National Park Service
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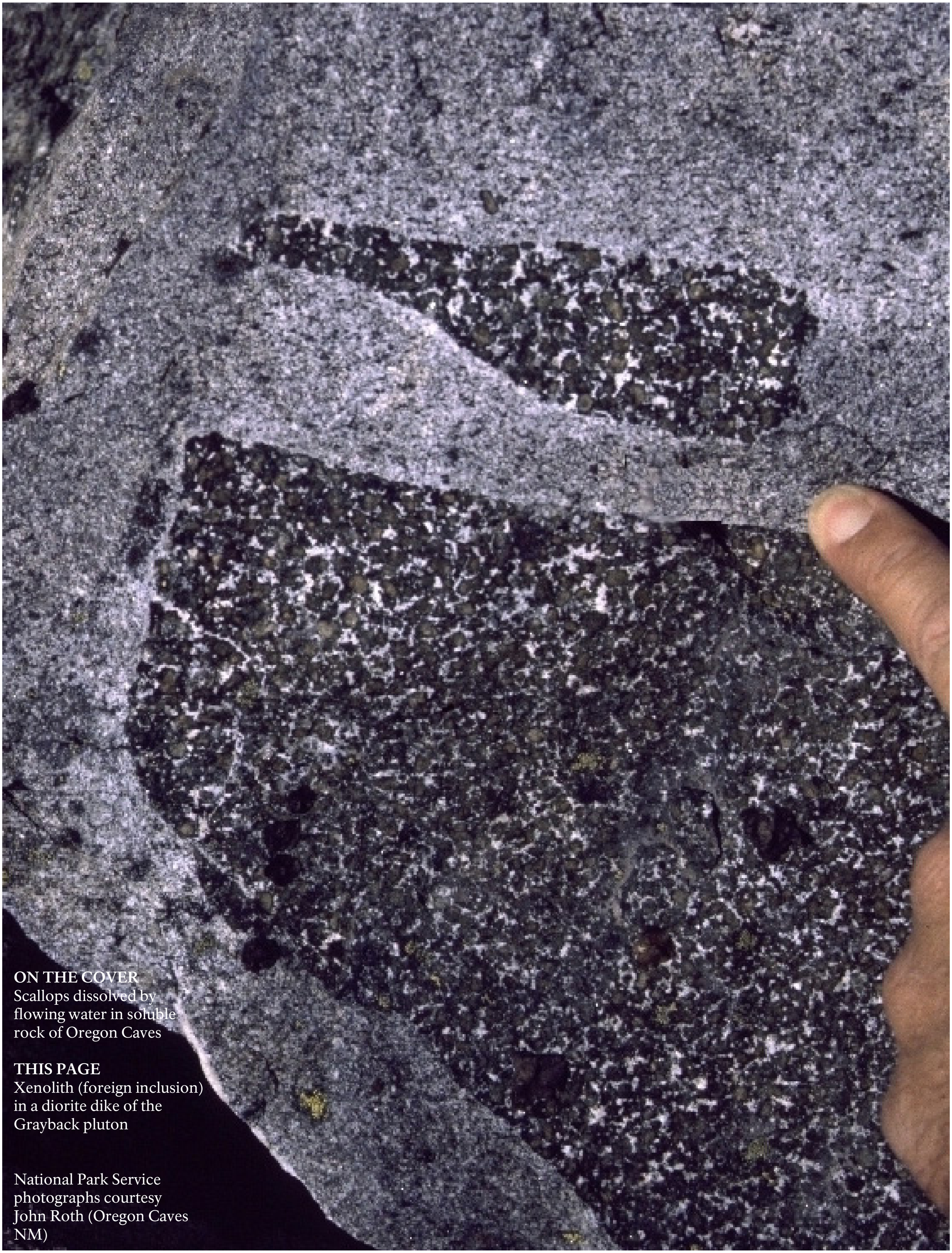
Natural Resource Stewardship and Science

Oregon Caves National Monument

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2011/457



ON THE COVER
Scallops dissolved by flowing water in soluble rock of Oregon Caves

THIS PAGE
Xenolith (foreign inclusion) in a diorite dike of the Grayback pluton

National Park Service photographs courtesy John Roth (Oregon Caves NM)

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

September 2011

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

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Executive Summary

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

In 1909, Oregon Caves National Monument was set aside as a national monument because of its "unusual scientific interest." Oregon Caves is noted for its narrow, twisting passages and the River Styx, the underground segment of Cave Creek that flows through the cave and enlarges it. Also, the cave is well decorated, displaying speleothems (cave mineral deposits) that have dazzled cave visitors since its recorded discovery in 1874.

Since the establishment of Oregon Caves as a national monument, the plate tectonics paradigm evolved. Plate tectonics is a theory that provides a unifying context for Earth's many diverse and dynamic features and processes. Geologic investigations in the Klamath Mountains physiographic province, of which the national monument is a part, have played a significant role in the development of the theory of plate tectonics, helping to shape the understanding of the formation of Earth's crust—in North America and the world.

Plate tectonic processes are readily apparent in the rocks and rugged landscape at Oregon Caves National Monument. The assemblages of rocks at the national monument were transported to this location via plate tectonic processes. They are made up of complete ophiolite (seafloor) sequences, broken formations (rock units disrupted by faults but retaining continuous strata), and mélange (units of fragmented rock). Plutons (intrusions of igneous rock) helped to weld the fragments to the continent. The diversity of rock types and minerals of these assemblages is spectacular, and includes rocks from the upper mantle, lava from a submarine fracture zone that erupted onto the seafloor, sediment derived from continental sources, magma intruded into country rock, and marble metamorphosed from limestone that originated as marine organisms.

During a 2004 scoping meeting, participants identified the following as the most significant resource management issues related to the geology of the national monument:

- Slope failure (mass wasting). The major geologic issue in the national monument is slope failure, which occurs in the form of landslides and debris flows. This process has severely damaged or destroyed structures at the national monument.
- Cave and karst protection and restoration. Protection, preservation, restoration, and interpretation of the cave and karst resources are of primary importance to the national monument.
- Paleontological resources. The cave hosts vertebrate fossils of national importance. The preservation and interpretation of vertebrate, invertebrate, and trace fossils are a management priority.

In addition, possible expansion of the national monument's boundaries is an issue that has the potential to affect resource management, including management of geologic resources. Ongoing geologic mapping will continue to aid understanding of the geology of the monument. All these issues are discussed in the "Geologic Issues" section of this report.

This Geologic Resources Inventory (GRI) report is written for resource managers, to assist in resource management and science-based decision making, but it may also be useful for interpretation. Therefore, in addition to geologic issues facing resource managers at the national monument, significant geologic features and processes within the national monument are discussed in this report. The "Geologic Features and Processes" section highlights the following:

- Cave features and processes. The primary feature at Oregon Caves National Monument is Oregon Caves, which developed in marble. The cave has multiple water inputs converging in a stream-like pattern, and a plethora of speleothems produced mainly by dripping water.
- Diversity of rocks. The digital geologic map of Oregon Caves National Monument used for this report—Barnard (2007), *Geologic Mapping of Oregon Caves National Monument, Cave Junction, Oregon*—incorporated rocks from the Rattlesnake Creek terrane, including marble (map unit symbol Jml); argillite (Ja); metasediment (Js); metachert (Jc); mélange (Jm); metavolcanic rock, basalt (Jv); metavolcanic rock, gabbro (Jg); skarn (Jsk); peridotite (Jp); and serpentinite (Jsr). In addition, the map shows diorite dikes (Jd) of the Grayback pluton, which intruded the Rattlesnake Creek terrane. While this report was in final review and production, an updated map based on field work in 2011 was completed (King et al. 2011).
- Ophiolites. The Josephine ophiolite underlies the Cave Junction part of the national monument. It is one of the largest and most complete ophiolite sequences in the world. The Josephine ophiolite is famous for its massive sulfide deposits, which yield gold, silver, copper, zinc, and cobalt.

- Accreted terranes. Situated on the continental margin of the North American plate, the Klamath Mountains physiographic province has repeatedly been the site of collision and accretion (gradual addition) of fragments of tectonic plates called "terranes." The accretion of terranes expanded North American towards the west. The terrane underlying most of Oregon Caves National Monument is the Rattlesnake Creek terrane.
- Grayback pluton. In addition to the rocks of the Rattlesnake Creek terrane and Josephine ophiolite, Oregon Caves National Monument hosts plutonic rocks. The molten material of the Grayback pluton was intruded into the rocks of the Rattlesnake Creek terrane about 160 million years ago. Dikes of the Grayback pluton are repeatedly exposed within the marble block of Oregon Caves. Plutonic intrusions metamorphosed much of the limestone (to marble) in the contiguous area.
- Mining and mineral resources. Mining began in southern Oregon in 1850, with the discovery of gold, in what is now Josephine County, the county in which Oregon Caves National Monument is situated. The presence of precious metals in southwestern Oregon relates to plate tectonics, primarily mineralization as part of past seafloor spreading, but also the formation of mineral ores as a result of intrusion of plutons. Gold, silver, copper, nickel, and chromium have been important commodities to the economy of Josephine County. In addition, marble used as building stone has been a significant industrial product.

Also included in this report is a geologic history that describes the events leading to the national monument's present-day landscape. Furthermore, in the "Geologic Map Data" section, an overview graphic illustrates the geologic data, and a map unit properties table summarizes the main features, characteristics, and potential management issues for all the rock units on the digital geologic map of Oregon Caves National Monument (see "Geologic Map Data" and Attachment 1).

This report also provides a glossary, which contains explanations of technical, geologic terms, including terms on the map unit properties table. Additionally, a geologic timescale shows the chronologic arrangement of major geologic events, with the oldest events and time units at the bottom and the youngest at the top. The timescale is organized using formally accepted geologic-time subdivisions and ages (see fig. 33).

Acknowledgements

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

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

GRI staff would like to thank John Roth (Oregon Caves National Monument), who answered numerous questions and provided an abundance of background information about Oregon Caves National Monument; Sid Covington (Geologic Resources Division, retired), who prepared the scoping summary in 2004; Art Palmer (State University of New York at Oneonta) for his guidance on the speleogenesis of Oregon Caves; Ron Kerbo (Geologic Resources Division, retired) for the information he provided about cave resources and management; Trista Thornberry-Ehrlich (Colorado State University) for assisting with the preparation of graphics used in the report; and Elizabeth Hale (Oregon Caves National Monument) for providing maps graphics for the report.

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Introduction

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

Purpose of the Geologic Resources Inventory

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

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

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

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

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

Regional Information

Situated in the Siskiyou Mountains of southwestern Oregon, Oregon Caves National Monument is located 10 km (6 mi) north of the California border and 74 km (46 mi) east of the Pacific Ocean. The Siskiyou Mountains comprise the Oregon part of the Klamath Mountains physiographic province—an arrowhead-shaped area of Paleozoic and Mesozoic rocks. Roughly speaking, the province is bounded to the north by the city of Roseburg; to the south, by the end of the Yolla Bolly Mountain, which lies west of the city of Red Bluff; to the east, by the Cascade and Sierra Mountains; and to the west, by the coastal mountains. Rivers cut the province into several distinct ranges, including the Siskiyou Mountains, which form the northern end of the province and display the greatest topographic relief (Orr and Orr 1999).

The rugged terrain at the national monument ranges in elevation from 408 m (1,337 ft) above sea level, in Cave Junction, to 1,680 m (5,500 ft) above sea level at the highest point in the main part of the national monument. The lowest entrance, the "Main Entrance," to Oregon Caves is situated at 1,220 m (4,000 ft) above sea level (fig. 1). The entrance is on the side of Mt. Elijah, which is named for the 24-year-old hunter who found the cave in 1874. Elijah Davidson—who was chasing his dog, who was chasing a bear—made the first recorded discovery of Oregon Caves. Although the native Takelma Indians lived for thousands of years along the Applegate and Rogue rivers in what is now southwestern Oregon, no current evidence indicates native use of Oregon Caves (National Park Service 2007).

Numerous caves have formed in pods and lenses of marble in the area, but the most notable is Oregon Caves (National Park Service 2006). Although its name is confusingly pluralized, Oregon Caves is a single cave with 4.8 km (3 mi) of interconnected passages. Oregon Caves is by far the largest known cave in the Siskiyou Mountains, and is the only cave in which public tours are given (National Park Service 2006).

After the discovery of Oregon Caves, its existence was promoted by a party of influential men, including Joaquin Miller, the "Poet of the Sierras," who visited the cave in 1907. Charmed by the cave, Miller wrote the "Marble Halls of Oregon" for *Sunset Magazine*, which popularized the cave and alerted federal officials of the need for preserving this resource (National Park Service 2005). At that time, the U.S. Forest Service, the original federal steward of the cave, was interested in a permitting system that would allow for tourist development of the area. Tourism was thought to be a tangible benefit derived from forest reserves, which had recently been designated but would not yield any timber at these elevations for many years (Mark 2006).

In 1909, President William Howard Taft proclaimed a rectangular tract of land, covering 197.49 ha (487.98 ac), as "Oregon Caves National Monument" (fig. 2). The legislation states that "certain natural caves, known as the Oregon Caves…are of unusual scientific interest and importance, and it appears that the public interests will be promoted by reserving these caves with as much land as may be necessary for the proper protection thereof, as a National Monument." In addition, the National Park Service administers 1.63 ha (4.03 ac) of land in Cave Junction, Oregon, which is the site of the Illinois Valley Visitor Information Center—an interagency visitor center constructed in 1990.

In 1922, an automobile road, the "Oregon Caves Highway" (Hwy 46), was completed and facilitated access into the rough landscape east of Cave Junction, allowing for increased visitation to Oregon Caves. The first permanent building at the national monument, the Chalet, was constructed in 1924; the Chalet presently houses the national monument's visitor center. In 1934, a six-story hotel, the Chateau, was completed (fig. 3), at which time the Chalet became the gift shop and guide residence. Also in 1934, stewardship of Oregon Caves National Monument was transferred from the Forest Service to the National Park Service. In February 1992, a large portion of the developed area in the national monument was listed as a national historic site, and the Chateau was designated as a national historic landmark.

Characteristic of the region, the bedrock of Oregon Caves National Monument originated elsewhere and was transported to its present location by plate-tectonic processes. With respect to the tectonic history and development of the Klamath Mountains, the bedrock makes up a series of four belts, composed of distinctive terranes (fig. 4). A terrane is a regionally extensive, fault-bounded body of rock, characterized by a geologic history different from that of contiguous terranes (Neuendorf et al. 2005). Along with accretion of terranes, repeated plutonic intrusions sutured the fragmented blocks of bedrock to the continent (fig. 5).

The surficial geology of the national monument has not been mapped in detail, and is not included on the digital geologic map for Oregon Caves National Monument (scale 1:10,000). However, 1:125,000-scale mapping of the area shows landslide deposits within the national monument (Ramp and Peterson 2004) (see "Mass Wasting"). Also, Furtney (2002) mapped thick glacial material, at higher elevations near the national monument. Such material may become part of the national monument, in the event of a boundary expansion (see "Boundary Expansion"). Moreover, Friday (1983) documented thick layers of colluvium in the national monument.

Figure 1. Main Entrance of Oregon Caves. At 1,220 m (4,000 ft) above sea level, the Main Entrance is the lowest known entrance to Oregon Caves. It is on the side of Mt. Elijah, which is named for Elijah Davidson, who made the first recorded discovery in 1874. National Park Service photograph.

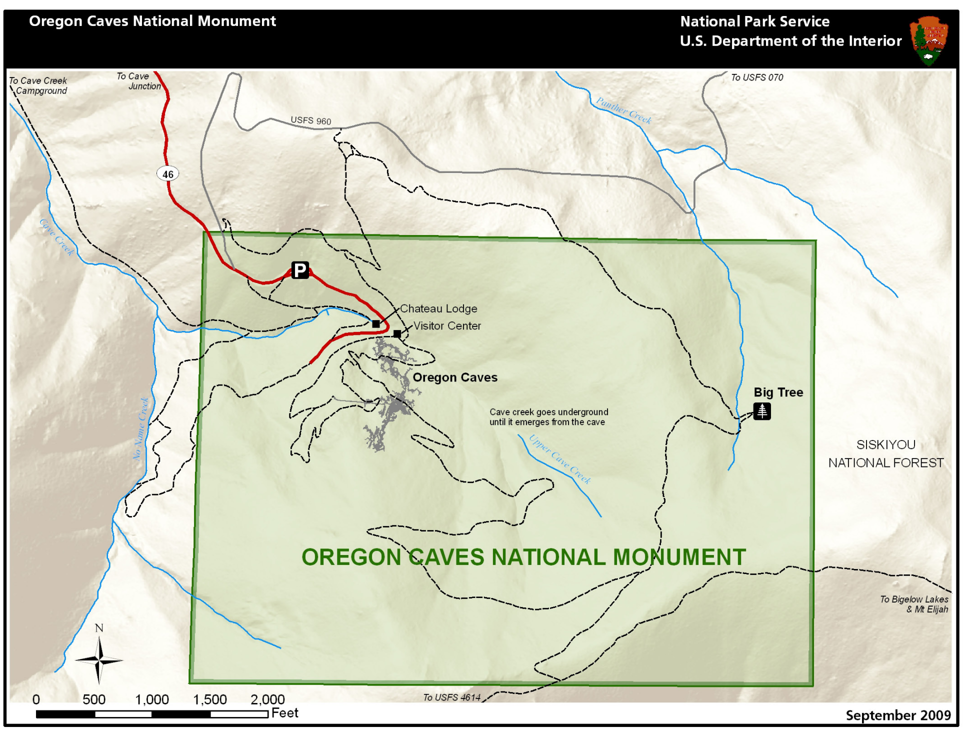

Figure 2. Location map for Oregon Caves National Monument. Situated in the Siskiyou Mountains of southwestern Oregon, Oregon Caves National Monument is located 10 km (6 mi) north of the California border and 74 km (46 mi) east of the Pacific Ocean. Highway 46, which was completed in 1922, provided access to Oregon Caves National Monument through the rugged terrain east of Cave Junction. National Park Service map, courtesy Elizabeth Hale (Oregon Caves NM).

Figure 3. The Chateau. One of approximately 3,000 national historic landmarks in the National Park System, the Chateau has a distinctive design based on the idea of fluidness with nature. Construction began in 1932 and was completed in 1934. Gust Lium, an architect and local carpenter, was hired to construct the Chateau. National Park Service photograph, courtesy John Roth (Oregon Caves NM).

