National Park Service
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Natural Resource Stewardship and Science

Russell Cave National Monument

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2014/856

ON THE COVER
View from the dry shelter entrance at Russell Cave. Cave breakdown blocks in the foreground demonstrate the processes responsible for the formation of the shelter above the adjacent stream channel. The shelter contains an archeological record extending back more than 9,000 years. National Park Service photograph.

THIS PAGE
Blocks of fossiliferous Mississippian limestone form the edges of a flooded sinkhole. Blocks fall periodically into the sinkhole, widening it. Photograph by Trista L. Thornberry-Ehrlich (Colorado State University).

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Executive Summary

The Geologic Resources Inventory (GRI) is one of 12 inventories funded by the National Park Service (NPS) Inventory and Monitoring Program. The Geologic Resources Division of the NPS Natural Resource Stewardship and Science Directorate administers the GRI. This report synthesizes discussions from a scoping meeting for Russell Cave National Monument (Alabama) on 25–26 March 2009 and a follow-up conference call on 5 February 2014, which were held by the Geologic Resources Division to determine geologic resources, the status of geologic mapping, and geologic resource management issues and needs. It is a companion document to previously completed GRI digital geologic map data.

Established on 11 May 1961, Russell Cave National Monument is one of seven NPS units created primarily to protect caves. The monument covers 125 ha (300 ac) on the northeastern flank of Montague Mountain in northeastern Alabama. American Indians intermittently used the dry shelter of Russell Cave for at least 9,000 years, leaving behind one of the richest archeological records in the southeastern United States. They were sustained by the abundant natural resources of what is now termed Doran Cove. The geologic foundation of the area was an important component in the formation of Russell Cave and other resources needed to sustain human life over many millennia.

Russell Cave formed through the dissolution of limestone (geologic map unit Ml) beneath an erosion-resistant "cap" of sandstone (PNp). The bedrock within the monument comprises these two units, which formed from sediments deposited in a shallow equatorial sea more than 300 million years ago. Much more recent weathering and erosion (less than 2.6 million years old) produced slope wash, colluvium, and alluvial fan (Qco, Qs, and Qt) deposits in overlapping lobes near the bottom of Doran Cove. Dry Creek, the monument's ephemeral stream, reworks alluvium (Qal) deposits along its channel and adjacent floodplains. When flowing after rainfall, Dry Creek runs into the "wet entrance" of Russell Cave and flows underground to reemerge at Widows Spring, several kilometers southeast of the monument.

This GRI report was written for resource managers to support science-informed decision making, but it may also be useful for interpretation. The report was prepared using available geologic information, and the NPS Geologic Resources Division conducted no new fieldwork in association with it. Sections of the report discuss distinctive geologic features and processes within Russell Cave National Monument, highlight geologic issues facing resource managers, describe the geologic history leading to the present-day landscape, and provide information about the GRI geologic map data. A Geologic Map Graphic (in pocket) illustrates these data. The Map Unit Properties Table (in pocket) summarizes report content for each geologic map unit.

Noteworthy geologic features and processes at Russell Cave National Monument include the following:

- Russell Cave and Other Karst Features. Russell Cave is the primary natural and cultural resource at the monument. The geologic foundation of the monument area includes erosion-resistant cap rock and soluble carbonate rock. That setting, combined with abundant precipitation and deep geologic time, led to the formation of Russell Cave. A sinkhole collapse exposed the entrance to the cave. Ceiling breakdown and sedimentation formed a dry shelter "perched" above the channel of Dry Creek and to the side of the wet entrance. Other karst features at the monument include sinkholes and springs.
- Differential Weathering. Weathering of distinct types of rock occurs at different rates. In the monument area, ridges such as Montague Mountain are topped by resistant, Pennsylvanian sandstone and conglomerate that weather more slowly than the underlying soluble limestones. Where the resistant cap rock has eroded away, karst sinkhole plains form (e.g., the valley floor of Doran Cove). Differential weathering also provides source material for slope movements.
- Slope Processes and Deposits. Slope deposits such as colluvium and talus occur on the slopes of Montague Mountain. They record the wearing away of the highlands and downslope transportation of materials under the force of gravity.
- Sedimentary Rocks and Features. Crossbeds, ripples, organic material, and ooliths occur within the bedrock of the monument. These types of feature record the marine or nearshore terrestrial conditions under which the original sediments were deposited.
- Paleontological Resources. The carbonate shelf forming in a marine basin and adjacent nearshore environments were filled with life during the Mississippian and Pennsylvanian periods. This ancient life is now preserved as fossil resources in the monument. Fossils are visible on Russell Cave's walls and in loose blocks of rock on the slopes of Montague Mountain. More recent, Pleistocene-aged fossils are preserved in the cave sediments.

Geologic resource management issues identified during the GRI scoping meeting and follow-up conference call include the following:

- Erosion within the Dry Shelter. Erosion is occurring within the dry shelter of Russell Cave. It is concentrated along the northwestern wall, coincident with the location of early archeological excavations. LiDAR scans revealed more than 5 cm (2 in) subsidence of the cave floor over a 1.5-year period. Although the exact cause(s) of this erosion has not yet been definitively determined, a variety of potential sources has been identified. Erosion may be related to flooding in the adjacent Dry Creek channel as rising floodwater removes sediment from beneath the dry shelter. Ongoing monitoring, research, and surveys are being conducted in attempts to determine the exact nature of the sediment loss.
- Flooding. Dry Creek flows ephemerally after rainfall. Anthropogenic modifications to its channel within and beyond monument boundaries have increased flash-flood risk. Floodwaters transport foreign material such as garbage into Russell Cave. Flooding undercuts trails and slopes adjacent to the dry shelter near the mouth of Russell Cave. Floods may also be contributing to the erosion of cave sediments.
- Caves and Associated Karst Hazards. Hazards associated with the karst features at Russell Cave National Monument include sinkhole flooding, sinkhole collapse, rockfall, cave instability, and exposure to radon in caves. Sinkholes within the monument flood after significant rainfall. Slopes adjacent to the sinkholes are subsiding. A cover-collapse sinkhole first exposed the opening to Russell Cave, and collapse or subsidence has the potential to damage overlying infrastructure. Ceiling collapse, or breakdown, was integral in the formation of the perched dry shelter. Bolts were installed in the cave ceiling in an attempt to mitigate this hazard for visitors. Russell Cave has been closed to the public since the late 1990s, primarily because of safety concerns. Access was further restricted after the detection of white-nose syndrome in bats at the cave in 2012. This restricted access to the cave lessens concerns about radon exposure.
- Slope Movement Hazards and Risks. The shales that mark the regional contact between the Pennington Formation (upper part of Ml) and the Pottsville Formation (PNp) form a regional slip surface that has the potential to fail, causing a significant landslide concern. Slope deposits mantle the slopes of Montague Mountain and are visible along the monument's nature trail.
- Abandoned Mineral Lands. Two coal mine openings in the monument predate the monument's establishment and illustrate the historic importance of coal mining in the area. These features have been mitigated. The Pennsylvanian Pottsville Formation (PNp) is the source of coal.
- Paleontological Resource Inventory, Monitoring, and Protection. All paleontological resources are non-renewable and subject to science-informed inventory, monitoring, protection, and interpretation. Crinoid disks, brachiopods, and blastoids that occur on the roof of Russell Cave could provide interpretive opportunities.
- Earthquake Hazards and Risks. Earthquakes that are noticeable by humans are uncommon in Alabama. A concentration of earthquake epicenters is associated with the Eastern Tennessee Seismic Zone northeast of the monument. Earthquakes may damage infrastructure via shaking or trigger slope movements and cave breakdown.

Products and Acknowledgements

The NPS Geologic Resources Division partners with institutions such as Colorado State University, the US Geological Survey, state geological surveys, local museums, and universities to develop Geologic Resources Inventory products. This section describes those products and acknowledges contributors to this report.

GRI Products

The objective of the GRI is to provide geologic map data and pertinent geologic information to support resource management and science-informed decision making in more than 270 natural resource parks throughout the National Park System. To realize this objective, the GRI team undertakes three tasks for each natural resource park: (1) conduct a scoping meeting and provide a summary document, (2) provide digital geologic map data in a geographic information systems (GIS) format, and (3) provide a GRI report (this document). These products are designed and written for nongeoscientists.

Scoping meetings bring together park staff and geologic experts to review and assess available geologic maps, develop a geologic mapping plan, and discuss geologic features, processes, and resource management issues that should be addressed in the GRI report. Following the scoping meeting, the GRI map team converts the geologic maps identified in the mapping plan to digital geologic map data in accordance with the GRI data model. After the map is completed, the GRI report team uses these data, as well as the scoping summary and additional research, to prepare the GRI report.

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

Additional information regarding the GRI, including contact information, is available at: http://www.nature.nps.gov/geology/inventory/. The current status and projected completion dates of products are at: http://www.nature.nps.gov/geology/GRI_DB/Scoping/Quick_Status.aspx.

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Geologic Setting and Significance

This section describes the regional geologic setting of Russell Cave National Monument, as well as summarizes connections between geologic resources and other park resources and stories.

Russell Cave National Monument preserves an archeological record stretching from more than 9,000 years ago until about the year 1650, one of the most complete records of prehistoric cultures in the southeastern United States (Speece 1979). The monument encompasses 125 ha (300 ac) on the northeastern slopes of Montague Mountain in Doran Cove of Jackson County, northeastern Alabama, less than 2 km (1 mi) south of the Tennessee border (fig. 1). Russell Cave was named for Colonel Thomas Russell and his family, who were property owners when the area was first mapped. The National Geographic Society purchased the cave and surrounding land from Oscar Ridley in the 1950s before donating it to the National Park Service (NPS) in 1961, when President John F. Kennedy designated it as a national monument. The monument is listed on the National Register of Historic Places (National Park Service 1999).

The landscape within the monument rises about 300 m (1,000 ft) from relatively flat open areas on the limestone-floored base of Doran Cove to steep, boulder-strewn slopes of Montague Mountain. The present floor of the dry shelter of Russell Cave is at an elevation of 191 m (625 ft). Russell Point, just outside the monument's northwestern boundary, reaches an elevation of about 520 m (1,700 ft). Doran Cove is about 10 km (6 mi) long and typically less than 800 m (0.5 mi) wide.

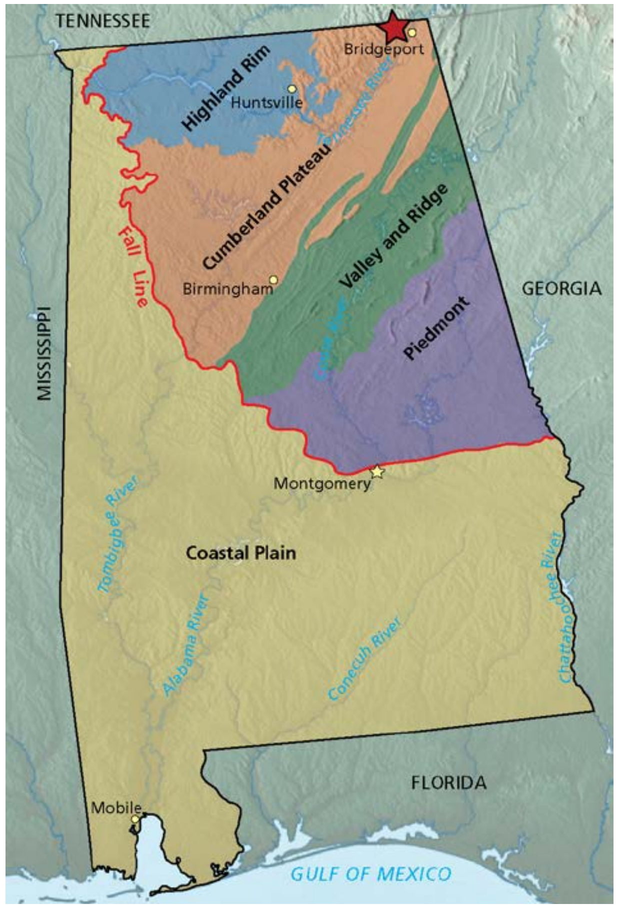

Figure 1. Physiographic provinces of Alabama. Russell Cave National Monument (red star) is located in northeast Alabama, within the Cumberland Plateau Province, which contains Paleozoic bedrock. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University), created using shaded-relief base map by Tom Patterson (National Park Service; available online at http://www.shadedrelief.com/physical/index.html [accessed 20 March 2014]) and information from University of Alabama Map Library (2013).

Geologic Setting

Alabama is divided into five primary physiographic regions (fig. 1) based on bedrock geology and surficial geomorphology: the Highland Rim, Cumberland Plateau, Valley and Ridge, and Piedmont, which are all underlain by Paleozoic bedrock; and the Coastal Plain, underlain by much younger, unconsolidated sediments such as clay, silt, sand, and gravel. The boundary separating the Coastal Plain from the other four regions is called the "fall line"—a low, east-facing escarpment that parallels the Atlantic coastline of the eastern United States and the Gulf coastline through Alabama.

Russell Cave National Monument is located on the Cumberland Plateau, which is composed of Paleozoic sandstones, shales, and limestones of modest relief. The monument is on the southeastern flank of the Nashville Dome, a Late Paleozoic uplifted region centered near Murfreesboro, Tennessee (Stearns and Reesman 1986), about 130 km (80 mi) northwest of Russell Cave. From central Tennessee to northern Alabama, the Nashville Dome tilts southward.

Russell Cave National Monument is just northwest of the Sequatchie Anticline, an arch-shaped bedrock fold. The Tennessee River follows the trace of the Sequatchie Anticline. During Appalachian Mountain building, this structure was the northwesternmost extent of rocks being shoved atop one another as North America and Africa collided. Farther inland, the rocks were only moderately deformed and the edge of the Cumberland Plateau is notched and scalloped by fingerlike spurs. One of these notches is Doran Cove (Griffin 1974a), where the bedrock is tilted only slightly from its original horizontal orientation.

Two major types of geologic unit occur at Russell Cave National Monument: Paleozoic-aged sedimentary bedrock that is hundreds of millions of years old, and Quaternary-aged surficial deposits with ages of a few million years or more (fig. 2) (Hack 1966). The bedrock formed during the Mississippian and Pennsylvanian periods (fig. 3), more than 300 million years ago, at the bottom and margins of an inland sea. The older, Mississippian bedrock is primarily fossiliferous (containing fossils) limestone and shale of the Monteagle Limestone, Bangor Limestone, and Pennington Formation, which are mapped together as “mostly shale and bioclastic and oolitic limestone” (geologic map unit Ml). Russell Cave formed in these limestones after millennia of dissolution by percolating groundwater. Younger rocks atop the limestones have less carbonate and are primarily shale and sandstone. The Pennsylvanian Pottsville Formation (PNp) caps Montague Mountain and contains no limestone at all. It is instead dominated by coarse-grained conglomerates and sandstones with layers of coal.

Karst underlies 63% of land within the monument boundary (Land et al. 2013). Karst is a landscape that forms through the dissolution of soluble rock, most commonly carbonates such as limestone or dolomite (Toomey 2009). Erosion and weathering of the sandstones and conglomerates atop the limestones created the characteristic landforms of northeastern Alabama and Doran Cove. The erosion-resistant Pottsville Formation (PNp) forms ridges, whereas soluble, less-resistant limestones (Ml) underlie the valleys. Karst features such as caves, swallets, sinkholes, windows, and springs are common in the monument area. Unconsolidated colluvium, slope wash, terrace deposits, and alluvial fans (Qco, Qs, and Qt) mantle portions of the mountain flanks and bases. Streams and rivers, such as Dry Creek flowing into the wet entrance of Russell Cave, rework these sediments and deposit them along their channels and floodplains as alluvium (Qal).

Geologic Significance and Connections

> “In their most basic conceptual form, caves are space. Their value to society stems from what occupies that space. Water, habitat, geological and cultural materials are a few of the many resources offered by caves and karst areas, which contain many of the world’s most important aquifers, rare ecosystems, and significant archeological and paleontological sites.”
>
> —Land et al. (2013, page 5)

The geologic foundation of Doran Cove is the setting in which Russell Cave formed. Millions of years of carbonate deposition in an equatorial inland sea created the thick carbonates of the Monteagle and Bangor limestones (parts of the unit mapped collectively as Ml). Deposition of mixed sandstone and conglomerate (coarse gravels) of the Pottsville Formation (PNp) atop the carbonates produced erosion-resistant cap rock. Groundwater infiltrating through fractures and fissures in the carbonates dissolved the rocks away, forming increasingly wider conduits and caverns beneath the cap rock.

Sometime between 9,000 and 11,000 years ago, a cavern roof collapsed beneath the northeastern flank of Montague Mountain, creating a sinkhole and “capturing” the flow of Dry Creek. The sinkhole exposed the opening to the 21-km- (13-mi-) long Russell Cave. Further ceiling collapse and sedimentation created the perched dry shelter 7 m (24 ft) above the Dry Creek channel and damp sinkhole base (Griffin 1974b; Hack 1974; Speece 1979).

American Indians began utilizing the east-facing cave during the Late Paleolithic age (approximately 10,000 to 8,500 years before present [BP]). Intermittent occupancies (most during winter) ensued during the Archaic, Woodland, and Mississippian archeological periods (Griffin 1974b). The dry shelter cave is 30 m (100 ft) wide, 8 m (25 ft) high, and 45 m (150 ft) deep and provided dry refuge, winter protection, and mineral resources such as chert nodules found in the limestone from which the cave was carved (Griffin 1974b). Dry Creek and local karst springs provided water, and the forested slopes provided food, tools, and fuel for these early inhabitants (Jones and Daniel 1961; Griffin 1974a, 1974b; Speece 1979; Thornberry-Ehrlich 2009; Kidd 2010). In addition to the cave, archeological sites at Russell Cave National Monument include a burial mound, open-air sites, other shelter sites, and quarry sites (Prentice 1994; National Park Service 1999).

The remains preserved in the archeological record of the natural sequence of cave sediments provide many details about these ancient humans’ existence and the world around them. The presence of many styles of spears and arrow points indicate that different American Indian groups used the cave as a permanent home, seasonally, or as a stopover location for more nomadic tribes (Accipiter Biological Consultants 2006; Soto 2013). A Dalton point found in the early 1970s at Russell Cave indicates that the cave was used during the transitional period between the Paleolithic and Early Archaic, approximately 8,000 BCE (Before Common Era; preferred to “BC”) (Griffin 1974b). The cave also contains evidence of prehistoric agriculture, such as 2,000-year-old carbonized fruits of domesticated *Chenopodium berlandieri* (lamb’s quarters), an herbaceous “pseudocereal” crop (Miller 1956; Smith 1984). These fruits were found in an ancient basket, and represent the earliest known evidence of deliberate storage (perhaps for subsequent spring planting) of *C. berlandieri* by prehistoric populations of the Eastern Woodlands (Smith 1984). Mussel shells from the Tennessee River are also found in nearly every layer of cave sediments, suggesting that they were a common and portable food source (Clench 1974).

Biological Connections

For thousands of years, Russell Cave has provided shelter not only to humans, but to a number of animal species. The cave environment continues to provide faunal habitat. Remains of animals, reptiles, and amphibians reveal past climatic conditions and American Indian hunting practices. Among thousands of vertebrate remains recovered, porcupine remains found in Russell Cave are of particular biogeographic interest, as this animal currently ranges no farther south than West Virginia. This ancient population was likely a carryover

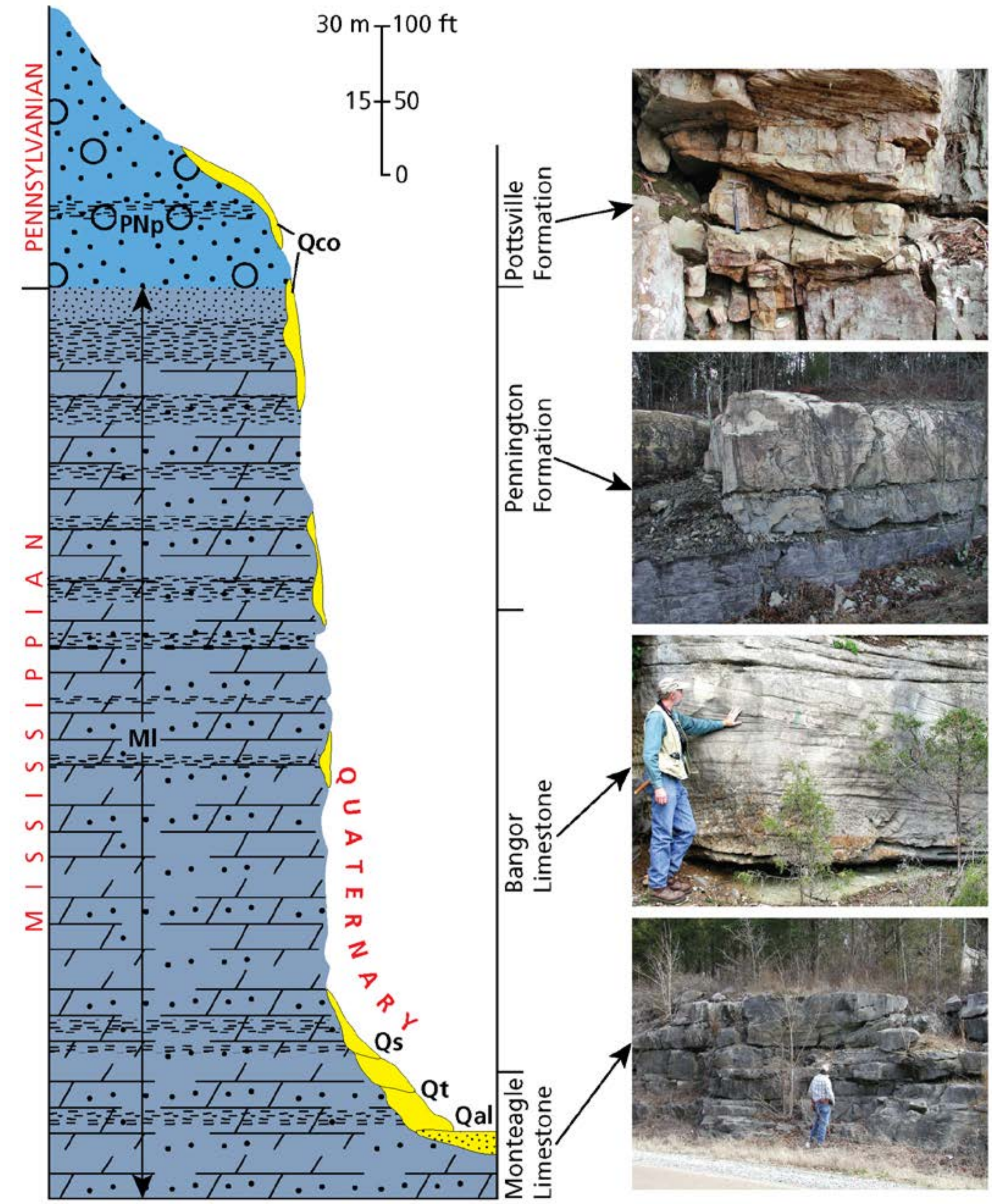

Figure 2. Stratigraphic column for Doran Cove area. Unit symbols are listed in the Map Unit Properties Table (in pocket). Colors are standard colors approved by the US Geological Survey to indicate different time periods on geologic maps, and correspond to the colors on the Map Unit Properties Table. Only units that appear within the boundaries of Russell Cave National Monument are included. See the Map Unit Properties Table for more detail. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University), created using information from Hack (1966) and Geological Survey of Alabama (2009). Photographs (showing locations outside the park) by Geological Survey of Alabama.

from the colder climates of the Pleistocene ice ages, when porcupines lived as far south as Florida (Weigel et al. 1974). As another remnant from an earlier time, molars from an extinct Pleistocene peccary (*Mylohyus* cf. *M. nasutus*; a pig-like mammal resembling a wild boar) are associated with human remains in the cave sediment layers from 5,000 to 7,000 BP. Remains of the well-known passenger pigeon are also within cave sediments at Russell Cave; these birds were killed during migration by netting and blows by stones or other weapons at roosting sites (Weigel et al. 1974). The species assemblage of amphibians and reptiles from the cave's archeological record is similar to that of today, indicating that no extreme climate change occurred during human occupancy of the cave (Weigel et al. 1974).

