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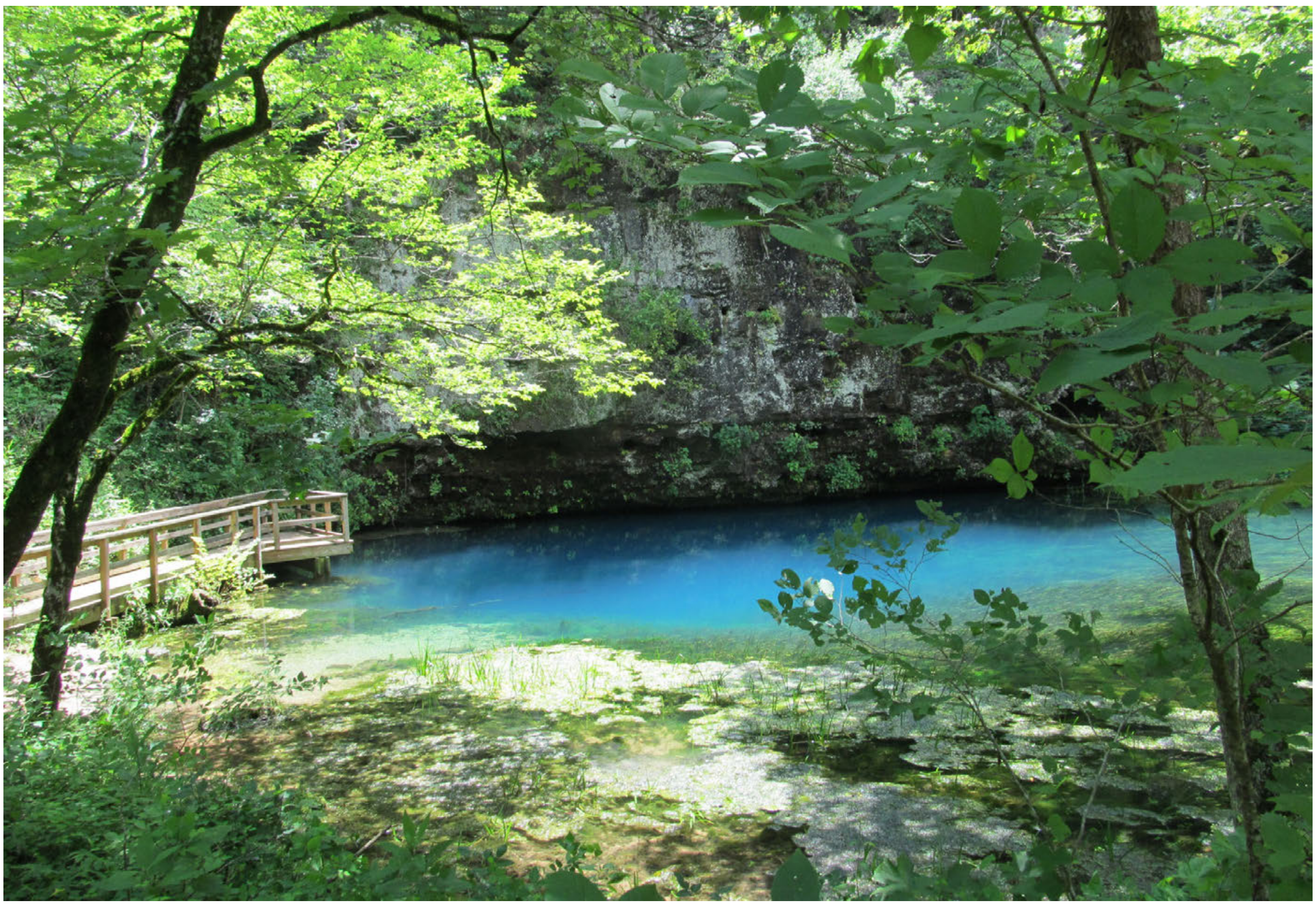
Natural Resource Stewardship and Science

Ozark National Scenic Riverways

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2016/1307



ON THE COVER: Mineral-laden waters emerge at Blue Spring along the Current River. High dissolved solids in the spring water lend a brilliant blue color to the water in sunlight. National Park Service photograph by Alianora Walker (Ozark National Scenic Riverways).

THIS PAGE: Steep bluffs of the Roubidoux Formation fronting the Jacks Fork. Photograph by J. Sigler (Creative Commons Attribution 2.0 [CC by 2.0] Generic License) available at https://commons.wikimedia.org/wiki/Category:Ozark_National_Scenic_Riverways (accessed 11 November 2015).

Ozark National Scenic Riverways

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2016/1307

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The National Park Service, Natural Resource Stewardship and Science office in Fort Collins, Colorado, publishes a range of reports that address natural resource topics. These reports are of interest and applicability to a broad audience in the National Park Service and others in natural resource management, including scientists, conservation and environmental constituencies, and the public.

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All manuscripts in the series receive the appropriate level of peer review to ensure that the information is scientifically credible, technically accurate, appropriately written for the intended audience, and designed and published in a professional manner. This report received informal peer review by subject-matter experts who were not directly involved in the collection, analysis, or reporting of the data.

This report is available from the Geologic Resources Inventory website (http://go.nps.gov/gripubs), and the Natural Resource Publications Management website (http://www.nature.nps.gov/publications/nrpm/). To receive this report in a format optimized for screen readers, please email irma@nps.gov.

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Executive Summary

The Geologic Resources Inventory (GRI) provides 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. The 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 held in 2001 and a follow-up conference call in 2015 (see Appendix A). Chapters of this report discuss the geologic setting, distinctive geologic features and processes within Ozark National Scenic Riverways, highlight geologic issues facing resource managers, describe the geologic history leading to the present-day landscape, and provide information about the previously completed GRI map data. Posters (in pocket) illustrate these data. The Map Unit Properties Table (in pocket) summarizes report content for each geologic map unit.

Soaring bluffs and cliffs; free-flowing rivers; cold, clear-blue springs; vast caverns, and rolling, forested uplands are the heart of Ozark National Scenic Riverways—the first designated national riverway. Authorized on August 27, 1964 and dedicated on June 10, 1972, the long and linear park protects the natural, Ozark cultural, and recreational resources along 216 km (134 mi) of the Current River and Jacks Fork. The rivers are the primary natural resources in the park, followed by springs, caves and karst features, bedrock bluffs, riparian zones, and rugged uplands.

Ozark National Scenic Riverways—hereafter referred to as "the park"—is part of a dissected karst plain on the Salem Plateau within the Ozark Plateaus physiographic province. The rivers and their tributaries cut through layers of soluble sedimentary rock punctuated by knobs of older, volcanic rock and create a landscape of picturesque low mountains, rolling hills, hollows, and bluff-flanked valleys. This landscape reflects where longstanding weathering and erosion have acted on two different types of bedrock: igneous (mostly volcanic) and sedimentary. The older igneous rocks are granite and rhyolite formed at the edge of an ancient rift via explosive caldera eruptions about 1.5 billion years ago. The younger sedimentary rocks, chiefly dolomite with minor amounts of quartz sandstone and chert, were deposited in an early Paleozoic shallow sea about 500 million years ago.

The park's karst features are outstanding, including one of the world's largest collection of first magnitude springs. The volcanic rocks are relatively insoluble and resistant to weathering contrasted with the soluble carbonate (dolomite) sedimentary rocks. In the soluble dolomite, dissolution created a karst landscape with myriad caves, sinkholes, and over 400 freshwater springs which empty thousands of gallons of cold, clear water into the park's waterways.

The geologic foundation of the park supports a vast and varied ecosystem with habitats ranging from forested uplands, caves, springs, and riparian zones. The geologic foundation has also influenced human history, from pre-contact American Indians who left a rich archeological record, to logging and resource extraction in the late 1800s, through the modern era of recreational land use.

This GRI report was written for resource managers to support science-informed decision making. 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 its preparation. This report is supported by GRI-compiled GIS geologic map of the park and surrounding areas. The US Geological Survey produced the data used to create the GRI GIS data set (Weary et al. 2014 and 2016). The Geologic Map Data chapter of this report contains additional information about the map and GIS data.

Geologic features and processes include the following:

- **Current River and Jacks Fork Systems**. The park's rivers are largely spring fed, which helps stabilize water levels and maintain a robust baseline flow despite regional climate change. Warm season water temperatures are relatively low. Fluvial features include meandering channels, gravel bars, low and high floodplains, and low terraces or uplands. These landforms are maintained through differential erosion and deposition that accompany past and contemporary floods.

- **Cave and Karst Features and Processes**. Caves, sinkholes, losing streams, and springs are prominent karst features at the park. Karst features form where, over time, soluble rocks, flowing groundwater, and a suitable gradient act in concert to dissolve solid bedrock. Bedrock features such as bedding planes and cracks control, in part, the location and nature of cave and karst features. At least 402 caves exist within the park. The caves exhibit beautiful formations called speleothems. The park's springs are world class in terms of sheer number, discharge, and water quality. Spring recharge areas bring in water from kilometers away through an underground network of conduits. The largest springs are Big, Alley, Blue, Round, Pulltite, and Welch springs. Sinkholes, formed either through slow subsidence or sudden collapse, are common along the Jacks Fork corridor. Streams that lose the bulk of their surficial flow to underground drainages are called losing streams. Many kilometers of designated losing streams exist in the Current River watershed.
- **Surficial Geologic Map Units**. Unconsolidated surficial deposits flank most of the river and stream valleys within the park. They record the most recent chapter of the park's geologic history. Earth surface processes of erosion and weathering formed these surficial deposits. In areas where the Gunter Sandstone member of the Gasconade Dolomite or the basal sandstone of the Roubidoux Formation are exposed, their differential resistance to erosion resulted in topographic benches on hillsides, small waterfalls, and streams "perched" on the sandstone.
- **Bedrock Weathering and Residuum Formation**. Long-term weathering of bedrock can produce residuum—a distinctive remnant or residual material left behind after the bedrock has eroded completely away. This residuum commonly includes large clasts of more or less intact bedrock parent material in a clay- and sand-rich matrix.
- **Slope Movements**. Mapped deposits of colluvium and talus mark areas that experienced slope movements or the downslope transfer of earth material. These areas may have the potential for future slope failures. Differential weathering created steep slopes and unconsolidated material. In areas where resistant blocks of sandstone were undercut by dissolution of carbonate rocks, rockfall hazards exist.
- **Periglacial Features**. Periglacial features form at the margins of glaciers under the influence of cold temperatures. Pleistocene glacial events and the accompanying cold global climate profoundly affected the Ozark landscape by accelerating frost weathering. Frost weathering occurs when repeated freezing and expanding of water within rocks or minerals wedges the rocks apart. Other periglacial features in the park include slope deposits and wind-blown glacial loess.
- **Sedimentary Rock Features**. The Paleozoic bedrock within the park is sedimentary and features relatively flat, undeformed bedding. Bedding becomes inclined near knobs of older, volcanic rocks that were islands during deposition of the sedimentary rocks. Sedimentary features within the rocks such as fossiliferous chert, oolites, and orthoquartzite provide clues about the original depositional environment and the history of the rocks since deposition.
- **Paleontological Resources**. The shallow seas that accumulated the park's sedimentary bedrock were filled with life during the Cambrian and Ordovician periods. This ancient life is now preserved as fossils in the park. Fossils are visible on cave walls and in loose blocks of rock and bedrock exposures along the river corridors. More recent, Pleistocene fossils are preserved in cave sediments. Park fossils are also found in cultural contexts at archeological sites.
- **Volcanic Rocks and the Eminence Caldera**. The volcanic rocks at the park are primarily rhyolites that were erupted during violent volcanism associated with the Eminence caldera. Collapse of the volcano caused some units to be tilted and later volcanism covered these units in untilted layers.
- **Radiometric Ages**. Radiometric dating methods compare the abundance of a naturally occurring radioactive isotope of a mineral with the abundance of its decay products, which form at a known constant rate of decay. Some igneous rocks in the park are dated, but additional dates would give geologists valuable information about the Mesoproterozoic (more than 1 billion years ago) geologic history of the park.

