National Park Service
U.S. Department of the Interior

Natural Resource Program Center

Jewel Cave National Monument
Geologic Resources Inventory Report

Natural Resource Report NPS/NRPC/GRD/NRR—2009/084

THIS PAGE:
Flowstone and Spar

ON THE COVER:
Speleothems . The clearly visible faces of calcite crystals in Jewel Cave create a back-drop for stalactites, deposited by droplets of water rich in calcium carbonate.

NPS Photos by: Cover photo by Art Palmer

Jewel Cave National Monument Geologic Resources Inventory Report

Natural Resource Report NPS/NRPC/GRD/NRR—2009/084

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

March 2009

U.S. Department of the Interior
National Park Service
Natural Resource Program Center
Denver, Colorado

The Natural Resource Publication series addresses natural resource topics that are of interest and applicability to a broad readership in the National Park Service and to others in the management of natural resources, including the scientific community, the public, and the NPS conservation and environmental constituencies. Manuscripts are peer-reviewed to ensure that the information is scientifically credible, technically accurate, appropriately written for the intended audience, and is designed and published in a professional manner.

Natural Resource Reports are the designated medium for disseminating high priority, current natural resource management information with managerial application. The series targets a general, diverse audience, and may contain NPS policy considerations or address sensitive issues of management applicability. Examples of the diverse array of reports published in this series include vital signs monitoring plans; "how to" resource management papers; proceedings of resource management workshops or conferences; annual reports of resource programs or divisions of the Natural Resource Program Center; resource action plans; fact sheets; and regularly-published newsletters.

Printed copies of reports in these series may be produced in a limited quantity and they are only available as long as the supply lasts. This report is also available online from the Geologic Resources Inventory website (http://www.nature.nps.gov/geology/inventory/gre_publications.cfm) and the Natural Resource Publication Management website (http://www.nature.nps.gov/publications/NRPM/index.cfm) or by sending a request to the address on the back cover.
Please cite this publication as:

KellerLynn, K. 2009. Jewel Cave National Monument Geologic Resources Inventory Report. Natural Resource Report NPS/NRPC/GRD/NRR—2009/084. National Park Service, Denver, Colorado.

Contents

Figures

Executive Summary

This report accompanies the digital geologic map for Jewel Cave National Monument in South Dakota, 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.

"During eons of time, undisturbed by sunlight, changeable weather, and the invasion of most forms of life, nature has fashioned caves into environments unlike anything found on the surface. Each cave is a unique laboratory of scientific study. Many are places of great beauty" (Conn and Conn 1977, p. 34). Beautiful Jewel Cave contains excellent examples of cave decorations, the hallmark being the calcite crystals or "jewels" for which it was named. Jewel Cave is also a scientifically interesting, complex cave system, composed of many passages in a mazelike pattern.

The underground resources of Jewel Cave National Monument are susceptible to damage. Fragile cave features, rare and delicate biota, open communication with groundwater, and its "invisibility" beneath the ground surface contribute to the vulnerability (Lange 1990). Surface geologic resources also may require management attention. Geologic issues of resource-management concern include the following:

- Airflow
  Airflow has been the most valuable tool for discovering new passages in Jewel Cave. Changes in airflow as a result of the addition and modification of openings alter temperature and relative-humidity regimes within the cave, which in turn may affect cave biota and speleothem growth.
- Cave Protection
  Visitor use and associated trail development have adverse effects on the cave environment. A primary concern is algal growth around the lights that line developed cave passages. Lint and other particulates brought in by thousands of visitors each year also have negative effects, degrading the cave's appearance, providing a food source for opportunistic organisms, and dissolving cave surfaces.
- Hydrology
  Park managers have fragmented information regarding water circulation through the cave and its interconnection with surface activities. However, various studies using dye traces revealed direct surface-cave conduits and a residence time of up to three years.
- Land Use and Surface Development
  More than 40% of the known cave exists outside the boundaries of the national monument, under Black Hills National Forest. Learning where the cave is in relation to surface features is imperative for continued cave protection. Development within the national monument—including roads, a paved parking lot, buildings, water and sewer systems, and underground fuel-storage tanks—alter infiltration patterns and introduce pollutants into the cave system. The placement of sod and timber harvesting at the surface also change drainage and infiltration patterns.
- Mining
  Although Jewel Cave's history is intertwined with a legacy of mining, no abandoned mine land (AML) sites are in the monument. Furthermore, mineral potential is presumed to be quite low throughout the limestone in the Jewel Cave area.
- Radon
  Caves are "traps" for the radioactive gas radon, where levels can build up in areas with little air movement. Human exposure to radon and its progeny results in an increased risk of developing lung cancer. The radon exposure of interpreters who regularly lead cave tours and resource managers who spend extended periods of time underground is a minor concern at the current levels of use, however. Employees at the monument have sampled radon levels in various parts of the cave since 1979.
- Geologic Hazards
  Resource managers have identified three areas in the national monument with a potential for geologic hazards (i.e., rockfall and landslides): (1) the landing near the bottom of the elevator shaft in the Target Room, (2) the historic entrance, and (3) along the uphill slopes of Highway 16 in Hell Canyon. Inspectors found the risk of injury from rockfall to be negligible in the Target Room. The rock exposed in the historic entrance appears reasonably competent and stable; however, limiting the time spent in the immediate area would reduce the exposure of visitors and staff to this hazard. The potential landslide area along Highway 16 in Hell Canyon does not show any telltale signs of imminent failure leading to emergency slope reduction.

Introduction

The following section briefly describes the National Park Service Geologic Resources Inventory and the regional geologic setting of Jewel Cave National Monument.

Purpose of the 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/).

Establishment of Jewel Cave National Monument

In 1908, Jewel Cave became the first cave to be designated as a national monument. Initially the U.S. Forest Service administered the monument, but as a result of Franklin Roosevelt's reorganization, the National Park Service became steward in 1933. At the time of its establishment, Jewel Cave was thought to be a small cave but nonetheless worthy of protection because of its scientific interest and the layers of calcite crystals lining its passages. Today the cave's currently explored length (233.0 km [144.8 mi] as of January 25, 2009) makes it the second longest cave in the world, surpassed only by Mammoth Cave in Kentucky at more than 587 km (365 mi) (http://www.nps.gov/maca/faqs.htm).

Regional Geologic Setting

As part of the Great Plains physiographic province, Jewel Cave National Monument shares a regional setting with many other National Park System units (fig. 1). Often maligned as drab and featureless, the Great Plains physiographic province is more correctly seen as a land of contrasts and variety: canyons carved into solid rock by the Pecos and Rio Grande, the seemingly endless prairies of Kansas, the desolation of the Badlands, and the beauty of the Black Hills. This physiographic province hosts many interesting, even spectacular, geologic features, a number of which are part of the National Park System. In the Black Hills, uplifted Precambrian (4.6 billion to 542 million years ago) rock is the medium for preserving the sculpted faces of four of the nation's most significant presidents at Mount Rushmore. Paleozoic (360–340 million years ago) limestone contains the remarkable Wind and Jewel cave systems. Magma generated during and after the Laramide uplift in the Black Hills (58–54 million years ago) produced a number of localized intrusions, including Devils Tower. Paleocene (65.5–55.8 million years ago) strata host the scenic badlands of Theodore Roosevelt National Park. Badlands National Park preserves Oligocene (33.9–23.03 million years ago) sediments and a fossilized collection of early mammals that lived in the vast Serengeti-like plains of western North America. Fluvial sediments containing fossil mammal bones at Agate Fossil Beds National Monument record mammalian evolution into Miocene time (23.0–5.3 million years ago). Capulin Volcano National Monument preserves post-Pleistocene (<1.8 million years old) volcanic outpourings. Much geologic time is represented (fig. 2), and all of these phenomena are part of the Great Plains.

Figure 1. Physiographic Areas of the Great Plains. Jewel Cave National Monument is part of the Black Hills subprovince of the Great Plains. Other National Park System units of the Great Plains include Agate Fossil Beds National Monument (Nebraska), Badlands National Park (South Dakota), Bent's Old Fort National Historical Site (Colorado), Capulin Volcano National Monument (New Mexico), Devils Tower National Monument (Wyoming), Mount Rushmore National Memorial (South Dakota), Theodore Roosevelt National Park (North Dakota), and Wind Cave National Park (South Dakota). Graphic by Melanie Ransmeier (National Park Service).

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	Elko Orogeny (W)
		Triassic		251		**Mass extinction** Flying reptiles First dinosaurs	Breakup of Pangaea begins 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	Ancestral Rocky Mountains (W)
		Mississippian		359.2		Variety of insects First amphibians First reptiles	
		Devonian		416	Fishes	**Mass extinction** First forests (evergreens)	Antler Orogeny (W) 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? Formation of the Earth	Oldest moon rocks (4–4.6 billion years ago) Earth's crust being formed

Figure 2. Geologic Timescale. Included are major events in life history and tectonic events occurring on the North American continent. Red lines indicate major unconformities between eras. Absolute ages shown are in millions of years (Ma). Compass directions in parentheses indicate the regional location of individual geologic events. Graphic adapted from the U.S. Geological Survey (http://pubs.usgs.gov/fs/2007/3015/) by Trista Thornberry-Ehrlich (Colorado State University).

Geologic Issues

The National Park Service held a Geologic Resources Inventory scoping session for Jewel Cave National Monument on June 13, 2001, 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.

Participants at the GRI scoping meeting in 2001 did not identify any geologic issues related to resource management at Jewel Cave National Monument. Therefore, the issues that appear in this section are a result of correspondence with staff at Jewel Cave National Monument and the Geologic Resources Division (GRD), and research of GRD files, government reports, and the scientific literature. Issues are listed in alphabetical order and are not prioritized.

Airflow

Jewel Cave is a barometric "breathing" cave. Changes in barometric pressure—between day and night and as a result of fluctuations in the weather—cause air to rush into or out of the cave, equalizing the pressure between the cave and outside conditions. When the barometer rises, air rushes into the cave; when the barometer drops, air rushes out (Conn 1966).

Airflow is a significant feature at Jewel Cave National Monument for two reasons. First, airflow is important for exploration. "Barometric breezes" have been the most valuable tool for discovering new passages (Wiles 1998a). In 1991 a strong breeze encouraged excavation of "The Stopper"—a rubble-choked entry into the largest rooms and passages yet found. Explorers discovered nearly 48 km (30 mi) of "new" cave passage as a result of following this breeze. Airflow within the cave is the single best indicator that large areas have yet to be discovered (http://www.nps.gov/jeca/naturescience/caveexploration.htm).

Second, understanding airflow is important for the preservation of cave resources. Changes in airflow as a result of the addition and modification of openings alter temperature and relative-humidity regimes within the cave, which in turn may affect cave biota and speleothem formation (National Park Service 1994a). The only known natural entrance to Jewel Cave is in the upper Pahasapa Limestone above the east wall of Hell Canyon. At the time of its discovery, "the entrance" was a hole too small for a person to crawl through. Early developers enlarged this opening with dynamite. Later, they excavated the opening still more to allow mining and tours. The new aditlike opening greatly simplified the process of entering the cave and eliminated the need to descend by way of rope or ladder (Lininger 2002). In the mid-1960s, the National Park Service added an entirely artificial entrance, which is now the "maintenance entrance." The elevator that provides access to the cave through the visitor center is another artificial entrance. Additionally, during the "Very Important Short Cut" (VISC) project in 1980, explorers enlarged a tiny opening in the cave, making a shortcut to western passages. Also as part of the VISC project, the National Park Service drilled a 15-cm- (6-in-) diameter hole from Hell Canyon into Jewel Cave through which they passed compressed-air and water lines. This hole in now capped (Mike Wiles, Jewel Cave National Monument, written communication, August 28, 2007).

These alterations have changed the natural airflow of the cave. The maintenance entrance has a fairly effective set of airlock doors, but the airflow control at the elevator entrance has not been as effective, though the actual leakage is still minor. No attempt has been made to limit airflow through the enlarged historic entrance or to restore normal airflows through the VISC opening (National Park Service 1991).

In an effort to better understand the dynamics of cave airflow, Andreas Pflitsch—a researcher from the Department of Geography, Workgroup on Cave and Subway Climatology, Ruhr-University of Bochum, Germany—placed ultrasonic anemometers and temperature loggers in barometric caves in the Black Hills (Mike Wiles, Jewel Cave National Monument, written communication, August 28, 2007). These instruments measure airflow velocity, direction, temperature, and vertical flow. Results of this study will help park managers calculate cave volume and determine whether the caves in the study (e.g., Jewel Cave and Wind Cave) are connected (http://www.nps.gov/jeca/naturescience/currentresearch.htm).

Using barometric airflow and other factors (e.g., cave surveys, geology, and hydrology), Cave Specialist Mike Wiles has developed a Geographic Information System (GIS) model to determine how far Jewel Cave is likely to extend. Preliminary extrapolation suggests that Jewel Cave's known extent represents only about 3% of the total volume (Wiles 2004). This model suggests that Jewel Cave could extend as far as Wind Cave, 29 km (18 mi) to the southeast (Ohms and Wiles 2006b). Actually finding and following such a passage that links these two caves would end a long-standing debate about whether these "sister caves" in the National Park System are connected. This GIS model also integrates structural contour data, limestone extent, and water-table depth to calculate the thickness and extent of limestone above the water table between the caves. The model shows that nowhere between Jewel Cave and Wind Cave is there less than 50 m (175 ft) of limestone above the present water table. These findings add validity to the possibility that Wind Cave and Jewel Cave are connected.

Cave Protection

The landmark Federal Cave Resources Protection Act of 1988 (Public Law 100-691) created a major impetus for cave and karst protection and management in the United States. The act directs the secretaries of the Department of the Interior and the Department of Agriculture to inventory and list significant caves on federal lands, provide management, and disseminate information about caves.

In 1990 Congress directed the secretary of the interior, acting through the National Park Service, to establish and administer a program of cave research and examine the feasibility of a centralized national cave and karst research institute. The National Park Service prepared the feasibility study in cooperation with other federal agencies that manage caves, organizations involved in cave-related topics, cave experts, and interested individuals. A bill (S.231), based on the results of the study, established the National Cave and Karst Research Institute in Carlsbad, New Mexico.

The early years of cave development in Jewel Cave had some unfortunate consequences for cave protection. Resulting from a lack of supervision early in the development history, visitors removed many crystals and delicate formations. Sadly, these treasures likely ended up in "obscure boxes in attics and eventually in trash heaps" (Kiver and Harris 1999). New discoveries of passageways and an artificial entrance leading to a portion of the cave not explored prior to NPS management now permit visitors to experience relatively pristine passages and chambers under NPS supervision.

Though not as blatant as past acts of vandalism, visitor use and associated trail development have adverse effects on the cave environment. As documented in *The Jewel Cave Adventure*, for example, "During 1968 and 1969, more than 50 aluminum stairways and bridges were built in pieces, carried into Jewel Cave, and assembled into position. At least 100 tons of cement, gravel, and asphalt were hand-carried, bucket by bucket, along the new trail. Permanent electric lighting was carefully concealed in whatever nooks and crannies the passages could furnish. Eventually, as a final touch of civilization, telephones were installed at strategic spots about the tour loop" (Conn and Conn 1977, p. 97).

A primary concern in developed cave passages is algal growth around the lights. In addition, cave lights and body heat from hundreds of visitors warm the air in the Scenic Tour loop as much as 14°C (7°F), which lowers relative humidity and alters speleothem formation (National Park Service 1991). Exotic (introduced) invertebrate communities may also be encouraged by the presence of electric lights (Elliott 1997, 2000).

Cave managers have used various methods to control the photosynthetic organisms that grow near electric lights in cave environments. Sodium hypochlorite (household bleach), formaldehyde, hydrogen peroxide, and steam generators temporarily reduce algae and other lamp flora. However, these techniques are inadequate solutions for several important reasons: (1) the growth of algae and other lamp flora is only temporarily mitigated, (2) other cave organisms are compromised in the process, and (3) depriving the algae of light is inadequate for controlling growth (Elliott 2006).