Hobbs (1994) completed a biological assessment, which revealed the presence in the cave of 12 species of troglobitic (living entirely in cave darkness) organisms, including cave fish and cave-specific (endemic) pseudoscorpions and millipedes (Rice et al. 2006; Thornberry-Ehrlich 2009; Soto 2013; Dale Pate, NPS Geologic Resources Division, National Cave and Karst Program Coordinator, written communication, 28 March 2014).

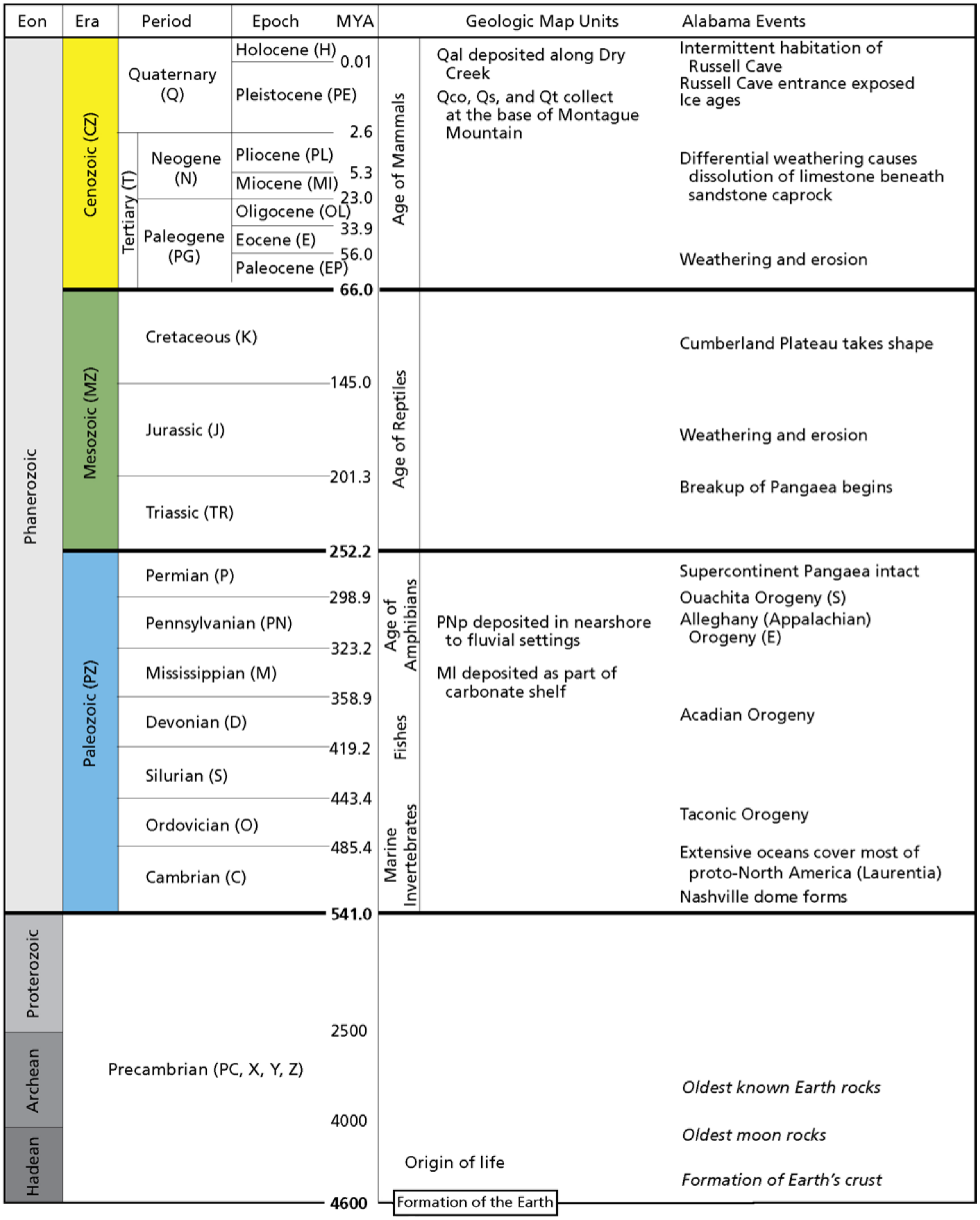

Figure 3. Geologic time scale. The divisions of the geologic time scale are organized stratigraphically, with the oldest divisions at the bottom and the youngest at the top. GRI map abbreviations for each time division are in parentheses. Geologic events relevant to Alabama are included as are the geologic map units for Russell Cave National Monument. Boundary ages are millions of years ago (MYA). National Park Service graphic created using dates from the International Commission on Stratigraphy (http://www.stratigraphy.org/index.php/ics-chart-timescale; accessed 21 August 2014).

Geologic Features and Processes

This section describes noteworthy geologic features and processes in Russell Cave National Monument.

During the 2009 scoping meeting (Thornberry-Ehrlich 2009) and 2014 conference call, participants (Appendix A) identified the following noteworthy geologic features and processes at Russell Cave National Monument:

- Russell Cave and Other Karst Features
- Differential Weathering
- Slope Processes and Deposits
- Sedimentary Rocks and Features
- Paleontological Resources

Russell Cave and Other Karst Features

Russell Cave is the namesake and primary natural and cultural resource of the monument. Caves are naturally occurring underground voids that are sufficiently large for human entry and sufficiently long to extend into darkness. Many types of cave exist, and they vary in size, origin, and appearance. They include solution caves (commonly associated with karst), volcanic or lava tubes, sea caves, talus caves (voids among collapsed boulders), regolith caves (formed by soil piping), and glacier (ice-walled) caves (Palmer 2007; Toomey 2009). A cave is just one of myriad karst features, including sinkholes, sinking streams, springs, and underground drainage. Karst is a landscape that forms through the dissolution of soluble rock (Toomey 2009). Meiman (2007) presented an inventory of karst features within and surrounding the monument.

Formation of Russell Cave

Cave and karst features require four geologic conditions to form:

- suitable, soluble rocks;
- flowing groundwater (as a solvent);
- hydrogeologic framework (hydraulic gradient); and
- time.

First among these conditions is the existence of a suitable body of rock, in this case Mississippian limestone (geologic map unit Ml), which occurs in gently inclined beds (Hack 1966). Limestone is ideal for the development of karst features because it is highly soluble in carbonic acid (White 1988).

The second condition required for extensive cave development is the presence of an abundant, suitable solvent—acidic groundwater. Dissolution occurs when acidic groundwater reacts with carbonate rocks along subterranean cracks and fractures (Toomey 2009). Most meteoric water is slightly acidic (relatively low pH) due to the reaction between atmospheric carbon dioxide (CO_2) and water (H_2O). The product of this reaction is carbonic acid (H_2CO_3). Groundwater may become even more acidic as it flows through decaying plant debris and soils. The increased saturation of water with carbon dioxide augments the ability of groundwater to dissolve limestone (White 1988). The acid reacts with calcium carbonate ($CaCO_3$) in the rocks to produce soluble calcium (Ca^{2+}) and bicarbonate (HCO^{3-}) ions. The result is the dissolution of limestone rocks, which are considered to be "in solution." Located in a temperate climate, northern Alabama receives an average of nearly 150 cm (60 in) precipitation per year—plenty of solvent for cave development (National Weather Service 2014). Anthropogenic sulfur and nitrogen compounds in the air contribute to the formation of acid rain, which may have a pH of 3.0 or lower. Simple studies have shown that acid rain has the potential to increase the rate of limestone dissolution by approximately 1,000 times (Volesky 2009).

The third basic element required for cave formation is the hydrogeologic framework, which provides a sufficient hydraulic gradient. When carbonic acid contacts limestone, the solution quickly reaches saturation, diminishing limestone dissolution. For this reason, a high hydraulic gradient inherent in steep slopes, such as those within Doran Cove of Montague Mountain, must be present to provide sufficient energy to rapidly move the solvent through the rock (Kuehn et al. 1994). The gentle regional dip of the limestone layers to the southeast, toward the base drainage of the Tennessee River (Guntersville Lake), influences groundwater circulation. Because cave passages tend to form parallel to the bedding, or sedimentary layers within the limestone, the bedding structures control the orientation of cave system formation (Hack 1974).

Time is the final major condition necessary for the formation of extensive cave-passage networks. Karst landscapes form through dissolution and erosion, which take geologic-scale periods of time (White 1988). Eventually, all of the rock will be dissolved away to become part of the base level of the sinkhole plain that forms the valley bottom of Doran Cove. At Russell Cave, groundwater first came into contact with the Bangor Limestone (part of Ml) millions of years ago. Over hundreds of thousands of years, dissolution occurred between the intergranular pores and along fractures in the Mississippian Monteagle and Bangor limestones (parts of Ml). Dissolution created increasingly larger voids, culminating in the formation of a large, tubular cavern—Russell Cave. Dissolution and cavern formation continue today.

The upper levels of Russell Cave, located on cliffs of Doran Cove, reflect formation in a vadose (above the water table) environment. These levels formed in association with subterranean stream invasion of the cap rock and have deep, canyon-like cross sections with vertical shafts and stair-stepping along sedimentary bedding (Crawford 1989). The lower, larger, more tubular reaches of Russell Cave formed in a phreatic (below the water table) environment. The main passage of Russell Cave formed in reaction to changes in regional base level (Tennessee River). Small streams (i.e., Dry Creek) do not account for the large, tubular passage dimensions; these passages formed when the cave was still below the water table (The Center for Cave and Karst Studies 2008).

Sometime between 9,000 and 11,000 years ago, after the tubular cavern formed, a portion of the flank of Montague Mountain collapsed, forming a sinkhole that opened Russell Cave to the surface (Hack 1974). The cave floor was at water level and prone to regular flooding. Continued deposition of flood and river sediments, as well as collapse of material from the roof of the cave, raised the floor on the northwestern side (facing the entrance) above the seasonal flood level of the stream flowing through the cave (Hack 1974). This "high and dry" rock shelter perched above the channel was thus more habitable than the actual cave floor.

Russell Cave System

Russell Cave is one of the longest caves in Alabama—it is approximately 21 km (13 mi) long. To date (summer 2014), it has not been comprehensively mapped or inventoried beyond the products of archeological excavations, many small mapping expeditions, and a cursory exploration by the National Speleological Society in 1958 (see http://www.caves.org/ for more information) (Torode 1990; Russell Cave National Monument staff, conference call, 5 February 2014). Flooded passages, narrow passages, and deep pits are among the challenges facing cave mappers at Russell Cave National Monument. Additionally, the closure of the cave in the late 1990s due to safety and liability concerns for recreational cavers by the landowner of a cave entrance on private land curtailed systematic mapping efforts (see "Caves and Associated Karst Hazards" section) (Mary Shew, Russell Cave National Monument, resource management specialist, written communication, 11 May 2014). Although Russell Cave has not yet been comprehensively mapped, Torode (1990) listed more than 11,000 m (37,000 ft) of formally surveyed territory; assessments and excavations have yielded information about the history of human use of the cave and biological resources associated with the cave environment.

The Russell Cave system contains more than 2,100 m (7,000 ft) of flooded stream passages, associated (not yet connected) caves, and at least 13 entrances—8 of which are known within monument boundaries (Torode 1990; Russell Cave National Monument staff, conference call, 5 February 2014). Ridley and Russell caves may be connected, but this has not yet been verified (Jones and Daniel 1960; Hunt-Foster et al. 2009). Montague Cave is beyond monument boundaries, but its upper levels may be connected to Russell Cave (Larry Beane, Russell Cave National Monument and Little River Canyon National Preserve, park ranger, written communication, 5 February 2014). During the summer, cave entrances at the bottom of Montague Mountain "blow air," indicating the existence of entrances on the slopes above. Caves "breathe" according to changes in barometric pressure and temperature on the land surface. Rising external barometric pressure forces air into a cave, and falling pressure reverses that flow (Limaris Soto, NPS Geologic Resources Division, karst scientist, written communication, 27 March 2014). Daily temperature changes can cause air to flow into and out of a cave. Several small pits 120 m (400 ft) above the valley floor may have connections to the Russell Cave system, including some prominent dome-shaped chambers in the upper levels of Russell Cave, but these connections remain undiscovered (Torode 1990). The vertical relief between the upper levels and base of the cave makes Russell Cave among the deepest caves in Alabama (The Center for Cave and Karst Studies 2008; Soto 2013). A list of the deepest known caves in the United States is available at http://www.caverbob.com/usadeep.htm (accessed 20 June 2014).

The main entrance to Russell Cave is divided into a "dry" and a "wet" entrance separated by a massive rock pillar. Collapse of rock units and accumulation of sediments formed the floor of the perched, dry shelter, which supported the cave's long history of intermittent human use. Named passages, levels, rooms, and features within Russell Cave include Flint Room, Picnic Pool, Mud Room, Wind Tunnel, Picnic Entrance, Buckeye Entrance, Gibraltar Room, High Pockets Pass, Waterfall Passage, Methane Alley, and Blacks Misery (Torode 1990; Meiman 2007; Russell Cave National Monument staff, conference call, 5 February 2014).

Cave Sediment Excavation

The rich archeological record of Russell Cave (entrained in geologic cave sediments) contributes to the cave's significance. Distinctive sediment layers correlate closely with changes in the archeological sequence (fig. 4). An understanding of the origins of cave sediments and geology of the site is thus essential in interpreting the cultural story at Russell Cave National Monument. The foundation of the dry shelter consists of a thick sequence of large limestone (Ml) blocks that fell from the ceilings and walls, called cave "breakdown." Fine-grained sediments fill most spaces among these blocks. Their composition of sand and silt, distinctly different from the adjacent limestone, indicates that they were deposited by Dry Creek floods (Hack 1974). Given the nature of its formation, the top of the breakdown layer is very irregular.

The layers of cave sediments atop the breakdown layer are identified from top to bottom as layers A through G (fig. 4) Cave sediment layers G and F overlie the irregular breakdown surface. Similar to the alluvium between breakdown blocks, these sediments were deposited by occasional flooding and contain crossbedding indicative of flowing water. Charcoal pellets (indicating fire),

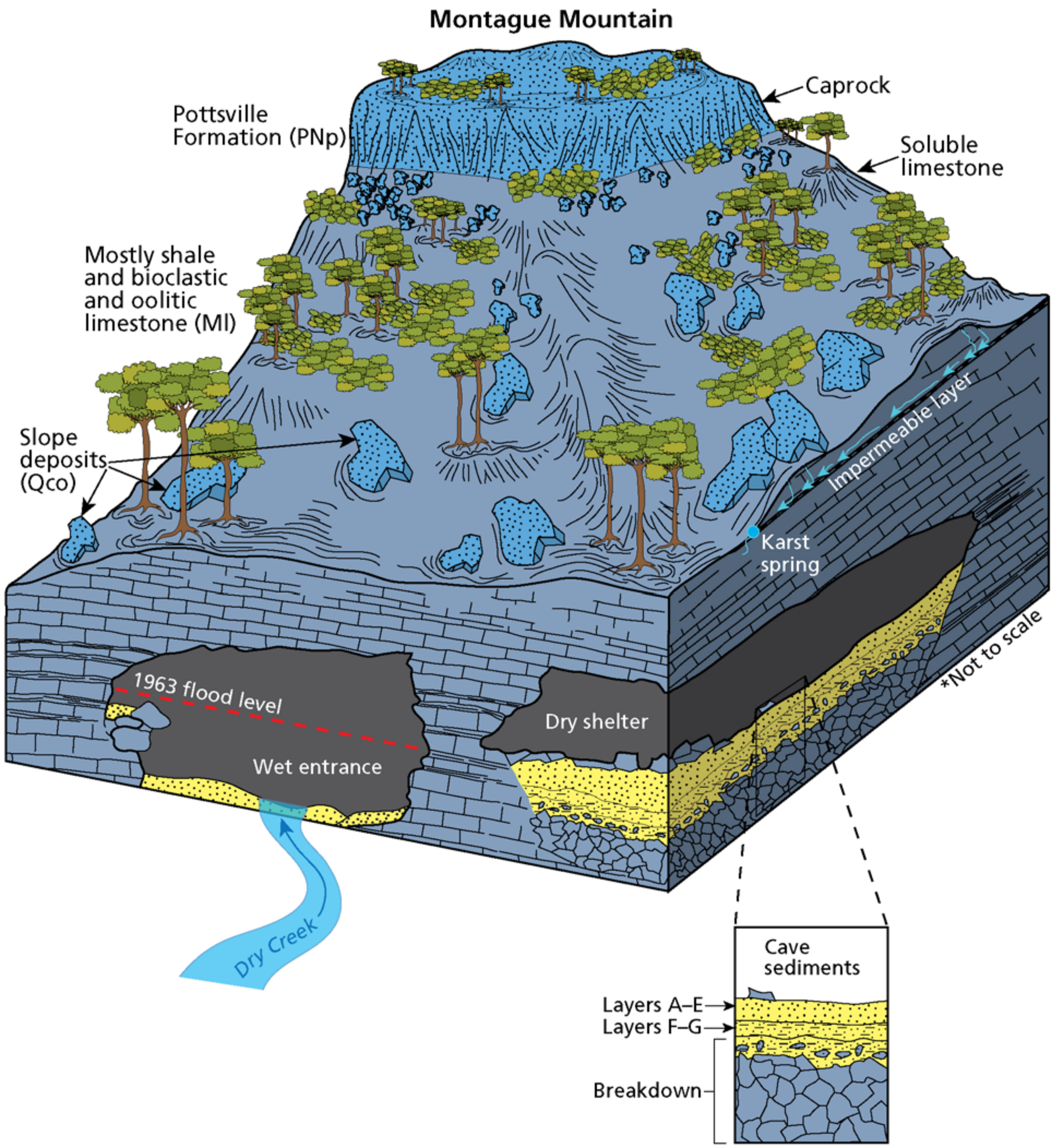

Figure 4. Cross-sectional view through the base of Montague Mountain. Schematic shows the dry shelter perched above the wet entrance to Russell Cave. Note the deposition of cave sediments atop blocks of ceiling breakdown in the dry shelter. Archeological resources are contained in layers A–G. Blocks of cap rock (Pottsville Formation [geologic map unit PNp]) mantle the slopes above the cave. Note the level of the 1963 flood event (dashed red line) and recent sediments associated with Dry Creek. High floods do not inundate the dry shelter, as it is about 7 m (23 ft) above the Dry Creek level. A karst spring emerges at the surface where an impermeable shale layer blocks the downward percolation of groundwater through dissolved conduits in the limestone (Ml). Graphic by Trista L. Thornberry-Ehrlich (Colorado State University), created using information from Hack (1974).

mussel shells from the Tennessee River, and human remains within these layers record intermittent human occupation, most likely during periods of low water (Clench 1974; Hack 1974; Snow and Reed 1974). The upper surface of layer F was levelled off by the inhabitants, and the sediments above show no further evidence of flooding (Hack 1974). Layer E is horizontally bedded and contains several fire pit layers, burned limestone, mussel shells, and bone fragments (Clench 1974; Hack 1974). It shows no sign of fluvial deposition. Compositionally, layer E is much more similar than layers F and G to the adjacent limestone, containing abundant oolite fragments weathered slowly from the cave rocks. Disconformably (non-continuously) deposited atop layer E, layer D contains abundant clay and other materials derived in part from outside the rock shelter. Inhabitants of the cave may have spread these materials about (Hack 1974). The uppermost layers are dominated by material derived from the cave walls, mixed with charcoal, shells, cultural detritus, and some quartz and mica (Griffin 1974a; Hack 1974).

Archeological excavations in Russell Cave commenced shortly after Paul H. Brown and Charles K. Peacock of the Tennessee Archeological Society discovered flint chips, projectile points, pottery fragments, animal bones, and freshwater shells just inside the cave in 1951. Several institutions, including the National Geographic Society, Tennessee Archaeological Society, and Smithsonian Institution, conducted excavations through the 1970s (Griffin 1974a; Torode 1990). Major publications describing their findings include Broyles (1958), Miller (1956, 1957), and Griffin (1974a). As of 2014, 13 m (49 ft) of cave sediments within the dry shelter had been excavated, but these cover only a portion of the total amount of cave sediments; deeper portions of the cave remain relatively undisturbed (Thornberry-Ehrlich 2009; Russell Cave National Monument staff, conference call, 5 February 2014). Carbon-14 dating of charcoal and human remains from layer G extends back to 8,500 ± 320 (approximately 9,500 calendar years) years BP (Snow and Reed 1974). Other notable excavated remains include a variety of spears and arrow points, tools, pottery pieces, and thousands of other artifacts in addition to human burials. These types of discovery yield a better understanding of early American Indian diet, lifestyle, and technology, and changes over time (Kidd 2010; Soto 2013; National Park Service 2014).

Sinkholes and Springs

Sinkholes and springs are two other common karst features at Russell Cave National Monument. A sinkhole is a closed depression, commonly round or ellipsoidal in map view, with a funnel-like cross section and subterranean drainage. Sinkholes typically form at least in part by collapse or slow subsidence of dissolved bedrock fragments into an existing underground conduit or void (figs. 5 and 6). In some cases, increased groundwater pumping or lowering of the water table causes a loss of the buoyant support of cavity walls, followed by subsidence or collapse into a sinkhole (Limaris Soto, NPS Geologic Resources Division, karst scientist, written communication, 27 March 2014). Collapse and subsidence associated with sinkhole development are perhaps most frequent during flooding events, but the process can be continuous (Stephen Greb, Kentucky Geological Survey, geologist, written communication, 2010).

Russell Cave National Monument contains the collapsed sinkhole that exposed the cave entrance, as well as a large steep-sided sinkhole near the visitor boardwalk. This sinkhole fills with water after prolonged or heavy rainfall events (fig. 7). Debris such as talus and colluvium falls or subsides into the sinkhole, and is then removed by subsequent floodwaters or dissolution over long periods of time.

