National Park Service
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Natural Resource Program Center

Wind Cave National Park
Geologic Resources Inventory Report

Natural Resource Report NPS/NRPC/GRD/NRR—2009/087

THIS PAGE:
Calcite Rafts record former water levels at the Deep End a remote pool discovered in January 2009.

ON THE COVER:
On the Candlelight Tour Route in Wind Cave boxwork protrudes from the ceiling in the Council Chamber.

NPS Photos: cover photo by Dan Austin, inside photo by Even Blackstock

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

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Executive Summary

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

Wind Cave National Park is situated on the easternmost uplift of the Great Plains, on the southeastern flank of the Black Hills. Wind Cave itself occurs in Mississippian Pahasapa Limestone, regionally known as Madison Limestone, which encircles the Precambrian core of the Black Hills. Wind Cave is one of the most complex cave systems in the world. Known as a network maze cave, Wind Cave contains multiple levels of passages controlled by joints and bedding planes. The cave hosts a variety of secondary cave formations and primary dissolution features, the hallmark being the cave's boxwork, which is unequalled in the world. Wind Cave is currently ranked as the third longest cave in the United States and the fourth longest cave in the world. It was the first cave to be designated as a national park.

Participants in the 2001 Geologic Resources Inventory (GRI) workshop identified only one issue of concern for resource managers—slumping in the Minnelusa Formation along Highway 385 and in Wind Cave Canyon as a result of road construction. Other issues that may require management attention include the following:

- Airflow
  Wind Cave is a barometrically breathing cave, and its discovery in 1881 is attributed to airflow. Wind Cave has two natural entrances, one of which has been artificially enlarged, and six associated natural blowholes. At the Natural Entrance and Walk-In Entrance, investigators have documented some of the strongest airflow speeds of cave winds in the world. The velocities of barometric winds are indicators of a cave's volume. On the basis of estimates for Wind Cave, resource managers infer that between 2% and 5% of the total cave passages have been discovered.
- Impacts on the Cave Environment
  Numerous investigators have studied the climatological conditions of Wind Cave, but early development resulted in undocumented changes to cave conditions, making assessment of changes in temperature, evaporation, and biota difficult. Introduction of ultraviolet light and foreign materials such as lint is also changing the cave environment.
- Exploration and Inventory
  Resource managers at the national park analyze, process, and retain all data collected during cave surveys. Surveyors use preprinted data forms and follow established park protocols. Because inventorying is now part of the survey process, the inventory of Wind Cave will not be complete until the cave has been fully explored, which "will not be for quite some time" (Nepstad 1991, p. 226).
- Fluvial Features and Processes
  Three perennial streams flow through Wind Cave National Park. Depending on the time of year and precipitation, several other streams may flow. Both perennial and intermittent streams lose their flow to the subsurface. The Natural Entrance of Wind Cave and the entire length of Coyote Cave—the second longest cave in the park—are susceptible to flash floods. Most park infrastructure lies outside of the 100-year floodplain.
- Geologic Hazards
  In addition to flooding, hazards include mass wasting, for example, slumping in the Minnelusa Formation along Highway 385 and rockfall (cave breakdown) in Wind Cave. Earthquakes also occur.
- Mining
  Though past mining has left some abandoned quarries, no significant mineral or energy resources are known to exist in the park. Furthermore, there are no valid mining claims within park boundaries. Nevertheless, Precambrian rocks throughout the region contain feldspar, which is mined primarily for its use in ceramics, porcelain, and glass. The park's 1993 general management plan and 1994 resource management plan identified a feldspar mine just outside the park's boundaries, and park managers know of an abandoned feldspar mine that may be inside the park. Researchers from Albion College in Michigan are mapping the Precambrian rocks in the park; park managers have requested that these researchers document any past mining activities.
- Surface-Subsurface Relationships
  Adjacent watersheds and land above the cave are essentially part of the cave and karst system. Park managers consider all activities within these areas with the protection of cave and karst resources in mind. Geographic Information System (GIS) technology has greatly facilitated an understanding of cave-surface relationships. Combining the locations of survey stations and associated data in the cave with surface features allows managers to view spatial relationships and make informed management decisions.

Introduction

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

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 Wind Cave National Park

Congress originally established Wind Cave National Park on January 9, 1903, to protect the cave from commercial exploitation. Subsequent legislation on August 10, 1912, established Wind Cave National Game Preserve on the surface of Wind Cave National Park. This action created a permanent range for a national herd of bison, which had been driven to the brink of extinction by natural and anthropogenic factors (Halbert et al. 2007). The preserve also protects other native game animals, such as pronghorn antelope and elk, as well as prairie dogs and black-footed ferrets. In 1935 the Department of the Interior, National Park Service, became the steward of the game preserve, which the U.S. Department of Agriculture had managed since 1912. Since its establishment, the purpose of Wind Cave National Park has evolved from protecting cave features to preserving both surface and subsurface resources.

Protection of Cave Resources

The landmark Federal Cave Resources Protection Act of 1988 (Public Law 100-691) created a major impetus for protecting and managing caves and karst 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, manage the caves, and disseminate information concerning them.

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.

Regional Geologic Setting

Situated in the Black Hills of South Dakota, Wind Cave National Park is actually two parks in one: an above-ground prairie park and an underground cavern park. At the surface, visitors can hike 48 km (30 mi) of trails, including the popular Rankin Ridge. In addition, visitors have their choice of five different cave tours (fig. 1). The combination of surface trails and underground passages provides an ideal setting for studying geologic processes and features and the interrelationship between surface and subterranean phenomena.

The landscape above ground has changed little since the late 1800s. The few changes include encroachment of pine forest on the prairie and the removal of some ranch and farm buildings. The park's rolling grasslands are one of the few remnants of native mixed-grass prairie in the country. The national park hosts a vast ecotone where eastern plants and animals reach their western extent, and western plants and animals reach their eastern extent.

As part of the Great Plains physiographic province, the park shares a similar regional setting with Mount Rushmore National Memorial, Badlands National Park, and Jewel Cave National Monument in South Dakota; Theodore Roosevelt National Park in North Dakota; Devils Tower National Monument in Wyoming; Agate Fossil Beds National Monument in Nebraska; Bent's Old Fort National Historic Site in Colorado; and Capulin Volcano National Monument in New Mexico (fig. 2). 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. The Great Plains 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, and Paleozoic (360–340 million years ago) limestone contains the remarkable Wind and Jewel cave systems. The scenic badlands of Theodore Roosevelt National Park developed in Paleocene (65.5–55.8 million years ago) strata. Magma generated during and after the Laramide uplift of the Black Hills (58–54 million years ago) produced a number of localized intrusions, including Devils Tower. 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 the story of mammal 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 of Capulin Mountain. Much geologic time is represented (fig. 3), and all of these phenomena are part of the Great Plains.

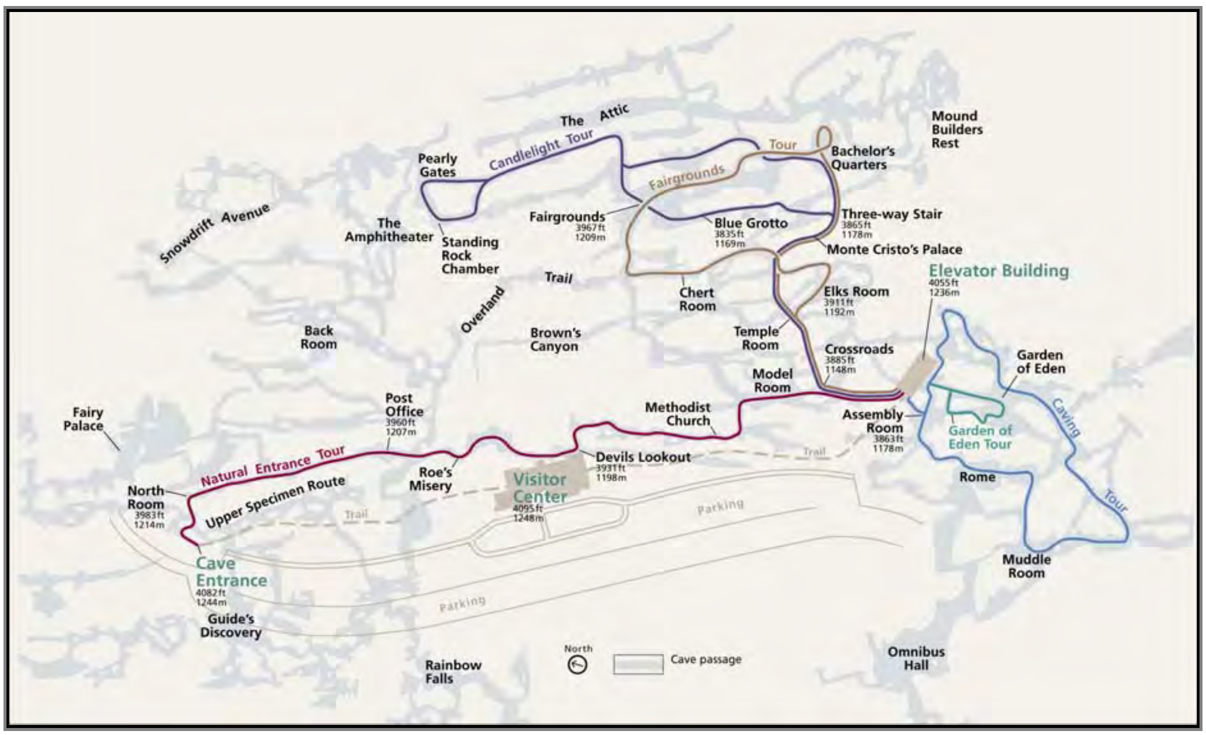

Figure 1. Cave Tour Map. Visitors to Wind Cave can choose from five cave tours: Candlelight Tour, Fairgrounds Tour, Garden of Eden Tour, Natural Entrance Tour, and Caving (or Wind Cave) Tour. The tours highlight some of the larger rooms in the developed area of Wind Cave and the cave's famous boxwork. The Caving Tour takes participants away from developed trails. Visitors can also explore the surface of the park on ranger-led walks. NPS graphic (Harpers Ferry Center).

Figure 2. The Great Plains Physiographic Province. Wind Cave National Park 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), Jewel Cave National Monument (South Dakota), Mount Rushmore National Memorial (South Dakota), and Theodore Roosevelt National Park (North Dakota). Graphic by Melanie Ransmeier (National Park Service).

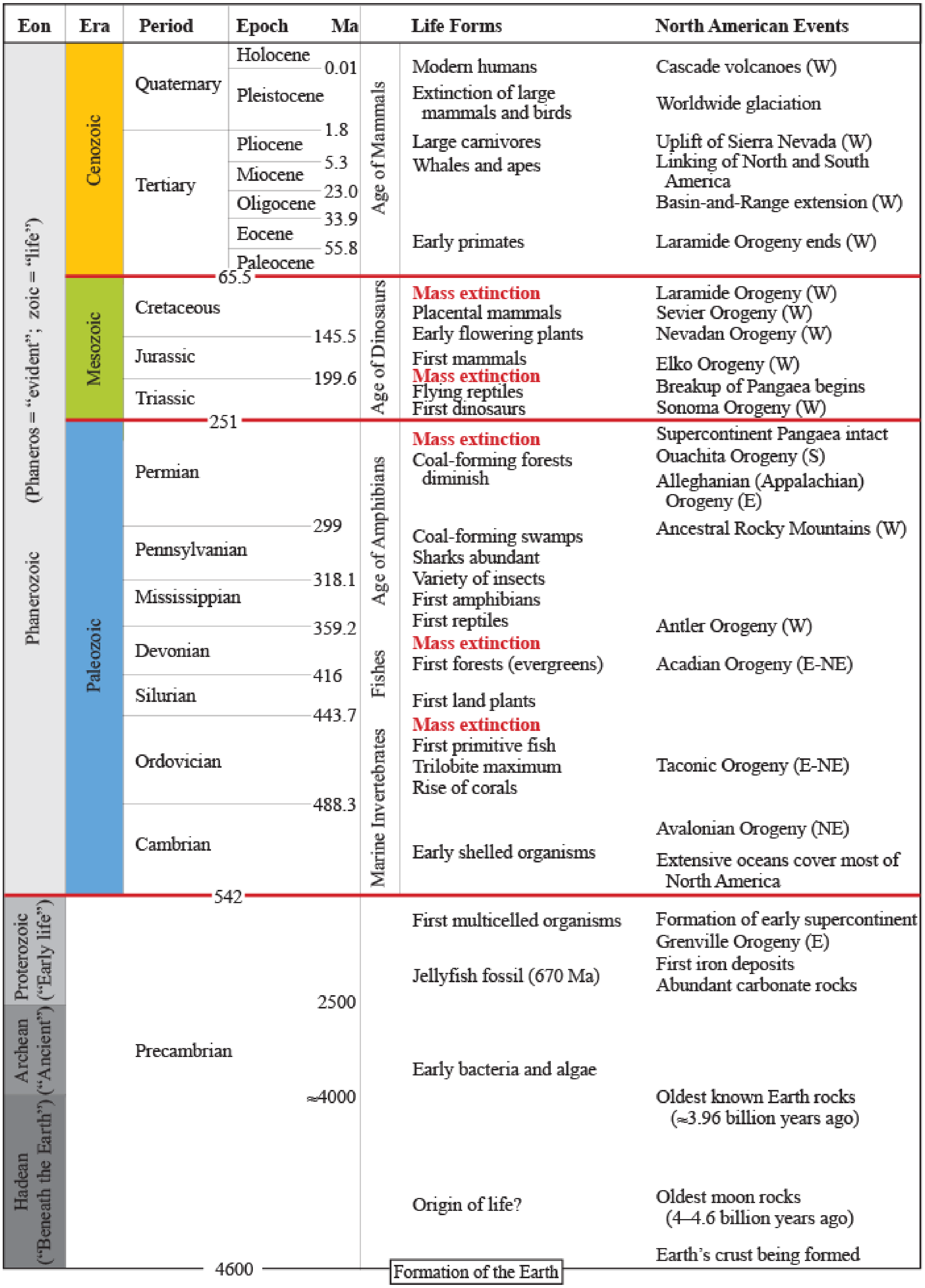

Figure 3. Geologic Timescale. Included are major events in life history and tectonic events occurring on the North American continent. Red lines indicate major unconformities between eras. Absolute ages shown are in millions of years (Ma). Compass directions in parentheses indicate the regional location 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 Wind Cave National Park 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 in the 2001 GRI workshop identified only one issue of concern for resource managers—slumping in the Minnelusa Formation along South Dakota Highway 385 and in Wind Cave Canyon as a result of road construction. This issue is discussed in the "Geologic Hazards" section. The other issues highlighted here are listed in alphabetical order and not prioritized.

Airflow

Airflow led to the discovery of Wind Cave in 1881. According to Schilberg and Springhetti (1988), a man named Jesse Bingham was hunting deer and noticed the grass waving on an otherwise still day. He investigated and peered into the hole, which blew with such force that it lifted the cowboy hat off his head. Joined by his brother Tom and half-brother John Dennis, the trio amused themselves by placing the hat over the hole and watching it fly aloft when they let go. At a later date, Jesse returned to the place with some disbelieving friends and proceeded to show them the hat trick, but on that day the barometric wind had reversed and the hat was sucked down into the hole, never to be seen again (or so the story goes).

This tale illustrates that Wind Cave is a barometric breathing cave. Changes in barometric pressure as a result of fluctuations between day and night and changes in weather cause air to rush into or out of the cave, equalizing the pressure between the inside and outside (Conn 1966). When the barometer rises, air rushes into the cave; when the barometer drops, air rushes out. In 2001 Dr. Andreas Pflitsch—a researcher from the Department of Geography, Workgroup on Cave and Subway Climatology, Ruhr-University of Bochum, Germany—began studying the climate and airflow of Wind Cave. He demonstrated that wind blows primarily inward during the winter and outward during the summer. He also found that the average outward-flow velocity is almost always higher than the inward-flow velocity year-round. Additionally, he found that the average mean temperature of air flowing outward at Wind Cave is quite stable (National Park Service 2007). Moreover, he documented airflow in the cave blowing in the same direction in excess of 81 hours (Pflitsch 2002; Andreas Pflitsch, personal communication, 2006, p. 30 *in* National Park Service 2007).