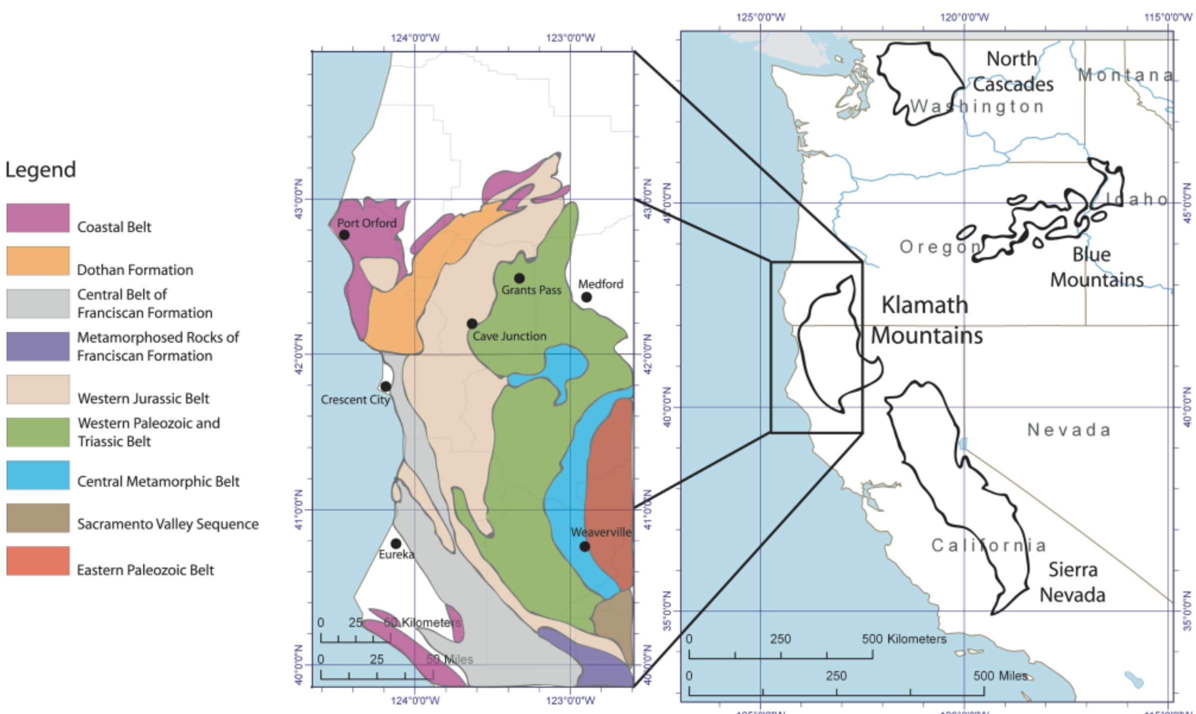

Figure 4. Lithic belts and terranes of the Klamath Mountains province. The Klamath region consists of four north-trending curved belts of rock that were gradually added to the western edge of North America. From east to west (and youngest to oldest) the belts are the (1) Eastern Paleozoic, (2) Central Metamorphic, (3) Western Paleozoic and Triassic, and (4) Western Jurassic. Oregon Caves National Monument is located within the western Paleozoic and Triassic belt, east of Cave Junction. There are other lithologic sequences in the Klamath Mountains, as mapped above, including the Sacramento Valley sequence, metamorphosed rocks of the Franciscan formation, the central belt of the Franciscan formation, and the Dothan formation, and the coastal belt. The belts are composed of terranes and intruded by plutons. Refer to figure 5 for a detailed map of terranes and plutons. The regional map on the right shows the locations of other areas where accreted terrane rocks are exposed: the North Cascades of Washington State, the Blue Mountains of Oregon and Idaho, and the Sierra Nevada of California. Graphic from Barnard (2007), modified from Snoke and Barnes (2006).

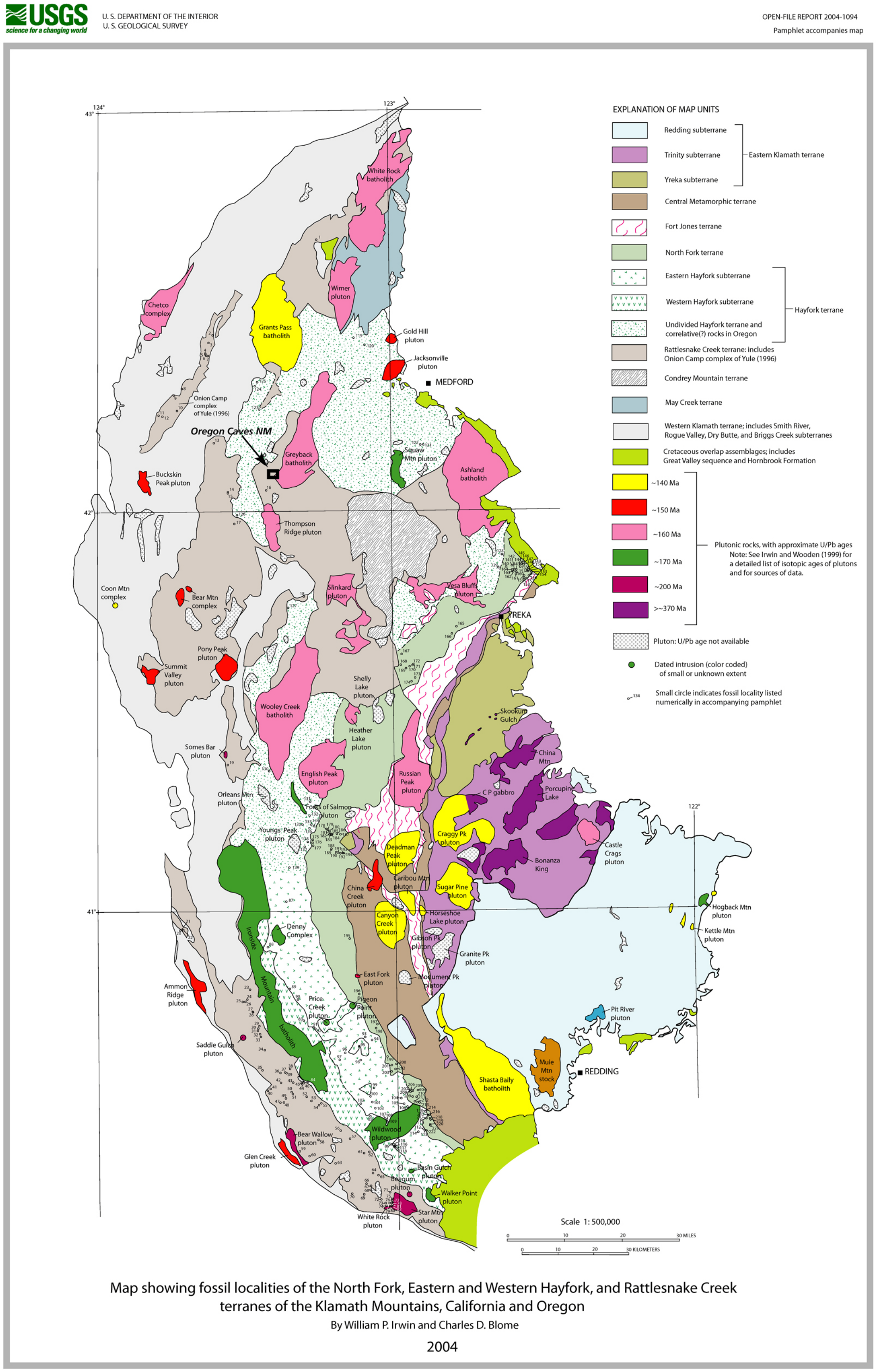

Figure 5. Terranes and plutons. The terranes that make up much of the western states of Washington, Oregon, and California (see fig. 4) were repeatedly intruded by molten material that solidified into plutons. The Rattlesnake Creek terrane underlies the main part of Oregon Caves National Monument (black box); the Grayback pluton intrudes the Rattlesnake Creek terrane. The Josephine ophiolite underlies the Cave Junction part of the national monument. The Josephine ophiolite is part of the Western Klamath terrane, which is part of the Western Jurassic belt. The Rattlesnake Creek terrane is part of the Western Paleozoic and Triassic belt. The Orleans fault bounds the Western Klamath terrane and the Rattlesnake Creek terrane. U.S. Geological Survey map by Irwin and Blome (2004), annotated to show the location of the main part of Oregon Caves National Monument.

Geologic Issues

The Geologic Resources Division held a Geologic Resources Inventory scoping meeting for Oregon Caves National Monument on March 4, 2004, to discuss geologic resources, address the status of geologic mapping, and assess resource management issues and needs. This section synthesizes the scoping results, in particular those issues that may require attention from resource managers. Contact the Geologic Resources Division for technical assistance.

In 2004, scoping participants, whose names are listed in the appendix, identified the following as significant resource management issues related to the geology at Oregon Caves National Monument: (1) slope failure (mass wasting), (2) cave and karst protection and restoration, and (3) paleontological resources (Covington 2004). A follow-up conference call on March 3, 2011, identified boundary expansion as another issue of management concern. Expansion would affect resource management, including management of geologic resources. Furthermore, at the time of publication of this report, King et al. (2011) had produced additional geologic mapping. These data cover the expanded boundary.

Mass Wasting

The combination of steep slopes, high rainfall, and erodible bedrock results in frequent occurrences of landslides and debris flows at Oregon Caves National Monument (Covington 2004). Irwin (2010a) noted that, surficially, the Rattlesnake Creek terrane is characterized by highly unstable hillsides. Ramp and Peterson (2004) mapped (at a scale of 1:125,000) a large, continuous landslide deposit cutting across the national monument (fig. 6). Other investigators, for example Baldwin and De la Fuente (1987), have recognized these deposits when mapping bedrock stratigraphy and structure in the Klamath Mountains. Landslides are frequently associated with zones of sheared serpentinite (see "Ultramafic Rocks") of the Western Jurassic belt and Western Paleozoic and Triassic belt, as well as the schist of the Condrey Mountain terrane (see figs. 4 and 5).

1964 Debris Flow

To date, the most notable mass-wasting event at Oregon Caves National Monument was a debris flow that occurred in the Cave Creek drainage in December 1964. At this location, the surface is covered by colluvium derived from the weathering of bedrock and transported by gravitational creep (Friday 1983). Known depths of colluvium range from a few inches thick, at the limestone outcrop near the rim of the basin, to more than 335 cm (132 in) thick near the Chalet (Friday 1983).

A series of extreme weather conditions led to the 1964 debris flow. Between December 14 and 17, western Oregon experienced unusually cold weather, with temperatures falling to 6°C (21°F) at Cave Junction, Oregon. On December 18, a Pacific storm deposited near-record accumulations of snow. By December 20, 100 cm (40 in) of wet snow had accumulated at the national monument. A warm front then moved inland bringing torrential rains. During the evening of December 21, the temperature was 16°C (60°F) at the Chateau. In a two-day period ending December 22, 30 cm (12 in) of rain had fallen at Cave Junction; rainfall at the Chalet was probably greater because the Chalet is 838 m (2,750 ft) higher than the weather station at Cave Junction (Friday 1983). On the evening of December 22, the snow at the Chateau had melted, and water flowed through the breezeway of the Chalet. At 9:00 pm, a slurry of gravel and mud moved through the breezeway, coming to rest against the upstream wall of the Chateau (fig. 7). Harry Christensen, the facilities manager in 1964, estimated that 2,600 m^3 (3,400 yd^3) of material had to be removed from inside the building (Friday 1983). Damage to facilities, roads, and trails exceeded $82,000; restoration of the privately owned concession cost $100,000 (Friday 1983).

The passage of the debris flow took no more than 10 or 15 seconds (Friday 1983). The source of the debris flow is evidenced by a scar on the north-facing slope of the Cave Creek drainage (fig. 8). The zone of depletion is about 76 m (250 ft) long and 1.8 m (6 ft) deep near the crown (measured normal to the sloping terrain) (Friday 1983).

Other Landslide Deposits

The destructive power of debris flows is also evident in No Name Creek, a small tributary entering Cave Creek 550 m (1,800 ft) downstream from the Chateau. Trees as large as 100 cm (40 in) in diameter, now toppled by mass movement, once grew along this segment of No Name Creek (Friday 1983).

Another hillside scar occurs north (up slope) of the day-use parking lot near the monument's entrance. Little information is available as to the date of occurrence or the magnitude of this landslide (Covington 2004). It appears that the movement might have been caused when the parking lot was widened; in the process, the supporting base of the slope was undercut (Friday 1983). Periodically, the Federal Highway Administration tries to mitigate the effects of mass wasting on the parking lot, but cracking continues (Covington 2004).

Hazard Assessment

As the 1964 debris flow illustrates, debris flows at the monument do not appear to be triggered by seismic activity, but rather from heavy rainfall and snowmelt (Covington 2004). To determine the potential risk from debris flows at Oregon Caves National Monument, Friday (1983) studied the properties of the soil at the source of the 1964 flow, and compared the material with the soils from other locations within the Cave Creek basin. The study identified two areas with high potential for debris flows within Cave Creek basin, although many more may exist. Sites having high permeability will probably fail first (Friday 1983). Hence, there continues to be a need for better mapping of debris flows at the monument, and to identify areas of potential mass movement (Covington 2004).

Because relocation of the Chalet and the Chateau is not feasible, hazard abatement with respect to debris flows in the vicinity of these facilities is limited to preventing injury and loss of life. Friday (1983) suggested three approaches. First, establish a weather station on the premises, from which hourly determination of rainfall, temperature, and snow melt could be made when hazardous conditions are believed imminent. Based on conditions prior to the 1964 event, vehicles and pedestrian traffic at these facilities could be halted until the hazard alert has passed. Second, install a piezometer, which measures water pressure, at the site of the 1964 failure. Freeze and Cherry (1979), Campbell (1975), and Wieczorek and Snyder (2009) provide guidelines for positioning piezometers. Third, plant deep-rooting ground cover in the unstable areas.

Wieczorek and Snyder (2009) described the various types of slope movements and mass-wasting triggers, and suggested five methods and "vital signs" for monitoring slope movements: types of landslides, landslide triggers and causes, geologic materials in landslides, measurement of landslide movement, and assessing landslide hazards and risks. Wieczorek and Snyder (2009) is a chapter in the publication, *Geological Monitoring*, which provides guidance using vital signs and monitoring methodology.

Rockfall

Although less significant and widespread than landslides at the national monument, another mass-wasting hazard is rockfall. Rockfall occurs primarily at cave entrances, where changes in weather and airflow promote freezing, drying, and dissolution of calcite. During extreme weather conditions, which have the potential to cause rockfall hazards, the superintendent may order the Main Entrance closed, shifting entry through the 110 Exit instead (National Park Service 2006) (see figs. 1, 11, and 12). Determinations of closure also take into consideration the formation of hazardous icicles at the cave entrance, and the protection of hibernating bats.

Rockfall within caves is inevitable and natural, but also rare (National Park Service 2006). Some rockfall does occur within Oregon Caves, as evidenced by boulders that have fallen from the ceiling alongside the main trail. Accumulations of collapsed rock, called "breakdown," is most common near entrances and in large rooms that have less ceiling support, especially rooms with many faults (see " Cave Features and Processes"). Much, if not all, the breakdown in Oregon Caves probably occurred as a result of crack propagation, most likely after the cave drained. The shattered material shows little sign of solution or evidence that it fell into water (John Roth, chief of Resources Management, Oregon Caves NM, written notes, April 6, 2011).

At present, rockfall hazards within the cave are most commonly caused during human exploration. The subsurface management plan suggests that, to avoid injury, cavers should (1) move carefully, (2) always wear a helmet, and (3) stay out from under others who may be climbing a rock or a rope (National Park Service 2006).

Cave Protection and Restoration

Since the recorded discovery of Oregon Caves in 1874, tunnels have been blasted, trails have been constructed, lights have been installed, and millions of visitors have entered. Human activities have noticeably altered the cave environment. For example, most of the fragile speleothems (cave formations), especially thin stalactites, are broken near the developed trail.

Starting in the mid-1980s, the National Park Service began the process of restoring the cave; that is, mitigating human-caused impacts on cave features and processes. Transformers, asphalt trails, sewage lines, and cabins were removed to prevent sewage and petroleum from leaking into the cave, or to help restore prehistoric patterns of water infiltration (National Park Service 2005). In 2004, geologic scoping participants identified the following issues related to cave restoration:

- Modifications to entrances
- Restoration of original airflow regimes
- Effects of fire suppression
- Compaction, primarily along the off-trail caving tour route

Modifications to Entrances and Restoration of Airflow

Oregon Caves has five known openings large enough for humans to enter; all of these have been modified, and one is a completely artificial exit tunnel. There are a number of entrances too small for human entry, but the exact number is not known (John Roth, chief of Resources Management, Oregon Caves NM, e-mail communication, July 9, 2011). There are 4.8 km (3.0 mi) of known cave passages.

In the 1930s, workers blasted tunnels and widened passages to accommodate tour groups. Rubble was stored in side passages. Such modifications changed airflow within the cave. Monument staff has removed more than 1,200 metric tons (1,400 tons) of this material, and, in the process, uncovered thousands of cave formations (National Park Service 2005). Naturally occurring breakdown (collapse rubble) that was displaced as part of trail development has been either moved back to original locations (when this can be determined) or used to approximate the original contour of the cave (National Park Service 2006). Airlocks have helped to restore natural cave winds by blocking airflow in artificial tunnels (National Park Service 2005). Restoring airflow in Oregon Caves is significant because air flowing into, through, and out of the cave affects cave temperature, relative humidity, and carbon dioxide levels, which in turn affect speleothem growth and cave life (see "Cave Features and Processes").

Fire Suppression

Changes in forest ecology on the surface of Oregon Caves National Monument can potentially affect conditions within the cave (National Park Service 1998). A significant ecological change is that no major fires have started within or entered Oregon Caves National Monument since 1921; this has been the longest fire-free period over the last 300 years (National Park Service 1998). At present, no prescribed burning occurs within the national monument, though monument staff undertakes manual thinning (John Roth, chief of Resources Management, Oregon Caves NM, conference call, March 3, 2011).

The exclusion of fire has contributed to significant fuel loading on monument lands, as well as the growth of shrubs and small trees near the cave (Covington 2004). This additional growth takes up surface water, increases the loss of water to the atmosphere via evapotranspiration, and, thereby, reduces the natural flow of water into the cave. Such changes will affect speleothem growth. However, the primary concern over the loss of water into the cave is that it may result in the extinction of some endemic cave species (John Roth, chief of Resources Management, Oregon Caves NM, conference call, March 3, 2011).

Compaction of Cave Sediments

Sediment compaction results from foot traffic on unpaved cave trails. Proper placement of both paved and unpaved trails can minimize the total area of compaction (National Park Service 2006). Mitigation of compaction may require the modification of existing cave trails (Covington 2004).

