loan from the Denver Museum of Natural History. The gazelle-like *Stenomylus* was a diminutive camelid measuring on average only 0.6 m (2 ft) tall. NPS Photo

Figure 6. Visitor center diorama at Agate Fossil Beds National Monument, Nebraska. From left to right, the diorama features one beardog skeleton of the genus *Daphoenodon*, two entelodonts (genus *Daeodon*, commonly called *Dinohyus*), a *Moropus* lying on its side, and three more sloth-like *Moropus* on the right side. Photograph courtesy of Jason Kenworthy, NPS.

Geologic Issues

A Geologic Resources Inventory scoping session was held for Agate Fossil Beds National Monument on March 3–4, 2003, to discuss geologic resources, address the status of geologic mapping, and assess resource management issues and needs. This section synthesizes the scoping results, in particular those issues that may require attention from resource managers.

At the Scoping session and through subsequent discussions, the geologic issues described in this section have been recognized at Agate Fossil Beds National Monument.

Research on the paleontology and geology at Agate Fossil Beds National Monument remains active. Currently, Agate Fossil Beds National Monument does not have a paleontologist on staff, which makes salvage, collection, and documentation of fossils within the park difficult to achieve. However, since the late 1970s, Dr. Robert Hunt and his students at the University of Nebraska-Lincoln have combined their research goals with the NPS Midwest Region's need to develop the Monument's public exhibits in paleontology. They continue their work on the geology and paleontology at the Monument as volunteers during the summers as part of the NPS Volunteers-In-Parks (VIP) program (Dr. Robert Hunt, written communication, December 15, 2008).

Preservation and Protection of Paleontological Resources

Fossils are non-renewable resources and have increased scientific value when they are preserved in-situ or excavated by professional paleontologists. The preservation and protection of fossil resources is parmount to the mission of Agate Fossil Beds National Monument. In the legislative act that authorized Agate Fossil Beds National Monument, Congress emphasized the importance of managing the paleontological and geological resources of the Monument. Specifically, the park is authorized to (Public Law 89-33):

- Preserve the outstanding paleontological sites known as the Agate Springs Fossil Quarries
- Provide for continuing paleontological research
- Provide for the display and interpretation of the scientific specimens uncovered at the sites.
- Protect nearby related geological phenomena

Dr. Hunt prepared two reports for the NPS in 1984 and 1988 (Dr. Robert Hunt, written communication, December 15, 2008). The history of the excavations on the main fossil hills that occurred between 1904 and 1923 was reviewed in the 1984 report. The 1988 report highlighted the value of the fields of sedimentology and bone taphonomy "in solving problems of paleoenvironment reconstruction involving occurrences of fossil vertebrates" (Hunt 1988). The report also included recommendations for conservation and development involving the paleontological resources in Agate Fossil Beds National Monument (Hunt 1988). Dr. Hunt based the following recommendations on Carnegie Hill excavations in 1985–86 and the opening of the Beardog Hill carnivore den site from 1981–1990.

- Present the story of the origin of the Agate fossil beds using the facilities planned for the projected visitor center and through the development of exhibits at the actual quarry sites on Fossil Hills.
- Test the east side of Carnegie Hill for bone content. As of 1988, the eastern and northeastern area on Carnegie Hill had not been tested for fossils by either Dr. Hunt's research group or the earlier excavators. Exploring the eastern and northeastern sector would complete the exploration of the perimeter of the hill and supply useful confirmation of the results presented in Hunt (1988). Dr. Hunt (1988) proposed using motorized excavating equipment (backhoe, bulldozers) and a field team of 10 to 15 people to adequately open a small quarry in this area.
- Develop a brief scientifically accurate explanatory pamphlet or brochure to explain the origin of the bonebed and the geological and paleontological significance of the quarries. In 1988, the published literature distributed at the Monument contained misconceptions about the fossil beds.
- Make the preservation of the den site at Beardog Hill a top priority. Since 1988, the dens have been covered by heavy plastic sheeting that was buried by dirt as a temporary protection. Plants should be kept off this surface since roots may grow through the sheeting and into the fragile dens. The recommendation also called for surface dirt to be periodically renewed in order to maintain a thickness of several feet.
- Add a full-time professional vertebrate paleontologist to the Agate Fossil Beds National Monument staff to help manage the paleontological resources. A qualified paleontologist could become involved in the progressive development of the fossil resources at the Monument and present the paleontological story at Agate Fossil Beds National Monument accurately and with clarity and effectiveness despite a limited budget.

In 2003, Tonia Superchi Culver finished a report entitled "Paleontological Locality Management Database and Condition Reporting Project" for Agate Fossil Beds National Monument (Mark Hertig, Museum Curator, Agate Fossil Beds National Monument, written communication, May 1, 2007). All 28 known paleontological localities in the Monument were surveyed and a database was created to document their

localities and condition. The report is in two volumes. The first volume is an overview of the project and site localities, and the second volume contains the restricted database with pictures and maps.

Carolyn Wallingford in the NPS Midwest Regional Office has been working on an Automated National Catalog System (ANCS) fossil database, and she has consulted Dr. Hunt and his colleagues during this inventory (Dr. Robert Hunt, written communication, December 15, 2008). As of summer 2008, the park did not have a comprehensive fossil taxa list (Jason Kenworthy, NPS, written communication, September 8, 2008).

According to Dr. Hunt, the two areas on the Monument that are most sensitive to weathering and erosion are the carnivore den site on Beardog Hill and the *Stenomylus* Quarry, especially the upper level on the south side of *Stenomylus* Hill (Dr. Robert Hunt, written communication, December 15, 2008).

Beardog Hill

The carnivore den site on Beardog Hill was considered to be the most threatened by erosion, weathering, and occasional vandalism in 1988 (Hunt 1988). One protection/preservation plan calls for a small building to be constructed over the site (Dr. Hunt, written communication, December 15, 2008). When the site was closed in 1990, sheet plastic was laid over the site. The plastic was buried by approximately 0.2 m (0.5 ft) of soft dirt, pending construction of the building.

Fossil Hills (Carnegie Hill and University Hill)

Today, the collection of fossils from the Monument is largely composed of fossils that weather from the quarries on Carnegie Hill. These fossils are conserved in the visitor center, an appropriate strategy for this material as long as the quarry producing these bones is noted. Most of the bones come from the quarry dumps that continue to erode and yield fossils left behind by the earlier excavators rather than from the actual bonebed (Dr. Robert Hunt, written communication, December 15, 2008). However, interpretations of the Tertiary environment and fossils come from the scientifically valuable material recovered from the main hills. This fossil material is conserved in three museums in the United States (Pittsburgh's Carnegie Museum, American Museum of Natural History in New York, and the University of Nebraska in Lincoln).

The historic quarries in the Monument are very accessible, and visitors are encouraged to visit the quarries. The Fossil Hills trail has been rerouted so that it is Americans with Disabilities Act (ADA) accessible. Numerous bone fragments can be found in and around the quarries (fig. 7). Visitors often pile them into "bone cairns," which park staff subsequently dismantle (Jason Kenworthy, NPS, written communication, September 8, 2008). The quarries are not monitored, and visitors may easily remove bone fragments. However, there is no documentation that such fossil theft occurs at the park.

Stenomylus Quarry

Prior to the *Stenomylus* Quarry becoming part of Agate Fossil Beds National Monument, expeditions removed fossils, and gave or exchanged specimens with at least 32 U.S., Canadian, and European institutions (Knudson 2004). In 2003 the first comprehensive report documenting past recoveries from the Agate Springs Quarries and investigating the detailed paleoecological and depositional environment of the *Stenomylus* site was prepared. Culver's 2003 report documented the need for well designed paleoecological and paleontological research at the *Stenomylus* Quarry as well as appropriate methods of protecting exposed fossil remains (Knudson 2004). Another researcher, Susanne J. Miller, has continued to study the *Stenomylus* Quarry, her report (which includes an overview, management plan, and database) is still in draft form (Mark Hertig, Museum Curator, Agate Fossil Beds National Monument, written communication, May 1, 2007).

The *Stenomylus* Quarry consists of two stratigraphic levels of small camels whose fossils continue to erode from the soft sandstone at the site (Dr. Robert Hunt, written communication, December 15, 2008). For many years, Dr. Hunt and his colleagues have been interested in the higher stratigraphic level of the *Stenomylus* Quarry. The fossils in this formation are scientifically important and warrant protection and careful monitoring for new material eroding from this site. Dr. Hunt and his research group have collaborated with park staff and identified the most critical area for monitoring. This site also may be documented in Miller's pending report.

According to Dr. Hunt, optimal management of the *Stenomylus* Quarry would involve periodically monitoring the fossils eroding from the sandstone and having an experienced paleontologist collect and transfer them to the collection in the visitor center. As long as the site remains closed to the public it is not expected to produce a significant amount of fossil material. For this reason the monitoring efforts are not expected to become burdensome to Monument staff.

Paleontology and Geology Research

Dr. Hunt's current research program involves completing a publication on the geology and paleontology of the main Fossil Hills and the Monument as it relates to the geology of the surrounding region. The geology and paleontology of Agate Fossil Beds National Monument is an integral part of the Cenozoic geology of northwest Nebraska and southeast Wyoming. Dr. Hunt plans to submit this publication by the end of 2009. The report is based on the two contract reports completed for the NPS in 1984 and 1988 and on Dr. Hunt's excavations from 1981 to 1990.

In addition, park collections contain fossils in their original field jackets. In a 1997 internal memorandum, Rachel Benton (NPS Badlands National Park) commented that these jackets should be opened and identified by a paleontologist. Two sources of paleontology expertise that might address these jackets include Dr. Hunt at the University of Nebraska and the South Dakota School of Mines and Technology (Jason

Kenworthy, NPS, written communication, September 8, 2008).

Interpretation and Display of Paleontological Resources

Interpreting the Tertiary ecosystem of the Great Plains, Tertiary climate change, and Tertiary mammalian evolution are all ongoing areas of study and provide important information for the interpretive staff at Agate Fossil Beds National Monument (Janis 2001, Dr. Robert Hunt, Jr., written communication, December 15, 2008). Dr. Hunt's research into the waterhole ecosystem and taphonomy is just one example of how the fossil research at Agate Fossil Beds National Monument is shaping a more detailed understanding of the Miocene environment and climate (Hunt 1990).

A cooperative effort between the University of Nebraska and the NPS Midwest Region resulted in the design and installation of a diorama and accompanying exhibits in 1997 that interpret the waterhole bonebed and explain the research methods used in the excavation (fig. 6). The diorama and exhibits reflect the science used to interpret the Miocene environment at the time of the death event that produced the Agate bonebed.

Agate Theft

Agates and other mineral specimens are non-renewable resources that require park protection. Collecting, rockhounding, and gold panning of rocks, minerals, and paleontological specimens, for either recreational or educational purposes is generally prohibited in all units of the National Park System (36 C.F.R. § 2.1(a) and § 2.5(a)). Violators of this prohibition are subject to criminal penalties.

As with exposed fossil materials at the quarries, visitors have easy access to the agates in the Monument. Many visitors come to the park expecting to collect agates, especially moss agate, since agate collecting is a popular and legal activity in the U.S. Forest Service Oglalla National Grassland, north of the park (Jason Kenworthy, NPS, written communication, September 8, 2008). The number of agates removed from the Monument has not been documented and it is unclear how large a problem mineral theft is for the Monument. Nevertheless, improving visitor education regarding the prohibition against collecting may help to eliminate mineral theft.

Rockfall

Signs warning visitors of rockfall hazards at University and Carnegie Hills have been installed (fig. 8). Overhanging cliffs pose a potential rockfall hazard for researchers working along the lower part of the hills and visitors who have easy access to the quarries. In the past, *in situ* exhibit cases covered exposed bones at Carnegie Hill. However, these were removed because they were subject to vandalism and rockfall damage (Jason Kenworthy, NPS, written communication, September 8, 2008).

Oil and Gas

Agate Fossil Beds National Monument is off-limits to oil and gas production. To date, exploration for conventional oil and gas resources has had very limited results in the area and Agate Fossil Beds is not known to overlay unconventional resources (oil shale, gas shale, coal bed methane etc.). However, there is a low probability that the Monument may experience some minor impacts from oil and gas development on adjacent lands in the future.

On the Nebraska panhandle, the largest oil fields are found in Kimball County and Cheyenne County, two counties that border Colorado. No major oil fields are found in Sioux County, but in 2007, two oil wells in Sioux County produced 981 barrels of oil (table 1). These wells produced oil from Pennsylvanian reservoirs and are located approximately 29–32 km (18–20 mi) south of the Monument. No gas was produced from the two wells. Two other wells have been temporarily abandoned since 2005. No drilling permits were issued in 2004, 2005, 2006, or in January 2007 for Sioux County.

Of the 234 oil and gas exploration wells that have been drilled in Sioux County, only four wells have been drilled in the same township and range as Agate Fossil Beds National Monument (table 2). The most recent wells were drilled in 1969. These four wells, along with fourteen other wells drilled in adjacent townships and ranges, did not find any oil or gas and were abandoned.