Investigators have documented airflow speeds at 56 kph (35 mph) through the Natural Entrance (Pflitsch 2002) and speeds exceeding 120 kph (75 mph) at the Walk-In Entrance (Nepstad and Pisarowicz 1989). These are some of the highest cave winds recorded in the world.

The velocities of barometric winds are indicators of a cave's volume. On the basis of speeds for Wind Cave, resource managers infer that between 2% and 5% of the total cave has been discovered. However, a significant part of this volume is probably not accessible to humans.

The construction of artificial entrances allowed a huge increase in airflow into and out of the cave, bringing with it changes in the cave climate (Nepstad and Pisarowicz 1989). Wind Cave has two natural entrances, one of which has been artificially enlarged, and six associated natural blowholes (National Park Service 2007). Entrepreneurs added a trap-door entrance next to the Natural Entrance in 1887. In 1935 the Civilian Conservation Corps (CCC) added an elevator shaft at the end of the current Natural Entrance Tour (fig. 1). In 1992 the National Park Service installed a revolving door at the Walk-In Entrance in order to create an airlock and in 1996 added airlock structures to each elevator landing to reduce the unnatural air exchange through the elevator shaft. Research completed in 2002, however, suggests that at times the revolving door allows the passing of as much air as passes through the Natural Entrance (Pflitsch 2002). Nevertheless, before these structures were built, strong air exchange would occasionally prevent the elevator doors from opening or closing.

Blasting during the 1890s and 1930s also altered natural airflow patterns: by enlarging the passages along the developed tour routes, more air is allowed to move through them. Workers often placed the blast rubble into side passages or pits, further altering or restricting natural airflow patterns. In 2003 a team of seven seasonal laborers began to manually haul out of the cave the artificial fill from past development projects. The rubble was much deeper than expected; many piles exceeded 1.5 m (5 ft) deep and contained tons of debris. However, by the end of the six-month project, staff had restored about 230 m (750 ft) of the tour route, dramatically improving the natural cave environment (Horrocks and Ohms 2003). This work was the first phase of a multiyear project to mitigate impacts of development during more than 100 years of touring.

Impacts on the Cave Environment

Starting in the 1960s, many investigators have studied the climatological conditions of Wind Cave: Shillinglaw (1960), Schnute (1963), Conn (1966), Mitchinson (1976), Nepstad (1985), T. E. Miller (1989), Nepstad and Pisarowicz (1989), Daniels (2000), Pflitsch (2002), and Ohms (2004). Long before this, however, opening up large entrances into Wind Cave irrevocably changed the climatic conditions. Hence, park managers do not have baseline data from which to assess change. Nevertheless, evidence of change is undeniable.

Algal Growth

Algal growth around the lights on developed routes affects the environment of the cave. The algae are unsightly and introduce an exotic color (green) into the cave. Moreover, the algae may be introducing artificially high levels of nutrients to what was formerly a nutrient-poor system. This could lead to "boom-and-bust" cycles in native invertebrates as the algae thrives and is subsequently reduced (National Park Service 1994).

Cave managers have used various methods to control photosynthetic organisms such as algae that grow near electric lights in caves. Sodium hypochlorite (household bleach), formaldehyde, hydrogen peroxide, and steam generators temporarily reduce algae and other photosynthetic flora. However, these techniques are inadequate solutions for several important reasons: (1) the growth of algae and other photosynthetic 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 application of selected light wavelengths, reduction in wattage, or light shielding and redirection (Elliott 2006). In summer 2006, park managers at nearby Jewel Cave National Monument experimented with a germicidal ultraviolet (UV) light (the type used for disinfection in hospitals) at one light where there was moderate algae growth along the Scenic Tour. 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 as long as 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 2006). On the basis of these results, UV light appears to have great potential for killing algal growth without the use of harmful chemicals. Longer exposure times or higher wattage may be necessary to completely kill the algae. Park managers at Wind Cave may find this promising alternative useful and worth testing.

Cave Fauna

According to Nepstad and Pisarowicz (1989), a change in the cave climate could disturb cave fauna. Fauna are relatively sparse at present and may have been more abundant sometime in the recent past, especially at entrances. On the other hand, both the revolving door at the Walk-In Entrance and the elevator shaft provide unnatural routes for biota to enter the cave.

Animals that have evolved in the cave environment over thousands of years have little tolerance for major temperature or moisture changes. For instance, as a result of increased volume of airflow into the cave, the loss of millions of gallons of water from the cave environment has likely impacted rare cave invertebrates, which live on moist surfaces that are subjected to evaporation and its resulting cooling effect (National Park Service 1994). Also, various species of bats prefer different environments in the cave for roosting, and a change in the cave climate could disturb them.

Evaporation

The greatest harm from cave-climate alterations may come from changes in evaporation. Aragonite tends to form rather than calcite in areas that have high evaporation rates (Hill and Forti 1986); thus a change in cave climate could potentially alter the very chemical structure of the speleothems in the cave (Nepstad and Pisarowicz 1989).

Lint and Other Particulates

Seemingly subtle human impacts include shedding of lint, dust, hair, and skin flakes. However, 90,000 visitors annually produce enough particulates to build up and impact many cave surfaces. Carried on air currents, lint from clothing coats stalactites and flowstone, accumulates on the cave floors adjacent to the established trails, and collects on inaccessible ledges. Samples of cave lint contain 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). These materials dissolve and hide the true colors of cave formations and provide unnatural food sources for cave biota (Horrocks and Ohms 2003). Investigators placed tagged lint (treated to be clearly visible under UV light) on the visitor trail and found that it moved as far as 90 m (300 ft) after 75 visitors had passed over several hours (Jablonsky et al. 1993). Testing also showed that lint moved to the edge or completely off the trail. Studies conclude that the most promising strategies to control lint deposits in caves involve careful attention to trail design and custodial and maintenance procedures (Jablonsky et al. 1993). Some "clean room" technologies that capture airborne particles through filtering systems may also be useful (Jablonsky et al. 1993).

Temperature

Anecdotal early accounts of temperatures in Wind Cave vary from 5.6°C to 8.3°C (42°F to 47°F). Moreover, the superintendent's 1920 annual report states that one could see one's breath anywhere in the cave, a phenomenon that has only been observed today at the low spot on the Blue Grotto Loop (National Park Service 2007). However, where these early temperature measurements were taken is not known; they may have been near the entrance, which is often cooler (Rod Horrocks, Wind Cave National Park, written communication, April 1, 2008).

In 2003 Marc Ohms monitored the temperature extensively to determine whether the lighting along tour routes was causing unnatural temperature fluctuations. He found that artificial lighting creates local "hot spots" that dry cave surfaces. He also found that the body heat of tour groups was raising the air temperature in areas as much as 1.1°C (2°F) and not returning to normal levels until two hours after the last tour. Furthermore, at two interpretive stops (Fairgrounds and Assembly Room; see fig. 1), the temperature ceased returning to normal levels midway through the tour season, not returning to normal until after the season ended in the fall (Ohms 2004).

Exploration and Inventory

Wind Cave poses unique concerns for explorers: complicated routes in areas without flagging, crumbly walls, temperature, and availability of water. The upper-middle level of the cave (see "Cave Complexity and Levels" section) is typified by crumbly rock that often falls apart when cavers try to climb through it. The low temperatures in the cave make hypothermia a concern, and the lack of water creates potential for dehydration. Nevertheless, the drive to explore Wind Cave continues. Explorers return to breezy passages to "hopefully find where the air [is] going" (Burger 1992).

Airflow plays a significant role in the exploration of Wind Cave because barometric breezes are a valuable tool for discovering new passages (see "Airflow" section). Prior to 1991, the 97 km (60 mi) surveyed in Wind Cave were almost entirely within the bounds of 1 sq mi (2.6 km^2) (fig. 4). On September 9, 1991, three cavers chased a tantalizing wind through an overlooked crawlway in the Silent Expressway, known since the early 1980s. On that trip they mapped 305 m (1,000 ft) of previously unexplored passage. This new discovery, named "Southern Comfort," was heading southwest, out of the roughly square footprint of the known cave (Burger and Allison 1998). Between 1999 and 2002, volunteers from the National Speleological Society (NSS) and park staff surveyed an average of 12 km (7.5 mi) per year (Horrocks and Szukalski 2002). At the current rate of 7.2 km (4.5 mi) a year, surveying all of the passages predicted to be within the current boundaries of Wind Cave will take another 28 years (Rod Horrocks, Wind Cave National Park, written communication, April 1, 2008). As of July 16, 2008, explorers had measured Wind Cave at 208.8 km (129.8 mi) long. Because inventorying is now part of the survey process, the inventory of Wind Cave will not be complete until the cave has been fully explored; "all indications are that this will not be for quite some time" (Nepstad 1991, p. 226).

Large faults in the limestone can limit exploration; small ones occur in many places, ordinarily with little effect. Many of the largest cave passages, for example the Club Room, are located at least partly along faults (Palmer 1995); however, where the cave intersects a large fault, a great deal of breakdown (see "Cave Breakdown" section) inhibits further exploration. Many passages end at these points, and they are perhaps the most serious hindrance to exploration (Palmer 1995). Still, with more than 3,190 unmapped leads, Wind Cave has great exploration potential (Horrocks 2007).

Exploration of Wind Cave has progressed in several stages (Palmer 1995). In the first stage, the McDonalds, particularly Alvin, ventured beyond the entrance into a labyrinth of passages that stretched into the hills. Alvin McDonald made extensive explorations into the cave and logged his discoveries and observations from 1891 to 1893. Sadly, he died of typhoid at the age of 20, ending a short but intense period of discovery that would not be matched for 70 years. The McDonalds also opened the cave for guided tours. For nearly a decade they led tours as a private business venture, then for the Department of the Interior until 1903.

The 1959 NSS expedition marks the second stage of exploration. In August 1959, NSS members mapped about 5 km (3 mi) of cave passage. They surveyed fauna and minerals and completed a geological reconnaissance. Their report contains an inventory, description, and evaluation of the cave features (Brown 1964).

Herb and Jan Conn, known better for their dedicated exploration of nearby Jewel Cave, participated in the third stage of exploration in the mid-1960s. At the invitation of Dave Schnute, an NPS employee, the Conns mapped the known sections of Wind Cave and pushed to the west, far beyond the previous limits of exploration (Palmer 1995). This small team made some of the most important discoveries yet in Wind Cave, including the Club Room and the Lakes (Rod Horrocks, Wind Cave National Park, written communication, April 1, 2008; see fig. 5).

The 1970s rang in the fourth stage of exploration, as the NSS Windy City Chapter, led by member John Scheltens, explored westward and mapped one of the largest known passages in Wind Cave—Half Mile Hall. This project eventually mapped 32 km (20 mi) of passage. In the 1970s, NPS employees participated in the exploration of the cave, eventually mapping 4.8 km (3 mi) of passage, but they provided no overall direction. During this era, cave management was not acknowledged as an important component of resource management, so the private caving community took up the leadership role in exploring the cave. Through the early 1980s, special interest groups continued to direct and participate in the exploration and preservation of cave resources. Problems developed because of this strategy, however. Cavers explored and surveyed the cave using such a wide variety of methods that data management became difficult. Because park managers asked nothing of the explorers, the explorers recorded little of what they were finding. Worse yet, some individuals or groups withheld survey data, leaving park managers with no information about newly discovered areas of the cave (National Park Service 1994).

With the creation of a cave management program in 1984 and a permanent cave management position in 1989, park managers started taking an active role in exploration, survey, and mapping. They established standards for the exploration program, ensuring that crews documented and provided information after each trip, particularly about newly discovered passages (National Park Service 1994). Hence, the fifth stage of exploration began.

Wind Cave National Park personnel continue to direct the exploration of the cave. Approximately 20% of cave management time is devoted to coordinating exploration and managing the resulting data (National Park Service 1994). The park's cave and karst management plan outlines the management of data, explicitly stating that "any data collected during survey or work trips will be analyzed and properly stored by the Physical Science staff" (National Park Service 2007, p. 52). Surveyors now use standard data forms, and inventories follow established park protocols, including written survey and inventory standards for data collection, accuracy, equipment, and duties. All original survey data sheets remain in the park and are properly stored in the park's museum collection. A GIS database houses inventory data and geographic and geologic features (e.g., cave entrances, karst features, and surficial geology). Data managers follow standards set by the Federal Geographic Data Committee, generating FGDC-compliant metadata as described in the *Content Standard for Digital Geospatial Metadata* (FGDC-STD-001-1998) and the *Content Standard for Digital Geospatial Metadata Workbook* (version 2.0). Much of this information is considered sensitive and is protected under the Federal Cave Resource Protection Act of 1988 (see "Protection of Cave Resources" section).

A "cave potential map"—a model to estimate the length of Wind Cave—now incorporates structural geologic features, passage density, surface contour maps, cave survey data, surface blowhole locations, and hydrologic maps. Investigators combined these data with GIS-generated triangular, irregular networks; slope and aspect data; orthophotoquads; a park boundary map; and land ownership maps. They determined that the current cave boundaries cover a tenth of the total potential, or maximum likely extent, of the cave. Furthermore, on the basis of passage density, the model determined that the potential length of Wind Cave is between 400 km (250 mi) and 1,760 km (1,095 mi) (Horrocks and Szukalski 2002).

In addition to estimating the likely maximum boundaries of Wind Cave, uses of the cave potential map include studying the possible connection with Jewel Cave and evaluating hypotheses regarding the cave's origin (Horrocks and Szukalski 2002). The cave potential map may also provide a means for judging the exploration potential for any section of the cave (Horrocks and Szukalski 2002).

Fluvial Features and Processes

Three perennial streams flow through Wind Cave National Park: Highland Creek, Beaver Creek, and Cold Spring Creek. Cold Spring Creek converges with Beaver Creek shortly after entering the park. Highland Creek and Beaver Creek both lose part or all of their flow to the subsurface. During a particularly wet year, Beaver Creek and Highland Creek averaged a combined loss of more than 9.5 million L (2.5 million gal) per day (Driscoll 2002). Depending on the time of year and precipitation, several other streams may flow in the park; Reeves Gulch, Red Valley, Fuson Canyon, and Wind Cave Canyon have flowing water at least part of the year. Similar to the perennial streams, the intermittent streams lose their flow to the subsurface.

Generally speaking, the developed area within Wind Cave National Park is not prone to flash flooding (National Park Service 1993); however, the Natural Entrance of Wind Cave and the entire length of Coyote Cave, the second longest cave in the park, are susceptible (National Park Service 1994). To protect human life, park employees disseminate flood warnings and evacuation information at key visitor contact points (e.g., visitor center, campground, and parking areas) (National Park Service 1993).

Most of the developed area of the park lies outside of the 100-year floodplain. Approximately 25% of the campground (i.e., all sites in loop C and a few sites in loop D), the cave entrance in Wind Cave Canyon, part of the visitor center (including the section for museum storage), electrical transformers (behind the visitor center), recreation hall, and part of the Mixing Circle—an open-air storage area for unused miscellaneous supplies and equipment, winter storage of excess vehicles, and temporary storage of garbage or road-building supplies—are within the floodplain.

Geologic Hazards

Geologic hazards at Wind Cave National Park include landslides, rockfall (cave breakdown), and earthquakes. Knowing about these hazards will help resource managers minimize risks to visitors, staff, and infrastructure.

Landslides

Landslides are widespread, naturally occurring geologic events. Only when such phenomena conflict with development or human activities do they constitute a serious hazard. The severity of such a problem is directly related to the extent of human activity in the affected area (Rogers et al. 1979). Early recognition and avoidance or corrective engineering can mitigate adverse effects. Actual loses can range from mere inconvenience where very slow or small-scale nondestructive slides occur to severe losses with high maintenance costs where large-scale, destructive slides are involved. Large, rapidly moving slides have the capacity to completely destroy buildings, roads, bridges, and other costly structures. Such slides also have the potential for inflicting loss of life when they occur in developed areas (Rogers et al. 1979).