Resource managers at Oregon Caves speculate that compaction is affecting organisms living in the sediments by altering the availability of nutrients in the clays (John Roth, chief of Resources Management, Oregon Caves NM, e-mail communication, March 10, 2011). In 2004, Pete Biggam (program manager, NPS Soils Program) responded to a technical assistance request to supply monument staff with procedures to identify indicators of soil compaction and to quantify increases in soil bulk density, as well as detect changes in total soil porosity (Pete Biggam, program manager, NPS Soils Program, e-mail communication, March 10, 2011). Sampling of the sediments, however, yielded inconsistent results, and no verifiable relationship between compaction and microbial populations has been found. The main effects on the microbes seem to be moisture levels (John Roth, chief of Resources Management, Oregon Caves NM, e-mail communication, March 10, 2011).

Compacted areas often have decreased particle sizes, which dry more quickly, thereby increasing the amount of dust that is kicked up and deposited off the cave trail (National Park Service 2006). In extreme cases, the transport of dust can decrease visibility in the cave by creating condensation fogs (National Park Service 2006). However, the existing public off-trail caving route in Oregon Caves is deep enough underground to have substantial water infiltration and close to 100% humidity year-round. Therefore, if airborne dust is present, the effects are minimal (John Roth, chief of Resources Management, Oregon Caves NM, written communication, June 15, 2011).

Other Impacts

Oregon Caves National Monument Subsurface Management Plan identified other impacts to cave resources not discussed during the geologic scoping meeting in 2004. These include broken speleothems and other forms of vandalism, artificial lighting and algal growth, and lint and other particulates in the cave (National Park Service 2006).

Broken Speleothems and Vandalism

Over the years, speleothems, primarily near developed cave trails, were unintentionally broken or intentionally removed as souvenirs. In addition, crystal pools were mined early in the cave's history, graffiti (some historic, some not) has been engraved into cave surfaces such as flowstone (deposit of calcium carbonate formed by flowing water), and coins have been tossed into cave pools (National Park Service 1998). As understanding of the length of time required for speleothems to grow—up to 519,000 years in Oregon Caves (see "Geologic History")—and as realization of the rarity of these formations dawned, what was once seen as innocent souvenir-collecting and fun are now considered vandalism and theft.

According to the national monument's subsurface management plan, broken speleothems can be repaired during the driest time of the year using a combination of glues, epoxies, and crushed calcite. For stalactites and draperies with small attachment areas, holes can be drilled (and progressively enlarged to prevent the calcite from cleaving) for the attachment of expansion bolts, steel pins, or screws. Drill holes, steps cut into flowstone, and other human modifications can be repaired by using "terrazzo" or a 5:1 ratio of cave mud to cement. Terrazzo is mostly crushed, bleached calcite, and it closely resembles cave formations. Altering its color to match adjacent cave features is easier to do than altering the color of most types of cement (National Park Service 2006). As with coin tossing, graffiti not promptly removed or obscured induces further graffiti. Graffiti can usually be removed by stiff nylon brushes and vinegar. In some cases, power washing is necessary (National Park Service 2006).

An ongoing cave inventory at the national monument includes a count of broken cave formations, regrowth measurements, and photo and video documentation of formations and artifacts (National Park Service 2006). Cave formations that were broken by human activity are unobtrusively marked with a UV fluorescing compound as a way to monitor vandalism. Resurveying reveals new damage (National Park Service 2009).

Artificial Lighting

Artificial lights in cave passageways cause algal growth, which would otherwise not be found in the cave environment. Detergent-rich lint from clothing helps fertilize these plants (see "Lint and Other Particulates"). Plant growth made possible by artificial light systems can dissolve cave formations and discolor cave walls. Moreover, this cause-and-effect scenario adds organic material to ecological communities adapted to food-poor conditions, introducing artificially high levels of nutrients to what was formerly a nutrient-poor system.

Cave managers have used various methods to control photosynthetic organisms, such as algae, that grow near electric lights in caves. At Oregon Caves National Monument, the most effective and least impacting treatment appears to be application of hydrogen peroxide (Faimon et al. 2003) or a combination of sodium hypochlorite (household bleach) and hydrogen peroxide (National Park Service 2006). However, this technique offers only a temporary solution, and regular spraying (from once a year to every few weeks) is required. Furthermore, such treatments impact air quality, especially in parts of the cave with low airflow, and cave organisms are compromised in the process (Elliott 2006).

Unnatural photosynthetic growth may be better controlled through use of selected light wavelengths, reduction in wattage, or light shielding and redirection (Elliott 2006). Park managers at Jewel Cave National Monument in South Dakota have experimented with a germicidal ultraviolet (UV) light—the type used for disinfection in hospitals. Investigators exposed a patch of moderate algal growth along a popular tour route 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 it had not completely disappeared (Ohms and Wiles 2006). On the basis of these results, UV light appears to have great potential for killing algae without the use of harmful chemicals. Longer exposure times or higher wattage may be necessary to completely kill the algae. Park managers at Oregon Caves may find this promising alternative useful and worth testing. Resource management staff at Mammoth Cave National Park (Kentucky) are also studying the impacts of artificial lighting on microbe growth (Thornberry-Ehrlich 2011).

Lint and Other Particulates

More than 80,000 visitors tour Oregon Caves annually. Humans have transported enough lint, dust, hair, and skin flakes into the cave environment to produce noticeable buildup on many surfaces. This exotic, organic matter dissolves and hides the true colors of cave formations (Horrocks and Ohms 2003). In some areas, a mixture of dust, lint, cyanobacteria (blue-green algae), and fungi blackens cave walls (National Park Service 2006). Significantly, this organic matter provides unnatural food sources for cave biota, and serves as the basis for alien communities that can include spiders, mites, ants, and nonnative invertebrates (Horrocks and Ohms 2003; National Park Service 2006). When cave conditions are wet, these particulates can increase the numbers of both naturally occurring and nonnative bacteria and fungus (National Park Service 2006).

Except in very dry conditions, an estimated 80% of lint falls within 1.2 m (4 ft) of the center of the trail (National Park Service 2006). Hence, installing curbs along a cave trail can inhibit most movement of lint, confining a major portion on the trail where, with a regular maintenance program, a good percentage of the lint accumulation can be collected (National Park Service 2006). This practice is consistent with testing in other caves. For example, in Wind Cave National Park in South Dakota, investigators concluded 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). Park managers at Oregon Caves installed a rough trail surface before the cave entrance, and grates at the entrance, to help clean the bottom of shoes just before entering (see fig. 1). This simple technique helps prevent the spread of foreign matter into the cave (National Park Service 2006). In addition, managers at Oregon Caves have installed plastic tarps under portions of the trail in order to catch and isolate particulate matter (National Park Service 2006).

Paleontological Resources

The majority of bedrock at Oregon Caves National Monument is the Rattlesnake Creek terrane (see "Geologic Map Data"). Fossils are rare in these rocks, with the exception of the low-grade, metamorphosed argillite, which contains some crinoid fossils (John Roth, chief of Resources Management, Oregon Caves NM, written communication, June 15, 2011). Elsewhere, the rocks of the Rattlesnake Creek terrane have produced significant fossils. A notable fossil locality is 5 km (3 mi) to the southwest of the national monument (Irwin and Blome 2004). This locality yielded Mesozoic echinoid spines (Santucci and Kenworthy 2009). The Rattlesnake Creek terrane also hosts Triassic and Jurassic radiolarians and conodonts (Irwin and Blome 2004). However, analysis in 2007 of samples from the marble block in Oregon Caves did not reveal any conodont or radiolarian fossils (Nelkie 2007).

By contrast to the mostly unfossiliferous bedrock at the national monument, the cave sediments within Oregon Caves host an impressive collection of fossils from the

Quaternary Period (the past 2.6 million years). These sediments range in age from less than 10,000 years old to at least 120,000 years old; some may be as old as 1.5 million years (Santucci et al. 2001).

In 1995, NPS paleontologist Greg McDonald identified the remains of a jaguar (*Panthera onca*), black bear (*Ursus americanus*) (fig. 9), and grizzly bear (*Ursus arctos*) from Oregon Caves. The limb bone from the grizzly bear yielded a radiocarbon date greater than 50,000 years old, which at the time represented the oldest known grizzly bear remains from North America (Santucci et al. 2009). The jaguar remains, which are 38,600 years old (National Park Service 2006), represent the most complete North American jaguar outside of Appalachia (Santucci et al. 2009) and the northernmost jaguar remains ever found (John Roth, chief of Resources Management, Oregon Caves NM, written communication, June 15, 2011). Quaternary vertebrate remains also include trace fossils. For example, an exceptionally well-preserved claw print, likely from a bear or cat, shows five claw points pushed into the mud. Moreover,at least 20 distinct claw scratch marks are preserved in the cave sediments (fig. 10) (National Park Service 2006; Santucci et al. 2006).

Between 1997 and 2000, investigators from Northern Arizona University conducted an inventory of paleontological resources within Oregon Caves. Field crews sieved, cleaned, and dried approximately 270 kg (600 lbs) of sediments from several localities within the cave (Santucci and Kenworthy 2009). The inventory yielded numerous faunal remains, with salamanders being the most common fossil. The majority of the salamander remains belonged to a large and complex group of plethodontids (lungless salamanders), including the genera *Aneides* and *Dicamptodon* (Mead et al. 2000). Investigators identified the following remains to the genus level: western alligator lizard (*Elgaria*), western skink (*Plestiodon*), fence lizard (possibly *Sceloporus*), rubber boa (*Charina*), shrew (*Sorex*), shrew-like mole (*Neurotrichus*), jumping mice (*Zapus)*, deer mice (*Peromyscus*), harvest mice (*Reithrodontomys*), packrat (*Neotoma*), mountain beaver (*Aplodontia*), smooth-toothed pocket gophers (*Thomomys*), vole (*Cleithrionomys*, *Microtus*, and *Phenacomys*/*Arborimus*), rabbit (*Lepus* and *Sylvilagus*), bear (*Ursus*), skunk (*Spilogale*), and deer (*Cervus* and *Odocoileus*) (Mead et al. 2000). The inventory also uncovered sciurids (rodents), colubrids (nonvenomous snakes), bats, snails, birds, and a rare anuran (frogs/toads) (Santucci et al. 2001; National Park Service 2006).

To date, investigators have documented more than 50 paleontological localities within the cave passages of Oregon Caves, and the potential is high for additional localities and collection sites (Santucci and Kenworthy 2009). Santucci et al. (2009) outlined threats to in situ paleontological resources, and suggested monitoring "vital signs" to qualitatively and quantitatively assess the impacts of these threats. Paleontological vital signs include (1) erosion (geologic factors), (2) erosion (climatic factors), (3) catastrophic geohazards, (4) hydrology/bathymetry, and (5) human access/public use. Santucci et al. (2009) presented detailed methodologies for monitoring each vital sign. Santucci et al. (2009) is a chapter in the publication, *Geological Monitoring*, which provides guidance using vital signs and monitoring methodology.

Boundary Expansion

In 1909, when President Taft created Oregon Caves National Monument, the boundary—in the shape of a rectangle—was thought to be adequate to protect the cave (National Park Service 1998). At that time, caves were considered "worlds apart," separate from the surface environment. Since then, scientific research and an improved understanding of the interconnectedness of surface and subsurface hydrology, as well as more detailed geologic mapping of the location of the "marble block" that supports Oregon Caves, suggest that the monument's boundary is not configured adequately to allow for the protection and management of cave resources (National Park Service 1998). Furthermore, the monument's public water supply is located outside the current boundary, on USDA Forest Service lands. Land uses such as logging and grazing, which are permissible on some Forest Service lands, have the potential to impact the national monument's public water supply (National Park Service 1998).

The proposed boundary expansion would add 1,380 ha (3,410 ac) to the existing 197 ha (487 ac). All the lands proposed for inclusion are federal lands within the Siskiyou National Forest. The boundary expansion would incorporate the upper watershed of Cave Creek, and the upper watershed and portions of the lower watershed of Lake Creek. The upper Cave Creek watershed is the principal water source of the River Styx and other subsurface flows into Oregon Caves. The monument's drinking-water supply is located in the upper Lake Creek watershed.

A boundary expansion could also incorporate geologic features not contained within the monument's current boundaries, namely glacial features such as moraines, and well-exposed contact zones (e.g., skarn) between the Grayback pluton and surrounding country rock (John Roth, chief of Resources Management, Oregon Caves NM, written communication, June 15, 2011).

Geologic Mapping

The geologic map for Oregon Caves National Monument used during the production of this report (Barnard 2007) does not cover the area of the expanded boundary. However, during the final review and publication of this report, King et al. (2011) had produced a geologic map covering the proposed boundary expansion. Neither Barnard (2007) nor King et al. (2011) included the Cave Junction portion of the national monument in their study. Notably, the map units of Barnard (2007), which were used to prepare this report, and King et al. (2011) vary in description and geologic age. King et al. (2011) identified the portion of the Rattlesnake Creek terrane within the main part of the national monument and expanded boundary as having formed during the pre-

Upper Triassic Period, not the Jurassic Period as Barnard (2007) did. Also, King et al. (2011) excluded some map units which Barnard (2007) included, namely metasediment (Js); mélange (Jm); and metavolcanic rock, gabbro (Jg) (see "Geologic Map Data"). King et al. (2011) included meta-igneous rock. In general, the other map units are consistent (see table 1). King et al. (2011) noted that a significant area of future research would be mapping the contact between the basement mélange and cover sequence of the Rattlesnake Creek terrane in the vicinity of Oregon Caves National Monument, and comparing these findings with that described by Donato et al. (1996) for the Bolan Lake area to the south of the national monument.

Table 1. Geologic map units for Oregon Caves National Monument

Barnard (2007)	King et al. (2011)
Diorite dikes of the Grayback[1] pluton (Jd)	Intrusive rocks of the Greyback[1] pluton (Jpl)
Marble (Jml)[2]	Calcite marble (TRml)[3]
Argillite (Ja)	Meta-pelite (TRmp), which includes slate, argillite, and phyllite
Metasediment (Js)	
Metachert (Jc)	Quartzite (TRq), which includes local chert
Melange (Jm)	
Metavolcanic rock, basalt (Jv)	Meta-basalt (TRb)
Metavolcanic rock, gabbro (Jg)	
	Meta-igneous rock (TRmi), without gabbro
Skarn (Jsk)	Skarn (TRsk)
Peridotite (Jp)	Serpentinized peridotite (TRps)
Serpentinite (Jsr)	Serpentinite (TRs)

[1]Barnard (2007) used the spelling "Grayback," whereas King et al. (2011) used "Greyback."

[2]J = Jurassic

[3]TR = Triassic

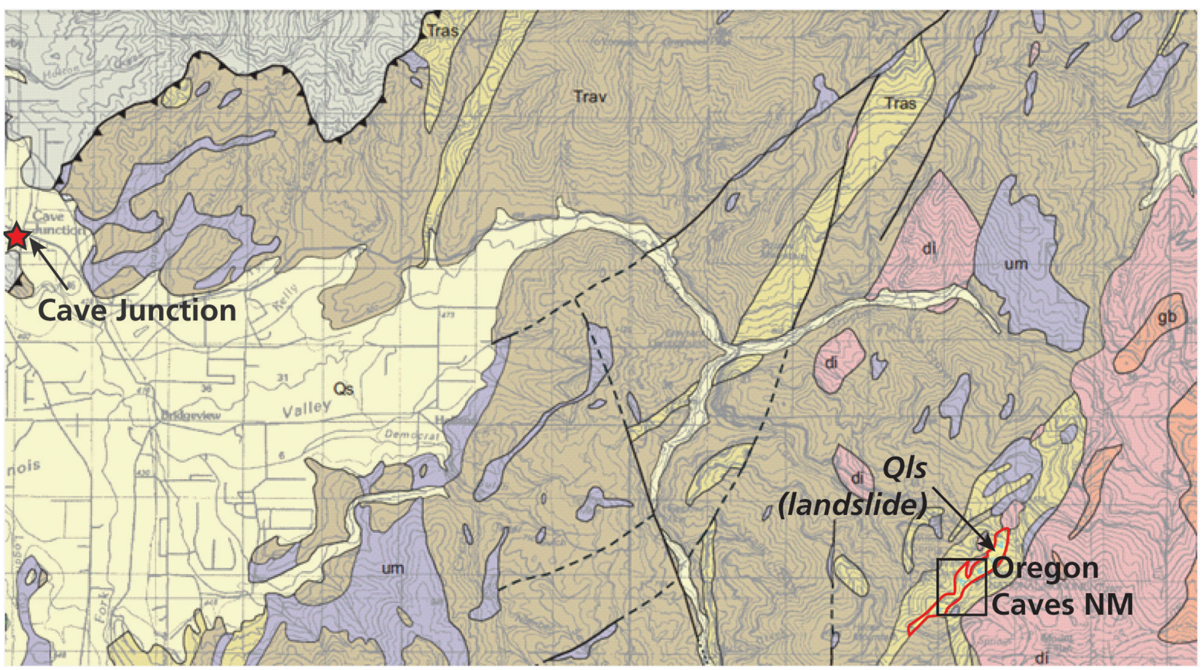

Figure 6. Geologic map showing Oregon Caves National Monument and Cave Junction. At a scale of 1:125,000, Ramp and Peterson (2004) mapped a large landslide deposit—Qls (outlined in red)—in the main part of Oregon Caves National Monument. Quaternary sediment (Qs) covers Cave Junction. Tras and Trav = Applegate Group. di = quartz diorite and related dikes. um = ultramafic rock. gb = gabbro. Graphic from Ramp and Peterson (2004).

Figure 7. Mass-wasting hazard. In December 1964, a debris flow entered the Chalet and deposited an estimated 2,600 m^3 (3,400 yd^3) of material in the breezeway. National Park Service photograph, printed in Friday (1983).

Figure 8. Debris flow scar. In December 1964, a debris flow devastated the developed area of Oregon Caves National Monument. This photo shows the denuded banks within the Cave Creek drainage 18 years after the debris flow occurred. Photograph from Friday (1983).

Figure 9. Black bear fossils. Remains of a 3,000-year-old black bear have been encased for protection, but left where they were found in Oregon Caves. Trail building in the 1930s uncovered the remains. National Park Service photograph, courtesy John Roth (Oregon Caves NM).