In 1938, Union Oil Company drilled the Agate No. 15-1 on the Agate anticline, an east-to west- trending fold with gentle dips of 1° to 3° (Noble 1939). The well originated in Upper Harrison beds and drilled to a depth of 2,087 m (6,846 ft), bottoming in Pennsylvanian-age calcareous shales and dolomitic limestones.

Cretaceous strata were encountered in the Agate 15-1 well from 1,208 m (3,635 ft) to 1,574 m (5,165 ft). Although the target formations are uncertain in the other three wells, comparison of drilling depths of the four wells with regional subsurface geologic maps and the drilling depth of the Agate 15-1 suggests the target reservoirs for the Agate 15-1 were in Cretaceous strata (Noble 1939; Harms 1966; Graham 1996, 2000).

Although the probability of future exploration seems low, if it occurs there may be impacts to the Monument's viewshed. These impacts could include road dust and visible drilling derricks, they would likely be temporary and are not expected to impact paleontological resources at the Monument.

Figure 7. Bone fragments litter the ground in the quarries at Agate Fossil Beds National Monument, Nebraska. As of this report, the Monument does not have a comprehensive paleontology inventory. Photograph courtesy of Jason Kenworthy, NPS.

Figure 8. Signs warn of rockfall potential at Agate Fossil Beds National Monument. Photograph courtesy of Jason Kenworthy, NPS.

Table 1. Oil production from two wells in Sioux County, Nebraska, for 2005–2007.

Operator	Petrowest Energy Co Inc. & Sunburst Inc	Petrowest Energy Co Inc. & Sunburst Inc
Well name	Bird-Corman 11-16-2x	Laucomer 13-8
API well number	26165211350000	26165211380000
Location (sec/T/R)*	sese11/T25N/R56W	nwsw8/T25N/R55W
Date drilling started	12/15/85	10/10/86
Date completed	2/28/86	12/4/86
Ground elevation#	4696	4712
Total feet drilled	7850	7810
Elevation at total depth	-3154	-3098
Age of reservoir	Pennsylvanian	Pennsylvanian
Oil produced in 2005	1,366 barrels	823 barrels
Oil produced in 2006	905 barrels	371 barrels
Oil produced in 2007	741 barrels	240 barrels

* Location is written in quarter-quarter section, township (T), range (R) format.
# Elevations are given in feet relative to mean sea level

Table 2. Oil and gas exploration wells drilled in Township 28 North, Range 55 West, Sioux County, Nebraska.

API well no.	Operator	Well name	Section location	Date PA*	Ground elevation (ft)	Total feet drilled	Elev. at total depth (ft)
26165210430000	K&M Associates	Skavdahl 1	nene2	5/22/69	4354	4616	-262
26165210610000	King Resources Co	Cherry 1-28	swsw28	11/5/69	4561	5100	-539
26165050690000	Union Oil of California	Agate 15-1	nwse15	4/26/38	4694	6846	-2152
26165050710000	Currently unassigned	Cook 1	ne15	11/15/20	4520	4554	-34

* PA: Plugged and Abandoned

These wells did not discover hydrocarbons. Agate Fossil Beds National Monument is located in sections 3, 4, 5, 8, 9, 10, and 12 of Township 28 North, Range 55 West

Geologic Features and Processes

This section describes the most prominent and distinctive geologic features and processes in Agate Fossil Beds National Monument.

Tertiary Climate Change and Mammalian Evolution

The Tertiary Period began the 'Age of Mammals.' The Tertiary was also a time of dramatic global climate change (fig. 9). Mammalian faunas from the Tertiary Period reflect the division between the 'hot house world' of the earliest Tertiary (Paleocene and Early Eocene), which was a continuation of the warm global temperatures and ice-free world of the Mesozoic, and the 'ice house world' of the later Tertiary to Recent (Janis 2001). In the early Tertiary, lush subtropical jungles—filled with palm trees—existed throughout much of western North America. By the Miocene, the climate was too cold and dry to support the jungle ecosystem. A savannah ecosystem developed with isolated scrubby trees, shrubs, and early grasslands.

The Miocene saw an explosive diversification of mammal groups in response to a drying climate and the opening of forests into savannahs. Agate Fossil Beds National Monument provides exceptionally preserved evidence of the savannah and grassland ecosystems as well as the Miocene fauna adapted to these ecosystems. In addition, five other NPS units in the western United States contain significant collections of Tertiary fossils that help document this global climate change and its effect not only on global ecosystems but also on mammalian evolution (fig. 9) (Kenworthy 2009).

Appearing first in the latest Triassic (fig. 12), mammals remained small (the largest was about the size of a house cat) throughout the Mesozoic. But with the demise of the dinosaurs at the end of the Cretaceous, mammals radiated into a great variety of body sizes and morphological diversities. Briefly, mammals of the Paleocene largely represent 'archaic' groups, holdovers from the Mesozoic. Rodents and bats are known from the Late Paleocene, but Primates, Cetacea (whales), and the ungulate orders Artiodactyla (pigs, camels, antelope) and Perissodactyla (horses, rhinos) date from the earliest Eocene. Large predators also did not appear until the Late Eocene. Extinction of the archaic groups is likely related to declining temperatures and changing vegetation in the Eocene (fig. 9). Major extinctions occurred in the late Middle Eocene in North America and close to the Eocene/Oligocene boundary in Europe (Janis 2001).

A lack of faunal diversity represents the Oligocene world. Grasslands were still unknown. Extinct families belonging to modern orders, such as carnivorous amphicyonids ('beardogs') and nimravids ('false sabre-tooths'), represent the major types of modern mammals. Most Oligocene lineages were extinct, or on the wane, by the late Early Miocene.

The Miocene Epoch was marked by changes in existing plant and animal species such that many animals and plants developed features recognizable in some species today. The late Miocene, especially, was a boom time for mammals as they reached their highest diversity of any time in the Tertiary. As savannahs spread across higher latitudes, mammals appeared that were adapted for grazing, running, and burrowing. A popular notion suggests that the longer-legged herbivores like horses, camels, and pronghorns evolved in order to escape pack-hunting carnivores. However, the fossil evidence shows that long-legged carnivores did not appear until the Pliocene.

The large carnivores found in the Upper Harrison beds at Agate Fossil Beds National Monument support this argument. The carnivores *Ysengrinia* and *Megalictis* are both short-footed and short-legged, with lower limb segments equal to or shorter than the upper limb segments (Hunt 1990). Powerful musculature accompanies this limb anatomy. These carnivores seem better adapted to ambush their prey and win the struggle through strength rather than pursue their prey with speed and endurance.

The rise of the Rocky Mountains resulted in a rainshadow drying effect, and this has been traditionally held responsible for the later Miocene continental climate in western North America and the spread of grassland biomes, lands dominated by grasses rather than large shrubs or trees. However, declining levels of atmospheric carbon dioxide may also have contributed to floral changes and caused a major shift in the carbon cycle biochemistry of grasses (from C_3 to C_4) at around 7 million years ago in the latest Miocene (Janis 2001). Drying was certainly a world-wide environmental factor, as evidenced by the desiccation of the Mediterranean Sea in the latest Miocene. Whatever the reasons, global climate change may be associated with the major Late Miocene extinctions of mammal faunas (Janis 2001).

By the start of the Pliocene, an Arctic ice sheet had formed and tundra and taiga vegetation were established. The emergence of the Isthmus of Panama produced a change in ocean currents which then triggered a profound cooling event approximately 2.5 million years ago. Glacial ice advanced and retreated from both poles several times during the period that followed.

The key to understanding mammalian evolution lies in understanding Tertiary environmental changes. Differences between early Tertiary and present-day mammals are largely the result of a change from equable, globally tropical conditions to a cooler, drier, and more climatically zoned world. Agate Fossil Beds National Monument offers a snapshot, or window, into the semiarid continental interior of North America during the Early Miocene. The sedimentary strata, faunal diversity, and paleoenvironments at Agate Fossil Beds

offer an extraordinary view into the changing global climate of the Tertiary and mammalian evolutionary history (Hunt 1990). Past and continuing research on the Miocene fauna discovered at the Monument provides insights about the fauna morphology as well as the community and ecosystem in which they lived.

Mammalian Fossils

The most prominent and unique features in Agate Fossil Beds National Monument, and the reason the Monument was established, are Tertiary (Miocene) vertebrate fossils and the corkscrew burrows, called *Daemonelix* (fig. 4). Excavations in University Hill and Carnegie Hill and in the isolated *Stenomylus* Quarry have resulted in an outstanding collection of mammalian fossils. The youngest fossils at Agate Fossil Beds National Monument are those found in the beardog dens discovered at Carnegie Hill. The beardogs are younger than the fauna from the upper and lower bonebeds. The small *Stenomylus* are older than the fauna discovered in the bonebeds, and the *Paleocastor* found in the *Daemonelix* burrows is the oldest Miocene fossil at Agate Fossil Beds National Monument.

Beardog Hill

Agate Fossil Beds National Monument contains the oldest evidence of large carnivore denning behavior found anywhere in the world. Excavations in the 1980s in Carnegie Quarry 3 at Beardog Hill resulted in the discovery of a carnivore den community whose origin was entirely different from the main fossil quarries on Carnegie and University hills (Hunt 1988, 1990). The dens are burrowed into the sediment fill of the waterhole and have produced remains of two species of amphicyonid beardogs, two species of mustelids, and a small canid. This site at Agate Fossil Beds National Monument is the oldest den community of carnivores known in the fossil record and allows a rare glimpse into the ecology of the carnivore community during the Early Miocene (Hunt 1990).

The largest carnivore found in the dens is the beardog *Daphoenodon*, which is the size of a wolf (fig. 10). The beardog present in the greatest numbers in the burrows is *Daphoenodon superbus*. A rare temnocyonine beardog was found less than 2 m (7 ft) from a male *Daphoenodon* skeleton but segregated in its own burrow. The only larger carnivore known from this time is the beardog *Ysengrinia*, which is about the size of a large black bear. *Ysengrinia* has not been found in the dens, but its bones have been found in the lower bonebed and other nearby sites.

The smaller carnivores found in the dens include the mustelids (*Promartes, Megalictis*) and canids (*Tomarctus*, *Phlaocyon*) (Hunt 1988, 1990). Most of the identifiable mustelid bones belonged to the large wolverine-like mustelid *Megalictis*. *Promartes* is a smaller marten-size mustelid. *Tomarctus* and *Phlaocyon* are small fox-size canids.

Fossil Hills

The 3 km (2 mi) Fossil Hills Trail leads from the visitor center to University and Carnegie hills (pictured on the cover of this report). The first excavations at University Hill and Carnegie Hill in the early 20th century uncovered large numbers of bones of the small rhinoceros *Menoceras arikarense* and a reasonably good sample of isolated bones of the chaliocothere *Moropus elatus*. The most striking discoveries inlcude a nearly complete skeleton of a large chalicothere and two superb skeletons of the huge entelodont *Daeodon hollandi*. These skeletons remain the most complete and best preserved skeletons of *Daeodon* ever found (Hunt 1988).

Carnegie Hill is the site of the principal fossil quarries for which Agate Monument is world famous. The lower bonebed at Carnegie Hill is the principal bonebed and contains skeletal remains of primarily two mammals: the small rhinoceros *Menoceras arikarense*, and the large chalicothere *Moropus elatus* (fig. 11). Rhinoceros bones number in the hundreds, but only 50–75 chalicotheres have been discovered. Two partial skeletons of a third mammal, the entelodont *Daeodon hollandi*, are present, but there are few bones from other mammals. Isolated, highly abraded bone fragments and teeth of horse, camel, oreodont, and carnivore are scattered through the bonebed, but skeletal remains belonging to mammals other than the small rhinoceros, chalicothere, and entelodont are extremely rare (Hunt 1990). Bone density commonly exceeds 100 bones per square meter within the central part of the lower bonebed. In the peripheral areas, bone density averages about 40 bones per square meter, excluding barren areas of the quarry floor.

The bones are generally disarticulated, but one of the rare entelodont *Daeodon* skeletons was partially articulated when it was discovered. The skull, jaws, and vertebral column were nearly intact and the ribs, sternum, girdles, and limbs were nearby (Hunt 1990).

Analysis of such death-assemblage characteristics as spatial orientations of the bones, proximity of skeletons, bone sorting by size and density, and bone abrasion suggest that the animals in the lower bonebed underwent little or no fluvial transport as carcasses. Rather, evidence indicates that the animals probably walked into a waterhole and died at or near the places where their bones were found (Hunt 1990).

Waterholes formed within wide shallow valleys carved into the grasslands of southwestern Wyoming and western Nebraska by ephemeral streams. The upper bonebed at Carnegie Hill is restricted to an area extending from the west bank of the ancient river channel a short distance eastward into the center of the waterhole. The upper bonebed at Carnegie Hill contains fewer rhinoceros and chalicothere bones than the lower bonebed and may have resulted from redistribution of skeletal remains found on the west bank of the former channel.