Unnatural photosynthetic growth can be better controlled through selection of light wavelength, reduction in wattage, light-shielding, and redirection (Elliott 2006). In summer 2006, park managers at Jewel Cave National Monument experimented with a germicidal ultraviolet (UV) light (the type used for disinfection in hospitals) at one light with moderate algae growth along the Scenic Tour route. Lee-Gray Boze, a caver and seasonal biological science technician, proposed the idea for this project. A patch of algae was exposed to the UV light for up to 24 minutes with no immediate visible change. However, within one week of exposure at such intervals, the algae had clearly diminished, though not completely disappeared (Ohms and Wiles 2006a). Based on these results, UV light appears to have great potential for killing algal growth without the use of harmful chemicals. Longer exposure times or a light with greater wattage may be necessary to completely kill the algae. Park staff will continue to explore this promising alternative to traditional bleach treatments (Ohms and Wiles 2006a).

Lint—another seemingly benign addition to the cave environment—has many detrimental effects: degradation of the cave's appearance, provision of a food source for opportunistic organisms, and a medium for dissolving cave surfaces (Jablonsky et al. 1993). Samples of cave lint contained synthetic and natural fibers, dirt, wood, insect parts, human hair, animal fur, fungi, processed tobacco, paper, and other debris. Unidentified mites also occurred in some of the samples (Pat Jablonsky, personal communication, p. 38 *in* Elliott 2006). Carried on air currents, lint from clothing coats stalactites and flowstone, accumulates on the cave floor below tour platforms, and collects on inaccessible ledges. Investigators placed tagged lint (treated to be clearly visible under UV light) on the trail and found that it had migrated as much as 90 m (300 ft) down the trail, after 75 visitors had passed over several hours. Testing also showed that lint moved to the edge or completely off the trail. Jablonsky et al. (1993) concluded that the most promising strategies to control lint deposits in caves involve careful attention to trail design and custodial and maintenance procedures. Some "clean room" technologies that capture airborne particles through filtering systems may also be useful (Jablonsky et al. 1993).

Hydrology

Although investigators have documented some connections between cave-water quality and surface features, knowledge of water circulation through Jewel Cave and its interconnection with surface activities is fragmented (National Park Service 1994a). Investigators flushed dye traces into the sewage line in September 1985 and recovered sporadic, short dye pulses at three sites along the Scenic Tour route within one week of the dye input. A second dye trace from the parking lot in July 1987 produced long-lasting pulses in drips along the spelunking tour (Davis et al. 1991). Investigators continued to recover dye for three years after input, during the contract period May 1, 1985–April 30, 1988. These findings indicate that any contaminant spilled over the cave will be present in the system for many years (Alexander et al. 1989).

According to National Park Service (1994a), one of the five highest priority projects at the national monument is to conduct a study to determine the hydrologic history of Hell Canyon and its correlation with the hydrology of Jewel Cave. As stated in *Jewel Cave National Monument, Water Resources Scoping Report* (Project Statement JECA-N-024), the objectives for such a study are to (1) determine any hydrologic connection between surface flows in Hell Canyon and apparent fluvial deposits in the cave, (2) determine the timing of flows and if they remain an important process, (3) identify the existence of water-dependent features in parts of the cave near the canyon, and (4) find indicators of the flow regime of Hell Canyon and determine if it has been significantly altered by human activity. Following this study an examination of consumptive water uses and land management in the Hell Canyon watershed might be in order (National Park Service 1994b).

Land Use and Surface Development

Learning where the cave is in relation to surface features is imperative for continued cave protection. For this reason, cave explorers meticulously survey each new passage and create a detailed map used for resource management and to inform future surface development.

At present, development within the national monument includes 2.4 km (1.5 mi) of NPS roads, a 150-car paved parking lot, the visitor center/office complex, the park housing area, the maintenance shop, water and sewer systems (National Park Service 1991), and underground fuel-storage tanks (National Park Service 1994a). The parking lot near the visitor center changes drainage and infiltration patterns of runoff entering the cave and may introduce pollutants into the cave system. The sewage ponds, unlined until 1986, leaked into the cave and may have altered both the quality and quantity of water. Major long-term water system leaks also may have had effects (National Park Service 1991).

The placement of sod also changes drainage and infiltration patterns on the surface above caves (Wiles 1998b) as does harvesting timber, which is common on forest lands adjacent to the monument (National Park Service 1991). The harvest itself probably alters the quantities of water and possibly the pattern of water infiltration into the cave. In areas where the overburden between the cave and surface roads is minimal (≤9 m [30 ft]), heavy timber trucks may adversely affect cave resources (National Park Service 1991).

In addition to park roads, State Highway 16 traverses the monument for 3.5 km (2.2 mi). Heavy commercial truck traffic along the highway travels directly over portions of the cave. Because the road winds sharply and has steep grades, trucking accidents are common and fuel and hazardous-material spills may occur. Any significant spill would threaten the cave (National Park Service 1991). Moreover, the highway's impermeable surface interrupts natural drainage, changes flow patterns, and likely changes cave hydrology.

In the 1990s the South Dakota Department of Transportation proposed rerouting the portion of the highway that goes through the monument. The National Park Service cooperated in the National Environmental Policy Act (NEPA) process (National Park Service 1994a) at that time. The NEPA process requires federal agencies to integrate environmental values into their decision making by considering the environmental impacts of their proposed actions and reasonable alternatives to those actions (http://www.epa.gov/compliance/nepa/index.html). Park staff and the South Dakota Department of Transportation have now agreed to abandon the rerouting proposals. Park staff is working with the State to do minimal widening and straightening along the current alignment in a manner compatible with a 45 mph speed limit [and thereby reducing the risk of accidents and associated spills] (Mike Wiles, Jewel Cave National Monument, e-mail, January 29, 2009). The department of transportation has widened the curve at the bottom of Hell Canyon by building a retaining wall on the road fill, which caused no increase of the footprint. Future plans will first consider geologically sensitive areas as defined by a cave vulnerability map. This map includes information on the geology, hydrology, topography, and mapped cave passages (Mike Wiles, Jewel Cave National Monument, e-mail, January 29, 2009).

In recent years the use of GIS has greatly facilitated resource management of cave passages in relation to surface features, processes, and land use. At Jewel Cave, managers have used GIS to show the location of noxious weed sites relative to the cave, calculate the depth of the cave below these sites, evaluate their proximity to drainages and other potential infiltration zones, and find locations of in-cave water drips near these sites. This analysis has helped the resource management staff make decisions regarding the use of herbicides to treat nonnative plants (Ohms and Reece 2002).

Park managers have also used GIS to determine precisely where Jewel Cave leaves the monument boundary (Ohms and Reece 2002). Jewel Cave is under about 8 km^2 (3 mi^2) of surface area. About 60% of the known cave exists within/under the monument boundaries. The remainder is under Black Hills National Forest. The surface-subsurface relationships that GIS revealed underscore the importance of establishing good working relationships with park neighbors (Ohms and Wiles 2006b).

Mining

Jewel Cave's history is intertwined with a legacy of mining. Gold prospectors discovered the cave in 1900, although the "blowing hole" was probably noticed earlier. The discovery of uranium in sandstone in the area in 1951 resulted in the scientific study of the southern Black Hills by the U.S. Geological Survey (e.g., Braddock 1963). Economic deposits of uranium occur in the Edgemont mining district south of the national monument; no known uranium deposits of importance occur in the Jewel Cave SW quadrangle, closer to the monument (Braddock 1963). Uranium occurs in Cretaceous rocks in the vicinity of (but not actually within) Jewel Cave National Monument. Solution of the Pennsylvanian and Permian rocks, from which substantial amounts of evaporite sediments have leached, is the suspected cause of uranium deposition in the region (Braddock 1963).

According to data of the NPS Abandoned Mine Land (AML) Program, no AML sites are in the monument. Moreover, future mineral potential is presumed to be quite low in the Pahasapa Limestone in which the cave formed (National Park Service 1994a). Threats posed by mining have been substantially reduced with the closure to mining of 966 ha (2,387 ac) of USDA Forest Service land known to overlie parts of Jewel Cave. The secretary of the interior signed the order to withdraw these lands on May 18, 1990. The withdrawal became permanent after an initial two-year probationary period (National Park Service 1994a).

In all probability, however, Jewel Cave extends far beyond the boundaries of the mining closure. The statement for management for the national monument contends that as exploration reveals more of the cave's location, the National Park Service will have to take additional protective measures (National Park Service 1991). An interagency agreement (IA 1569-2-9002) between Jewel Cave National Monument and Black Hills National Forest facilitates cooperation between the two entities in management of Forest Service lands that overlie or otherwise affect cave resources (National Park Service 1994a). In addition, the enabling legislation of Jewel Cave National Monument directs that the cave be preserved "with as much land as may be necessary for the proper protection thereof." If future studies or inventories indicate that activities outside the monument would be detrimental to surface or subsurface resources within the monument, the National Park Service has the means to investigate such issues. A possible resolution is a boundary adjustment through legislation. A decision to pursue any boundary adjustment would be based on scientific data and follow the procedures described in "National Park Service Criteria for Boundary Adjustments," a supplement to *Planning Process Guideline* (NPS-2) (National Park Service 1994a).

Radon

As uranium in soils and rocks naturally decays, radon—a radioactive gas—is released and emanates from the ground. Caves are "traps" for radon, where levels can build up in areas with little air movement. Human exposure to radon gas and the progeny of its own radioactive decay results in an increased risk of developing lung cancer. Airborne alpha radiation from radon gas and its progeny is sufficient to pose a potential health hazard for employees or other persons exposed for long periods of time.

From 1976 to 1978 Dr. Keith Yarborough (NPS Division of Natural Resources Management, Southwest Regional Office, Santa Fe, New Mexico) measured radon along the Scenic Tour route in Jewel Cave. Levels ranged between 98.0 picocuries per liter (pCi/L) and 46.0 pCi/L (Bobby C. Carson, Mammoth Cave National Park, e-mail, July 31, 2007). For comparison the average indoor radon level is about 1.3 pCi/L, and the U.S. Environmental Protection Agency recommends that citizens fix their homes if their test results exceed 4 pCi/L (U.S. Environmental Protection Agency 2005). As a result of Dr. Yarborough's study, park managers continued sampling radon on the Scenic Tour route in 1979 and 1987, then implemented a radon monitoring program throughout the Historic Tour and Scenic Tour routes during the 1990s.

From August 1998 through October 2004, park staff monitored radon throughout the entire cave, with the Target Room serving as a control site (Mike Wiles, Jewel Cave National Monument, written communication, August 28, 2007). At present, park employees periodically monitor radon levels every one or two years (Mike Wiles, Jewel Cave National Monument, personal communication, August 23, 2007). An interesting finding revealed through monitoring is that radon appears to decrease deeper in the cave. Managers suspect a connection between exposures of Minnelusa fill material, which decrease deeper in the cave, and higher radon levels (Mike Wiles, Jewel Cave National Monument, personal communication, August 23, 2007).

Airflow from Jewel Cave through the elevator shaft into the visitor center resulted in high radon concentrations in the visitor center and office areas (National Park Service 1991); sampling of radon in the 1980s showed that the risk of radon exposure was quite high for full-time staff working in the visitor center during the winter months. Wall insulation and no external ventilation contributed to the problem. Radon levels decreased during the summer months when the doors and windows were open all day (park buildings did not have air conditioning at that time) (Mike Wiles, Jewel Cave National Monument, e-mail, February 23, 2009).

In the early 1990s, park managers responded to the concern of radon concentrations in the visitor center by having an extra set of doors installed at the main-floor and basement elevator lobbies. The doors kept the radon out of the visitor center except in the elevator room, which is now vented to the outside. Subsequent monitoring documented a significant decrease in radon in the visitor center offices (Mike Wiles, Jewel Cave National Monument, e-mail, February 23, 2009).

The radon exposure of interpreters who regularly lead cave tours and resource managers who study and explore the cave is a minor concern because of the current amount of time spent underground (Mike Wiles, Jewel Cave National Monument, written communication, November 27, 2007). Furthermore, the U.S. Environmental Protection Agency has determined that the public has no significant health risk from exposure to radon in caves because of the limited time spent underground (National Park Service 1990).

In 1990, the National Park Service developed NPS-14 as guidance for NPS employees, visitors, and contractors in cave areas to minimize potential health hazards. In developing this guideline the National Park Service relied heavily on input from the Department of Labor, Mine Safety and Health Administration, which has extensive experience in radon management. Ultimately, Reference Manual 50B (Occupational Safety and Health Program) will supersede NPS-14; however, this particular guideline (section 19) is "under development" (http://www.nps.gov/policy/DOrders/DOrder50B.html). Park managers may contact John Burghardt (Geologic Resources Division) at john_burghardt@nps.gov and 303-969-2099, or Bobby Carson (Mammoth Cave National Park) at bob_carson@nps.gov and 270-758-2136, for more information about radon safety in and around underground environments.

Geologic Hazards

In 2003, staff at Jewel Cave National Monument requested technical assistance from the Geologic Resources Division to inspect and evaluate the potential for geologic hazards (i.e., rockfall and landslides) in three areas: (1) the landing near the bottom of the elevator shaft in the Target Room, (2) the historic entrance, and (3) along the uphill slopes of Highway 16 in Hell Canyon.

Target Room

While an inspection of the Target Room showed overall structural stability, the intersecting Surprise Loft, located above the entrance doors, is geologically less stable and will continue to be a higher risk area for occasional rockfall (Phil Cloues, Geologic Resources Division, memorandum to chief of Geoscience and Restoration Branch, September 16, 2003). At the time of inspection, the existing protective wooden structure was deteriorating and posed a potential safety threat to tour groups passing below the upper loft area (fig. 3). The rotting wood also was serving as an unnatural food source for bacteria, fungus, and mold. Mitigation alternatives included a structure made of stainless-steel support struts and netting. Such a structure would be less imposing without sacrificing protection.

The skills required for designing such a structure are knowledge of underground confined spaces, dangerous heights, potentially hazardous substances (mold/fungus), and protection of delicate cave features. GRD staff recommended that an engineering team from Colorado School of Mines (CSM) design a structure for park consideration. In 2005, the design team provided cost estimates, engineering criteria and specifications, strength-parameter testing with computer modeling, installation procedures (DVD), and a scale model of the design. The CSM design team transferred the completed project to the Geologic Resources Division as the client-sponsor; GRD staff gave these materials to park managers for consideration of future funding and possible replacement of the aging wooden structure. Ultimately, the senior design project did not meet park needs. Park staff contracted to have a new design, but the final cost was projected to be several times higher than expected, mostly because of the skyrocketing cost of stainless steel. Therefore, staff from the Midwest Regional Office evaluated the risk of not replacing the structure. Because the risk was found to be negligible, park staff simply demolished and removed the original structure (Mike Wiles, Jewel Cave National Monument, e-mail, January 29, 2009).

Historic Entrance

While the overall entrance area appears relatively safe, it is well fractured and subject to possible rockfall (Phil Cloues, Geologic Resources Division, memorandum to chief of Geoscience and Restoration Branch, September 16, 2003). One of the improvements to reduce potential hazard exposure would be to limit the time spent in the immediate area of the cave entrance. Visitors should be instructed to avoid, as much as possible, touching the walls or ceiling of the cave. The cave tour guide should advance expediently away from the outside opening into the more stable cave passages with the group. To improve safety and reduce the risk of falling rock, proper training with a scaling bar (to sound the rock for competency) could be combined with a periodic inspection procedure. The low ceiling allows for close inspection and reduces the energy (i.e., fall time) of a rock. While all exposed rock is subject to erosion, GRD staff felt "comfortable" at the time of inspection that the entrance appeared reasonably competent and stable (Phil Cloues, Geologic Resources Division, memorandum to chief of Geoscience and Restoration Branch, September 16, 2003).

Exposed, weathered rock lines the trail from the parking lot to the historic entrance. This area poses a rockfall hazard to passing visitors and staff. In connection with the park's Loss Control Program, it might be possible to establish a program of documented inspection in balance with park budget limitations and other time constraint priorities. Many rockfalls are triggered by severe weather changes (e.g., rain, snow, and rapid change in temperature). This "weather factor" reduces the risk potential because many people are not out and about at this time. However, other triggering mechanisms can be root growth, animal disturbance, seismic vibration, and thermal expansion or contraction that can happen at any time. During inspection, GRD staff found the trail to be reasonably safe and typical of such trails in a similar geologic setting and observed no obvious geohazards meriting removal. However, awareness and preventative maintenance should remain a part of the safety program in this area (Phil Cloues, Geologic Resources Division, memorandum to chief of Geoscience and Restoration Branch, September 16, 2003).