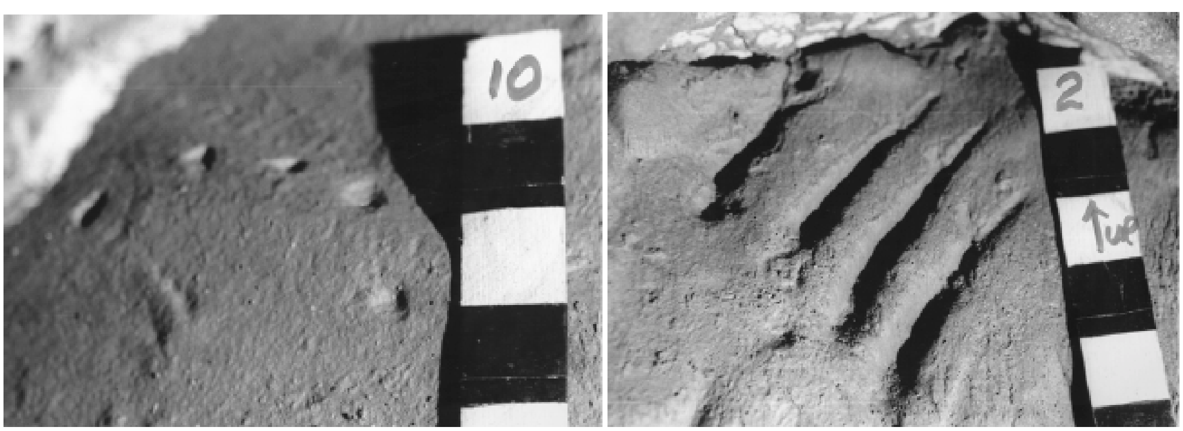

Figure 10. Claw prints and scratch marks. Oregon Caves hosts exceptionally well-preserved trace fossils in the cave sediments, for example, a claw print of an "ice age" bear or cat (left), and scratch marks from a large Pleistocene mammal (right). National Park Service photographs.

Geologic Features and Processes

This section describes the most prominent and distinctive geologic features and processes in Oregon Caves National Monument.

Oregon Caves National Monument is located in the Siskiyou Mountains of Oregon, which are part of the Klamath Mountains physiographic province. This province is characterized by the accretion of terranes (accumulations of oceanic and continental material added to the continent at an active plate margin). Numerous plutons (molten rock) intruded the accreted terranes and helped to weld them to the edge of the continent. The collision and deformation associated with accretion shaped the mountainous topography of the area. For instance, Josephine County, the county in which the national monument lies, is characterized by steep mountains and narrow river valleys. The county is known for its unusual rocks, distinctive mineral resources, and features of geologic interest, such as caves (Ramp and Peterson 1979; Orr and Orr 1999).

Cave Features and Processes

The primary feature at Oregon Caves National Monument, and the reason for its establishment as a national monument, is "the caves." Although its name is confusingly pluralized, Oregon Caves is a single cave with 4.8 km (3.0 mi) of interconnected passages (figs. 11 and 12). There are eight other known caves within the national monument, but all are much smaller than Oregon Caves, and none have any noteworthy speleothems (cave decorations) (National Park Service 1998). Oregon Caves is known for its narrow, twisting crawlways and walkways (Halliday 2009), and is unusual because it occurs in marble (fig. 13); most dissolution caves occur in limestone.

As part of the Rattlesnake Creek terrane (see "Rattlesnake Creek Terrane"), the marble (map unit symbol Jml) in which Oregon Caves formed is surrounded by a mélange of igneous, ultramafic (dark-colored, iron- and magnesium-rich), metavolcanic, and metasedimentary rock. The cave, however, is contained exclusively within a marble lens (Brooks 1989). Thick soil and dense vegetation at the surface make exact boundaries of individual blocks of marble difficult to determine (Halliday 2009). However, Oregon Caves penetrates the side of Mt. Elijah for about 305 m (1,000 ft) (Knutson 2006), and the marble block is, therefore, at least that long. Moreover, based on the extent of the cave, the marble block in which the cave formed is at least 150 m (490 ft) wide and 120 m (390 ft) thick (Halliday 2009).

Although the cave is housed in marble, generally speaking it behaves like a limestone cave, with multiple water inputs converging in a stream-like pattern, and with speleothems produced mainly by drip water (Art Palmer, professor, State University of New York at Oneonta, e-mail communication, April 8, 2011) (fig. 14).

Speleothems and Speleogens

Oregon Caves is well decorated: The underground passages are adorned with many and varied cave formations called "speleothems," which are produced by the deposition of minerals, namely calcite in the case of Oregon Caves. Features called "speleogens," which are produced by the dissolution of bedrock, also help to decorate the cave.

The following are some selected speleothems and speleogens within Oregon Caves. Many types occur within the cave, and this list is not all-inclusive; it highlights those features mentioned in the descriptions of the four areas of the cave (see "Physical Characteristics of Oregon Caves"). *The Underground World of Oregon Caves* (Contor 1963), *Awesome Caverns of Marble in the Oregon Caves National Monument—Documentary* (Webber and Webber 1998), *Oregon Caves National Monument Subsurface Management Plan—Environmental Assessment* (Roth 2005), and the glossary in *Oregon Caves National Monument Subsurface Management Plan* (National Park Service 2006) list more cave features and provide additional descriptive information. Webber and Webber (1998) also provided a lexicon of place names within Oregon Caves.

- Breakdown—Heaps of rubble on a cave floor caused by the collapse of walls or ceiling (fig. 15). In Oregon Caves, breakdown consists of rockfall material that ranges from huge blocks to bits of sediment largely composed of chert. Breakdown is more common near entrances, for instance just past the Dry Room, and in larger rooms that lack ceiling support, especially rooms with fractured rock. Much if not all of the breakdown in Oregon Caves probably happened after the cave drained (John Roth, chief of Resources Management, Oregon Caves NM, written notes, April 6, 2011).
- Cave fill—A chaotic (unsorted, unbedded, and unstratified) mixture of particle sizes and rock types within cave passages. High-energy flood events carried and deposited much of the fill into the cave. Most silt-sized particles come from weathered metamorphic rock at the surface, in particular phyllite. Many of the angular clasts come from chert in the marble, with some coming from andesitic dikes and quartz veins within the cave. A small amount of rounded pebbles of quartz diorite indicate the Grayback pluton as the source (John Roth, chief of Resources Management, Oregon Caves NM, written notes, April 6, 2011).
- Cave ghosts—Whitish, rounded masses of calcite, typically chalky but sometimes translucent. In Oregon Caves, cave ghosts appear as corroded patches or masses on ceilings, walls, or at the junction of the two. Examples of cave ghosts in Oregon Caves occur just

before the 110 Exit, where historic signatures have been carved into the now-soft marble. Cave ghosts are generally smooth, though pitting can occur, as in Watson's Grotto (see figs. 11 and 12).

- Coralloids—Nodules of mineral deposits. Coralloids range in size from tiny beads to masses more than 1 m (3.3 ft) in diameter (Hill and Forti 1997). A common coralloid is cave popcorn, which resembles this popular snack in size and shape (fig. 16). In Oregon Caves, cave popcorn is formed mostly from evaporation and slow seepage of water on the walls (Webber and Webber 1998). Evaporation resulting from airflow is believed to be the cause of oriented coralloids: higher evaporation and degassing rates, and corresponding cave-popcorn growth, occur on the sides of cave features facing colder, drier air flowing into a cave (Hill and Forti 1997). Examples of oriented coralloids in Oregon Caves are in Petrified Gardens and near the 110 Exit. Where these oriented specimens are soft, they are known as "bumpy moonmilk;" where they are hard, they are known as "lizard skin popcorn." Both types are rare (Roth 2005).
- Draperies—Hanging speleothems in the forms of curtains or drapes that are created from water droplets running down a wall or ceiling (figs. 17 and 18). Small bumps in the bedrock, especially on low-angle walls, can cause a drapery to become slightly curved. Most ceilings in Oregon Caves are tilted, which likely reduces the number of curved draperies (Roth 2005). Some draperies resemble bacon, with organic materials providing the color to the bacon-like stripes.
- Dripstone—A calcite deposit left by dripping water (see "Stalactite" and "Stalagmite").
- Flowstone—A calcite deposit left by flowing water along a cave wall or floor. Scoping participants identified flexible flowstone as an unusual geologic feature worthy of interpretation at Oregon Caves (Covington 2004). During formation of this rare speleothem type, large additions of mud are suspected to impart a spongy feel to the rock (John Roth, chief of Resources Management, Oregon Caves NM, written notes, April 6, 2011).
- Moonmilk—White cave mud, with the consistency of cream cheese when wet and powdered milk when dry. Most of the moonmilk in Oregon Caves is probably "mundmilch," that is, moonmilk with more than 95% calcite (Roth 2005). Mundmilch is most common in caves where temperatures are near freezing, which used to be the case in parts of Oregon Caves. In 1995, analysis of moonmilk from Oregon Caves found filamentous bacteria with sheaths of calcite around them. Another study in 2001 found yeasts and bacteria, possibly *Corynebacterium*, *Runella*, and *Actinomycetes*, in Oregon Caves' moonmilk (Roth 2005). Hence, the genesis of moonmilk may have an organic component. Moreover, moonmilk commonly occurs near cave entrances, which suggests that cyclic seasonal patterns of acidic dew (atmospheric corrosion) and precipitation play a role (John Roth, chief of Resources Management, Oregon Caves NM, written communication, June 10, 2011).
- Rimstone—A calcite deposit around the edge of a pool (fig. 19). The inside (basin side) is usually slightly overhung (facing upstream), while the spillway side usually slopes downstream (Hill and Forti 1997). The height of rimstone dams is related to the gradient of the cave passage; the greater the slope, the higher the dams (Hill and Forti 1997).
- Stalactite—A calcite speleothem that grows downward like an icicle as a result of deposition by dripping water (see figs. 23 and 24). Soda straws are a type of hollow stalactite, inside which drops of water descend (fig. 20). The diameter of a soda straw varies with the diameter of a water droplet; approximately 2 mm (0.08 in) to 9 mm (0.4 in) is common (Hill and Forti 1997). The thickness of the tube wall is approximately 0.1 mm (0.004 in) to 5 mm (0.2 in) (Hill and Forti 1997).
- Stalagmite—A calcite speleothem that grows upward from a cave floor, as a result of deposition by dripping water (see figs. 23 and 24). When a drop of water falls from the ceiling or an overhead stalactite, it still has some carbonate material left in solution. When the drop hits the floor, carbon dioxide is given off and carbonate is precipitated as a mound below the point of dripping. Most stalagmites in Oregon Caves are narrow or small mounds (Roth 2005).
- Vermiculations—Lines of clay or other particulate matter that cling together on cave surfaces; also called "clay worms" (fig. 21). Scoping participants identified vermiculations as an unusual geologic feature that is well represented in Oregon Caves and worthy of interpretation (Covington 2004). These thin, discontinuous deposits likely formed from flocculation of drying, liquid films. Flocculation is the process by which particulate matter comes out of suspension to form "floc" or flakes. Vermiculations are created from loose, unconsolidated material, such as mud or clay, but also lint, carbon (from candles or carbide lamps), or algae. Any fine-grained material can be a component for vermiculations, the common parameter being that any such material must be capable of being suspended in water films (Hill and Forti 1997). In Oregon Caves, many vermiculations are inactive (no longer wet) and some are covered by a thin layer of calcite (Webber and Webber 1998). The rate of formation varies, but simple, rounded, or non-branching vermiculations have formed in a year or so on PVC piping within Oregon Caves. More complex forms composed of carbon from carbide lamps probably took decades to a century to form (Roth 2005).

Physical Characteristics of Oregon Caves

Based on physical characteristics, Knutson (2006) divided Oregon Caves into four distinct areas, each about one-fourth of the cave in size: (1) Lower Cave, (2) Middle Cave, (3) Ghost Room area, and (4) South End (fig. 12). The configuration of the cave is somewhat unusual in that the cave rises in elevation from its entrance (Knutson 2006). That is, the Main Entrance is the lowest point of the cave (fig. 11); more commonly, one thinks of descending (not ascending) into a cave.

Lower Cave

The Lower Cave area of Oregon Caves extends from the Main Entrance to the 110 Exit, named because it is 110 feet higher than the Main Entrance (fig. 11). Much of the Lower Cave developed along intersecting joints (fractures in rocks) as Upper Cave Creek was being pirated (captured) from the surface to underground. The main area of the Lower Cave consists of tall, narrow, intersecting passages. Near entrances, moonmilk gives this part of the cave a white, powdery appearance. Rounded, white cave ghosts appear on the ceiling of the Imagination Room in the Lower Cave area. These are the remains of calcite "eaten away" by carbonic acid. The eastern portion of the Lower Cave contains the channel of the River Styx, which splits off from the main trend of the rest of the cave (fig. 22). Cave fill plugs up passages at the upper end of the river in the Lower Cave (Knutson 2006).

Middle Cave

The Middle Cave is likely the area of Oregon Caves that charmed its earliest visitors (Knutson 2006). This part of the cave extends from the 110 Exit to Joaquin Miller's Chapel, and includes the site of Niagara Falls (figs. 11 and 12). Moving from the Lower Cave to the Middle Cave, dryness disappears, and the Middle Cave becomes quite wet, although there are no streams (Knutson 2006). This likely occurs because greater depth from the surface allows winter water to infiltrate year-round. Flowstone is profuse, and stalagmites, stalactites, draperies, soda straws, and coralloids abound. Pools lined with crystals are common. Joaquin Miller's Chapel is part of the Middle Cave (figs. 11 and 12). Here, soda straws have grown to wide stalactites, and thick deposits of flowstone cover many surfaces (fig. 23). Notably, the "Grand Column" occurs in this area of the cave (fig. 24). Furthermore, the site of Neptune's Grotto, within the Middle Cave, is known for stalactites, stalagmites, and flowstone, as well as silt-rich vermiculations that appear as brown lace on the walls. There are no sizeable rooms or domes in the Middle Cave area. Rather, long passages that formed along bedding planes characterize the Middle Cave. The passages occur as distinct levels that vary from walkways to crawlways.

Ghost Room Area

The Ghost Room area makes up the central part of the cave. It is characterized by spacious passages and rooms throughout, although low-ceilinged crawlways occur along its sides (Knutson 2006). About the size of a football field, the Ghost Room itself is the largest room in Oregon Caves. It likely formed via breakdown of a ceiling/floor between two superimposed passages (Knutson 2006). Vermiculations are a primary speleothem in this part of the cave. Just beyond the Ghost Room, striking parachute-like flowstone decorates the site of Paradise Lost (fig. 25). Draperies, some with the appearance of cave bacon, also occur. At the foot of Paradise Lost, a section of rimstone named "Devil's Washboard," resembles miniature waves on the sea. Diorite dikes (Jd) of the Grayback pluton project from the ceiling of the Ghost Room (Webber and Webber 1998) (fig. 26). The west part of the Ghost Room area has the Exit Tunnel, which leads cave tours back to the surface.

South End

The tour route does not lead into the South End of the cave; climbing over boulders and a belly crawl are required to enter. A distinctive characteristic of the South End is a series of domes that lead to the highest known point of Oregon Caves, some 120 m (400 ft) above the Main Entrance. The South End hosts most of the upper (and oldest) parts of Oregon Caves, which are branch-work passages that formed along the intersections of bedding planes and steeply dipping fractures (John Roth, chief of Resources Management, Oregon Caves NM, written communication, June 15, 2011). The South Room, the second largest room in the cave, formed as a result of water flowing down steeply dipping fractures in non-marble rock; with less carbonate in solution, the water was highly capable of dissolving the marble (John Roth, chief of Resources Management, Oregon Caves NM, written communication, June 15, 2011). The South End terminates in a massive deposit of breakdown.

Although the South End may appear stark, with lots of breakdown and almost no flowstone, this is a significant area of the cave where fossils of Pleistocene mammals (bones and tracks) were found (see "Paleontological Resources"). Moreover, vermiculations and thin quartz dikes are beautifully displayed in this area of the cave (Knutson 2006) (fig. 27).

Diversity of Rocks

In the three-minute walk from the parking lot to the cave entrance, serpentinite, peridotite, diorite, phyllites (tan, black, and red), metachert, marble, limestone, agglomerate, conglomerate, metavolcanic sandstone, breccia, metabreccia, greenstone, amphibolite, and schist all crop out (John Roth, chief of Resources Management, Oregon Caves NM, written communication, April 6, 2011). In addition, more than 30 minerals are known from the monument, mainly in metamorphic and igneous rocks of the Rattlesnake Creek terrane (John Roth, chief of Resources Management, Oregon Caves NM, written communication, April 6, 2011).

The digital geologic map for Oregon Caves National Monument (Barnard 2007), mapped the rocks within the main part of the national monument. Map units include diorite dikes (Jd) of the Grayback pluton, and the rocks of the Rattlesnake Creek terrane: marble (Jml), argillite (Ja), metasediment (Js), metachert (Jc), mélange (Jm), metavolcanic rock (basalt) (Jv), metavolcanic rock (gabbro) (Jg), skarn (Jsk), peridotite (Jp), and serpentinite (Jsr). Barnard (2007) does not include the 1.6 ha (4 ac) of the national monument in Cave Junction. This part of the national monument hosts the Josephine ophiolite (John Roth, chief of Resources Management, Oregon Caves NM, written communication, June 15, 2011). The rocks in ophiolite sequences include peridotite, gabbro, basalt, and sedimentary rocks (see "Ophiolites").

Barnard (2007) noted that the rocks of the Rattlesnake Creek terrane, as well as and Western Hayfork terrane (which is not part of the national monument), have been correlated with rocks of the southernmost part of the Applegate Group. As a point of clarification, "Rattlesnake Creek terrane" is not an officially designated rock formation, and is not included in the geologic names lexicon, "Geolex," of the U.S. Geological Survey. However, the "Applegate Group" is included (U.S. Geological Survey 2007). The Applegate Group appears on many geologic maps of the area, and is the unit name typically used in discussions of mineral resources. Based on lithologic similarity, structural style, and geochemistry, investigators have correlated the Applegate Group with the Rattlesnake Creek terrane (Donato et al. 1996). This correlation places the rocks of the Applegate Group within the context of plate tectonics that is so significant for the region.

Ultramafic Rocks

Ultramafic rocks originate in the upper mantle, below Earth's crust. In the Klamath Mountains province, they have been brought to the surface via accretion (gradual addition) of terranes and deformation along faults. The largest concentrations of ultramafic rocks in North America are in the accreted terranes of the Klamath Mountains (Alexander 2000, 2005). Because ultramafic rocks are seldom seen at Earth's surface, their occurrence at Oregon Caves National Monument is a rare geologic treat.

Oregon Caves National Monument hosts two kinds of ultramafic rocks—peridotite (Jp) and serpentinite (Jsr) (Barnard 2007). Peridotite—a plutonic rock and major constituent of the upper mantle—is the igneous precursor of serpentinite. Serpentinite is produced through hydrothermal alteration of peridotite, in a metamorphic process called serpentinization.