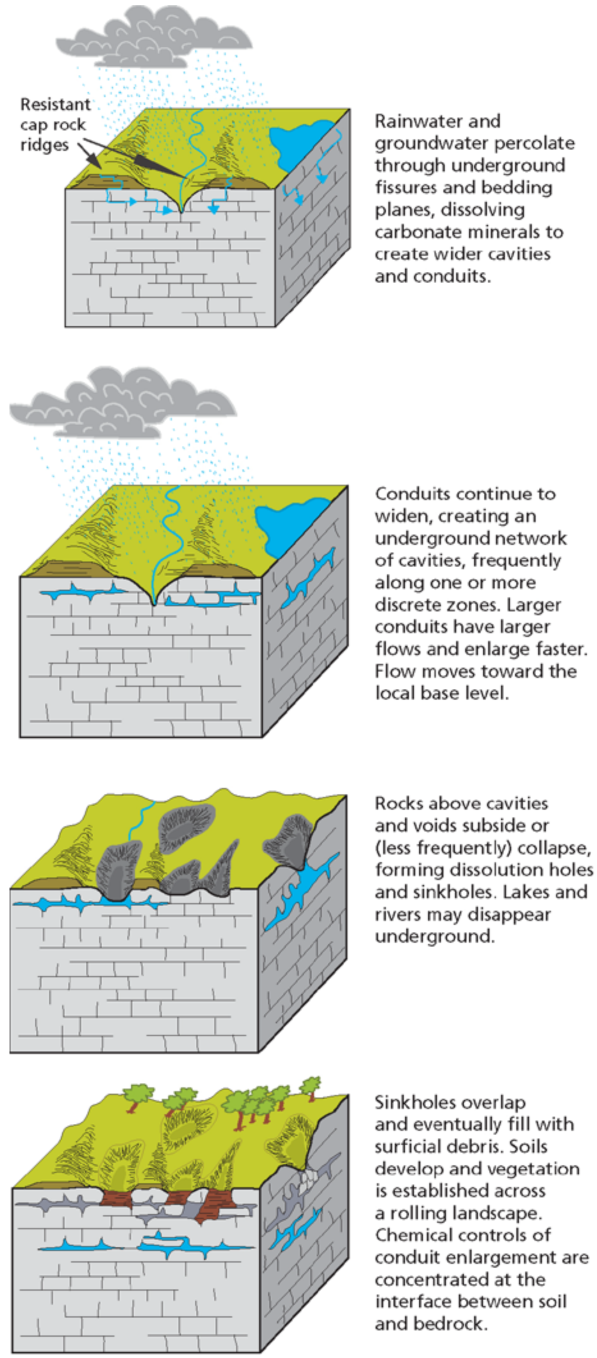

Figure 5. Schematic, three-dimensional illustration of sinkhole development. Resistant cap rock ridges include the heights of Montague Mountain above Russell Cave. Sinkholes are common throughout the area of Russell Cave National Monument, where karst landscapes dominate and continue to develop today in the Mississippian limestone (geologic map unit Ml). Graphic by Trista L. Thornberry-Ehrlich (Colorado State University), created using information from Hack (1974).

In karst landscapes, springs typically form where groundwater, percolating through conduits within a limestone layer, intersects a relatively insoluble (confining) rock layer, such as a siliceous sandstone or shale. The groundwater then flows along the confining layer until it intersects the ground surface, creating a spring. Within the limestones of the Monteagle Limestone, Bangor Limestone, and Pennington Formation (Ml) are several siliceous and shaly layers that

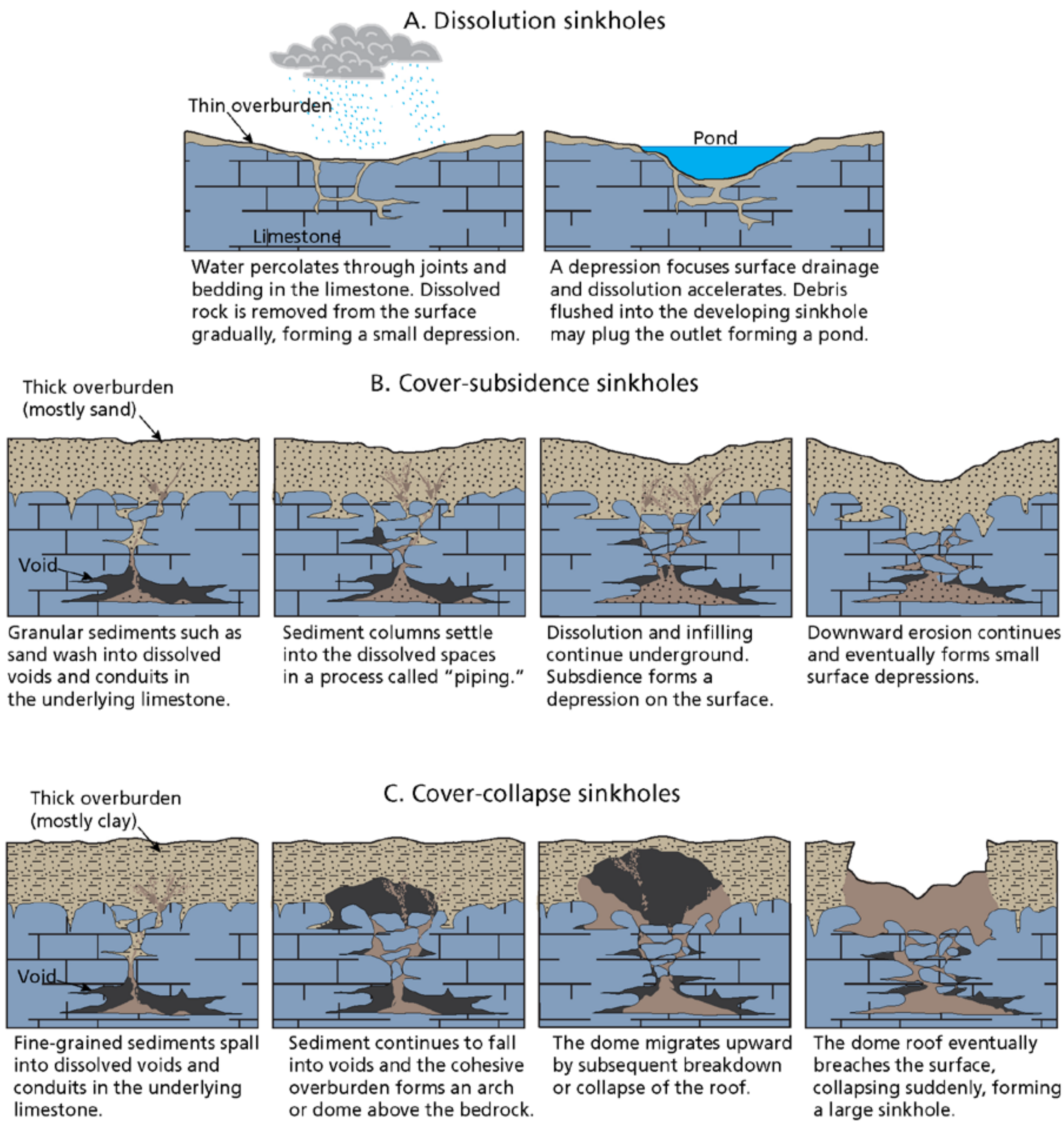

Figure 6. Sinkhole types. Dissolution, cover-subsidence, and cover-collapse sinkholes develop from dissolution and downward erosion of unconsolidated material into the underlying cavities. Sinkholes can be a combination of the three types or may form in several overlapping phases. The type of sinkhole that develops is controlled in part by the thickness and type of overburden and the local hydrology. The sinkhole that exposed the entrance to Russell Cave formed by collapse. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after figures by Tihansky (1999, p.126–127).

Figure 7. Flooded sinkhole. This sinkhole is near the boardwalk trail in Russell Cave National Monument. The depression fills with water flowing from springs during prolonged or heavy rainfall events. Photograph by Trista L. Thornberry-Ehrlich (Colorado State University), taken in March 2009.

act as confining layers and sources of springs upslope of Russell Cave. The sinkhole at the entrance to Russell Cave also has a perennial, spring-fed pool that flows into the chamber beside the dry shelter. Water flows from the sinkhole into Russell Cave even when ephemeral Dry Creek is waterless (Griffin 1974a; Hack 1974). This "Entrance Spring" is a major flow point for the groundwater system of Russell Cave National Monument (Meiman 2007; The Center for Cave and Karst Studies 2008). Widows Spring (2.4 km [1.5 mi]

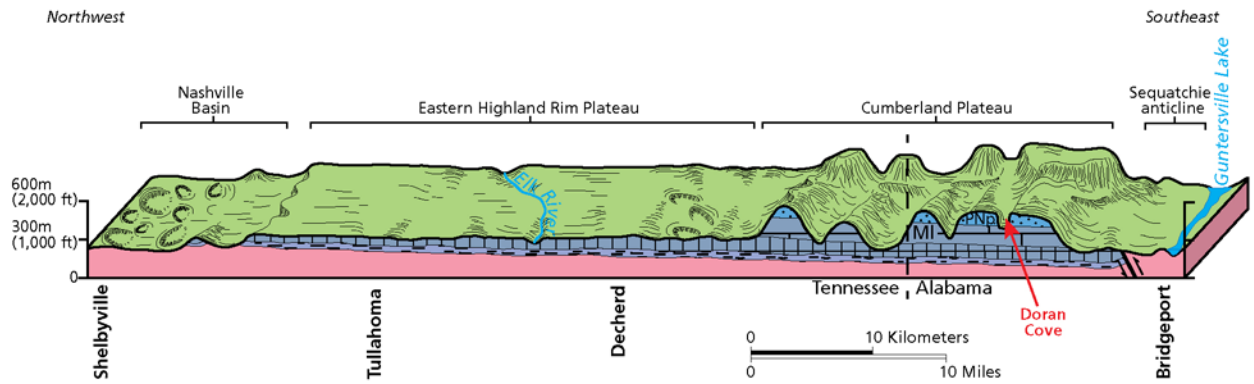

Figure 8. Three-dimensional, cross-sectional view through the Cumberland Plateau. Doran Cove (red text), part of the Cumberland Plateau, is underlain by Mississippian carbonates (geologic map unit Ml) and ridges supported by resistant Pennsylvanian sandstones and conglomerates (PNp). Colors are standard colors approved by the US Geological Survey to indicate different time periods on geologic maps, and correspond to the colors on the Map Unit Properties Table. Map unit symbols for units occurring within Russell Cave National Monument are included. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after figure 2 in Hack (1966).

southeast of the monument) is the ultimate outlet for groundwater flow in Russell Cave. Like other springs, Widows Spring emerges where flow intersects an impermeable chert or shale layer in the base of the Monteagle Limestone (part of Ml) (The Center for Cave and Karst Studies 2008).

Differential Weathering

Differential weathering or erosion is the process by which earth materials wear away or break down at different rates based on their composition, structural integrity, geographic location, exposure, and local climatic conditions. For example, a coarse-grained, well-cemented, quartz-rich sandstone is much more resistant to erosion than a weakly cemented shale or soluble limestone.

At Russell Cave National Monument, the results of differential weathering are on striking display as a succession of gently dipping sedimentary rocks beneath imposing escarpments. One of the most pronounced contrasts is that between Pennsylvanian sandstones of the Pottsville Formation (PNp) capping Montague Mountain (and the Cumberland Escarpment) and the Mississippian limestones (Ml) that underlie its lower slopes and the valley floor of Doran Cove (fig. 8) (Hack 1966). As weathering progresses, the escarpments and ridges retreat. Blocks of sandstone atop the escarpments and ridges collapse when the limestone beneath them erodes or dissolves away. Blocks of sandstone and other colluvium (Qco and Qs) collect on the slopes and may be further weathered and transported to form extensive alluvial fan deposits or terraces (Qt) in coves, such as Doran Cove. The grain size of alluvial deposits (Qal) decreases downstream because smaller grains are transported farther downstream than heavier, coarser grains.

Slope Processes and Deposits

Differential weathering created steep slopes and unconsolidated material, which favor slope movements, at Russell Cave National Monument. Slope movements are the downslope transfer of soil, regolith, and/or rock under the influence of gravity (fig. 8). Soil creep, rockfalls, debris flows, and avalanches are common types of slope movement (fig. 9). These processes and the resultant deposits are also known as “mass wasting” and commonly grouped as “landslides.” Slope movements occur on time scales ranging from seconds to years. They create geologic hazards and associated risk in many parks. Hazards and risks associated with slope movements in Russell Cave National Monument are described in the “Geologic Resource Management Issues” section.

Steep slopes, which are particularly susceptible to landslide events, characterize the flanks of Montague Mountain below the ridge of sandstones and conglomerates of the Pottsville Formation (PNp) in Russell Cave National Monument. The slopes above the cave are littered with large blocks of the Pottsville Formation (fig. 10), as parts of large aprons of talus, slope wash, alluvial fans, and colluvium (Qco, Qt, and Qs).

Sedimentary Rocks and Features

The three main types of sedimentary rock are clastic, chemical, and biogenic. Clastic sedimentary rocks are the products of weathering, erosion, transportation, and deposition of rock fragments called “clasts.” Higher-energy depositional environments, such as fast-moving streams, deposit larger (heavier) clasts while transporting smaller (lighter) clasts, which then settle out when the water flows slowly or stops flowing. Chemical sedimentary rocks form when materials in solution (charged ions) combine to form molecules of rock that precipitate out of water, slowly accumulating layers of sediment. For example, carbonate rocks, such as limestone (calcium) or dolomite (calcium and magnesium) have a carbonate (CO_3^{2-}) ion. Biogenic sedimentary rocks are composed of organic matter, such as coal (remains of plant life) or limestone (commonly shells of ancient animals).

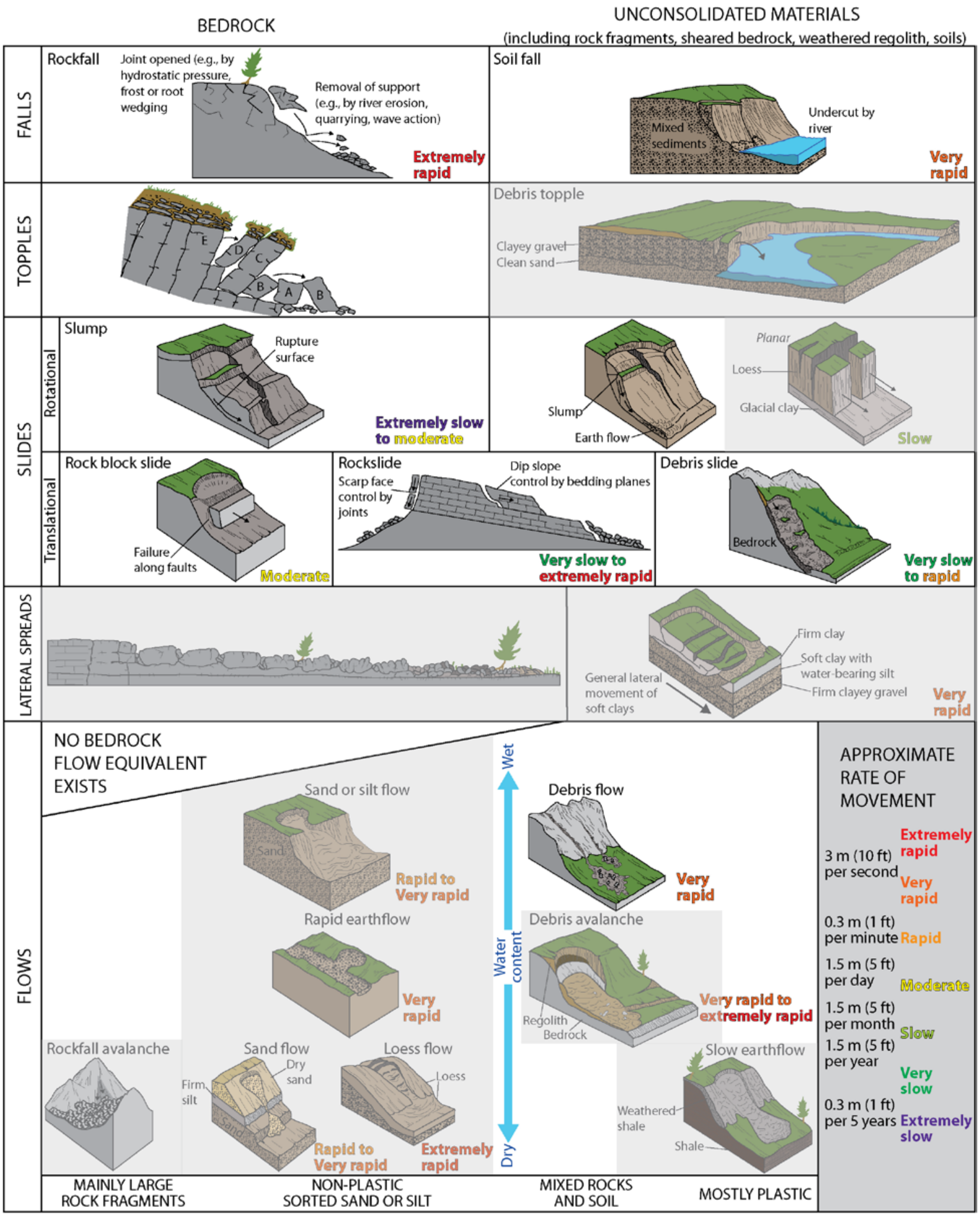

Figure 9. Schematic illustrations of slope movements. Different categories of slope movement are defined by material type, nature of the movement, rate of movement, and moisture content. Grayed areas indicate conditions that are not likely to exist at Russell Cave National Monument. Graphic by Trista Thornberry-Ehrlich (Colorado State University), redrafted after a graphic and information in Varnes (1978).

All three types of sedimentary rock have been mapped at Russell Cave National Monument. Geologic map unit Ml ("mostly shale and bioclastic and oolitic limestone") comprises, from oldest to youngest, the Monteagle Limestone, Hartselle Sandstone, Bangor Limestone, and Pennington Formation. Map unit Ml is primarily chemical and biogenic limestone, with some clastic shale layers. Separated by a sharp contact (fig. 11), the overlying Pottsville Formation (PNp) is primarily clastic

Figure 10. Large boulders and mixed colluvium on the slopes of Montague Mountain. These types of deposit occur along the nature trail above Russell Cave as blocks of bedrock are wedged free from the ridge above and tumble downslope under the force of gravity. Geologic map unit is "thin colluvium and slope wash on limestone and shale" (Qco). Photograph by Ronald C. Thornberry, Sr., taken in March 2009.

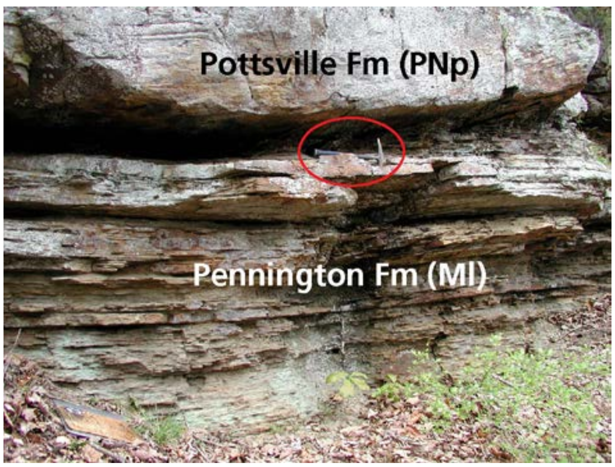

Figure 11. Contact between the Pennington and Pottsville formations. The contact, marked by the rock hammer (red circle), reflects a shift from nearshore marine conditions to alternating high-energy, nearshore areas such as beaches and low-energy, marsh-like environments. Grain size (not visible at this scale) is abruptly coarser and the bedding is more massive (less distinct layers) in the Pottsville Formation (geologic map unit PNp) than in the Pennington Formation (part of Ml). See the Map Unit Properties Table for more detail. Geological Survey of Alabama photograph.

shale, sandstone, and conglomerate, with some biogenic coal layers (Hack 1966, 1974).

Sedimentary features in rocks can preserve a record of the original depositional environment or processes. These features are described in detail in the Map Unit Properties Table (in pocket). Of particular interest within the monument are oolites, coal beds, and ripples, all features that suggest fluvial (river) and marsh settings (Hack 1966). Oolites are sedimentary rocks composed chiefly of ooliths—small, BB-sized grains. Ooliths form as successive, concentric layers of minerals (commonly carbonates) around a nucleus in shallow, wave-agitated water. The nucleus may be an organic fragment, but ooliths commonly form through inorganic precipitation. Coal beds form when deposits containing more than 50% carbonaceous (plant) material are buried, compacted, solidified, and/or heated. Peat bogs and swamps are modern analogs of environments that collected carbonaceous material to become coal. Coal deposits are characteristic of Pennsylvanian and Mississippian rocks around the world; in Europe, those time periods are referred to as the "Carboniferous." Ripples indicate deposition by flowing water. Their sizes and shapes record the rate, volume, and type of water flow. For example, water flow may have oscillated (waves on shoreline) or been unidirectional (stream channel).

Paleontological Resources

Paleontological resources (fossils) are any evidence of life preserved in a geologic context (Santucci et al. 2009). All fossils are non-renewable. Body fossils are any remains of an organism, such as bones, teeth, shells, or leaves. Trace fossils are evidence of biological activity; examples include burrows, tracks, and coprolites (fossil dung). Fossils in NPS areas occur in rocks and unconsolidated deposits, museum collections, and cultural contexts such as building stones and archeological resources. As of August 2014, 246 parks had documented paleontological resources in at least one of these contexts. Russell Cave National Monument may contain fossils from all three contexts. Fossil resources present opportunities for resource management, including field surveys, inventory and monitoring, education, and interpretation. Refer to the NPS Geologic Resources Division paleontology website for more information: http://www.nature.nps.gov/geology/paleontology/index.cfm.

According to Hunt-Foster et al. (2009), the Monteagle Limestone (part of Ml) contains documented fossil resources within the monument boundaries (fig. 12). Crinoid disks from *Agassizocrinus coniens*, as well as remains of brachiopods and blastoids, occur on the roof of Russell Cave (Jones and Daniel 1960; Santucci et al. 2001). Limestone blocks placed along the boardwalk to limit access to cave walls contain prominent fossils (Thornberry-Ehrlich 2009). Horn corals, gastropods (snails), brachiopods, bryozoans, echinoderms, crinoids (*Pterotocrinus triebrachiatus*), and plant fragments have been discovered in Mississippian-aged limestones (Ml) outside of the monument. The Pennsylvanian Pottsville Formation (PNp) also has the potential to contain fossil resources within the monument; in nearby Little River Canyon National Preserve, it contains plant remains including *Lepidodendron*, *Calamites*, and bark impressions, as well as crinoids (Buta et al. 2005; Hunt-Foster et al. 2009 after communication from Larry Beane, Russell Cave National Monument and Little River Canyon National Preserve, park ranger, March 2009). Coal from the Pottsville Formation was mined in two small-scale operations (see "Abandoned Mineral Lands" section).