Road construction caused slumping in the Minnelusa Formation along Highway 385. Removing natural supporting material immediately beneath or adjacent to the slump area may result in further mass movement. Support may be added in the form of rock- or earth-fill buttressing, retaining walls or cribbing, concrete slurry, rock bolting, and reinforced pilings. Another approach is to permanently improve and control surface and subsurface drainage in the vicinity of the slump. This greatly decreases the effects of lubrication and pore-water pressure. This approach is often very effective but may involve complex dewatering systems and costly long-term maintenance and monitoring (Rogers et al. 1979). Such an approach may also change infiltration and drainage patterns in the vicinity of the cave (see "Surface-Subsurface Relationships" section).

Cave Breakdown

In parts of Wind Cave, the ceilings and walls have fallen away and accumulated on the floor (Harris and Tuttle 1990). Called "breakdown" or "collapse blocks," most deposits are small, but in wide chambers such as the Club Room and Half Mile Hall, some breakdown is the size of semitrucks (Palmer 1995).

These blocks fell long ago while the cave was still forming, as shown by deep weathering and sediment on their surfaces. In places the boxwork (see "Boxwork" section) on the underside of the collapse block is undamaged, so the blocks probably loosened and fell when the cave was flooded. Had the cave been dry, the impact of the fall would have shattered the delicate structures (Harris and Tuttle 1990). Today, the chance of fresh pieces breaking off is small, especially in areas open to the public (Palmer 1995).

Although natural breakdown is rare, several large collapses have occurred along the entrance stairs as a result of frost wedging. The National Park Service added roof supports, including rock bolting, chain-link fencing, and concrete pillars to these unstable areas. In 1992, park managers installed a revolving door to limit the amount of cold air that sinks into that entrance during the winter months. Although this door still allows some air to pass, it has been effective in preventing roof collapse in the cave (Rod Horrocks, Wind Cave National Park, written communication, August 25, 2008).

Earthquakes

Although the southern Black Hills are prone to earthquakes, most register less than magnitude 3.0 on the Richter Scale and do not cause any damage. Except for a single rock that toppled onto the paved trail within Wind Cave in 1907 and a small roof collapse in 1964, most earthquakes are heard but not felt within the cave. If cave visitors happen to be standing or sitting quietly when an earthquake occurs, they will hear a rumbling sound above, below, or rolling down the passage. This sound is created when the fast-moving P waves, which radiate from the earthquake's epicenter, encounter the cave. When these waves first intersect the cave, they generate a one-dimensional acoustic wave in the air-filled cave within a fraction of a second of their arrival at that interface. As these waves oscillate through the cave walls, the changes in pressure create acoustic waves at 30 Hz (30 oscillations per second), which visitors hear as rolling thunder (Horrocks 2008a).

Mining

No significant mineral or energy resources are known to exist in the park, and there are no valid mining claims within park boundaries (National Park Service 1993). However, park managers recognize the need for periodic monitoring of mining in the vicinity of the park because hard-rock mining could impact the Cold Springs Canyon, Beaver Creek, and Highland Creek drainages, with potential contamination of park surface and subsurface waters (National Park Service 1994).

The park's 1994 general management plan identified an active feldspar operation located approximately 10 km (6 mi) west of the park boundary; however, this mine is not a known threat to park resources (National Park Service 1993). Feldspar mining has been a relatively steady industry in the Black Hills since 1923 (Gries 1994). Feldspar crystals occur as part of pegmatite inclusions in Precambrian rocks. Feldspar is the only pegmatite mineral occurring in sufficient abundance and purity to be profitable for mining for that commodity alone. Viable deposits run at least 30% feldspar, in crystals generally ranging from 0.3 to 3 m (1 to 10 ft) in diameter. Feldspar is used primarily in the ceramic, porcelain, and glass industries; small quantities are used as a mild abrasive in scouring powders (Gries 1994).

Correspondence in January 2008 with Rod Horrocks (Wind Cave National Park) confirmed that feldspar mines in the Precambrian rocks near Pringle and Custer, South Dakota, are numerous. Additionally, Horrocks writes,

> This last summer I just visited a feldspar mine [Gladys Wells Mine] that is 2–3 miles outside of the park. It is actually accessed by driving on a road from within the park. . . . It is a really interesting mine, with some underground workings and an open pit. We also just learned about a potential mine site that may be inside of the park. From the description, it was uncertain if the mine was just outside or just inside of park boundaries. We have a geologist couple [Tim and Beth Lincoln, Albion College, Michigan] that is currently mapping the Precambrian rocks in that section of the park, so I asked them if they ran across that mine yet in their mappings. They have not, but are going to keep an eye out for it.

Precambrian rocks in Wind Cave National Park contain notable, coarse-grained pegmatite; good examples of pegmatite occur at a parking area, called "Ancient Foundations," along the driving tour (see http://www.nps.gov/wica/Geology_Driving_Tour.htm). Visitors are encouraged to look for whitish and glassy quartz; pink feldspar having shiny, flat surfaces; and long, slender black tourmaline. The host of the pegmatite is the Harney Peak Granite, which comprises hundreds of intrusions, with more than 24,000 separate bodies of pegmatite and granite known (DeWitt 2004).

Surface-Subsurface Relationships

The land above Wind Cave and the adjacent watersheds are essentially part of the cave and karst system. Changes in drainage patterns or cave moisture could irreversibly damage cave formations and features and detrimentally affect the invertebrate population of the cave (National Park Service 1993). Therefore, park managers have "chosen to manage any surface activities above the surface exposures of the Madison Limestone or within the cave and karst watersheds of the limestone the same way they would manage activities directly above known cave" (Horrocks and Szukalski 2002, p. 69). This policy is based on the assumptions that other sizeable caves exist in other areas of the park and that Wind Cave may extend beyond the maximum boundaries identified using the cave potential map (see "Exploration and Inventory" section).

GIS Technology

GIS technology has greatly facilitated an understanding of the relationship between the cave and the surface. Being able to combine the locations of cave survey stations and associated data with surface features allows managers to view and analyze spatial relationships and make informed management decisions. For instance, knowing the relationship of the cave to the main parking lot, particularly the amount of overburden in the area, was important to the remodeling project, as well as the runoff treatment system (Ohms and Reece 2002).

Park Development

Most development is in the southwestern section of the park and covers about 405 ha (1,000 ac). Development includes the visitor-center complex with vending machine area, bookstore, display areas, restrooms, administrative offices, and 164-car parking lot; the 76-site Elk Mountain Campground; an informal 7-site picnic area; access roads; elevator building; maintenance area; historical and modern park housing; three sewage lagoons; and two well sites. In addition, the 40-ha (100-ac) detached unit contains the spring that serves as the park's backup water supply (National Park Service 1993).

In Wind Cave Canyon, much of the park's infrastructure lies on Pahasapa Limestone, right above Wind Cave. Investigators have found high nitrate levels in cave drip waters below this area (Alexander et al. 1989; Nepstad 1993; Heakin 2004). In as few as 9.5 hours, water from the parking lot reached Upper Minnehaha Falls in Wind Cave (Nepstad 1996). At this site, trace amounts of chloroform; caffeine; toluene; acetone; benzene; ethyl benzene; meta-, para-, and ortho-xylene; methyl isobutyl ketone; and styrene occur in drip water (Heakin 2002). Additionally, investigators found trace amounts of hydrocarbons in other locations in Wind Cave. Furthermore, water-quality testing revealed pentachlorophenol, chromium, copper, and arsenic in cave water at two sites downdip from the Mixing Circle (Alexander et al. 1989). This led to the 1994 general management plan recommending the removal of this storage facility. However, this task has never been carried out because the (previous) park superintendent and facility manager deemed the storage area necessary for park operations (Rod Horrocks, Wind Cave National Park, e-mail, February 23, 2009).

Threats within the Park

Some known surface threats are parking-lot runoff, hazardous materials transported via park roads, resurfacing park roads with oil-based products, sewage-line and lagoon leakage, exotic-weed control, new construction, and expansion of the pine forest (National Park Service 2007). According to Horrocks and Szukalski (2002), "the three most severe threats presented by these structures and facilities have either been mitigated or are in the process of being addressed" (p. 66). First, park managers replaced the asphalt parking lot with Portland concrete and added a storm-water treatment system that catches the hydrocarbons washed off the lot during the first flush of precipitation. Second, park managers removed the inadequate sewage lagoons in 2007. Although these lagoons were outside the known boundaries of the cave, managers suspect that the lagoons could be over undiscovered cave (James Nepstad, personal communication, 1999, p. 66 *in* Horrocks and Szukalski 2002). Third, the campground's toilets were once connected to the septic tanks, which were unnatural sources of moisture that could affect the cave. In 2001, park managers replaced 2,400 m (7,874 ft) of the aging sewer system with dual-contained HDPE lines and inspection ports to check for inner line leaks.

In addition, park managers use manual, mechanical, biological, prescribed fire, and chemical treatments to control exotic plant species at the surface within park boundaries. However, because of potential negative impacts on cave resources resulting from chemical applications, managers have developed a model that identifies areas most sensitive to chemical-control methods (e.g., over known cave passages) and restricts spraying in those areas (National Park Service 2007).

In the 1930s, the Civilian Conservation Core (CCC) planted 5,000 trees above the cave. Anecdotal evidence indicates that a mature ponderosa takes up hundreds of gallons of water a day, if available; most of this water is then lost to the atmosphere via evapotranspiration. The expansion of pine forest at the surface is likely resulting in a reduced amount of water entering the cave (National Park Service 2007).

Threats on Adjacent Lands

On adjacent lands, activities such as mining; application of pesticides, fertilizers, and road salts; logging; irrigation; drilling of wells; and stock diversions may be affecting surface and subsurface water flow through the park. This in turn may affect how water enters and travels through the cave. Additionally, developers are planning housing tracts adjacent to Beaver Creek to the northwest of the park and have already diverted the flow of this creek into catchments, one near the western boundary of the park. Beaver Creek enters the park, and a large proportion of its flow disappears underground into Beaver Creek Cave (Horrocks and Szukalski 2002). This capture, along with the capture of Highland Creek, likely represents a significant part of the recharge for the Madison Aquifer in this region.

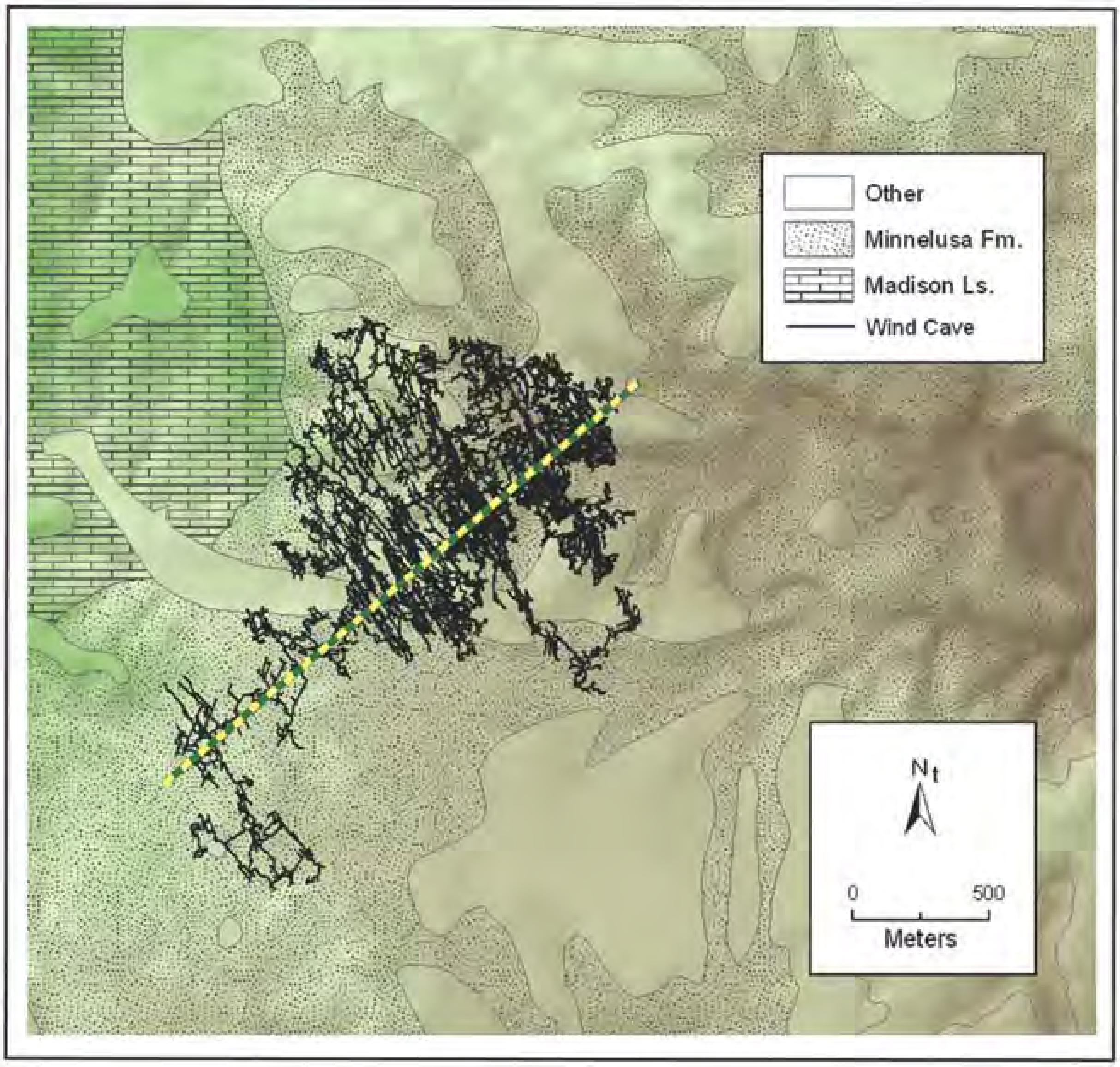

Figure 4. Footprint of Wind Cave. This figure shows the relationship of the Madison (Pahasapa) Limestone outcrops to the surveyed passages of Wind Cave. The major trend of the cave is marked with a yellow-and-green striped line. The Minnelusa Formation lies directly above the Madison Limestone. This illustration combines a shaded relief DEM, geology layer, and survey lineplot. Graphic from Horrocks and Szukalski (2002), fig. 2. Used by permission of the author.