A characteristic of landscapes underlain by ultramafic rocks, especially serpentinite, is that they are commonly unstable (see "Mass Wasting"). During serpentinization, an expansion of approximately 33% occurs, which is typically accompanied by extensive fracturing and shearing (Alexander 2009). Consequently, most serpentinite breaks into smaller blocks than does peridotite. The shearing commonly smoothes and polishes fracture surfaces in serpentinite, reducing its shear strength and making it more susceptible than peridotite to mass failure (Alexander 2009).

Geologists are interested in ultramafic rocks because of their origins in Earth's mantle. The mantle lies between 100 km (60 mi) and 200 km (120 mi) below Earth's surface, so opportunities for first-hand study are uncommon (Robertson 2011). At the main part of Oregon Caves National Monument, the mantle has been brought to the surface as part of the ophiolite sequence in the Rattlesnake Creek terrane. Mountain-building events, in particular doming in the north-central part of the Klamath Mountains, tilted the Rattlesnake Creek terrane and exposed an oblique cross section through disrupted and metamorphosed oceanic crust and mantle (Garlick et al. 2009). Under the Cave Junction part of the monument, the Josephine ophiolite exposes mantle material. Thrusting along a fault put the Josephine ophiolite under the Rattlesnake Creek terrane in the vicinity of the visitor center at Cave Junction (John Roth, chief of Resources Management, Oregon Caves NM, written communication, June 15, 2011).

Ecologists are interested in ultramafic rocks—commonly referred to as "serpentine"—because serpentine materials are sparse in continental crust and provide an unusual substrate for plants. The plants that grow on the serpentine within Oregon Caves National Monument add to the rich biological diversity of the monument and the region. The Klamath Mountains province contains among the country's highest biodiversities of vascular plants (~3,800 species) and animals (~50,000 species). Per acre, the national monument's approximately 500 plant species, 5,000 animal species, 2,000 fungal species, and an estimated >1 million bacterial species are among the highest recorded amounts of biodiversity anywhere (John Roth, chief of Resources Management, Oregon Caves NM, written communication, June 15, 2011).

Ophiolites

Ophiolites are assemblages of mafic and ultramafic rocks that represent oceanic crust. Ophiolites are distinctive because they allow first-hand examination of rocks from the seafloor on land. In some cases, ophiolite sequences expose rocks from the upper mantle at Earth's surface. In a complete ophiolite sequence (from bottom to top), sheared and serpentinized ultramafic rocks, for example peridotite, of the mantle, are overlain by accumulations of mafic igneous rocks, such as gabbro, which formed at the base of the ocean crust. These, in turn, grade upward into sheeted dikes, which represents volcanic activity along a zone of rifting. Sheeted dikes are topped by pillow basalts that were extruded as lava onto the seafloor. Deep marine sediments, such as chert, cap the sequence (fig. 28). Ophiolite sequences in the Klamath Mountains can be up to 5 km (3 mi) thick (Orr and Orr 1999), although an entire sequence is rarely preserved (Neuendorf et al. 2005).

Josephine Ophiolite

The Josephine ophiolite underlies the Cave Junction part of Oregon Caves National Monument (John Roth, chief of Resources Management, Oregon Caves NM, written communication, June 15, 2011). The Josephine ophiolite is one of the largest and most complete ophiolite sequences in the world (Orr and Orr 1999). The ophiolite contains rocks of ancient ocean crust and upper mantle that are rich in magnesium, iron, and sepentinite. The Josephine ophiolite is famous for its massive sulfide deposits, which yield gold, silver, copper, zinc, and cobalt (Orr and Orr 1999) (see "Mining and Mineral Resources"). On an ancient spreading ridge, hydrothermal activity from submarine hot springs precipitated the minerals at temperatures up to 343°C (650°F) (Orr and Orr 1999).

Accreted Terranes

Situated on the active margin of the North American plate, the Klamath Mountains province has repeatedly been the site of collision and accretion of fragments of tectonic plates called "terranes." The Klamath region consists of four north-trending, curved belts of terranes that were added to the western edge of the continent. From east to west, these belts are the Eastern Paleozoic, Central Metamorphic, Western Paleozoic and Triassic, and Western Jurassic (Irwin 1960) (see fig. 4). In general, and as the geologic-time terms in their names indicate, older belts are to the east of successively younger belts to the west. Each belt is bounded by east-dipping thrust faults, along which older rocks have overridden younger rocks (Irwin 1966).

Rattlesnake Creek Terrane

The terrane underlying the majority of Oregon Caves National Monument is the Rattlesnake Creek terrane (Irwin 1994; Barnard 2007). This terrane is a mélange (mixture) of rocks, consisting mostly of extremely dismembered ophiolite (Irwin 2010b). Addition of the Rattlesnake Creek terrane to the western edge of the North American continent is part of a longer history of accretion, involving the progressive welding of a series of island-arc (offshore volcanoes above a subduction zone) (fig. 29), ocean-basin, and subduction-zone assemblages (Wright and Wyld 1994). Successive terranes were thrust under previously accreted terranes, resulting in a series of imbricated plate fragments that resemble westward-leaning books toppled on a shelf.

Irwin (1972) originally recognized the Rattlesnake Creek terrane as a mappable subdivision of the Western Paleozoic and Triassic belt, with respect to rock types and geologic age provided by fossils. To the east of the Rattlesnake Creek terrane is the Western Hayfork terrane, which also is part of the Western Palezoic and Triassic belt. The Western Hayfork terrane and Rattlesnake Creek terrane are bounded by the Salt Creek thrust, which placed the Western Hayfork terrane above the Rattlesnake Creek terrane. To the west of the Rattlesnake Creek terrane, and bounded by the Orleans fault, is the Western Klamath terrane, which is also referred to as the "Western Jurassic terrane" (Irwin 2010b). The Western Klamath terrane is part of the Western Jurassic belt. The Western Jurassic belt consists of the Josephine ophiolite and overlying Galice Formation (Frost et al. 2006).

Grayback Pluton

In addition to the rocks of the Rattlesnake Creek terrane and Josephine ophiolite, Oregon Caves National Monument hosts rocks of the Grayback pluton (figs. 30 and 31). Barnard (2007) mapped diorite dikes (Jd) of the Grayback pluton throughout the main part of the national monument.

The Grayback pluton is part of the Wooley Creek pluton suite that was emplaced 165 million to 156 million years ago (Johnson and Barnes 2006) (see fig. 4). The Grayback pluton intruded the Rattlesnake Creek terrane and the Western Hayfork terrane to the east. The magma of the Grayback pluton contains materials derived from Earth's crust, mantle, and a mixing/mingling of the two (see photograph on inside front cover). This is a distinctive feature of the crystallization history of the Grayback pluton, and it differs from other plutons in the suite (Johnson and Barnes 2006). The magma of the Grayback plution was produced in a back-arc setting (fig. 29). Rifting (crustal extension) was associated with the setting at the time.

Within Oregon Caves National Monument, the diorite dikes (Jd) of the Grayback pluton repeatedly intruded the marble block, as evidenced by the cave's interior (Barnard 2007). The dikes exposed at the surface range in length from 15 m (50 ft) to 110 m (350 ft). The dikes are mostly dioritic, but some are slightly gabbroic; gabbro contains less silica and more mafic minerals than diorite. The dikes contain pyroxene or hornblende, euhedral (well-formed) plagioclase crystals, biotite, and quartz. Most of the black crystals and plagioclase are suspended in a light gray matrix of quartz and other small gray and green minerals within the dikes (Barnard 2007).

Mining and Mineral Resources

Mining began in southern Oregon in 1850, with the discovery of gold along the Illinois River near the mouth of Josephine Creek, in what was to become Josephine County, the county in which Oregon Caves National Monument is situated. Mining within the Klamath Mountains has focused on the Josephine ophiolite (Orr and Orr 1999). The presence of precious metals in southwestern Oregon relates primarily to mineralization as part of the seafloor spreading process. Secondarily, the intrusion of plutons resulted in the formation of mineral ores (Orr and Orr 1999). Gold, silver, copper, and chromium have been important commodities to the economy of Josephine County (Ramp and Peterson 1979). Additionally, marble (metamorphosed limestone)—associated with plutonism—has also been an important commodity for the economy of Josephine County (Ramp and Peterson 1979).

No commercial mining activities have occurred within Oregon Caves National Monument. However, both recreational and commercial mining have occurred downstream of the monument. Activities include hydraulic gold mining in adjacent Siskiyou National Forest and Bureau of Land Management lands. These activities cause disturbances such as turbidity in streams, which likely impact salmonoid and stream macroinvertebrate populations (John Roth, chief of Resources Management, Oregon Caves NM, written communication, June 15, 2011). Larger-scale mining in the late 1800s and early 1900s dramatically altered transverse (crosswise) profiles of many streams, resulting in higher temperatures and lower amounts of dissolved oxygen via the shallowing and widening of channels (John Roth, chief of Resources Management, Oregon Caves NM, conference call, March 3, 2011).

Many of the rock units within the national monument are of mineralogical interest. For example, the Applegate Group is composed of metavolcanic and metasedimentary rocks. The metavolcanic rocks host metallic minerals, including numerous gold-bearing quartz veins (Ramp and Peterson 2004). The metasedimentary rocks of the Applegate Group host high-purity limestone (marble), as well as the gemstone rhodonite (pink, rose, or violet garnet). Lens-shaped masses of marble in the Applegate Group are the only commercial source of limestone in the region. The Marble Mountain limestone quarry north of the national monument operated from 1924 to 1967, producing high-quality limestone for the paper and cement industries (Ramp and Peterson 1979). Rhodonite is associated with quartzites that were probably recrystallized from cherts of the Applegate Group (Ramp and Peterson 1979).

Additionally, in Josephine County, bodies of quartz diorite contain pegmatite veins that host high-purity quartz and feldspar, as well as minor gold, copper, and molybdenite near contacts with older rocks. Also, ultramafic rocks—largely serpentinite, with some residual peridotite—host chromite, nickel, and minor amounts of copper and gold. Finally, some gabbros have minor copper sulfides (Ramp and Peterson 2004).

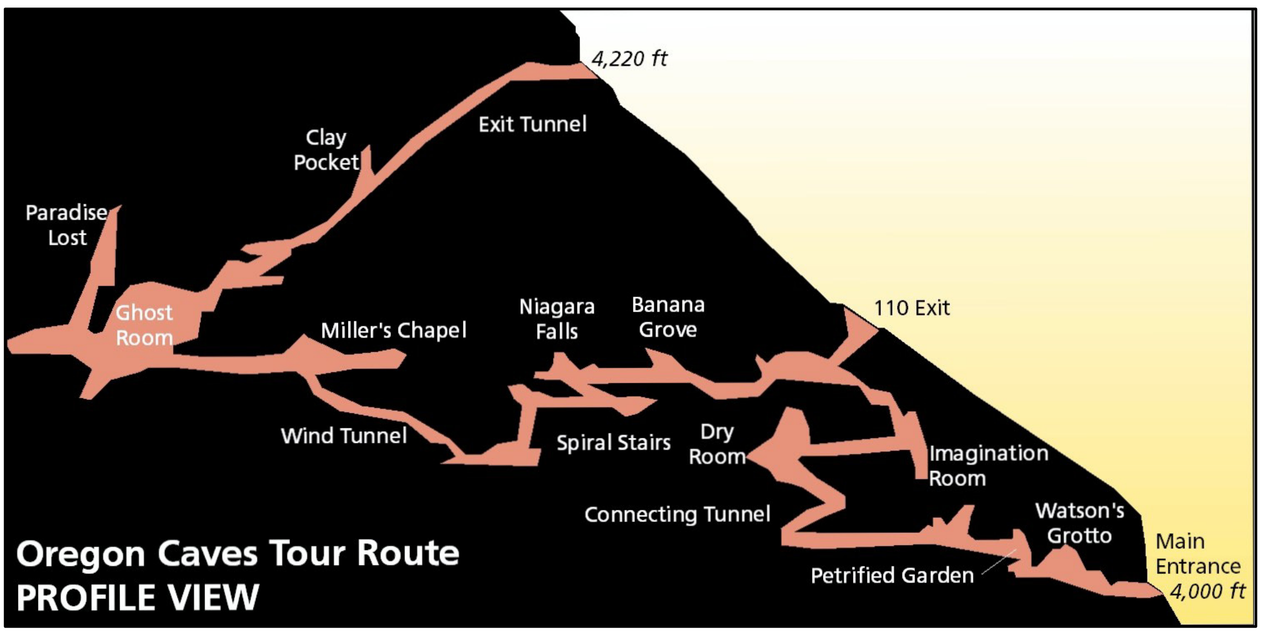

Figure 11. Profile view of Oregon Caves. This profile highlights the various levels of Oregon Caves along the cave tour. The 110 Exit is 110 feet above the Main Entrance. National Park Service graphic, courtesy Elizabeth Hale (Oregon Caves NM).

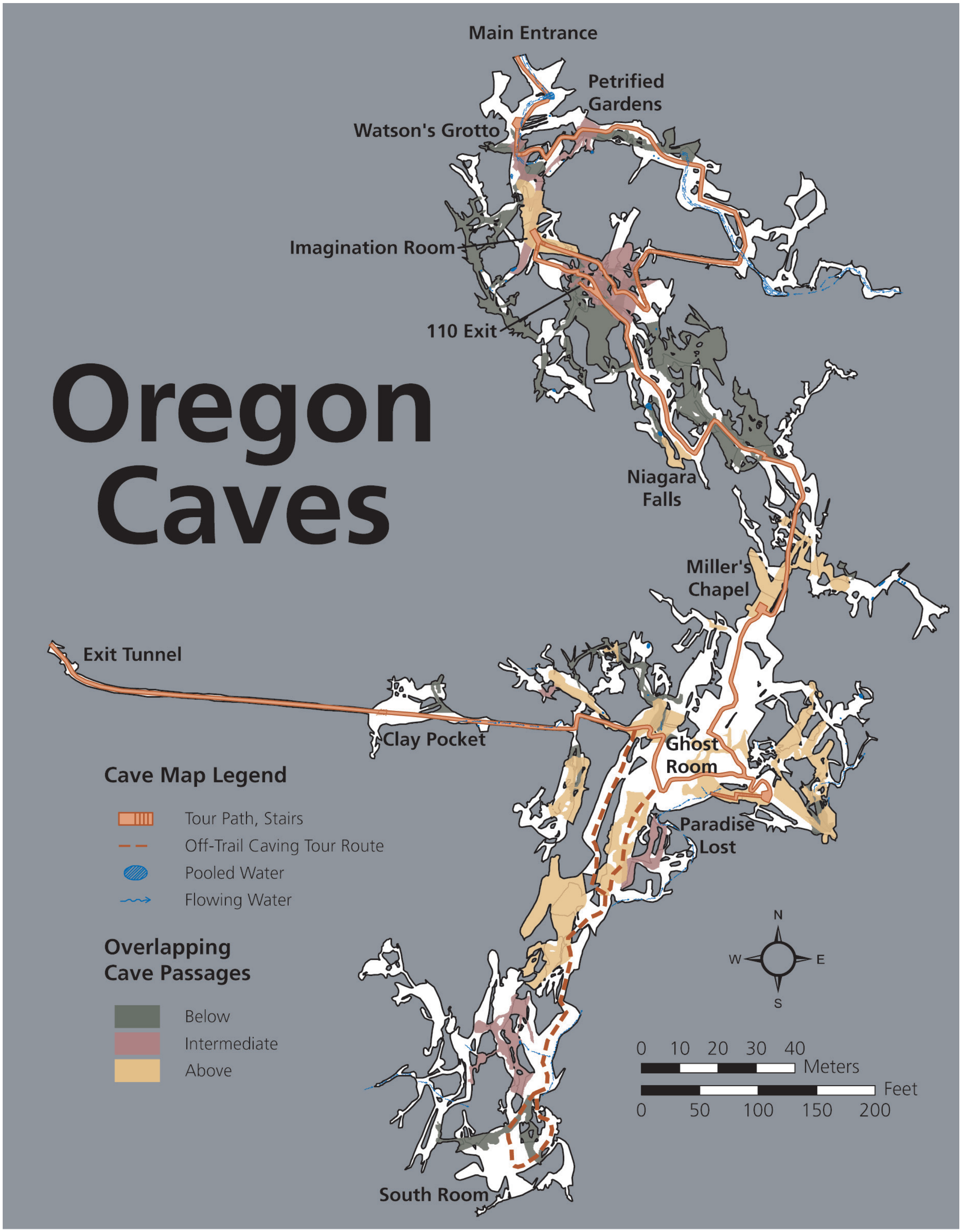

Figure 12. Map view of Oregon Caves. Oregon Caves has 4.8 km (3 mi) of known passages within four distinct areas: Lower Level (Main Entrance to 110 Exit), Middle Cave (110 Exit to Joaquin Miller's Chapel), Ghost Room area, and South End, including the South Room. National Park Service graphic courtesy Elizabeth Hale (Oregon Caves NM).

Figure 13. Marble exposed within Oregon Caves. Oregon Caves formed in marble of the Rattlesnake Creek terrane. National Park Service photograph, courtesy John Roth (Oregon Caves NM).

Figure 14. Dripping water. In Oregon Caves, speleothems form primarily by dripping water. The cave has multiple water inputs converging in the River Styx. National Park Service photograph, courtesy John Roth (Oregon Caves NM).

Figure 15. Breakdown. Heaps of rubble called "breakdown" occur most commonly near entrances. The Ghost Room formed as a result of breakdown, that is, collapse of a floor/ceiling between two superimposed passages. Notice the large blocks of breakdown below and to the sides of the stairs in this photo. National Park Service photograph, courtesy John Roth (Oregon Caves NM).

Figure 16. Cave popcorn. A type of coralloid, cave popcorn is a mineral deposit (calcite) that resembles the popular snack. National Park Service photograph, courtesy John Roth (Oregon Caves NM).

Figure 17. Draperies. Draperies hang above the Spiral Stairs within the Middle Cave area of Oregon Caves. An ancient waterfall and stream used to flow in this location. National Park Service photograph, courtesy John Roth (Oregon Caves NM).

Figure 18. Angel Falls. Draperies at Angel Falls exhibit luminescence (light emission) when exposed to ultraviolet (UV) black light. Angel Falls are located in the Ghost Room area of Oregon Caves. National Park Service photograph, courtesy John Roth (Oregon Caves NM).