Stenomylus Quarry

There is no public access to the *Stenomylus* Quarry. The tiny gazelle-camel *Stenomylus* is less than 0.6 m (2 ft) tall at the shoulder and looks much like the living African antelope called the gerenuk (fig. 5).

Daemonelix

The 1.6 km (1 mi) *Daemonelix* Trail leads to a *Daemonelix* burrow encased in plexiglass (fig. 4). Bones of the dry-land beaver, *Paleocastor*, were discovered in the bottom of *Daemonelix* burrows. The abundant spiral-shaped *Daemonelix* burrows, some more than 2 m (6 ft) deep, suggest that these dry-land beavers lived in colonies, perhaps like prairie dogs do today (NPS 1980; Kiver and Harris 1999).

Vertebrate Tracks

Vertebrate tracks are documented at Carnegie Hill, University Hill, and at the *Stenomylus* Quarry. An interpretive wayside panel along the Fossil Hills Trail suggests that these tracks may have been made by entelodonts (Hunt 1992; Santucci et al. 2006).

Avian Fossils

Fossil birds that were collected in 1908 by field crews from the University of Nebraska were first identified and reported upon by Chandler (1995). The genera, and species collected from the Agate Fossil Beds are listed in the Map Unit Properties Table in this report. Agate Fossil Beds National Monument produced many holotype specimens, which became the type specimen for the species. Holotypes collected from Carnegie Hill include *Buteo ales*, *Boreortalis tantala*, and *Paractiornis perpusillus* (Chandler 1995). The holotype specimen for *Palaeastur atavus* comes from the *Stenomylus* Quarry (Chandler 1995). Other holotypes collected from the Upper Harrison beds in the Monument include *Palaealectoris incertus* and *Promilio efferus*.

The fossil birds of Agate Fossil Beds National Monument are significant for a number of reasons. First, some of the fossils represent new genera and species. Secondly, the birds can be used as environmental indicators of certain habitats and can be used to evaluate the health of the environment. In this fashion, the birds at Agate Fossil Beds National Monument support Hunt's (1990) interpretation of the Early Miocene environment as one with ephemeral stream channels, open plains, and riparian areas along the streams. Thirdly, the Miocene birds of Agate Fossil Beds represent a global avifauna that has only recently been recognized in a few other localities in Quercy, France; Messel, Germany; Green River, Wyoming; and the Naze in England (Chandler 1995).

Miocene Paleoenvironments

The stratigraphy at Agate Fossil Beds National Monument is a significant feature with regards to understanding Tertiary paleoenvironments. The Monument is located on the Hartville Table, a physiographic feature that offers nearly continuous outcrop over approximately 3,100 km^2 (1,200 mi^2) in southwestern Wyoming and western Nebraska (Hunt 1990). The sedimentologic, faunal, and taphonomic characteristics found in the Tertiary exposures, like the ones at Agate Fossil Beds National Monument (fig. 8), record a semiarid continental interior with seasonal climate characterized by sandy ephemeral or intermittent braided streams, interchannel plains mantled by fine-grained volcaniclastic loess, and shallow ephemeral holomictic lakes (lakes that experience complete mixing).

One excellent exposure that has been critical to defining the Miocene paleoenvironments of the region is found at Carnegie Hill (Hunt 1990). The lithologies, lithofacies associations, and biota of the Upper Harrison beds represent the following paleoenvironments, listed in stratigraphic order from oldest (bottom) to youngest (top) (Hunt 1990):

Paleoenv.	Lithofacies	Biota
Ephemeral Lake	Shallow lake	Aquatic invertebrates & plants
Interchannel Plain	Volcaniclastic loess with paleosols	Mammals (chiefly ungulates), partially articulated to fully disarticulated, widely dispersed.
Braided Stream	Fluvial channel & floodplain	
Waterhole	Intertongued pond marl & fluvial sandst	Mammal bone beds. Aquatic invertebrates Carnivore dens.

Furthermore, detailed analysis of the waterhole has revealed two distinct bone layers within the ephemeral channel axis. The pond marl-fluvial sandstone lithofacies has been subdivided into four sedimentation units (A through D) (Hunt 1990). The sedimentation units can, in turn, be grouped into two sedimentation events (A–B, C–D). Each sedimentation event consists of a marl overlain by a fluvial sandstone tongue. The primary lower bonebed at Carnegie Hill is found within sedimentation unit A while the upper bonebed is found in unit C.

World renowned mammalian bonebeds are preserved at Agate Fossil Beds National Monument. These tuffaceous waterhole muds that intertongue with fluvial volcaniclastic sediments are the locus of major mammalian bones belonging to chalicothere, rhinoceros, and entelodont. These outcrops and paleontologic resources at Agate Fossil Beds National Monument provide critical pieces to the Tertiary puzzle.

Volcaniclastic Sedimentation and Fossil Preservation

Volcaniclastic sedimentation was critical to the preservation of the terrestrial paleocommunities in the Upper Harrison beds (Hunt 1990). The mammalian communities of stream valley and interchannel plains would not have been preserved without the influx of enormous quantities of volcanic ash into the midcontinent during the early Miocene. Mid-latitude westerly winds blew pyroclastic material from as far away as the Basin-and-Range physiographic province into the continental interior where it mixed with sedimentary material eroded form the rising Rocky Mountains. Grassland vegetation probably played an important role in trapping the pyroclastic debris on the relatively level regional geomorphic surface.

Exposures such as the one at Carnegie Hill record the presence of shallow, wide, sandy, ephemeral to intermittent streams of low gradient and low sinuosity.

These streams traversed the plains, eventually filling with fine loessic (wind-blown) volcaniclastic sediment. Lacustrine limestones formed in ephemeral, shallow, holomictic lakes that occupied depressions in the interchannel plains. Almost all of these lacustrine limestones are enclosed within volcaniclastic loess. They would not have been preserved without the influx of volcanic detritus into the region (Hunt 1990).

Taphonomic reconstructions of the Agate bonebeds suggest that the death assemblages found at the waterholes developed over a period of months. Subsequent filling of the waterholes with fine-grained tuffaceous sediments took an equivalent amount of time (Hunt 1990). Without the volume of volcaniclastic sediments, the fossil record of these mammalian communities would be poorly represented.

Abundant volcaniclastic debris has also helped preserve the carnivore beardog den communities in the Monument. The burrows that made up the den complex are excavated in fine-grained volcaniclastic sandstone. Preservation of the den community at Agate Fossil Beds National Monument has helped researchers define the ecology of the predator community and the sudden death event that probably drowned the animals in the burrows. The presence of volcaniclastics illustrates the importance of these sediments in preserving the biota.

The prolonged, episodic introduction of fine-grained volcaniclastic detritus into the semiarid to arid continental interior provided the essential conditions for preservation of land mammals in all major environments (Hunt 1990). Bone material continued to decay and disintegrate in the seasonally dry climate, but the steady input of sediment ensured burial of some of this skeletal material. Because of the influx of volcaniclastics, Agate Fossil Beds National Monument provides a rare glimpse into both interchannel and stream-border environments. Exposures of such detail as are found at Agate Fossil Beds National Monument are not usually encountered in the terrestrial Cenozoic record.

Agates

The agates that give the park its name are found in a thin band along ash deposits just above the Miocene bonebeds. Although agates are well-known and appreciated for their polish and luster, their origin is complicated and less understood. In simple terms, silica-rich solutions fill cavities in a variety of rocks and precipitate chalcedony in the void. However, the actual process of agate formation is surprisingly complex.

One of the better host rocks for agates is the volcanic rock, basalt. Extruded onto the surface, basalt contains abundant water and carbon dioxide, which will bubble out and leave voids in the rock, a process analogous to the formation of Swiss cheese. The voids are then filled with hot fluids rising from deep within Earth. These fluids contain an abundance of dissolved silica. About 90% of an agate is quartz. The other 10% of an agate has the same chemical composition as quartz, silica dioxide, but a different structure that's known as 'moganite' (Heaney 2001).

An agate consists of banded layers of quartz and moganite and fibrous crystals of quartz that nucleate on the wall of the void and radiate inward like the spokes on a bicycle wheel. Agate fibers also twist or grow in a helical fashion, and it's the repeated change in crystal size, type, and direction that causes the characteristic banding patter of agates. The colors come from trace elements like iron or manganese. In addition, high concentrations of silica cause silica polymerization, which contributes to the oscillating or banding pattern.

Agates form close to the surface, at low pressures and temperatures, and can be found in dinosaur bones as well as volcanic rocks. With weathering, the encasing rock or bone is worn away, leaving a roundish, rough-coated lump that can be polished to its characteristic shine. At Agate Fossil Beds National Monument, the most desirable agate for collectors is a form called 'moss' agate. Moss agate may look like moss, but it does not contain organic matter and is usually formed from weathered volcanic rocks. Trace amounts of iron or chrome impart its characteristic green coloring and moss-like design.

Niobrara Valley and Niobrara River

Along with the fossils, agates, and a significant piece of Tertiary history, Agate Fossil Beds National Monument preserves an area of the High Plains that escaped glaciation during the Pleistocene Ice Age. The complex array of late Pleistocene and Holocene geomorphology, stratigraphy, and paleosols in today's Niobrara Valley record significant climatic variations during the past 12,000-15,000 years. Radiocarbon dates from current research in the Monument document thousand-year-(or less) fluctuations between warm and cooler climates and varying amounts of annual moisture.

The Niobrara River flows unconfined through the Monument, and its riparian zones of lush vegetation provide diverse habitats for both animal and plant communities. Riparian wetlands extend from the Niobrara River to ancient river terraces, breaks, and buttes.

Although flowing for only 6 km (4 mi) through the Monument, the river meanders and curves to create 18 km (11 mi) of riverbank. Because it is unconfined, the Niobrara River carves a broad floodplain and changes course relatively often. This creates a landscape of river twists and turns, oxbow ponds, and sloughs. Oxbow ponds are U shaped and form when an extreme curvature in the river channel is cut off from the main river, leaving only a neck of land between two parts of the stream.

The Niobrara River is the only continuously flowing water in Agate Fossil Beds National Monument. Ephemeral tributaries contribute water to the Niobrara River following a major rain event or during snowmelt. Flash floods may occur in these ephemeral streams, which may then become erosive and contribute large amounts of sediment to the river.

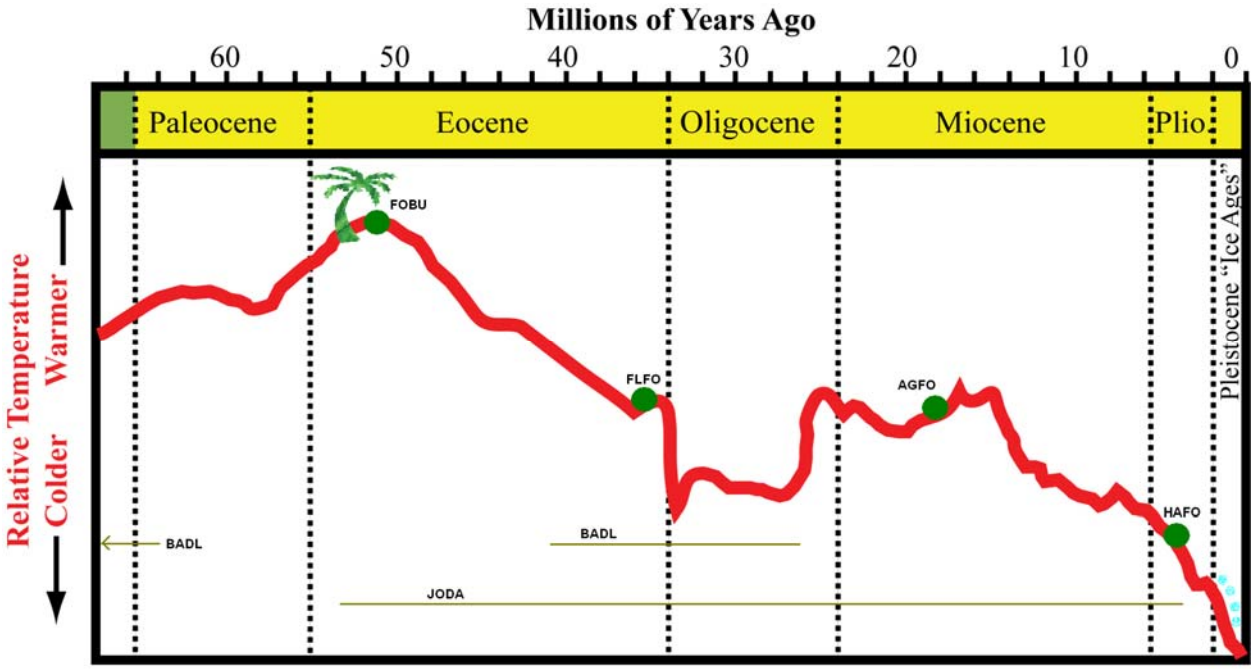


Figure 9. Relative global temperature change during the Tertiary Period. The red line is plotted from ocean temperature data from Zachos and others (2001). The NPS parks that are noted on the graph contain scientifically significant Tertiary fossils and include Agate Fossil Beds National Monument (AGFO), Badlands National Park (BADL), Florissant Fossil Beds National Monument (FLFO), Fossil Butte National Monument (FOBU), Hagerman Fossil Beds National Monument (HAFO), and John Day Fossil Beds National Monument (JODA). Graphic adapted from a John Day Fossil Beds National Monument exhibit and modified from Kenworthy (2009). Original data from Zachos and others (2001).