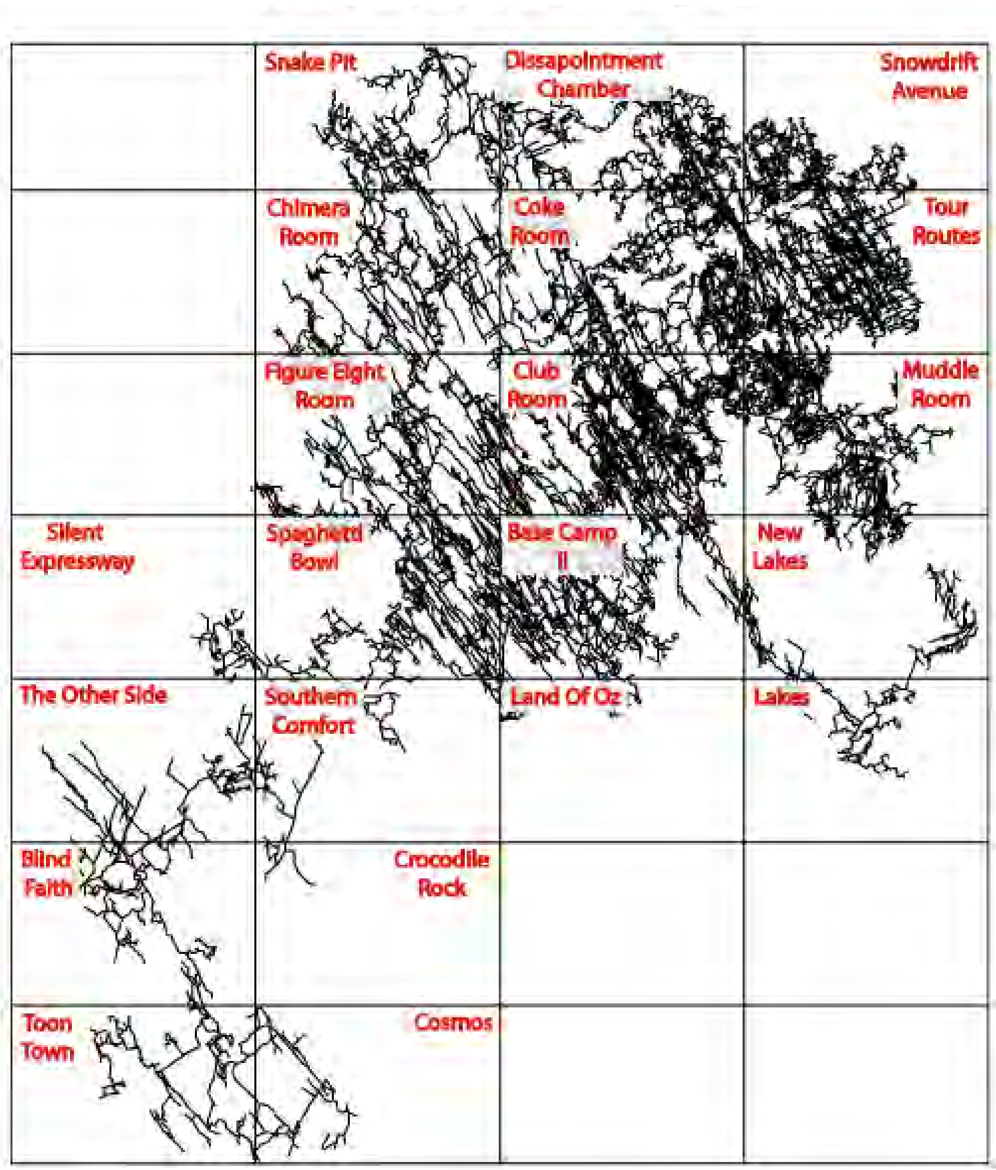

Figure 5. Cave Quadrangles. Park managers use various quadrangle names to aid in the exploration of Wind Cave. These are not USGS quadrangles. Discovery of cave passages is expanding the cave's original boxlike footprint to the southwest. Graphic by Rod Horrocks (National Park Service).

Geologic Features and Processes

This section describes the most prominent and distinctive geologic features and processes in Wind Cave National Park. The features and processes are listed in alphabetical order and not prioritized.

Currently measured as the as the third longest cave in the United States and the fourth longest cave in the world, Wind Cave's discovered length is a fraction of the volume yet to be found. Blowholes, karst features, and reports of blowing wells suggest that other major cave systems may be located within the boundaries of the national park (National Park Service 2003). In addition to length, Wind Cave is notable for its complexity and cave features such as paleokarst, lakes, speleothems, and speleogens. Though Wind Cave is the primary resource, the national park also contains many smaller backcountry caves. The park also is becoming known for its paleontological resources (see McDonald and Horrocks 2004). These features are highlighted in alphabetical order here.

Backcountry Caves

Records show a total of 43 other caves besides Wind Cave scattered throughout the park (Rod Horrocks, Wind Cave National Park, written communication, August 25, 2008). Park personnel manage these backcountry caves under the policies and guidelines established in the cave and karst resource management plan. Currently, all backcountry caves are closed under authorization of the Superintendent's Compendium CFR 1.5(a). The Physical Science Office issues permits for entry.

The largest backcountry cave is Coyote Cave, discovered in 1974 (National Park Service 1993). Surveying extended the length of Coyote Cave to more than 1.6 km (1 mi) in 2005—the seventh cave in the state to reach this distinction (Ohms 2005). Coyote Cave is developed in a thin layer of limestone near the middle of Minnelusa sandstone. Significant breezes in the farthest reaches of Coyote Cave suggest that the cave may drop into a major cave system in the underlying Pahasapa Limestone (National Park Service 1994), but Coyote Cave is probably not connected to Wind Cave (Pflitsch 2002).

The cave's small passages and tight squeezes have not made exploration easy or appealing (Ohms et al. 2000). The most interesting room in the cave is the Sodastraw Room, roughly 76 m (250 ft) southeast of the entrance. This room contains multitudes of soda-straw stalactites (see "Stalactites and Stalagmites" section) as long as 0.6 m (2 ft), columns exceeding 1.2 m (4 ft) in height, and many small helictites (see "Helictite Bushes" section). All of these speleothems are coated with black silt and organic debris (Hill et al. 1988). Located at the bottom of a drainage and prone to flash flooding (see "Fluvial Features and Processes" section), parts of the cave are filled with organic material (National Park Service 1994).

Other notable caves include Salamander Cave, which is roughly 61 m (200 ft) in length (National Park Service 2003) and known for its paleontological resources (see "Paleontological Resources" section), and Elk Antler Cave, northeast of park headquarters, which contains a pit and exceedingly tight crawlways. The floor of Elk Antler Cave is covered with droppings of small animals, probably rodents that have left nests in the crawlway (Hill et al. 1988).

Cave Complexity and Levels

Wind Cave is an intricate, three-dimensional maze of branching passages. Wind Cave's exceptionally complex pattern has required assistance from many volunteers to survey and inventory its cave resources (Nepstad 1991). To date, more than 1,050 people have participated in at least one survey trip into Wind Cave (Horrocks 2007).

Nearly all the caves in the Black Hills share this same general pattern (fig. 6). With few exceptions, they are mazes that occupy several distinct levels corresponding to favorable strata in the carbonate rocks. Wind Cave has three major levels (upper, middle, and lower). Structures (i.e., fractures and bedding planes) control the location of cave passages.

Upper Level

The upper level of Wind Cave is typified by smooth, scalloped walls and many confusing, intertwining crawlways and passages that terminate in dead-end domes. This level consists of isolated wide, vaulted rooms or irregular galleries in massive, light-gray limestone containing many fossil shells near the base (possibly corresponding to the Charles Member of the Madison Limestone). The rocks in the upper level record a time during the Mississippian Period when deepwater—possibly as much as 656 m (200 ft) deep—predominated (Horrocks 2008b). Corrosion residue (see "Corrosion Residue" section) is common in this level. Some of the upper level formed in paleokarst (see "Paleokarst" section). Solution pockets mark a period of karstification before the overlying Minnelusa Formation was deposited. These voids are generally connected to underlying passages by narrow vertical funnels in the bedded chert, which separates the bedded limestone-dolomite from the overlying massive limestone (Palmer and Palmer 2000). The ceiling of the Fairgrounds and the Garden of Eden (see fig. 1) are characteristic locales of this level, which is between 24 and 40 m (80 and 130 ft) thick. The upper level is above the prominent chert layer (see fig. 6).

Middle Level

The middle level is 30–37 m (100–120 ft) thick and lies below the prominent chert zone. This level is characterized by bedded limestone (possibly corresponding to the Canyon Member of the Madison Limestone); wide, irregular, low-ceilinged corridors; and an abundance of boxwork and frostwork. The rocks of the middle level correspond to a time when shallow water, <9 m (30 ft) deep, predominated (Horrocks 2008b). The middle level of Wind Cave is divided into three sublevels: upper middle, middle middle, and lower middle.

The upper-middle level has nodules of chert, poorly developed boxwork, crumbly bedrock, zebra rock, spar-filled vugs, and fossils (see "Paleontological Resources" section). The low, wide passages of the middle-middle level have well-developed boxwork and lots of moonmilk; chert is rare in this sublevel. Canyon passages with wall coatings and hard, hollow floors (see "Rafts and False Floors" section) characterize the lower-middle level.

Lower Level

The lowest level of Wind Cave looks entirely different than the other levels, almost like a different cave (Scheltens 1988). High, narrow fissures follow the natural cracks in the limestone of this level. Excellent examples of calcite-coated walls, false floors, gypsum splatter, and miles of canyon or fissure passages characterize this level. Large vugs, many filled with dogtooth spar and crystals (see "Crystals and Coatings" section), and cave rafts (see "Rafts and False Floors" section) abound at this level. The walls and floors are coated with several inches of granular calcite; everything appears to have a sugar coating.

The many parallel passages in the lower level look confusingly similar, so the area is aptly called the Calcite Jungle (Scheltens 1988). The passages between the Club Room and the Lakes (see fig. 5), which are not open to the public, are in this level. Possibly corresponding to the Lodgepole Member of the Madison Limestone, this level formed in thick-bedded dolomite, which is cracked by prominent fractures. The passages in this level tend to be narrow and strongly controlled by the joint system. Because of the large fractures, which radiate from the center of the Black Hills, narrow fissures can extend for long distances in straight lines.

Lakes

Wind Cave is generally dry, containing little standing or flowing water. However, three small, perennial streams (known as "What the Hell," "Rebel River," and "Rio Colorado") trickle towards the water table, where five underground lakes (e.g., Windy City and Calcite Lake) and numerous smaller pools occur. The largest lake is 50 m (164 ft) long, 20 m (66 ft) wide, and as much as 14 m (46 ft) deep (Harris and Tuttle 1990). The lakes are at 1,120 m (3,675 ft) above sea level, a position that corresponds to the local water table (Palmer 1995), where the cave intersects the saturated zone. They are the only direct connection to the Madison (Pahasapa) Aquifer (National Park Service 2007). Similar lakes are not known in other Black Hills caves, though possibly explorers simply have not found them yet (Bakalowicz et al. 1987).

The lakes in Wind Cave appear to be stagnant backwaters fed from below. Though permanent, their level has varied seasonally by approximately 5.8 m (19 ft) since their discovery in 1968 (Rod Horrocks, Wind Cave National Park, written communication, April 1, 2008). The water level also fluctuates daily, probably as a result of changes in barometric pressure (Greene 1989).

Paleokarst

Wind Cave is one of the oldest caves in the world (Palmer and Palmer 2000). The cave developed along gypsum deposits and paleokarst zones (Palmer and Palmer 2000) and intersects one of the world's best examples of paleofill—ancient sediment that filled caves and sinkholes that existed before Wind Cave formed (National Park Service 2007). Major cave expansion occurred during Paleocene–Eocene time (60–40 million years ago), but proto-cave passages and sinkholes were an important pathway for the dissolution of Wind Cave. The proto-cave passages and sinkholes formed about 310 million years ago, when a low-elevation karstic plain developed in a zone where sea and meteoric waters mixed. These Mississippian karst features were filled with basal Pennsylvanian sediment (now paleofill) during a rise in sea level about 300 million years ago, when the Minnelusa Formation was deposited (Palmer and Palmer 1989). These sediment-filled cave passages are relics of that time (Palmer 1984). Typical Pennsylvanian fill consists of fine- to medium-grained, subrounded quartz sand (60%), undeformed grains of muscovite and biotite (20%), feldspar (10%), and chlorite (10%), with trace amounts of clay, hornblende, and tourmaline (Palmer and Palmer 1995).

Present-day cave passages intersect the paleokarst, which is distinctively bright red and yellow. In many places, this sediment spills into more recent passages, exhuming some of the paleocaves (Palmer and Palmer 1989). Omnibus Hall (see fig. 1) leads through a heavily fractured zone (probably faulted) having excellent exposures of paleokarst fill (Scheltens 1988). The Fairgrounds—the largest room open to the public—and Garden of Eden also display prime examples of paleofill. Additionally, explorers have noted an impressive "sediment wall" in Selenite Avenue in Wind Cave; at 6–12 m (20–40 ft) high, this exposure is one of the thickest sections of fill known (LaRock and Cunningham 1992).

Investigators associate the paleokarst exposed in Wind Cave with the widespread Kaskaskia paleokarst—part of the Mississippian-Pennsylvanian unconformity and the most clearly exposed relict karst system in North America. In a broad sense, the Kaskaskia paleokarst is not a simple buried karst but is instead the product of a complex sequence of dissolution, diagenesis, precipitation, and detrital filling that spanned more than 300 million years (Palmer and Palmer 1995). This paleokarst can be neither described nor adequately explained without reference to earlier sulfate-related processes and later (post-Laramide) cave origin. Each process modified earlier features and was also guided by them. This interdependence complicates any attempt to isolate the individual karst-forming events in the Black Hills (Palmer and Palmer 1995).

Paleontological Resources

Both the caves and bedrock at Wind Cave National Park host paleontological resources. Investigators have documented 19 separate paleontological sites within Wind Cave (Horrocks 2006), and many of the smaller caves also contain fossil localities. The *Cave and Karst Resource Management Plan, Wind Cave National Park 2007* sets desired future conditions for paleontological resources within the cave and methods to achieve them:

- Complete a systematic paleontological survey of caves.
- Record locations of paleontological resources in conjunction with data collection of cave features.
- Research historic literature sources regarding paleontological resources in caves.
- Establish levels of acceptable impacts with thresholds and management actions when reached.
- Establish monitoring for impact thresholds.
- Mitigate impacts where possible; develop plans to remove impacts that cannot be mitigated.
- Mark paleontological resources in highly traveled areas of the caves with flagging tape so they will be avoided and protected.

Though badly needed, the park does not have an established inventory and monitoring program for paleontological resources at the surface (Rod Horrocks, Wind Cave National Park, e-mail, February 20, 2009).

Discovery of fossilized filamentary iron-fixing bacterial strands highlights the diversity of paleontological resources in the park. Similar to the fossilized bacteria found at Lechuguilla Cave in New Mexico (see Provencio 2000), the strands in Wind Cave have a manganese coating. Current scientific thinking interprets these fossils as Paleozoic (320–300 million years ago) bacterial strands. Sulfuric acid dissolved the limestone, creating small voids in which the bacteria grew. The filaments grew in rather neutral pH conditions where fresh meteoric water and anoxic water mixed (Palmer and Palmer 1991). Drs. Margaret and Arthur Palmer speculate that these fossils were autochemolithotrophs, living off the iron (Rod Horrocks, Wind Cave National Park, e-mail, January 31, 2008). The famous quartz formations such as the Crown Jewels and Bed of Nails in Wind Cave (see "Crystals and Coatings" section) are the same type of fossil filaments but covered with quartz crystals (Rod Horrocks, Wind Cave National Park, written communication, April 1, 2008).

Pahasapa Limestone

The invertebrate fossils in the limestone at Wind Cave National Park are fairly abundant; molds and casts of brachiopods are common. Researchers have recognized at least four brachiopod types, three colonial corals, a horn coral, two types of gastropods, and five types of burrows (Horrocks 2008b). Preferential dissolution commonly leaves the corals, gastropods, and burrows standing in relief. During deposition, storms pulverized many of the shells on the shallow sea floor into a fossil hash (carbonate sand) that was reworked into cross-bedded layers (Horrocks 2008b).

The brachiopods are usually found in the upper-middle level of the cave (see "Cave Complexity and Levels" section). The rest of the fossils occur throughout the middle level and sparsely in the upper and lower levels (Rod Horrocks, Wind Cave National Park, written communication, April 1, 2008). Dolomitization destroyed many fossils in the middle level; the process of recrystallization literally obliterated the remains. Some of these recrystallized fossils have a sugary appearance (K. Rohde, personal communication, 1986, p. 38 *in* Santucci et al. 2001).

Minnelusa Formation

The Minnelusa Formation in the park contains conodont fossil sites (Robert Stamm, U.S. Geological Survey, personal communication to Rod Horrocks, Wind Cave National Park, 1999). However, these sites have never been formally studied. Conodonts appear as toothlike remains but may not have actually served this function (Neuendorf et al. 2005).

Morrison Formation

The Morrison Extinct Ecosystem Project—a joint National Park Service–U.S. Geological Survey interdisciplinary study to reconstruct the Late Jurassic ecosystem throughout the Western Interior during deposition of the Morrison Formation (155–148 million years ago)—documented exposures in many national parks, including Wind Cave (Turner et al. 1998). Integration of data from the Morrison project resulted in a fuller understanding of an ancient continental ecosystem (Turner et al. 1998). Though this formation is known worldwide for the skeletons of large dinosaurs, especially the giant sauropods, it is very thin within the park, and no such fossils have been found within park boundaries (Rod Horrocks, Wind Cave National Park, written communication, April 1, 2008).