Fossils and Remains in Russell Cave

Russell Cave National Monument is among at least 35 NPS units (as of 2014) that preserve fossils within cave resources. Fossils are preserved in the cave-forming Mississippian limestone bedrock (Ml), and have also

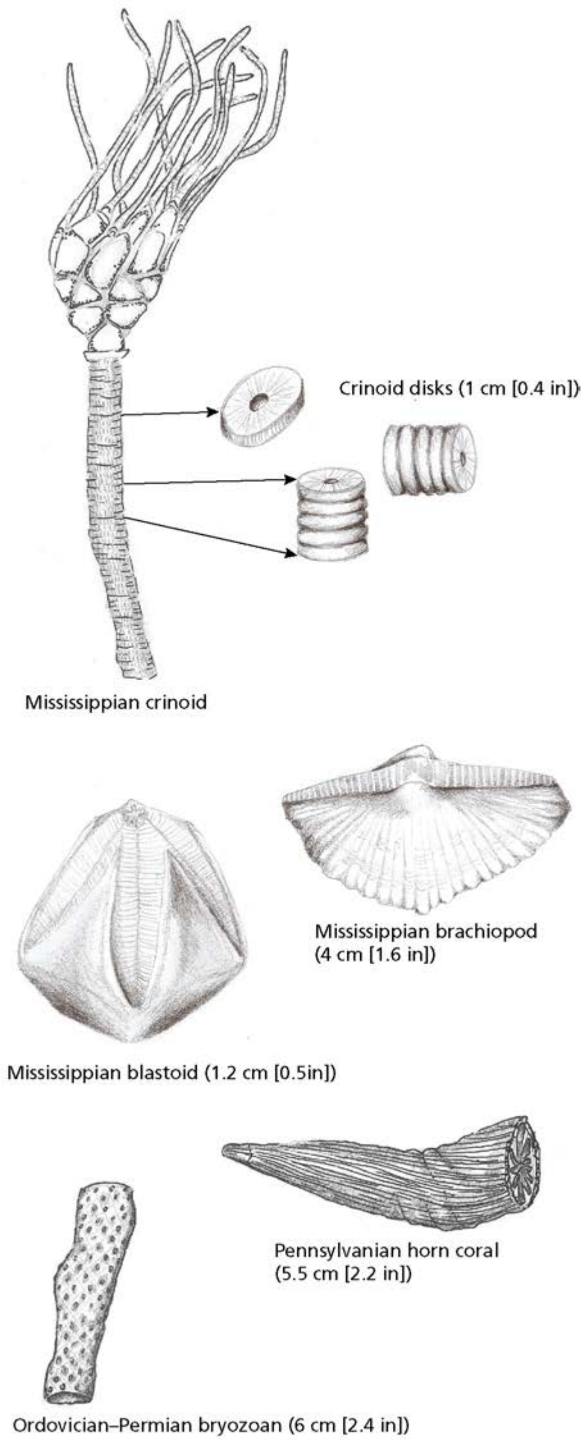

Figure 12. Fossil sketches. These representative fossils may occur within the mapped units (PNp and Ml) of Russell Cave National Monument, but are not necessarily from within the monument. Mississippian crinoid disks, brachiopods, and blastoids are the most common fossils visible in the walls of Russell Cave. Sketches by Trista L. Thornberry-Ehrlich (Colorado State University).

accumulated within the cavern. Caves and other karst features can attract and trap animals; other fossils may have been transported into the cave via flooding, habitation by organisms such as packrats (Santucci et al. 2001), or humans.

National Geographic Society excavations conducted in Russell Cave from 1956 to 1958 recovered teeth of a Pleistocene peccary (*Mylohyus* cf. *M. nasutus*; a pig-like mammal resembling a wild boar) (Weigel et al. 1974; Santucci et al. 2001; Thornberry-Ehrlich 2009), representing the first known occurrence of this species in Alabama (Santucci et al. 2001). Ridley and other unnamed caves within the monument have the potential to contain similar fossils. The Southeast Archeological Center in Tallahassee, Florida, curates a collection of 16 fossil specimens identified as collected from Russell Cave. Most of the specimens are crinoids, which would have been recovered from the limestone bedrock of the cave; two mammal specimens, one identified as "Carnivora," were also excavated (Hunt-Foster et al. 2009).

Fossil specimens have also played a role in the archeological story at Russell Cave. Limestone blocks associated with the Cotton Patch Mound in the monument have the potential to contain fossils (Hunt-Foster et al. 2009). Animal and plant remains uncovered in cave sediments during archeological excavations include carbonized fruits and seeds, and more than 60 species of vertebrates: mammals (e.g., deer, raccoons, bears, and squirrels), birds (commonly turkeys), reptiles (snakes and turtles), fish, and mollusks. These findings provide information about the local diets of American Indian inhabitants (Weigel et al. 1974; Speece 1979; Smith 1984; Kidd 2010). Excavations have also recovered crinoid rings used as beads (Mary Shew, Russell Cave National Monument, resource management specialist, written communication, 13 May 2014). Kenworthy and Santucci (2006) presented a summary of NPS fossils in cultural resource contexts, with recommendations for interpretation and management.

Geologic Resource Management Issues

This section describes geologic features, processes, or human activities that may require management for visitor safety, protection of infrastructure, and preservation of natural and cultural resources in Russell Cave National Monument. The NPS Geologic Resources Division provides technical and policy assistance for these issues.

During the 2009 scoping meeting (Thornberry-Ehrlich 2009) and 2014 conference call, participants (Appendix A) identified the following geologic resource management issues at Russell Cave National Monument:

- Erosion within the Dry Shelter
- Flooding
- Caves and Associated Karst Hazards
- Slope Movement Hazards and Risks
- Abandoned Mineral Lands
- Paleontological Resource Inventory, Monitoring, and Protection
- Earthquake Hazards and Risks

Resource managers may find *Geological Monitoring* (Young and Norby 2009; http://go.nps.gov/geomonitoring) useful for addressing these geologic resource management issues. The manual provides guidance for monitoring vital signs—measurable parameters of the overall condition of natural resources. Each chapter covers a different geologic resource and includes detailed recommendations for resource managers and suggested methods of monitoring.

Erosion within the Dry Shelter

In addition to erosion associated with flooding along Dry Creek (see “Flooding” section), erosion is removing cave sediment from the dry shelter of Russell Cave (fig. 13). Erosion within the dry shelter is a significant concern due to the potential loss of cultural resources, particularly those that have not been excavated or studied. Since 2009, visible cracks have extended under the boardwalk. In addition, subsidence and slumping have occurred along the wall in the northwestern corner of the cave, where some of the initial National Geographic Society excavations were conducted. As of 2011, approximately 2 m^3 (70 ft^3) of material had eroded away (Joe Meiman, Cumberland Piedmont Network, hydrologist, written communication, 10 March 2011). LiDAR data show that the elevation of the dry shelter floor dropped at least 5 cm (2 in) in a 1.5-year period; rates of change appear to be increasing with time (Joe Meiman, written communication, 10 March 2011; Russell Cave National Monument staff, conference call, 5 February 2014).

Figure 13. Erosion features along the northwestern wall of Russell Cave. Exposure of previously buried conduit is an indicator of the extent of erosion. Erosion area coincides with the location of early archeological excavations. Rock weirs attempt to slow erosion. Scalloped layers on the adjacent walls correlate with sedimentary bedding, with solubility differing among layers. National Park Service photographs courtesy of Mary Shew (Russell Cave National Monument and Little River Canyon National Preserve).

The erosion occurring in the dry shelter of Russell Cave is visible and obvious—flowing water is removing material. The processes driving this erosion are unclear. Water consistently drips into the shelter, forming drip pools, but these have only anecdotally been correlated with the area of erosion. North–south-trending joints in the cave's ceiling exhibit signs of recent dripping in the area of erosion. Rills and gullies on the shelter floor between the boardwalk and cave wall indicate the presence of channelized flowing water (fig. 13) (John Carmichael, US Geological Survey, groundwater specialist, written communication, 28 October 2011). Passive ("natural") subsidence of the ground surface into inadequately compacted backfill from early archeological excavations is possible. Although why this process would take nearly 50 years to manifest is unclear, photographs of the excavations show that the deepest parts of trenches coincide almost exactly with the erosion area (Joe Meiman, written communication, 10 March 2011; John Carmichael, written communication, 28 October 2011). Residual effects of the 1950s excavations and their disturbances to the shelter floor may be responsible for much of the local soil instability and subsidence (John Carmichael, written communication, 28 October 2011).

High flows in Dry Creek may be affecting the breakdown sediments buried beneath the dry shelter, thereby contributing to erosion. Geologists noted that the area of subsidence and erosion coincides with the elevation of a prominent bedding plane in the limestone of the cave walls. The bedding plane may facilitate hydraulic connectivity (water flow) between Dry Creek and materials beneath the dry shelter (John Carmichael, written communication, 28 October 2011). Groundwater flow beneath the dry shelter may thus be removing material, causing subsidence and collapse of the overlying material. This process is common in karst settings, where sinkhole subsidence or collapse also occurs (see "Caves and Associated Karst Hazards" section). The adjacent Dry Creek rises into overlying or adjacent sediments during floods and, upon the water's return to non-flood levels, transports the sediment away. As this cycle is repeated during subsequent floods, a void develops, eroding upwards into the overlying sediment until slumping and subsidence are expressed on the surface (Joe Meiman, written communication, 10 March 2011; John Carmichael, written communication, 28 October 2011). Geologists have witnessed this process during an incursion of floodwater and the removal of fine sediments from among breakdown boulders 40 to 50 m (130 to 160 ft) farther into the cave (fig. 14) (Joe Meiman, written communication, 10 March 2011). The existence of a void beneath the slumping sediments in the dry shelter remains to be determined.

Several factors are likely working in concert to concentrate erosion in the dry shelter at Russell Cave. Currently, research is underway to test some of the ideas about what is driving this erosion. The monument's resource management staff is photo-monitoring the area and have placed a stream gauge just inside the wet entrance to document visible changes that may correlate with changes in water flow (Mary Shew, Russell Cave National Monument and Little River Canyon National Preserve, resource management specialist, written communication, 6 February 2014). The installation of a shallow well near the erosion area to monitor

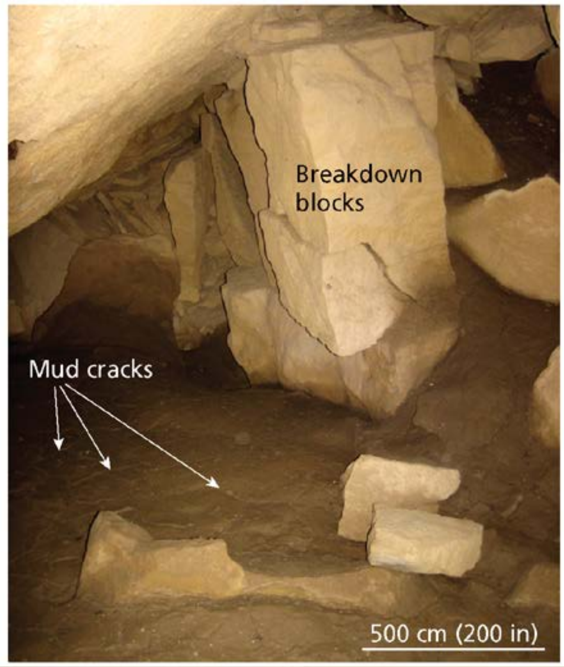

Figure 14. Erosion of cave sediments. Mud cracks are present in cave sediments (upper image) among breakdown blocks 7 m (20 ft) above the stream level, indicating recent wet conditions followed by a period of drying. Following a 7-cm (3-in) precipitation event in March 2011, muddy floodwaters rose about 7 m (23 ft) overnight and inundated the adjacent jumble of breakdown blocks (bottom image), flooding the area depicted in the upper image. National Park Service photographs and information courtesy of Joe Meiman (Cumberland Piedmont Network).

groundwater level beneath the shelter may help determine the nature of the hydraulic connection with Dry Creek and magnitude of water level changes (John Carmichael, written communication, 28 October 2011). Measurement and monitoring of the amount of drainage from the cave roof may help determine how "drip water" may impact the erosion; this water may be re-routed away from the eroding area as part of a remediation plan (John Carmichael, written communication, 28 October 2011). The US Geological Survey also proposed dye tracing or other chemical tracing methods to determine where the eroding material is exiting the cave system (Russell Cave National Monument staff, conference call, 5 February 2014). Geophysical investigation via electrical resistivity or ground-penetrating radar (GPR) might reveal sedimentary structures or voids below the surface.

GPR transects conducted by researchers from Mississippi State University in 2010 to identify a void were inconclusive, possibly due to the high clay content of the cave sediments (Russell Cave National Monument staff, conference call, 5 February 2014).

Flooding

In the Doran Cove area, surface water collects in the uplands and flows across the resistant cap rock of the Pottsville Formation (geologic map unit PNp) until it encounters the dissolved conduits of the underlying limestone (Ml), wherein it flows underground to emerge at springs or base-level streams (The Center for Cave and Karst Studies 2008). Russell Cave acts as a natural conduit, draining along the western edge of Doran Cove within Montague Mountain (Torode 1990).

The fluvial system in Russell Cave National Monument comprises the ephemeral flow of Dry Creek and several perennial springs and seeps. During heavy or prolonged precipitation events, surficial runoff from an area of more than 36 km^2 (14 mi^2) flows into the system (Torode 1990). Dry Creek, supplemented by a perennial spring near the entrance to Russell Cave, floods into the cave's wet entrance (fig. 15) and resurges at Widows Spring, 2.4 km (1.5 mi) southeast of Russell Cave (Torode 1990). Dry Creek floods almost annually (Thornberry-Ehrlich 2009). Significant floods occurred in 2013, 1986 to 1987, 1963, 1945, and 1900 (Hack 1974; Russell Cave National Monument staff, conference call, 5 February 2014; Larry Beane, Russell Cave National Monument and Little River Canyon National Preserve, park ranger, written communication, 5 February 2014). The NPS modified the Dry Creek channel in the 1960s and 1970s, and again in 1990 to 1993, in response to flooding and erosion. The US Army Corps of Engineers straightened upstream portions of the creek (Larry Beane, written communication, 5 February 2014). Modifications of the Dry Creek course (its "fluvial geomorphology"), including artificial straightening and removal of cobble bars (part of Qal), have diminished the capacity of an otherwise naturally meandering system to reduce flow energy via friction along its banks and channel bottom, increasing the potential for flash floods (fig. 15) (Thornberry-Ehrlich 2009). When a flood exceeds the cave's discharge capacity, the water flows downvalley to Montague and beyond, frequently along an overflow channel (visible on topographic maps) 200 m (700 ft) upstream from Russell Cave (Hack 1974; Mary Shew, Russell Cave National Monument, resource management specialist, written communication, 11 May 2014).

The impacts of Dry Creek flooding include the introduction of garbage and agricultural runoff to the cave system and undercutting or erosion of the riverbanks (Thornberry-Ehrlich 2009). The sharp bend in Dry Creek just before it enters the cave forms a natural eddy that collects trash and debris near the wet cave entrance. Community trash disposal was regulated and dumping was reduced by 2009; however, since that time, garbage service has been terminated in the community north of the cave (Thornberry-Ehrlich 2009; Russell Cave National Monument staff, conference call, 5 February 2014). The presence and accumulation of garbage and organic debris remains common throughout the area downstream of Russell Cave (Thornberry-Ehrlich 2009; Russell Cave National Monument staff, conference call, 5 February 2014). As described in the "Caves and Associated Karst Hazards" section, closure of the cave in the late 1990s also put an end to annual garbage cleanups (Russell Cave National Monument staff, conference call, 5 February 2014).

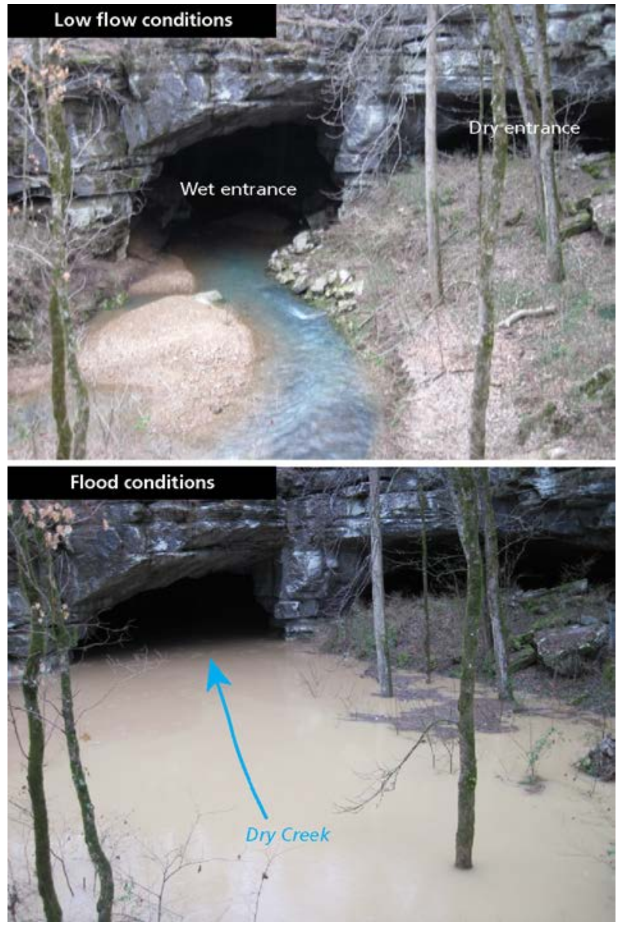

Figure 15. Low flow and flood conditions of Dry Creek. These two images were taken 20 hours apart on 8 and 9 March 2011 following a 7-cm (3-in) precipitation event. Note the trees in the foreground. Muddy or turbid floodwaters rose about 7 m (23 ft) overnight. Such flood events introduce foreign material into Russell Cave and erode the edges of the perched dry shelter. National Park Service photographs and information courtesy of Joe Meiman (Cumberland Piedmont Network).

Baseline water quality studies conducted in 1999 and 2013 by the Cumberland Piedmont Network and the study by Meiman (2007) revealed that the overall water quality was good, with low pH values and high bacteria levels occurring only during large flow events. Local bacteria sources include agricultural animal waste and private septic systems (Meiman 2007; National Park Service 2013). Because of the characteristically high infiltration rates and permeability of karst landscapes, little to no adsorption of surficial contaminants occurs. These contaminants flow quickly through the karst conduit system and into Dry Creek (Thornberry-Ehrlich 2009). Dye tracing studies conducted to determine the groundwater watershed of the "Entrance Spring" indicated that water from at least 5 ha [12 ac] of Doran Cove is hydrologically connected to the flow within Russell Cave (The Center for Cave and Karst Studies 2008). In this way, contaminants introduced some distance from the monument may be transported into the cave system. The Cumberland Piedmont Network Water Quality Monitoring Program has ranked water resources at Russell Cave National Monument in the category of greatest concern (The Center for Cave and Karst Studies 2008). A full discussion of water quality and hydrology is beyond the scope of this report; information and guidance related to these issues is available from the NPS Water Resources Division: http://www.nature.nps.gov/water/.

Flooding erodes and undercuts the banks of Dry Creek before it enters Russell Cave. Where the undercutting is sufficiently severe, the stream bank collapses, trees fall into the stream area, and the riparian area along the channel is damaged. In the 1990s, an observation platform in the monument collapsed because of undercutting along Dry Creek and the presence of karst crevices beneath the platform footings (Thornberry-Ehrlich 2009). Storms in the winter of 1986 to 1987 caused flooding that severely eroded the toe of the slope in front of the cave. About 240 m^3 (8,500 ft^3) sediment near the dry shelter entrance washed into Dry Creek (Larry Beane, written communication, 5 February 2014). With assistance from the Tennessee Valley Authority, monument staff attempted to stabilize the slope using GEOWEB® (http://www.prestogeo.com/geoweb_cellular_confinement). However, a 2013 flood re-exposed the GEOWEB® material (Russell Cave National Monument staff, conference call, 5 February 2014). Similarly, floods potentially contribute to erosion in the dry shelter (see "Erosion within the Dry Shelter" section) (Hack 1974a; Joe Meiman, Cumberland Piedmont Network, hydrologist, written communication, 10 March 2011).

Stream channel surveys are not frequently conducted at Russell Cave National Monument. A stream gauge has been installed just inside Russell Cave's wet entrance (Mary Shew, written communication, 6 February 2014). The GRI GIS data include two stream channel measurements (numbers 73 and 74) taken from the original mapping by Hack (1966). These measurements include drainage area (in square miles), length, slope (in feet per mile), width, depth, and bed material. These values have undoubtedly changed since 1966, particularly in light of the stream channel modifications; however, the data may provide a baseline against which to compare current conditions. In the *Geological Monitoring* chapter about fluvial geomorphology, Lord et al. (2009) described methods for inventorying and monitoring geomorphology-related vital signs, including: (1) watershed landscape (vegetation, land use, surficial geology, slopes, and hydrology), (2) hydrology (frequency, magnitude, and duration of stream flow rates), (3) sediment transport (rates, modes, sources, and types of sediment), (4) channel cross section, (5) channel planform, and (6) channel longitudinal profile. A Geoscientists-in-the-Parks internship (see http://www.nature.nps.gov/geology/gip/) may provide the research needed to monitor the Dry Creek channel. Submitting a Technical Assistance Request to the NPS Geologic Resources Division is another potential source of assistance.

Caves and Associated Karst Hazards

Cave features are non-renewable resources. Cave or karst resources are known in at least 140 parks as of August 2014. The 1988 Federal Cave Resources Protection Act (FCRPA) regulations state at 43 CFR § 37.11(d) that the policy of the NPS, pursuant to its Organic Act of 1916 (16 U.S.C. 1, et seq.) and Management Policies (Chapter 4:20, December 1988), is that all caves are afforded protection and will be managed in compliance with approved resource management plans. All caves on NPS lands are considered "significant." The FCRPA requires the regulation or restriction of use as needed to protect cave resources and inclusion of significant caves in land management planning. The act also imposes penalties for harming a cave or cave resources and exempts park managers from releasing specific location information for significant caves in response to a Freedom of Information Act request (see also Appendix B). A monument-specific cave management plan has not yet been updated for Russell Cave National Monument. Such plans include comprehensive evaluation of current and potential visitor use and activities, as well as plans to study known and discover new caves. Land et al. (2013), as part of a National Cave and Karst Research Institute (http://www.nckri.org/) effort, compiled survey results from NPS cave and karst units to help identify and prioritize research, remediation, interpretation, and other activities to best understand and manage cave and karst resources. The NPS Geologic Resources Division can facilitate the development of a current cave management plan. For more information, visit the NPS Geologic Resources Division Cave and Karst Resources website: http://www.nature.nps.gov/geology/caves/index.cfm. The cave was closed to visitors in the late 1990s, and access was completely restricted in 2012 due to the discovery of white-nose syndrome (see "White Nose Syndrome" section) (National Park Service 2012; Russell Cave National Monument staff, conference call, 5 February 2014).

Karst Hazards

Several hazards are unique to cave and karst environments and relevant to Russell Cave National Monument, including underground and sinkhole flooding, sinkhole collapse, rockfall and cave instability ("breakdown"), and circulation and concentration of radon (Thornberry-Ehrlich 2006).

Sinkhole flooding is a natural hydrologic process that occurs during intense rainfall events when the quantity of storm water flowing into the sinkhole exceeds its capacity to drain into underlying conduits. As described in the "Flooding" section, Dry Creek floods impact the cave environment and may be contributing to erosion of cave sediment in the dry shelter. Garbage and debris lodged in the ceiling of Russell Cave downstream of the dry shelter record extreme "flash flood" events, which flow through the cave on average once per year (Thornberry-Ehrlich 2009). The large sinkhole adjacent to the nature trail floods regularly after prolonged or heavy rainfall (fig. 7). The rapid flow of water into and out of the sinkhole may change its morphology, potentially widening and/or deepening it; it eventually may undermine the nature trail foundation.