Hell Canyon

The potential landslide area along Highway 16 in Hell Canyon does not show any telltale signs of imminent failure leading to emergency slope reduction. In addition, GRD staff observed no historical evidence of prior landslides in this area. Furthermore, the canyon hills did not appear to be of substantive height, and the soil and rock (limestone and some sandstone) appeared to have good drainage characteristics. Also, no surface cracks suggested partial failure, and no leaning trees indicated pending failure.

The long-term goals of highway safety and natural resource protection of the cave may be best met by rerouting the highway to the north and getting it out of the canyon (Phil Cloues, Geologic Resources Division, memorandum to chief of Geoscience and Restoration Branch, September 16, 2003). Therefore, GRD staff recommended that geologic-engineering professionals of the South Dakota Department of Transportation address this problem and present their findings in a report for review by NPS geotechnical staff (see "Surface Development and Land Use" section).

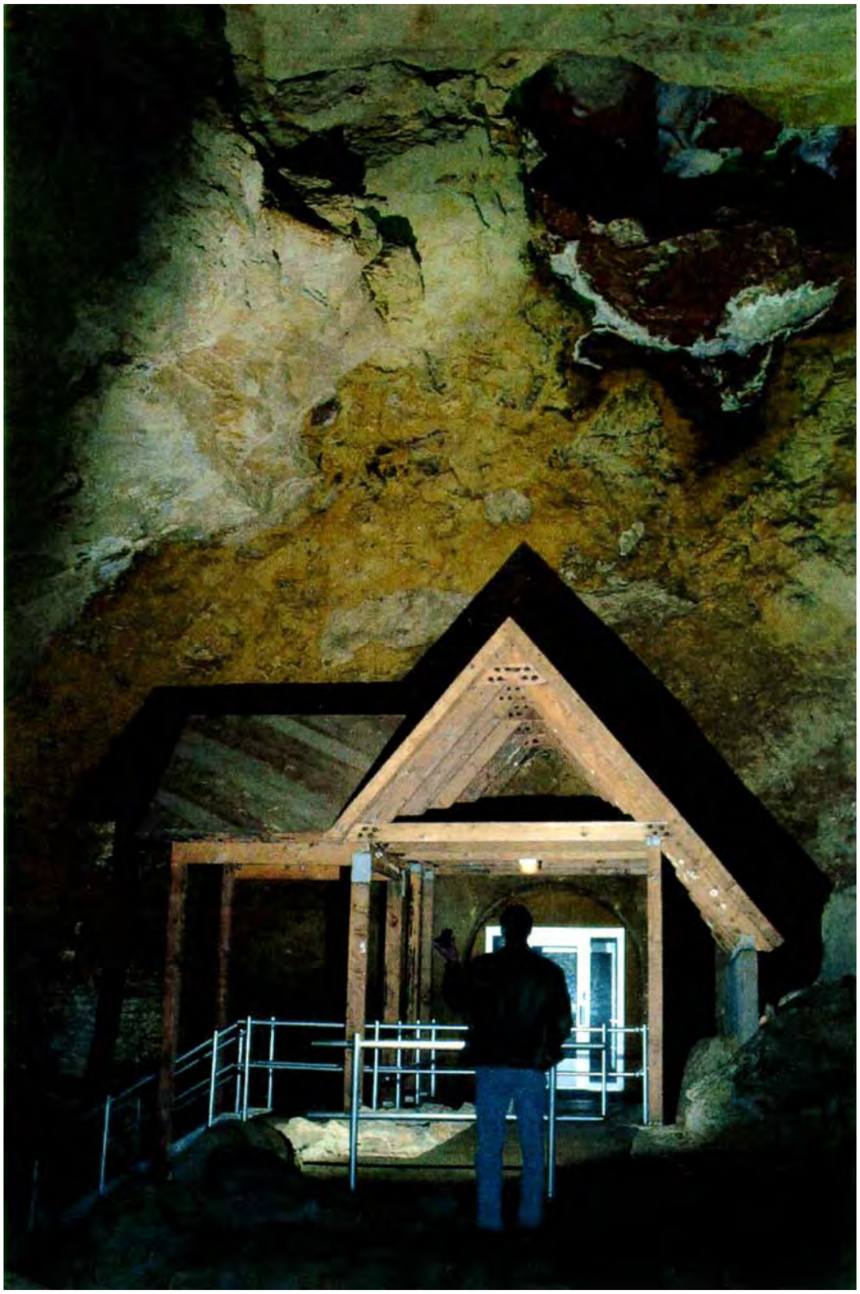


Figure 3. Protective Structure in the Target Room. The wooden roof and structure near the bottom of the elevator shaft in the Target Room was meant to provide protection from falling rocks. The hazard was determined to be negligible and the structure has since been removed. Photo by Phil Cloues (National Park Service).

Geologic Features and Processes

This section describes the most prominent and distinctive geologic features and processes in Jewel Cave National Monument.

In addition to Jewel Cave, a number of other caves exist at the monument, including Secret Cave, Bush's Cave, Cove Cave, and Midden Cave (Schubert et al. 1995), as well as small blowholes in Hell Canyon (Schilberg and Springhetti 1988). However, the primary resource is Jewel Cave itself. Currently measured as the second longest cave in the world (Miller 2006), its discovered length is a fraction (possibly 3%) of the volume yet to be found (Wiles 2004). Its deepest known point is 228 m (749 ft) below ground; passage elevations range from 1,648 m (5,406 ft) to 1,455 m (4,775 ft) above sea level. Recent exploration trips have focused on the southeastern area of the cave where strong airflow (see "Airflow" section) has revealed many previously unexplored passages.

In addition to its length, Jewel Cave is notable for its beauty, complexity, and scientific interest. This section highlights the cave's genesis, levels, distinctive features, and speleothems.

Cave Complexity and Levels

The caves of the Black Hills have formed complex, mazelike patterns. Although many passages, especially larger ones, tend to run in a fixed direction, others wander about in random fashion (Conn and Conn 1977). Unlike many caves, Jewel Cave does not have a main or "trunk" passage. What seems like a main passage for a short distance may stop abruptly, become drastically reduced in size, or resume at a different level after a brief discontinuity. Sometimes the smaller meandering passages provide a route more continuous than the large, straight passages (Conn and Conn 1977).

Jewel Cave formed in Pahasapa Limestone—dolomitic limestone of Mississippian age (see fig. 2). Limestone and dolomite have their own character, and each affects the cave differently, resulting in distinctive layers or levels as part of the whole. Explorers have identified five levels in Jewel Cave. From upper to lower, they are the loft level, chert level, main level, lower level, and basement level.

Loft Level

The lofts are wide, vaulted rooms that formed in massive, light-gray limestone with granular texture. They are wider than they are high because no large, vertical cracks occur in this portion of bedrock (Palmer 1984). The lofts are an assortment of sprawling, disconnected caverns that seldom lead anywhere as continuous routes (Schilberg and Springhetti 1988). Many major lofts are located in weathered iron-oxide breccia (Palmer and Palmer 1989), which contains nodules of white calcite. This combination makes the lofts very colorful. Another distinctive breccia bed of chaotic, light-gray limestone lies above the dark-red breccia. The greatest passage widths in the lofts occur at the contact between these two breccia beds (fig. 4).

Chert Level

The chert level separates the lofts from the main level of Jewel Cave (fig. 4). This level is composed of a series of closely spaced chert beds with a total thickness of 3 m (10 ft). The lofts are about 10 m (33 ft) above the chert. The chert level is resistant to dissolution, forming a barrier breached only by narrow openings (Palmer 1984).

Main Level

The main level of the cave consists of wide tubes formed in dolomite with minor limestone and chert beds. Pink dolomite breccia, 3–6 m (10–20 ft) thick, occurs in places. The passages of the main level are covered in a thick crystal lining that commonly hides the bedrock beneath. Where limestone is hard (generally the yellow and pink layers, higher in the passage), the crystals hold tightly and form extensively; on the lower, softer, light-gray dolomite, crystal coatings have fallen away from cave surfaces.

Lower Level

The lower level consists of fracture-controlled fissures in massive dolomite. The passages are highly interconnected but junctions are abrupt and ungraded with sharp jogs in the ceiling and floor (Palmer and Palmer 1989).

Basement Level

The basement level, occurring in dolomitic limestone, is 15–18 m (50–60 ft) beneath the lower level. It does not have good connectivity with other passages and is notable because of the absence of the calcite-crystal coating so common in the rest of the cave. Explorers have discovered only 122 m (400 ft) of passages in this level (Mike Wiles, Jewel Cave National Monument, written communication, March 10, 2009).

Cave Genesis

Hypotheses about the origin of the caves in the Black Hills are controversial. Starting in the 1930s (i.e., Tullis and Gries 1938), investigators began proposing models to explain these complex cave systems. During the 1960s (i.e., Howard 1964; Deal 1968) and 1980s (i.e., Palmer 1981; Bakalowicz et al. 1987; Ford 1989; Palmer and Palmer 1989) additional investigators put forth views to explain the origin of caves in the Black Hills. The following is a generally accepted timeline for cave genesis:

- 350 million years ago: Pahasapa Limestone is deposited in a shallow sea. During high rates of evaporation and poor circulation, a zone of gypsum and anhydrite forms as part of the limestone.

- 330 million years ago: Dissolution of gypsum and anhydrite in the Pahasapa Limestone results in a fractured, brecciated zone; calcite replaces gypsum in this zone.
- 320–300 million years ago: Lowering of sea level and exposure of limestone at the surface.
- 300–65 million years ago: Deep burial of the limestone by sediments (up to 2 km [1.2 mi] thick), starting with the Minnelusa Formation (primarily sandstone). Calcite lines preexisting voids (not filled with sediment) in the Pahasapa Limestone; quartz crystals from on this calcite and other cave surfaces as the Black Hills begin to uplift.
- 65–40 million years ago: Laramide Orogeny with uplift of the Black Hills 58–54 million years ago (Lisenbee and DeWitt 1993). Thermal rise of groundwater/deep fluid moves through the bedrock, depositing quartz as a result (see above). Artesian groundwater flow established. Primary cave development guided by brecciated zone, voids, and prominent joints. Precambrian (Redden and DeWitt 2008) and Mississippian (Palmer 2007) structures may have influenced the location of Laramide fractures.
- After the main cave dissolution: A thick layer of calcite crystals lines the walls of many Black Hills caves; Ford (1989) provided an age of 2.5 million years old.
- 500,000–300,000 years ago: Drainage of caves. Formation of vadose speleothems.

Although the overall geologic history is fairly clear (see “Geologic History” section for greater detail), the main cause of solutional enlargement of the caves is not, nor are a number particular issues regarding cave genesis at Jewel Cave.

Cause of Solutional Enlargement

With respect to the present state of knowledge and evidence, a “mixing model” of cave genesis provides the best explanation for the solutional enlargement of Jewel Cave. The model proposed in Palmer and Palmer (1989) and summarized in Palmer (2007) is based on extensive field mapping, lab analysis of samples, and geochemical modeling; it takes into account the interplay between different rock types, chemical environments, and patterns of water flow, which geologic and geochemical evidence support. In this model, two or more sources of water are combined. One source is almost certainly the artesian flow that dominates the aquifer today. Indeed Jewel Cave did receive a small amount of late-stage thermal water that deposited quartz along veins. The other source could have been a deep source, infiltration through the overlying sandstone, or both (Art Palmer, State University of New York, College of Oneonta, e-mail, August 22, 2007). Each of these sources would have been essentially saturated with dissolved limestone, rendering them incapable of dissolution. However, where deep water rose and mixed with near-surface water, a boost in aggressiveness would have occurred as a result of the CO_2 contrast. When these sources mixed, dissolving capacity would have been regained and cave passages enlarged.

Particular Issues for Jewel Cave

Recent mapping of surface geology and cave passages at Jewel Cave National Monument and the surrounding area is providing new evidence for the genesis of Jewel Cave. First, the stratigraphic location of the caves is significant for understanding cave genesis. Caves in the Black Hills do not extend to the bottom of the Pahasapa Limestone. Jewel Cave and Wind Cave both extend only 76 m (250 ft) down into the limestone. Regionally, the maximum thickness of the Pahasapa Limestone is 210 m (690 ft), but at Jewel Cave National Monument it is only 137 m (450 ft) and only 107 m (350 ft) at Wind Cave National Park. The Mississippian depositional setting explains the caves’ similarity in stratigraphic location and the difference of 30 m (100 ft) between the thickness of the Pahasapa Limestone at Jewel Cave and Wind Cave. That is, Wind Cave limestone was closer to the shoreline of the Mississippian sea, which thinned to the southwest. Even though Wind Cave formed in lower (older) strata of the limestone, its relationship to the overlying Minnelusa Formation is the same as at Jewel Cave (Mike Wiles, Jewel Cave National Park, written communication, March 10, 2009).

Investigators have suggested that the caves are concentrated in the upper parts of the limestone because this is the location of former calcium-sulfate deposits (i.e., gypsum and anhydrite), which have since dissolved away (e.g., Palmer and Palmer 1989; Palmer 2007). However, a more recent proposal focuses on stratigraphic location as a function of depth of circulation relative to the water sources that enlarged the caves (Mike Wiles, Jewel Cave National Park, written communication, March 10, 2009). One likely source was the groundwater within the basal sandstone of the overlying Minnelusa Formation. Although initial permeability was very low, uplift and fracturing of the Minnelusa Formation (and underlying Pahasapa Limestone) during the Laramide Orogeny would have allowed water from the sandstone aquifer to circulate within the fractures of the limestone, forming cave passages. Consequently, most cave passages are largest where they are adjacent to known faults and prominent joints. Furthermore, this proposal explains why the large caves in the Black Hills are only found beneath the Minnelusa cap (Mike Wiles, Jewel Cave National Park, written communication, March 10, 2009). Most of the large caves in the Black Hills occur only in limestone that is capped with Minnelusa sandstone (fig. 5), and in the southern Black Hills, no known caves longer than 60 m (200 ft) exist in the uncapped portions of the limestone (Mike Wiles, Jewel Cave National Monument, written communication, November 27, 2007).

Second, as more passages are discovered, explorers have found that both Jewel Cave and Wind Cave extend into the overlying Minnelusa Formation at many points. Jewel Cave, in particular, formed up into the preexisting (and already lithified) basal sandstones of the Minnelusa Formation.

Third, past interpretations suggested that karst topography (paleokarst), with relief up to 24 m (80 ft), formed in the Pahasapa Limestone between 320 million and 300 million years ago. However, detailed mapping at Jewel Cave National Monument and the surrounding area has revealed no mappable relief in the paloeotopography between the Pahasapa Limestone and Minnelusa Formation; only minor solution features appeared to have formed at the surface (Mike Wiles, Jewel Cave National Monument, written communication, December 10, 2007). Furthermore, there is little evidence of paleocaves within Jewel Cave; no one has yet found an unambiguous example of a cross-cutting relationship of present cave passages intersecting a Mississippian-age passage. The present-day passages of Jewel Cave do indeed contain Minnelusa fill material, but much of the fill includes large lithified sandstones and siltstones that are identical to the basal Minnelusa Formation found in surface outcrops. This strongly indicates that the source of the fill material was the oldest (Pennsylvanian) subunits of the Minnelusa Formation and not Mississippian-aged caves (Mike Wiles, Jewel Cave National Monument, e-mail, March 2, 2009). Loskot (1973) made similar observations at Wind Cave. At Jewel Cave, the material collapsed into the developing cave passages when they intersected the already deposited, lithified material. Hence, paleocave development appears to have been relatively minor and probably did not play a significant role (i.e., serving as a pathway for water) in subsequent dissolution of Jewel Cave.

Fourth, past investigations (e.g., Ford 1989) identified a lack of connection between surface topography and the underlying cave system as a piece of morphological evidence to be worked into a cave-genesis model. However, mapping of surface geology and subsurface cave passages at Jewel Cave has contradicted this criterion. That is, a connection between the cave system and surface topography is being revealed (Mike Wiles, Jewel Cave National Monument, e-mail, March 2, 2009). The then-forming (Paleocene-Eocene) surface canyons appear to have strongly influenced groundwater hydrology. The pattern of passages shows a near-perfect correlation with present-day topography and geologic contacts (Mike Wiles, Jewel Cave National Monument, written communication, December 10, 2007).