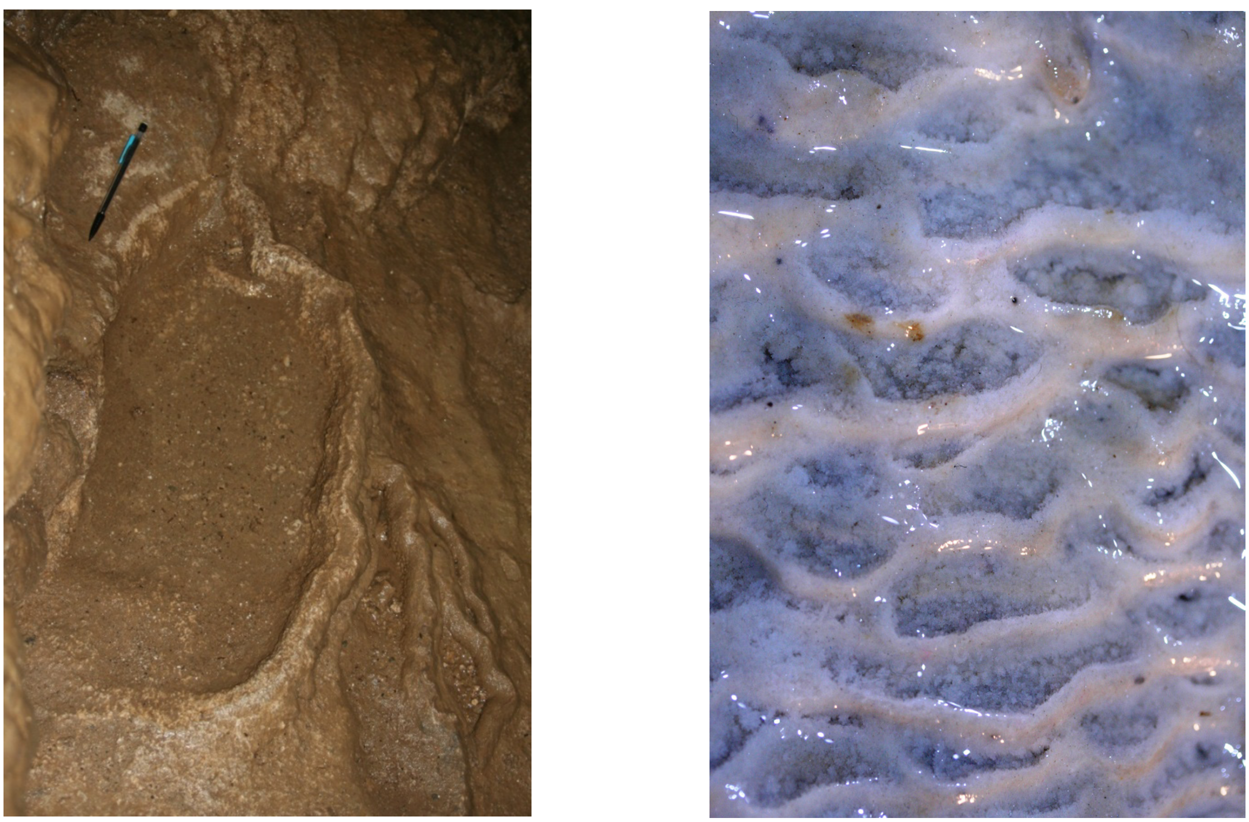

Figure 19. Rimstone. Examples of rimstone from Oregon Caves show the variety of these calcite deposits, which form a rim around the edge of a pool. Sometimes a pool may be dry, but the rim remains. National Park Service photographs, courtesy John Roth (Oregon Caves NM).

Figure 20. Soda straws. Delicate soda straws are a result of deposition of calcite by dripping water. Some soda straws may grow to become stalactites. National Park Service photograph, courtesy John Roth (Oregon Caves NM).

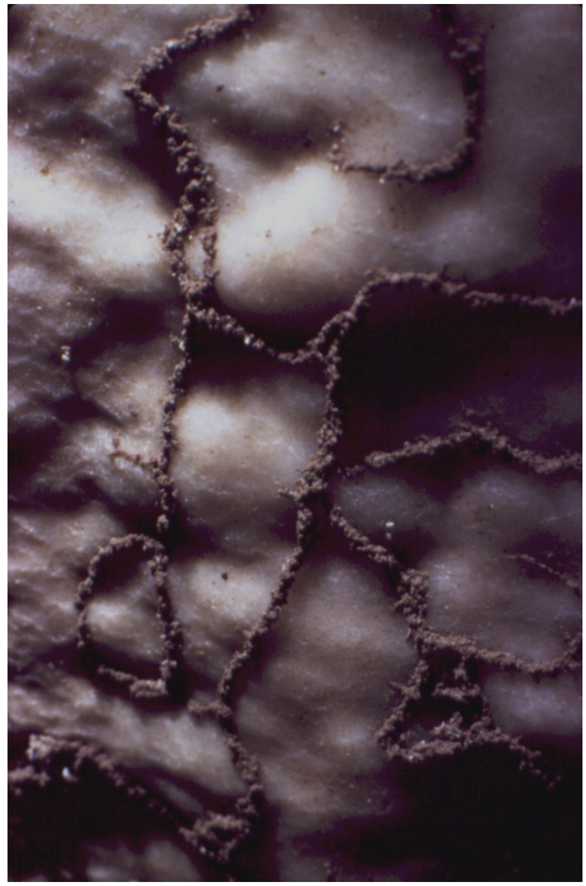

Figure 21. Vermiculations. Commonly called “cave worms,” vermiculations are lines of clay (and other materials) that cling together forming lace-like displays on cave surfaces. National Park Service photograph, courtesy John Roth (Oregon Caves NM).

Figure 22. River Styx. The River Styx flows at the lowest level of Oregon Caves, which is the youngest part of the cave. Flowing water continues to erode the cave, creating new passages. National Park Service photograph, courtesy John Roth (Oregon Caves NM).

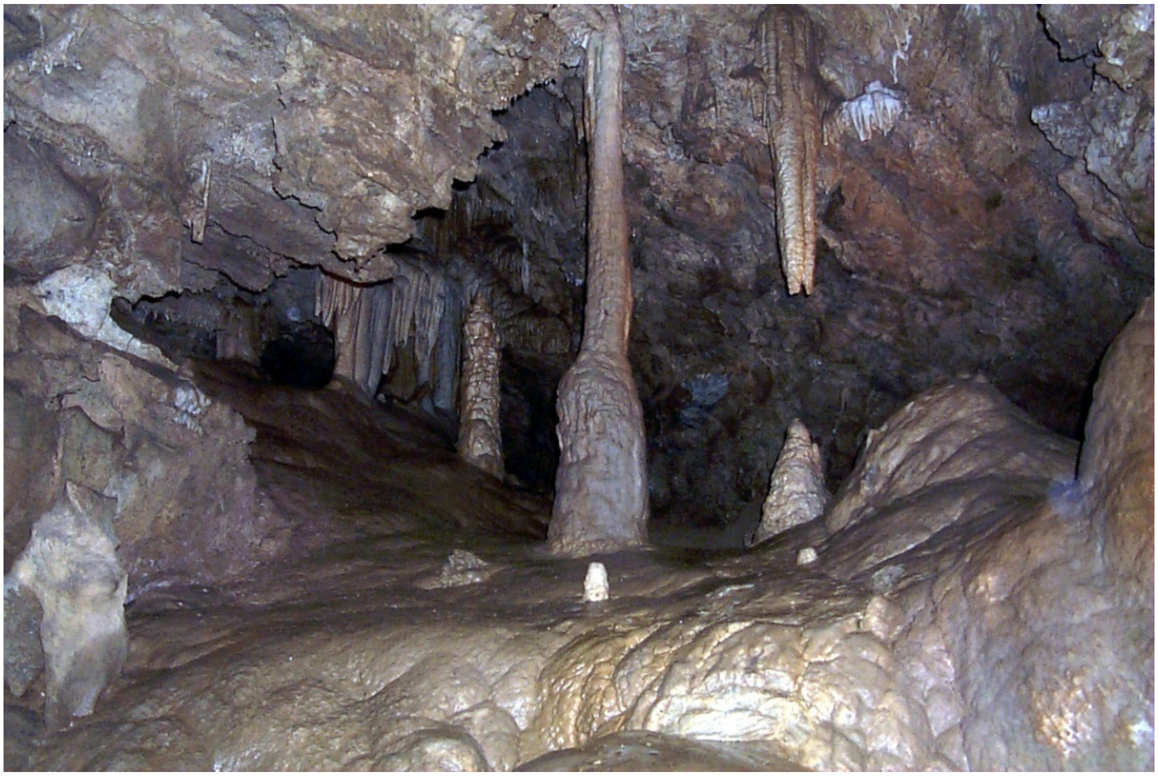

Figure 23. Joaquin Miller's Chapel. Stalagmites grow upward and stalactities grow downward in Joaquin Miller's Chapel, which was named for Joaquin Miller, the "Poet of the Sierras," who visited the cave in 1907. His article in *Sunset Magazine* helped publicize Oregon Caves. National Park Service photograph, courtesy John Roth (Oregon Caves NM).

Figure 24. Grand Column. A column forms when a stalactite and a stalagmite join together, such as the Grand Column in the Middle Cave area of Oregon Caves. National Park Service photograph, courtesy John Roth (Oregon Caves NM).

Figure 25. Paradise Lost. Joaquin Miller was the first to use "Paradise Lost" to describe this area of Oregon Caves near the Ghost Room. The name reflects that someone in Miller's caving party got lost, but also the influence that John Milton, the author of the epic poem *Paradise Lost*, had on Miller as a Romanic poet. Miller described Paradise Lost as simultaneously "creepy" and "wonderful," illustrating his dualistic view (good vs. evil) of the world. Excellent examples of flowstone decorate Paradise Lost. National Park Service photograph, courtesy John Roth (Oregon Caves NM).

Figure 26. Ghost Room. A dike associated with the Grayback pluton cuts across the roof of the Ghost Room. The dike crosses the upper left corner of this figure and casts an eerie shadow. For scale, the white deposit below the dike is about 0.9 m (3 ft) tall. National Park Service photograph, courtesy John Roth (Oregon Caves NM).

Figure 27. Quartz crystals. Quartz dikes or veins protrude from cave walls when the surrounding marble bedrock dissolved away. National Park Service photograph, courtesy John Roth (Oregon Caves NM).

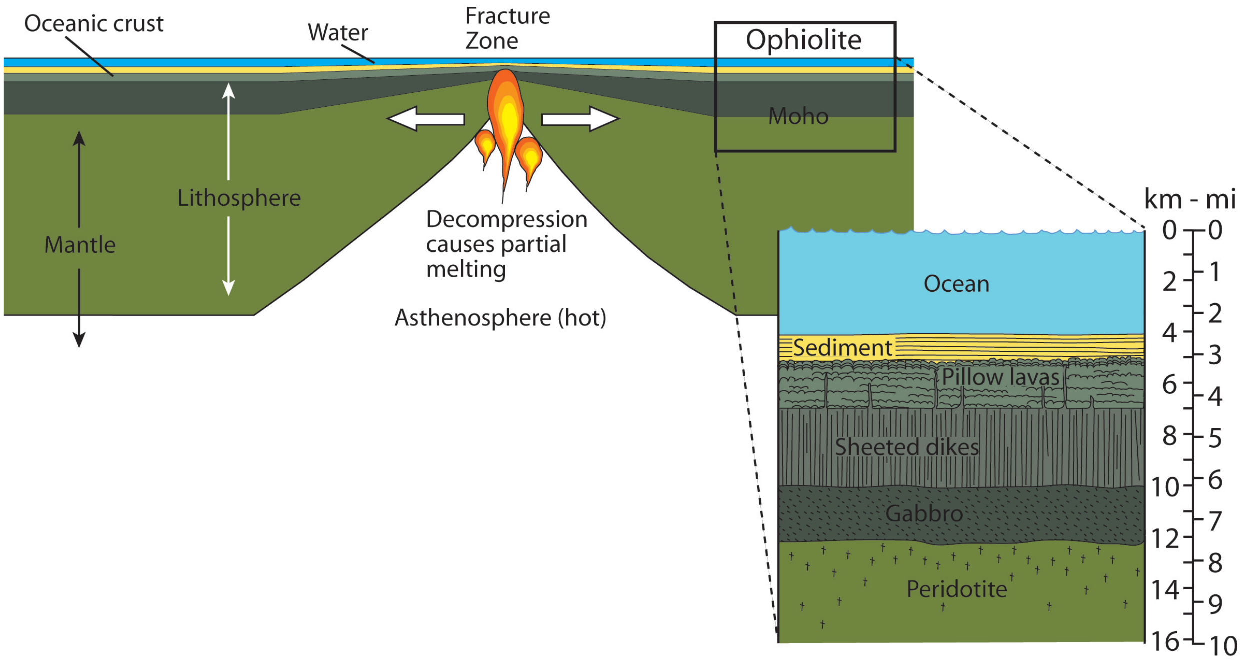

Figure 28. Ophiolite. An ophiolite is an assemblage of ultramafic and mafic, intrusive and extrusive rocks that originates as oceanic crust. "Moho" refers to the Mohorovicic discontinuity, the boundary between Earth's crust and mantle. Graphic after Lillie (2005), figure 3.28 (formation of an ophiolite), and Strahler (1981), figure 10.28 (composition and structure of oceanic crust), by Trista Thornberry-Ehrlich (Colorado State University).

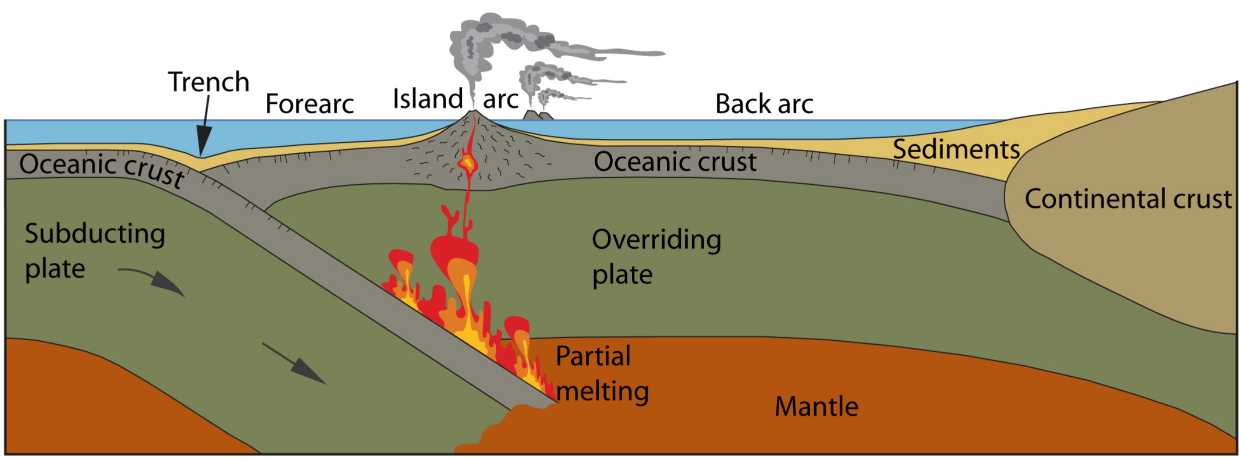

Figure 29. Island-arc setting. The setting for part of the geologic story of the Rattlesnake Creek terrane was an island arc. Such a setting includes a chain of offshore, island volcanoes above a subducting plate. The back arc is located opposite the trench and subducting plate, behind the chain of volcanoes called an "island arc." The forearc is located between the trench and the volcanoes. Graphic by Trista Thornberry-Ehrlich (Colorado State University).

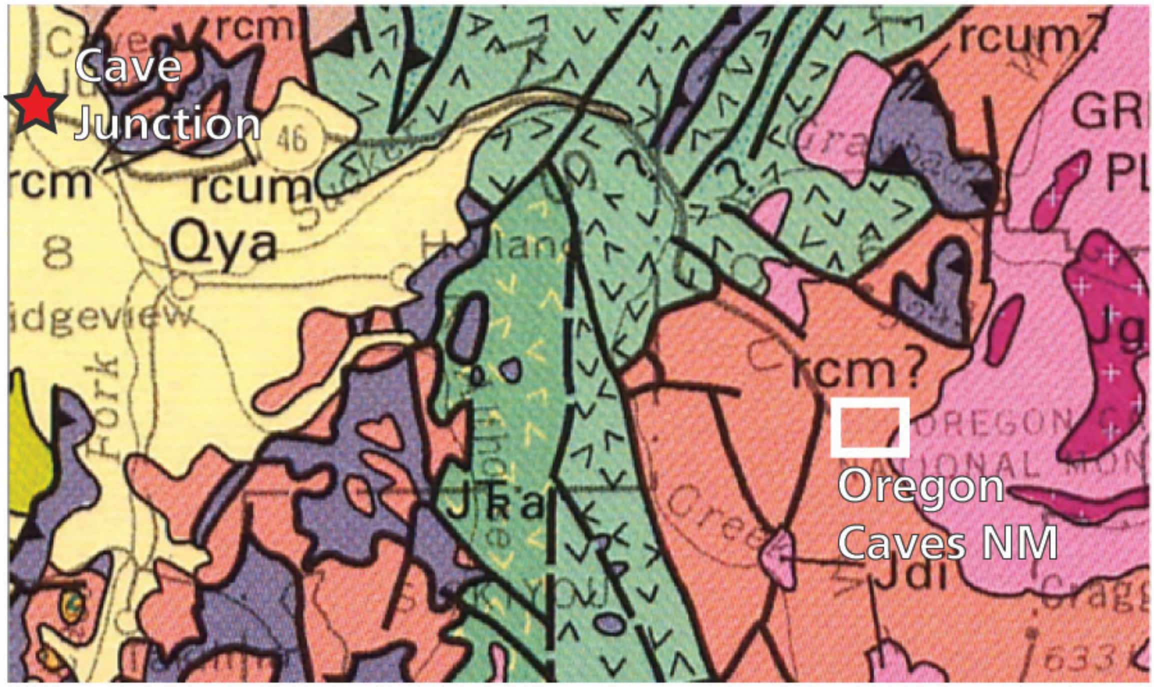

Figure 30. Geologic map showing the Grayback pluton. Irwin (1994) (scale 1:500,000) mapped the Grayback pluton (pink on the figure) covering the southeast corner of Oregon Caves National Monument. Cave Junction is covered by younger alluvial deposits (Qya) of Quaternary age (yellow). Jdi = plutonic rocks, diorite (Jurassic) (pink). Jgb = plutonic rock, gabbro (Jurassic) (dark pink with white crosses). JTRa = Hayfork terrane, andesitic and dacitic volcanic rocks (green with yellow carrots). JTRpv = Haystack Fork terrane, pyroxene volcanic rocks (green with black carrots). rcm = Rattlesnake Creek terrane, mélange (orange). rcum = Rattlesnake Creek terrane, serpentinized ultramafic rocks (purple). Screen capture from Irwin (1994). Annotated to show location of Cave Junction and Oregon Caves National Monument.