Most sinkholes form slowly through solution and subsidence and thus can be identified and avoided. However, sinkholes sometimes collapse suddenly. For example, sinkhole collapse created the opening to Russell Cave about 9,000 years ago. Sudden sinkhole collapse could damage roads and other infrastructure within the monument with little to no warning. The depth of such a collapse is limited to the depth of the conduit below; however, the collapsed area may spread laterally over a significant distance. Areas most susceptible to collapse are shallow conduits at or just beneath the water table (Palmer 1990).

The term "cave breakdown" refers to the collapse of a cave ceiling or wall, or to the debris accumulated through such collapse. The entrance to Russell Cave continues to change over time. Following its exposure, further collapse and sedimentation formed the perched dry shelter (fig. 16). Processes such as cold weather (frost weathering), changes in airflow patterns, earthquakes, groundwater fluctuations, mineral growth, and anthropogenic activities contribute to breakdowns at scales ranging from small rocks to large boulders or slabs. In addition to earthquakes, mining, blasting, quarrying, or drilling may trigger cave breakdown. Blasting in the 1970s at a strip mine atop Montague Mountain reduced the "Entrance Spring" flow (Larry Beane, Russell Cave National Monument and Little River Canyon National Preserve, park ranger, written communication, 5 February 2014 with information from resident Billie Guedon).

The following characteristics can signal areas of past or potential breakdown: (1) irregular patterns of wall and ceiling fractures with visible gypsum veins following the fractures; (2) breakdown debris containing thin, irregular splinters and shards of bedrock; (3) curved plates of bedrock hanging from the ceiling at steep angles; and (4) vertical gradation of collapse debris size, with irregular blocks at the base and symmetrical mounds of rock flour at the top (White and White 2003). The breakdown process has been slowed in some areas of Russell Cave following the 1960s installation of roof bolts into the cave roof and walls (composed of Monteagle Formation [Ml]) by the Bureau of Mines. These bolts anchor loose slabs to the adjacent intact rock in an attempt to stabilize the cave ceiling (fig. 16). The Bureau of Mines inspected the bolts until 1992 (Gail Bishop, Russell Cave National Monument, superintendent, written communication, 29 April 2014). Detailed cave mapping and assessment of potential hazards would help resource managers identify areas at particular risk.

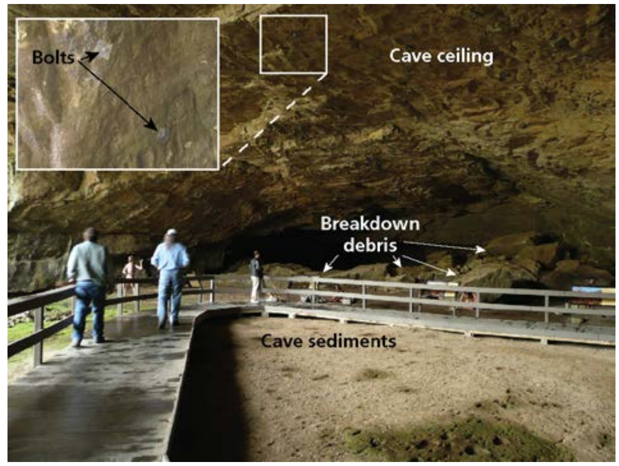

Figure 16. Breakdown and ceiling bolts at Russell Cave. Past ceiling collapse and deposition created the dry shelter that allowed habitation of Russell Cave. Breakdown debris attest to this active process. Bolts were installed at periodic intervals on the cave ceiling to prevent further spalling and to ensure visitor safety. Photographs by Lisa Norby (NPS Geologic Resources Division) and Trista L. Thornberry-Ehrlich (Colorado State University), taken in March 2009.

Radon

Radon (^{222}Rn) is a colorless, odorless, radioactive gas that accumulates in buildings and enclosed underground spaces, such as caves and basements. Radon is created through the decay of uranium-238 and thorium-232, which occur naturally in the local bedrock. Cave microclimate (e.g., airflow patterns) can concentrate or transport radon throughout the cave. The airflow in Russell Cave is a function of interior cave and exterior ambient temperatures (seasonally variable) and of the cave's configuration. Temperature gradients produce pressure differences between the cave interior and exterior, causing air to move under the action of gravity (Yarborough 1980, 1981). Because the half-life of ^{222}Rn is 3.8 days, it can travel far from its origin.

Management of the radon threat at Russell Cave National Monument has so far been restricted to testing within monument buildings. Results revealed minimal concentrations. Because access to Russell Cave has been limited, radon testing is not a current (as of 2014) management concern for the cave or shelter (Russell Cave National Monument staff, conference call, 5 February 2014).

Vandalism and Dumping

Speleothems and other features in Russell Cave have been vandalized, and cultural resources in the cave have been stolen or damaged. For these reasons, monument staff installed a surveillance camera to monitor the dry shelter area (Thornberry-Ehrlich 2009). Monument staff have noted that visitors continue to trespass by climbing over the railing at the cave entrance and may be removing cultural resources. Altering the camera system or field of view may provide additional coverage (Mary Shew, Russell Cave National Monument, resource management specialist, written communication, 11 May 2014).

Local sinkholes and caves were used as garbage dumps and have been the target of several clean-up efforts (Michaud 2009). Notable among these efforts is the Russell Cave watershed restoration project conducted by the Sewanee Mountain Grotto. Since 2006, the group has removed more than 45,000 kg (100,000 lbs) of debris from the watershed, with activities focused on roadside dumps along Orme Mountain Road and at Gross Hole Cave and other caves used as dump sites (Sewanee Mountain Grotto 2011).

White-Nose Syndrome

White-nose syndrome, a disease affecting hibernating bats, is caused by the white fungus *Pseudogymnoascus destructans* and has been spreading throughout the US, killing more than 5.7 million bats in eastern North America. Researchers continue to study this disease, but there is no cure at this time and resource managers are cautious about using fungicide treatments in caves for fear of disrupting the delicate subterranean ecosystem (National Park Service 2012). Although Russell Cave was closed to recreational visitation in the late 1990s, researchers with permits were allowed access until the US Fish and Wildlife Service requested complete cave closures to prevent the spread of white-nose syndrome in 2009 (Mary Shew, written communication, 11 May 2014). After confirmation of the disease's presence in Russell Cave National Monument in March 2012, all caves in the monument were closed to all public access (excepting the archeological site) to minimize the spread of white-nose syndrome (http://nature.nps.gov/biology/WNS/index.cfm or http://www.whitenosesyndrome.org/).

Cave and Karst Monitoring and Management

In the *Geological Monitoring* chapter about caves and associated landscapes, Toomey (2009) described methods for inventorying and monitoring cave-related vital signs, including the following: (1) cave meteorology, such as microclimate and air composition; (2) airborne sedimentation, including dust and lint; (3) direct visitor impacts, such as breakage of cave formations, trail use in caves, graffiti, and artificial cave lighting; (4) permanent or seasonal ice; (5) cave drip and pool water, including drip locations, rate, volume, and water chemistry, pool microbiology, and temperature; (6) cave microbiology; (7) stability issues associated with breakdown, rockfall, and partings; (8) mineral growth of speleothems, such as stalagmites and stalactites; (9) surface expressions and processes that link the surface and the cave environment, including springs, sinkholes, and cracks; (10) regional groundwater levels and quantity; and (11) fluvial processes, including underground streams and rivers.

The NPS Cumberland Piedmont Inventory and Monitoring Network monitoring program at Russell Cave National Monument includes three vital signs related to the cave environment: cave aquatic biota, cave bats, and water quality. For more information, visit their website: http://science.nature.nps.gov/im/units/cupn/parks/ruca.cfm (accessed 26 March 2014).

Slope Movement Hazards and Risks

As described in the "Slope Processes and Deposits" section, slope movements are a common type of geologic hazard. These natural or human-caused conditions may impact monument resources, infrastructure, or visitor safety. Risk is the probability of occurrence combined with the expected degree of damage or loss that may result from exposure to a hazard, or the likelihood of a hazard causing losses (see also Holmes et al. 2013).

The shales that mark the regional contact between the Pennington (upper part of Ml) and Pottsville (PNp) formations form a surface along which movement may occur, causing a significant landslide or rockfall. In the mid-1980s, large blocks of Pottsville Formation sandstone collapsed over the weaker shale layers of the Pennington Formation and rolled or slid down the slopes. Affected slopes appeared "scratched" with landslide scars (Thornberry-Ehrlich 2009).

Colluvium, slope wash, terrace deposits, and alluvial fans (geologic map units Qco, Qs, and Qt) occur on the slopes and fan out from the base of Montague Mountain. A colluvial fan deposit is present above the entrance to Russell Cave, indicating that slope movement has taken place there (Hack 1966; Thornberry-Ehrlich 2009).

Slope movements are of particular concern where steep slopes intersect monument roads or trails. Large blocks of sandstone and conglomerate from the Pottsville Formation are strewn across the slopes along the monument's nature trail, creating a potential hazard to trail users (fig. 10). Off-trail hiking may increase the potential for slope movements. Social trails decrease vegetation on the slopes of Montague Mountain. Because vegetation often stabilized slopes, social trails can exacerbate erosion and slumping on the slopes and along riparian areas bordering streams, such as Dry Creek.

In the *Geological Monitoring* chapter about slope movements, Wieczorek and Snyder (2009) described five vital signs for understanding and monitoring slope movements: 1) types of landslide, 2) landslide causes and triggers, 3) geologic materials in landslides, 4) measurement of landslide movement, and 5) assessment of landslide hazards and risks. Wieczorek and Snyder (2009), Highland and Bobrowsky (2008), the US Geological Survey landslides website (http://landslides.usgs.gov/), and the NPS Geologic Resources Division Geohazards (http://www.nature.nps.gov/geology/hazards/index.cfm) and Slope Movement Monitoring (http://www.nature.nps.gov/geology/monitoring/slopes.cfm) websites provide detailed information regarding slope movements, monitoring, and mitigation options.

Abandoned Mineral Lands

Coal mining was among the factors driving the early development of the Doran Cove area. At least seven abandoned coal mine tunnels are present on the slopes of Montague Mountain (Jones and Daniel 1960).

According to the NPS abandoned mineral lands (AML) database (accessed 23 December 2013) and Burghardt et al. (2014), Russell Cave National Monument contains two AML features (coal mine entrance and tunnel) at two sites. AML features present a variety of resource management issues, such as visitor and staff safety and environmental quality of air, water, and soil. AML features can also provide habitat for bats and other animals. Resource management of AML features requires accurate inventory and reporting. At the 2009 GRI scoping meeting, monument staff estimated that three or four mine entrances existed within the monument (Thornberry-Ehrlich 2009). All AML features should be recorded in the AML database (the NPS Geologic Resources Division may be able to provide assistance). An accurate inventory can identify human safety hazards and facilitate the closure, reclamation, and restoration of AML features. When appropriate for resource management and visitor safety, AML features can also present opportunities for interpretation as cultural resources. The AML features within the monument have already been mitigated (closed in); despite the presence of visible scars on the hillside, no feature is currently known to be in need of mitigation (Burghardt et al. 2014; Russell Cave National Monument staff, conference call, 5 February 2014; Mary Shew and Gail Bishop, Russell Cave National Monument, resource management specialist and superintendent, respectively, written communication, 11 May 2014). The NPS AML Program website (http://nature.nps.gov/geology/aml/index.cfm) provides further information.

Paleontological Resource Inventory, Monitoring, and Protection

All paleontological resources are non-renewable and subject to science-informed inventory, monitoring, protection, and interpretation, as outlined by the 2009 Paleontological Resources Preservation Act (see Appendix B). As of August 2014, Department of the Interior regulations associated with the act were being developed. Fossils are known from within the bedrock of Russell Cave (Paleozoic invertebrates) and in cave deposits (Pleistocene vertebrates); they are described in the "Paleontological Resources" section. A field-based paleontological resource survey can provide detailed, site-specific descriptions and resource management recommendations that are beyond the scope of this report. Although no monument-specific survey has been completed for Russell Cave National Monument, a paleontological resource summary outlines known or potential fossils within the monument (Hunt-Foster et al. 2009). Contact the Geologic Resources Division for assistance.

In the *Geological Monitoring* chapter about paleontological resources, Santucci et al. (2009) described five methods and vital signs for monitoring in situ paleontological resources: (1) erosion (geologic factors), (2) erosion (climatic factors), (3) catastrophic geohazards, (4) hydrology/bathymetry, and (5) human access/public use.

Fossils are visible in limestone blocks along the boardwalk and in the walls of Russell Cave, and may provide interpretive opportunities (Jones and Daniel 1960; Santucci et al. 2001). Interpreters may consider the development of programs detailing fossil resources in cultural contexts (i.e., use of fossils such as crinoids for beads, or use as trade or ceremonial items) (Mary Shew, Russell Cave National Monument, resource management specialist, written communication, 13 May 2014).

Earthquake Hazards and Risks

Earthquakes are ground vibrations—shaking—that occur when rocks suddenly move along a fault, releasing accumulated energy (Braile 2009). Earthquake intensity or magnitude ranges from imperceptible by humans to total destruction of developed areas and alteration of the landscape. The "Richter magnitude" is a measure of the energy released by an earthquake. Earthquakes can damage monument infrastructure directly or trigger other hazards, such as slope movements on Montague Mountain or ceiling collapse within Russell Cave, which may impact monument resources, infrastructure, or visitor safety. Braile (2009), the NPS Geologic Resources Division Seismic Monitoring website (http://nature.nps.gov/geology/monitoring/seismic.cfm), and the US Geological Survey Earthquakes Hazards website (http://earthquake.usgs.gov/) provide more information.

According to geologists from the Geological Survey of Alabama, Russell Cave National Monument is in an area of moderately low earthquake risk. The US Geological Survey's earthquake probability maps (https://geohazards.usgs.gov/eqprob/2009/index.php, accessed 24 July 2014) indicate that the probability of a magnitude-5.0 or greater earthquake within 100 years in this area is 6% to 8% (fig. 17) (Peterson et al. 2008). However, frequent low-magnitude earthquakes occur in the area and may be associated with the Eastern

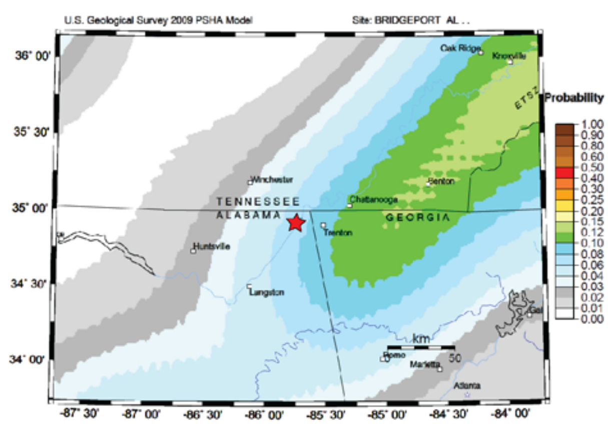

Figure 17. Probability of the occurrence of earthquakes with magnitudes greater than 5.0. This probability assumes a 100-year timespan and a 50-km (30-mi) radius around the site of interest (red star), Bridgeport, Alabama. Russell Cave National Monument (also the red star) is on the southwestern fringe of the zone. ETSZ, Eastern Tennessee Seismic Zone. Graphic was generated by the US Geological Survey Probabilistic Seismic Hazards Assessment (PSHA) mapping program (https://geohazards.usgs.gov/eqprob/2009/index.php) accessed 15 January 2014.

Tennessee Seismic Zone (fig. 17, green area). It is one of the most active seismic zones in eastern North America; more than 44 detectable (felt by humans) earthquakes have occurred since 1982 (Chapman et al. 2002). Intraplate seismic zones such as the Eastern Tennessee Seismic Zone are far from plate boundaries, which are the typical locations of earthquakes. The focal depths of most earthquakes in the seismic zone range from 5 to 22 km (3 to 13 mi), beneath large Paleozoic-aged detachment surfaces (faults) (Chapman et al. 2002). Fault movement in the Eastern Tennessee Seismic Zone is primarily lateral (strike-slip), with right-lateral motion on north–south-trending faults and left-lateral motion on east–west-trending faults (Chapman et al. 2002). Epicenters near Russell Cave National Monument include those located near Hartsville, Tennessee, and Ft. Payne, Alabama, which experienced a magnitude-4.9 earthquake as recently as 2006 (Thornberry-Ehrlich 2009).

In the *Geological Monitoring* chapter about earthquakes and seismic activity, Braile (2009) described the following methods and vital signs for understanding earthquakes and monitoring seismic activity: (1) monitoring earthquakes, (2) analysis and statistics of earthquake activity, (3) analysis of historical and prehistoric earthquake activity, (4) earthquake risk estimation, (5) geodetic monitoring and ground deformation, and (6) geomorphic and geologic indications of active tectonics.

Geologic History

This section describes the chronology of geologic events that formed the present landscape of Russell Cave National Monument.

The geologic history of the bedrock in Russell Cave National Monument is dominated by the presence of a longstanding marine basin during the Paleozoic Era (figs. 3 and 18). During the Mississippian Period, this basin collected vast amounts of carbonate sediments that are now called the Monteagle Limestone, Bangor Limestone, and Pennington Formation (geologic map unit Ml). As the marine basin regressed (sea level lowered), terrestrial sandstones, coal beds, and conglomerates of the Pennsylvanian Pottsville Formation (PNp) were deposited atop the carbonates (Hack 1966). During several Paleozoic mountain-building events (orogenies) that ultimately formed the Appalachian Mountains, local buckling and uplift of the Nashville Dome occurred and great masses of rock called thrust sheets were pushed northwest along faults. Since the Late Paleozoic, weathering and erosion of the highlands have been the dominant forces of landscape change in the monument area. Differential weathering of the soluble limestone and more resistant sandstones created Doran Cove and ultimately the setting for Russell Cave. Slope processes continue to wear away the rocks of Montague Mountain, whose flanks are mantled with colluvium, slope wash, and other slope deposits (Qco, Qs, and Qt).

Paleozoic Era (541 million to 252 million years ago)—Longstanding Marine Deposition and Supercontinent Formation

At the dawn of the Paleozoic Era, 541 million years ago, the area that would become northern Alabama was a marine basin and tectonic forces were stretching Earth's crust apart. This extension or rifting created deep grabens (basins) separated by horsts (ranges or ridges) (Stearns and Reesman 1986). These deep-seated basement structures were tectonically active throughout the Paleozoic, creating low-lying depositional basins separated by uplifted arches and domes (fig. 19a). One such structure is the Nashville Dome, which marks the southern end of the Cincinnati Arch. Russell Cave National Monument is located on the southern flank of the Nashville Dome. The dome and adjacent depositional basins—the Illinois Basin to the west, the Appalachian Basin to the east, and the Black Warrior Basin to the south—were present throughout most of the Paleozoic, collecting sediments that now compose the bedrock in the monument and the rest of the Cumberland Plateau.

Within the longstanding marine basin, sea level fluctuated as a result of factors such as climate, deposition, and tectonic unrest. During the Mississippian, shallow, nearshore conditions (represented by carbonate rocks, such as limestone) alternated with deeper water settings (represented by shale) (fig. 19b) (Hack 1966; Thomas 1972; Raymond et al. 1988). The Monteagle and Bangor limestones (lower parts of Ml) accumulated at this time. The massive, cross-bedded oolitic and bioclastic limestones of these units occur in a linear trend that parallels the edge of an ancient carbonate platform—the East Warrior Platform, in the northeastern limb of the Black Warrior Basin (Raymond et al. 1988).

Sea level lowered and deltaic depositional environments prevailed. The Pennington Formation (upper part of Ml), containing clastic shales, limestones, and mudstones that grade upward into shales, siltstones, sandstones, siderites, and thin coal seams, records these deltaic environments (Hack 1966; Thomas 1979). Marine bays, small bars, and coastal lagoons and marshes were typical at this time (Thomas 1979; Raymond et al. 1988). Sources of sediment were northeast and southwest of the basin (Raymond et al. 1988). The coarser sediments toward the top of the Pennington Formation record a shift to environments such as marine bays, small bars, coastal lagoons, and marshes (Thomas 1979).

At the beginning of the Pennsylvanian Period, deltaic, barrier, and back-barrier depositional environments dominated the landscape. These environments are now represented by the sandstones, shales, siltstones, and thin, irregular coal beds of the lower Pottsville Formation (PNp) (Hack 1966; Smith 1979; Rheams and Benson 1982; Raymond et al. 1988). As the Pennsylvanian Period continued, the depositional setting changed to fluvial-deltaic conditions (fig. 19c) (Thomas 1979; Raymond et al. 1988). Pennsylvanian rocks thicken to the southwest, toward the depocenter of the basin (Raymond et al. 1988).

The Pennsylvanian–Permian Alleghany Orogeny (about 330 million to 270 million years ago) involved collision of the North American and African continents, which ultimately formed the supercontinent Pangaea and lifted the Appalachian Mountains to their maximum height. During the Alleghany Orogeny, folding and faulting produced the parallel folds of the Valley and Ridge Province and mildly deformed the rocks of the Cumberland Plateau (Moore 1994). Large thrust faults transported and buckled the overlying sheets of rock. The Sequatchie Valley, southeast of Russell Cave National Monument, marks the location of an anticline that was the leading edge or northwesternmost advance of the thrust sheets.