Faults and Joints

Uplift of the Black Hills caused the rocks to fracture, creating both faults (with movement) and joints (no movement). Surface outcrops and aerial photographs in the vicinity of the national monument show faults such as the Jewel Cave Fault Zone—a prominent fault that crosses the monument about 450 m (1,500 ft) north of the cave's entrance and extends for many miles in an east-west direction. Highway 16, which follows the Jewel Cave Fault Zone, parallels cliffs of Pahasapa Limestone that mark the edge of the upthrown fault block. South of the highway, along the downthrown block of the fault, the lower part of the Minnelusa Formation lies opposite the upper part of the Pahasapa Limestone (Dyer 1961). The fault begins in the Precambrian rocks to the east of the monument and extends to the west side, causing a pronounced offset in the escarpment. West of the monument, the fault breaks into two diverging branches and disappears within a very short distance (Dyer 1961).

Faults in the area are displaced down to the south to about 140 m (450 ft) (Fagnan 2002). Deal (1962b) originally made this observation, which Wiles (1992) confirmed. Since then, investigators have documented faults that are displaced up to the south, though they appear to be the exception to the rule (Mike Wiles, Jewel Cave National Monument, written communication, November 27, 2007).

In the 1960s cave explorers started speculating about the surface-subsurface connection of fractures. Unexposed minor fault zones, roughly parallel to the local fault system, block the continuation of Jewel Cave passages (Deal 1962b). The most imposing of these within the cave is along a line running for 1,070 m (3,500 ft) east-southeast of the Floating Loft. This barrier separates the various southern discoveries from the main part of the cave (Schilberg and Springhetti 1988). The primary barriers to exploration are faults, which shatter the rock around them (Palmer 1984). However, recent GIS analysis of cave passages and surface faults shows that the axes of synclines and anticlines inhibit the growth of cave passages, creating obstructions to exploration. Cave passages are better developed in the limbs of synclinal and anticlinal folds (Fagnan 2002; Ohms and Reece 2002).

Over the history of exploration in Jewel Cave, barriers have periodically stopped the progress of exploration, but cavers have repeatedly bypassed or breached these seemingly impenetrable points, revealing extensive passages beyond. Recent efforts to push past an axis of a monoclinal fold have not yet been successful (Wiles 2005). Strong barometric winds, indicating large passages beyond the obstruction, encourage persistence and future attempts. Moreover, geologic mapping of the area shows no visible offset at the surface, supporting the idea that the lineament is indeed a fold axis (rather than a fault), which is a less severe obstruction (Wiles 2005).

All the major joints and faults in and around Jewel Cave National Monument appear to be older than the cave. A few minor faults originated after the cave formed, and some of the older faults experienced further shifting (Palmer 1984). Faults usually exert only local control of cave passageways and determine the overall trend of relatively few caves (Kastning 1977). By contrast, where joints are prominent, they can determine the pattern of nearly every passage in a cave (Palmer 1991). However, faults and joints both are important for the origin of caves in the Black Hills because they provided the original pathways for groundwater to flow through the limestone (Palmer 1984). Recent interpretations specify that cave passageways formed via dissolution from paleohydraulic gradients in the direction of the cave fractures (Fagnan 2002). Jewel Cave formed mainly by widening of many intersecting joint and faults. Almost all of the joints and faults in the area are vertical or nearly so, producing high, narrow, fissurelike cave passages.

The low, wide passages in the cave formed along partings that separate individual beds in the rocks (Palmer 1984).

Manganese and Other Deposits

Deposits of manganese (fig. 6) occur in all cave levels, but particularly in the lowest levels (Palmer 1984). The deposits consist of manganese oxides and hydroxides. The specific mineralogies are not known, so the deposits are simply referred to as "manganese." Manganese occurs in such abundance that during the earliest period of cave exploration it was considered for its economic potential (Lininger 2002). The deposits are sticky and slippery when wet and difficult to wipe away when dry. Cavers inevitably track isolated deposits onto cave floors and walls, marring the beauty of some chambers (Conn and Conn 1977). Where the deposits are not immediately present underfoot, they are located under a surface layer of crystal slabs and breakdown (Conn and Conn 1977).

Deposition of manganese sometimes formed thick layers. For instance, cavers excavated a 1.5-m- (5-ft-) thick layer of manganese to provide headroom during trail construction in 1968 and 1969. Also, workers drove a grounding rod at one of the electrical transformers through a 2.4-m- (8-ft-) deep deposit (Conn and Conn 1977). Dried surfaces of manganese layers have formed polygonal plates, evident along cave tour routes (Lininger 2002).

Deposition of manganese was nearly the last event before the final draining of the cave. Virtually all of the manganese was deposited subaqueously as a chemical precipitate after the subaqueous deposition of the calcite crystal coating (Mike Wiles, Jewel Cave National Monument, written communication, November 27, 2007). In a few locations within the cave, manganese is bedded within deposits of Minnelusa fill (Mike Wiles, Jewel Cave National Monument, written communication, November 27, 2007).

Other cave sediments such as thin coatings of red and brown clay occur in Jewel Cave. Where the walls are void of crystals, exposure to moist cave air has resulted in weathering of the limestone to soft, fluffy powder. Much of this weathered material remains close in color to the original beige limestone; however, some has turned bright red, yellow, or pink (Palmer 1984).

Paleontological Resources

Jewel Cave formed in the Pahasapa Limestone (regionally known as the Madison Limestone), which was deposited in a shallow sea 350 million years ago. Much later (60–40 million years ago), the main cave levels formed. Common fossils in the limestone include brachiopods, cephalopods, and a spongelike creature, possibly a bryozoan (Mike Wiles, personal communication, p. 27 *in* Santucci et al. 2001).

Investigators have conducted two separate excavations inside Jewel Cave during which they identified fragmented skeletal remains of a snake (*Crotalus*), bats, sciurid and cricetid rodents, *Neotoma* sp. (also middens), *Microtus* sp., lagomorphs, an unidentified large mammal, and a number of gastropods. The large mammal bones commonly display rodent gnaw marks. One excavation also uncovered nonrodent coprolites (Schubert et al. 1995). Though researchers have not yet conducted absolute-age analysis, most of the remains appear to represent extant, late-Pleistocene or Holocene species. No additional paleontological resources are known from the documented cave passages (Mike Wiles, personal communication, p. 27 *in* Santucci et al. 2001).

Speleothems

The features that arouse the greatest curiosity of most cave visitors are speleothems. As defined in Moore (1952), a speleothem is a secondary mineral deposit formed in caves. These mineral formations exhibit bizarre patterns and otherworldly forms and give caves a wonderland appearance. Speleologists have taken three basic approaches to classifying speleothems: (1) morphology, (2) origin, and (3) crystallography. This report uses morphology (how they look) but also includes information about origin and crystallography as needed. Identified in Deal 1962a, 1962b, 1966; Conn and Conn 1977; Palmer 1984; Schilberg and Springhetti 1988; Ford 1989; Olson et al. 1991; and Lininger 2002, the speleothems of Jewel Cave are categorized using *Cave Minerals of the World* (i.e., Hill and Forti 1997) and listed in alphabetical order.

Balloons

Balloons are round, thin-walled speleothems with gas inside a mineralized, baglike pouch (fig. 7). Believed to be short-lived, these rare, fragile speleothems quickly dry, crack, deflate, and change in luster, especially in low-humidity environments. Jewel Cave has one of the best displays of balloons in the world. Cavers have reported dozens of good specimens along with a few hundred others of all shapes, sizes, and lesser degrees of perfection (Cahill and Nichols 1991). The balloons in Jewel Cave are typically pearly to silvery white, opaque, and have wall thicknesses of 0.02 mm (0.0008 in) and diameters up to 5 cm (2 in). They appear to have grown as little sacks, some of which are distended and others puckered and deflated in appearance (Hill and Forti 1997). Analysis of a balloon from Jewel Cave showed a composition of 79% hydromagnesite, 15% calcite, and 6% aragonite. X-ray spectroscopy detected trace amounts of silica and evaporite salts; the silica appears to be the glue that binds the balloon to the wall (Olson 1991).

Boxwork

Boxwork is so named because it resembles a cluster of post-office boxes. Intricate networks of fins or plates protrude in relief from bedrock walls, ceilings, or floors. Boxwork is a relic from the very earliest stages of cave formation (Palmer 1995). As such, boxwork is technically a speleogen (rather than a speleothem), forming when preexisting calcite veins were preferentially weathered from the bedrock as the cave developed. Boxwork can be composed of any mineral more resistant than its surrounding medium, but calcite is most common. Calcite protrusions (i.e., fins, plates, or veins) are common in all limestone layers, but boxwork forms only in caves that have experienced long periods of intense weathering (Palmer 1984). Altered bedrock between the coarse calcite veins disintegrates and falls by its own weight, especially in zones of condensation moisture and periodic rises in water table (Palmer and Palmer 1995). This leaves the calcite veins standing in relief.

The best exposures of boxwork in the world are in the caves of the Black Hills, most remarkably in Wind Cave, but small arrays of boxwork are located in Jewel Cave, for example, along the Rum Runner's Lane on the Scenic Tour route.

Conulites

In 1977 Herb and Jan Conn described conulites as "cone-shaped cups of water" (Conn and Conn 1977). Also referred to as "mud cups" and described as "drip linings," conulites are conical shells of material that stick apex down into the cave floor. Conulites form as simple, drip-tube pits in mud or other soft material, which later becomes lined with calcite or other minerals. Subsequent erosion removes the soft material surrounding the harder lining, leaving the hollow, usually cone-shaped speleothem free-standing (Hill and Forti 1997).

Coralloids

Coralloid (or corallite) is a catchall term describing knobby, nodular, botryoidal, or corallike speleothems. The most well-known coralloid in Jewel Cave is cave popcorn, although coralloids appear as grapes, knobstone, coral, cauliflower, globularites, and grapefruit in other caves. After stalactites, stalagmites, and flowstone, coralloids are probably the most common speleothem type (Hill and Forti 1997). Coralloids range in size from tiny beads to globular masses about a meter in diameter. Coralloids can form both in the open air and underwater. In Jewel Cave, semidry or intermittently seeping areas have the most development (Schilberg and Springhetti 1988).

In the central part of Jewel Cave, including the Hub Loop, popcorn covers some large stalagmites. These are called "pseudomorphs" or when they have a central hole, "logomites" (see "Stalagmites" section).

Draperies or Cave Bacon

When drops of water flow down a sloped ceiling before dripping onto the floor, calcite can build up in a line. These lines gradually form draperies, also called "cave bacon." Iron oxide or organic solutions form the baconlike stripes. This type of speleothem is found in almost every cave in the world and is universally popular because of the close resemblance to its namesake (Nelson 2000). As the formations grow, small undulations in the bedrock cause the draperies to become slightly curved. With time, these curves become more and more accentuated so that the draperies become highly folded or furled along their lower edges. Near the Inner Sanctum of Jewel Cave, a 6-m- (20-ft-) tall drapery contains alternating bands of translucent red and yellow calcite, which accentuate its furls (Palmer 1984).

Fibrous Speleothems

Cave Minerals of the World has a category called "fibrous speleothems" into which many of the gypsum speleothems of Jewel Cave fit: beards, cotton, hairs, needles, and spiders. Fibrous speleothems are those that display a fibrous or filamentary crystal habit, for example gypsum ($CaSO_4 \cdot 2H_2O$), which forms in only the driest parts of Jewel Cave. Most water that seeps into the cave contains dissolved gypsum picked up from the limestone and sandstone. As the water evaporates in the cave's dry areas, fibrous gypsum is deposited. Gypsum beards, tufts, and needles are common in some of the passages in the central part of Jewel Cave. Along the Hub Loop, some gypsum needles reach incredible lengths (Schilberg and Springhetti 1988). Conn and Conn (1977) described two straight needle crystals measuring 66 cm (26 in) long and a single hair of gypsum 160 cm (63 in) long hanging from the ceiling in the vicinity of the Mind Blower area of the cave. A single 8-m- (25-ft-) long strand of gypsum hangs from the ceiling in the Loose End (Mike Wiles, Jewel Cave National Monument, written communication, November 27, 2007).

Flowers

Caves are greenhouses for flowers composed of cave minerals, typically gypsum. The crystal petals of these speleothems radiate out from a common center (fig. 8). Variations in crystal structure produce unique, curved, flowerlike petals. Magnificent gypsum flowers occur in some of the southernmost passages of Jewel Cave such as Wildflower Walk and other places beyond the Mini-Miseries and Mind Blower (Schilberg and Springhetti 1988). South of the Adamantine Alley area, explorers discovered a gypsum flower that stretches more than a meter (40 in) (Mike Wiles, Jewel Cave National Monument, written communication, November 27, 2007).

Flowstone

Described as "melted cake icing" and "frozen waterfalls," flowstone is usually composed of calcite or other carbonate minerals that are deposited in layers or bands. Individual flowstone layers may be very colorful—yellows, reds, and oranges.

Cave Minerals of the World distinguishes between flowstone and draperies, though many Jewel Cave explorers combine these forms as "flowstone draperies." According to Hill and Forti (1997), however, flowstone differs from draperies in that it forms as a result of flowing water only; draperies are a composite flowstone-dripstone speleothem (Hill and Forti 1997). Hence, draperies are discussed separately in this report (see "Draperies or Cave Bacon" section).

Flowstone forms both in the open air and underwater and assumes a variety of forms: "petrified" or "frozen" waterfalls, cascades, rivers, glaciers, or organ pipes. While a few fairly massive deposits such as the frozen waterfall have built up in parts of Jewel Cave (fig. 9), the semiarid climate of the Black Hills and the spongelike nature of the Pahasapa Limestone dictate that such deposits are not widespread (Schilberg and Springhetti 1988).

Frostwork

Frostwork—also referred to as “anthodites” by Jewel Cave investigators—is a spiny speleothem resembling a cactus or thistle. The second edition of *Cave Minerals of the World* (1997) clarifies that frostwork and anthodites are separate types. The reason for this change from the first edition (1986) is that Henderson (1949), the first to describe anthodites from Skyline Cave in Virginia, included “tabular” as a specification for anthodites, and frostwork definitely does not consist of tabular branches; rather, it has acicular (“needlelike”) ones. The needlelike habit of aragonite gives most frostwork this particular appearance. However, frostwork can be composed of calcite, opal, gypsum, and other minerals, as well as ice, though not identified as such in Jewel Cave. It is usually white but can also be other colors, including blue (Hill and Forti 1997).

The most common occurrence of frostwork is with coralloids: clusters of needles frequently radiate from the tips of popcorn nodules. Frostwork also forms on stalactites, walls, ceilings, ledges, and less occasionally on floors (Hill and Forti 1997). Frostwork grows in areas of high evaporation, particularly where air movement is rapid.

Frostwork displays can be dazzling and are among the most exquisite of all speleothem types (fig. 10). The beautiful and unusual miniature “bonsai trees” in the Japanese Gardens of Jewel Cave are fragile and intricate accumulations of frostwork. Unfortunately, their beauty makes frostwork speleothems prime targets for vandalism, and their delicate nature makes them easily destroyed by carelessness. Frostwork grows primarily in the upper levels of Jewel Cave. Conn and Conn (1977) reported that the nicest frostwork seen at that time was in the Rambling Loft. Another interesting form is a “frostwork foot.” At 2 m (7 ft) long, the largest of these specimens is Paul Bunyan’s Foot in Bunyan’s Loft. “The base of such a foot is remarkably horizontal as if it had formed over a water surface” (Conn and Conn 1977, p. 141).

Helictites and Scintillites

Helictites are contorted speleothems that twist in any direction, seemingly in defiance of gravity. The term “helictite” comes from the Greek root “helix,” meaning to spiral. Helictites have been compared to “the horrible, snaky tresses of Medusa” (Hill and Forti 1997) and described as threads, beads, worms, antlers, and twigs. Helictites grow on cave ceilings, walls, and less often on cave floors, as well as on other speleothems. Regardless of size or shape, all helictites have one thing in common: they possess a tiny central channel through which their extremities and diameters are fed and increased by seeping capillary water. Small helictites occur in the Formation Room (fig. 9) and in many other locations in conjunction with stalactites and stalagmites; larger helictites occur south of Hurricane Corner and near Never Never Spring (Conn and Conn 1977).

Scintillites are helictite-shaped deposits of chert that have been coated with tiny sparkling crystals of reddish euhedral quartz. They are located on the bottom of the main chert zone near the top of the Pahasapa Limestone (Palmer 1984) (see fig. 5). They appear to be the fossilized casts of small roots, which have been replaced by chert carried down in solution from the overlying beds. Although quartz crystals are known in other caves, scintillates of the rootlike variety are unique to Jewel Cave.