- **Faults and Fractures**. Faults in the bedrock are part of the GRI GIS data for the park. Most of the park's faults are nearly vertical and probably experienced lateral (strike-slip) motion. The faults are predominantly oriented northeast and northwest. Faults and through-going fractures influence groundwater movement in a highly permeable karst system.
- **Folds**. Minor folds—synclines, anticlines, and monoclines—are included in the park's GRI GIS data. At the park, folding occurred near faults during compression of the rocks or near dissolution of large voids that are part of the karst landscape.

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

- **Flooding and Fluvial Geomorphology**. The park was established in part to preserve the Current River and Jacks Fork as free-flowing streams whose courses are largely unimpaired by dams or other control methods. The morphology of a stream channel is integral to the fluvial and riparian ecosystem. Human modifications to the streambanks and floodplains have altered the natural system, affecting discharge, sediment supply, and erosional resistance of the banks. The riparian zones are among the most disturbed ecosystems in the park. Seasonal flooding is a natural process in the riparian corridor, but also threatens some park infrastructure.
- **Climate Change Impacts**. Climate change may impact fluvial processes; models predict increased temperatures and frequency of strong storms. This may increase water temperature, sediment load, and channel morphology thereby affecting dependent ecosystems.
- **Caves and Associated Landscape Management**. Caves are nonrenewable resources and integral to the park's landscape. Caves also pose specific resource management challenges including sinkhole flooding and collapse, cave breakdown, radon, vandalism and dumping, white-nose syndrome in bats, and slippery surfaces, precipitous drops, and drowning hazards. Cave breakdown is a natural process by which cave ceilings or walls collapse. Sinkholes occur throughout the park and are part of the GRI GIS data. Some mapped units and geologic settings are more susceptible to sinkhole formation such as the Gasconade Dolomite over the Eminence Dolomite. Because of the discovery of white-nose syndrome, all park caves, except for guided trips to Round Spring Cavern, are closed for recreational entry. Several park cave entrances are gated. This restriction limits some of the dumping, vandalism, and overuse of park caves. The park prepared a cave management plan in 2010 to provide strategies for dealing with cave-specific issues.
- **Ozarks Aquifer and Springs Protection**. The Ozarks aquifer is unconfined and supplies water to the park's many springs. Groundwater at the park travels up to 5 km (3 mi) per day. Because of the characteristically high infiltration rates and permeability of karst landscapes, little to no adsorption of any surficial contaminants occurs in karst-forming rocks. Therefore, in order to protect the park's springs, the aquifer recharge areas should also be protected, delineated, and studied; land use changes in adjacent areas should be carefully monitored.
- **Erosion**. The construction of roads, trails, parking lots, and other infrastructure; logging of forests with subsequent agricultural development; and human impacts from foot traffic, vehicles, and domestic animals can increase erosion throughout the park. Erosion can increase sediment load in streams which in turn can cause enhanced channel meandering.
- **Paleontological Resource Inventory, Monitoring, and Protection**. Theft and erosion threaten fossils from the park. All paleontological resources are nonrenewable and subject to science-informed inventory, monitoring, protection, and interpretation. To achieve this goal, a field-based, park-specific paleontological resource survey could be completed for the park.
- **Slope Movement Hazards and Risks**. The park's steep river bluffs, fractured rocks, and processes of erosion and weathering have created a setting where slope movements are possible. Slope deposits such as colluvium and landslide deposits mark areas most prone to natural slope movements.
- **Seismic Activity Hazards and Risks**. The park experiences infrequent earthquakes, including one in October 2015. The park's proximity to the New Madrid Seismic Zone should be an item of concern. Ground shaking could damage park infrastructure

including bridges and building foundations, as well as delicate cave formations.

- **Abandoned Mineral Lands**. The park has one listed abandoned mineral lands feature—the Partney dolomite quarry. This feature is considered historic. Other abandoned mineral lands may exist within the park, but have yet to be catalogued.
- **External Mineral Development**. The park is near active lead and zinc mines within the Viburnum Trend. Pumping associated with mining practices could affect groundwater quantity nourishing the springs. Additionally, further exploration for mineral resources occurs on lands adjacent to the park, including Mark Twain National Forest and the Eleven Point River area.

Products and Acknowledgments

The NPS Geologic Resources Division partners with the Colorado State University Department of Geosciences to produce GRI products. The US Geological Survey developed the source maps and reviewed GRI content. This chapter describes GRI products and acknowledges contributors to this report.

GRI Products

The GRI team undertakes three tasks for each park in the Inventory and Monitoring program: (1) conduct a scoping meeting and provide a summary document, (2) provide digital geologic map data in a geographic information system (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 GIS 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 GRI team conducts no new field work in association with their products.

The compilation and use of natural resource information by park managers is called for in the 1998 National Parks Omnibus Management Act (§ 204), 2006 National Park Service Management Policies, and the Natural Resources Inventory and Monitoring Guideline (NPS-75). The “Additional References” chapter 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://go.nps.gov/gri. The current status and projected completion dates of products are available at http://go.nps.gov/gri_status.

Acknowledgments

The GRI team thanks the participants of the 2001 scoping meeting and 2015 conference call (see Appendix A) for their assistance in this inventory. **Jonathan Beard** (Springfield Plateau Grotto of the National Speleological Society), **Justin Tweet** (NPS Geologic Resources Division), and **Scott House** (Cave Research Foundation) provided additional information.

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Geologic Setting and Significance

This chapter describes the regional geologic setting of the park and summarizes connections among geologic resources, other park resources, and park stories.

Park Establishment and Landscape

Ozark National Scenic Riverways encompasses a landscape of picturesque rivers, low mountains, rolling hills, hollows, and bluff-flanked valleys in southeastern Missouri. The landscape contains spectacular karst features including some of the nation's—and world's—largest springs. Caves and sinkholes are other classic karst features prominent in the park.

In the 1940s, the US Army Corps of Engineers suggested the Current River and Jacks Fork valleys were ideally located for a dam (White 1985). Following public outcry and a lengthy campaign, Ozark National Scenic Riverways was authorized on 27 August 1964 and dedicated on 10 June 1972 as the first designated national scenic riverway "for the purpose of conserving and interpreting unique scenic and other natural values and objects of historic interest, including preservation of portions of the Current River and the Jacks Fork in Missouri as free-flowing streams, preservation of springs and caves, management of wildlife, and provisions for use and enjoyment of the outdoor recreation resources" (Public Law 88-492). The park's mission is to protect the natural, Ozark cultural, and recreational resources along 216 km (134 mi) of riverine corridor through Shannon, Carter, Dent, and Texas counties in southeastern Missouri. About 1.5 million visitors come to the park each year (National Park Service 2015).

The Current River and Jacks Fork are the primary fluvial (riverine) resources at the park, lending to its sideways Y-shaped boundary (fig. 1, in pocket), but many smaller tributaries are also important throughout the nearly 32,800 ha (81,000 ac). The park includes the Current River corridor from Montauk State Park, near Salem, Missouri on the northwest, to the Ripley County line at the southeast end, and along the Jacks Fork from near the community of Mountain View northeast, to the confluence with the Current River. The rivers meander through the Courtois Hills, the most rugged landscape in the Ozarks (Stevens Jr. 1991). Two 6-km (4-mi) gaps in the park occur along the Current River near Van Buren and along the Jacks Fork near Eminence.

From its source at the confluence of Pigeon Creek and Montauk Springs near Montauk, Missouri, the Current River flows approximately 296 km (184 mi) southeast to its junction with the Black River near Pocahontas in northeast Arkansas. The Current River watershed drains a land area of approximately 6,788 km^2 (2,621 mi^2) in 11 counties in Missouri and Arkansas. About 18% of this watershed is the Jacks Fork drainage. The park manages less than 3% of the total watershed area (Vana-Miller 2007). The confluence of the park's two large rivers is 8 km (5 mi) east-northeast of Eminence, Missouri (National Park Service 2015). The Current River system, including Jacks Fork, drains the well-developed karst terrane along the southeastern margin of the Salem Plateau. One hundred and sixty named tributaries join the river system; many of these are "losing streams," meaning they are above the water table and contribute water to the saturated zone. These streams often flow only after rainfall events (Vana-Miller 2007). Incision of these drainages has produced a relatively steep, rugged topography with local relief reaching 50 m (160 ft) or more (Lowell et al. 2010). The dissected and forested nature of the region makes accessibility a challenge (Lowell et al. 2010).