Lakota Sandstone

The Lakota Sandstone within the park contains pieces of petrified wood (Rod Horrocks, Wind Cave National Park, written communication, April 1, 2008).

White River Group

In 1986 Dr. James Martin and his students inventoried the Brule Formation of the White River Group within the park. They surveyed seven fossil sites, which they named after Rich Klukas, the park's biologist, who first found the sites. Investigators surveyed additional White River Group sediments in 2003. These 34-million-year-old (Oligocene) sediments are similar in age to the fossils of Badlands National Park. Park managers initiated this project to determine whether additional fossils were weathering out of the exposures, evaluate the condition of the Klukas sites, and prepare standards for their management. During the examination of these exposures, investigators found a previously unknown site where bone was eroding out of the hillside, which they named "Centennial Site" in honor of its discovery during the park's 100th anniversary. Because of the exposed state of the resources, park managers, in conjunction with the Mammoth Site, the NPS Geologic Resource Division, and Badlands National Park, partly excavated the site. At the same time, evidence of fossil theft was documented at all seven of the Klukas sites.

In addition to an initially discovered skull of a rhinoceros *(Subhyracodon occidentalis)* at the Centennial Site, investigators found more rhinoceros bones (fig. 7), indicating that the skull was not an isolated find but part of a disarticulated skeleton (McDonald and Horrocks 2004). Further excavation uncovered remains of a small early horse (*Mesohippus*), a rabbit (*Paleolagus*), a Hyenodon carnivore, a tortoise, and an early deerlike animal (*Leptomeryx*).

Salamander Cave

Salamander Cave (referred to as "McKirihan Cave" *in* National Park Service 1994, p. II.8) is roughly 61 m (200 ft) in length. Its entrance pit has trapped a variety of small mammals, as evidenced by the large number of skeletons found there. The many small species presently being trapped in the entrance pit include tiger salamander (*Ambystoma tigrinium*)—the cave's namesake—deer mice (*Peromyscus* sp.), and porcupine (*Erethizon dorsatum*). In the Porcupine Room, fragments of a horse (*Equus*) occur in a cemented talus cone located below the entrance. Uranium-series dating of the speleothems and *Equus* fragment gave an approximate age of 252,000 years (Mead et al. 1996). Farther into the cave, in a small room called the Horse Room, investigators found large, partially fossilized bones in old fill material, which massive popcorn (see "Coralloids" section) covers. The Horse Room has yielded 14 taxa introduced via a currently plugged paleoentrance. These taxa include one rabbit, eight rodents, two carnivores, one horse, and two artiodactyl species (Mead et al. 1996). The most common taxon is prairie dog (*Cynomys* sp.). Six taxa are now extinct, and two are currently extralimital. The specimens are currently held in the Laboratory of Quaternary Paleontology, Quaternary Studies Program, Northern Arizona University (Santucci et al. 2001).

Graveyard Cave

Graveyard Cave is located in the same area of the park as Salamander Cave. It is a solution cave that has acted as a selective natural trap for the past several thousand years. The one small room is littered with a variety of middle to late Holocene vertebrate remains, ranging from 2,290 to 290 years old (Manganaro 1994). Mammal remains are most abundant and include species whose presence in the Black Hills had previously been questioned. The fauna also include herpetological and avian remains, as well as an abundant molluscan assemblage. This site is significant in that it is only the third known Holocene faunal locality within the Black Hills and the first that is not associated with cultural remains (Manganaro 1994).

Beaver Creek Shelter

The Beaver Creek Shelter is an important Holocene archaeological and paleontological site. The main part of this rock shelter collapsed in antiquity, leaving only a narrow overhang. It hosts one of the most complete Holocene sections in the Black Hills and provides evidence for the regional cultural transition between the Early and Middle Archaic periods from approximately 6,720 years to 3,800 years ago (Martin et al. 1993). The radiocarbon dates from the shelter range from 9,380 to 1,750 years B.P. Extensive artifacts at the site support human occupation of the shelter (Alex 1991). Vertebrate, plant, and gastropod remains have also been recovered from the shelter (Abbott 1989; L. Miller 1989; Benton 1991, 1993, 1999; Martin et al. 1993). Investigators have identified a total of 40 species extant in the Black Hills. Except for a few water-dependent species, all major taxonomic groups found in the Black Hills occur at the site. The presence of pocket mouse (*Perognathus* sp. indet.), kangaroo rat (*Dipodomys* sp. indet.), grasshopper mouse (*Onychomys* sp. indet.), and a member of the family Iguanidae indicate warming and drying during the altithermal period. These vertebrate remains were disarticulated, and many were broken. Few of the bones were truly in situ, as most were either transported into the cave by humans or fluvial processes, or carried in by carnivores or raptors (Santucci et al. 2001).

Chamber of Lost Souls

In 1984 investigators discovered bones of five mammalian taxa in the Chamber of Lost Souls, one of the rooms of Wind Cave near the Natural Entrance. Vertebrates from such cave deposits are extremely rare, and this research provided the first description of paleocave fauna in South Dakota. Such finds provide insight into the paleoenvironment that existed when the remains of these animals were entombed and serve as evidence of former natural cave entrances that have since closed (National Park Service 2003).

In 1985 Dr. James Martin (South Dakota School of Mines and Technology) started identifying the bones from the Chamber of Lost Souls. Continued research revealed a rather unusual assemblage of gastropod (snail?), salamander, chorus frog (*Pseudacris*), toad (*Bufo*), rabbit, gray fox (*Urocyon*), passerine bird, hawk, owl, shrew (*Sorex*), bats (*Myotis* and *Eptesicus*), possible chipmunk, woodchuck (*Marmota*), ground squirrel (*Spermophilus*), grasshopper mouse, white-footed mouse (*Peromyscus*), woodrat (*Neotoma*), redback vole (*Cleithrionomys*), meadow vole (*Microtus*), deer (*Odocoileus*), and *Bison* (Martin and Anderson 1997). Nearly all of the larger bones from the collection exhibit evidence of rodent gnawing, primarily that of pack rats (*Neotoma*). At least some of the specimens appear to have been derived from a pack-rat nest. The occurrence of raptors within the assemblage suggests that some small bones may be from pellets. Other bones appear to be from creatures that inhabited and expired within the cave.

All specimens were located at least 150 m (490 ft) from the nearest existing opening, and no remains were found anywhere between the opening and the concentrations of bones. The site is only 18 m (60 ft) from the surface, so investigators surmised that these vertebrate remains accumulated in a former entrance to the Chamber of

Lost Souls. In 2000 a team surveying passages off the chamber discovered the proposed paleoentrance, which members named Root 89. This former entrance is located 15 m (50 ft) from the Natural Entrance in the bottom of the same drainage. The discovery of Root 89 in the bottom of Wind Cave Canyon explains the observation that most of the skeletal remains had been reworked by water (Martin and Anderson 1997).

Speleothems and Speleogens

The features that arouse the greatest curiosity in most cave visitors are speleothems. As defined in Moore (1952), a speleothem is a secondary mineral deposit formed in caves. Some of the cave features described in this section are actually speleogens that predate Wind Cave. They formed as the present passages of the cave were forming. Identified from resource management plans (National Park Service 1994, 2003, and 2007) and the scientific literature (i.e., White and Deike 1960, 1962; Schilberg 1980; Bakalowicz et al. 1987; Scheltens 1988; Davis 1989, 1991; Harris and Tuttle 1990; Nepstad 1991; LaRock and Cunningham 1995; Palmer 1995; Palmer and Palmer 1995; and Kiver and Harris 1999), the speleothems and speleogens of Wind Cave are categorized using *Cave Minerals of the World* (Hill and Forti 1997) and listed in alphabetical order.

Boxwork

Coined at Wind Cave and now used worldwide, “boxwork” was named because of its resemblance to a cluster of post-office boxes. Boxwork can be composed of any mineral more resistant than the surrounding bedrock, which weathers away, but calcite is most common. Calcite protrudes as fins, plates, or veins in all limestone layers, but boxwork forms only in caves that have had long periods of intense weathering (Palmer 1984). However, long exposure to weathering by itself is not enough, as shown by the near absence of boxwork in the upper level of Wind Cave. The combination of crystalline veins of calcite surrounded by crumbly, altered bedrock is necessary for the formation of boxwork. In the public passages of Wind Cave, some of the best displays of boxwork are in the Post Office and the Elks Room (Palmer 1995) (see fig. 1).

Boxwork is a relic from the very earliest stages of cave formation (Palmer 1995). As such, boxwork is a speleogen, forming when bedrock between preexisting calcite veins were preferentially weathered away as the cave developed. The calcite veins (now fins) were originally gypsum (or anhydrite) that filled cracks in the dolomite; pseudomorphs of the original gypsum crystals are commonly preserved within these fins. The intervening bedrock is porous and crumbly, having been altered by sulfuric acid. In many places crumbly, weathered, brown or black bedrock still occupies the gaps between the boxwork fins. Altered bedrock between boxwork veins disintegrates and falls out at the slightest touch, especially in zones of condensation and periodic rises in the water table (Palmer and Palmer 1995).

Boxwork fins tend to intersect one another at various angles, forming open chambers. Blades of crystalline material protrude outward from walls, ceilings, and floors. Estimates of maximum protrusion in Wind Cave vary: 60 cm (24 in) (Hill and Forti 1997), 1 m (3.3 ft) (Bakalowicz et al. 1987), and “three and four feet” (0.9 and 1.2 m) (Scheltens 1988). Regardless of the exactness of protrusion measurements, the famous boxwork of Wind Cave is in scale, extent, and complexity the finest yet described (Bakalowicz et al. 1987). Just beyond the Nudist Colony the boxwork is so big it is called “cratework” (Scheltens 1988). Boxwork can also be paper thin and very delicate. Its many shapes and colors—ranging from translucent orange-yellow to dusky brown or black—give the impression of an extraterrestrial landscape (Palmer 1995). In the lower level of the cave, a lining of calcite crystals or weathered wall powder coasts the boxwork. Water seeping out of the walls also deposits frostwork (see “Frostwork” section) and popcorn (see “Coralloids” section) on the edges of the boxwork. In this way, most of the original boxwork veins have been strengthened and decorated (Palmer 1995).

Coralloids

“Coralloid” is a catchall term describing knobby or nodular speleothems. Coralloids appear as grapes, knobstone, coral, cauliflower, globularites, and grapefruit in caves, but the most common coralloid in Wind Cave is cave popcorn. Occurring throughout the cave, popcorn is most visible in the Fairgrounds, the Pearly Gates, and the Garden of Eden along the public trails (Palmer 1995). Coralloids in Wind Cave range in size from tiny beads to rounded knobs 2.5 cm (1 in) in diameter. A spiky version is also common throughout the cave. The fascinating array of shapes that coralloids can assume depends on their particular history of development. One variety in Wind Cave resembles buttons and is called button popcorn. Speleologists used to think that all coralloids formed under water but now know that most coralloids are subaerial deposits, generally forming by capillary-film water. Subaerially formed coralloids are usually small and knobby in shape, while subaqueous coralloids tend to be larger and more uniformly contoured (Hill and Forti 1997).

Corrosion Residue

Unlike other features in Wind Cave, not much appears in the scientific literature about corrosion residue, also called “weathering residuum.” Nevertheless, its colors make it distinctive and worth noting. Traditionally, scientists thought that corrosion residue was composed of insoluble iron and manganese left over from the dissolution of the cave. However, because most of this material is found on the ceilings, more recent studies have suggested that the corrosion residue may actually be the byproduct of microbial processes. Palmer (1995) includes the following description:

> Where there is no lining of calcite crystals, weathering of the cave walls has produced a soft powdery coating of disintegrated bedrock. It contains many colors such as red, yellow, pink, brown, and black, which contrast vibrantly with the dull gray of unweathered limestone. Iron oxides and clay minerals cause most of these colors, although manganese dioxide produces some of the blue-gray and

black. In places the weathered coating on the walls is several inches thick (p. 54).

Crystals and Coating

Two kinds of crystals are common in Wind Cave: calcite and quartz. “Spar” is a general term for calcite crystals with clearly visible faces. Dogtooth spar is composed of sharp-ended crystals that come to a point, resembling a dog’s tooth. The largest of these in Wind Cave is about 5 cm (2 in) long. Groundwater deposited dogtooth spar in isolated pockets in the limestone. When breakdown fell from the ceiling (see “Cave Breakdown” section), the spar-lined pockets became exposed and now resemble geodes (see “Geodes” section). Though less common, nailhead spar also occurs in Wind Cave. Nailhead spar forms blunt knobs with several crystal faces that join at obtuse angles and resemble an old-style square nail.

Although uncommon in most limestone caves, displays of quartz crystals are notable in Wind Cave. The crystals are usually clear and reflect light brilliantly. Some have grown around fossilized, iron-fixing bacterial strands, which appear as dark brown or black cores (see “Paleontological Resources” section). Some of the crystals have taken on spectacular forms, for instance the “Crown Jewels,” which are sparkling, fingerlike projections hanging from the ceiling (Schilberg and Springhetti 1988). More typically, crystals are tiny, transparent euhedral specimens in druses on the walls. Quartz crystals also line many of the boxwork veins and small fractures throughout the cave (Palmer 1995).

The thickest coatings of crystals in Wind Cave are in the Calcite Jungle, where they create a bumpy surface on the walls and boxwork. Crystal linings are very thin along the public trails in Wind Cave and merely form a sparkling glaze over the bedrock (Palmer 1995).

Dripstone

The Minnelusa Formation (primarily sandstone) forms a cap over much of Wind Cave, preventing calcite from going into solution and being deposited in the cave. What little there is, is immediately deposited in the upper level, where water first encounters the cave (Rod Horrocks, Wind Cave National Park, e-mail, February 12, 2008). Hence, the most well-known speleothem forms—stalactites and stalagmites—are scarce at Wind Cave. They occur at perhaps 5% or 10% of the survey stations, all in the upper level (Rod Horrocks, Wind Cave National Park, e-mail, February 12, 2008).

Cave Minerals of the World distinguishes between stalactites, stalagmites, flowstone, and draperies as speleothem types. It does not have a specific category for “dripstone”—a term that many explorers of Wind Cave use. Investigators of Wind Cave seem to lump all of these “wet forms,” possibly because of the scarcity of each in Wind Cave. Following the lead of Wind Cave investigators, stalactites, stalagmites, draperies, and flowstone are grouped here.

Stalactites and Stalagmites

Stalactites resemble icicles or carrots hanging from cave ceilings; in Wind Cave they range in size from small, slender, soda straws to thick pendants several feet long. Like stalactites, stalagmites can also assume a fascinating variety of shapes; cavers have compared them to broomsticks, totem poles, toadstools, bathtubs, Christmas trees, beehives, coins and buttons, and even fried eggs. Stalagmites are usually larger in diameter than the stalactites above them and they generally have rounded tops, not pointed tips like stalactites.

Flowstone and Draperies

Described as “melted cake icing” and “frozen waterfalls,” flowstone is composed of calcite or other carbonate minerals that are deposited in layers or bands in both open air and underwater settings. Individual flowstone layers may be very colorful—yellows, reds, and oranges. Flowstone assumes a variety of forms, often referred to as “cascades,” “rivers,” or “glaciers.” Flowstone forms smooth, rippled sheets or draperies where water runs down sloping ceilings in the cave. The semiarid climate of the Black Hills and the spongelike texture of the Pahasapa Limestone dictate that such deposits are not widespread (Schilberg and Springhetti 1988). However, small cascades of yellow flowstone decorate the walls near Devils Lookout and beside the staircase leading downward from the Garden of Eden (Palmer 1995) (see fig. 1).

Fibrous Speleothems and Flowers

Gypsum is a soft, white mineral that forms in only the driest parts of Wind Cave, where the Minnelusa Formation covers the Madison Formation, mostly under hills or ridges. Most of the gypsum is picked up from gypsum beds within the overlying sandstone, although some is formed by the weathering of iron pyrite (“fool’s gold”) in the limestone. As the water evaporates in the cave’s dry areas, fibrous gypsum is deposited.