Pearls

Cave pearls, found in a few isolated places near the visitor trails, are concentrically banded concretions that form in shallow cave pools where water is dripping or slowly flowing into a pool. Sand grains, bat bones, shell and wood fragments, or pieces of other speleothems may act as nuclei for cave-pearl growth; all of these fragments become rounded as they grow into cave pearls of different shapes—spherical, cylindrical, irregular, cubical, or even hexagonal (Hill and Forti 1997). Cave pearls range in size from smaller than a sand grain up to 20 cm (8 in) in diameter. Cave explorers have described cave pearls as marbles, hailstones, cupcakes, cigars, oranges, pigeon’s eggs, and balls. The luster of cave pearls justified their naming back in 1874, but they can also be rather dull.

Dripping water can agitate cave pearls, but it does not rotate them, round them, or polish them. Instead, cave pearls become rounded because the growth rate of the outer layer of the pearl is the same in all directions in the supersaturated pool in which the pearl forms. Because a spherical shape is the structure that allows for the greatest amount of material for the smallest surface area, it is naturally promoted even for pearls with highly irregular nuclei (Hill and Forti 1997).

Rafts

Cave rafts are thin, planar speleothems of crystalline material that float on the surfaces of cave pools. These are usually composed of carbonate minerals (i.e., calcite or aragonite) but may be composed of other minerals such as gypsum or native sulfur (Hill and Forti 1997). Rafts composed of calcite form on water surfaces in Jewel Cave today, especially where a dusting of finely weathered debris provides nucleation sites. When rafts grow too large to stay afloat, they settle to the bottom of pools. Large areas of rafts occur in the Land of Milk and Honey and in much of the Volksmarch. Some of these rafts reach 25 cm (10 in) in diameter (Mike Wiles, Jewel Cave National Monument, written communication, November 27, 2007).

Rims and Vents

According to Conn and Conn (1977), a vent is an opening with a scoured throat and a projecting rim of calcite that resembles the bell of a horn. Some vents are only a few centimeters in diameter, while others are large enough to climb through. Usually the flaring rims point upward, indicating a consistent flow pattern through much of Jewel Cave. Thereby, geologists hypothesize that vents formed underwater (Conn and Conn 1977): as warm currents of water, perhaps from submerged hot springs, circulated through colder, “standing” water, the upward slopes of calcite rims formed.

Cave Minerals of the World identifies rims as a speleothem type but not vents. Rims are projections of material such as calcite, aragonite, and less commonly gypsum that form around holes in cave floors and walls where small constricted passages join with large rooms (Hill and Forti 1997). Rims are smooth on the inside but rough on the outside and conform to the shape of the hole they rim. Rims can be perfectly circular or convoluted like a shell or ear. They are variable in size with an average height of about 25 cm (10 in) (Hill and Forti 1997).

Jewel Cave explorers have noted that vents seem to form in conjunction with rims. Because rims often surround passages with perceptible airflow, cavers follow rims to find new cave passages. However, airflow is not necessarily needed in the formation of rims. Maltsev (1994) reported that capillary forces and evaporation-condensation of irregular surfaces are more than enough to move thin films in an upward direction, allowing for the precipitation of rims even without any external (wind) impact.

Rimstone

Though generally rare in the caves of the Black Hills (Schilberg and Springhetti 1988), small rimstone-lined pools have formed in Jewel Cave on the flowstone floor of the Formation Room (see fig. 9) and nearby areas (Palmer 1984). Rimstone dams are reminiscent of rice paddies situated on the hill slopes of Asia; each terrace is horizontal and stair-stepped, one above the other (Hill and Forti 1997). Rimstone in Jewel Cave forms around the edges of pools, building up natural dams that make the water deeper.

Spar

The most obvious and widely displayed speleothem in Jewel Cave is its "jewels" of crystallized calcium carbonate (Schilberg and Springhetti 1988), which form extensive crystal linings in cave passages. Individual crystals exceed 8 cm (3 in) in length (Lininger 2002). Except in the upper lofts where dissolution has occurred and elsewhere where the coated rock has fallen away as breakdown, extensive sheets of spar, averaging 15 cm (6 in) in thickness, line the passages.

"Spar" is a general term for calcite crystals with clearly visible faces. Investigators have not yet determined why dogtooth vs. nailhead spar forms; however, some controlling factors are probably the type and amount of dissolved materials in the water, the rate of crystal growth, temperature of the water, and character of the surface on which the crystal grows (Palmer 1984).

Two primary types occur in Jewel Cave: dogtooth and nailhead. Dogtooth spar is composed of sharp-ended crystals that come to a point, thereby resembling a dog's tooth. Nailhead spar terminates in a blunt, three-sided end. Most of the crystal linings are the nailhead form, which are large and blunt on the undersides of ledges and smaller and thinner on upward-facing surfaces (Schilberg and Springhetti 1988). Dogtooth spar generally occurs as small, pure-white crystals that line Pennsylvanian-age cavities that did not become filled with later sediment.

Spar formed under subaqueous conditions. The water became supersaturated by either CO_2 degassing into air-filled upper caves or by heating, which would have caused more pronounced degassing. Warming (that was perhaps cyclical) appears necessary to account for the great extent and volume of crystals in Jewel Cave (Bakalowicz et al. 1987). Though varying widely in the number of layers, the calcite coating may be composed of as many as 20 distinct growth layers (fig. 11) (Palmer and Palmer 1989).

Stalactites

Stalactites are the most common and most familiar of all speleothems; they resemble icicles or carrots hanging from cave ceilings (see fig. 9). Stalactites range in size from small, slender, soda straws to thick, massive pendants tens of feet long and wide. In Jewel Cave, calcite crystals coat some stalactite ends, enlarging them to several times their own diameter. These resemble billy clubs or bottle brushes. Stalactites are usually composed of calcite but may consist of other minerals.

Stalactites form through the release of carbon dioxide from water droplets (see cover photo). A water droplet collects on the cave ceiling by condensation or by water coming through a fracture in the rock. With the loss of carbon dioxide, a thin film of carbonate material precipitates and covers the surface of the drop. Similarly with evaporation in arid cave environments, a thin film of sulfate or other noncarbonate material can precipitate over the surface of the drop. As the drop accumulates more water and becomes heavier, it begins to oscillate. This causes the film of material to move up toward the ceiling and to adhere there by surface tension. When the drop falls to the floor, this film is left on the ceiling as a round rim of material—the initial growth ring (Hill and Forti 1997). As drop after drop follows a similar path, an infinitesimal trace of mineral material is left behind. As long as water continues to drip, a tube is created and eventually enlarged. It is not surprising, then, that the word stalactite is Greek for "oozing out in drops." In the case of "bottle brushes," these stalactites grow above a pool. When the water level of the pool rises slightly, the tips of the stalactite became immersed, allowing a brushlike coating of dogtooth spar to grow on the end (Palmer 1984).

Stalagmites

"That which drops" is the Greek meaning of stalagmites. When a drop of water falls from the ceiling or a stalactite, it still has some carbonate material left in solution. When the drop hits the floor, carbon dioxide is given off and carbonate is precipitated as a mound below the point of dripping. If a noncarbonate mineral makes a stalagmite, evaporation drives precipitation of mineral material. Because falling water droplets tend to splash, stalagmites spread out as they gradually build up from the floor. Hence stalagmites are usually larger in diameter than the stalactites above them and they generally have rounded tops, instead of pointed tips like stalactites. Stalagmites can assume a fascinating variety of shapes, and cavers have compared them to broomsticks, toadstools, bathtubs, Christmas trees, beehives, coins, buttons, and even fried eggs.

Popcorn stalagmites are scattered in many sections of Jewel Cave (Conn and Conn 1977), but their locations are mutually exclusive from the areas of active dripping or even dry travertine. The popcorn is distinctly different from that found in wet areas. Additionally, some of the popcorn stalagmites are hollow with vertical holes. These are called "logomites" because of their resemblance to hollow logs. The largest of these is in RJ Hall. Explorers have measured the depth of a couple of logomites with a plumb line. One is 3.3 m (11 ft) tall, but the hole extends down into the floor to 5 m (15 ft). The diameter is about 1.2 m (4 ft).

An unusual kind of stalagmite in Jewel Cave is a mud stalagmite. A semiliquid slurry of mud and sand drips from calcite crystals overhead and forms stalagmites on the cave floor. They typically have dimensions of 5–8 mm (0.2–0.3 in) in diameter and 40–50 mm (1.6–2.0 in) in height. Nearby walls become splattered with mud. Mud stalagmites probably form quickly by a single mudflow (Deal 1966).

Speleothems as Paleoclimate Indicators

Speleothems are among the best indicators of the ancient climate of land areas (Moore and Sullivan 1997). They record both past temperature and precipitation. Speleologists use thorium-230 (^{230}Th) to numerically date speleothems. Natural water contains minute amounts of uranium held in solution; thorium-230 is the decay product of uranium-234 (^{234}U). The uranium replaces some of the calcium in the calcite ($CaCO_3$) of speleothems. The ^{230}Th method has an effective range of up to 300,000 years. Beyond that, the buildup of thorium-230 ceases because greater amounts are destroyed by their own radioactivity as fast as they are produced from uranium-234 (Moore and Sullivan 1997).

Another numerical dating method measures the ratio of the isotopes of oxygen—^{18}O:^{16}O—contained in small cavities in a speleothem. Oxygen is chiefly composed of oxygen-16 but contains about 0.2% of oxygen-18. In calcite ($CaCO_3$) this percentage varies with the temperature of formation because oxygen-18 concentrates in calcite relative to water, and the concentration becomes less with increasing cave temperature (Moore and Sullivan 1997).

Investigators sampled a vadose calcite flowstone about 12 cm (5 in) thick with strong color banding from Jewel Cave. Their findings showed that this speleothem in the heart of the continent is recording global climate change in the same manner as well-established marine and northern latitude records (Ford et al. 1997). The speleothem only grew during interglacial and interstadial conditions; all growth ceased during the coldest parts of the glacial stades. Investigators interpret the ranges of oxygen-18 to represent a regional mean annual temperature from +8°C to 0°C ± 2°C (+46°F to 32°F ± 36°F) as the speleothem was growing. During the penultimate interglacial, short-lived warm peaks occurred at 238,000 and 198,000 years ago and periods of moderate temperatures around 215,000 and between 182,000 and 176,000 years ago. Speleothem growth ceased between 170,000 and 133,000 years ago. Peak climatic conditions during the last interglacial (stage 5e) extended from 129,500 to 119,000 years ago with minor oscillations. The paleoclimate record from Jewel Cave correlates well with the SPECMAP (marine) and computed 60°N insolation (seasonal changes) records during stage 5e (Ford et al. 1998).

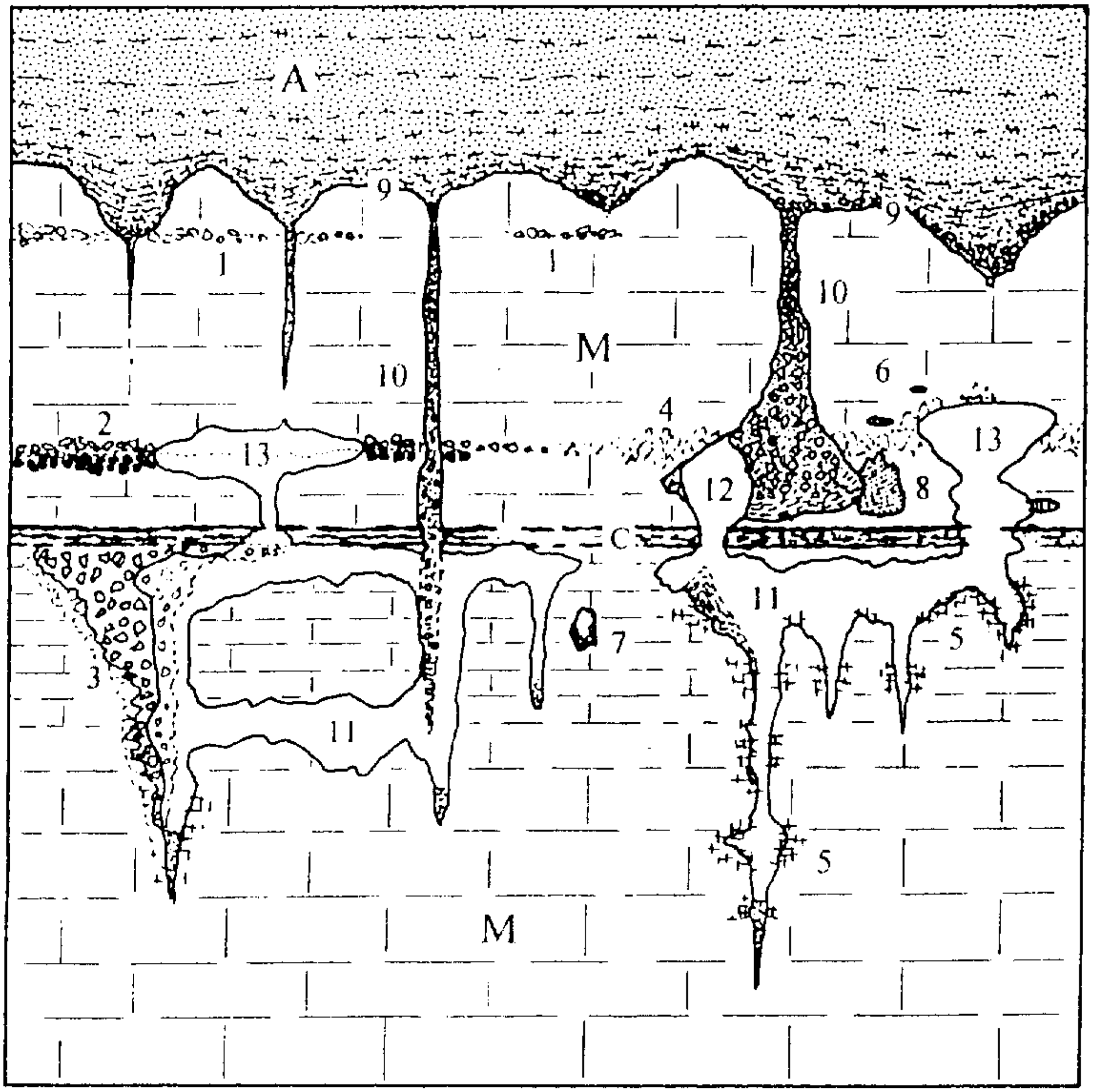


Figure 4. Idealized Cross Section through the Pahasapa Limestone. The figure shows multiple stages of karst and related processes. Vertical range of the diagram is roughly 150 m (490 ft) but the horizontal scale is unspecified. M = Madison Limestone (locally known as Pahasapa Limestone); A = Amsden Formation (locally known as Minnelusa Formation); C = major chert horizon; 1 = uppermost sulfate solution breccia; 2 = lower sulfate solution breccia with redox boundary; 3 = discordant angular breccia (formed by sulfate wedging) with calcite matrix; 4 = mosaic sulfate solution breccias near basin margin; 5 = mosaic breccias (from anhydrite hydration) with yellow-brown calcite veins and boxwork; 6 = quartz-lined nodules; 7 = Middle Mississippian solution voids (resulting from H_2S-H_2SO_4 dissolution) with brecciated walls; 8 = early phase of mixing-zone cave development with authigenic carbonate sediment; 9 = Late Mississippian paleokarst surface with sinkholes and fissures; 10 = fissures and caves filled with allogenic Pennsylvanian clastics; 11 = Cenozoic caves, which intersect early breccias and paleokarst features; 12 = exhumed Late Mississippian caves; 13 = possible Mississippian mixing-zone caves not filled with Pennsylvanian sediment, enlarged by Cenozoic cave development. Graphic from Palmer and Palmer (1995), fig. 3. Used by permission of the author.