Figure 10. Skeletons of the wolf-size *Daphoenodon* beside the entelodont *Daeondon* (*Dinohyus*) from the diorama in the visitor center at Agate Fossil Beds National Monument, Nebraska. Photograph courtesy of Jason Kenworthy, NPS.

Figure 11. Mammalian bonebed as part of the diorama in the visitor center at Agate Fossil Beds National Monument. The display represents the lower bonebed at Carnegie Hill. The bonebed consists of bones primarily from the small rhinoceros *Menoceras arikarense* and the chalicothere *Moropus elatus*. Bones occur in intertongued calcareous tuff-fluvial sandstone deposited in an early Miocene waterhole that filled with fine-grained ash-rich sediment. Photograph courtesy of Jason Kenworthy, NPS.

Map Unit Properties

This section identifies characteristics of map units that appear on the Geologic Resources Inventory digital geologic map of Agate Fossil Beds National Monument. The accompanying table is highly generalized and is provided for background purposes only. Ground-disturbing activities should not be permitted or denied on the basis of information in this table.

Geologic maps facilitate an understanding of Earth, its processes, and the geologic history responsible for its formation. Hence, the geologic map for Agate Fossil Beds National Monument informed the "Geologic History," "Geologic Features and Processes," and "Geologic Issues" sections of this report. Geologic maps are essentially two-dimensional representations of complex three-dimensional relationships. The various colors on geologic maps illustrate the distribution of rocks and unconsolidated deposits. Bold lines that cross or separate the color patterns mark structures such as faults and folds. Point symbols indicate features such as dipping strata, sample localities, mines, wells, and cave openings.

Incorporation of geologic data into a Geographic Information System (GIS) increases the usefulness of geologic maps by revealing the spatial relationships to other natural resources and anthropogenic features. Geologic maps are indicators of water resources because they show which rock units are potential aquifers and are useful for finding seeps and springs. Geologic maps do not show soil types and are not soil maps, but they do show parent material, a key factor in soil formation. Furthermore, resource managers have used geologic maps to make connections between geology and biology; for instance, geologic maps have served as tools for locating sensitive, threatened, and endangered plant species, which may prefer a particular rock unit.

Although geologic maps do not show where earthquakes will occur, the presence of a fault indicates past movement and possible future seismic activity. Geologic maps do not show where the next landslide, rockfall, or volcanic eruption will occur, but mapped deposits show areas that have been susceptible to such geologic hazards. Geologic maps do not show archaeological or cultural resources, but past peoples may have inhabited or been influenced by various geomorphic features that are shown on geologic maps. For example, alluvial terraces may preserve artifacts, and formerly inhabited alcoves may occur at the contact between two rock units.

The geologic units listed in the following table correspond to the accompanying digital geologic data. Map units are listed in the table from youngest to oldest. Please refer to the geologic timescale (fig. 12) for the age associated with each time period. This table highlights characteristics of map units such as susceptibility to hazards; the occurrence of fossils, cultural resources, mineral resources, and caves; and the suitability as habitat or for recreational use.

The GRI digital geologic maps reproduce essential elements of the source maps including the unit descriptions, legend, map notes, graphics, and report. The following reference is source data for the GRI digital geologic map for Agate Fossil Beds National Monument:

Hunt, Robert M. Jr. 1988. *Geologic Map of the Agate Fossil Beds National Monument, University of Nebraska*, in Hunt, Robert M. Jr. 1988. University of Nebraska Paleonotological Excavations 1985–1986, Agate Fossil Beds National Monument: State Museum and Department of Geology, University of Nebraska. Scale 1:16,896. Report prepared for the Midwest Region, National Park Service.

The GRI team implements a geology-GIS data model that standardizes map deliverables. This data model dictates GIS data structure including data layer architecture, feature attribution, and data relationships within ESRI ArcGIS software, increasing the overall quality and utility of the data. GRI digital geologic map products include data in ESRI personal geodatabase and shapefile GIS formats, layer files with feature symbology, Federal Geographic Data Committee (FGDC)-compliant metadata, a Windows help file that contains all of the ancillary map information and graphics, and an ESRI ArcMap map document file that easily displays the map and connects the help file directly to the map document. GRI digital geologic data are included on the attached CD and are available through the NPS Data Store (http://science.nature.nps.gov/nrdata/).

Map Unit Properties Table

Age	Unit Name (Symbol)	Features and Description	Erosion Resistance	Suitability for Development	Hazards	Paleontological Resources	Cultural Resources	Mineral Occurrence	Habitat	Recreation	Geologic Significance
QUATERNARY (Pleistocene–Holocene)	Alluvium & Terrace (Qat)	Silt, sand & gravel. Thickness: 0- 15 m (0- 50 ft).	Low, especially during floods	Floodplain deposit	Flooding	None	Ancient campsites; potential Native American & pioneer sites; sites buried in floodplain?	Sand & gravel	Riparian habitat & wetlands vegetation (cottonwoods, sedges, reeds, iris)	Hiking trails (Fossil Hills Tr & Devil's Corkscrew Tr); bird watching; Niobrara River	Niobrara River continues to carve its Holocene terrace
TERTIARY (Miocene)	Unconformity										
	Ogallala Group Runningwater Formation (Trw)	Non- marine light buff to orange sand, massive, often with local zones of carbonate cementation, & occasional lenses of crystalline gravel, sand & silt of fluvial origin. Thickness: 107 m (350 ft).	Moderate; mapped in the uplands N. of the Monument	Limited exposures in the monument	None documented	CARNIVORA: Procyonidae: *Edaphocyon*, *Bassariscus*. Canidae: *Pblaocyon, Cynarctoides*, *Tomarctus*, *Leptocyon*. Amphicyonidae: *Daphoenodon*, *Cynelos, Amphicyon*. Ursidae: *Cephalogale*. Mustelidae: *Potamotherium, Brachypsalis*, *Leptarctus, Oligobunis*. PERISSODACTYLA: Rhinocerotidae: *Menoceras*. *Chalicotheriidae*. *Tapiridae*. Equidae: *Parahippus pawniensis, Parahippus cognatus, Archaeohippus*, *anchitheres*. ARTIODACTYLA: Tayassuidae: *Desmathyus*. Anthracotheriidae: *Arretotherium*. Entelodontidae: *Dinohyus*. Moschidae: *Blastomeryx sp*. Dromonerycidae: *Aletomeryx, Barbouromeryx*. Oreodonts: *Merycochoerus*.	None documented; potential Native American & pioneer sites	None documented	Mixed grass prairie (western, slender, & crested wheat grasses; Blue grama grass; threadleaf sedge; needle & thread grass); cacti; cheat grass	Mapped N of Monument	World renown vertebrate fossils; much less pyroclastic debris than in formations of the Arikaree Group
	Unconformity										
	Arikaree Group Upper Harrison beds (now recognized as the informal "Anderson Ranch Fm.") (Thu)	Non- marine light gray to light brown fine sand & silt of pyroclastic origin, massive in its upper part within the monument area, & in its lower part often reworked by fluvial & aeolian processes into horizontally laminated & cross- stratified deposits, with buff to white lenses rich in mammalian fossils filling the base of local channels. Includes local dense freshwater limestones (Agate Limestone), volcanic ash & lithic pebble conglomerate. Locally, contains a prominent silica-cemented land surface (Agate paleosurface) at or near its top that is extensively burrowed & rich in root casts. Thickness: 90 m (300 ft).	Relatively high; forms resistant cliffs and flat-topped ridges	Hills of Thu contain fossil quarries; also exposed as narrow ridges	Potential rockfall	CARNIVORA: Canidae: *Pblaocyon, Cynarctoides*, *Tomarctus*. Amphicyonidae: *Daphoenodon, Ysengrinia, Cynelos*, temnocyonines. Ursidae: *Cephalogale*. Mustelidae: *Oligobunis, Promartes, Megalictis*. PERISSODACTYLA: Rhinocerotidae: *Menoceras, Diceratherium*. Chalicotheriidae. Tapiridae. Equidae: *Parahippus nebrascensis, Parahippus wyomingensis*, anchitheres. ARTIODACTYLA: Tayassuidae: *Cynorca, Desmathyus*. Hypertragulidae: *Nanotragulus*. Entelodontidae: *Daeondon* (*Dinohyus*). Protoceratidae: *Syndyoceras*. Camelidae: *Stenomylus*. Moschidae: *Blastomerys advena, Blastomerys alcotti*. Oreodonts: *Promerycochoerus, Merycochoerus*. FALCONIFORMES: *Buteo ales* GALIFORMES: *Boreortalis tantala, Palaealectoris incertus*, CHARADRIIFORMES: *Paractiornis perpusillus* Accipitridae indeterminate: *Palaeastur atavus*	Unknown	Agates	Plants that tolerate dry, rocky conditions (little blue stem grass, threadleaf sedge, sandhills muley & tufted milk vetch); also 3 species of cacti along rocky bluffs & trails (brittle, prickly pear, & ball cactus); 64 lichen species	Hiking trails lead to fossil quarries	World renown vertebrate fossils; University Hill & Carnegie Hill quarries
	Unconformity										

Age	Unit Name (Symbol)	Features and Description	Erosion Resistance	Suitability for Development	Hazards	Paleontological Resources	Cultural Resources	Mineral Occurrence	Habitat	Recreation	Geologic Significance
TERTIARY (Miocene)	Arikaree Group Harrison Fm. (Th)	Non- marine gray to dark gray fine sand of pyroclastic origin, massive, but locally reworked by fluvial & aeolian processes into horizontally laminated & cross- stratified deposits, & including throughout the monument the Agate Ash (KS 48). Combined thickness of Harrison, Monroe Creek, & Gering Formations: 30- 120 m (100- 400 ft) (Thaa = Agate Ash).	Relatively high due to stabilization by plant roots; low if disturbed	Forms gentle, grassy slopes probably suitable for development	None documented	CARNIVORA: Procyonidae: *Zodiolestes*. Canidae: *Pblaocyon*, *Tomarctus*, *Leptocyon*. Amphicyonidae: *Daphoenodon*, temnocyonines. Mustelidae: *Oligobunis*, *Promartes*. PERISSODACTYLA: Rhinocerotidae: *Menoceras?*, *Diceratherium*. Chalicotheriidae. Tapiridae. Equidae: *Parahippus wyomingensis*, anchitheres. ARTIODACTYLA: Tayassuidae: *Desmathyus*. Hypertragulidae: *Nanotragulus*. Entelodontidae: *Dinohyus*. Protoceratidae: Syndyoceras, Protoceras. Camelidae: *Stenomylus*. Oreodonts: *Promerycochoerus*. *Paleocastor* & *Daemonelix* burrows.	Potential Native American & pioneer sites; possible artifacts from Cook Ranch	None documented	Mixed grass prairie (western, slender, & crested wheat grasses; Blue grama grass; threadleaf sedge; needle & thread grass); cacti; cheat grass	Hiking trails; bird watching	World renown verbetrate fossils; *Stenomylus* Quarry; *Paleocastor* fossils & *Daemonelix* burrows
	Arikaree Group Monroe Creek Fm.	Gray, brownish- gray, & grayish brown volcaniclastic silty very fine- grained sandstones; carbonate- cemented horizons common; often mapped with Harrison Fm.	Low	Not exposed in Monument	Not exposed in Monument	Not exposed in Monument	Not exposed in Monument	Not exposed in Monument	Not exposed in Monument	Not exposed in Monument	Air- fall & wind blown detritus; originally deposited on low relief topography
TERTIARY (Oligocene)	Arikaree Group Gering Fm.	Gray, brownish- gray, & grayish brown volcaniclastic fine- to medium- grained sandstones, silty sandstones, brown sandy silts, & local beds of ash, coarse sand, & fine gravel.	Low	Not exposed in Monument	Not exposed in Monument	Not exposed in Monument	Not exposed in Monument	Not exposed in Monument	Not exposed in Monument	Not exposed in Monument	Fills paleovalleys
	Unconformity										
	Arikaree Group Unnamed Lithic Unit (now known as the Sharps Fm) (Tl)	Non- marine light orange to light brown sand & silt of pyroclastic origin, massive, with frequent small vertically oriented carbonate concretions scattered throughout the unit. Thickness: unknown.	Moderate; exposed on upthrown block of normal fault	Limited exposures in monument – SE part of map	None documented	None documented in monument; vertebrate fossils have been discovered in the Sharps Fm. outside Agate Fossil Beds NM	None documented	None documented	Limited exposures	Limited exposures	Pyroclastic eolian deposits; ash- fall from volcanic eruptions as far away as the Great Basin
	White River Group Brule Formation	Brown Siltstone beds: brown volcaniclastic sandy siltstones & silty very fine- grained sandstones; local mudstones; correlative zone of ash beds in lower part. Whitney Mbr: brown volcaniclastic siltstones; local mudstones & fine- to medium- grained sandstones; two regionally correlative ash beds Orella Mbr: brown to greenish- gray volcaniclastic mudstones & siltstones; upper part has fine- to medium- grained sandstones & thinly bedded mudstones; regionally correlative ash bed in lower part.	Low; mudst. & siltstones less resistant than sandstones	Not exposed in Monument	Not exposed in Monument	Not exposed in Monument	Not exposed in Monument	Not exposed in Monument	Not exposed in Monument	Not exposed in Monument	West- east trending paleovalley fill deposit
	White River Group Chadron Formation	Gray & greenish- gray bentonitic claystones & mudstones; fine- to coarse- grained sandstones & local conglomerates underlie the claystones- mudstones. Combined thickness of Brule Fm. & Chadron Fm.: 170- 180 m (550- 600 ft)	Low; mudst less resistant than sandstones	Not exposed in Monument	Not exposed in Monument	Not exposed in Monument	Not exposed in Monument	Not exposed in Monument	Not exposed in Monument	Not exposed in Monument	Fills complex pattern of paleovalleys
	Unconformity										
CRETACEOUS	Pierre Shale Fm.	Black & gray clay shale with thin sandstone beds in upper part. Thickness: 760+ m (2500+ ft).	Low	Not exposed in Monument	Not exposed in Monument	Not exposed in the monument; marine invertebrate (clam) fossils & fish scales are known in the Pierre Shale outside Agate Fossil Beds NM	Not exposed in Monument	Not exposed in Monument	Not exposed in Monument	Not exposed in Monument	Remnants of marine environments within the Cretaceous Western Interior Seaway