Geologic Setting

The landscape in Missouri is divisible into three broad physiographic regions from north to south: the Central Lowlands, the Ozark Plateaus, and the Coastal Plain (fig. 2). The northern and west-central part of Missouri, the Central Lowlands, has gently rolling hills and broad valleys. It was glaciated during the Pleistocene ice ages and still has mantles of glacial deposits over the subdued topography (Gillman 2013). The park is within the Ozark Plateaus, which includes much of central and southern Missouri and covers a broad, uplifted region of about 130,000 km^2 (50,000 mi^2) that extends into northern Arkansas, southeastern Kansas, and northeastern Oklahoma. Thick sequences of Paleozoic limestone and dolomite underlie much of the plateau and the weathering of these units resulted in the characteristic steep-bluffed valleys, large springs, and cave networks. In areas of the plateau, ancient volcanic rocks punctuate the sedimentary rocks (Gillman

Figure 2. Map of physiographic provinces in Missouri. Ozark National Scenic Riverways (green-lined area) is within the Salem Plateau of the Ozarks Plateaus province. Although during the most recent ice age (Wisconsinan) glacial ice did not extend as far south as Missouri, the terminal extent or limit of earlier Pleistocene glaciation is marked by the dashed purple line. Bold red lines indicate regional escarpments. The yellow dashed area is the approximate location of the Viburnum Trend (a lead and zinc mining district). Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) using ESRI ArcMap basemap and information from the Missouri Department of Natural Resources (2002), Gillman (2013), and Weary (2015).

2013). In the extreme southeast corner of Missouri, a thick accumulation of fluvial deposits underlies the coastal plain. Today, large rivers such as the Mississippi continue to build the plain southward into the Gulf of Mexico (Gillman 2013).

Within the Ozark Plateaus province are the Boston Mountains (in Arkansas and Oklahoma), the Springfield Plateau, and the Salem Plateau (both in Missouri). The Eureka Springs escarpment separates the Springfield Plateau and the dissected karst plain (see "Cave and

Karst Features and Processes" section) of the Salem Plateau. The park traverses the Salem Plateau which is characterized by rolling uplands and rugged hills ranging between about 305 and 425 m (1,000 and 1,400 ft) in elevation with deeply entrenched stream valleys at about 155 m (510 ft) in elevation (National Park Service 2007).

Three main categories of rock are mapped within and surrounding the park (figs. 3 and 4; Weary et al. 2014; see also National Park Service 2007 and Lowell et al. 2010):

- (1) Very old igneous (previously molten) rocks that are approximately 1.4 billion years old (Mesoproterozoic Era; "**Y**" map units). These rocks formed when magma cooled beneath the surface of the earth (intrusive igneous rocks such as granite) or where lava erupted onto the surface by violent volcanic eruptions (extrusive igneous rocks such as rhyolite). The oldest igneous rocks are exposed as subtle, eroded hills. They also form an irregular bedrock "basement" upon which the younger sedimentary rocks were deposited.
- (2) Up to 550 m (1,800 ft) of relatively flat-lying sedimentary rocks about 500 to 470 million years old (Cambrian and Early Ordovician periods; "**C**" and "**O**" map units) such as dolomite, sandstone, and chert. Dissolution of the dolomite formed the caves, sinkholes, springs, and other karst features. Over 400 freshwater springs—one of the world's largest collection of first magnitude springs—empty millions of liters of cold, clear water into the park's waterways (Vana-Miller 2007; Bowles et al. 2011; National Park Service 2015).
- (3) Much younger unconsolidated surficial deposits and accumulations of material derived from deeply weathered older bedrock (Quaternary and Tertiary periods "**Q**" and "**QT**" map units). These rocks and deposits mostly formed in the past few tens or hundreds of thousands of years.

Geologic Significance and Connections

The geologic resources at Ozark National Scenic Riverways have supported varied human habitats and human history for thousands of years. There is a rich record of Archaic (8,000 to 1,000 BCE [Before Common Era]), Woodland (1,000 BCE to 1000 CE [Common Era]), and Mississippian (900 to 1500 CE) archeological resources along the Current River (Stevens Jr. 1991). Prior to European settlement around 1800, Ozark caves sheltered hunter-gatherer American Indians who used the caves for shelter and storage and built small villages and farms on the river terraces (Panfil and Jacobson 2001; White 1985). During dry periods, people inhabited the lowest floodplains and terraces. During wetter times, the higher terraces were favored (Stevens Jr. 1991). American Indians used chert for chipped-stone dart points and plant collecting tools. Bedrock and clay deposits were used to make limestone-tempered cord-marked ceramics (Stevens Jr. 1991). By the late 1700s, the inhabitants of the Current River valley had mostly migrated to larger settlements in the lowlands of southeast Missouri and northeast Arkansas. The park area was intermittently used for hunting until permanent settlement (Stevens Jr. 1991).

The Spanish were among the earliest European explorers to the Ozarks in the 1500s and were looking for precious ores. Some lead deposits were uncovered, but the region was too remote and isolated to support large settlements. Beginning in the 1720s, the famous Missouri lead resources (lead-bearing galena is the state mineral) were exploited by the French; mining in areas such as the Viburnum Trend, north of the park, started in the 1950s and continues today (Stevens Jr. 1991; Missouri Department of Natural Resources 2016).

Eminence, Missouri was founded and named for its elevation; lending its name later to the Eminence Dolomite (**Ce**) upon which it is perched. Both the Eminence Dolomite and Gasconade Dolomite (**Og**) contain caves, which are also part of local history (Eaton 1918). During the American Civil War, caves in the park were used as a source of saltpeter for gunpowder (e.g., Powder Mill Cave), a center of recuperation (e.g., Hospital Cave), a hiding place for town records (e.g., Courthouse Cave), and places to hide or seek refuge (White 1985).

After about 1800, European settlers cleared riparian areas and floodplains along the Current River and Jacks Fork for pasture and row crops, and logged timber from valley slopes (Panfil and Jacobson 2001). When a railroad reached the area in the 1870s, increased logging spawned a population increase between 1880 and 1920. This clearing of stabilizing vegetation would have caused a period of erosion and soil loss in the upland, sloped, and floodplain areas (White 1985). The fast-moving, larger rivers were used to facilitate the transfer of logs from site to mill (Buck et al. 2000). After

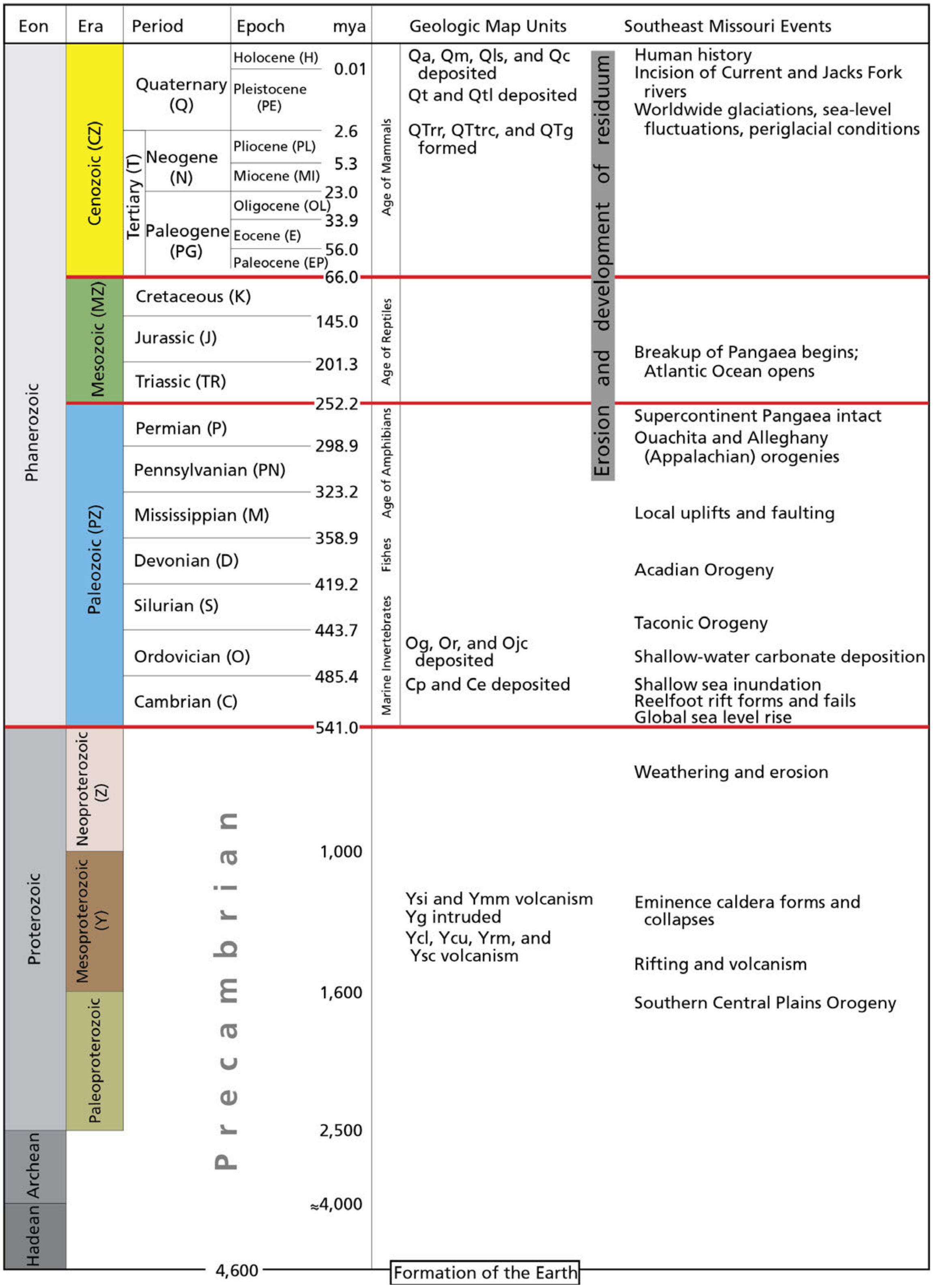


Figure 3. Geologic time scale. The divisions of the geologic time scale are organized stratigraphically, with the oldest divisions at the bottom and the youngest at the top. GRI map abbreviations for each time division are in parentheses. Boundary ages are millions of years ago (MYA). Major geologic events affecting southeast Missouri are highlighted, as well as geologic map units that appear within park boundaries. National Park Service graphic using dates from the International Commission on Stratigraphy (http://www.stratigraphy.org/index.php/ics-chart-timescale).