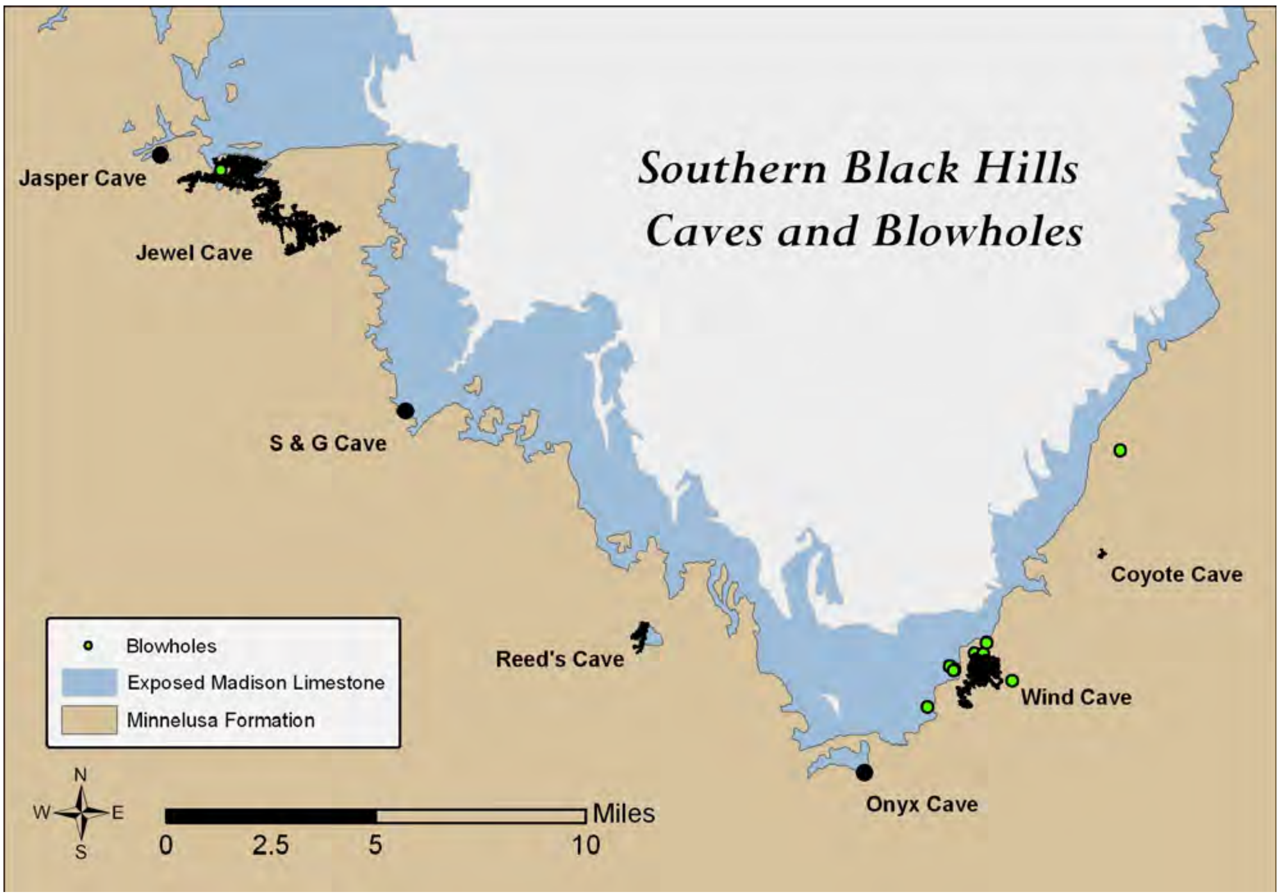


Figure 5. Caves in the Southern Black Hills. More than 560 km (350 mi) of cave passages occur in the southern Black Hills. The blue color on the figure represents the Madison Limestone, locally known as Pahasapa Limestone. The tan color represents the overlying subunits of the Minnelusa Formation (sandstone, limestone, and dolomite). In the areas where the limestone is not capped by the Minnelusa Formation, no caves with lengths greater than 60 m (200 ft) occur. Graphic by Rene Ohms (National Park Service).

Figure 6. Manganese. Abundant deposits of manganese oxides and hydroxides occur in all levels of Jewel Cave. The ubiquitous deposits are sticky and slippery when wet and difficult to wipe away when dry. Photo by Shawn Thomas (National Park Service).

Figure 7. Balloon. Jewel Cave has one of the best displays of cave balloons in the world, including this pearly earring balloon. Cavers have reported hundreds of specimens of all shapes, sizes, and degrees of perfection. Photo courtesy of Art Palmer.

Figure 8. Flower. The curved "petals" of gypsum flowers like this one decorate some of the southernmost passages of Jewel Cave. NPS photo.

Figure 9. Formation Room. Explorers first entered the Formation Room on May 26, 1962. The stalactites, flowstone, and helictites in this room are now a highlight during cave tours. Photo courtesy of Art Palmer.

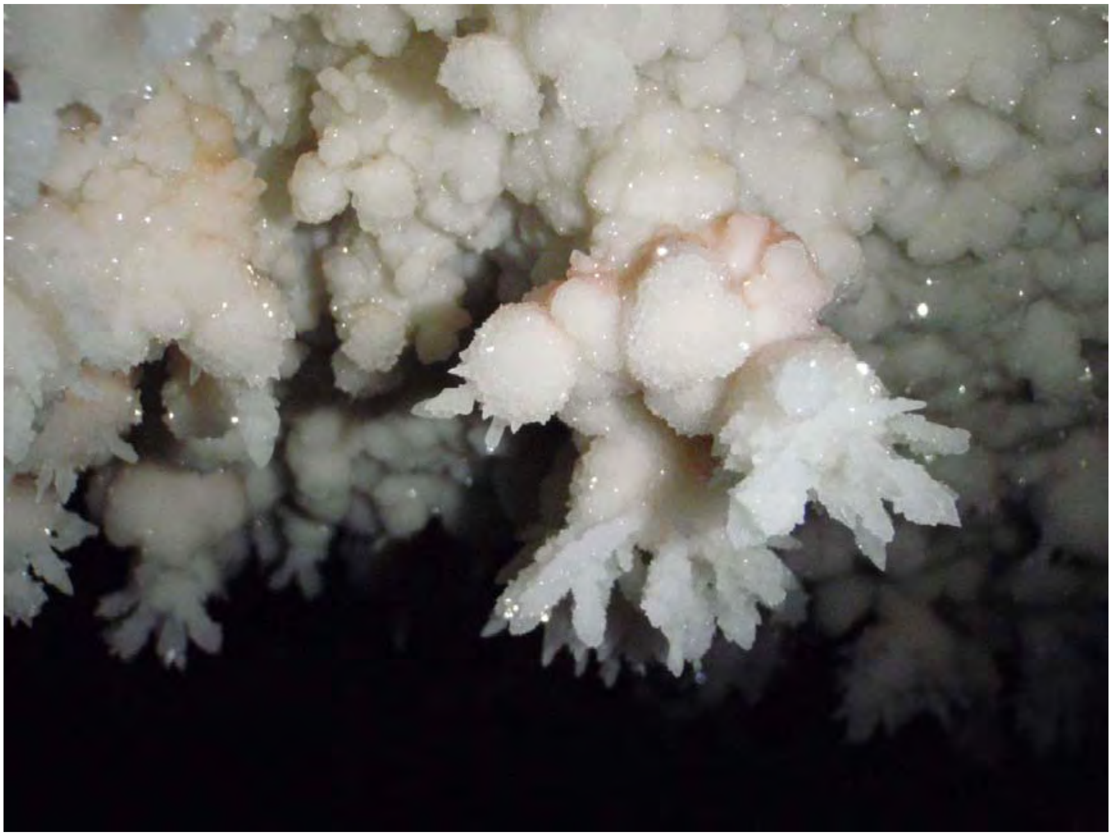


Figure 10. Frostwork. In Jewel Cave, sugary frostwork forms on walls, ceilings, ledges, floors, and other speleothems, most commonly with coralloids such as cave popcorn. NPS photo.

Figure 11. Growth Pattern of Spar. Growing in distinct layers, the thickness of calcite spar averages 15 cm (6 in) in Jewel Cave. Photo courtesy of Art Palmer.

Map Unit Properties

This section identifies characteristics of map units that appear on the Geologic Resources Inventory digital geologic map of Jewel Cave National Monument. The accompanying table is highly generalized and 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 Jewel Cave 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. 2) 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 provided the source data for the GRI digital geologic map for Jewel Cave National Monument:

DeWitt, E. 2004. Geologic map of the Mount Rushmore and Rapid City 60' × 60' quadrangle, South Dakota. Scale 1:100,000. Unpublished Mylar maps. Reston, VA: U.S. Geological Survey.

This map covers Jewel Cave National Monument, Wind Cave National Park, and Mount Rushmore National Memorial. Not all of the map units of DeWitt (2004) are included in the map unit properties table that follows. The table highlights the 11 units of interest for Jewel Cave National Monument and presents a tabular view of these strata. Geologic features and processes are often restricted to a particular formation (or deposit), and resource-management issues may also be associated with a particular unit. In addition to the map unit descriptions of the source map, the table incorporates information from Dyer (1961), Braddock (1963), Gries (1974), Palmer and Palmer (1989), Strobel et al. (1999); Benison and Goldstein (2000), and Neuendorf at al. (2005).

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 shapefile and coverage GIS formats, 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 with appropriate symbology. 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 for Jewel Cave National Monument

Age	Map Unit (Symbol)	Description and Distinctive Features	Mineral Resources	Paleontological Resources	Suitability for Development/Recreation	Depositional Setting
QUATERNARY (Holocene and Pleistocene)	Alluvial deposits (Qal)	Mud, silt, sand, and gravel; maximum thickness 10 m (33 ft)	Gravel deposits	None documented	Local aquifer where saturated	Holocene streams
	Terrace gravel and alluvial-fan deposits (Qt)	Gravel, sand, and silt; maximum thickness 30 m (100 ft); some higher elevation deposits could be Pliocene age	Gravel deposits	None documented	Potential for landslides on north- and east-facing scarps	Pleistocene and Pliocene (?) streams
TRIASSIC PERMIAN	Spearfish Formation (ŦPs)	Red shale and siltstone, minor limestone and gypsum; collapse structures (limestone-dolomite breccias) produced by the solution of anhydrite in early Cenozoic; 70–275 m (230–900 ft) thick	Gypsum	None documented	Minor deformational structures (e.g., small thrust faults, minor folds, dolomite breccia, and pull-apart structures [in gypsum])	Low-energy environment; flat, hot desert plain near the ocean
PERMIAN	Minnekahta Limestone (Pm)	Pinkish gray, thin-bedded limestone; 10–18 m (33–60 ft) thick	High-purity limestone used for cement and lime; source of crushed rock, ballast, riprap, and building stone; calcite and anhydrite crystals	Pelecypod shells, gastropod casts, fragmentary fish remains, possible algal structures	Minor deformational structures (e.g., small thrust faults, minor folds, dolomite breccia, and pull-apart structures [in gypsum]); subsidence structures from dissolution of anhydrite; aquifer	Marine
	Opeche Shale (Po)	Red to maroon shale and siltstone; 20–40 m (66–130 ft) thick	None documented	None documented	Unknown	Probable inland playa setting
PERMIAN PENNSYLVANIAN	Minnelusa Formation (Ᵽm)	Maximum thickness in the southwestern Black Hills 183 m (600 ft), with only the lower 107 m (350 ft) present in the immediate vicinity of Jewel Cave; collapse structures (breccias) associated with dissolution of underlying cave passages up into lithified subunit I, occur in the upper Minnelusa, several miles south of the known passages of Jewel Cave Subunit VI: Brecciated sandstone (limestone and anhydrite), varicolored but often brilliant red; some interbedded limestone; ~37 m (120 ft) thick Subunit V: Varicolored sandstones (bright red and yellow, light tan); limestone near base weathers like upper dolomite of subunit IV; ~37 m (120 ft) thick Subunit IV: Interbedded dolomite, sandstone, with uppermost layer of dolomite; sandstones may be bright red and yellow in places; ~37 m (120 ft) thick Subunit III: ~37 m (120 ft) thick total; subdivided into IIIm: limestone cap, often very sandy, ~6–9 m (20–30 ft) thick; and IIIs: varicolored sandstone, often quartzitic; well-cemented gravel quartzite near bottom; ~24–27 m (80–90 ft) thick Subunit II: Limestone interbedded with sandstones, and shales; prominent chert near the top; limestone beds up to 0.6 m (2 ft) thick; clastic beds up to 15 cm (6 in) thick; overall thickness ~15 m (50 ft) Subunit I: Cross-bedded, varicolored sandstone at base; red siltstone and mudstone at top; ~12 m (40 ft) thick	Oil produced from lower part of formation south of Jewel Cave National Monument; sand used for glass manufacturing; accessory minerals in sandstone: zircon, tourmaline, leucoxene, carbonate, pyrite with anhydrite, and fluorite	Millipore fossils are a distinctive marker on the upper bedding surface of IIIm	Sandstone intervals are good aquifers but probably contain only minor amounts of water near Jewel Cave Extensive minor faults and folds, predominantly reflecting the structure of the underlying Madison (Pahasapa) Limestone	Fluvial sand; deltaic and estuarine sediments
MISSISSIPPIAN	Pahasapa Limestone (Mp)	Called "Pahasapa" where it outcrops in the Black Hills and "Madison" in the sub-surface (Mike Wiles, Jewel Cave National Monument, written communication, November 27, 2007) Gray, tan, brown, and white limestone and dolomite; surfaces of natural outcrops often stained bluish gray or red Thickest limestone layer in Black Hills (80–210 m [260–690 ft]); ~137 m (450 ft) thick in the vicinity of Jewel Cave Three equally thick subunits: (1) upper subunit—massive fossiliferous limestone; (2) middle subunit—prominently bedded limestone and dolomites, with thicknesses ranging from 10 cm (4 in) to 3 m (10 ft), capped with 3–4.5 m (10–15 ft) of interbedded chert and carbonates; (3) lowest subunit—massive, prominently fractured dolomite	Chert separates lofts from main level of cave; calcite spar lining in cave and many smaller cavities lined with calcite; has been mined for limestone and dolomite	Fossil shells (brachiopods); colonial corals primarily in the upper 76 m (250 ft)	Hosts nearly all Black Hills caves; Jewel Cave occupies upper 76 m (250 ft) of formation; forms steep-walled cliffs in canyons; regional aquifer but supplies no water in monument	Platform carbonate deposited in shallow sea; records multiple sea-level advances and retreats and periodic high evaporation

Age	Map Unit (Symbol)	Description and Distinctive Features	Mineral Resources	Paleontological Resources	Suitability for Development/Recreation	Depositional Setting
MISSISSIPPIAN DEVONIAN	Englewood Limestone (MDe)	Pink to lavender shaley limestone; 10–20 m (33–66 ft) thick	None documented	Uppermost 2.4 m (8 ft) highly fossiliferous	Unknown	Marine
ORDOVICIAN CAMBRIAN	Deadwood Formation (O€d)	Glauconitic sandstone, shale, siltstone, and conglomerate; up to 200 m (650 ft) thick	Silica	None documented	Upper 30 m (100 ft) serves as aquifer for Jewel Cave National Monument water supply Extensive minor folds and faults	Sand deposits carried to shallow sea by streams; represents nearshore deposition of a regressing sea
PRECAMBRIAN (Early Proterozoic)	Metagabbro (Xgb)	Predominantly sill-like bodies of dark-green amphibolite, actinolite schist, or greenstone; though not lithologically distinct, minor chemical differences in selected samples indicate at least two distinct types of different ages; highly variable thicknesses up to 305 m (1,000 ft)	None	None documented	Jewel Cave Fault Zone originates in Precambrian rocks and resulted in pronounced offset of escarpment	Igneous intrusion
	Distal metagraywacke (Xgwd)	Grayish tan, siliceous schist; maximum thickness 3,600 m (11,810 ft)	Garnet, staurolite, and sillimanite			Rapid erosion, transportation, deposition, and burial of original sediments (marine turbidites) and later metamorphism

Geologic History

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

By the time shallow Cambrian seas began to move across and cover much of North America, erosion had reduced the Precambrian mountains to low relief (see fig. 2). The Precambrian rocks in the vicinity of Jewel Cave National Monument are metamorphic, having been altered during mountain building from their sedimentary (turbidites) and igneous (sill-like bodies) forms. For 470 million years, South Dakota was situated along the shoreline of an inland sea, either slightly above or slightly below sea level. The Deadwood Formation (primarily sandstone), Englewood Limestone (shaley limestone), Pahasapa Limestone (limestone with gypsum lenses), Minnelusa Formation (sandstone, limestone, and dolomite), Opeche Shale, Minnekahta Limestone, and Spearfish Formation (shale, siltstone, and bedded gypsum) represent marine, coastal, and inland (e.g., playa and desert plain) environments (see Map Unit Properties Table). Fluctuating sea levels resulted in shifting saltwater and freshwater conditions: At times of lower sea levels, groundwater displaced saline water, encouraging the deposition of dolomitic limestone. Streams transported sand and soluble minerals to the seas, resulting in sandstone. Mud became sedimentary siltstone. When evaporation was high and water circulation poor, gypsum was deposited.