Geologic History

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

This section provides a more detailed description of the structure, tectonics, depositional and erosional history, and general stratigraphy of Agate Fossil Beds National Monument and surrounding area. The sedimentary rock layers exposed in the Monument are only a fraction of the thick sediment package that was deposited in the high Great Plains physiographic region. These sedimentary rocks overlie an ancient Precambrian crust consisting of igneous and metamorphic rocks, similar to those exposed in the core of the Black Hills in South Dakota. A more detailed Precambrian history of this region may be found in the GRI report for Mount Rushmore National Memorial (Natural Resource Report NPS/NRPC/GRD/NRR-2008/038).

Pre-Tertiary History

The Precambrian basement rocks that are buried beneath the Monument are billions of years old and form the North American craton (fig. 12). The rock record of the Paleozoic Era (251–542 million years ago) is also buried beneath the Monument. The Agate 15-1, the deepest of the four oil and gas exploration wells drilled near Agate Fossil Beds National Monument (table 2), encountered the top of the Paleozoic strata at a depth of 1,649 m (5,409 ft) (Nebraska Oil and Gas Commission website, http://www.nogcc.ne.gov).

Since the Precambrian, shallow seas have advanced and retreated many times onto the North American continent. The Paleozoic sedimentary rocks are dominated by limestone formed from calcareous sediments deposited in these shallow seas (fig. 13). Uplift of the Ancestral Rocky Mountains in the late Paleozoic generated large quantities of clastic sediments (mostly sand and clay) that filled basins across the interior of North America (fig. 14).

Additional terrestrial sediments were deposited across the region during the Triassic and Jurassic Periods of the Mesozoic Era (fig. 12). By the Early Triassic, the process of plate tectonics had assembled all of the large landmasses around the globe into one large supercontinent, Pangaea. Soon after forming, however, Pangaea began to split apart and the lithospheric plates moved away from one another. Rivers draining westward from the Appalachian region flowed into a low, subdued mid-continent landscape. On the west coast of North America, the Cordilleran mountain belt was actively developing, and ongoing volcanism and mountain building began the event that would lead to the formation of the vast Western Interior Seaway in the Cretaceous Period (fig. 15). The Pierre Shale, which is exposed in the region but not in the Monument, is a marine shale that was deposited in this seaway that connected the early Gulf of Mexico with the Arctic Ocean. After the seas withdrew in the early Tertiary, the region was close to sea level and a humid, subtropical climate prevailed.

Tertiary Period: Paleocene–Oligocene

As the Cretaceous Period neared an end, the seas gradually receded from the continent's interior. The offshore marine Pierre Shale was overlain by nearshore marine sediments that are not exposed in the Monument. The Laramide Orogeny, which began in the Late Cretaceous, continued into the Eocene Epoch and resulted in the rise of the Rocky Mountains, including the Black Hills.

The oldest rocks exposed at Agate Fossil Beds National Monument are volcanic pyroclastic deposits from the Oligocene Epoch, which began 34 million years ago (fig. 12). Limited exposures of these Oligocene deposits may be found in the southeastern part of the Monument. Oligocene rocks are abundant at Badlands National Park, 210 km (130 mi) northeast of Agate, and Scotts Bluff National Monument, approximately 80 km (50 mi) to the south, but at Agate Fossil Beds National Monument, they are mostly buried beneath younger Miocene deposits.

In the Oligocene, eastward flowing rivers deposited vast sheets of sediment over the Great Plains, filling in structural basins that formed adjacent to the Rocky Mountains during the Laramide Orogeny (Kiver and Harris 1999). The Eocene-Oligocene transition probably records a more dramatic change in climate and habitat than any other time in the Tertiary. Prior to the Oligocene, the region was close to sea level with a humid, subtropical climate (Swinehart et al. 1985; Hunt 1990). During Oligocene and Miocene time, vegetation transitioned from subtropical forests savannah ecosystems with grasslands dotted with abundant patches of trees and shrubs.

Ash-fall deposits and alluvial sediments of the Oligocene Sharps Formation are exposed in the upper block of a normal fault in the southeastern portion of Agate Fossil Beds National Monument (Hunt 1988). The ash-fall deposits are associated with tremendous ignimbrite-style volcanic eruptions in the Great Basin region, which impacted western Nebraska and the Dakotas at this time. The tuffaceous sandstones, stream channel sand and floodplain mud deposits in the Sharps Formation are typical of steppe or even desert-like conditions. In western Nebraska, low-relief landscapes reflected the continuous aggradation, or build-up, of pyroclastic eolian material.

This continuous aggradation was interrupted in the late Oligocene by widespread fluvial erosion. Erosion produced the unconformity between the Sharps Formation and the overlying Gering Formation (Map Unit Properties Table). Two major west-to-east-trending drainage systems and at least one smaller drainage system developed in western Nebraska (Swhinehart et al. 1985). River valleys that cut into the underlying Sharps Formation ranged from 30–91 m (100 –300 ft) deep. The west-to-east trend of these river systems represents a significant shift from the south-easterly trend of the region's major early Oligocene paleovalley. These river valleys were later filled with sediments eroding from highlands to the west. The Gering Formation records the complex alluvial and eolian deposits that filled these paleovalleys.

Tertiary Period: Miocene Epoch

As a result of plate tectonic interactions at the western margins of North America during the Tertiary, voluminous amounts of volcanic ash were blown eastward into the continental interior. The volcaniclastic wind-blown (loess) deposits formed a thick, sheet-like geometry over large geographic areas of the interior and contributed significantly to the preservation of important terrestrial biotas of vertebrate, invertebrate, and plant remains in the fossil record (Hunt 1990).

Miocene volcaniclastics (Monroe Creek and Harrison Formations) accumulated on flat, gently east-sloping geomorphic surfaces that extended from the front ranges of the Rocky Mountains into the midcontinent (fig. 16). Rather than the deep paleovalleys associated with pre-Gering erosion, regional erosion produced low paleotopographic relief and low angle side slopes between plains and streams. In the semi-arid climate, water was probably seasonally available and would fill channels during times of rainfall, pools along intermittent or ephemeral stream courses, and shallow lakes on the open plains.

Like the savannas of East Africa today, the rich volcanic soils of the Miocene supported early grasses, which, together with small trees and bushes growing along shallow streams, were a ready food source for the great herds of plant-eating mammals and their predators. Many of the animals (such as chalicotheres, rhinoceros, entelodonts, beardogs, land beavers, camels, horses, and pocket gophers) thrived in this early Miocene climate and their numbers expanded to the capacity of the available food supply (Hunt 1981, 1990).

The plains of northwestern Nebraska and southeastern Wyoming were drier than the stream-border environment and supported grassland, possibly with a few sparse shrubs or low trees. Warm, shallow, holomictic lakes were present on the open plains between stream drainages. When the drainages became choked with volcaniclastic sediments and streamflow ceased, these lakes became the only source of water in the region. Water-dependent mammalian species were forced to ephemeral waterholes during times of drought where lack of forage led to mass deaths extending over intervals of months. A number of drought-resistant species, however, seem to have been little affected by dry conditions (Hunt 1990).

Research on grass species from the ancient savanna suggests that a major period of drought occurred in the Agate Fossil Beds area during the early Miocene about 19–20 million years ago (Hunt 1990). During a time of increasing aridity, the waterhole that would become the Agate bonebeds began to dry and volcanic ash and calcareous mud began to accumulate on the old channel floor. The ash and mud mixed with fine-grained sand at the west channel margin. The dead mammals decomposed and their bones were gradually buried. Falling water levels exposed bones at the periphery of the waterhole to subaerial weathering and additional scavenging and trampling. Other mammals, including huge entelodonts, trampled the bones that were accumulating in the deeper parts of the waterhole.

The lower bonebed was completely buried during a brief period of seasonal rainfall that rejuvenated streams and introduced fine ash-rich sand into the western margin of the waterhole. Fine ash and calcareous mud continued to accumulate over the remainder of the waterhole in the standing water that remained after the rains. The second bonebed formed when scavengers redistributed the skeletal debris left on the west bank of the waterhole after the first death event over the floor of the waterhole. This upper bonebed has less areal extent than the lower bonebed. Fine sand and ash gradually buried the upper bonebed, and mammals visiting the pond trampled the bones.

With the following wet season, streams, swollen with rainfall, overtopped their banks and carried fine sand over the waterhole, burying both upper and lower bonebeds. The pond dried after the wet season, and a soil developed over the bone deposit.

Research on the fossils and sedimentary rocks in the two bonebeds at Carnegie Hill suggests the following chronology of events at the waterhole (Hunt 1988, 1990):

1. Cut off from its master channel, a stream segment loses its vigorous streamflow and becomes a waterhole.
2. The waterhole attracts mammals whose normal deaths contribute some skeletal material. Their skeletons are heavily scavenged and subsequently abraded and polished on the floor and margins of the pond by the activity of other mammals coming to the waterhole.
3. A severe drought attracts the more water-dependent mammals, such as small rhinoceros and chalicotheres, to the local waterholes. They are reluctant to leave the vicinity of the waterhole and so forage for only a limited radius around the waterhole. When all edible vegetation is utilized, they die in and around the waterhole in large numbers from malnutrition. The waterhole, however, is not completely dry.
4. Carnivores and omnivores (entelodonts) scavenge the bones, and the disarticulated bones settle and decay into the carbonate mud and fine sand that slowly accumulates on the floor of the waterhole. As prolonged aridity in the region dries up other waterholes, water-dependent rhinoceros and

chalicotheres begin a slow persistent migration to the Agate waterhole where their deaths steadily add to the mass of carcasses available to scavengers. Daily disturbance of the sandy substrate by the hooves of ungulates gradually polishes and abrades the steadily accumulating bone residue. As the drought reaches its climax, even the scavengers migrate or die, which leaves the last carcasses and those in the more inaccessible parts of the waterhole largely untouched.

5. Renewed rainfall fills the waterhole. Fine ash sand from a nearby stream channel gradually fills the waterhole and covers the irregular surface of dried to moist carbonate mud and sand in which the lower bonebed is now buried. Mammals only infrequently visit the waterhole because numerous other water sources are available in the valley during this time.
6. The wet season ends and water again becomes restricted to isolated pools in the wide, shallow river valley. Mammals are again attracted to the standing water of the pond, rich in carbonate and populated by aquatic crustaceans and snails. The earlier scenario is repeated. Again, chalicotheres and rhinoceros are the principal species affected by the drought, and again deaths contribute skeletons to the deposit, only not in the numbers of the first death event. Skeletons on the west bank that have remained unburied from the first death event are scavenged and weathered and gradually worked eastward by animal activity to mix with the newer carcasses from recent deaths. The waterhole continues to evaporate accelerating carbonate precipitation and subsequent bioturbation by animal hooves.
7. Before the pond completely dries, rainfall returns. Sandy sediment is transported into the pond. The sand grades into the carbonate mud below and fills mammal tracks impressed into its viscous surface. In a relatively short time, fine-grained sand completely fills the waterhole. A soil develops over the abandoned channel segment and its bone-rich sediment fill.
8. Long after the channel segment is buried, a carnivore den community of beardogs develops along the margin of the channel fill. A series of dens are excavated in the soft sediments of the stream valley where the beardogs raise their young and find shelter from the temperature extremes of a semiarid plains environment deep within the continental interior. Small canid and mustelid carnivores later occupy the dens. A flood event marks the beginning of the wet season. The flood traps a number of beardogs in their dens, drowning young and old alike. Scavenged by other carnivores, their carcasses are eventually buried by fine ash transported into burrows by wind and water.