Cave Minerals of the World has a category called “fibrous speleothems” into which many of the gypsum speleothems of Wind Cave fit: beards, starbursts, ropes, hair, cave cotton, splatter, and luster. In a few places gypsum forms long thin needles clustered together in white, life-size “beards” (Palmer 1995). Gypsum as “cave cotton” grows out of the wall behind the Pearly Gates in a formation referred to since early days as “Noah’s Beard” (Schilberg and Springhetti 1988). “Starbursts” of radiating gypsum crystals a few inches long hug the surfaces of breakdown in the lower level of Wind Cave. *Cave Minerals of the World* also has a category called “flowers,” in which the rare gypsum flowers of Wind Cave may be placed (National Park Service 1994). Gypsum flowers have crystal “petals” that radiate from a common center (Hill and Forti 1997).

Frostwork

The resemblance of frostwork to needles of ice that cover surfaces on a frosty morning led early Wind Cave guides to coin the term now used to describe similar features found in other caves around the world (Kiver and Harris 1999). The needlelike habit of aragonite gives most frostwork this particular appearance, though frostwork can consist of calcite, opal, gypsum, and other minerals, as well as ice, though not known to be present in Wind Cave. Frostwork in Wind Cave is usually white but can also be other colors, including orange or red—a result of iron-oxide staining.

Frostwork displays can be dazzling. They are among the most exquisite of all speleothem types. Varying shapes and amounts of frostwork occur in Wind Cave. Some take the shape of delicate snow-covered, foot-tall Christmas trees. Most frostwork crystals form as radiating sprays and are about the diameter of a pin and less than 5 cm (2 in) long (Palmer 1995).

Frostwork grows from nearly every kind of rock or mineral in Wind Cave, but it is most abundant where the cave walls are porous dolomite. Frostwork seems to form best in areas where airflow is significant, such as narrow spots in a passage (Palmer 1995). In a crawlway known as the Frostline, the walls are covered with delicate aragonite clusters as much as 10 cm (4 in) in length (Scheltens 1988). Such observations have led some speleologists to suspect that rapid evaporation or loss of carbon dioxide (CO_2) is important for frostwork formation (Kiver and Harris 1999).

In Wind Cave, frostwork and popcorn are usually found together as coatings and decorations on boxwork and other speleothems (fig. 9). Large, frostwork-covered stalagmites (see "Stalactites and Stalagmites" section) with central drip holes are found near Christmas Tree Park (Schilberg and Springhetti 1988); these forms are called "logomites." Frostwork is well developed in parts of the Fairgrounds and Garden of Eden. However, it is in scattered parts of the "new" part of the cave where frostwork is most intensively and extensively developed. Groups traveling to the Club Room pass through the stunning Frostline, but more dramatic and picturesque displays exist farther into the cave, at the Snow Room.

Geodes

Geodes are hollow, globular bodies found in limestone and other rocks. They have a thin yet dense outer layer and are partially filled by inward-projecting crystals, generally calcite or quartz. Most geodes in Wind Cave were originally small blobs of gypsum deposited along with the limestone. Groundwater later dissolved the gypsum, which calcite replaced; the calcite formed dogtooth spar, which quartz later covered. As Wind Cave formed and grew, it intersected the geodes in the Pahasapa Limestone. Hence, like boxwork, geodes are speleogens, rather than speleothems.

In Wind Cave, geodes range from a few inches to a few feet in diameter (Palmer 1995); smaller geodes tend to be circular while larger ones (several feet in diameter) tend to be irregular in shape. The hard outer shell allows many geodes to weather out of the bedrock as nearly round balls, for example those exposed in the Calcite Jungle or Geode Hall. In the maze of the Calcite Jungle, crystal geodes are exposed in the breakdown blocks that have separated from the wall, and unopened geodes appear as spherical bulges that protrude from the calcite-covered walls (Scheltens 1988).

Helictite Bushes

First discovered in Wind Cave and second only to boxwork in distinction, helictite bushes are a feature for which Wind Cave is famous (fig. 10). Helictites seem to defy gravity, twisting in any direction; they epitomize the meaning of their name ("to spiral"). In Wind Cave, intertwining bushes of long, wormlike helictites grow to huge size. The largest helictite bushes—about 2 m (7 ft) tall, with individual branches that are as thick as fingers—are near the Lakes and are lined by the same calcite crust that coats the adjacent walls. One particular oddity in this area is a small bush ensconced with calcite rafts that were left when a previously higher lake receded. Another curiosity is a helictite bush covered with pool spar that resembles a cactus. Also, the loop route to the Club Room passes some bushes that, though small, have remarkably thick (finger-sized) branches (Schilberg and Springhetti 1988).

In Wind Cave, helictite bushes grow communally upward from floors. In other caves, helictites more commonly grow from cave ceilings and walls. Most helicitie bushes have internal canals too large to convey capillary water, so a probable interpretation is that they formed under water, in areas where water was seeping upward from below. Work by D. G. Davis (1988, 1989, and 1991) suggests that the helictites bushes in Wind Cave could be subaqueous in origin, and studies by LaRock and Cunningham (1995) propose that the helictite bushes in Wind Cave formed in a shallow pool by bacterial processes and CO_2 degassing. These authors determined (from isotope paleotemperature calculations) that the Wind Cave helictite bushes formed about 200,000 years ago in thermal water varying from 33°C to 42°C (91°F to 108°F). The only other known examples of this kind of helictite are in Lechuguilla Cave, New Mexico, where a mixture of calcite-saturated and gypsum-rich waters forced the less soluble calcite to precipitate (Palmer 1995).

Most helictite bushes in Wind Cave are located along the trend of a major fracture system that runs northwest and southeast of the Club Room (see. fig. 5) (Palmer 1995). The geologic and hydrologic influences guiding the alignment of helictite bushes are not entirely clear, but investigators are using GIS to perhaps explain this pattern (Ohms and Reece 2002).

Moonmilk and Balloons

One of the last minerals deposited in Wind Cave is hydromagnesite—$Mg_5(OH)_2(CO_3)_4 \times 4H_2O$ (White and Deike 1960). It occurs as white patches and forms two types of speleothems: moonmilk and balloons. Moonmilk is pasty when wet and powdery when dry. Wet moonmilk looks and feels like cream cheese; dry moonmilk resembles talcum powder. Moonmillk coats many surfaces and forms small blisters on frostwork, blobs on cave walls, or powdery deposits on cave floors. Moonmilk is formed where magnesium-rich water seeps into the cave and evaporates in particularly dry and windy areas (Palmer 1995).

Also composed of hydromagnesite are cave balloons. These thin-walled speleothems appear as mineralized, baglike pouches with gas inside. Believed to be short-lived, cave balloons quickly dry, crack, deflate, and change in luster, especially in low-humidity environments. The extreme fragility of cave balloons probably accounts for the scarcity of this speleothem type. Investigators have documented only two possible balloons in Wind Cave (National Park Service 2003).

Rafts and False Floors

In the lower level of the cave, the Lakes region hosts subterranean waters saturated with calcite and covered with paper-thin rafts. Some of these rafts are as long as 18 cm (7 in) (Tom Miller, personal communication, p. 684 *in* Kiver and Harris 1999). They may even coalesce into a continuous sheet as at Calcite Lake (Palmer 1995). In January 2009, explorers discovered another pool with many calcite rafts in an area they named The Deep End (see inside front cover).

Other names for cave rafts are “snowflakes,” “floe calcite,” “calcite platelets,” and “cave ice,” though *Cave Minerals of the World* recommends avoiding this last term because it invites confusion with frozen-water speleothems. Usually composed of carbonate minerals (i.e., calcite or aragonite), cave rafts may also consist of other minerals such as gypsum or native sulfur (Hill and Forti 1997).

Rafts commonly form where a faint dust of weathered limestone settles onto a pool surface, providing nucleation sites for calcite. The resulting rafts look like lily pads except that they are usually pure white or yellow (Palmer 1995). Cave rafts form in quiet pools where carbon dioxide degasses at the water’s surface and surface tension supports precipitated material. Growth of rafts is rapid (weeks to months), with the crystals forming radially around a nucleus (Pomar et al. 1976). Crystals grow more slowly (and hence longer) on the undersides of rafts because carbon dioxide cannot escape into the atmosphere as easily as on the smoother top side. A floating raft continues to grow until (1) it sinks from its own weight, (2) dripping water disturbs the cave pool’s surface, or (3) water quickly recedes from the pool (Hill and Forti 1997). If not cemented, rafts lying on the bottom of drained pools may float again on rising water (Viehmann 1992).

False floors probably mark former pool surfaces (Bakalowicz et al. 1987). False floors are composed of calcite and are generally about 5 cm (2 in) thick (Scheltens 1988). In most areas of Wind Cave with false floors, they are broken, and the real floor is easily seen 0.3–9 m (1–30 ft) below. However, in areas where the calcite floor is intact, Scheltens (1988) recommends walking along the edges and not in the center.

Spongework

Though not included in *Cave Minerals of the World*, various sources describe spongework as a cave formation in Wind Cave. Described as an “intricate maze of random solutional openings” that forms a “Swiss cheese–like pattern, especially in the upper cave levels,” the openings in spongework range in size from a few inches to several feet across. In some places, spongework forms a three-dimensional network of passages large enough for a person to crawl through (Harris and Tuttle 1990).

Spongework is a primary speleogen formed during the initial dissolution of the cave, as the most soluble material was selectively removed (Harris and Tuttle 1990). Later enlargement of passageways usually destroyed spongework that had developed earlier in the middle and lower levels of the cave (Kiver and Harris 1999).

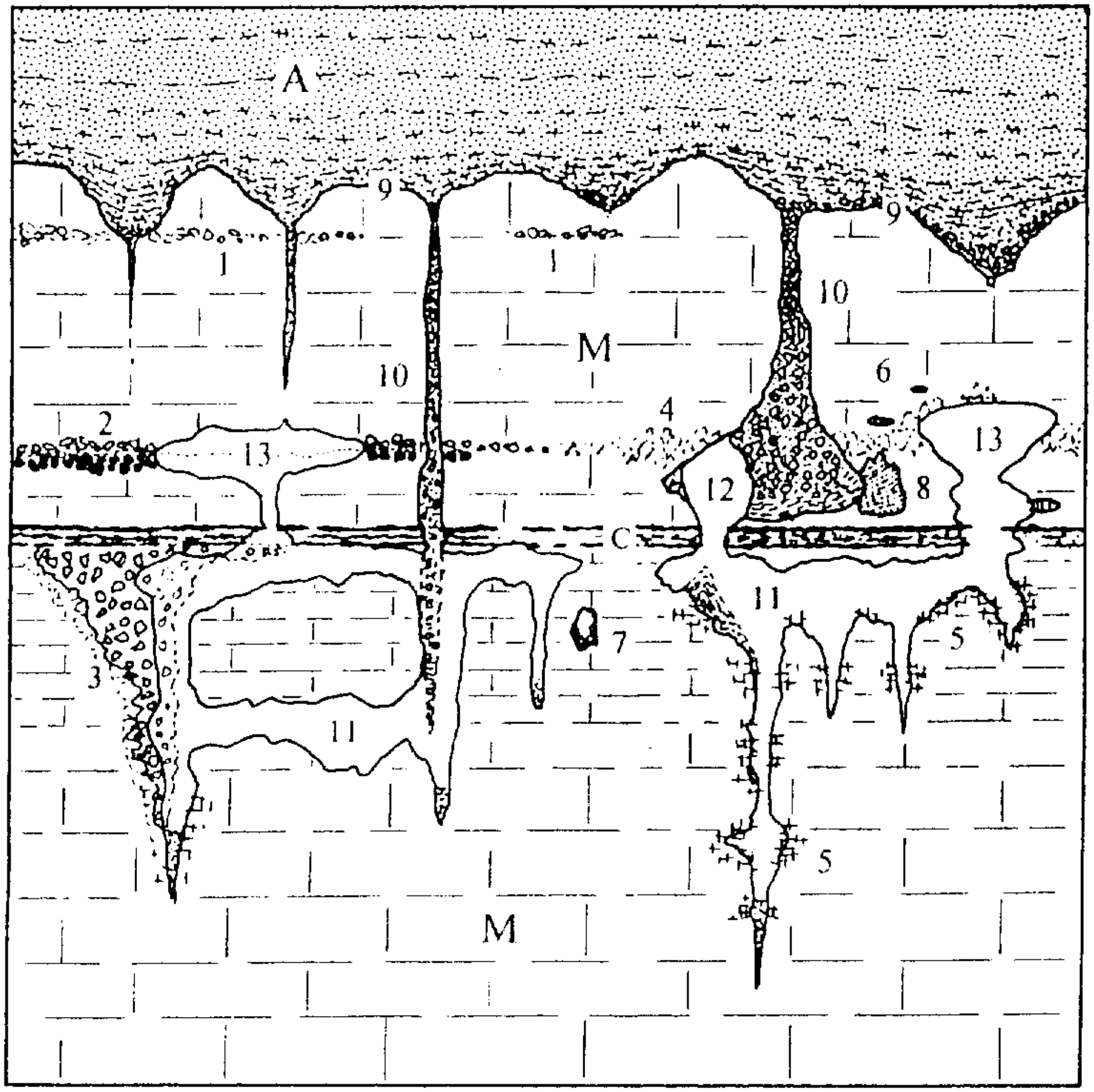

Figure 6. Idealized Cross Section through the Pahasapa Limestone. The figure shows multiple stages of karst and related processes. Vertical range of the diagram is roughly 150 m (490 ft) but the horizontal scale is unspecified. M = Madison Limestone (locally known as Pahasapa Limestone); A = Amsden Formation (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 7. Rhinoceros Remains. Rod Horrocks and Kali Pace (Wind Cave National Park) apply plaster to an articulated foot of a rhinoceros fossil *(Subhyracodon occidentalis)* discovered in the park in 2003. NPS photo.

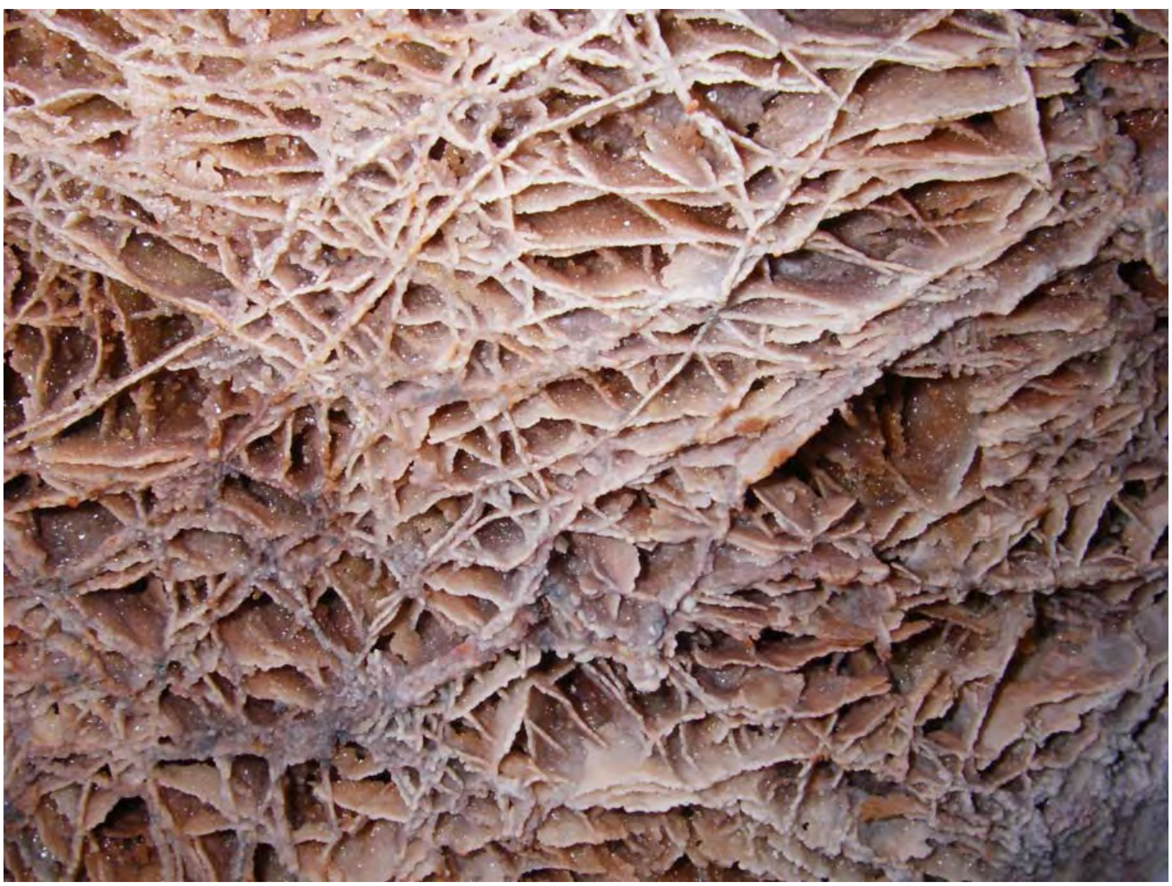

Figure 8. Boxwork. Named for its resemblance to a cluster of post-office boxes, boxwork such as this in the Arrow Passage of Wind Cave is a relic from the earliest stages of cave formation and, as such, is technically a speleogen. Photo by Ken Geu.