Mesozoic and Cenozoic Eras (252 million years ago to present)—Weathering and the Exposure of Russell Cave

Since the end of the Paleozoic Era, the geologic history of the Doran Cove and Russell Cave National Monument area has been characterized primarily by differential

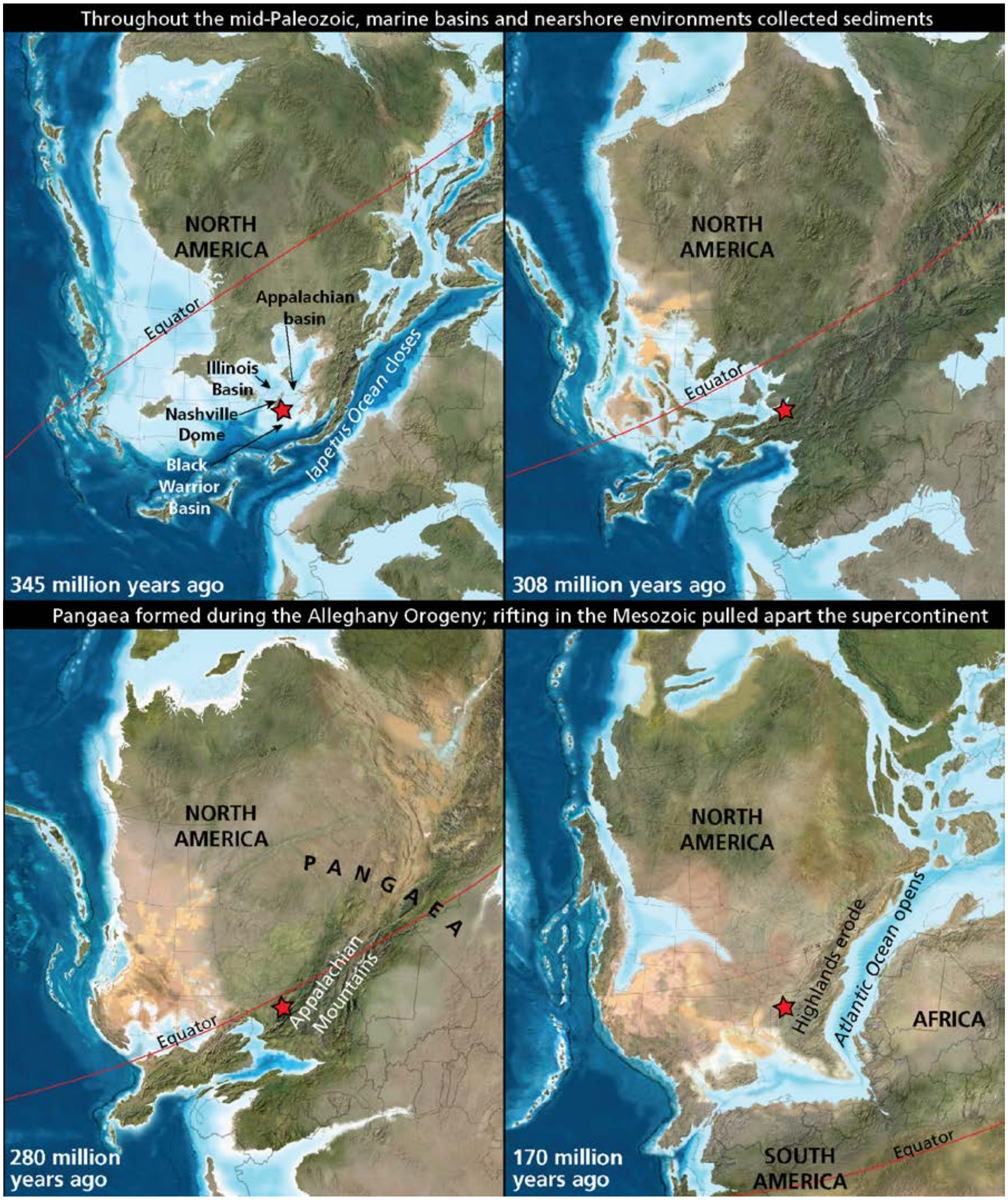

Figure 18. Paleogeographic maps of North America. During the Mississippian Period, 345 million years ago, the area of Russell Cave National Monument was dominated by open marine conditions and carbonate sedimentation. Terrestrial and nearshore conditions dominated during the Pennsylvanian Period (308 million years ago) as the Alleghany Orogeny was forming the Appalachian Mountains. The Appalachian Mountains reached their greatest elevations during the Alleghany Orogeny. By the Jurassic Period of the Mesozoic Era (170 million years ago), the supercontinent Pangaea had broken up and roughly the continents that exist today drifted away from North America as the Atlantic Ocean spread. Red stars indicate the location of Russell Cave National Monument. Red lines mark the location of the equator. Paleogeographic maps by Ron Blakey (Colorado Plateau Geosystems; available online: http://cpgeosystems.com/paleomaps.html, accessed 25 March 2014), annotated and adapted by Trista L. Thornberry-Ehrlich (Colorado State University).

erosion of the soluble limestones beneath the resistant sandstones capping the Cumberland Plateau. Late Pennsylvanian, Permian, and younger sediments were eroded from the Cumberland Plateau following the Alleghany Orogeny. Rivers, incising features such as the Sequatchie Valley, transported vast amounts of sediment toward what would become the Gulf of Mexico, forming the coastal plain of southern Alabama. By the Cretaceous, many physiographic regions of northern Alabama, including the Highland Rim and Cumberland Plateau, were significantly developed (fig. 19d) (Moore 1994).

As erosion was breaching the Pottsville Formation (PNp) cap rock and forming Doran Cove, limestone (Ml) dissolution of the conduits of Russell Cave was likely already occurring. Because the cave is a void, it is inherently difficult to date directly (Schmidt 1982). Multiple approaches may be employed to determine the minimum age of Russell Cave, such as dating of cave clastic and chemical sediments, (e.g., stream-transported sediments and speleothems). Techniques for dating cave sediments include radiometric (e.g., radiocarbon ["C-14"] and uranium/thorium) dating of speleothems, cosmogenic isotope dating of clastic sediments, and paleomagnetic reversals (Granger et al. 2000; White 2007). This last technique was employed successfully at Mammoth Cave, Kentucky, where some clastic-sediment deposits retained a magnetic signature, with some grains aligned to the north–south polarity of Earth's magnetic field at the time. The direction of polarity is not constant and the poles occasionally reverse. The record of polarity reversals has been well dated (Schmidt 1982; White 2007).

Although the timing of the initiation of Russell Cave's formation is not well constrained, its exposure via sinkhole collapse occurred between 9,000 and 11,000 years ago (Hack 1974). Breakdown and sedimentation elevated the dry shelter above the Dry Creek channel soon thereafter, and the cave became the site of intermittent habitation for thousands of years.

Ongoing weathering and erosion of geologic units within the monument create distinctive landforms (fig. 19e). Blocks of the Pottsville Formation (PNp), capping the heights of Montague Mountain, are wedged apart and tumble downslope in a mantle of slope deposits (Qco, Qs, and Qt) (Hack 1966). Karst groundwater conduits, sinkholes, and caves form through karst dissolution and subsidence and/or collapse. These processes of weathering and erosion continue to shape the landscape today. The alluvial processes of channel incision, migration, flooding, and deposition continue to change the Dry Creek channel. Terrace deposits (Qt) record former river elevations and alluvium (Qal) is collecting in the modern channel (Hack 1966). The landscape that visitors see today is continuing to evolve from the landscape that greeted American Indian groups frequenting the Doran Cove area more than 9,000 years ago.

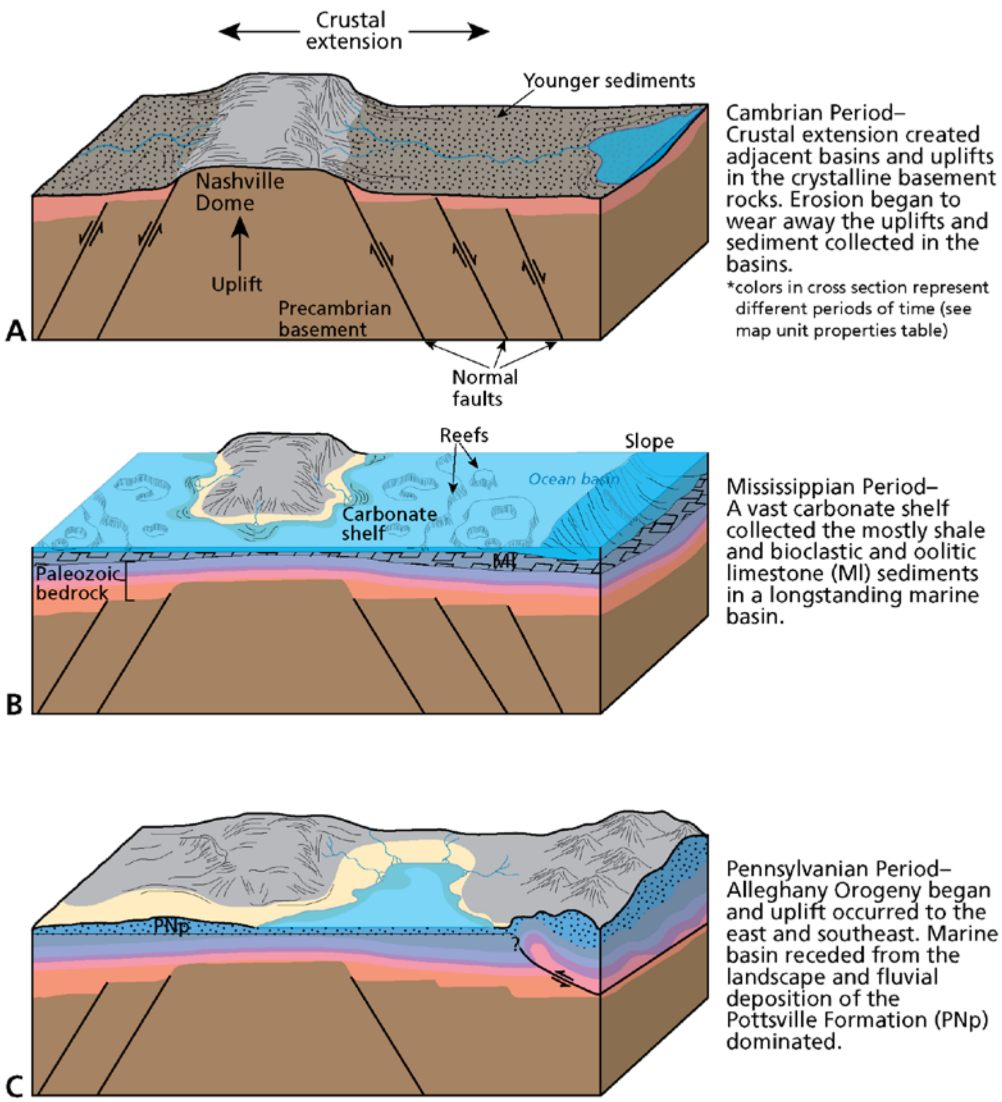

Figure 19A-C. Geologic evolution of the landscape (continued on next page). Diagrams are not to scale. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University), created using information from Crawford (1989) and Thomas (1979).

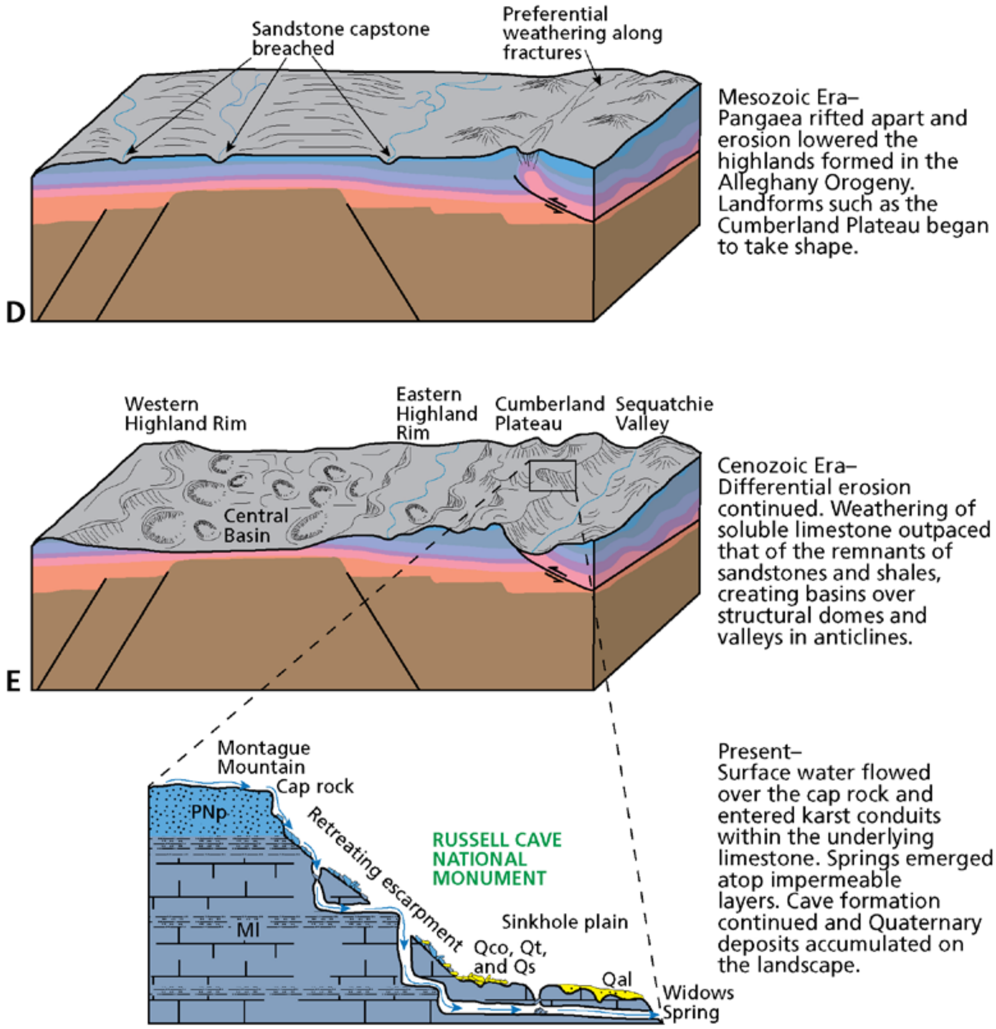

Figure 19D-E. Geologic evolution of the landscape, continued. Diagrams are not to scale. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University), created using information from Crawford (1989) and Thomas (1979).

Geologic Map Data

This section summarizes the geologic map data available for Russell Cave National Monument. The Geologic Map Graphic (in pocket) displays the map data draped over imagery of the park and surrounding area. The Map Unit Properties Table (in pocket) summarizes this report's content for each geologic map unit. Complete GIS data are included on the accompanying CD and are also available at the GRI publications website: http://go.nps.gov/gripubs.

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, these maps portray the spatial distribution and temporal relationships of rocks and unconsolidated deposits. Geologic maps can be divided into two primary types: surficial and bedrock. Surficial geologic maps typically encompass deposits that are unconsolidated and formed during the past 2.6 million years (the Quaternary Period). Surficial map units are differentiated by geologic process or depositional environment. Bedrock geologic maps encompass older, typically more consolidated sedimentary, metamorphic, and/or igneous rocks. Bedrock map units are differentiated based on age and/or rock type.

Geologic maps often depict geomorphic features, structural interpretations (such as faults or folds), and locations of past geologic hazards that may be susceptible to future activity. Anthropogenic features such as mines or quarries, as well as observation or collection locations, may be indicated on geologic maps. The American Geosciences Institute website, http://www.agiweb.org/environment/publications/mapping/index.html, provides more information about geologic maps and their uses.

Source Maps

The GRI team digitizes paper maps and converts digital data to conform to the GRI GIS data model. The GRI digital geologic map product includes essential elements of the source maps, such as map unit descriptions, a correlation chart of units, a map legend, map notes, references, and figures. The GRI team used the following source to produce the digital geologic data set for Russell Cave National Monument. This source also provided information for this report.

Hack, J. T. 1966. Geologic map of part of Doran Cove, Alabama and Tennessee (scale 1:24,000). Plate 1 *in* J. T. Hack, author. Interpretation of Cumberland escarpment and Highland rim, south-central Tennessee and northeast Alabama. Professional paper 524-C. US Geological Survey, Reston, Virginia. http://pubs.er.usgs.gov/publication/pp524C (accessed 17 December 2013).

GRI 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 at 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 Russell Cave National Monument using data model version 2.1. The GRI Geologic Maps website, http://www.nature.nps.gov/geology/inventory/geo_maps.cfm, provides more information about GRI map products.

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

The following components are part of the data set:

- A GIS readme file (PDF) that describes the GRI data formats, naming conventions, extraction instructions, use constraints, and contact information.
- Data in ESRI personal geodatabase and shapefile GIS formats
- Layer files with feature symbology (table 1)
- Federal Geographic Data Committee (FGDC)-compliant metadata
- An ancillary map information document (PDF) that contains information captured from source maps, such as map unit descriptions, geologic unit correlation tables, legends, cross sections, and figures.
- An ESRI map document (.mxd) that displays the digital geologic data

Table 1. Geology data layers in the Russell Cave National Monument GIS data.

Data Layer	On Map Graphic?
Geologic Observation Localities	No
Geologic Contacts	Yes
Geologic Units	Yes

Geologic Map Graphic

The Geologic Map Graphic displays the GRI digital geologic data draped over a shaded relief image of the monument and surrounding area. Not all GIS feature classes may be inc luded on the graphic (table 1). Geographic information and selected monument features have been added to the graphic. Digital elevation data and added geographic information are not included in the GRI GIS data set, but are available online from a variety of sources. Contact GRI for assistance locating these data.

Map Unit Properties Table

The Map Unit Properties Table lists the geologic time division, symbol, and a simplified description for each of the geologic map units in the GRI GIS data. Following the structure of the report, the table summarizes the geologic features, processes, resource management issues, and history associated with each map unit.

Use Constraints

Graphic and written information provided in this report is not a substitute for site-specific investigations. Ground-disturbing activities should neither be permitted nor denied based upon the information provided here. Please contact GRI with any questions.

Minor inaccuracies may exist regarding the locations of geologic features relative to other geologic or geographic features on the Geologic Map Graphic. Based on the source map scale (1:24,000) and US National Map Accuracy Standards, geologic features represented in the geologic map data are horizontally within 12 m (40 ft) of their true locations.

Glossary

This section contains brief definitions of selected geologic terms relevant to this report. Definitions are based on those in the American Geosciences Institute Glossary of Geology *(5th edition; 2005). Additional terms are defined at http://geomaps.wr.usgs.gov/parks/misc/glossarya.html.*

aeolian. Describes materials formed, eroded, or deposited by or related to the action of wind.

alluvial fan. A low, relatively flat to gently sloping, fan-shaped mass of loose rock material deposited by a stream, especially in a semiarid region, where a stream issues from a canyon onto a plain or broad valley floor.

alluvial terrace. A stream terrace composed of unconsolidated alluvium, produced by renewed downcutting of the floodplain or valley floor by a rejuvenated stream or by the later covering of a terrace with alluvium.

alluvium. Stream-deposited sediment.

anticline. A fold, generally convex upward ("A"-shaped) whose core contains the stratigraphically older rocks. Compare with "syncline."

aquiclude. A saturated geologic unit that is incapable of transmitting significant quantities of water under ordinary hydraulic gradients. Replaced by the term "confining bed."

aquifer. A rock or sedimentary unit that is sufficiently porous to hold water, sufficiently permeable to allow water to move through it, and saturated to some level.

axis. A straight-line approximation of the trend of a fold along the boundary between its two limbs. "Hinge line" is a preferred term.

bank. A submerged ridge of sand in the sea, a lake, or a river, usually exposed during low tide or low water.

barrier island. A long, low, narrow island consisting of a ridge of sand that parallels the coast.

base level. The lowest level to which a stream channel can erode. The ultimate base level for the land surface is sea level, but temporary, local base levels exist.

basement. The undifferentiated rocks, commonly igneous and metamorphic, that underlie rocks exposed at the surface, commonly sedimentary. In many regions the basement is of Precambrian age, but it may be much younger.

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

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

beach. A gently sloping shoreline covered with sediment, usually sand or gravel, extending landward from the low-water line to the place where there is a definite change in material, physiographic form, or permanent vegetation.

bed. The smallest sedimentary stratigraphic unit, commonly ranging in thickness from about 1 cm (0.4 in) to 1 to 2 m (40 to 80 in) and distinguishable from beds above and below.

bedding. Depositional layering or stratification of sediments.

bedrock. Solid rock that underlies unconsolidated, superficial material and soil.

body fossil. Evidence of past organisms such as bones, teeth, shells, or leaf imprints. Compare to "trace fossil."

brachiopod. Any marine invertebrate belonging to the phylum Brachiopoda, characterized by two bilaterally symmetrical valves that are commonly attached to a substratum but may also be free. Range: Lower Cambrian to Holocene.

breakdown. Collapse of a cave ceiling or walls of a cave. Also, the accumulation of debris thus formed.

bryozoan. Any invertebrate belonging to the phylum Bryozoa; characterized by colonial growth and a calcareous skeleton. Range: Ordovician (and possibly Upper Cambrian) to Holocene.

calcareous. Describes a substance that contains calcium carbonate. When applied to a rock name it implies that as much as 50% of the rock is calcium carbonate.

calcium carbonate. A solid, $CaCO_3$, occurring in nature as primarily calcite and aragonite.

calcic. Describes a mineral or igneous rock containing a significant amount of calcium.

calcite. A carbonate (carbon + oxygen) mineral of calcium, $CaCO_3$; calcium carbonate. It is the most abundant cave mineral.

carbonaceous. Describes a rock or sediment with considerable carbon, especially organic material, hydrocarbon, or coal.

carbonate. A mineral group composed of carbon and oxygen plus an element or elements; for example calcite, $CaCO_3$; and dolomite, $CaMg(CO_3)_2$.

carbonate rock. A rock, for example, limestone, calcite, and dolomite, that consist primarily of carbonate minerals.

cement (sedimentary). Mineral material, usually chemically precipitated, that occurs in the spaces among the individual grains of sedimentary rocks, thus binding the grains together.

cementation. The process by which clastic sediments become lithified or consolidated into hard, compact rocks, usually through deposition or precipitation of minerals in the spaces among the individual grains of the sediment; may occur simultaneously with sedimentation or at a later time.

channel. A relatively narrow sea or stretch of water between two nearby landmasses, connecting two larger bodies of water.

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 providing more stablity in the current environment.

chert. An extremely hard sedimentary rock with conchoidal fracturing, consisting mostly of interlocking crystals of quartz.

clast. An individual constituent, grain, or fragment of a rock or unconsolidated deposit, produced by the mechanical or chemical disintegration of a larger rock mass.

clastic. Describes rocks or sediments made of fragments of preexisting rocks.

clay. Refers to clay minerals and sedimentary fragments that are less than 1/256 mm (0.00015 in) across.

coarse-grained. Describes a crystalline rock and texture in which the individual minerals are relatively large, specifically an igneous rock whose particles have an average diameter greater than 5 mm (0.2 in). Also, describes sediment or sedimentary rock and texture in which the individual constituents are easily seen with the unaided eye, specifically sediment or rock whose particles have an average diameter greater than 2 mm (0.08 in).

coastal plain. Any lowland area bordering a sea or ocean, extending inland to the nearest elevated land, and sloping very gently seaward; may result from the accumulation of material along a coast.

colluvium. A loose, heterogeneous, and incoherent mass of rock fragments and soil material deposited via surface runoff or slow continuous downslope creep; usually collects at the base of a slope or hillside, but includes loose material covering hillsides.

confining bed. A body of relatively impermeable or distinctly less permeable material stratigraphically adjacent to one or more aquifers. Replaced the term "aquiclude."

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

contact. The surface between two types or ages of rocks.

continental crust. Earth's crust that is rich in silica and aluminum and underlies the continents and the continental shelves; ranges in thickness from about 25 km (15 mi) to more than 70 km (40 mi) under mountain ranges, averaging about 40 km (25 km) thick.

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. Range: Paleozoic to Holocene, through very common in the Paleozoic and rare today.

cross-bed. A single bed, inclined at an angle to the main planes of stratification; the term is commonly restricted to a bed that is more than 1 cm (0.4 in) thick.

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

cross section. A graphic interpretation of geology, structure, or stratigraphy based on mapped and measured geologic extents and attitudes, depicted in a vertical plane (i.e., a cut or profile view).

crust. Earth's outermost layer or shell. Compare to "oceanic crust" and "continental crust."

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

debris flow. A moving mass of rock fragments, soil, and mud, with more than half of the particles larger than sand size. Slow debris flows may move less that 1 m (3 ft) per year; rapid ones reach 160 kph (100 mph).

deformation. The process of folding, faulting, shearing, or fabric development in rocks as a result of Earth stresses.

delta. The low, nearly flat, alluvial tract of land at or near the mouth of a river, commonly forming a triangular or fan-shaped plain of considerable area; resulting from the accumulation of sediment supplied by the river in such quantities that it is not removed by tides, waves, and currents.

depocenter. An area or site of maximum deposition.

differential erosion. Erosion that occurs at irregular or varying rates due to differences in the resistance and hardness of surface material: softer and weaker rocks are rapidly worn away, whereas harder and more resistant rocks remain to form ridges, hills, or mountains.