Landscape development in western Nebraska underwent a major change following deposition of the "Anderson Ranch Formation." Erosion during the last two thirds of the Miocene created a wide variety of drainage systems and paleovalleys of different sizes (Swinehart et al. 1985). Alluvial sediments of the Runningwater Formation fill a paleovalley about 24 km (15 mi) wide and as much as 98 m (300 ft) deep in eastern Sioux, southern Dawes, and northern Box Butte Counties. In contrast to formations in the Arikaree Group, the Runningwater Formation (and other formations in the Ogallala Group) contains much less pyroclastic debris.

Regional uplift following the Laramide Orogeny was accompanied by local faulting and folding in western Nebraska. The northeast to southwest trending Agate Fault and other faults in Sioux County cut the "Anderson Ranch Formation" and the Runningwater Formation (Hunt 1981; Swinehart et al. 1985). About 70 m (230 ft) of vertical displacement across the Agate fault has been measured in one locality outside of the Monument.

Post-Miocene History

Uplift during the last five million years elevated the High Plains to their current elevation of about 1,341 m (4,400 ft) above mean sea level (Kiver and Harris 1999). As the area rose, rivers and streams meandered across the plains and eroded the older deposits, forming the bluffs and valleys of today's landscape.

During the last 5 million years, erosion greatly exceeded deposition in western Nebraska so that little sedimentary record is available over most of the area. Erosional unconformities separate Pliocene sands and gravels from the underlying Miocene rocks and the overlying Quaternary sediments (Swinehart et al. 1985).

Global climate became much colder in the Pliocene (fig. 9). The Arctic ice sheet and changes to ocean currents, with the emergence of the Isthmus of Panama 2.5 million years ago, plunged Earth into a series of ice ages (fig. 17). During the wetter episodes of the Pleistocene Ice Age, the modern Niobrara River channel established its course. Silt, sand, and gravel continue to be eroded, transported and deposited by the Niobrara River, as it actively carves its Holocene terrace.

Eon	Era	Period	Epoch	Ma		Life Forms	North American Events
Phanerozoic (Phaneros = "evident"; zoic = "life")	Cenozoic	Quaternary	Holocene	0.01	Age of Mammals	Modern humans	Cascade volcanoes (W)
			Pleistocene	1.8		Extinction of large mammals and birds	Worldwide glaciation
		Tertiary	Pliocene	5.3		Large carnivores	Uplift of Sierra Nevada (W)
			Miocene	23.0		Whales and apes	Linking of North and South America
			Oligocene	33.9			Basin-and-Range extension (W)
			Eocene	55.8		Early primates	Laramide Orogeny ends (W)
			Paleocene	65.5			
	Mesozoic	Cretaceous		145.5	Age of Dinosaurs	**Mass extinction** Placental mammals Early flowering plants	Laramide Orogeny (W) Sevier Orogeny (W) Nevadan Orogeny (W)
		Jurassic		199.6		First mammals **Mass extinction** Flying reptiles	Elko Orogeny (W) Breakup of Pangaea begins
		Triassic		251		First dinosaurs	Sonoma Orogeny (W)
	Paleozoic	Permian		299	Age of Amphibians	**Mass extinction** Coal-forming forests diminish	Supercontinent Pangaea intact Ouachita Orogeny (S) Alleghanian (Appalachian) Orogeny (E)
		Pennsylvanian		318.1		Coal-forming swamps Sharks abundant Variety of insects	Ancestral Rocky Mountains (W)
		Mississippian		359.2		First amphibians First reptiles	Antler Orogeny (W)
		Devonian		416	Fishes	**Mass extinction** First forests (evergreens)	Acadian Orogeny (E-NE)
		Silurian		443.7		First land plants	
		Ordovician		488.3	Marine Invertebrates	**Mass extinction** First primitive fish Trilobite maximum Rise of corals	Taconic Orogeny (E-NE)
		Cambrian		542		Early shelled organisms	Avalonian Orogeny (NE) Extensive oceans cover most of North America
Proterozoic ("Early life")		Precambrian		2500		First multicelled organisms Jellyfish fossil (670 Ma)	Formation of early supercontinent Grenville Orogeny (E) First iron deposits Abundant carbonate rocks
Archean ("Ancient")				≈4000		Early bacteria and algae	Oldest known Earth rocks (≈3.96 billion years ago)
Hadean ("Beneath the Earth")				4600		Origin of life?	Oldest moon rocks (4–4.6 billion years ago) Earth's crust being formed
						Formation of the Earth	

Figure 12. Geologic time scale; adapted from the U.S. Geological Survey and International Commission on Stratigraphy. Red lines indicate major unconformities between eras. Included are major events in life history and tectonic events occurring on the North American continent. Absolute ages shown are in millions of years.

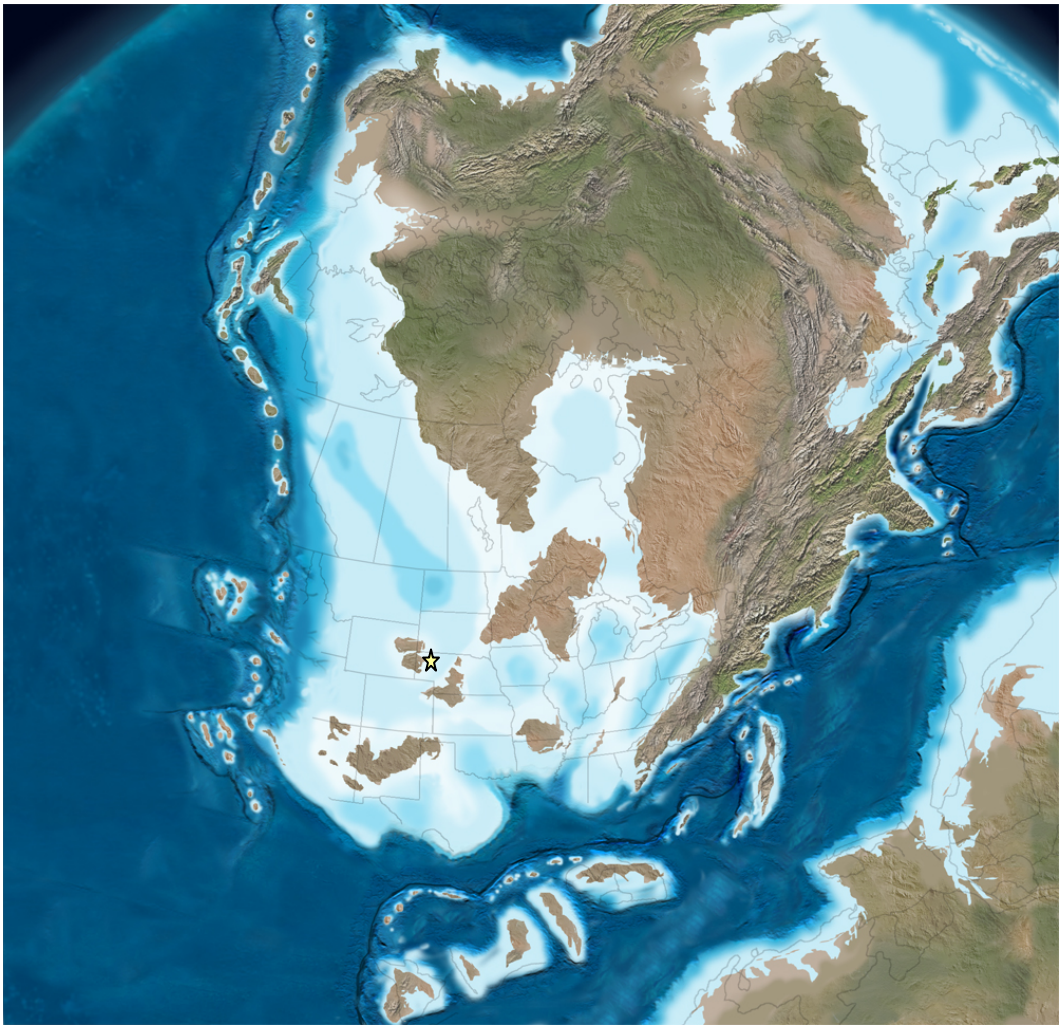


Figure 13. Paleogeographic map of the North American continent during the Late Devonian, approximately 360 million years ago, showing one time slice during the Paleozoic when the continental interior was inundated by marine environments. Agate Fossil Beds National Monument (yellow star) is located in the panhandle of western Nebraska. Subaerial topography is shown in shades of brown; shallow marine is light blue; deeper marine is dark blue. Map courtesy of Dr. Ron Blakey, Northern Arizona University, available at http://jan.ucc.nau.edu/rcb7/namD360.jpg (accessed December 22, 2008).

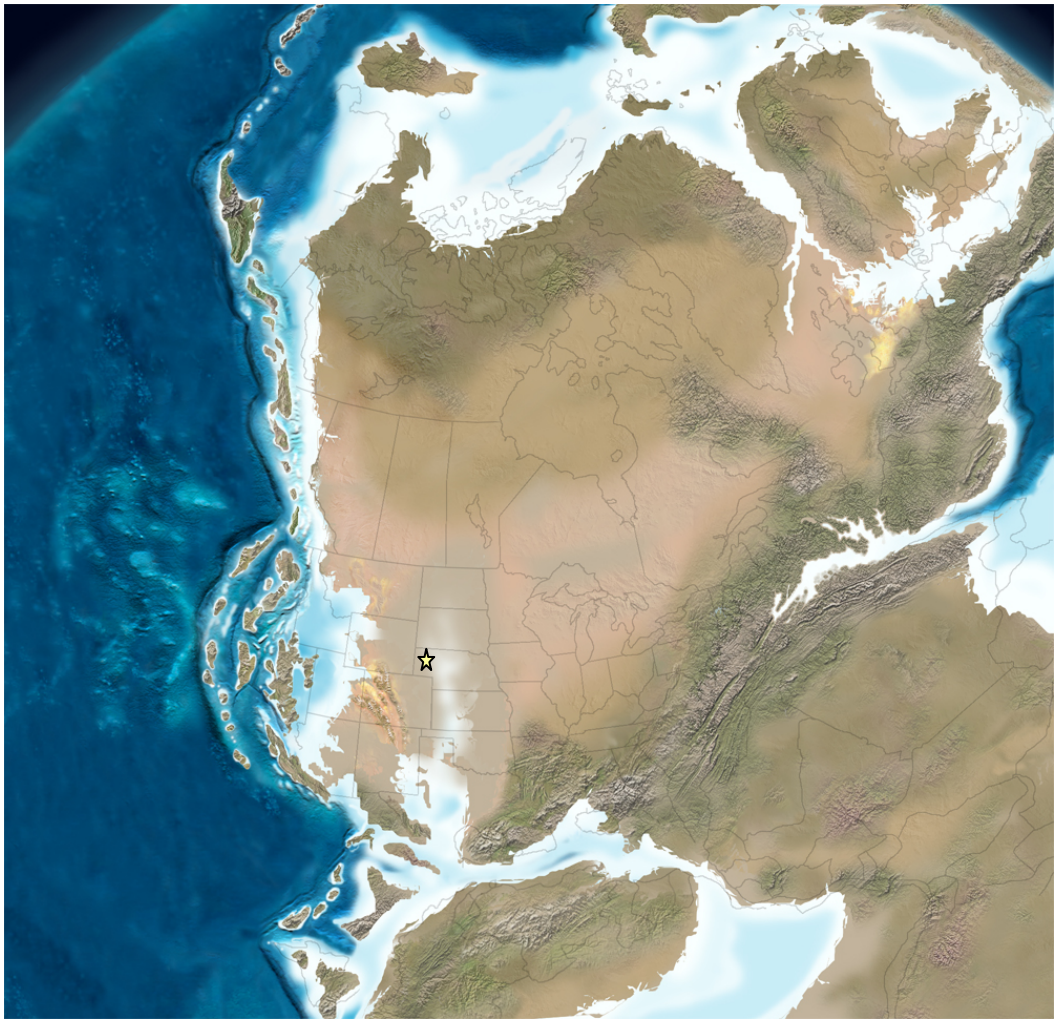


Figure 14. Paleogeographic map of the North American continent during the Late Permian, approximately 260 million years ago. Beginning in the Pennsylvanian, forces from the collision between the South American plate and North America produced the Ancestral Rocky Mountains in Colorado. Streams transported sediments eroded from the Ancestral Rocky Mountains into the Agate Fossil Beds National Monument (yellow star) area where the final remnants of a shallow sea were disappearing. To the east, the plate tectonic collision of the African plate with North America resulted in the Alleghenian Orogeny. Map courtesy of Dr. Ron Blakey, Northern Arizona University, available at http://jan.ucc.nau.edu/rcb7/namP260.jpg (accessed December 22, 2008).