Figure 9. Frostwork. Frostwork forms on many cave surfaces but most commonly in occurrence with coralloids such as this cave popcorn in the Freshman Frostline area of Wind Cave. Photo by Ken Geu.

Figure 10. Helictite Bush. Twisting, spiraling helictite bushes are distinctive speleothems in Wind Cave because of their unique forms and their age; researchers calculated the age of helictite bushes such as this one on the route to the lakes to be about 200,000 years old. Photo by Jason Walz.

Map Unit Properties

This section identifies characteristics of map units that appear on the Geologic Resources Inventory digital geologic map of Wind Cave National Park. 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 Wind Cave National Park 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 is source data for the GRI digital geologic map for Wind Cave National Park:

DeWitt, E. 2004. Geologic map of the Mount Rushmore and Rapid City 30' × 60' quadrangle, South Dakota. Scale 1:100,000. Unpublished Mylar maps. Reston, VA: U.S. Geological Survey.

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/).

This digital product covers Wind Cave National Park, Jewel Cave National Monument, and Mount Rushmore National Memorial. Not all of the units in the digital geologic map are listed in the Map Unit Properties Table that follows. This table highlights only the units of interest for Wind Cave National Park and presents a tabular view of the park's strata. The table includes the name, age, and symbol adopted for each map unit, a brief description, and characteristics such as mineral and paleontological resources and suitability for development.

In addition to the source reference, the table incorporates information from Dyer (1961), Braddock (1963), Gries (1974), DeWitt et al. (1989), Schilberg and Springhetti (1988), Palmer and Palmer (1989), Frelund (1996), Strobel et al. (1999), and Redden and DeWitt (2008).

The map included with this report is at a scale of 1:100,000. In summer 2008, investigators from the South Dakota Department of Environment and Natural Resources, Geological Survey Program; South Dakota School of Mines and Technology; and Albion College (Michigan) embarked upon a three-year project of mapping the six quadrangles of interest for Wind Cave National Park—Cicero Peak, Butcher Hill, Mt. Coolidge, Pringle, Wind Cave, and Boland Ridge—at a scale of 1:12,000. The South Dakota Department of Environment and Natural Resources, Geological Survey Program, will publish the map. Mark Farenbauch and Brian Fagnan are the geologists from the State who will be supervising geology interns; Dr. Alvis Lisenbee (South Dakota School of Mines and Technology) will assist with the project (Rod Horrocks, Wind Cave National Park, e-mail, February 7, 2008). Drs. Tim and Beth Lincoln (Albion College) are mapping the Precambrian rocks in the park.

Map Unit Properties Table for Wind Cave National Park

Age	Map Unit (Symbol)	Description	Mineral Resources	Paleontological Resources	Suitability for Development/Recreation
QUATERNARY (Holocene and Pleistocene)	Alluvial deposits (Qal)	Mud, silt, sand, and gravel; fluvial deposits; maximum thickness 10 m (33 ft)	Gravel deposits	None documented	Local aquifer where saturated; active gullying in Highland Creek drainage
	Landslide deposits (Ql)	Small colluvial deposits typically along escarpments of Pierre Shale	None documented	None documented	Unsuitable
	Colluvium or talus (Qc)	Angular blocks and debris masking bedrock; maximum thickness 10 m (33 ft)	None documented	None documented	Generally not an aquifer, even when saturated
	Terrace gravel and alluvial-fan deposits (Qt)	Gravel, sand, and silt; some higher elevation terrace deposits could be of Pliocene age; four alluvial terrace levels and numerous alluvial fans in Highland Creek drainage; maximum thickness 30 m (100 ft)	Well-rounded gravel in Highland Creek drainage	*Bison* vertebra and charcoal (Ponderosa pine) in Highland Creek drainage	Potential for landslides on north- and east-facing scarps
TERTIARY	White River Group (Tw)	Silty claystone and poorly indurated sandstone, arkose, and conglomerate; gravel at higher elevations; divided into Brule (top) and Chadron (base) formations; maximum thickness 120 m (390 ft)	Gravel deposits, skarns	Bones of rhinoceros and early horse; remains of tortoise, deerlike mammal, and unidentified carnivore	Minor aquifer where saturated
CRETACEOUS	Pierre Shale (Kp)	Dark-gray to black shale; maximum thickness 500 m (1,640 ft)	Concretions	Teepee buttes underlain by fossiliferous limestone formed by methane-rich spring deposits	Bentonite beds
	Niobrara Formation (Kn)	Gray to yellowish-tan, thin-bedded limestone and calcareous shale; thickness 60–100 m (200–330 ft)	None documented	None documented	
	Carlile Shale (Kc)	Gray shale and a few tan siltstone and resistant sandstone beds; thickness 100–200 m (330–660 ft)	None documented	None documented	
	Greenhorn Limestone (Kg)	Light-gray to tan, thin-bedded limestone and calcareous shale; thickness 70–120 m (230–390 ft)	None documented	None documented	
	Belle Fourche Shale (Kb)	Gray to black shale; thickness 70–200 m (230–660 ft)	Concretions	None documented	
	Mowry Shale (Km)	Dark-gray shale, locally somewhat siliceous; thickness 40–70 m (130–230 ft)	Lead and manganese	Fish scales	
	Skull Creek Shale (Ks)	Dark-gray to black shale; underlies minor valleys where Newcastle Sandstone is present; thickness 55–80 m (180–260 ft)	Iron-stained concretions	None documented	None documented
	Fall River Formation (Kf)	Sandstone interbedded with gray to dark-gray shale near top; thickness 35–70 m (115–230 ft)	Uranium	None documented	Landslides on north- and east-facing scarp of hogback; major regional aquifer
	Lakota Formation (Kl)	Sandstone, mudstone, and shale; upper part is hard siltstone; thickness 85–150 m (280–490 ft)	Uranium	Petrified wood	Major regional aquifer
JURASSIC	Morrison Formation and Unkpapa Sandstone, undivided (Jmu)	Morrison Formation: Shale and sandstone; minor limestone; maximum thickness 50 m (160 ft) Unkpapa Sandstone: Fine-grained eolian (windblown) sandstone; lenses out to the west; thickness as much as 85 m (280 ft).	None documented	Morrison Formation: Known worldwide for skeletons of large dinosaurs, especially giant sauropods; significant for reconstructing Late Jurassic, predominately terrestrial ecosystem throughout the Western Interior	Very small slumps (Ql) in Jurassic rocks
	Sundance and Gypsum Spring formations, undivided (Jsg).	Sundance Formation: Interbedded shale, siltstone, and sandstone; thickness 70–160 m (230–525 ft) Gypsum Spring Formation: Gypsum and shale; maximum thickness 25 m (80 ft)	Gypsum	None documented	Very small slumps; readily eroded Sundance Formation: Locally productive aquifer where saturated
TRIASSIC	Spearfish Formation (TRPs)	Red shale and siltstone, minor limestone and gypsum; collapse structures (limestone-dolomite breccias) produced by the solution of anhydrite in early Cenozoic; thickness 70–275 m (230–900 ft)	Gypsum	None documented	Minor deformational structures (e.g., small thrust faults, minor folds, dolomite breccia, and pull-apart structures [in gypsum]); readily eroded
PERMIAN	Minnekahta Limestone (Pm)	Pinkish-gray, thin-bedded limestone; thickness 10–18 m (33–60 ft)	Calcite and anhydrite crystals; source for crushed rock, ballast, riprap, and building stone; used for cement and lime	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
	Opeche Shale (Po)	Maroon shale and siltstone; thickness 20–40 m (66–130 ft)	None documented	None documented	Unknown

Age	Map Unit (Symbol)	Description	Mineral Resources	Paleontological Resources	Suitability for Development/Recreation
PENNSYLVANIAN	Minnelusa Formation (ℙhm)	Red, thin-bedded sandstone, limestone, and minor shale; fills paleokarst features in upper Pahasapa Limestone; collapse structures (breccias) produced by the solution of anhydrite in early Cenozoic under humid conditions; persistent layer of red mudstone marks Pennsylvanian-Permian boundary; correlative to Amsden Formation in Wyoming; forms irregular slopes and low ledges at surface; thickness 120–200 m (395–660 ft)	Sand used for glass manufacturing; accessory minerals in sandstone: zircon, tourmaline, leucoxene, carbonate, pyrite with anhydrite, and fluorite	Foraminifera confirm Permian age of upper red mudstone layer, conodonts	Sandstone intervals are good aquifers; too thinly bedded for cave development; extensive faults and folds (reflect structure of underlying Pahasapa Limestone); areas of solution and collapse regionally
MISSISSIPPIAN	Pahasapa Limestone (Mp)	Thickest limestone layer in Black Hills; mainly thick-bedded dolomitic limestone; reeflike bluish limestone in uppermost part; correlative with Madison Limestone of Wyoming and Montana, Leadville Limestone of Colorado, and Redwall Limestone of Arizona; thickness 80–210 m (260–690 ft) <u>Upper unit</u>: Massive limestone characterized by pre-Pennsylvanian caves and solution pockets; smooth arched ceilings and walls in cave, very little boxwork; prominent cliffs at surface <u>Middle unit</u>: Chert beds separate upper and middle unit; pre-Pennsylvanian solution pockets and fossils near top; predominantly bedded limestone and dolomite; low, wide rooms and passages in upper beds in cave, much boxwork; irregular fissures in lower beds; slopes with low ledges at surface <u>Lower unit</u>: Massive, limy dolomite; boxwork, prominent fissure passages, wall coatings of calcite crystals in cave; prominent cliffs at surface	Chert beds; calcite spar lining in cave and many smaller cavities lined with calcite; mined for limestone and dolomite; gold and silver in dolomitic zones	Fossil shells (brachiopods and gastropods), colonial corals, burrows	Contains nearly all Black Hills caves; forms steep-walled cliffs in canyons; regional aquifer; feebly thermal/highly mineralized hot springs
MISSISSIPPIAN DEVONIAN	Englewood Limestone (MDe)	Impure lavender limestone; thickness about 9 m (30 ft)	None documented	Uppermost 2.4 m (8 ft) highly fossiliferous	Unknown
ORDOVICIAN CAMBRIAN	Deadwood Formation (OꞒd)	Glauconitic sandstone, shale, siltstone, and conglomerate; thickness about 9 m (30 ft)	Silica	None documented	Aquifer; extensive minor faults and folds
PRECAMBRIAN	Harney Peak Granite (Xh)	Layered granite, pegmatitic granite, and pegmatite; consists of hundreds of intrusions, more than 24,000 separate bodies of pegmatite and granite	Pegmatite contains tourmaline, biotite, feldspar, and beryl	None documented	Numerous faults of diverse types and ages cut Precambrian rocks in the Black Hills
	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 ages; highly variable thicknesses up to 305 m (1,000 ft)	None		
	Distal metagraywacke (Xgwd)	Grayish-tan and siliceous schist; calc-silicate lenses developed from former concretions; exceeds 3,600 m (11,810 ft) in thickness	Garnet, staurolite, and sillimanite		
	Proximal metagraywacke (Xgwp)	Light-tan, thick-bedded quartzose schist; total thickness about 2,200 m (7,220 ft)	None		
	Metagraywacke unit 2 (Xgw2)	Middle part of Xgw (greenish-gray to grayish-tan siliceous schist); lithologically similar to Xgw3 (gray to tan siliceous schist); may be as much as 2,000 m (6,560 ft) thick	None		
	Metamorphosed younger alkalic basalt, tuff, and volcaniclastic rocks (Xby)	Pillowed chloritic greenstone or amphibolite, and layered amphibole schist and amphibole-bearing or biotite-rich schist; intertongues with tuffaceous shale, tuff, and volcaniclastic rocks (unit Xtv) that have U-Pb zircon age of 1,884±29 million years; maximum thickness 1,000 m (3,280 ft)	Sulfide minerals or graphite		
	Metamorphosed quartzite, debris-flow conglomerate, pelite, and graywacke (Xqc)	Heterogeneous, gray to tan quartzite, metaconglomerate, and phyllite or schist; thickness 30–700 m (100–2,300 ft)	Garnet, staurolite, andalusite, and sillimanite		
	Metamorphosed quartzite and pelite (Xqs)	Interbedded quartzite, grayish-tan schist, and phyllite; maximum thickness 1,200 m (3,940 ft)	Metamorphic-grade quartzite and sillimanite schist		
	Metamorphosed black shale (Xbs2)	Thin-bedded, dark phyllite, biotite schist, or garnet schist, depending on metamorphic grade; maximum thickness 700 m (2,300 ft)	None		
	Metamorphosed carbonate-facies, iron-formation (Xif)	Banded metachert containing ankerite and siderite, and schist; average thickness about 25 m (80 ft)	Cummingtonite-grunerite and garnet; locally sulfide-rich and graphitic		

Geologic History

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

The Precambrian rocks of Wind Cave National Park are primarily metamorphic, having been altered during mountain building from their previous sedimentary and igneous forms. The youngest Precambrian rock unit in the park, the Harney Peak Granite, however, is igneous and known for its pegmatite. By the time shallow Cambrian seas began to move across and cover much of North America, erosion had reduced the preexisting Precambrian mountains to low relief. For 470 million years, South Dakota was situated along a 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, Spearfish Formation (shale, siltstone, and bedded gypsum), Sundance and Gypsum Spring formations (primarily shale), Morrison Formation (shale and sandstone), and Unkpapa Sandstone represent marine, coastal, and inland (e.g., playa and desert plain) environments. Changing sea levels resulted in fluctuating saltwater and freshwater conditions: At times of lower sea levels, groundwater displaced saline water, promoting the deposition of dolomitic limestone. Streams transported sand and soluble minerals to the seas, resulting in sandstone; wind also transported and deposited sand. Mud became sedimentary siltstone or shale, and later metamorphic schist. When evaporation was high and water circulation poor, gypsum and anhydrite were deposited.

The most significant Paleozoic event for Wind Cave was the deposition the Pahasapa Limestone 360–340 million years ago. Wind Cave occupies the upper 76 m (250 ft) of this formation. Most of the steep-walled cliffs in the canyons of the park are also composed of Pahasapa Limestone. The sediments of the Pahasapa Limestone were deposited in a shallow sea subject to high rates of evaporation; therefore, lenses of chert, gypsum, and anhydrite are a distinctive feature. Later, dissolution of evaporites created voids into which overlying limestone collapsed. This period of dissolution set the pattern for the main phase of cave formation, which would occur much later (60–40 million years ago).

At the end of the Mississippian Period, sea level dropped, exposing the Pahasapa Limestone to wet climatic conditions. Solution fissures, sinkholes, and some caves formed. Palmer and Palmer (1995) referred to these dissolution features as the "Kaskaskia paleokarst," part of the Mississippian-Pennsylvanian unconformity and the most clearly exposed relict karst system in North America. Fresh groundwater displaced the original saline water in which the Pahasapa Limestone was deposited, and calcite replaced gypsum and anhydrite.