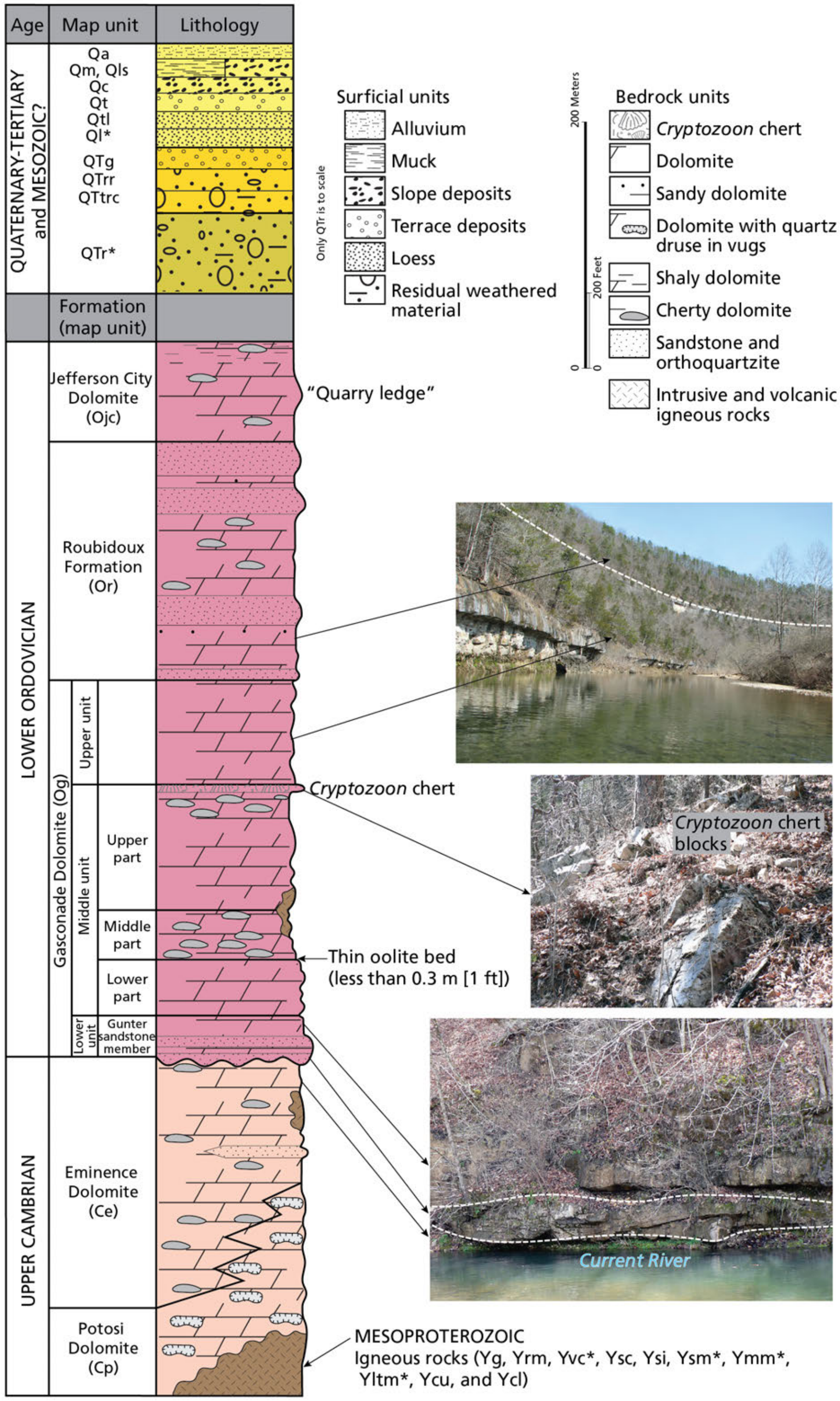


Figure 4. Stratigraphic column. Ozark National Scenic Riverways includes exposures of ancient volcanic bedrock ("Y" geologic map units), early Paleozoic sedimentary rocks (Cp, Ce, Og, Or, and Ojc), and younger, unconsolidated surficial deposits (Qa, Qm, Qls, Qc, Qt, Qtl, Ql, and QTg) and weathered bedrock remnants (QTrr, QTtrc, and QTr). Colors are standards defined by the US Geological Survey. White dashed lines on photographs represent approximate geologic contacts between units. Asterisks indicate units that are not mapped within park boundaries. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) with information from and after figure 2 in Weary et al. (2014). Photographs are, from top to bottom, cover image from Weary et al. (2014) taken by Victoria Grant (National Park Service), and figures 3 and 5 from Weary (2015).

the timber boom, residents returned to agriculture, annually burning upland areas to increase open range for grazing (Panfil and Jacobson 2001). The impacts of this past land use on the hydrogeologic system at the park are not well understood (Buck et al. 2000).

The karst spring system at the park provided many functions for human use including mills (e.g., Alley Spring and Mill, Pulltite Spring complex, and Welch Spring), fishing resorts (e.g., Pulltite and Welch springs), and mineral spa resorts (e.g., Welch Spring) (National Park Service 2015). Alley Spring was a Civilian Conservation Corps (CCC) work camp for World War I veterans in the 1930s (Lowell et al. 2010). CCC crews constructed state park facilities at Alley and Big springs (White 1985). The crews used local Cambrian or Ordovician rocks to construct many of the facilities.

A thorough examination of the park's cultural resources is beyond the scope of this report. Valuable references regarding the park's human history include Stevens Jr. (1991), and cultural landscape inventory reports such as National Park Service (2013a, 2013b).

Ecosystem Connections

Ozark National Scenic Riverways is part of the Current River Hills ecological subsection with moderately rolling to steeply dissected hills associated with the major rivers and their tributaries. The geology is karstic (see "Cave and Karst Features and Processes" section).

According to National Park Service significance statements presented in Vana-Miller (2007), five fundamental natural resources are associated with the park:

- The high water quality and clarity in the free-flowing Current River and Jacks Fork
- The high density of caves and springs
- The fragile, karst-based hydrogeological system
- A significant diversity of high-quality ecosystems within the river corridors
- The assemblage of unique plants and animals.

These resources are either purely geologic or have strong ties to the geologic foundation of the park.

Cave environments are relatively stable with regards to temperature and humidity, generally have fewer food sources, and low biodiversity; nevertheless they provide important habitat for a variety of specially adapted species (Baker et al. 2015). The constant water temperatures and distinctive water chemistry of the many karst springs at the park are important for plants and sensitive animals not otherwise found in the local rivers (Bowles et al. 2011; National Park Service 2015). Aquatic plants provide sustenance and habitat for at least 38 animal species found only in Ozark springs and subterranean waters (Vana-Miller 2007; National Park Service 2015). The springs support fish species such as sculpins and bleeding shiners that require clean gravel and cobble substrates (Bowles et al. 2011). Caves shelter cave-obligate species, including the Ozark big-eared bat, 46 cave-aquatic species, and 31 cave-terrestrial species (Vana-Miller 2007; Baker et al. 2015). Many cave species are largely unknown due to their small populations, restricted ranges, and low rates of reproduction.

In addition to supporting cave ecosystems, the bedrock in the park creates cliffs and ledges for raptors, rocky-slope exposures for more than 184 taxa of lichen, and open glades that support distinctive plant communities at the contacts between rock units (specifically between the Eminence Dolomite (**Ce**), Gasconade Dolomite (**Og**), and Roubidoux Formation (**Or**) (Weary et al. 1999; Bennett and Wetmore 2005). The rocky slopes provide substrate for native vegetation, mainly oak-hickory and oak-shortleaf pine forests and woodlands (Buck et al. 2000). Weathering of bedrock gives rise, in part, to the development of soils. A detailed soils map of the park was produced by the NPS Soil Resources Inventory and is available at https://irma.nps.gov/App/Reference/Profile/1048949.

Wetlands within the park include marshes, doline lakes (sinkhole ponds), bottomland forests, riparian low-lying areas, and groundwater seeps (Vana-Miller 2007). Sinkholes that have collected substantial debris and wetland deposits are mapped as "muck" (**Qm**) in the GRI GIS data (Weary et al. 2014). Some of these areas, such as Tupelo Gum Pond and Cupola Pond in Mark Twain National Forest, support rare flora and fauna (Dave Weary, US Geological Survey, geologist, written communication, 24 June 2016). Groundwater seeps tend to be found at the base of slopes and where groundwater contacts an impermeable unit and flows horizontally until it emerges at the surface. Alkaline groundwater produces seeps called fens, which may contain plants more typical of northern states and are rare or endangered in Missouri. More than 30 fens are known from the Current and Jacks Fork watersheds (Vana-Miller 2007). Little is known about the size, extent, and species composition of the park's wetlands (Vana-Miller 2007). A wetlands inventory study could be a potential project for the Geoscientists-in-the-Parks program (http://www.nature.nps.gov/geology/gip/).

Riparian habitats are a major natural component of the park, and are considered some of the most diverse, dynamic, and complex habitats in the terrestrial environment (Vana-Miller 2007; National Park Service 2015). The riparian area encompasses the stream channel between low and high water levels meaning it is susceptible to floods. Flood frequency, soil and regolith characteristics, and elevation above and distance from the river channel are important determinants of plant species distributions (Buck et al. 2000). Some of the more stable riparian and floodplain areas support second- and third-growth bottomland hardwood forests (Buck et al. 2000). The riparian areas support at least 66 woody species of plants and 442 species of ground plants (Buck et al. 2000). Cane (*Arundinaria gigantea*), a riparian plant that forms canebreaks or areas of ground covered with a dense growth of canes, was once widespread but is now considered critically endangered (Vana-Miller 2007). The watersheds provide habitat for 43 species and subspecies of mussels (two of which are federally listed as endangered) and 14 species of crayfish, including the Salem cave crayfish (*Cambarus hubrichti*) which is a species of conservation concern (Vana-Miller 2007).

The ancient Ozark highlands is a significant biodiversity center in North America with over 200 endemic species (Vana-Miller 2007). This diversity is due to the integrity and protection of its connected region and the rich-array of geology-supported aquatic, terrestrial, and subterranean habitats that are concentrated within the Current River and Jacks Fork corridors (Vana-Miller 2007). The Ozarks region may be one of the oldest continuously exposed land masses that make up North America; it served as refugium for organisms exposed to climatic extremes associated with ice ages. In its history, it has been a mixing zone of boreal, prairie, desert, deciduous forest, and alluvial floodplain ecosystems (Vana-Miller 2007).

Geologic Features and Processes

These geologic features and processes are significant to the park's landscape and history.

During the 2001 scoping meeting (see National Park Service 2001) and 2015 conference call, participants (see Appendix A) identified the following geologic features and processes:

- Current River and Jacks Fork Systems
- Cave and Karst Features and Processes
- Surficial Geologic Map Units
- Bedrock Weathering and Residuum Formation
- Slope Movements
- Periglacial Features
- Sedimentary Rock Features
- Paleontological Resources
- Volcanic Rocks and the Eminence Caldera
- Radiometric Ages
- Faults and Fractures
- Folds

Weary et al. (2014) provided a comprehensive overview of the geology of the Current River and Jacks Fork drainages in a report that accompanies the 1:100,000-scale map used to develop the GRI GIS data. That publication is a key resource to understanding the geologic framework of the area, particularly with regards to groundwater flow through the karst drainage basin.