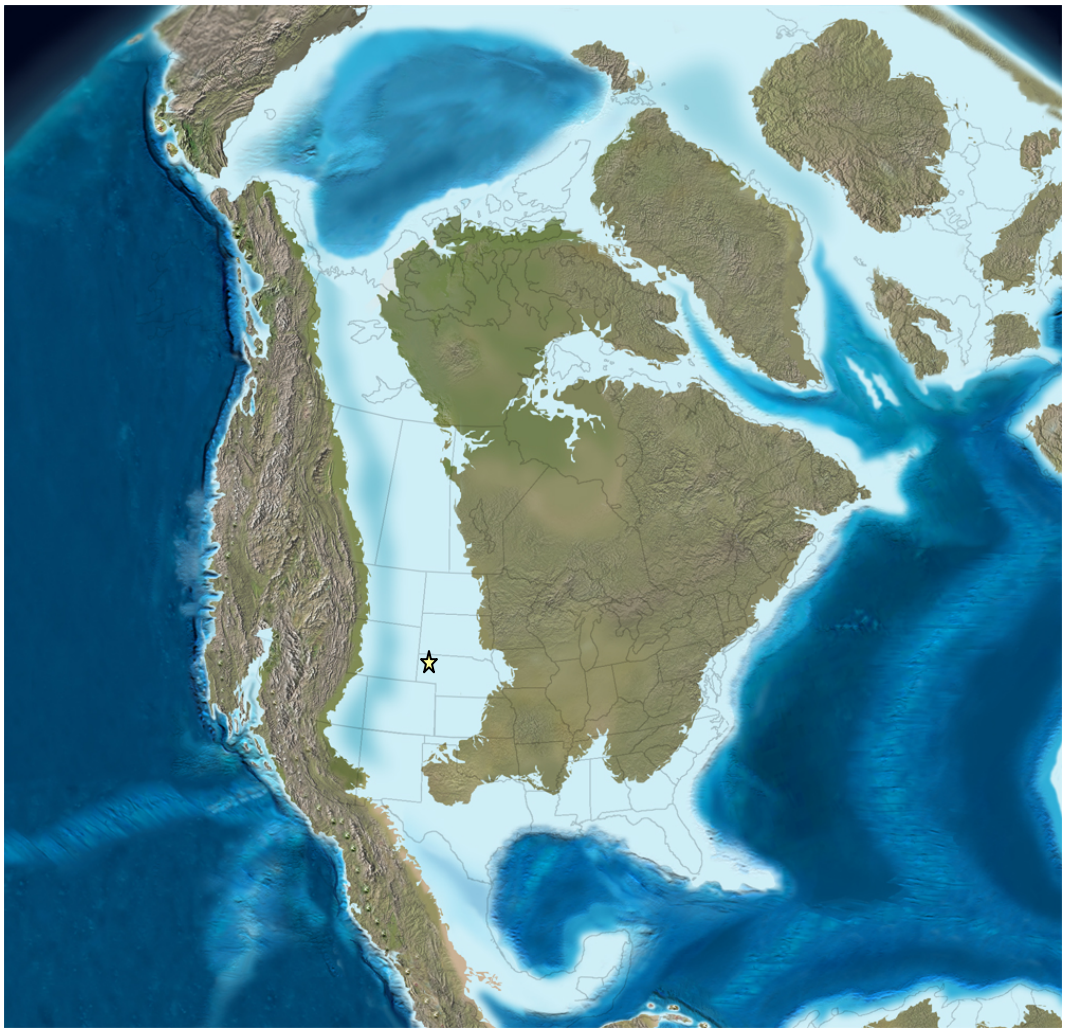


Figure 15. Paleogeographic map of the North American continent during the Late Cretaceous, approximately 85 million years ago. The Western Interior Seaway covers the Agate Fossil Beds National Monument (yellow star) region. The mountain belt that borders the western margin of North America from Alaska to Mexico is a result of the Sevier Orogeny, which in turn is the result of subduction of oceanic crust beneath North America continental crust. Map courtesy of Dr. Ron Blakey, Northern Arizona University, available at http://jan.ucc.nau.edu/rcb7/namK85.jpg (accessed December 22, 2008).

Figure 16. Paleogeographic map of the North American continent during the Early Miocene Epoch, approximately 15 million years ago. Agate Fossil Beds National Monument (yellow star) is located on a gently sloping plain extending eastward from the Rocky Mountains. Volcanoes in western and southwestern North America produced abundant volcanic ash that drifted into the continental interior and helped preserve terrestrial biota. Map courtesy of Dr. Ron Blakey, Northern Arizona University, available at http://jan.ucc.nau.edu/rcb7/namNm15.jpg (accessed December 22, 2008).

Figure 17. Paleogeographic map of the North American continent during the Pleistocene Epoch of the Quaternary Period, approximately 0.126 million years ago. The continental ice sheet does not impact the Agate Fossil Beds National Monument (yellow star) region. Map courtesy of Dr. Ron Blakey, Northern Arizona University, available at http://jan.ucc.nau.edu/rcb7/namQ.jpg (accessed December 22, 2008).

Glossary

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

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

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

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

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

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

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

bedding. Depositional layering or stratification of sediments.

bedrock geology. The geology of underlying solid rock as it would appear with the sediment, soil, and vegetative cover stripped away.

bioturbation. The reworking of sediment by organisms.

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

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

conglomerate. A coarse-grained sedimentary rock with rounded or sub-rounded clasts larger than 2 mm (0.1 in) in a fine-grained matrix.

continental crust. The type of crustal rocks underlying the continents and continental shelves; having a thickness of 25–60 km (16–37 mi) and a density of approximately 2.7 grams per cubic centimeter

craton. The relatively old and geologically stable interior of a continent.

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

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 an oriented vertical plane.

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

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

dip. The angle between a structural surface and a horizontal reference plane measured normal to their line of intersection.

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

ephemeral stream. A stream that flows only in direct response to precipitation.

escarpment. A long, more or less continuous cliff or relatively steep slope facing in one general direction.

extrusive. Of or pertaining to the eruption of igneous material onto the surface of Earth.

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

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

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

holomictic lake. A lake that undergoes a complete mixing of its waters during periods of circulation or overturn.

holotype. The one specimen designated as the reference in describing a new species.

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

ignimbrite. The deposit of a pyroclastic flow.

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

lithosphere. The relatively rigid outmost shell of Earth's structure, 50 to 100 km (31 to 62 mi) thick that encompasses the crust and uppermost mantle

meanders. Sinuous lateral curves or bends in a stream's channel.

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

metamorphism. Literally, "change in form". Metamorphism occurs in rocks with mineral alteration, genesis, and/or recrystallization from increased heat and pressure. Createsthe 'metamorphic' class of rock.

normal fault. A dip-slip fault in which the hanging wall (rocks above the fault plane) moves down relative to the footwall (rocks below the fault plane).

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

orogeny. A mountain-building event, particularly a well-recognized event in the geological past (e.g. the Laramide orogeny).

orographic. Said of the precipitation that results when moisture-laden air encounters a high barrier and is forced to rise over it.

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 geography from past geologic periods.

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

paleosol. A soil that formed on a landscape in the past.

pebble. Generally, small, rounded, rock particles from 4–64 mm (0.2-2.5 in) in diameter.

pyroclastic flow. A density current of pyroclastic material, usually very hot and composed of a mixture of gases and particles.

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

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

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

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

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

strata. Tabular or sheetlike masses or distinct layers (e.g., of rock).

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

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

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

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

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

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

type locality. The geographic location where a stratigraphic unit is well displayed, is formally defined as a typical section, and derives its name.

unconformity. A surface within sedimentary strata that marks a prolonged period of nondeposition or erosion.

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

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

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

References

This section lists references cited in this report. A more complete geologic bibliography is available from the National Park Service Geologic Resources Division.

Chandler, R. M. 1995. *Additions and comments on the fossil birds of Agate Fossil beds National Monument, Sioux County, Nebraska*. Milledgeville, GA: Department of Biological and Environmental Sciences, Georgia College & State University. http://www2.nature.nps.gov/geology/paleontology/pub/grd3_3/agate1.htm.

Emery, P. A. 1966. *Reconnaissance survey of the geology and ground-water resources of the proposed Agate Fossil Beds National Monument, Sioux County, Nebraska*. Reston, VA: U.S. Geological Survey unpublished report.

Graham, J. P. 1996. Revised stratigraphy and reservoir definition of the Lower Cretaceous Muddy Sandstone, Northern Denver Basin. PhD diss, Colorado State University.

Graham, J. P. 2000. Revised stratigraphy, depositional systems, and hydrocarbon exploration potential for the Lower Cretaceous Muddy Sandstone, Northern Denver Basin. *American Association of Petroleum Geologists Bulletin* 84: 183-209.

Harms, J. C. 1966. Stratigraphic traps in valley-fill, western Nebraska. *American Association of Petroleum Geologists Bulletin* 50: 2118-2149.

Heaney, P., interview by N. M. Brown. 2001. *How do agates form?* PennState Online Research, http://www.rps.psu.edu/0109/form.html.

Hunt, R. M., Jr. 1981. *Geology and vertebrate paleontology of the Agate Fossil Beds National Monument and surrounding region, Sioux County, Nebraska (1972-1978)*. Research Reports 13. Washington, D.C.: National Geographic Society.

Hunt, R. M., Jr. 1988. *Report on paleontological excavations at Agate Fossil Beds National Monument undertaken by the University of Nebraska State Museum from June 25, 1985 to August 16, 1986. Lincoln, NE*: State Museum and Department of Geology, University of Nebraska. Includes the Geologic map of the Agate Fossil Beds National Monument. Scale 1:16,896.

Hunt, R. M., Jr. 1990. Taphonomy and sedimentology of the Arikaree (lower Miocene) fluvial, eolian, and lacustrine paleoenvironments, Nebraska and Wyoming: A paleobiota entombed in fine-grained volcaniclastic rocks. In *Volcanism and fossil biotas*, ed. M. G. Lockley and A. Rice, 69-113. Boulder, CO: Geological Society of America, Special Paper 244.

Hunt, R. 1992. *Death of a 19 million year old waterhole*. Museum Notes 83. Lincoln, NE: University of Nebraska State Museum.

Hunt, R. M. 1999. The Miocene carnivore dens of Agate Fossil Beds NM, Nebraska: Oldest known dennin behavior of large mammalian carnivores. *NPS Paleontological Research 2*. Technical Report NPS/NRPO/NRTR-93/11. http://www2.nature.nps.gov/geology/paleontoloty/pub/grd2/gsa01.htm.

Janis, C. M. 2001. Radiation of Tertiary Mammals. In *Palaeobiology II*, ed. D. E. G. Griggs and P. R. Crowther, 109-112. Malden, MA: Blackwell Publishing.

Kenworthy, Jason. 2009. Changing fossils in a changing world: Interpreting long term climate change at Tertiary fossil parks of the NPS. MS thesis. Oregon State University.

Kiver, E. P., and D. V. Harris. 1999. Geology of U.S. parklands. 5th ed. New York: John Wiley & Sons, Inc.

Knudson, R., and S. J. Miller. 2004. Stenomylus research and management needs at Agate Fossil Beds National Monument. *Geological Society of America Abstracts with Programs* 36: 53-54.

LaGarry, H. E., L. A. LaGarry, J. B. Swinehart, and M. B. Leite. 2007. Revised lithostratigraphy of late Paleogene and Neogene strata of the High Plains Aquifer in western Nebraska, USA. *Geological Society of America Abstracts with Programs* 39 (3): 65-66.

Martin, L. 2005. *Hydrology of Agate Fossil Beds National Monument, Nebraska*. Water Resources Division Technical Report NPS/NRWRD?NRTR-2005/327. Fort Collins, CO: National Park Service.

Mayor, A. 2005. Fossil legends of the first Americans. Princeton: Princeton University Press.

National Park Service. 1980. *Agate Fossil Beds: Agate Fossil Beds National Monument, Nebraska*. Handbook 107. Washington, D.C.: National Park Service.

Noble, E. B. 1939. Test on Agate anticline, northwestern Nebraska. *American Association of Petroleum Geologists Bulletin* 23: 101-104.

Santucci, V. L., A.P. Hunt, T. Nyborg, and J. P. Kenworthy. 2006. Additional fossil vertebrate tracks in National Park Service areas. In *America's antiquities: 100 years of managing fossils on Federal lands*, ed. S. G. Lucas, J. A. Spielmann, P. M. Hester, J. P. Kenworthy, and V. L. Santucci, 152-158. Albuquerque: New Mexico Museum of Natural History and Science Bulletin 34.