Figure 31. Grayback pluton. Between 165 million and 156 million years ago, the Grayback pluton intruded the Rattlesnake Creek terrane. This outcrop of the Grayback pluton shows brecciated clasts of black diorite within a light-colored matrix of mainly feldspar. National Park Service photograph, courtesy John Roth (Oregon Caves NM).

Geologic History

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

The geologic story of Oregon Caves National Monument is, to say the least, complex. It involves formation of the Rattlesnake Creek terrane; accretion of this terrane to the North American continent; and intrusion of the Grayback pluton into the terrane, while development of the Josephine ophiolite was occurring to the west. Fracturing within the Rattlesnake Creek terrane and associated marble block led to the formation of Oregon Caves.

At the surface, landscape evolution involved glacial sculpting of mountainous areas, with deposition of glacial outwash and moraines in valleys. Glacial meltwater created floodplains covered with silt, which became available for eolian (windblown) transport and re-deposition via fluvial transport into the cave. Changes in climate during interglacial (warm) periods influenced the formation of speleothems (cave mineral deposits).

At the present time, debris flows alter the surface. Below ground, speleothems slowly form by dripping water, and the River Styx flows and erodes cave passages.

Pre-Upper Triassic Period (before 228 million years ago): Formation of the Rattlesnake Creek Terrane Basement Mélange

Wright and Wyld (1994) proposed a polygenetic evolution for the Rattlesnake Creek terrane (fig. 32). Before and during the Upper Triassic Period, oceanic crust and upper mantle, as represented by serpentinized peridotite, formed in an oceanic fracture zone. The serpentinized peridotite later served as the host rock for blocks of other rock such greenstone, amphibolite, pillow basalt, chert, and limestone, all together making up the basement mélange. The mélange developed in an open-ocean environment away from sources of terrigenous sediment, except eolian. The paleogeographic setting of the Rattlesnake Creek terrane is inferred to be proximal to western North America (Frost et al. 2006). Patchett and Gehrels (1998) suggested that the closest source of continental material at that time was 1,500 km (930 mi) distant.

Investigators proposed that seamounts formed in the vicinity of the fracture zone and became part of the basement mélange (Wright and Wyld 1994). Seamounts are a stage in the life of an island volcano. As a volcano erodes and subsides, it becomes a seamount that is submerged but still forms an elevated area on the seafloor. The elevated topography creates locally shallow waters. Reefs composed of limestone (the remains of marine fauna) formed in the shallow waters, capping and flanking the seamounts. This limestone is significant for Oregon Caves National Monument because later it becomes metamorphosed to marble and fractured for cave formation.

Upper Triassic–Lower Jurassic Period (228 to 175 million years ago): Formation of the Rattlesnake Creek Terrane Cover Sequence

The next phase of development of the Rattlesnake Creek terrane occurred during the Upper Triassic and Lower Jurassic periods. At this time, a cover sequence was deposited directly on the basement mélange. Within a "sequence," the rocks are arranged chronically (older at the bottom, younger towards the top), and represent a series of geologic events. The rocks of the cover sequence are a mixture of volcanic-arc debris and river-borne, terrigenous sediment (Frost et al. 2006).

At this point in the geologic story, the fracture zone was transitioning to a subduction zone. The eastward-dipping plate subducted and created a chain of volcanic islands called an "island arc" (fig. 29). This island-arc system developed closer to a landmass than the underlying basement mélange (Scherer et al. 2006). Wright and Wyld (1994) proposed that the subduction zone was west of the Rattlesnake Creek terrane rocks, allowing an influx of terrigenous sediments from the continental landmass that lay to the east of the terrane (fig. 32). Hence, the cover sequence contains both volcanic (from the active arc setting) and clastic (from the continent) rocks.

Middle Jurassic–Upper Jurassic (175 to 145 million years ago): Accretion of the Rattlesnake Creek Terrane to the North American Continent

During Upper Triassic (approximately 200 million years ago) through Middle Jurassic (approximately 165 million years ago), the Rattlesnake Creek terrane (basement mélange and cover sequence) was part of an arc and forearc system that dominated the western continental margin (Donalto et al. 1996) (fig. 29). Today, the rocks at Oregon Caves National Monument retain evidence of the island-arc system that was destroyed during addition of the terrane to the North American continent.

Middle Jurassic–Upper Jurassic (165 to 156 million years ago): Intrusion of the Grayback Pluton

As successive terranes were added to the west of the Rattlesnake Creek terrane along the edge of the North American continent, the Rattlesnake Creek terrane became deformed and metamorphosed. In this active arc setting, numerous igneous bodies of rock—including the Wooley Creek suite of which the Grayback pluton is a part—intruded the rocks of the Rattlesnake Creek terrane. As a result of intrusion and deep burial, the limestone of the Rattlesnake Creek terrane, which represents the reefs of Upper Triassic seamounts, metamorphosed to marble.

The elongate nature of the Grayback pluton and its intrusion into an area of high-angle faulting suggest emplacement in an extensional (pulling apart) environment (Barnes et al. 1995), probably a back arc behind a contemporaneous island arc (Johnson and Barnes 2006) (see fig. 29). Rifting in the back-arc environment likely facilitated the ascent of mantle-derived magmas into the Grayback system (Johnson and Barnes 2006). Intrusion of the Grayback pluton occurred in two stages: a main stage about 160 million years ago, and a late stage about 157 million years ago (Johnson and Barnes 2006). The late stage is characterized by dikes (Johnson and Barnes 2006).

Depending on the timing and location of a particular intrusion, different limestone blocks metamorphosed to marble at different times. The marble of Oregon Caves was metamorphosed when the Western Hayfork and Rattlesnake Creek terranes came into contact (172 million to 167 million years ago), and when the Grayback pluton intruded the Rattlesnake Creek terrane (Medaris et al. 2009; John Roth, chief of Resources Management, Oregon Caves NM, e-mail communication, April 22, 2011).

Towards the end of the Jurassic Period, thrusting along the Orleans fault put the Western Klamath terrane, including the Josephine ophiolite, under the Rattlesnake Creek terrane, in the vicinity of the visitor center at Cave Junction (John Roth, chief of Resources Management, Oregon Caves NM, e-mail communication, April 22, 2011). The Josephine ophiolite was thrust beneath the Rattlesnake Creek terrane 155 million to 150 million years ago (Allen and Barnes 2006). At this time, rifting gave way to convergence, further imbricating and accreting terranes along the Orleans fault.

Middle Jurassic–Upper Jurassic (164 to 162 million years ago): Development of the Josephine Ophiolite

Between 164 million and 162 million years ago, the Josephine ophiolite developed in a subduction zone where one tectonic plate was descending beneath another. The ophiolite contains rocks from both island-arc and mid-ocean ridge settings (Harper 2003). The Josephine ophiolite and overlying Galice Formation, which is composed of submarine debris flows called "turbidites," make up the footwall of the Orleans fault.

Neogene Period (23 to 2.6 million years ago): Uplift and Erosion of the Marble Block

Regional uplift and erosion during the Miocene Epoch (23.03 million to 5.3 million years ago) resulted in two significant features that influenced Oregon Caves. First, the bedrock of the Rattlesnake Creek terrane, including the pods and lenses of marble, was positioned relatively near the surface. Second, fracturing of the rock allowed water to penetrate into the subsurface. Fracturing also regulated alignment of the cave passages (Turgeon and Lundberg 2001). High-angle (60° to 85°), north-south–trending normal faults and a northeast-southwest–oriented joint system control the locations of cave passages (Turgeon and Lundberg 2001). (Note the orientation of cave passages on fig. 12.) In addition, closeness to the land surface permitted flowing water from streams and near-surface colluvial deposits to flow into and enlarge cave passages (National Park Service 1998).

By the end of the Miocene Epoch, the northwest Klamath Mountains region was at or below sea level (Stone 1992, 1993). Regional uplift during the Pleistocene Epoch (2.6 million to 11,700 years ago) elevated these surfaces (Aalto 2006). Hence, through a combination of erosion and uplift during the Miocene and Pleistocene epochs, the marble of the Rattlesnake Creek terrane both fractured and emerged relatively close to the surface by the early Quaternary Period.

Quaternary Period (2.6 million years ago to the present): Formation of Oregon Caves and Development of the Present-day Landscape

With the marble relatively close to the surface and fractures serving as conduits for water, speleogenesis (cave formation) began during the Quaternary Period. Park staff estimates that the present-day Oregon Caves is approximately 1.7 million years old (see explanation below). However, it is likely that an older part of the cave existed that has since eroded away (John Roth, chief of Resources Management, Oregon Caves NM, written communication, September 15, 2011). Like a surface stream, the River Styx eroded (and continues to erode) its bed and banks, further enlarging cave passages. As younger passages formed, older passages became filled with air, promoting speleothem growth. Although some speleothem types form under submerged conditions, most types in Oregon Caves formed via dripping water in drained cave passages (Art Palmer, professor, State University of New York at Oneonta, e-mail communication, April 8, 2011).

Using uranium-series dating, Turgeon and Lundberg (2001) obtained ages of speleothems in Oregon Caves. The oldest specimen, a flowstone from Neptune's Grotto, was 370,000 years old. Turgeon and Lundberg (2004) extended the speleothem chronology through correlation with global paleoclimate records from Greenland and Antarctic ice cores, using work by Chappellaz and Jouzel (1982), Imbrie et al. (1984), and Johnsen et al. (1993). Correlation with these records suggests that speleothem growth within Oregon Caves could have started as early as 519,000 years ago. According to Turgeon and Lundberg (2004), given that the flowstone yielding this age is located on the most extensive level within the cave, this could be a good age estimate for the beginning of widespread speleothem deposition within present-day Oregon Caves.

Hence, between the time of fracturing and the widespread development of speleothems, Oregon Caves formed. Staff at the monument has tried to refine the timing of cave formation based on the hypothesis that the present-day cave most likely formed during a time when a much greater amount of water was available to penetrate the cracks in the marble (John Roth, chief of Resources Management, Oregon Caves NM, written notes, April 6, 2011). Generally speaking, more surface water would have been available during an interglacial period (warm period of glacial retreat) than a glacial period (cold period of glacial advance). Given the 519,000-year-ago age, an interglacial period before that time would be a good candidate for the initiation of speleothem growth. The proposed timing is during the Bramertonian interglacial (John Roth, chief of Resources Management, Oregon Caves NM, written notes, April 6, 2011). The Bramertonian stage extended from 2.4 million to 1.8 million years ago (Gibbard et al. 2005) and is based on sediments from the British Isles.

Other lines of evidence for the age of Oregon Caves include the phylogeny of endemic species within the cave, namely Grylloblattodea, known as ice bugs, ice crawlers, and rock crawlers (Jarvis and Whiting 2006). Grylloblatta are restricted to cold and extreme habitats, and are either nocturnal or cavernicolous (inhabiting caves). Climatic events, such as glaciations, cause subterreanean invasion of species (Porter 2008). The evolutionary lines of these rarely encountered insects, which inhabit Oregon Caves, date back to the late Pleistocene Epoch when glacial conditions enveloped most of the current distribution area of grylloblatta (Jarvis and Whiting 2006). Furthermore, the known/calculated rate for speciation of new cave animals averages more than 6 million years, and no known speciation events have been calculated to be less than 2 million years (Porter 2008). Hence, given the number of endemic species within Oregon Caves, it is likely that a much older cave once existed and has now been eroded away. In short, there are too many endemics (currently, eight known) to have evolved within the present-day cave. As the oldest parts of the cave eroded away, these endemic creatures moved down into younger cave (John Roth, chief of Resources Management, Oregon Caves NM, e-mail communication, September 15, 2011).

Although estimating the timing of speleogenesis of Oregon Caves is complex, involving multiple lines of evidence, the process of speleogenesis for Oregon Caves is rather straightforward (Halliday 2009). That is, vadose (zone of aeration) features such as speleothems, scallops (see front cover photo), and pendants are superimposed on a basic phreatic (zone of saturation) pattern (Halliday 2009). Halliday (2005) likened the speleogenesis of Oregon Caves to Lilburn Cave in Redwood National and State Parks in California. Both caves are characterized by an extraordinarily rapid dissolution rate and development of a three-dimensional, braided network of passages in a limited vertical range below steep feeder routes (conduits through which water passes) (Halliday 2005). Also, both caves formed in marble of an accreted terrane. Lilburn Cave is the longest and most-studied cave in California (Tinsley 2003).

At the same time the cave was forming, the surface landscape was developing. During the Pleistocene ice ages, glaciers were a primary landscape architect in the Klamath Mountains province. Glaciers formed at high elevations on north-facing slopes, and modified the terrain by scouring out cirques, flowing down valleys, and depositing till as moraines and outwash (Alexander et al. 2007). During the last major glaciation, the climatic snowline was about 2,400 m (8,000 ft) in elevation (Alexander et al. 2007). Sites of classic glacial landforms such as moraines, U-shaped valleys, and cirques occur at higher elevations in the Klamath Mountains (Woods 1988). Boundary expansion would likely add some lower-elevation glacial features to Oregon Caves National Monument, such as a thick glacial deposit in the Bigelow Lakes area, immediately to the north of Mt. Elijah (Furtney 2002). Currently, the closest glacial features are about 1 km (1.6 mi) outside the present boundary.

Although Oregon Caves National Monument is located south of the maximum limit of Pleistocene glaciers in the area (Turgeon and Lundberg 2004), climatic variations influenced the growth of speleothems. Speleothems formed primarily during interglacial periods, when conditions were wetter and more water was available for speleothem growth (Ersek et al. 2009). Paleoclimate studies at Oregon Caves National Monument by investigators such as Vasile Ersek and Alan Mix have provided a high-resolution, long-term dataset, second only to the Greenland ice cores (John Roth, chief of Resources Management, Oregon Caves NM, e-mail communication, September 15, 2011) (see Ersek et al. 2009, 2010).

In addition, loess (windblown dust) from Pleistocene floodplains was re-deposited by streamflow within Oregon Caves. Interestingly, re-deposited loess occurs in older parts of the cave, such as the Ghost Room and South Room, and likely was deposited during an earlier glacial period when the drainages of Lake Creek and Cave Creek were one and the same. Since that time, Lake Creek has incised more rapidly, and the two drainages are now separate. Hence, River Styx, the underground extension of Cave Creek, has no re-deposited loess. Moreover, this scenario—earlier glacial period, and, thereby a longer period of time for erosion—helps explain why the Ghost Room and South Room are so large compared to the other rooms in Oregon Caves (John Roth, chief of Resources Management, Oregon Caves NM, e-mail communication, September 15, 2011). Glacial floodwaters also deposited fluvial terraces along stream channels on the surface in the vicinity of Oregon Caves.

Today, the primary geologic agents are mass wasting and hydrologic processes. Debris flows alter the surface topography. The River Styx and other flowing and dripping water alter and decorate cave passages.

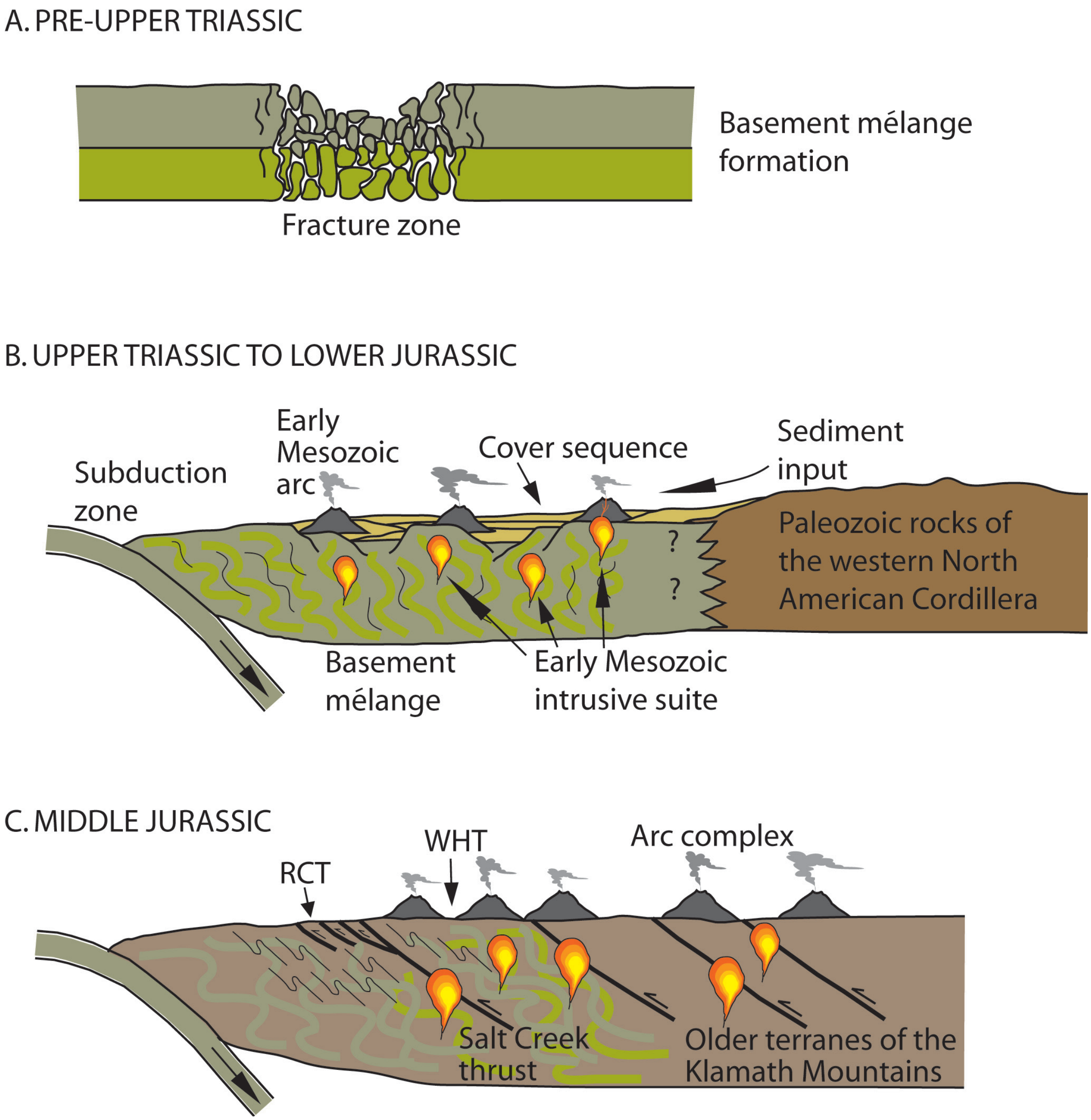

Figure 32. Evolution of the Rattlesnake Creek terrane. A. Oceanic crust and upper mantle are tectonically disrupted in an oceanic fracture zone, forming basement mélange. B. Subduction initiates within or near the fracture zone by at least the Upper Triassic, resulting in construction of an early Mesozoic arc of volcanoes, now represented by the cover sequence and early Mesozoic intrusive suite, across the basement mélange. The arc develops near a terrigenous sediment source, probably Paleozoic rocks of the western North American cordillera, and arc magmatism is apparently accompanied by deposition of sediments, extension, and normal faulting. C. The Rattlesnake Creek terrane (RCT) is regionally metamorphosed and deformed during overthrusting by the Western Hayfork terrane (WHT), causing remobilization of basement serpentinite and incorporation of fragments of the early Mesozoic arc into the mélange. At this time, the Rattlesnake Creek terrane is incorporated into the basement of a developing Middle Jurassic arc complex whose plutonic roots intrude most of the older terranes of the Klamath Mountains province. Some Middle Jurassic arc plutons thus also locally intrude the Rattlesnake Creek terrane. Graphic after Wright and Wyld (1994), redrafted by Trista Thornberry-Ehrlich (Colorado State University).