Current River and Jacks Fork Systems

Long and linear, Ozark National Scenic Riverways encompasses portions of the Jacks Fork and Current rivers, two of the three designated Outstanding National Resource Waters in Missouri. The Jacks Fork flows 55

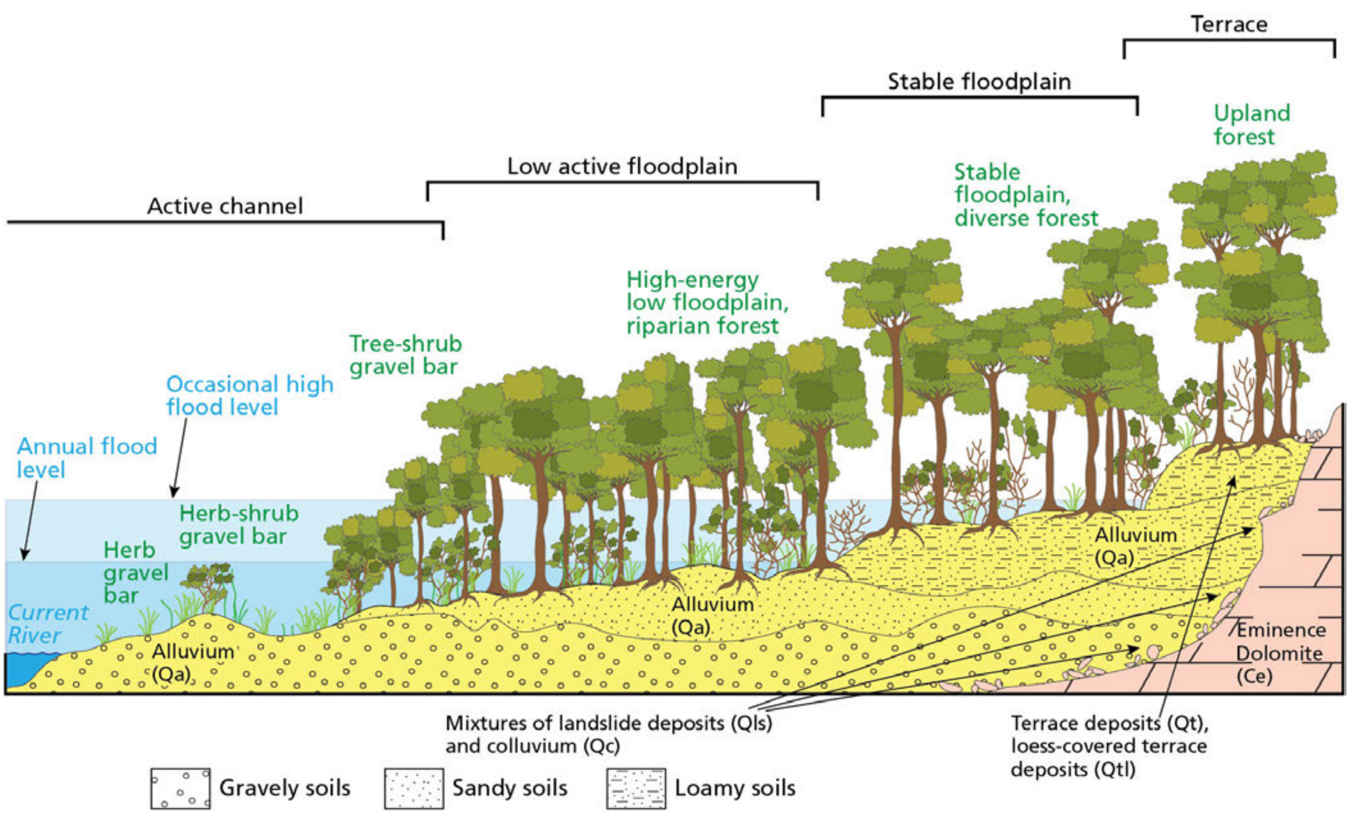


Figure 5. Cross-sectional illustration of a typical riparian area or floodplain of the Current River. Green text refers to habitat types associated with each level above the river channel. Soil composition varies with age and distance from and above the river. Annual and occasional flood levels are indicated by blue areas. Colors are standard US Geological Survey designations for different units of geologic time. Graphic by Trista Thornberry-Ehrlich (Colorado State University) adapted from an unnumbered figure in appendix C of Buck et al. (2000).

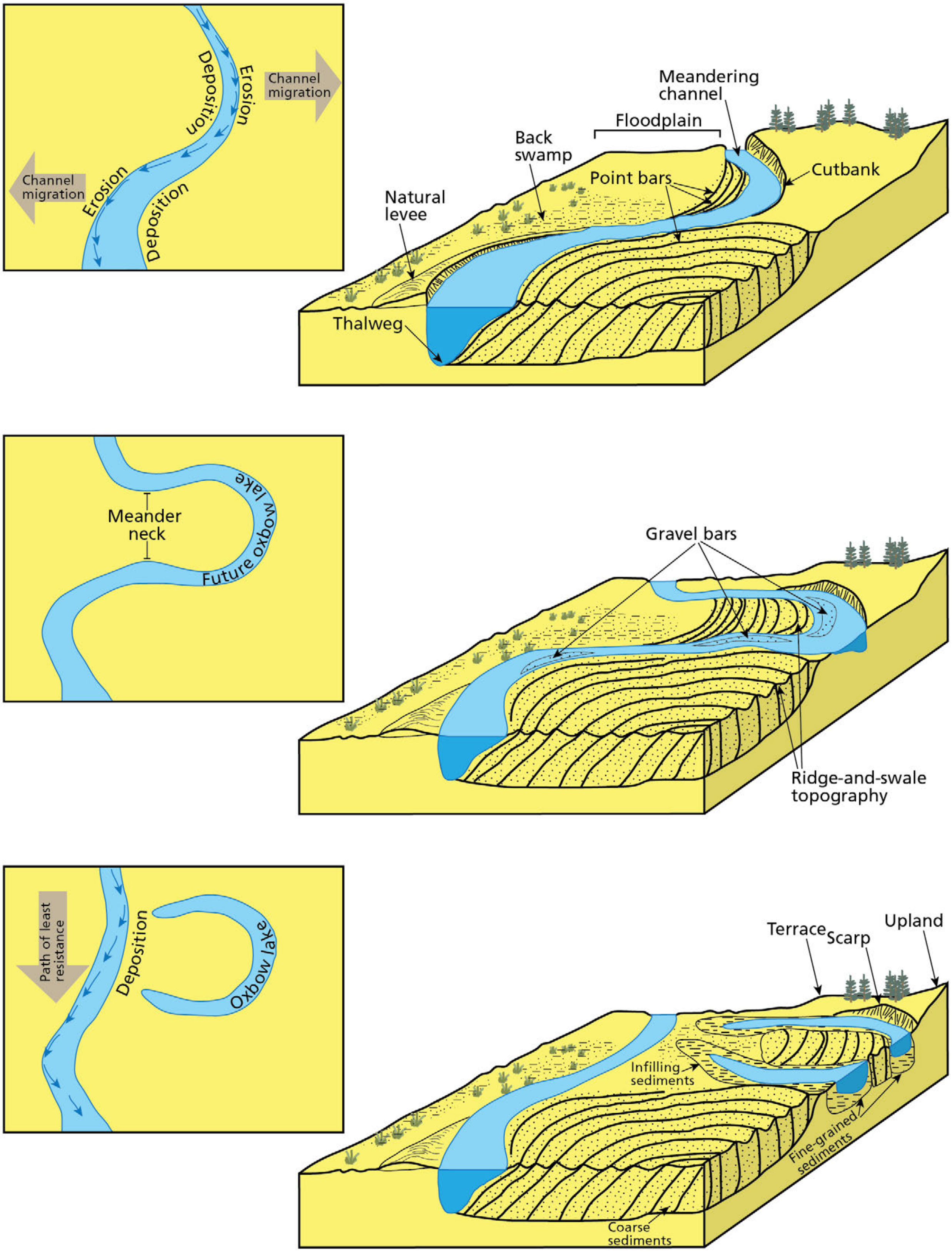


Figure 6. Illustration of fluvial processes of meandering. River meandering creates abandoned channels that infill with fine-grained sediments. Floodplain and riparian areas are characteristic landforms of meandering rivers. They are visible along the channels of the Current River and Jacks Fork (see also fig. 5). Graphic by Trista Thornberry-Ehrlich (Colorado State University) with information from Allen (1964).

km (34 mi) through the park at a gradient of 1.8 m/km (9.5 ft/mi) and the Current River courses 161 km (100 mi) at a gradient of 1.12 m/km (5.92 ft/mi). The overall gradient of their channels is relatively steep compared to the state average of 0.65 m/km (3.45 ft/mi), creating swifter currents (Wilson 2001; Vana-Miller 2007). This also creates the possibility of large, flood-producing flows accompanying east-moving precipitation systems (Wilson 2001).

As much as 90% of the flow in the major rivers, streams, and tributaries of the system comes from karst springs, therefore the drainage system is considered karstic (see "Cave and Karst Features and Processes" section); it is characterized by dendritic and radial drainages (Mugel et al. 2009; Buck et al. 2000). The high input from springs creates a relatively stable base flow and cool water temperatures (Wilson 2001; Vana-Miller 2007). Suspended sediment and dissolved minerals give the river waters distinctive blue colors. With the exception of exposures of Potosi Dolomite (**Cp**) near Eminence-Stegall Mountain and downstream near Van Buren, the main channel of the Current River flows over Eminence Dolomite (**Ce**) and Gasconade Dolomite (**Og**) throughout the length of the park (Lowell et al. 2010; Weary et al. 2014). The Jacks Fork flows over the Roubidoux Formation (**Or**), Gasconade Dolomite (**Og**), Eminence Dolomite (**Ce**), and Potosi Dolomite (**Cp**) through the map area (Weary et al. 2014).

Seasonal floods are a major driving force of landscape evolution at the park; along the river, landforms are maintained through the differential erosion and deposition that accompany past and contemporary floods (Buck et al. 2000). Typical, yearly floods raise water levels on both major rivers from 2 to 3 m (6.5 to 9.8 ft) above baseflow; 25- to 50-year floods reach 4 to 6 m (13.1 to 19.7 ft) above baseflow (Jacobson and Primm 1994; Buck et al. 2000).