Swinehart, J. B., V. L. Souders, H. M. DeGraw, and R. F. Diffendal, Jr. 1985. Cenozoic paleogeography of western Nebraska. In *Cenozoic paleogeography of the west-central United States*, ed. R. Flores and S. S. Kaplan, 209-229. Denver, CO: Rocky Mountain Section, Society for Sedimentary Geology.

Vicars, R. G. 1979. Sedimentology of the Upper Harrison Formation in the Agate Fossil Beds National Monument area, northwest Nebraska. MS thesis, Texas Christian University.

Weimer, R. J., S. A. Sonnenberg, W. M. Berryman, and T. L. Davis. 1994. Sequence stratigraphic concepts applied to integrated oil and gas field development, Denver Basin, Colorado, USA. In *American Association of Petroleum Geologists Hedberg Research Conference proceedings*, Paris, France, 1-15.

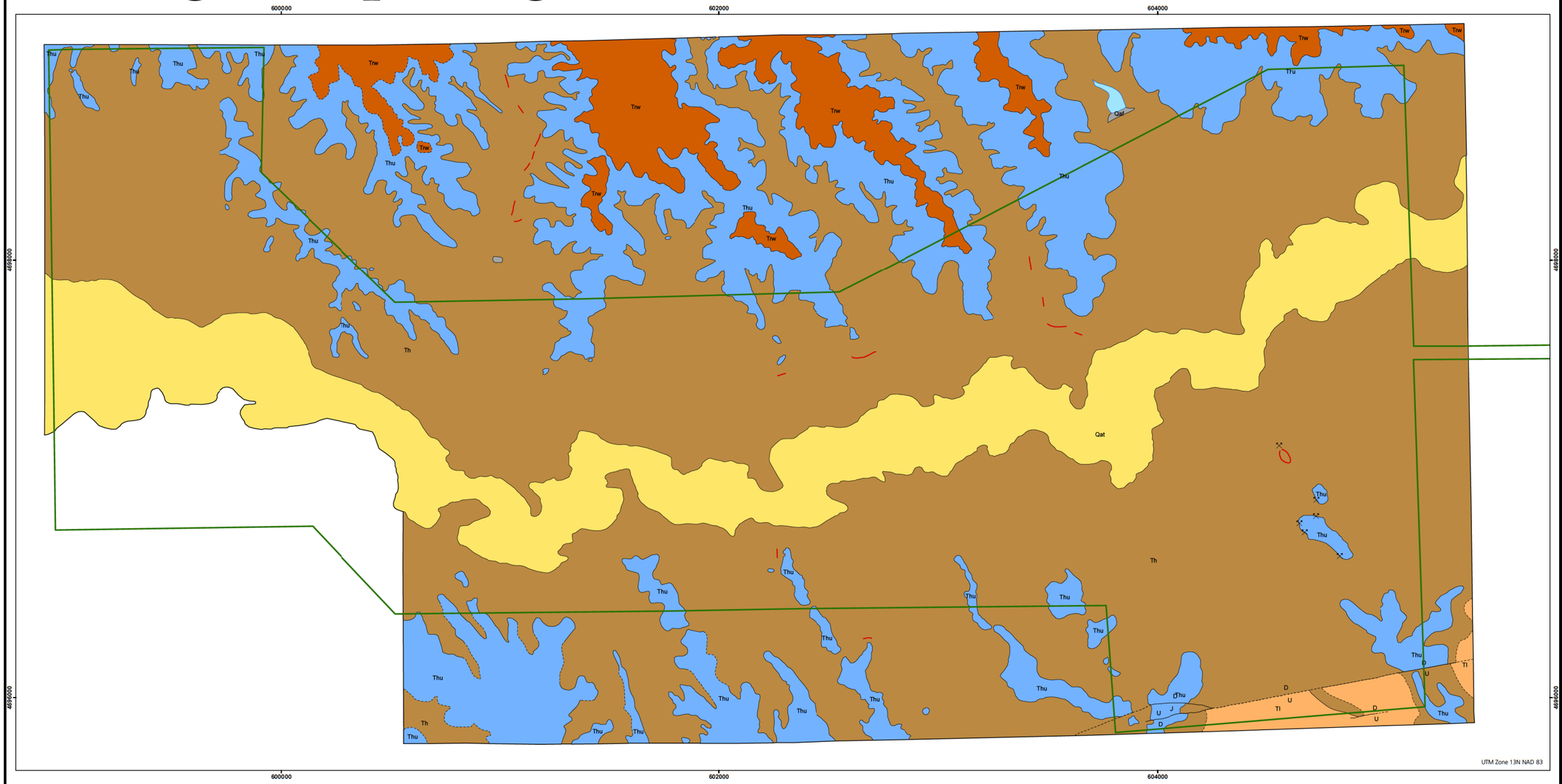
Zachos, J., M. Pagani, L. Sloan, E. Thomas, and K. Billups. 2001. Trends, rhythms, and aberrations in global climate 65 million years ago to present. *Science* 292 (5517): 686-693.

Appendix A: Geologic Map Graphic

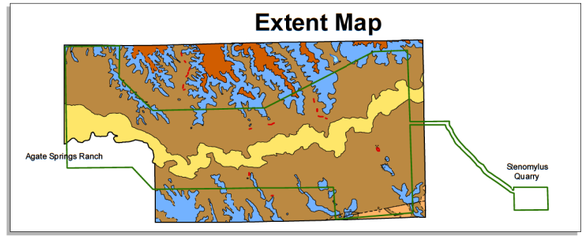
The following page is a snapshot of the geologic map for Agate Fossil Beds National Park. For a poster-size PDF of this map or for digital geologic map data, please see the included CD or visit the Geologic Resources Inventory publications Web page (http://www.nature.nps.gov/geology/inventory/gre_publications.cfm).

National Park Service
U.S. Department of the Interior

Geologic Map of Agate Fossil Beds National Monument



Extent Map



N

0 1 2 Kilometers

0 1 2 Miles

This map graphically presents digital geologic data 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:

Hunt, Robert M. Jr.,1988. Geologic Map of the Agate Fossil Beds National Monument. Scale 1:16,896. University of Nebraska.

Digital geologic data and cross sections for Agate Fossil Beds National Monument, and all other digital geologic data prepared as part of the Geologic Resources Inventory, are available online at the NPS Data Store: http://science.nature.nps.gov/nrdata/

NPS Boundary

Geologic Attitude Observation Localities

- U upthrown side of fault
- D downthrown side of fault

Mine Point Features

- fossil quarry

Linear Geologic Units

- Thaa - Agate Ash

Geologic Contacts

- known or certain
- inferred
- map extent
- shoreline

Faults

- Unknown Offset/Displacement, known or certain
- Unknown Offset/Displacement, inferred

Geologic Units

- Water
- Qaf - artificial fill
- Qat - Alluvium and Terrace
- Trw - Runningwater Formation
- Thu - Upper Harrison Beds
- Th - Harrison Formation
- Tl - Unnamed Lithic Unit

Produced by the Geologic Resources Inventory

January 2009

Appendix B: Scoping Summary

The following excerpts are from the GRI scoping summary for Agate Fossil Beds National Monument. The scoping meeting was on March 3–4, 2003; therefore, the contact information and Web addresses referred to in this appendix may be outdated. Please contact the Geologic Resources Division for current information.

Summary

A Geologic Resources Inventory (GRI) workshop was held for Agate Fossil Beds National Monument (AGFO), Scotts Bluff National Monument (SCBL), and Fort Laramie National Historic Site (FOLA) on March 3–4, 2003. The purpose was to view and discuss the park's geologic resources, to address the status of geologic mapping for compiling both paper and digital maps, and to assess resource management issues and needs. Cooperators from the NPS Geologic Resources Division (GRD), AGFO, SCBL, FOLA, Fossil Butte National Monument (FOBU), and the University of Nebraska were present for the workshop.

This involved field trips to various points of interest in Agate Fossil Beds National Monument and Scotts Bluff National Monument, as well as a half-day scoping session to present overviews of the NPS Inventory and Monitoring (I&M) program, the GRD, and the on-going GRI. Round table discussions involving geologic issues for AGFO, SCBL and FOLA included the status of geologic mapping efforts, interpretation, sources of available data, and action items generated from this meeting. Because of time and logistical limitations, FOLA did not get a site visit during the scoping session.

For a list of meeting attendees, see the list of attendees at the end of the scoping summary.

Agate Fossil Beds National Monument

Bob Hunt (University of Nebraska) furnished GRI staff with the "Geologic Map of the Agate Fossil Beds National Monument" (created in 1977). It is a very large-scale map of the entire monument (with the exception of the Agate Springs Ranch area. However, Bob noted that he does have aerial photo coverage of that area and could easily incorporate it into this existing map. This map has never been digitized, so GRI staff will digitize and attribute as per the GRI model and will report back when it is complete.

Bob noted some changes in terminology from the 1977 map as well. The Miocene "Upper Harrison beds" are now defined as the informal "Anderson Ranch Formation" and his "unnamed lithic unit" is now recognized as the Oligocene Sharp's Formation.

Bob also mentioned that he is currently mapping the 7.5' quadrangles of interest to AGFO (Agate and Whistle Creek) as part of the Nebraska StateMap project, so there will be a significant buffer around the park as well when it is complete. His interest in mapping this area stems from it having one of the best mammalian records of evolution in the world. GRI staff offered to digitize these maps as well when they are complete.

As mentioned, additional digital data sets exist for soils and vegetation for Agate Fossil Beds National Monument. Ruthann Knudson (AGFO superintendent) is interested in deriving a more useful surficial geologic map of the area based on the combination of soils, vegetation and bedrock geology.

Specifically Mentioned Park Management Needs Related to Geology: AGFO

Ruthann Knudson plans to have a paleontological inventory done this summer

Along University and Carnegie Hills, there are a few locations of geologic instability and rock falls that have been previously addressed. The park has put signs up to warn visitors of potential rock fall areas.

The park does have some regional minor oil and gas issues.

Geologic Reports

Ruthann says there is no encompassing geologic report for all three parks, so it would need to be written. However, on an individual basis, each park might have suitable reports. A few references are cited below:

- Pabian, R. K., and Swinehart, J. B. II, Geologic history of Scotts Bluff National Monument. Lincoln: University of Nebraska, 1979.
- Swinehart, J. B. II, et al. Cenozoic paleogeography of western Nebraska. Rocky Mountain Section- SEPM, Lincoln: University of Nebraska, 1985.
- Swinehart, J. B. II, Loope, D. B., Late Cenozoic geology along the summit to museum hiking trail, Scotts Bluff National Monument, western Nebraska, North Central Section: Geological Society of America Centennial Field Guide, 1987.
- Trimble, D. E., The geologic story of the Great Plains, Medora, North Dakota: Theodore Roosevelt Nature and History Association, 1990.

List of attendees

NAME	AFFILIATION	TITLE	PHONE	E-MAIL
Tammy Benson	NPS - FOLA	Chief Ranger	307-837-2221	Tammy_Benson@nps.gov
Tim Connors	NPS - GRD	Geologist	(303) 969-2093	Tim_Connors@nps.gov
Mark Hertig	NPS - AGFO	Curator	308-668-2211	Mark_Hertig@nps.gov
Bob Hunt	U. of Nebraska- Lincoln	Geologist	402-472-2650	rhunt2@unl.edu
Ruthann Knudson	NPS - AGFO	Superintendent	308-668-2211	Ruthann_Knudson@nps.gov
Robert Manasek	NPS - SCBL	Natural Resources	308-436-4340	Robert_Manasek@nps.gov
Lil Morava	NPS - AGFO	Visitor Use Assistant	308-668-2211	Lil_Morava@nps.gov
Valeri Naylor	NPS - SCBL	Superintendent	308-436-4340	Valerie_Naylor@nps.gov
Vince Santucci	NPS - FOBU	Paleontologist	(307) 877-4455	Vincent_Santucci@nps.gov

Agate Fossil Beds National Monument

Geologic Resources Inventory Report

Natural Resource Report NPS/NRPC/GRD/NRR—2009/080

National Park Service

Acting Director • Dan Wenk

Natural Resource Stewardship and Science

Associate Director • Bert Frost

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Geologic Resources Division

Chief • Dave Steensen
Planning Evaluation and Permits Branch Chief • Carol McCoy

Credits

Author • John Graham
Review • Jason Kenworthy, Vincent Santucci, and Pat O'Dell
Editing • Thomas W. Judkins and Melanie Ransmeier
Digital Map Production • Stephanie O'Meara and Trista Thornberry-Ehrlich
Map Layout Design • Dave Green

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U.S. Department of the Interior

Geologic Resources Division
Natural Resource Program Center
P.O. Box 25287
Denver, CO 80225

www.nature.nps.gov