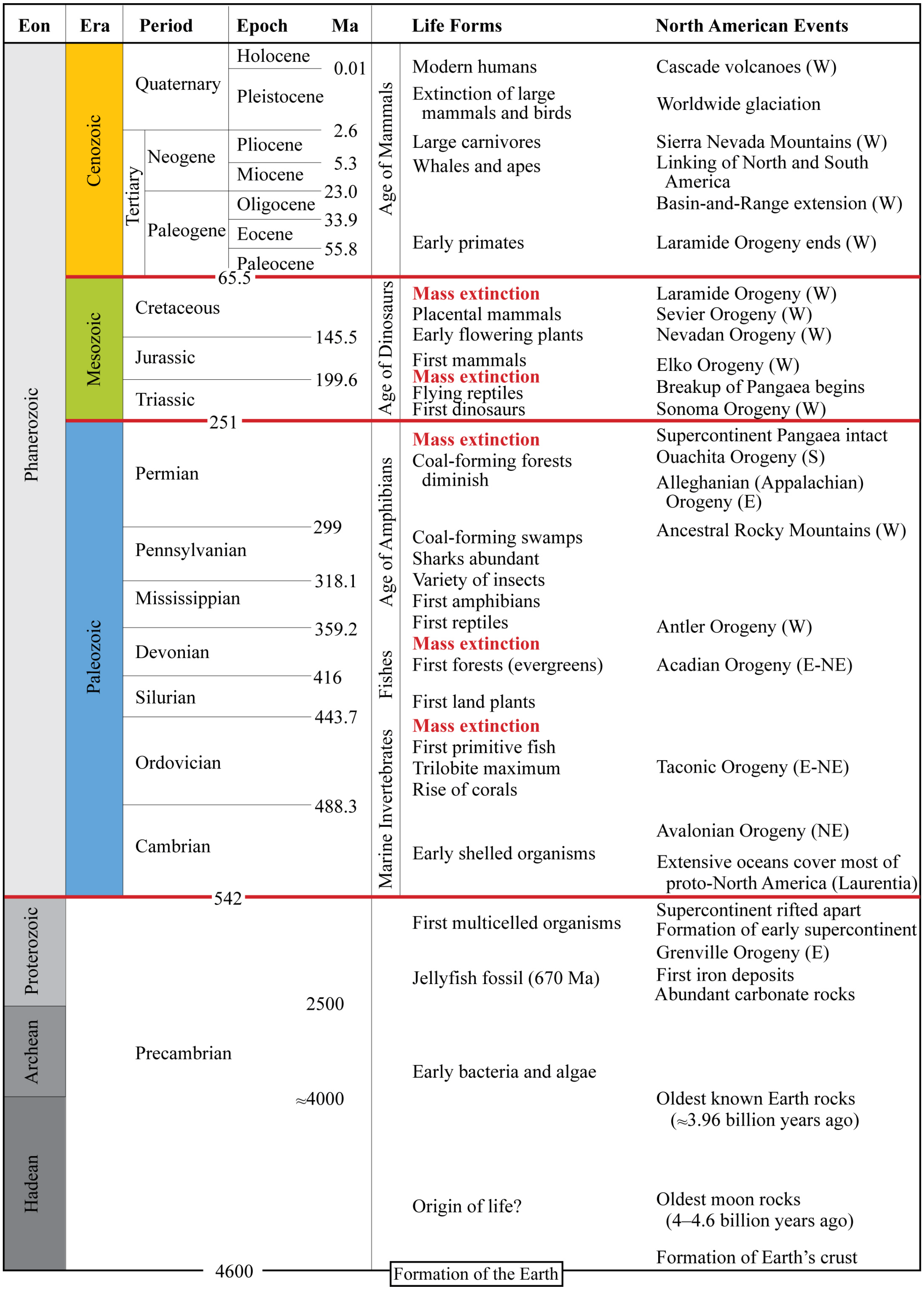

Figure 33. Geologic timescale. Included are major life history and tectonic events occurring on the North American continent. Red lines indicate major unconformities between eras. Radiometric ages shown are in millions of years (Ma). Compass directions in parentheses indicate the regional location of individual geologic events. Graphic by Trista Thornberry-Ehrlich with information from the U.S. Geological Survey (http://pubs.usgs.gov/fs/2007/3015/) and the International Commission on Stratigraphy (http://www.stratigraphy.org/view.php?id=25).

Geologic Map Data

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

Geologic Maps

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

Source Maps

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

Barnard, K. N. 2007. Geologic mapping of Oregon Caves National Monument, Cave Junction, Oregon. Geology report and geologic map prepared by Geological Society of America, GeoCorps participant. Oregon Caves National Monument, Cave Junction, Oregon, USA.

These source maps provided information for the "Geologic Issues," "Geologic Features and Processes," and "Geologic History" sections of this report. Updated mapping, completed as this report was in final review and production, was compiled by King et al. (2011).

Geologic GIS Data

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

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

- Data in ESRI geodatabase and shapefile GIS formats
- Layer files with feature symbology
- Federal Geographic Data Committee (FGDC)–compliant metadata
- A help file (PDF) document that contains all of the ancillary map information and graphics, including geologic unit correlation tables and map unit descriptions, legends, and other information captured from source maps.
- An ESRI ArcMap document that displays the digital geologic data.

Table 2. Geology data layers in the Oregon Caves National Monument GIS data

Data Layer	Code	On Geologic Map Overview?
Geologic Cross Section Lines	SEC	Yes
Geologic Attitude and Observation Localities	ATD	Yes
Faults	FLT	Yes
Geologic Contacts	GLGA	Yes
Geologic Units	GLG	Yes

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

Geologic Map Overview

The fold-out geologic map overview displays the GRI digital geologic data draped over an aerial image of Oregon Caves National Monument, and includes basic geographic information. For graphic clarity and legibility, not all GIS feature classes are visible on the overview. The aerial imagery and geographic information are not included with the GRI digital geologic GIS data for the park, but are available online from a variety of sources.

Map Unit Properties Table

The geologic units listed in the fold-out map unit properties table correspond to the accompanying digital geologic data. Following the overall structure of the report, the table highlights the geologic issues, features, and processes associated with each map unit. The units, their relationships, and the series of events the created them are highlighted in the "Geologic History" section. Please refer to the geologic timescale (fig. 33) for the geologic period and age associated with each unit.

Use Constraints

Graphic and written information provided in this section is not a substitute for site-specific investigations, and ground-disturbing activities should neither be permitted nor denied based upon the information provided here. Minor inaccuracies may exist regarding the location of geologic features relative to other geologic or geographic features on the overview graphic. Based on the source map scale (1:10,000) and U.S. National Map Accuracy Standards, geologic features represented here are within 5 meters / 17 feet (horizontally) of their true location.

Please contact GRI with any questions.

Glossary

This glossary contains brief definitions of technical geologic terms used in this report. Not all geologic terms used are referenced. For more detailed definitions or to find terms not listed here please visit: http://geomaps.wr.usgs.gov/parks/misc/glossarya.html. Definitions are based on those in the American Geological Institute Glossary of Geology (fifth edition; 2005).

accretion. The gradual addition of new land to old by the deposition of sediment or emplacement of landmasses onto the edge of a continent at a convergent margin.

active margin. A tectonically active margin where lithospheric plates come together (convergent boundary), pull apart (divergent boundary) or slide past one another (transform boundary). Typically associated with earthquakes and, in the case of convergent and divergent boundaries, volcanism. Compare to "passive margin."

alluvium. Stream-deposited sediment.

amphibole. A common group of rock-forming silicate minerals. Hornblende is the most abundant type.

amphibolite. A metamorphic rock consisting mostly of the minerals amphibole and plagioclase, with little or no quartz.

andesite. Fine-grained volcanic rock commonly associated with subduction zone volcanoes. Named for the subduction zone volcanoes of the Andes Mountains.

aphanitic. Describes the texture of fine-grained igneous rocks, where the different components are not distinguishable with the unaided eye.

arc. See "volcanic arc" and "magmatic arc."

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

argillite. A compact rock, derived from mudstone or shale, more highly cemented than either of those rocks. It does not easily split like shale or have the cleavage of slate. It is regarded as a product of low-temperature metamorphism.

basalt. A dark-colored, often low-viscosity, extrusive igneous rock.

bedding. Depositional layering or stratification of sediments.

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

biotite. A widely distributed and important rock-forming mineral of the mica group. Forms thin, flat sheets.

bioturbation. The reworking of sediment by organisms.

braided stream. A sediment-clogged stream that forms multiple channels which divide and rejoin.

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

breccia (volcanic). A coarse-grained, generally unsorted volcanic rock, consisting of partially welded angular fragments of ejected material such as tuff or ash.

broken formation. A rock formation broken by faults but retaining substantial continuity of contacts and internal stratigraphic units.

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

carbonate. A mineral that has CO_3^{-2} as its essential component (e.g., calcite and aragonite).

carbonate rock. A rock consisting chiefly of carbonate minerals (e.g., limestone, dolomite, or carbonatite).

cave popcorn. In speleology, a colloquial name for small, rounded coralloids.

chemical weathering. Chemical breakdown of minerals at Earth's surface via reaction with water, air, or dissolved substances; commonly results in a change in chemical composition that is more stable under the prevailing conditions.

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

cirque. A deep, steep-walled, half-bowl-like recess or hollow, located high on the side of a mountain and commonly at the head of a glacial valley. Produced by the erosive activity of a mountain glacier.

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

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

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

colluvium. A general term applied to any loose, heterogeneous, and incoherent mass of rock fragments deposited by unconcentrated surface runoff or slow continuous downslope creep, usually collecting at the base of gentle slopes or hillsides.

conglomerate. A coarse-grained, generally unsorted, sedimentary rock consisting of cemented, rounded clasts larger than 2 mm (0.08 in).

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

convergent boundary. A plate boundary where two tectonic plates are colliding.

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

cordillera. A Spanish term for an extensive mountain range; used in North America to refer to all of the western mountain ranges of the continent.

country rock. The rock surrounding an igneous intrusion or pluton. Also, the rock enclosing or traversed by a mineral deposit.

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

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

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

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

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

diorite. A type of plutonic igneous rock. It is the approximate intrusive equivalent of andesite.

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

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

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

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

dripstone. A general term for a mineral deposit formed in caves by dripping water.

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

epiclastic rock. A rock formed at Earth's surface by consolidation of fragments of pre-existing rocks.

erosion. The movement of earth materials, either as clastics or in dissolved form, generally to lower elevations and usually by water or wind.

evapotranspiration. Loss of water from the soil both by evaporation and by transpiration from the plants growing therein.

extension. Forces pulling rock apart. Results in rocks breaking along normal faults.

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

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

fluvial. Of or pertaining to a river or rivers.

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

foraminifer. Any protozoan belonging to the subclass Sarcodina, order Foraminiferida, characterized by the presence of a test ("shell") of one to many chambers, composed of secreted calcite (rarely silica or aragonite) or of agglutinated particles. Most foraminifers are marine, but freshwater forms are known. Range—Cambrian to Holocene.

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

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

frost wedging. The breakup of rock due to the expansion of water freezing in fractures.

gabbro. A group of dark-colored, intrusive igneous rocks. The intrusive equivalent of basalt.

garnet. A hard mineral that has a glassy luster, often with well defined crystal faces, and a variety of colors, dark red being characteristic. Commonly found in metamorphic rocks.

greenstone. A general term for any compact, dark green, altered or metamorphosed basic igneous rock, owing its color to chlorite, actinolite, or epidote minerals.

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

high-angle fault. A fault with a dip greater than 45°.

hornblende. The most common mineral of the amphibole group. Hornblende is commonly black and occurs in distinct crystals, or in columnar, fibrous, or granular forms.

hydrogeologic. Refers to the geologic influences on groundwater and surface water composition, movement and distribution.

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

imbrication. Commonly displayed by pebbles on a stream bed, where flowing water tilts the pebbles so that their flat surfaces dip upstream.

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

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

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

joint. A 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.

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

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

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

lithic. A sedimentary rock or pyroclastic deposit that contains abundant fragments of previously formed rocks.

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

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

luster. The reflection of light from the surface of a mineral.

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

magma. Molten rock beneath Earth's surface capable of intrusion and extrusion.

mantle. The zone of Earth's interior between the crust and core.

marble. A metamorphic rock consisting predominately of fine- to coarse-grained recrystallized calcite and/or dolomite. In commerce, any crystalline carbonate rock, including true marble and certain types of limestone (orthomarble), that will take a polish and can be used as architectural or ornamental stone.

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

matrix. The fine grained material between coarse (larger) grains in igneous rocks or poorly sorted clastic sediments or rocks. Also refers to rock or sediment in which a fossil is embedded.

mélange. A mappable body of jumbled rock that includes fragments and blocks of all sizes, both formed in place and those formed elsewhere, embedded in a fragmented and generally sheared matrix.

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

meta–. A prefix used with the name of a sedimentary or igneous rock, indicating that the rock has been metamorphosed.

metamorphic. Describes the process of metamorphism or its results. One of the three main classes of rocks—igneous, metamorphic, and sedimentary.

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

metavolcanic. An informal term for volcanic rocks that show evidence of metamorphism.

mica. A prominent rock-forming mineral of igneous and metamorphic rocks. It has perfect basal cleavage, meaning that it forms flat sheets.

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

moldic porosity. Porosity resulting from the removal, usually by dissolution, of an individual constituent of rock, such as a shell or a marble fragment in a dike with breccia.

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

moraine. A mound, ridge, or other distinct accumulation of unsorted, unstratified glacial drift, predominantly till, deposited by glacial ice movement.

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

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

ophiolite. An assemblage of ultramafic and mafic intrusive and extrusive igneous rock, probably representing oceanic crust.

orogeny. A mountain-building event.

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

outwash. Glacial sediment transported and deposited by meltwater streams.

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

pegmatite. An exceptionally coarse-grained intrusive igneous rock, with interlocking crystals, usually found in irregular dikes, lenses, and veins, especially at the margins of batholiths.

pendant. A solutional remnant hanging from the ceiling or wall of a cave.

peridotite. A coarse-grained plutonic (intrusive) rock composed chiefly of olivine and other mafic minerals; commonly alters to serpentinite.

permeability. A measure of the relative ease with which fluids move through the pore spaces of rocks or sediments.

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

phyllite. A metamorphosed rock, intermediate in grade between slate and mica schist, with minute crystals of graphite, sericite, or chlorite that impart a silky sheen to the surfaces ("schistosity").

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

placer mining. The extraction and concentration of heavy metals or minerals from placer deposits by various methods, generally using running water.

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

pluton (plutonic). A body of intrusive igneous rock that crystallized at some depth beneath Earth's surface.

pyroxene. A common rock-forming mineral. It is characterized by short, stout crystals.

rodent. Any of the order Rodentia of relatively small, gnawing animals (as a mouse, squirrel, or beaver) that have in both jaws a single pair of incisors with a chisel-shaped edge.

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

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

scallop (speleology). One of a mosaic of small, shallow intersection hollows formed on the surface of soluble rock by turbulent dissolution. They are steeper on the upstream side, and smaller sizes are formed by faster-flowing water.

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

seafloor spreading. The process by which tectonic plates pull apart and new lithosphere is created at oceanic ridges.

seamount. An elevated portion of the sea floor, 1,000 m (3,300 ft) or higher, either flat-topped or peaked.

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

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

serpentinite. A rock consisting almost wholly of serpentine-group minerals such as antigorite and chrysotile. Commonly derived from the alteration of peridotite.

sequence. A major informal rock-stratigraphic unit that is traceable over large areas and defined by sediments associated with a major sea level transgression-regression.

sheeted dike. A swarm of parallel or subparallel igneous dikes so closely spaced that little or no intervening wall rock is preserved.

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

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

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

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

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

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

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

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

strike. The compass direction of the line of intersection of an inclined surface with a horizontal plane.

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

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

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

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

terrane. A large region or group of rocks with similar geology, age, or structural style.

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

terrigenous. Derived from the land or a continent.

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

till. Unstratified drift, deposited directly by a glacier without reworking by meltwater, and consisting of a mixture of clay, silt, sand, gravel, and boulders ranging widely in size and shape.

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

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

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

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

turbidite. A sediment or rock deposited from a turbidity current (underwater flow of sediment) and characterized by graded bedding, moderate sorting, and well-developed primary structures in the sequence noted in the Bouma cycle.

ultramafic. Describes rock composed chiefly of mafic (dark-colored, iron and magnesium rich) minerals.

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.

vitreous. Having the luster and appearance of glass.

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

volcanic arc. A commonly curved, linear, zone of volcanoes above a subduction zone.

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

volcanogenic. Describes material formed by volcanic processes.

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

xenolith. A rock particle, formed elsewhere, entrained in magma as an inclusion.

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

Resource Management/Legislation Documents

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

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

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

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

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

Geological Survey Websites

Oregon Department of Geology and Mineral Industries (DOGAMI): http://www.oregongeology.org/sub/default.htm

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

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

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

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

Other Geology/Resource Management Tools

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

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

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

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

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

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

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

Appendix: Scoping Meeting Participants

The following is a list of participants from the GRI scoping meeting for Oregon Caves National Monument, held on March 4, 2004. A follow-up conference call was held on March 3, 2011 as the Geologic Resources Inventory report writing was initiated (participants on next page). The contact information and email addresses in this appendix may be outdated; please contact the Geologic Resources Division for current information. The scoping meeting summary was used as the foundation for this GRI report. The original scoping summary document is available on the GRI publications website: http://www.nature.nps.gov/geology/inventory/gre_publications.cfm.

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Anne Poole	Geologic Resources Division	Geologist		
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A follow-up conference call, with the following participants, was held on March 3, 2011 as the Geologic Resources Inventory report writing was initiated.

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