The most significant Paleozoic event for Jewel Cave was the deposition of the Mississippian Pahasapa Limestone 350 million years ago; virtually all of Jewel Cave formed in this limestone. The steep-walled cliffs of the canyons in the monument are also composed of Pahasapa Limestone. The Pahasapa Limestone was deposited in a shallow sea; fossils such as brachiopods and colonial corals and lenses of gypsum are distinctive components of the unit. Dissolution of gypsum created voids (small pockets and fissures) into which the overlying limestone collapsed, creating breccia. Also, reddish brown, coarsely crystalline calcite filled many fractures and replaced gypsum. These calcite-filled fractures are continuous with the veins that developed the structures for boxwork, which formed later. In addition, chert formed in horizontal zones prior to final lithification of the Pahasapa Limestone (Deal 1962a). Because silica can remain in an amorphous state indefinitely (Hsü 1976), chert was most likely introduced as freshwater influxes of silica derived from weathering of Precambrian silicates of the North American craton (Mike Wiles, Jewel Cave, written communication, March 10, 2009). Because the Deadwood and Englewood formations covered the "paleo–Black Hills" (regional Precambrian rocks) during Mississippian time, the source of silica came from farther away. The Great Lakes area was the topographically highest region of the continent and the ultimate source for all Paleozoic rocks. Material was transported fluvially (as sediments and in solution) to the Paleozoic seas and then redistributed by ongoing transgression and regression of the shoreline. (Even the calcium in the limestone was transported this way; the sea life incorporated it into their shells.)

At the end of the Mississippian Period, sea level dropped, exposing the limestone to wet climatic conditions that resulted in dissolution of bedrock at the surface. Fresh groundwater displaced the original saline water in which the Pahasapa Limestone was deposited.

Sea level rose again in the early Pennsylvanian Period (about 320 million years ago). Streams deposited the Minnelusa Formation on top of the Pahasapa Limestone in fluvial, deltaic, and estuarine settings.

By the end of the Cretaceous Period (65.5 million years ago), as much as 2 km (1.2 mi) of sediment had been deposited on top of the Pahasapa Limestone (see Map Unit Properties Table). A layer of white calcite (dogtooth spar) was deposited in preexisting cavities that had not filled with sediment; quartz crystals covered the calcite as Laramide uplift began about 65 million years ago.

Marine domination ended with the Laramide Orogeny (mountain-building event). Uplift of the Black Hills proper began about 58 million years ago and was completed by about 54 million years ago (Lisenbee and DeWitt 1993). The central uplifted core of the Black Hills is composed of Precambrian metamorphic and igneous rocks. Harney Peak and Mount Rushmore, northeast of Jewel Cave National Monument, exemplify the uplift. The limestone, sandstone, and shales deposited in the Paleozoic and Mesozoic seas were eroded to form roughly concentric rings around the flanks of the elongated, dome-shaped Black Hills. Paleozoic and Mesozoic units dip away from the uplifted Black Hills at angles exceeding 10° in some places but decreasing with distance away from the uplift (Strobel et al. 1999). Significant for the genesis of Jewel Cave is the resultant fracturing in conjunction with the orogeny (see "Faults and Joints" section). Both joints and faults correlate with the local structure developed during the Laramide uplift, though differ significantly from the regional structure. Prominent jointing determined the pattern of nearly every cave passage (Palmer 1991).

Early in Cenozoic time (60–40 million years ago) the main passages of Jewel Cave formed under humid conditions. At the surface, canyons were forming, and their locations influenced groundwater hydrology. The loft level formed primarily in the fractured, brecciated zone. The chert-level passages formed between the lofts and the main level. The main level formed in massive limestone with minor chert beds. The lower and basement levels formed in dolomitic limestone (see "Cave Complexity and Levels" section). The entire known cave system developed under phreatic (saturated zone below the water table) conditions but was not necessarily the product of simple artesian groundwater flow, infiltration from the surface, or hydrothermal water rising from depth (Palmer and Palmer 1989). Advocates of the "mixing model" (see "Cave Genesis" section) contend that cave formation is the result of mixing between two or more of these water sources, which produced a zone of solutionally aggressive water.

As cave formation ceased, a lengthy episode of spar development occurred. The calcite wall coatings, including the "jewels," are subaqueous deposits from water brought to supersaturation, probably by heating (Bakalowicz et al. 1987; Palmer and Palmer 1989). However, remnants of aragonite needles between layers in the spar indicate periodic subaerial exposure (Palmer and Palmer 1989). Black manganese minerals were subsequently deposited under continuing subaqueous conditions in all cave levels, with the greatest thicknesses (of more than a meter) in the lower cave level (see "Manganese and Other Deposits" section).

Regional uplift in late Pliocene or early Pleistocene led to renewed downcutting at the surface (Redden 1999). As erosion and intermittent uplift continued, as well as a change to a drier climate, Jewel Cave slowly drained. The water table fluctuated considerably during its overall gradual descent to the present level. Today, Jewel Cave lies completely above the water table, and the Pahasapa Limestone in the vicinity of the national monument no longer hosts the Madison aquifer (Mike Wiles, Jewel Cave National Monument, written communication, March 10, 2009). Studies indicate that during the last 400,000 years, the water table lowered at a steady rate of 0.4 m (1.3 ft) each 1,000 years (Ford et al. 1993). Before final drainage, however, re-solution caused previously deposited crystals of dogtooth spar to become etched, rounded, and sometimes removed altogether (Deal 1962a), as in the loft and chert levels. Minor amounts of gypsum from either the Minnelusa Formation or Pahasapa Limestone reprecipitated in the main and lower levels. Also, preferential weathering created boxwork in areas where the calcite-crystal coating had fallen away from the walls and ceiling.

Horizontally (and from a surface perspective), a zone of dripping water and dripstone formed in cave passages beneath and adjacent to canyons. Gypsum reprecipitated in passages farther from the canyons, with more in the lower levels and virtually none in the loft levels. In passages farthest from the canyons, little to no gypsum occurs (Olson 1977).

After the final draining of the cave, loss of carbon dioxide to the cave atmosphere from dripping and seeping water caused precipitation of travertine, hydromagnesite, and aragonite in the form of subaerial cave deposits such as draperies, balloons, and frostwork. Joints and faults provided flow paths for infiltrating water. Fractures in the rock are also responsible for cave breakdown and may have allowed possible access to hydrothermal solutions.

Although the Black Hills were topographically high during the Pleistocene Epoch, no glaciers formed in the area. Nevertheless, the fluctuating climate influenced the growth of speleothems as wetter conditions resulted in more water infiltrating the Pahasapa Limestone. Calcite helictites formed at or near the water table, some in pools. Calcite rafts formed on the water surfaces, ultimately settling to the bottom of pools; rafts continue forming today in a few localized areas in Jewel Cave. Speleothems that formed in the drained cave passages are the most recent to decorate the cave. The most common vadose (aerated zone above the water table) speleothems in Jewel Cave are aragonite needles and calcite popcorn, but many other types occur (see "Speleothems" section).

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.

allogenic. Generated elsewhere.

aragonite. A mineral; one of the three forms of calcium carbonate ($CaCO_3$); calcite and vaterite are the other forms.

aquifer. Rock or sediment that is sufficiently porous, permeable, and saturated to be useful as a source of water.

authochthonous. Formed or produced in the place where now found. Similar to "authigenic," which refers to constituents rather than whole formations.

axial plane. A planar axial surface dividing the two limbs of a fold.

axial surface. The surface that passes through successive hinge lines in a stack of folded surfaces and divides the two limbs of a fold.

axis (fold). A straight line approximation that when moved parallel to itself generates the shape of a fold (see and use "hinge line").

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 lithostratigraphic unit, distinguishable from beds above and below, and commonly ranging in thickness from one centimeter to a meter or two.

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.

block (fault). A crustal unit bounded by faults.

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

breccia. A coarse-grained, generally unsorted, sedimentary rock consisting of cemented angular clasts.

chert. An extremely hard sedimentary rock with conchoidal (smoothly curved surface) fracturing. It consists chiefly of interlocking crystals of quartz (syn: flint).

calcite. Calcite is a carbonate mineral and the most stable form of calcium carbonate ($CaCO_3$). The other forms are the minerals aragonite and vaterite. Aragonite will change to calcite at 470°C (878°F), and vaterite is even less stable.

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

clastic. Said of rock or sediment made of fragments of preexisting rocks or minerals.

clay. Clay minerals or sedimentary fragments the size of clay minerals (<1/256 mm [0.00015 in]).

cleavage (mineral). The tendency of a mineral to break preferentially in certain directions along planes of weaknesses in the crystal structure.

cleavage (rock). The tendency of rock to break along parallel planes that correspond to the alignment of platy minerals.

coprolite. Fossil dung (a trace fossil).

cross section. A graphical interpretation of geology, structure, and/or stratigraphy in the third (vertical) dimension.

crystalline. Having a regular molecular structure (orderly, repeating arrangement of atoms) that may be outwardly expressed by plane faces.

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

discordant. Having contacts that cut across or are set at an angle to the orientation of adjacent rocks.

dome. A doubly plunging anticline that dips radially in all directions.

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

evaporite. Chemically precipitated mineral(s) formed by the evaporation of solute-rich water under restricted conditions.

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

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

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

glauconite. Derived from the Greek glaucos (γλαυκος) meaning "gleaming" or "silvery" to describe the blue-green color, presumably relating to the sheen and blue-green color of the sea's surface. Normally, glauconite is considered diagnostic of continental shelf marine depositional environments with slow rates of accumulation.

hydromagnesite. A white, earthy mineral—$Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$. It occurs as amorphous masses or chalky crusts in caves.

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

intrusion. A body of igneous rock that invades older rock. The invading rock may be a plastic solid or magma that pushes its way into the older rock.

isotope. An atom of an element having the same atomic number (i.e., same number of protons in the nucleus) but differing mass number (i.e., the sum of protons and neutrons in the nucleus).

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

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

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

limb. Either side of a structural fold.

lineament. A linear topographic feature of regional extent that probably reflects crustal structure.

matrix. The groundmass of an igneous rock or the finer grained material enclosing the larger grains in a sedimentary rock; also the rock or sediment in which a fossil is embedded.

metamorphic. Pertaining to the process of metamorphism or its results.

metamorphism. Literally, "change in form." Metamorphism occurs in rocks through mineral alteration, genesis, and/or recrystallization from increased heat and pressure.

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

orogeny. A mountain-building event.

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

overburden. Loose or unconsolidated rock material that overlies a mineral deposit and must be removed before mining; also the upper part of a sedimentary deposit, compressing and consolidating the material below.

paleofill. Ancient sediment that filled caves and sinkholes that existed before present cave passages formed.

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

partings. A plane or surface along which a rock readily separates.

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

platform. Any level or nearly level surface, ranging in size from a terrace or bench to a plateau or peneplain.

pseudomorph. A mineral whose outward crystal form is that of another mineral; described as being "after" the mineral whose outward form it has (e.g., quartz after fluorite).

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

radiometric age. An age in years determined from radioisotopes and their decay products.

recharge. Infiltration processes that replenish groundwater.

rock. An aggregate of one or more minerals.

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

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

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

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

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

silica. Silicon dioxide (SiO_2), occurring in crystalline, amorphous, and impure forms (as in quartz, opal, and sand respectively).

sill. A tabular, igneous intrusion that is concordant with the country rock.

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

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

slickenside. A smoothly polished and commonly striated surface representing deformation of a fault plane.

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

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

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

spring. A site where water flows out at the surface due to the water table intersecting the ground surface.

stock. An igneous intrusion exposed at the surface; <100 km^2 (40 mi^2) in size.

strata. Tabular or sheetlike masses or distinct layers of rock.

stade. A substage of a glacial stage marked by a glacial readvance.

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

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

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

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

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

terrace. A relatively level bench or steplike surface breaking the continuity of a slope (see "marine terrace" and "stream terrace").

travertine. A finely crystalline massive deposit of calcium carbonate, of white, tan, or cream color, formed by chemical precipitation from solution in surface water or groundwater, as around mouths of springs, especially hot springs. It also occurs in limestone caves. It is a spongy, less compact variety of tufa (see "tufa").

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

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

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

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

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

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.

Alexander E. C. Jr., M. A. Davis, and S. C. Alexander. 1989. Final report: Hydrologic study of Jewel Cave/Wind Cave. Contract CX-1200-5-A047. Minneapolis, MN: Department of Geology and Geophysics, University of Minnesota.

Bakalowicz, M. J., D. C. Ford, T. E. Miller, A. N. Palmer, and M. V. Palmer. 1987. Thermal genesis of dissolution caves in the Black Hills, South Dakota. *Geological Society of America Bulletin* 99(December 1987):729–738.

Benison, K. C., and R. H. Goldstein. 2000. Sedimentology of ancient saline pans: An example from the Permian Opeche Shale, Williston Basin, North Dakota, U.S.A. *Journal of Sedimentary Research* 70(1):159–169.

Braddock, W. A. 1963. *Geology of the Jewel Cave SW quadrangle, Custer County, South Dakota*. Geology and Uranium Deposits of the Southern Black Hills. Bulletin 1063-G. Washington, D.C.: U.S. Geological Survey, prepared on behalf of the U.S. Atomic Energy Commission.

Cahill, T., and M. Nichols. 1991. Charting the splendors of Lechuguilla Cave. *National Geographic* 179(3):34–59.

Conn, H. W. 1966. Barometric wind in Wind and Jewel caves, South Dakota. *The National Speleological Society Bulletin* 28(2):55–69.

Conn, H., and J. Conn. 1977. (1981 revised printing). *The Jewel Cave Adventure: Fifty miles of discovery under South Dakota*. St. Louis, MO: Cave Books.

Davis, M. A., E. C. Alexander Jr., and S. C. Alexander. 1991. Dye traces at Wind and Jewel caves. *NSS Bulletin* 53(1):26.

Deal, D. E. 1962a. Cavern formation in the Black Hills of South Dakota, with special reference to Jewel Cave. *NSS News* 20(8, part 2):117–120.

Deal, D. E. 1962b. Geology of Jewel Cave National Monument, Custer County, South Dakota, with special reference to cavern formation in the Black Hills. MS thesis, University of Wyoming.

Deal, D. E. 1966. Mud stalagmites in Jewel Cave, South Dakota. *Journal of Cave and Karst Studies* 28(2):106–107.

Deal, D. E. 1968. Origin and secondary mineralization of caves in the Black Hills of South Dakota, USA. In *Proceedings of the 4th International Congress of Speleology*, 1965, Yugoslavia, vol. 3, 67–70. Ljubljana, Yugoslavia: Speleological Society of Yugoslavia.

DeWitt, E. 2004. *Geologic map of the Mount Rushmore and Rapid City 60' x 60' quadrangle, South Dakota*. Scale 1:100,000. Unpublished Mylar maps. Reston, VA: U.S. Geological Survey.

Dublyansky, V. N. 1980. Hydrothermal karst in the alpine fold belt of southern parts of U.S.S.R. *Kars I Speleologia* (Poland) 3(12):18–36.

Dyer, C. F. 1961. *Geology and occurrence of ground water at Jewel Cave National Monument, South Dakota*. Hydrology of the Public Domain. Water-supply paper 1475-D. Washington, D.C.: U.S. Geological Survey.

Elliott, W. R. 1997. *A survey of ecologically disturbed areas in Carlsbad Cavern, New Mexico*. Report to Carlsbad Caverns National Park. Carlsbad, NM: National Park Service.

Elliott, W. R. 2000. Conservation of the North American cave and karst biota. In *Ecosystems of the World 30: Subterranean Ecosystems*, ed. H. Wilkens, D. C. Culver, and W. F. Humphreys, chapter 34, 665–689. Amsterdam: Elsevier.

Elliott, W. R. 2006. Biological dos and don’ts for cave restoration and conservation. In *Cave Conservation and Restoration*, ed. V. Hildreth-Werker and J. Werker, 33–46. Huntsville, AL: National Speleological Society.