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

discharge. The rate of flow of surface water or groundwater at a given moment, expressed as volume per unit of time.

disconformity. An unconformity in which the bedding of strata above and below is parallel.

dolomite (mineral). A carbonate (carbon and oxygen) mineral of calcium and magnesium, $CaMg(CO_3)_2$.

dolomite (rock). A carbonate sedimentary rock containing more than 50% of the mineral dolomite (calcium-magnesium carbonate).

dolomitic. Describes a rock containing dolomite, especially one that contains 5%–50% of the mineral dolomite in the form of cement and/or grains or crystals.

dome. Any smoothly rounded landform or rock mass; more specifically, an elliptical uplift in which rocks dip gently away in all directions.

downcutting. Stream erosion in which cutting is directed primarily downward, as opposed to laterally.

drainage. The manner in which the waters of an area flow off in surface streams or subsurface conduits; also, the processes of surface drainage of water from an area by streamflow and sheet flow, and the removal of excess water from soil by downward flow.

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

electrical resistivity survey. A measure of the difficulty with which electric current flows through unconsolidated sediment and rock.

ephemeral stream. A stream that flows briefly, only in direct response to precipitation, and whose channel is always above the water table.

epicenter. The point on Earth's surface directly above the initial rupture point of an earthquake.

erosion. The general process or group of processes that loosen, dissolve, wear away, and simultaneously move from one place to another, the materials of Earth's crust; includes weathering, solution, abrasive actions, and transportation, but usually excludes slope movements.

escarpment. A steep cliff or topographic step resulting from vertical displacement on a fault or as a result of slope movement or erosion. Synonymous with "scarp."

fan delta. A gently sloping alluvial deposit produced where a mountain stream flows out onto a lowland.

fault. A break in rock characterized by displacement of one side relative to the other.

fine-grained. Describes a crystalline or glassy rock and texture in which the individual minerals are relatively small, specifically an igneous rock whose particles have an average diameter less than 1 mm (0.04 in). Also, describes sediment or sedimentary rock and texture in which the individual constituents are too small to distinguish with the unaided eye, specifically sediment or rock whose particles have an average diameter less than 1/16 mm (0.002 in), that is, silt-size particles and smaller.

flint. The homogeneous, dark-gray or black variety of chert.

floodplain. The surface or strip of relatively smooth land composed of alluvium and adjacent to a river channel, constructed by the present river in its existing regimen and covered with water when the river overflows its banks. A river has one floodplain and may have one or more terraces representing abandoned floodplains.

fluvial. Of or pertaining to a river or rivers.

fold. A curve or bend in an originally flat structure, such as a rock stratum, bedding plane, or foliation; usually a product of deformation.

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

fossil. A remain, trace, or imprint of a plant or animal that has been preserved in the Earth's crust since some past geologic time; loosely, any evidence of past life.

fracture. The breaking of a mineral other than along planes of cleavage. Also, any break in a rock such as a crack, joint, or fault.

frost wedging. A type of mechanical disintegration, splitting, or breakup of a rock by which jointed rock is pried and dislodged by ice acting as a wedge.

geomorphology. The study of the general configuration of surface landforms and their relationships to underlying structures, and of the history of geologic changes as recorded by these surface features.

Gondwana. The late Paleozoic continent of the Southern Hemisphere and counterpart of Laurasia of the Northern Hemisphere; both were derived from the supercontinent Pangaea.

gradient. A degree of inclination (steepness of slope), or a rate of ascent or descent, of an inclined part of Earth's surface with respect to the horizontal; expressed as a ratio (vertical to horizontal), a fraction (such as m/km or ft/mi), a percentage (of horizontal distance), or an angle (in degrees).

graben. An elongated, downdropped trough or basin, bounded on both sides by high-angle normal faults that dip toward one another. Compare to "horst."

gravel. An unconsolidated, natural accumulation of typically rounded rock fragments resulting from erosion; consists predominantly of particles larger than sand, greater than 2 mm (1/12 in) across.

ground penetrating radar. A means of exploration of the Earth's shallow subsurface with radar energy. Commonly the two-way traveltime for reflected radar waves defines depth in the Earth where changes in radar propagation occur..

groundwater. That part of subsurface water that is in the zone of saturation, including underground streams.

groundwater basin. An area of bedrock in a karst spring that collects drainage from all the sinkholes and sinking streams in its drainage area.

gully. A small channel produced by running water in unconsolidated material.

horst. An elongated, uplifted block that is bounded on both sides by normal faults that dip away from one another. Compare to "graben."

hydrogeology. The science that deals with subsurface waters and related geologic aspects of surface waters, including the movement of groundwater; the mechanical, chemical, and thermal interaction of groundwater with the porous medium; and the transport of energy and chemical constituents by the flow of groundwater. Synonymous with "geohydrology."

hydrology. The study of liquid and solid water properties, circulation, and distribution, on and under the Earth's surface and in the atmosphere.

igneous. Describes a rock or mineral that solidified from molten or partly molten material; also, describes processes leading to, related to, or resulting from the formation of such rocks.

incision. Downward erosion by a stream, resulting in a deepened channel and commonly a narrow, steep-walled valley.

isotopic age. An age (in years) calculated from the quantitative determination of radioactive elements and their decay products.

isotopic dating. Calculating an age in years for geologic materials by measuring the presence of a short-lived radioactive element (e.g., carbon-14) or by measuring the presence of a long-lived radioactive element plus its decay product (e.g., potassium-40/argon-40). The term applies to all methods of age determination based on nuclear decay of naturally occurring radioactive isotopes.

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

karstification. The action of water, mainly solutional but also mechanical, that produces features of karst topography.

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

karst valley. A closed depression formed by the coalescence of several sinkholes.

karst window. A collapse sinkhole opening into a cave.

lagoon. A narrow body of water that is parallel to the shore and between the mainland and a barrier island; characterized by minimal or no freshwater influx and limited tidal flux, which cause elevated salinities. Also, a shallow body of water enclosed or nearly enclosed within an atoll.

landslide. A collective term covering a wide variety of slope-movement landforms and processes that involve the downslope transport of soil and rock material en masse under the influence of gravity.

Laurasia. The late Paleozoic continent of the Northern Hemisphere and counterpart of Gondwana of the Southern Hemisphere; both were derived from the supercontinent Pangaea.

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

light detection and ranging/LiDAR. A method and instrument that measures distance to a reflecting object by emitting timed pulses of light and measuring the time between emission and reception of reflected pulses; the measured interval is converted to distance.

limb. One side of a structural fold.

limestone. A carbonate sedimentary rock consisting of more than 95% calcite and less than 5% dolomite.

loess. Windblown silt-sized sediment.

marine terrace. A relatively flat-topped, horizontal or gently inclined, surface of marine origin along a coast, commonly veneered by a marine deposit (typically silt, sand, or fine gravel).

mass wasting. Dislodgement and downslope transport of a mass of rock and/or unconsolidated material under the direct influence of gravity. In contrast to "erosion," the debris removed is not carried within, on, or under another medium. Synonymous with "slope movement."

matrix. The fine-grained material between coarse grains in an igneous or sedimentary; also refers to rock or sediment in which a fossil is embedded.

meander. One of a series of sinuous curves, bends, loops, turns, or windings in the course of a stream, produced by a mature stream swinging from side to side as it flows across its floodplain or shifts its course laterally toward the convex side of an original curve.

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

medium-grained. Describes an igneous rock and texture in which the individual crystals have an average diameter in the range of 1 to 5 mm (0.04 to 0.2 in.). Also, describes sediment or sedimentary rock and texture in which the individual particles have an average diameter in the range of 1/16 to 2 mm (0.002 to 0.08 in), that is, sand size.

meteoric water. Water of recent atmospheric origin.

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

mold. An impression made in the surrounding earth by the exterior or interior of a fossil shell or other organic structure and then preserved. Also, a cast of the inner surface of a fossil shell.

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

mollusk. A solitary invertebrate such as gastropods, bivalves, and cephalopods belonging to the phylum Mollusca. Range: Lower Cambrian to Holocene.

oceanic crust. Earth's crust that underlies the ocean basins and is rich in iron and magnesium; ranges in thickness from about 5 to 10 km (3 to 6 mi).

ooid. One of the small round or ovate accretionary bodies in a sedimentary rock, resembling the roe of fish, formed by accretion around a nucleus of shell fragment, algal pellet, or sand grain; laminated grains may reach 2 mm (0.08 in) across, but are commonly 0.5 to 1 mm (0.02 to 0.04 in) across. Synonymous and preferred to "oolith" (to avoid confusion with "oolite").

oolite. A sedimentary rock, usually limestone, composed of ooids.

orogeny. A mountain-building event.

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

overburden (sedimentary geology). Loose soil, silt, sand, gravel, or other unconsolidated material overlying bedrock.

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

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

Pangea. A supercontinent that existed from about 300 to about 200 million years ago and included most of the continental crust of the Earth, from which the present continents were derived by fragmentation and continental drift. During an intermediate stage of the fragmentation—between the existence of Pangea and that of the present continents—Pangea split into two large fragments, Laurasia on the north and Gondwana on the south.

parent rock. Rock from which soil, sediment, or other rock is derived.

pebble. A small rounded rock, especially a waterworn stone, between 4 and 64 mm (0.16 and 2.5 in) across.

permeability. A measure of the relative ease with which a fluid moves through the pore spaces of a rock or unconsolidated deposit.

phreatic. Of or relating to groundwater.

phreatic zone. The zone of saturation.

piping. Erosion or solution by percolating water in a layer of subsoil, resulting in the formation of narrow conduits, tunnels, or "pipes" through which soluble or granular soil material is removed.

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

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

pull-apart basin. A topographic depression created by an extensional bend or extensional overstep along a strike-slip fault.

quartz. The only silicate (silicon + oxygen) mineral consisting entirely of silicon and oxygen, SiO_2; silicon dioxide. Synonymous with "crystalline silica."

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

radiocarbon age. An isotopic age expressed in years and calculated from the quantitative determination of the amount of carbon-14 remaining in an organic material. Synonymous with "carbon-14 age."

radiometric age. An age (in years) calculated from the quantitative determination of radioactive elements and their decay products. The preferred term is "isotopic age."

recharge. The addition of water to the saturated zone below the water table.

regolith. The layer of unconsolidated rock material that forms the surface of the land and overlies or covers bedrock; includes rock debris of all kinds, volcanic ash, glacial drift, alluvium, loess, and aeolian deposits, vegetal accumulations, and soil. Etymology: Greek "rhegos" (blanket) + "lithos" (stone).

rift. A region of Earth's crust where extension results in formation of many related normal faults, commonly associated with volcanic activity.

right-lateral fault. A strike-slip fault on which the side opposite the observer has been displaced to the right.

rill. A very small brook or trickling stream of water usually without any tributaries. Also, the channel formed by such a stream.

ripple marks. The undulating, approximately parallel and usually small-scale pattern of ridges formed in sediment by the flow of wind or water.

rock. An aggregate of one or more minerals (e.g., granite), a body of undifferentiated mineral matter (e.g., obsidian), or a body of solid organic material (e.g., coal).

rockfall. The most rapid type of slope movement in which a newly detached fragment of bedrock of any size falls from a cliff or other very steep slope, traveling straight down or in a series of leaps and bounds down a slope.

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

sand. A clastic particle smaller than a granule and larger than a silt grain, with a diameter ranging from 1/16 to 2 mm (0.0025 to 0.08 in).

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

saturated zone. A subsurface zone in which all the interstices are filled with water under pressure greater than that of the atmosphere; separated from the unsaturated zone (above) by the water table.

scarp. A steep cliff or topographic step resulting from displacement on a fault or as a result of slope movement or erosion. Synonymous with "escarpment."

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

sedimentary rock. A rock resulting from the consolidation of loose sediment that has accumulated in layers; it may be "clastic," consisting of mechanically formed fragments of older rock; "chemical," formed by precipitation from solution; or "organic," consisting of the remains of plants and animals. One of the three main classes of rock—igneous, metamorphic, and sedimentary.

sedimentation. The process of forming or accumulating sediment into layers, including the separation of rock particles from parent rock, the transportation of these particles to the site of deposition, the actual deposition or settling of the particles, the chemical and other changes occurring in the sediment, and the ultimate consolidation of the sediment into solid rock.

sequence. A succession of geologic events, processes, or rocks, arranged in chronologic order to show their relative position and age with respect to geologic history as a whole.

shale. A clastic sedimentary rock made of clay-sized particles and characterized by fissility.

sheet flow. The downslope movement or overland flow of water, in the form of a thin, continuous film, over relatively smooth soil or rock surfaces and not concentrated into channels larger than rills.

sheetwash. A sheetflood occurring in a humid region. Also, the material transported and deposited by the water of a sheetwash. Used as a synonym of "sheet flow" (a movement) and "sheet erosion" (a process).

silica. Silicon dioxide, SiO_2, an essential constituent of many minerals, occurring as crystalline quartz, cryptocrystalline chalcedony, and amorphous opal.

silicate. A mineral group composed of silicon (Si) and oxygen (O) plus an element or elements, for example, quartz, SiO_2; olivine, $(Mg, Fe)_2SiO_4$; and pyroxene, $(Mg,Fe)SiO_3$; as well as the amphiboles, micas, and feldspars.

silt. Clastic sedimentary material intermediate in size between fine-grained sand and coarse clay, 0.0039 to 0.063 mm (0.00015 to 0.0025 in) across.

siltstone. A clastic sedimentary rock composed of silt-sized grains.

sinkhole. A circular, commonly funnel-shaped depression in a karst area with subterranean drainage.

slope. The inclined surface of any part of Earth's surface, such as a hillslope. Also, a broad part of a continent descending into an ocean.

slope movement. The gradual or rapid downslope movement of soil or rock under gravitational stress. Synonymous with "mass wasting."

slope wash. Soil and rock material that is or has been transported down a slope under the force of gravity and assisted by running water not confined to channels; also, the process by which slope-wash material is moved.

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

soil. The unconsolidated portion of the Earth's crust modified through physical, chemical, and biotic processes into a medium capable of supporting plant growth.

sorted. Describes an unconsolidated sediment consisting of particles of essentially uniform size.

sorting. The dynamic process by which sedimentary particles having some particular characteristic (such as similarity of size, shape, or specific gravity) are naturally selected and separated from associated but dissimilar particles by the agents of transportation.

spalling. The process by which scales, plates, or flakes of rock, from less than a centimeter to several meters in thickness, successively fall from the bare surface of a large rock mass. A form of "exfoliation."

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

spring. A place where groundwater flows naturally from a rock or the soil onto the land surface or into a body of surface water. Its occurrence depends on the nature and relationship of rocks, especially permeable and impermeable strata; the position of the water table; and topography.

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

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

strata. Tabular or sheetlike layers of sedimentary rock; layers are visually distinctive from other layers above and below. The singular form of the term is stratum, but is less commonly used.

stratification. The accumulation, or layering, of sedimentary rocks as strata. Tabular, or planar, stratification refers to essentially parallel surfaces. Cross-stratification refers to strata inclined at an angle to the main stratification.

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

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

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

stream terrace. A planar surface along the sides of a stream valley representing the remnants of an abandoned floodplain, stream bed, or valley floor produced during a former stage of erosion or deposition.

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

strike-slip fault. A fault with measurable offset where the relative movement is parallel to the strike of the fault. Described as left-lateral (sinistral) when relative motion of the block opposite the observer is to the left, and right-lateral (dextral) when relative motion is to the right.

structure. The attitudes and relative positions of the rock masses of an area resulting from such processes as faulting, folding, and igneous intrusion.

subsidence. The sudden sinking or gradual downward settling of part of Earth's surface.

syncline. A generally concave upward fold of which the core contains the stratigraphically younger rocks. Compare with "anticline."

talus. Rock fragments, usually coarse and angular, lying at the base of a cliff or steep slope from which they have fallen.

tectonic. Describes a feature or process related to large-scale movement and deformation of Earth's crust.

terrace. Any long, narrow, relatively level or gently inclined surface (i.e., a bench or steplike ledge) that is bounded along one edge by a steeper descending slope and along the other edge by a steeper ascending slope, thus breaking the continuity of the slope; commonly occurs along the margin and above the level of a body of water, marking a former water level.

terrestrial. Describes a feature, process, or organism related to land, Earth, or its inhabitants.

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

topography. The general morphology of Earth's surface, including relief and locations of natural and human-made features.

trace fossil. A fossilized feature such as a track, trail, burrow, or coprolite (dung), that preserves evidence of an organism's life activities, rather than the organism itself. Compare to "body fossil."

trend. The direction or bearing of an outcrop of a geologic feature such as an ore body, fold, or orogenic belt.

unconformable. Describes strata that do not succeed the underlying rocks in immediate order of age or in parallel position, especially younger strata that do not have the same dip and strike as the underlying rocks. Also, describes the contact between unconformable rocks.

unconformity. A substantial break or gap in the geologic record where a rock unit is overlain by another that is not next in stratigraphic succession, resulting from either a change that caused deposition to cease for a considerable span of time or erosion with loss of the previously formed record.

undercutting. The removal of material at the base of a steep slope by the erosive action of water (such as a meandering stream), sand-laden wind in a desert, or waves along the coast.

unsaturated zone. A subsurface zone between the land surface and the water table that includes air, gases, and water held by capillary action. Synonymous with "vadose zone" and "zone of aeration."

uplift. A structurally high area in Earth's crust produced by movement that raises the rocks.

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

water table. The surface between the saturated zone and the unsaturated zone. Synonymous with "groundwater table" and "water level."

weathering. The physical, chemical, and biological processes by which rock is broken down, particularly at the surface.

Wisconsinan. Pertaining to the classical fourth glacial stage of the Pleistocene Epoch in North America, following the Sangamonian interglacial stage and preceding the Holocene Epoch.

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Additional References

This section lists additional references, resources, and websites that may be of use to resource managers. Web addresses are valid as of August 2014. Refer to Appendix B for laws, regulations, and policies that apply to NPS geologic resources.

Geology of National Park Service Areas

NPS Geologic Resources Division (Lakewood, Colorado): http://nature.nps.gov/geology/

NPS Geologic Resources Inventory: http://www.nature.nps.gov/geology/inventory/index.cfm

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

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

NPS Resource Management Guidance and Documents

1998 National parks omnibus management act: http://www.gpo.gov/fdsys/pkg/PLAW-105publ391/pdf/PLAW-105publ391.pdf

Management policies 2006 (Chapter 4: natural resource management): http://www.nps.gov/policy/mp/policies.html

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 (Young, R., and L. Norby, editors. 2009. Geological monitoring. Geological Society of America, Boulder, Colorado): http://nature.nps.gov/geology/monitoring/index.cfm

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

Climate Change Resources

NPS Climate Change Response Program resources: http://www.nps.gov/subjects/climatechange/resources.htm

US Global Change Research Program: http://globalchange.gov/home

Intergovernmental Panel on Climate Change: http://www.ipcc.ch/

Geological Surveys and Societies

Geological Survey of Alabama: http://www.gsa.state.al.us/

US Geological Survey: http://www.usgs.gov/

National Cave and Karst Research Institute: http://www.nckri.org/

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

American Geophysical Union: http://sites.agu.org/

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

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

US Geological Survey Reference Tools

National geologic map database (NGMDB): http://ngmdb.usgs.gov/

Geologic names lexicon (GEOLEX; geologic unit nomenclature and summary): http://ngmdb.usgs.gov/Geolex/geolex_home.html

Geographic names information system (GNIS; official listing of place names and geographic features): http://gnis.usgs.gov/

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

Publications warehouse (many publications available online): http://pubs.er.usgs.gov

Tapestry of time and terrain (descriptions of physiographic provinces): http://tapestry.usgs.gov/Default.html

Appendix A: Scoping Participants

The following people attended the GRI scoping meeting for Russell Cave National Monument, held on 25–26 March 2009, or the follow-up report writing conference call, held on 5 February 2014. Discussions during these meetings supplied a foundation for this GRI report. The scoping summary document is available on the GRI publications website: http://go.nps.gov/gripubs.

2009 Scoping Meeting Participants

Name	Affiliation	Position
Shawn Benge	NPS Chattanooga and Chickamauga NMP	Superintendent
Tim Connors	NPS Geologic Resources Division	Geologist
Kelly Gregg	Jacksonville State University	Professor of Geology
Mike Hoyal	Tennessee Division of Geology	Geologist
Kenneth Kuehn	Western Kentucky University	Professor of Geology
Joe Meiman	NPS Gulf Coast and Cumberland Plateau networks	Hydrologist
Lisa Norby	NPS Geologic Resources Division	Geologist
Jim Ogden	NPS Chattanooga and Chickamauga NMP	Historian
Ed Osborne	Geological Survey of Alabama	Geologist
Nathan Rinehart	Western Kentucky University	Graduate WKU
Mary Shew	NPS Russell Cave NM and Little River Canyon NPres	Resource Management Specialist
Jim Szyjkowski	NPS Chattanooga and Chickamauga NMP	Chief of Resource Management
Trista Thornberry-Ehrlich	Colorado State University	Geologist/Graphic Designer

2014 Conference Call Participants

Name	Affiliation	Position
Larry Beane	NPS Russell Cave NM and Little River Canyon NPres	Park Ranger
Gail Bishop	NPS Russell Cave NM and Little River Canyon NPres	Superintendent
Jason Kenworthy	NPS Geologic Resources Division	Geologist, GRI Reports Coordinator
Dale Pate	NPS Geologic Resources Division	Cave and Karst Program Coordinator
Mary Shew	NPS Russell Cave NM and Little River Canyon NPres	Resource Management Specialist
Limaris Soto	NPS Geologic Resources Division	Contractor
Trista Thornberry-Ehrlich	Colorado State University	Geologist/Graphic Designer

Appendix B: Geologic Resource Laws, Regulations, and Policies

The NPS Geologic Resources Division developed this table to summarize laws, regulations, and policies that specifically apply to NPS minerals and geologic resources. The table does not include laws of general application (e.g., Endangered Species Act, Clean Water Act, Wilderness Act, National Environmental Policy Act, or National Historic Preservation Act). The table does include the NPS Organic Act when it serves as the main authority for protection of a particular resource or when other, more specific laws are not available. Information is current as of August 2014. Contact the NPS Geologic Resources Division for detailed guidance.

Resource	Resource-Specific Laws	Resource-Specific Regulations	2006 Management Policies
Caves and Karst Systems	**Federal Cave Resources Protection Act of 1988, 16 USC. §§ 4301 – 4309** requires Interior/Agriculture to identify "significant caves" on Federal lands, regulate/restrict use of those caves as appropriate, and include significant caves in land management planning efforts. Imposes civil and criminal penalties for harming a cave or cave resources. Authorizes Secretaries to withhold information about specific location of a significant cave from a FOIA requester. **National Parks Omnibus Management Act of 1998, 16 USC. § 5937** protects the confidentiality of the nature and specific location of cave and karst resources. **Lechuguilla Cave Protection Act of 1993, Public Law 103-169** created a cave protection zone (CPZ) around Lechuguilla Cave in Carlsbad Caverns National Park. Within the CPZ, access and the removal of cave resources may be limited or prohibited; existing leases may be cancelled with appropriate compensation; and lands are withdrawn from mineral entry.	**36 C.F.R. § 2.1** prohibits possessing/ destroying/disturbing…cave resources…in park units. **43 C.F.R Part 37** states that all NPS caves are "significant" and sets forth procedures for determining/releasing confidential information about specific cave locations to a FOIA requester.	**Section 4.8.1.2** requires NPS to maintain karst integrity, minimize impacts. **Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity. **Section 4.8.2.2** requires NPS to protect caves, allow new development in or on caves if it will not impact cave environment, and to remove existing developments if they impair caves. **Section 6.3.11.2** explains how to manage caves in/adjacent to wilderness.