The rivers contain typical fluvial landforms such as meandering channels, gravel bars, low and high floodplains, and low terraces or uplands (figs. 5, 6, and 7; Buck et al. 2000). At the park, river channels are

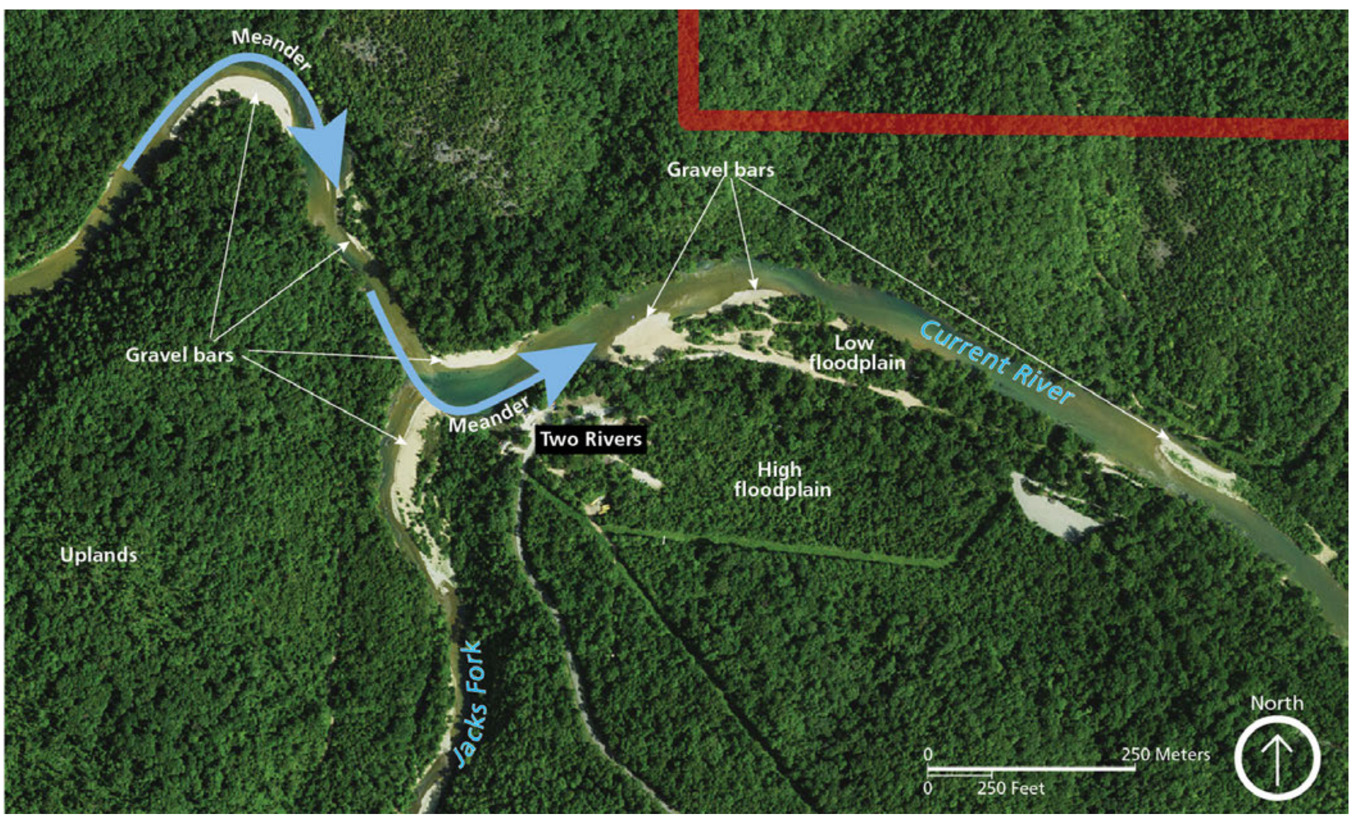


Figure 7. Aerial image of the confluence of the Current River and Jacks Fork. Both rivers are meandering across their floodplains, creating sharp bends and gravel bars on the inside of the bends and near confluences of tributaries. Thick red line is the park boundary for Ozark National Scenic Riverways. Graphic by Trista Thornberry-Ehrlich (Colorado State University) using ESRI World Imagery basemap (accessed 9 May 2016).

gravelly, and are mostly eroding although deposition in gravel bars does occur. Gravel and sand bars occur within active channels, typically in point bar settings along the inside of bends or where tributaries join, and may be submerged or emergent. Low floodplains have sandy and very gravelly sandy soils, a wavy to smooth surface, and flood annually to elevations between 2 and 5 m (6 and 15 ft) above the active channel. High floodplains are characterized by loamy, gravelly loamy, and silty soils, smooth to flat surfaces. They flood occasionally to elevations between 5 and 10 m (15 and 30 ft) above the active channel. The surfaces of high floodplains are hundreds to thousands of years old while low floodplain surfaces can be a few decades to 100 years old. Terraces have distinctive soil development, loamy to silty soils, elevated flat surfaces, and rarely flood (Buck et al. 2000). They are perched 10 to 15 m (30 to 45 ft) above the channel and are remnants of former floodplains above former active-channel levels, thousands or tens of thousands of years ago (Buck et al. 2000).

Cave and Karst Features and Processes

Caves are naturally occurring underground voids such as solutional caves (commonly associated with karst), lava tubes, sea caves, talus caves (a void among collapsed boulders), regolith caves (formed by soil piping), and glacier caves (ice-walled caves) (Toomey 2009). Karst is a landscape that forms through the dissolution of soluble rock, most commonly carbonates such as limestone or dolomite (Toomey 2009). Caves, sinkholes, "losing streams," springs, and internal drainage are characteristic features of karst landscapes. As of July 2016, cave or karst resources are documented in at least 160 parks, including Ozark National Scenic Riverways. Baker et al. (2015) included the park among those in the National Park System that contain notable solution caves. According to Land et al. (2013), 99% of the park is karst. The NPS Cave and Karst website, https://www.nps.gov/subjects/caves/index.htm, provides more information. Weary and Doctor (2014) compiled a karst database for the United States; Ozark National Scenic Riverways is mapped in the "carbonate rocks at or near the land surface" unit, which is typically karst.

Since 2010, all caves in the park are closed to visitation with the exception of guided tours of Round Spring Cavern. The closure is to minimize the spread of white-nose syndrome, a fungal disease that has killed millions of bats in North America. See the "Geologic Resource Management Issues" chapter for more information.

Nearly 7,000 caves have been documented in the state of Missouri (Missouri Speleological Survey 2016) and more than 402 solution caves are within Ozark National Scenic Riverways (Kimberly Houf, terrestrial ecologist, Ozark National Scenic Riverways, email, 8 September 2016). The park ranks first for the greatest number of solution caves in a unit of the National Park System (statistics compiled by Dale Pate, cave and karst program coordinator, NPS Geologic Resources Division, 9 September 2016). The caves in the park range from simple rock overhangs to extensive, networks of passages, including Powder Mill Cave with more than 14.2 km (8.8 mi) of mapped passages; all together the mapped passages in the park total 45 km (28 mi) (Scott House, Ozark operations manager, Cave Research Foundation, email, 9 September 2016). Sixty caves in the park have perennial streams, 33 have intermittent water sources, and seven have lakes (Vana-Miller 2007). Notable cave examples include Bear Cave and Bunker Hill Cave along the Jacks Fork, Devils Well near Pulltite, and Round Spring Cavern near the crossing of Highway 19 and the Current River. The lake in Devils Well Cave is about 122 m (400 ft) long, up to 15 m (50 ft) wide, and up to 61 m (200 ft) deep—one of the largest cave lakes in the country (Vana-Miller 2007). Cave divers explored the underground conduit of Blue Spring reaches to a depth of at least 90 m (300 ft) (National Park Service 2015). More than 900 m (3,000 ft) of Alley Spring Cave has been mapped by divers (fig. 8; Ozark Diving Alliance 2005; Lowell et al. 2010).

The Missouri Speleological Society maintains a database (available at http://www.mospeleo.org/) of cave information which includes the number of caves in the state and cave maps (Crews 2008).

Development of Caves and Karst Features

Caves, sinkholes, losing streams, and springs are prominent karst features that formed in the Paleozoic-age carbonate bedrock at the park (National Park Service 2015). Cave and karst development requires four geologic conditions:

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

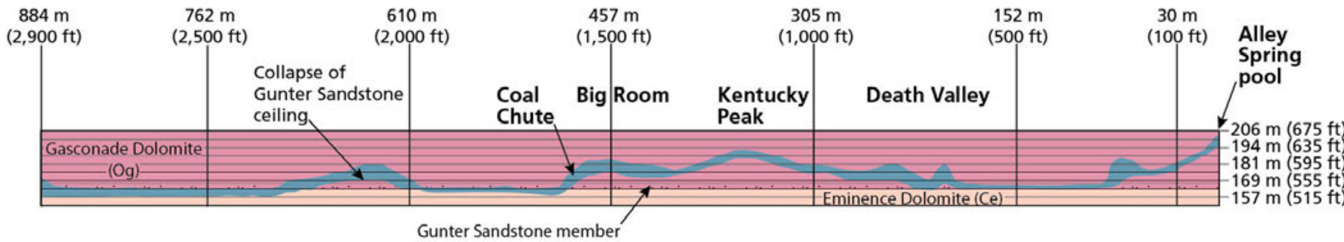


Figure 8. Graphic of the Alley Spring cave profile. The western edge of the known cave system is 30 m (100 ft) below the spring pool surface. Hydrostatic pressure from a confined aquifer forces the water from depth up to the surface to emerge in the spring pool. Regional faults may also facilitate groundwater movement. The cave is in both the Eminence Dolomite (Ce) and the Gasconade Dolomite in areas where the Gunter Sandstone member has been breached and/or collapsed. Graphic by Trista Thornberry-Ehrlich (Colorado State University) redrafted after figure 6.2 in Lowell et al. (2010).

Soluble Rocks

First among these conditions is the existence of a suitable body of rock, in this case Paleozoic carbonate rocks (geologic map units **Ojc**, **Og**, **Ce**, and **Cp**), which occur in flat-lying to gently inclined beds (Hack 1966; Weary et al. 2014). Limestone and dolomite are ideal for the formation of karst features because they are highly soluble in carbonic acid (White 1988). The upper Gasconade Dolomite (**Og**) contains the most caves in the park area, with the upper part of the Eminence Dolomite (**Ce**) also containing significant caves (Lowell et al. 2010). Caves tend to form beneath sandstone layers, with the cave passages trending more or less parallel to bedding (Weary and Orndorff 2001; Lowell et al. 2010).