As sea level rose again in the early Pennsylvanian Period (about 300 million years ago), streams deposited the Minnelusa Formation, which filled dissolution features at and near the top of the Pahasapa Limestone. The red sand and clay deposits in Wind Cave (e.g., in the Beauty Parlor, W.C.T.U. Hall, and the Garden of Eden) are sediment-filled cavities that mark the presence of paleokarst. A layer of white calcite (dogtooth spar) was deposited in preexisting cavities that had not filled with sediment.

By the end of the Cretaceous Period (65.5 million years ago), as much as 2 km (1.2 mi) of sediment covered the Pahasapa Limestone. These sediments became the Permian, Triassic, Jurassic, and Cretaceous shales and other rock units (i.e., siltstone, limestone, sandstone, and mudstone) at Wind Cave National Park (see "Map Unit Properties Table"). During the Paleocene and Eocene epochs (65–40 million years ago), streams eroded all but the Minnelusa Formation from the area above the cave. However, the age of the landscape is clear because these other rock units, including the fossil-rich Oligocene White River Group, are present in the eastern part of the park. The White River Group eroded from the higher hills and formed a sheet of material that extends far to the east, where it is the main attraction of Badlands National Park (Palmer 2007). At the surface of Wind Cave National Park, vertebrate fossils such as bones of a rhinoceros, early horse, and tortoise (see "Paleontological Resources" section) record the presence of early mammals.

Starting about 58 million years ago, the Laramide Orogeny began uplifting the Black Hills, thereby ending marine domination. During the early stages of the Laramide Orogeny, quartz crystals coated the dogtooth spar (Palmer and Palmer 1995). According to Lisenbee and DeWitt (1993), Laramide uplift was probably complete by about 54 million years ago. The central uplifted core is composed of Precambrian metamorphic and igneous rocks. Harney Peak, the highest mountain in South Dakota, exemplifies the uplift. The Paleozoic and Mesozoic rocks form roughly concentric rings around the flanks of the elongated, dome-shaped Black Hills and typically dip away from the center of the dome at angles that approach or exceed 10° (Strobel et al. 1999). Uplift exposed the eroded edges of the sedimentary rocks, including the Pahasapa Limestone, around the perimeter of the Black Hills. As groundwater moved through the rocks, the cave was enlarged, especially along zones of older cave development and alteration (Palmer and Palmer 1999).

As erosion and intermittent uplift continued into the Pliocene Epoch (5.3 million years ago) Wind Cave slowly drained. The water table fluctuated considerably during its gradual lowering to the present position. 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). Today the water level at the Lakes region in Wind Cave is about 150 m (500 ft) below the surface. Faulting may have provided discharge areas for water flow, allowed access to hydrothermal solutions, and produced extensive breakdown. Most breakdown collapse probably occurred during the final draining of the cave. Before final draining, preferential weathering took place, ultimately creating boxwork (see "Boxwork" section).

At the same time as the cave formed, the surface landscape was developing. Regional uplift in late Pliocene or early Pleistocene epochs (see fig. 3) led to exhumation of the old erosional/depositional surfaces and renewed downcutting (Redden 1999).

Although the Black Hills were topographically high during the Pleistocene Epoch, no glaciers formed. However, climatic variations during the Pleistocene caused fluctuations in river levels, which left a series of terraces in the major river valleys. Additionally, the fluctuating climate influenced the growth of speleothems: wetter conditions resulted in more water infiltrating the Pahasapa Limestone. Continuing landscape development at the surface included the formation of alluvial fans, talus and landslide deposits, and alluvium along stream channels.

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.

actinolite. A bright green or grayish green mineral of the amphibole group—$Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2$. It occurs in slender needlelike crystals and in fibrous form in metamorphic rocks.

allogenic. Generated elsewhere.

altithermal. A period of high temperature, especially the postglacial thermal optimum.

amphibole. An important group of generally dark colored rock-forming minerals, composed of double chain SiO_4 tetrahedra, linked at the vertices and generally containing ions of iron and magnesium in their structures. Amphiboles are minerals of either igneous or metamorphic origin.

amphibolite. A rock produced by metamorphic recrystallization consisting mostly of amphibole and plagioclase with little or no quartz.

andalusite. An orthorhombic mineral, Al_2SiO_5, commonly occurring in thick, nearly square prisms in schist and gneiss.

ankerite. A mineral—$CaCO_3 \cdot (Mg,Fe,Mn)CO_3$; a variety of dolomite that contain ferrous iron.

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

Archaic Period. Of or relating to the period from about 8000 BC to 1000 BC and the North American cultures at that time.

arkose. A feldspar-rich sandstone, typically coarse grained and pink or red, derived from the rapid disintegration of granite or granitic rocks and often resembling them.

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

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.

bentonite. Soft clay or claystone formed by the chemical alteration of glassy volcanic ash in contact with water. Bentonite is known for its shrink-swell potential and hazardous nature when wet, making trails and roads very slippery.

biotite. A common rock-forming mineral of the mica group—$K(Mg,Fe^{+2})_3(Al,Fe^{+3})Si_3O_{10}(OH)_2$. It is black in hand specimen, brown or green in thin section, and has perfect basal cleavage.

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

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

chlorite. A group of platy, greenish minerals of the general formula $(Mg,Fe^{2+},Fe^{3+})_6AlSi_3O_{10}(OH)_8$. Chlorite is associated with and resembles mica; it is also considered as clay minerals. It is widely distributed, especially in low-grade metamorphic rocks, or as alteration products of ferromagnesian minerals.

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]).

claystone. Lithified clay having the texture and composition of shale but lacking its fine lamination or fissility.

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

cummingtonite. Dark-green, brown, gray, or beige mineral of the amphibole group—$(Mg,Fe^{2+})_2(Mg,Fe^{2+})_5Si_8O_{22}(OH)_2$.

dolomitization. The process by which limestone is wholly or partly converted to dolomite rock or dolomitic limestone by the replacement of the original calcium carbonate (calcite) by magnesium carbonate (mineral dolomite), usually through the action of magnesium-bearing water (seawater or percolating meteoric water).

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

druse. An irregular cavity or opening in a vein or rock, having its interior surface or walls encrusted with small projecting crystals, usually the same minerals as those of the enclosing rock, and sometimes filled with water.

ecotone. A transition area between two adjacent ecological communities.

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

evapotranspiration. The total transfer of liquid water to water vapor at Earth’s surface: evaporation + transpiration.

extralimital. Not present in a given area.

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

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

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

garnet. A semiprecious stone, also used as an abrasive; garnet has a vitreous luster, no cleavage, and can be a variety of colors, dark red being characteristic.

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.

granite. A plutonic rock in which quartz makes up 10% to 50% of the felsic components and the alkali feldspar.

greenstone. A field term for any compact dark-green metamorphosed basic igneous rock that owes its color to chlorite, actinolite, or epidote.

grunerite. The iron-rich variety of cummingtonite—$Fe^{2+}_2(Fe^{2+}Mg)_5Si_8O_{22}(OH)_2$.

hornblende. The commonest mineral of the amphibole group—$(Ca,Na)s\text{-}3(Mg, Fe^{2+}, Fe^{3+}, Al)_5(Al,Si)_8O_{22}(OH)_2$. Hornblende is commonly black and occurs in distinct crystals or in columnar, fibrous, or granular forms.

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.

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.

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.

muscovite. A mineral of the mica group—$KAl_2(AlSi_3)O_{10}(OH)_2$. It is colorless to pale brown and is a common mineral in gneiss, schist, granite, pegmatite, and sandstone.

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.

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

pegmatite. An exceptionally coarse-grained igneous rock, with interlocking crystals, usually found in irregular dikes, lenses, and veins, especially at the margins of batholiths. The composition of pegmatite is generally that of granite.

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

phyllite. A metamorphosed rock with a silky sheen, intermediate in composition between slate and mica schist.

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).

quartzose. Containing quartz as a principal constituent, applied especially to sedimentary rocks.

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.

schist. A strongly foliated crystalline rock with parallel arrangement of mineral grains, formed by dynamic metamorphism.

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.

siderite. A brownish rhombohedral mineral of the calcite group, $FeCO_3$, commonly containing magnesium and manganese.

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

sillimanite. A brown, gray, pale-green, or white mineral—Al_2SiO_5. It occurs in long, slender, needlelike crystals often in wisplike or fibrous aggregates in schist and gneiss (syn: fibrolite).

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.

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.

skarn. Calcium-bearing silicates derived from nearly pure limestone and dolomite with the introduction of large amounts of Si, Al, Fe, and Mg.

speleothem. A mineral deposit formed in a cave from chemical solution or by the solidification of a fluid.

staurolite. A dark reddish-brown, blackish-brown, yellowish-brown, or blue mineral—$(Fe, Mg)_4Al_{17}(Si, Al)_8O_{45}(OH)_3$. Twinned crystals often resemble a cross. It is a common constituent of rocks such as mica schist and gneiss that have undergone metamorphism (syn: staurotide, cross-stone, grenatite, and fairy stone).

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

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

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

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

stream terrace. One of a series of level surfaces in a stream valley, flanking and more or less parallel to the present stream channel. It is above the level of the stream and represents the dissected remnants of an abandoned floodplain, streambed, or valley floor produced during a former stage of erosion or deposition.

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 "stream terrace").

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

tourmaline. A group of minerals of general formula $(Na,Ca)(Mg, Fe^{2+},Fe^{3+}, Al,Li)_3Al_6(BO_3)_3Si_6O_{18}(OH)_4$. When transparent and flawless, tourmaline is cut into gems.

travertine. A finely crystalline massive deposit of calcium carbonate, or 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 (also 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.

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

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..

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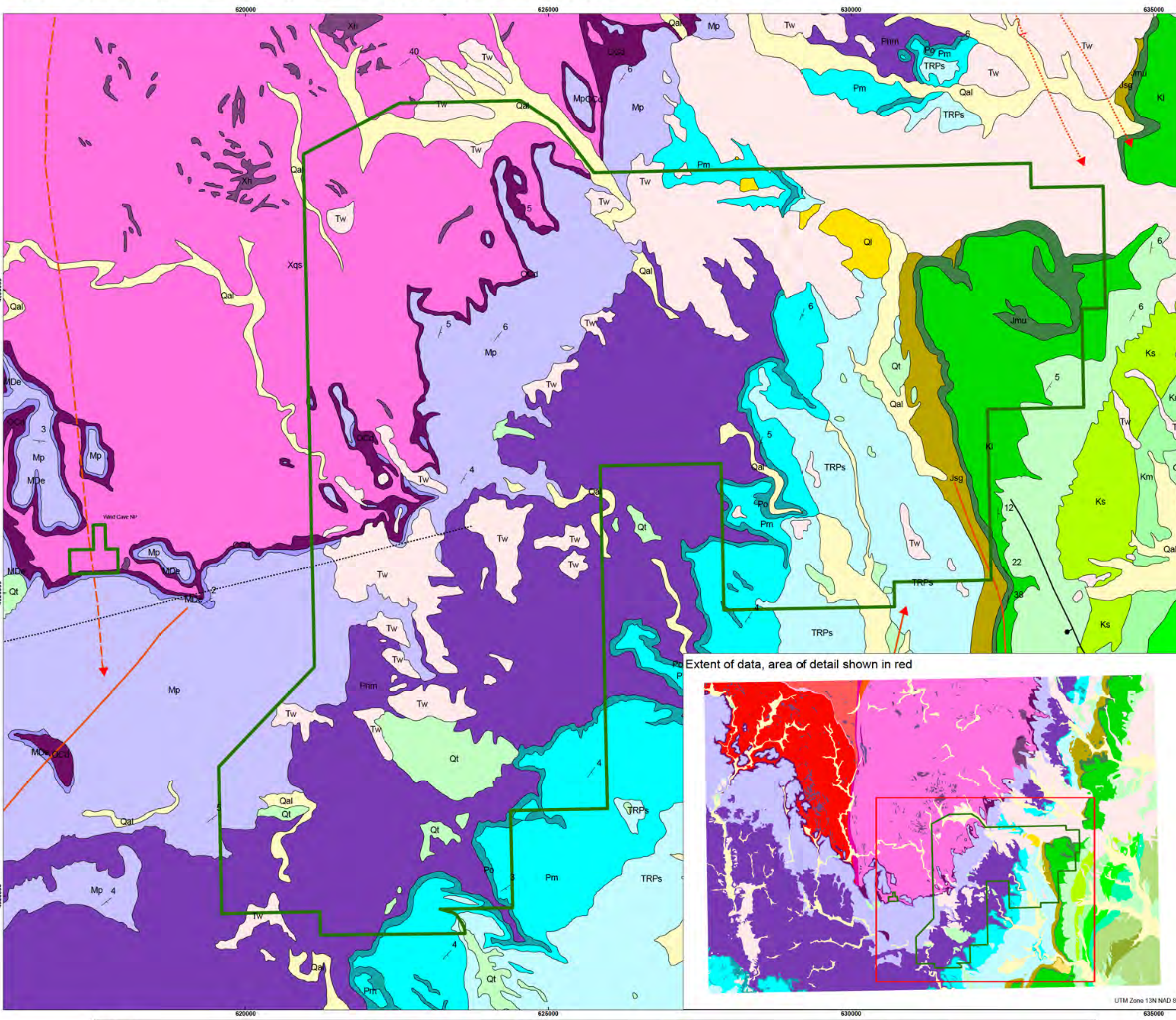
Appendix A: Geologic Map Graphic

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

Wind Cave National Park
South Dakota

National Park Service
U.S. Department of the Interior

Geologic Map of Wind Cave National Park



NPS Boundary

Geologic Attitude and Observation Localities
- strike and dip of beds
- strike of vertical beds
- strike and dip of foliation
- fold plunge arrow head
- fault down-thrown block indicator
- anticline
- syncline
- monocline, anticlinal bend
- monocline, synclinal bend
- right-lateral fault block movement arrow
- plunge of fold axis

Folds
- known or certain
- approximate
- concealed
- cleavage trough, inferred

Faults
- thrust fault, known or certain
- thrust fault, approximate
- thrust fault, concealed
- known or certain
- approximate
- concealed

Unique Geologic Features
- breccia pipe

Isograd Lines
- metamorphic isograd, known or certain

Linear Geologic Units
- Xgb - Metagabbro
- Xif - Metamorphosed carbonate-facies iron formation

Geologic Contacts
- known or certain
- approximate
- concealed
- quadrangle/map boundary

Geologic Units
- Qal - Alluvial deposits
- Ql - Landslide deposits
- Qc - Colluvium or talus
- Qt - Terrace gravel and alluvial-fan deposits
- Tw - White River Group
- Kp - Pierre Shale
- Kn - Niobrara Formation
- Kc - Carlile Shale
- Kg - Greenhorn Limestone
- Kb - Belle Fourche Shale
- Km - Mowry Shale
- Ks - Skull Creek Shale
- Kf - Fall River Formation
- Kl - Lakota Formation
- Jmu - Morrison Formation and Unkpapa Sandstone, undivided
- Jsg - Sundance and Gypsum Spring Formations, undivided
- TRPs - Spearfish Formation
- Pm - Minnekahta Limestone
- Po - Opeche Shale
- Phm - Minnelusa Formation
- Mp - Pahasapa Limestone
- MDe - Englewood Limestone
- Oed - Deadwood Formation
- Xh - Harney Peak Granite
- Xgb - Metagabbro
- Xgwd - Distal metagraywacke
- Xgwp - Proximal metagraywacke
- Xgw2 - Metagraywacke unit 2
- Xby - Metamorphosed younger alkalic basalt, tuff, and volcaniclastic rocks
- Xqc - Metamorphosed quartzite, debris flow conglomerate, pelite, and graywacke
- Xqs - Metamorphosed quartzite and pelite
- Xbs2 - Metamorphosed black shale
- Xif - Metamorphosed carbonate-facies iron-formation

0 1 2 Kilometers
0 1 2 Miles

Display scale is greater than the source scale

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, E. 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 Wind Cave National Park 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

Wind Cave National Park
Geologic Resources Inventory Report

Natural Resource Report NPS/NRPC/GRD/NRR—2009/087

National Park Service

Acting Director • Dan Wenk

Natural Resource Stewardship and Science

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