Resource	Resource-Specific Laws	Resource-Specific Regulations	2006 Management Policies
Paleontology	**National Parks Omnibus Management Act of 1998, 16 USC. § 5937** protects the confidentiality of the nature and specific location of paleontological resources and objects. **Paleontological Resources Preservation Act of 2009**, **16 USC. § 470aaa *et seq.*** provides for the management and protection of paleontological resources on federal lands.	**36 C.F.R. § 2.1(a)(1)(iii)** prohibits destroying, injuring, defacing, removing, digging or disturbing paleontological specimens or parts thereof. **36 C.F.R. § 13.35** prohibition applies even in Alaska parks where the surface collection of other geologic resources is permitted. Regulations in association with 2009 PRPA are being finalized (December 2013).	**Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity. **Section 4.8.2.1** emphasizes Inventory and Monitoring, encourages scientific research, directs parks to maintain confidentiality of paleontological information, and allows parks to buy fossils only in accordance with certain criteria.
Rocks and Minerals	**NPS Organic Act**, **16 USC. § 1 *et seq.*** directs the NPS to conserve all resources in parks (which includes rock and mineral resources) unless otherwise authorized by law. **Exception: 16 USC. § 445c (c) – Pipestone National Monument enabling statute**. Authorizes American Indian collection of catlinite (red pipestone).	**36 C.F.R. § 2.1** prohibits possessing, destroying, disturbing mineral resources…in park units. **Exception: 36 C.F.R. § 7.91** allows limited gold panning in Whiskeytown. **Exception: 36 C.F.R. § 13.35** allows some surface collection of rocks and minerals in some Alaska parks (not Klondike Gold Rush, Sitka, Denali, Glacier Bay, and Katmai) by non-disturbing methods (e.g., no pickaxes), which can be stopped by superintendent if collection causes significant adverse effects on park resources and visitor enjoyment.	**Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity.
Park Use of Sand and Gravel	**Materials Act of 1947, 30 USC. § 601** does not authorize the NPS to dispose of mineral materials outside of park units. **Exception:** 16 USC. §90c 1(b) the non-wilderness portion of Lake Chelan National Recreation Area, where sand, rock and gravel may be made available for sale to the residents of Stehekin for local use as long as such sale and disposal do not have significant adverse effects on the administration of the National Recreation Area.	None applicable.	**Section 9.1.3.3** clarifies that only the NPS or its agent can extract park-owned common-variety minerals (e.g., sand and gravel), and -Only for park administrative uses. -After compliance with NEPA and other federal, state, and local laws, and a finding of non-impairment. -After finding the use is park's most reasonable alternative based on environment and economics. -Parks should use existing pits and create new pits only in accordance with park-wide borrow management plan. -Spoil areas must comply with Part 6 standards -NPS must evaluate use of external quarries. Any deviations from this policy require written waiver from the Secretary, Assistant Secretary, or Director.

Resource	Resource-Specific Laws	Resource-Specific Regulations	2006 Management Policies
Upland and Fluvial Processes	**Rivers and Harbors Appropriation Act of 1899, 33 USC. § 403** prohibits the construction of any obstruction on the waters of the US that is not authorized by Congress or approved by the USACE. **Clean Water Act 33USC. § 1342** requires a permit from the USACE prior to any discharge of dredged or fill material into navigable waters (waters of the US, including streams). **Executive Order 11988** requires federal agencies to avoid adverse impacts to floodplains (see also D.O. 77-2). **Executive Order 11990** requires plans for potentially affected wetlands (including riparian wetlands; see also D.O. 77-1).	None applicable.	**Section 4.1** requires NPS to manage natural resources to preserve fundamental physical and biological processes, as well as individual species, features, and plant and animal communities; maintain all components and processes of naturally evolving park ecosystems. **Section 4.1.5** directs the NPS to re-establish natural functions and processes in human-disturbed components of natural systems in parks unless directed otherwise by Congress. **Section 4.4.2.4** directs the NPS to allow natural recovery of landscapes disturbed by natural phenomena, unless manipulation of the landscape is necessary to protect park development or human safety. **Section 4.6.4** directs the NPS to (1) manage for the preservation of floodplain values and (2) minimize potentially hazardous conditions associated with flooding. **Section 4.6.6** directs the NPS to manage watersheds as complete hydrologic systems and minimize human-caused disturbance to natural upland processes that deliver water, sediment, and woody debris to streams. **Section 4.8.1** directs the NPS to allow natural geologic processes to proceed unimpeded. Geologic processes…include…erosion and sedimentation…processes. **Section 4.8.2** directs the NPS to protect geologic features from the unacceptable impacts of human activity while allowing natural processes to continue.

Resource	Resource-Specific Laws	Resource-Specific Regulations	2006 Management Policies
Soils	**Soil and Water Resources Conservation Act, 16 USC. §§ 2011 – 2009** provides for the collection and analysis of soil and related resource data and the appraisal of the status, condition, and trends of these resources. **Farmland Protection Policy Act, 7 USC. § 4201 *et seq.*** requires NPS to identify and take into account the adverse effects of Federal programs on the preservation of farmland; consider alternative actions, and assure that such Federal programs are compatible with State, unit of local government, and private programs and policies to protect farmland. NPS actions are subject to the FPPA if they may irreversibly convert farmland (directly or indirectly) to nonagricultural use and are completed by a Federal agency or with assistance from a Federal agency. Applicable projects require coordination with the Department of Agriculture's Natural Resources Conservation Service (NRCS).	**7 C.F.R. Parts 610 and 611** are the US Department of Agriculture regulations for the NRCS. Part 610 governs the NRCS technical assistance program, soil erosion predictions, and the conservation of private grazing land. Part 611 governs soil surveys and cartographic operations. The NRCS works with the NPS through cooperative arrangements.	**Section 4.8.2.4** requires NPS to -Prevent unnatural erosion, removal, and contamination. -Conduct soil surveys. -Minimize unavoidable excavation. -Develop/follow written prescriptions (instructions).

The Department of the Interior protects and manages the nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its special responsibilities to American Indians, Alaska Natives, and affiliated Island Communities.

NPS 414/126779, October 2014

National Park Service
US Department of the Interior

Natural Resource Stewardship and Science
1201 Oakridge Drive, Suite 150
Fort Collins, CO 80525

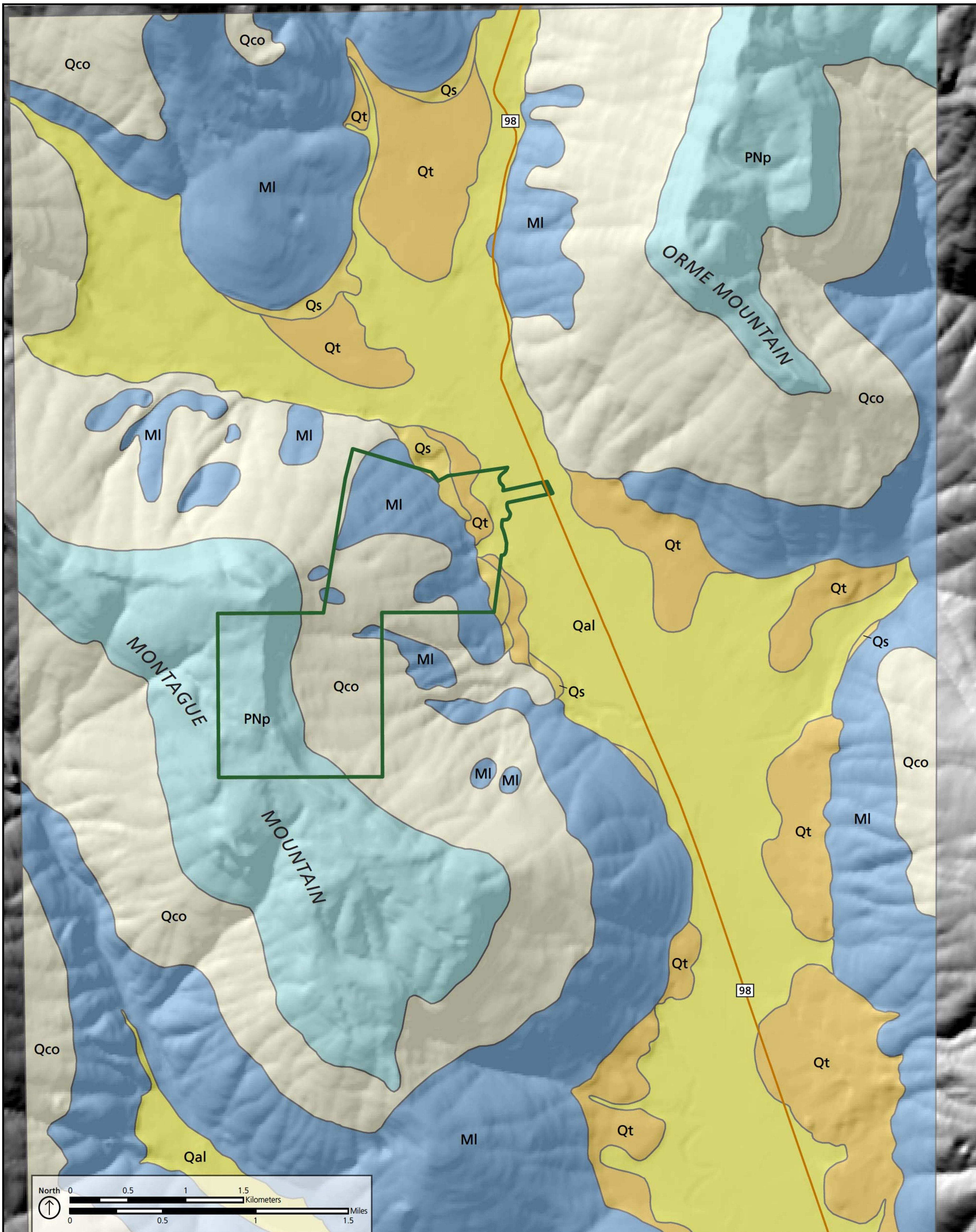
www.nature.nps.gov

Geologic Map of Russell Cave National Monument

Alabama

National Park Service
U.S. Department of the Interior

Geologic Resources Inventory



NPS Boundary

Map Symbols

local road

Geologic Contacts

known or certain

Geologic Units

Qco	Thin colluvium and slope wash on limestone and shale (Quaternary)
Qal	Alluvium of Recent [Holocene] age (Recent)
Qs	Terrace deposits and slope wash, locally derived, containing abundant chert fragments (Quaternary)
Qt	Terrace deposits and alluvial fans (Quaternary)
PNp	Pottsville Formation (Pennsylvanian)
Ml	Mostly shale and bioclastic and oolitic limestone (Mississippian)

This map was produced by Kari Lanphier (Colorado State University) in August 2014. It is an overview of compiled geologic data prepared as part of the NPS Geologic Resources Inventory. This map is not a substitute for site-specific investigations.

The source map used in creation of the digital geologic data was:

Hack, J. T. 1966. Geologic Map of Part of Doran Cove, Alabama and Tennessee (scale 1:24,000). Plate 1 *in* Interpretation of Cumberland Escarpment and Highland Rim, South-Central Tennessee and Northeast Alabama. Professional Paper 524-C. U.S. Geological Survey.

As per source map scale and U.S. National Map Accuracy Standards, geologic features represented here are within 12 m (40 ft) of their true location.

All digital geologic data and publications prepared as part of the Geologic Resources Inventory are available at the NPS Integrated Resource Management Applications Portal (IRMA): https://irma.nps.gov/App/Reference/Search. Enter "GRI" as the search text and select a park from the unit list.

Map Unit Properties Table: Russell Cave National Monument

All units are mapped within Russell Cave National Monument. Color in "Map Unit" column corresponds to the geologic map poster (in pocket). **Bold text** refers to report sections.

Age	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
QUATERNARY	Thin colluvium and slope wash on limestone and shale (Qco)	Colluvium consists of clast-supported, rather angular to slightly rounded cobbles and boulders that collect at the bases of slopes. Slope wash may contain a mixture of colluvium, talus, and landslide deposits, all of which form as accumulations of materials that fell, slid, or rolled downslope after being dislodged from above. **Qco** occurs over bedrock of limestone and shale, such as **PNp** and **Ml**. **Qco** occurs on the slopes of Montague Mountain within the monument, between the heights capped by **PNp** and the base of the slope covered by **Qs** and **Qt**.	**Differential Weathering**—**Qco** collects on the slopes of Montague Mountain as a result of weathering of blocks of **PNp**. **Slope Processes and Deposits**—large aprons of talus and colluvium nearly cover the base of Montague Mountain, the result of the gravity-driven transportation of blocks of **PNp** and other material downslope.	**Slope Movement Hazards and Risks**—**Qco** collects on the flanks of Montague Mountain as a result of slope movements. Unconsolidated slope deposits have the potential for subsequent movement.	**Weathering and the Exposure of Russell Cave**—Dry Creek flows across the terraced alluvial valley floor of Doran Cove. Several terraces and at least three alluvial deposits of different ages border the stream channel. At the foot of Montague Mountain, older alluvium is mixed with slope wash and other slope deposits. It may date to between 125,000 and 75,000 years ago. Intermediate-age alluvium encloses much of Dry Creek's channel; it was likely deposited during the most recent period of ice-age glacial advance (termed the "Wisconsinan") about 26,500 to 19,000 years ago. This alluvium may be younger. The youngest alluvium is confined to a narrow band along the channel of Dry Creek. It is still being deposited and reworked by Dry Creek. Just upstream to the entrance of Russell Cave, Dry Creek and its channel of **Qal** cut through a deposit of **Qt**. Between 9,000 and 11,000 years ago, a cavern roof collapsed to form a sinkhole and exposed the entrance to Russell Cave. The archeological record in Russell Cave covers more than 9,000 years. Inside the cave entrance, terraces 5 to 6 m (16 to 20 ft) high border the Dry Creek channel. These features correlate to the youngest alluvium in the valley, but further in the cave, the deposits are non-correlative.
	Alluvium of recent age (Qal)	**Qal** is associated with fluvial processes and is deposited along streams, floodplains, riparian areas, and alluvial plains. Sediment types may include clay, silt, sand, and gravel. **Qal** covers the floor of Doran Cove and appears at the lowest elevation in the monument.	**Differential Weathering**—**Qal** is accumulating along Dry Creek's channel. Its grain size decreases downstream because the water transports smaller grains farther downstream.	**Flooding**—modifications to Dry Creek's channel within and beyond the monument boundary are exacerbating flooding issues at the monument. Removal of natural "cobble bars" and artificial channel straightening decrease the system's ability to dissipate flash flood waters and energy.	
	Terrace deposits and slope wash (Qs)	Terrace deposits typically contain coarser sand and gravel perched above the modern floodplain; terraces represent former stream levels. Similar to **Qco**, **Qs** contains slope wash deposits. **Qs** is locally derived from bedrock such as **PNp** and **Ml**. **Qs** and **Qt** occur in lobe-shaped deposits at the bases of local hills, including Montague Mountain in the monument. **Qs** was deposited atop **Qt** within the monument; however, in other locations the temporal relationship is less clear or the two units do not appear together.	**Russell Cave and Other Karst Features**—chert fragments in **Qs** may have been a source for stone tools and trade material. **Differential Weathering**—**Qs** collects on the slopes of Montague Mountain as a result of weathering of blocks of **PNp**. **Slope Processes and Deposits**—slope wash deposits result from the gravity-driven transportation of loose accumulations of sediments down the slopes of Montague Mountain.	**Slope Movement Hazards and Risks**—**Qs** collects on the flanks of Montague Mountain as a result of slope movements. Unconsolidated slope deposits have the potential for subsequent movement.	
	Terrace deposits and alluvial fans (Qt)	Similar to **Qs**, **Qt** contains terrace deposits. Alluvial fans deposited by streams form at the bases of slopes, where they issue from narrow mountain valleys onto more level, open areas. They may contain coarse cobbles and boulders with sand, silt, and/or clay matrix material. Alluvial fans and sheets may coalesce to form aprons at the bases of slopes. **Qs** and **Qt** occur in lobe-shaped deposits at the bases of local hills, including Montague Mountain in the monument. **Qs** was deposited atop **Qt** within the monument; however, in other locations the temporal relationship is less clear or the two units do not appear together.	**Differential Weathering**—**Qt** collects at the bases of the slopes of Montague Mountain. **Slope Processes and Deposits**—alluvial fans form at the base of Montague Mountain.	**Slope Movement Hazards and Risks**—**Qt** collects on the flanks of Montague Mountain as a result of slope movements. Unconsolidated slope deposits have the potential for subsequent movement.	

All units are mapped within Russell Cave National Monument. Color in "Age" column corresponds to the geologic map poster (in pocket). **Bold text** refers to report sections.

Age	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
PENNSYLVANIAN	Pottsville Formation (PNp)	**PNp** consists of shale, coal, sandstone, and conglomerate beds. Only the lower portions of **PNp** are mapped in the monument area; the upper beds have eroded away. Within the monument, **PNp** caps the highest elevations of Montague Mountain. It provided much of the source material for **Qco**.	**Russell Cave and Other Karst Features**—the resistant **PNp** provides the cap rock that supports the heights of Montague Mountain and thus the hydraulic gradient that transports water through the conduit system within underlying **Ml**. **Differential Weathering**—**PNp** is more erosion resistant than **Ml** and forms the capstone atop Montague Mountain. Blocks of **PNp** collect on the mountain's slopes. **Slope Processes and Deposits**—blocks of **PNp** compose much of the talus and colluvium littering the slopes of Montague Mountain. **Sedimentary Rocks and Features**—shale, coal, sandstone, and conglomerate beds in **PNp** formed in depositional settings alternating between high-energy, nearshore areas such as beaches and low-energy, marsh-like environments. The contact between **PNp** and **Ml** is sharp and distinctive in outcrop. **Paleontological Resources**—**PNp** contains coal beds and carbonized plant fragments. At nearby Little River Canyon National Preserve, **PNp** contains remains of *Lepidodendron*, *Calamites*, bark impressions, and crinoids. Surface collections (now part of the interpretive materials) by monument staff include a blastoid *Pentremites pyriformis*, *Calamites* bark impressions, horn corals, the bryozoan *Archimedes*, brachiopods, gastropods, and crinoids.	**Flooding**—surface water flows over **PNp** before entering dissolved conduits in **Ml**, which rapidly transport groundwater through the system. When the drainage capacity of Russell Cave is exceeded, flooding and runoff occur upstream. **Slope Movement Hazards and Risks**—the shales marking the transition from **Ml** upwards into **PNp** form a surface along which blocks may slide. Blocks of **PNp** occur along the monument's nature trail. **Abandoned Mineral Lands**—at least seven abandoned coal mine tunnels are present in Montague Mountain (Russell Cave is at the base of the mountain). Two abandoned coal mine features in the monument have been mitigated. **Paleontological Resource Inventory, Monitoring, and Protection**—all paleontological resources are non-renewable and subject to science-informed inventory, monitoring, protection, and interpretation, as outlined by the 2009 Paleontological Resources Preservation Act. A monument-specific paleontological resource survey has not yet been conducted. Surface collections of fossils by monument staff have provided materials for interpretive programs.	**Longstanding Marine Deposition and Supercontinent Formation**—**PNp** was deposited in a prodelta/barrier/back-barrier island system. These systems were part of an inland sea near the equator at this time of the Paleozoic. The depositional environment became increasingly terrestrial and river dominated as the Alleghany Orogeny uplifted the Appalachian Mountains to the east and southeast. The highlands were an abundant source of sediment.

All units are mapped within Russell Cave National Monument. Color in "Age" column corresponds to the geologic map poster (in pocket). **Bold text** refers to report sections.

Age	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
MISSISSIPPIAN	Mostly shale and bioclastic and oolitic limestone (Ml)	**Ml** is a thick sequence of limestone with thin calcareous (carbonate-bearing) shale interlayers. The limestone contains oolites and bioclastic (derived from marine life forms) material. Oolites are spherical grains composed of concentric layers. They form as layers of chemically precipitated calcite that accumulate around a "seed" grain. **Ml** includes, from youngest to oldest: the Pennington Formation, the Bangor Limestone, the Hartselle Sandstone, and the Monteagle Limestone, also known as the Gasper Formation. The base of the Monteagle Limestone is not exposed on Montague Mountain within the monument.	**Russell Cave and Other Karst Features**—the limestone in **Ml** provides soluble material for karst feature development. Karst features within **Ml** include caves, sinkholes, springs, and internal drainage. **Differential Weathering**—**Ml** is softer and more soluble than **PNp** and underlies the slopes of Montague Mountain and the sinkhole plain (valley floor) of Doran Cove. **Sedimentary Rocks and Features**—oolites formed in **Ml** as wave action in a nearshore environment washed sediment grains back and forth in the shallows. The contact between **PNp** and **Ml** is sharp and distinctive in outcrop. **Paleontological Resources**—exposed on the roof of Russell Cave are disks from the crinoid *Agassizocrinus coniens*, as well as remains of brachiopods and blastoids. Some limestones in the unit may contain coral, bryozoans *Prismopora serrulata*, echinoderms *Pentremites pyramidatus* and *Pentremites brevis*, and crinoid *Pterotocrinus triebrachiatus*. The shale and mudstone may contain gastropods, molds of fenestrate bryozoans, brachiopods, and plate fragments. Horn corals and other fossils were collected from a sinkhole in the monument in 1987. Surface collections (now part of the interpretive materials) by monument staff include a blastoid *Pentremites pyriformis*, *Calamites* bark impressions, horn corals, the bryozoan *Archimedes*, brachiopods, gastropods, and crinoids.	**Flooding**—the dissolved conduits in **Ml** rapidly transport groundwater through the system. When the drainage capacity of Russell Cave is exceeded, flooding and runoff occur upstream. **Caves and Associated Karst Hazards**—the karst features formed in **Ml** are prone to flooding, collapse, rockfall, and instability. The Federal Cave Resources Protection Act of 1988 states that all National Park Service caves are significant and all caves are afforded protection and must be managed in compliance with approved resource management plans. The monument lacks a current cave management plan. Cave microclimate may cause radon concentrations. Russell Cave has been subjected to vandalism and is currently monitored. Dumping in local caves has been the target of clean-up efforts. Russell Cave has been closed since 2000. White-nose syndrome was detected in cave bats at the monument in 2012. **Slope Movement Hazards and Risks**—the shales marking the transition from **Ml** upwards into **PNp** form a surface along which blocks may slide. **Paleontological Resource Inventory, Monitoring, and Protection**—all paleontological resources are non-renewable and subject to science-informed inventory, monitoring, protection, and interpretation, as outlined by the 2009 Paleontological Resources Preservation Act. A monument-specific paleontological resource survey has not yet been conducted. Surface collections of fossils by monument staff have provided materials for interpretive programs.	**Longstanding Marine Deposition and Supercontinent Formation—Ml** records a variety of depositional settings ranging from prodeltas and deltas to marine shelves. These environments were part of a longstanding sea when North America was near the equator.