Solvent (Groundwater)

The second condition required for extensive cave development is the presence of abundant solvent—acidic groundwater. Located in a temperate climate, southern Missouri receives an average of 115.75 cm (45.57 in) precipitation per year which provides a substantial amount of water to the hydrogeologic system (National Weather Service 2015). Cave formation occurs below the water table where 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 and dolomite (White 1988). The acid reacts with calcium carbonate ($CaCO_3$) or dolomite ($CaMg(CO_3)_2$) in the carbonate rocks to produce soluble calcium (Ca^{2+}) or magnesium (Mg^{2+}) and bicarbonate (HCO^{3-}) ions. The result is the dissolution of carbonate rocks, which are considered to be "in solution."

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. Acid rain has the potential to increase the rate of dissolution by approximately 1,000 times (Volesky 2009). Sullivan (2016) ranked the park's estimated acid pollutant exposure and exposure to sulfur and nitrogen emissions as "high." The NPS Air Resources Division provides guidance for servicewide air quality monitoring (see http://nature.nps.gov/air/Monitoring/index.cfm). Ozark National Scenic Riverways is not a participating park. The closest participating parks are Mammoth Cave National Park (Kentucky) and Buffalo National River (Arkansas). Both of those parks have similar karst landscapes. Although acid rain greatly increases the rate of carbonate rock solution, in terms of a human time-scale, it is still a fairly slow process.

Hydrogeologic Framework

The third basic element required for cave formation is a hydrogeologic framework which provides a sufficient hydraulic gradient as well as permeability and porosity within the bedrock to allow water to flow through the rock. When carbonic acid dissolves soluble bedrock, the solution quickly reaches saturation, preventing further dissolution. For this reason, a high hydraulic gradient, inherent in steep slopes such as those that exist between the uplands and the valley floors within the Ozark Plateau, must be present to provide sufficient

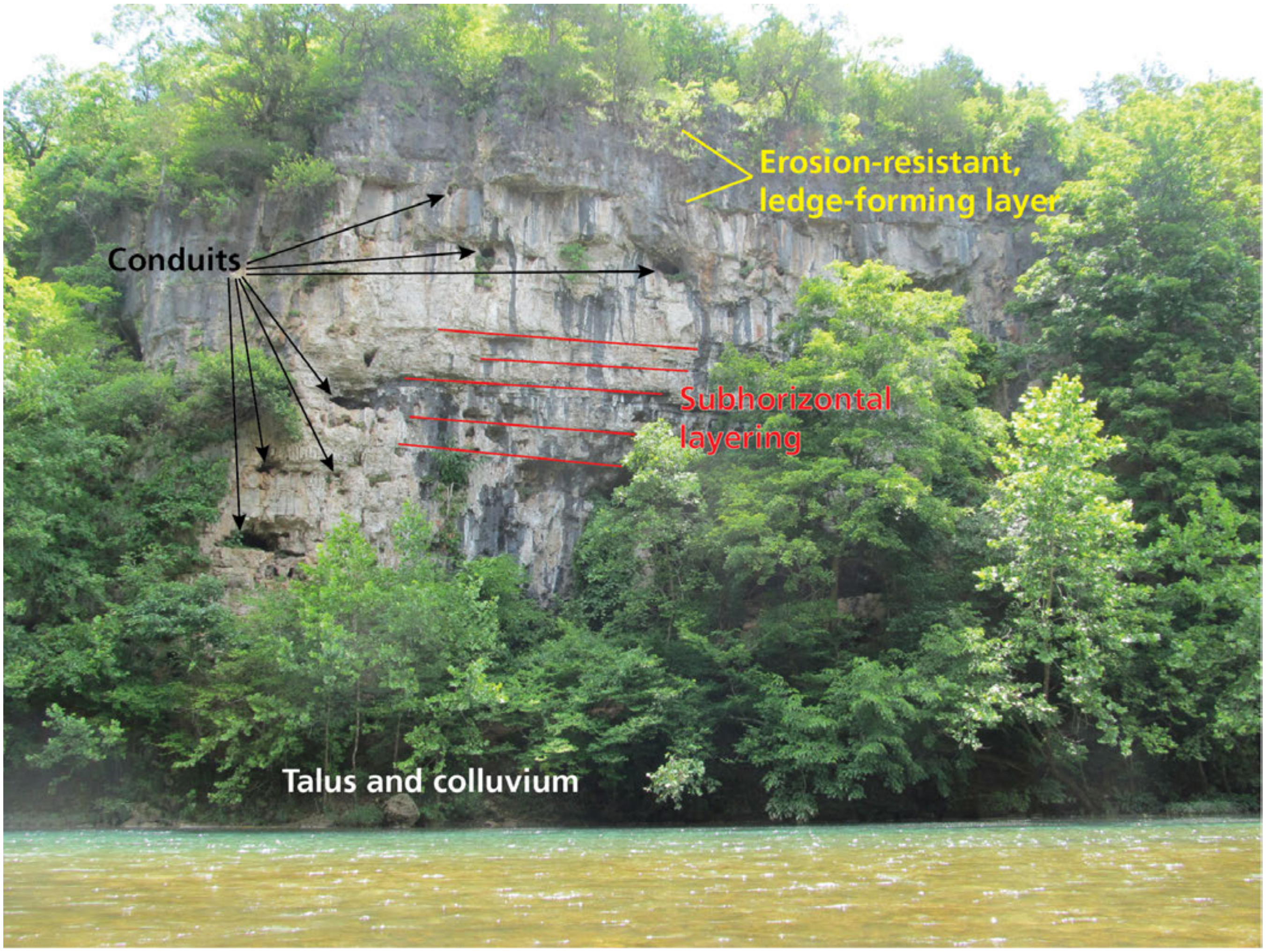


Figure 9. Photograph of dissolution conduits forming in the Eminence Dolomite. Dissolution of dolomite layers into caves and smaller conduits tends to be concentrated in subhorizontal carbonate bedrock below prominent sandstone layers such as within the Eminence Dolomite (Ce). As the outcrop slowly weathers away, blocks fall to litter the toe of the slope as colluvium or talus. National Park Service photograph courtesy of Alianora Walker; annotation by Trista L. Thornberry-Ehrlich (Colorado State University).

energy to rapidly move the solvent through the rock (Kuehn et al. 1994). In some cases the solutional "aggressiveness" of the groundwater can be rejuvenated when dissimilar groundwater masses mix. This mixing may be controlled by features in the hydrogeologic framework, like fractures and faults. Detailed mapping suggests initial dissolution and the beginning of cave branching development was controlled by bedding planes and stratigraphic variations within the bedrock of the Salem Plateau (fig. 9; Orndorff et al. 2006). The gentle regional dip of the dolomite layers to the southeast, toward the base drainage of the Black River (and eventually the Mississippi River), influenced groundwater circulation. Because cave passages tended to form parallel to bedding, or sedimentary layers within the dolomite, the bedding structures may have controlled the orientation of cave system formation (Hack 1974).

Caves in the park are either hypogenic or epigenic and this relates to their position relative to the sandstone layers. Hypogenic caves form in and follow bedrock beneath impermeable sandstone layers. They form below the water table, possibly under enhanced hydrostatic pressure. Epigenic caves, a more common type of cave, form in layers above sandstone where water flows downward and along the top of an impermeable sandstone layer (Vana-Miller 2007).

Orndorff et al. (2006) suggested the park's cave development is driven by confining conditions beneath prominent sandstone layers that occur within the Eminence Dolomite (**Ce**; fig. 10), at the base of the Gasconade Dolomite (**Og**), and within the Roubidoux Formation (**Or**). This setting creates hydrostatic pressure that affects the chemistry and solvent strength of groundwater (see "Springs" subsection). The contact between the Eminence Dolomite (**Ce**) and the overlying Gunter Sandstone member of the Gasconade Dolomite (part of **Og**) is visible at Baptist Camp and perhaps most spectacularly, in parts of the Left-Hand Route of Round Spring Cavern (Lowell et al. 2010). The contact between the Gasconade Dolomite (**Og**) and Roubidoux Formation (**Or**) may be seen on State Highway 106, 1.2 km (0.73 mi) west of Alley Spring (Lowell et al. 2010).

Time

Time is the final 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). Yearly dissolution rates are low, but when this is multiplied by hundreds of thousands or millions of years, huge cavities may form. Eventually, all of the rock will be dissolved away to become part of the base level of the Current River's and Jacks Fork's valleys. At the park, groundwater first came into contact with the Jefferson City Dolomite (**Ojc**), the uppermost soluble unit (Weary et al. 2014). Over hundreds of thousands of years, dissolution occurred among the intergranular pores and along fractures in the bedrock, creating voids (**Ojc**, **Og**, **Ce**, and **Cp**) (Crews 2008; Weary et al. 2014). Continued dissolution enlarged the voids, culminating in the formation of large caverns and extensive spring-drainage networks. Dissolution and cavern formation continue today (Crews 2008).