Ellis, A. J., and W. A. J. Mahon. 1977. *Chemistry and geothermal systems*. New York: Academic Press.

Fagnan, B. A. 2002. Correlation of surface geology with subsurface geology and karst development at Jewel Cave National Monument, Custer County, South Dakota. Structural geology poster presented at 2002 Geological Society of America Annual Meeting, Denver, Colorado, October 23–30, 2002. http://gsa.confex.com/gsa/2002AM/finalprogram/abstract_41178.htm.

Ford, D. C. 1989. Features of the genesis of Jewel Cave and Wind Cave, Black Hills, South Dakota. *The NSS Bulletin* 51(December 1989):100–110.

Ford, D. C., J. Lundgerg, A. N. Palmer, M. V. Palmer, W. Dreybrodt, and H. P. Schwarcz. 1993. Uranium-series dating of the draining of an aquifer: The example of Wind Cave, Black Hills, South Dakota. *Geological Society of America Bulletin* 105(February 1993):241–250.

Ford, D., H. Schwarcz, H. Stuart-Williams, and N. Swinburne. 1997. A long interglacial and instadial record in North American mid-continent from vadose and phreatic speleothems, Jewel Cave and Wind Cave, South Dakota, U.S.A. In *Proceedings of the 12th International Congress of Speleology*, La Chaux-de-Fonds, Switzerland, August 10–17, 1997, vol. 1, 5. La Chaux-de-Fonds, Switzerland: Swiss Speleological Society (SSS/SGH).

Ford, D. C., H. P. Schwarcz, H. L. Q. Stuart-Williams, N. H. M. Swinburne, and J. Londberg. 1998. Climates of the last two interglacials in the North American mid-continent from vadose and phreatic speleothem records. In *Program with Abstracts 23*, Geological Association of Canada, Mineralogical Association of Canada, and Canadian Geophysical Union Joint Annual Meeting, A56–A57. Waterloo, ON, Canada: Geological Association of Canada.

Gries, J. P. 1974. *Mineral resources of Black Hills area, South Dakota and Wyoming*. Preliminary report 194, September 1974. Rapid City, SD: United States Department of the Interior, Bureau of Mines.

Henderson, E. P. 1949. Some unusual formations in Skyline Caverns, Virginia. *National Speleological Society Bulletin* 11:31–34.

Hill, C., and P. Forti. 1986. *Cave minerals of the world*. Huntsville, AL: National Speleological Society.

Hill, C., and P. Forti. 1997. *Cave minerals of the world*. 2nd edition. Huntsville, AL: National Speleological Society.

Howard, A. 1964. Model for cavern development under artesian ground water flow, with special reference to the Black Hills. *National Speleological Society Bulletin* 26(1):7–16.

Hsü, K. J. 1976. Paleoceanography of the Mesozoic Alpine Tethys. Special Paper 170. Boulder, CO: Geological Society of America.

Jablonsky, P., S. Kraemer, and B. Yett. 1993. Lint in caves. In *1993 National Cave Management Symposium Proceedings,* ed. D. L. Pate, Carlsbad, New Mexico, October 27–30, 1993, 73–81. Huntsville, AL: National Cave Management Symposium Steering Committee.

Kastning, E. H. 1977. Faults as positive and negative influences on groundwater flow and conduit enlargement. In *Hydrologic Problems in Karst Regions*, ed. R. R. Dilamarter and S. C. Csallany, 193–201. Bowling Green, KY: Western Kentucky University.

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

Lange, A. L. 1990. *Natural-potential profiles at Jewel Cave National Monument*. Project 13 for Jewel Cave National Monument and University of Wyoming–National Park Service Research Center (8 August 1990). San Diego, CA: The Geophysics Group.

Lininger, J. L. 2002. The unique mineralogy of South Dakota's Jewel Cave. *Matrix* 10(2):81–90.

Lisenbee, A. L., and E. DeWitt. 1993. Laramide evolution of the Black Hills uplift. In *Geology of Wyoming*, ed. A. W. Snoke, J. R. Steidtman, and S. M. Roberts. Memoir 5. Laramie, WY: Geological Survey of Wyoming.

Loskot, C. L. 1973. Deposition of cave material in Wind Cave. MS thesis, South Dakota School of Mines and Technology.

Maltsev, V. A. 1994. Aerosol origin of speleothems: A critical view on current hypotheses. In *Problems of Physical Speleology*, 89–99. Moscow: Moscow Institute of Physics and Technology (in Russian).

Miller, S. 2006. Hills cave now second longest in the world. *Rapid City Journal*, February 16.

Moore, G. W. 1952. Speleothem—A new cave term. *National Speleological Society News* 10(6):2.

Moore, G. W., and N. Sullivan. 1997. *Speleology: Caves and the cave environment*. St. Louis, MO: Cave Books.

National Park Service. 1990. Cave radiation safety and occupational health. In *NPS-14*, release 2 (December). Washington, D.C.: NPS Occupational Safety and Health Program.

National Park Service. 1991. *Statement for management, Jewel Cave National Monument*. Custer, SD: Jewel Cave National Monument.

National Park Service. 1994a. *Final general management plan, environmental impact statement, Jewel Cave National Monument*. Denver, CO: United States Department of the Interior, National Park Service, Denver Service Center.

National Park Service. 1994b. *Jewel Cave National Monument, water resources scoping report.* Technical report NPSINRWRDINRTR-94/36. Fort Collins, CO: Water Resources Division. http://www.nature.nps.gov/water/Scoping_Reports/jewel_cave_screen.pdf.

Nelson, J. 2000. *Glenwood Caverns and the historic Fairy Caves*. Glenwood Springs, CO: Blue Chicken, Inc.

Neuendorf, K. K. E., J. P. Mehl Jr., and J. A. Jackson. 2005. *Glossary of geology*. 5th edition. Alexandria, VA: American Geological Institute.

Ohms, R., and M. Reece. 2002. Using GIS to manage two large cave systems, Wind and Jewel caves, South Dakota. *Journal of Cave and Karst Studies* 64(1):4–8.

Ohms, R., and M. Wiles. 2006a. Jewel Cave National Monument: A new way to kill algae. *Inside Earth* 9(1):6–7.

Ohms, R., and M. Wiles. 2006b. Jewel Cave National Monument: The potential extent of Jewel Cave. *Inside Earth* 9(1):8.

Olson, R. 1977. The hypogene ecology of Jewel Cave National Monument, Custer County, South Dakota. MS thesis, University of Illinois.

Olson, R. A. 1991. The ultrastructure and composition of hydromagnesite balloons from Jewel Cave National Monument and Carlsbad Caverns National Park. *The NSS Bulletin* 53(1):59.

Palmer, A. N. 1981. *The geology of Wind Cave*. Hot Springs, SD: Wind Cave Natural History Association.

Palmer, A. N. 1984. *Jewel Cave: A gift from the past*. Hot Springs, SD: Wind Cave/Jewel Cave Natural History Association.

Palmer, A. N. 1991. Origin and morphology of limestone caves. *Geological Society of America Bulletin* 103(January):1–21.

Palmer, A. N., and M. V. Palmer. 1989. Geologic history of the Black Hills caves, South Dakota: *The NSS Bulletin* 51(December):72–99.

Palmer, A. N., and M. V. Palmer, 1995. The Kaskaskia paleokarst of the northern Rocky Mountains and Black Hills, northwestern U.S.A. *Carbonates and Evaporites* 10(2):148–160.

Redden, J. A. 1999. Relationship between Tertiary erosion surfaces and solution structures in the Black Hills, South Dakota and Wyoming. In *Hydrology of the Black Hills*, Proceedings of the 1999 Conference on the Hydrology of the Black Hills, ed. M. L. Strobel, A. D. Davis, J. F. Sawyer, P. H. Rahn, C. J. Webb, and C. A. Naus, 80–86. Bulletin 20. Rapid City, SD: South Dakota School of Mines and Technology.

Redden, J. A., and E. DeWitt. 2008. *Maps showing geology, structure, and geophysics of the central Black Hills, South Dakota*. Scientific Investigations Map 2777. Reston, VA: U.S. Geological Survey.

Santucci, V. L., J. Kenworthy, and R. Kerbo. 2001. *An inventory of paleontological resources associated with National Park Service caves*. Geologic Resources Division Technical Report NPS/NRGRD/GRDTR-01/02 (September). Lakewood, CO: National Park Service, Geologic Resources Division.

Schubert, B., B. Agenbroad, and L. Agenbroad. 1995. *The excavation of two test units in the dry entrance, Jewel Cave National Park, South Dakota*. Report prepared for Jewel Cave National Monument, Superintendent K. Cannon, October 11, 1995. Custer, SD: National Park Service.

Schilberg, G., and D. Springhetti. 1988. Jewel Cave. In *Caves and Associated Features of the Black Hills Area, South Dakota and Wyoming*. Guidebook for the Forty-Fifth Annual Convention, National Speleological Society, Hot Springs, South Dakota, June 27–July 1, 1988, 67–80. Huntsville, AL: National Speleological Society.

Strobel, M. L., G. J. Jarrell, J. F. Sawyer, J. R. Schleicher, and M. D. Fahrenbach. 1999. *Distribution of hydrogeologic units in the Black Hills area, South Dakota*. Scale 1:100,000, 3 sheets. Hydrologic Investigations Atlas HA-743. Denver, CO: U.S. Geological Survey.

Tullis, E. L., and J. P. Gries. 1938. Black Hills caves. *Black Hills Engineering* 24:233–271.

U.S. Environmental Protection Agency. 2005. *A citizen's guide to radon: The guide to protecting yourself and your family from radon*. EPA 402-K02-006. Washington, D.C.: U.S. EPA. http://www.epa.gov/radon/pdfs/citizensguide.pdf.

Wiles, M. E. 1980. The Pahasapa Limestone of the Black Hills, South Dakota. Unpublished paper. Rapid City, SD: South Dakota School of Mines and Technology.

Wiles, M. E. 1992. Infiltration and Wind and Jewel Caves, Black Hills, SD. MS thesis, South Dakota School of Mines and Technology.

Wiles, M. 1998a. Jewel Cave exploration, Jewel Cave National Monument, South Dakota. In *1998 NSS Convention Program,* Sewanee, Tennessee, August 3–7, 1998, 52. American Exploration Session. Huntsville, AL: National Speleological Society.

Wiles, M. 1998b. Off-site housing at Jewel Cave. *Inside Earth* 1(2):6–7.

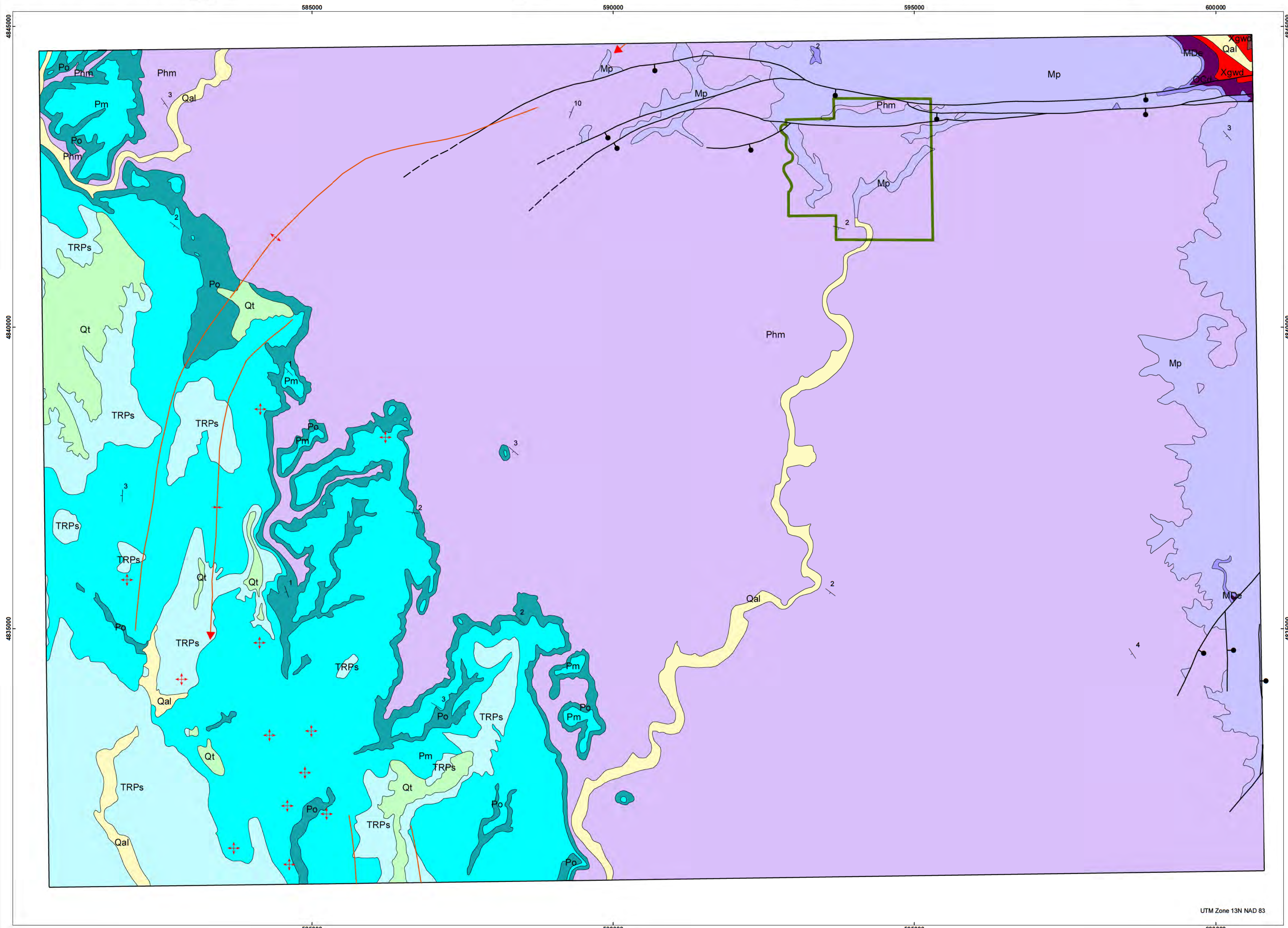
Wiles, M. E. 2004. Mapping surface geology to protect cave and karst resources. *Geological Society of America Abstracts with Programs* 36(5):167.

Wiles, M. E. 2005. Recent exploration at Jewel Cave. 2005 NSS convention abstracts. *Journal of Cave and Karst Studies* 67(3):198.

Appendix A: Geologic Map Graphic

The following page is a snapshot of the geologic map for Jewel Cave National Monument. 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).

Geologic Map of Jewel Cave National Monument



NPS Boundary

Geologic Attitude Observation Localities

- strike and dip of beds
- fold plunge arrow head
- fault down-thrown block indicator
- anticline
- syncline
- dome

Folds

- know or certain
- approximate

Normal Faults

- known or certain
- approximate

Geologic Contacts

- known or certain
- quadrangle boundary

Geologic Units

- Qal - Alluvial deposits
- Qt - Terrace gravel and alluvial-fan deposits
- TRPs - Spearfish Formation
- Pm - Minnekahta Limestone
- Po - Opeche Shale
- Phm - Minnelusa Formation
- Mp - Pahasapa Limestone
- MDe - Englewood Limestone
- Oed - Deadwood Formation
- Xgb - Metagabbro
- Xgwd - Distal metagraywacke

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:

DeWitt, Ed. 2004. Geologic map of the Mount Rushmore and Rapid City 60' x 60' Quadrangle, South Dakota. Scale 1:100,000. USGS unpublished mylar maps.

Digital geologic data and cross sections for Jewel Cave 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/

Produced by the Geologic Resources Inventory

January 2009

Jewel Cave National Monument
Geologic Resources Inventory Report

Natural Resource Report NPS/NRPC/GRD/NRR—2009/084

National Park Service
Acting Director • Dan Wenk

Natural Resource Stewardship and Science
Associate Director • Bert Frost

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

Geologic Resources Division
Chief • Dave Steensen
Planning Evaluation and Permits Branch Chief • Carol McCoy
Geosciences and Restoration Branch Chief • Hal Pranger

Credits
Author • Katie KellerLynn
Review • Mike Wiles and Andrea Croskrey
Editing • Mary Kidd
Digital Map Production • Stephanie O'Meara
Map Layout Design • Aaron Rice

NPS D-52, March 2009

National Park Service
U.S. Department of the Interior

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

www.nature.nps.gov