Speleothems

Cave formations or deposits known as speleothems may form in passages that are above the water table. Lowering of the water table occurs via downcutting of surface streams. Groundwater trickling through overlying soluble bedrock is saturated with dissolved minerals. Upon reaching the air in the cave, it releases carbon dioxide (degasses) and the minerals that were in solution precipitate out to form dripstones (e.g., stalagmites and stalactites) and flowstone (e.g., rimstone

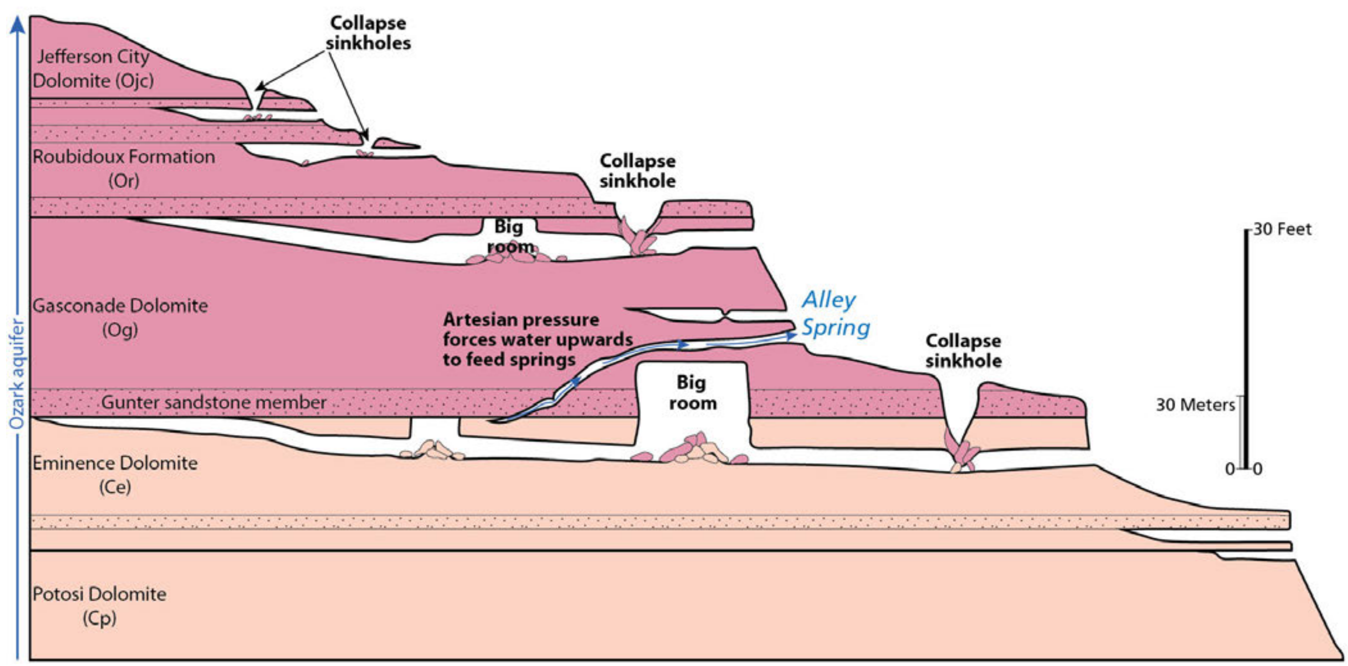


Figure 10. Illustration of stratigraphy and cave development. Dissolution of dolomite layers into karst features such as caves and sinkholes tends to be concentrated in carbonate bedrock below prominent sandstone layers such as within the Roubidoux Formation (geologic map unit Or), Gasconade Dolomite (Og), and Eminence Dolomite (Ce). The most complex cave networks form beneath the thick Gunter sandstone member at the base of the Gasconade Dolomite. The units depicted are also all part of the Ozarks aquifer above an underlying confining unit. Colors are standard US Geological Survey designations for different units of geologic time. Graphic by Trista Thornberry-Ehrlich (Colorado State University) redrafted after figure 7 in Orndorff et al. (2006).

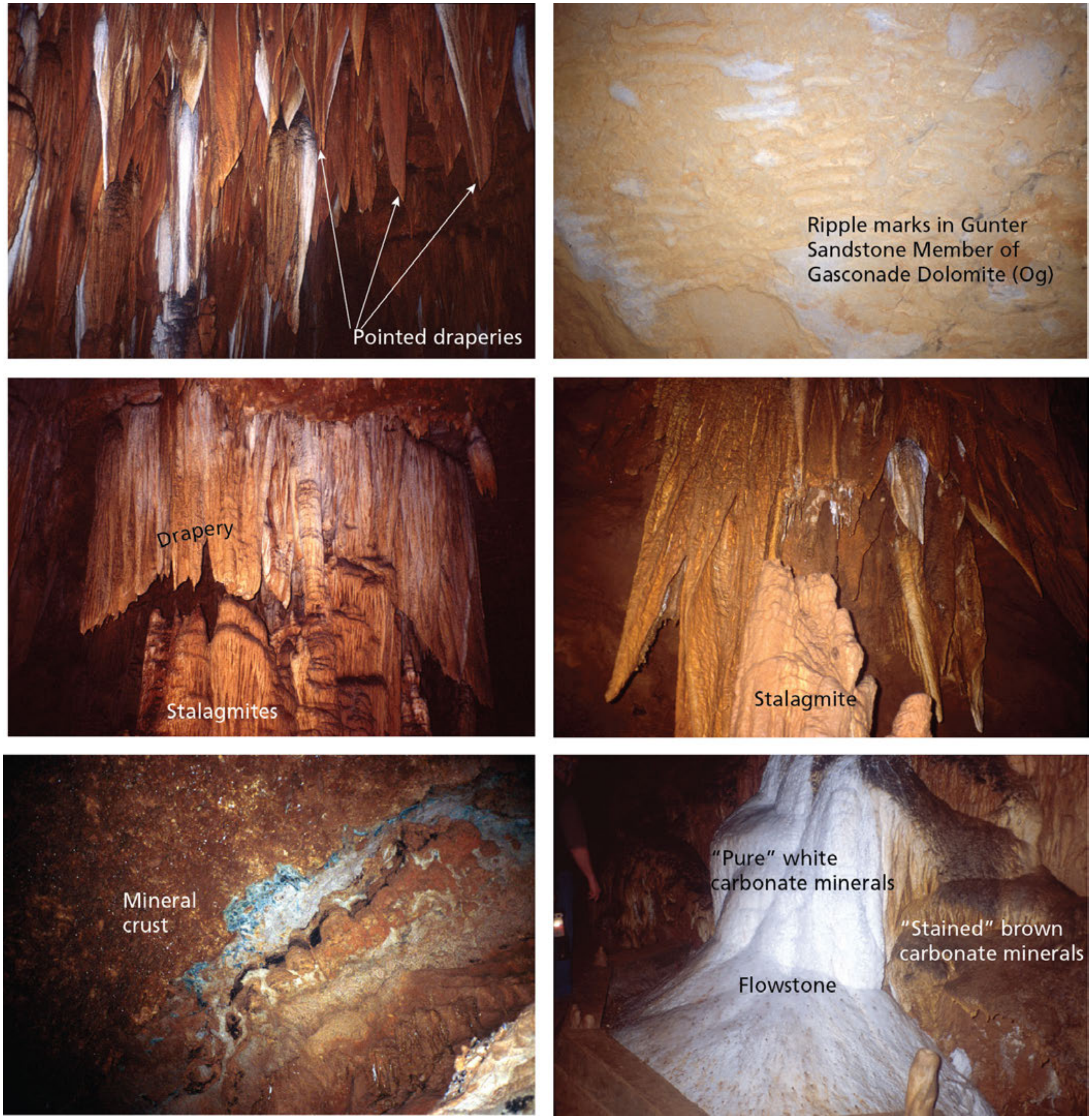


Figure 11. Photographs of speleothems and other bedrock features of Round Spring Cavern. Cave formations such as these form drip by drip as minerals precipitated out of groundwater exposed to the atmosphere of an underground cavern. Round Spring Cavern has been a tourist attraction for decades and is the only cave currently open to visitors (guided hikes only). Visitors can damage cave formations and make incremental, but significant changes to the cave environment. Photographs by Sid Covington (NPS Geologic Resources Division) taken in February 2002.

dams, mineral crusts, and draperies; fig. 11). Impurities within the solution such as iron, manganese, and organic tannins will stain the otherwise white minerals into shades of red, orange, brown, gray, and black (Crews 2008).

Caves within the park are well known for their speleothems (fig. 11). Since commercial tours began in 1932, visitors have marveled at the cave formations within Round Spring Cavern (Lowell et al. 2010). Speleothems such as stalactites, stalagmites, flowstone, dripstone, rimstone and rimstone dams, soda straws, helictites, and columns are well known from the park caves. Speleothems have been vandalized and some have been restored (see "Caves and Associated Landscape Management" section; National Park Service 2015; Jonathan Beard, Springfield Plateau Grotto of the National Speleological Society, secretary/treasurer, written communication, 10 July 2016). Some of the speleothems are not common to caves outside the park, including spathites (Dave Weary, US Geological Survey, geologist, written communication, 21 June 2016). Spathites are tubular stalactites consisting of a vertical succession of overlapping, delicate, petal-shaped cones.

Interest in the park's speleothems extends to seismic studies. During earthquakes, speleothems may be broken. Dating these fractures may help determine paleoseismicity. Speleothems in Round Spring Cavern are being researched for determining when earthquakes occurred (Tinsley 2014; Dave Weary, US Geological Survey, geologist, written communication, 21 June 2016).

Springs

Ozark National Scenic Riverways contains one of the world's largest collection of first magnitude springs, defined as those which discharge more than 245 million L (65 million gallons) of water daily, among more than 400 total known springs (Vana-Miller 2007; Bowles et al. 2011; National Park Service 2015). The largest of these "Jewels of the Ozarks" include Big, Alley, Blue, Round, Pulltite, and Welch springs. As one of the largest single-orifice karst springs in the world, Big Spring (fig. 12) discharges about 1.1 billion L (288 million gallons) of water per day and has a peak flow of about 3 billion L (800 million gallons) per day. Alley Spring flows at an average of 307 million L per day (81 million gallons). Round Spring averages 98 million L (26 million gallons) per day (Vineyard and Feder 1982; National Park Service 2015). During base flow conditions, the 13 largest springs in the park area account for over 80% of the Current River flow measured downstream of Big Spring. Including discharge from other springs, the cumulative discharge from springs is over 90% of the river flow (Mugel et al. 2009). Because of their stable, year-round temperatures and distinct water chemistry, springs provide habitat for flora and fauna not otherwise associated with the Current River and Jacks Fork corridors (see "Geologic Significance and Connections" section; National Park Service 2015). Resource managers monitor aquatic vegetation, aquatic invertebrates, fish, habitat, and water quality for spring communities at six springs within the park (Bowles et al. 2011).

Dissolved carbonate minerals in the spring water, in conjunction with spring depth and the blue of the sky, create a vivid blue color for many of the springs. Fine-grained sediments flushed into the springs from subterranean conduits after precipitation can create a "milky" appearance of the springs and rivers (National Park Service 2015).

Karst dissolution has regionally created a vast network of caves, cracks, and passages that funnel water from the recharge areas at the surface to the Ozark springs. For example, the recharge area for (1) Blue Spring is about 277 km^2 (107 mi^2), (2) Pulltite Spring encompasses 418.2 km^2 (161.5 mi^2), and (3) Welch Spring includes about 313 km^2 (121 mi^2) (Aley and Aley 1987; National Park Service 2015). Dye tracing tests revealed groundwater

Figure 12. Photographs of Big Spring. (A) Big Spring has flowed from different conduits through time, some of which are left as cave openings. (B) Gushing flows are forced from underground under hydrostatic pressure in a confined groundwater setting. (C) Clear, blue-colored water from Big Spring flowing down the Big Spring branch toward the Current River. Photographs by Sid Covington (NPS Geologic Resources Division) taken in February 2002.

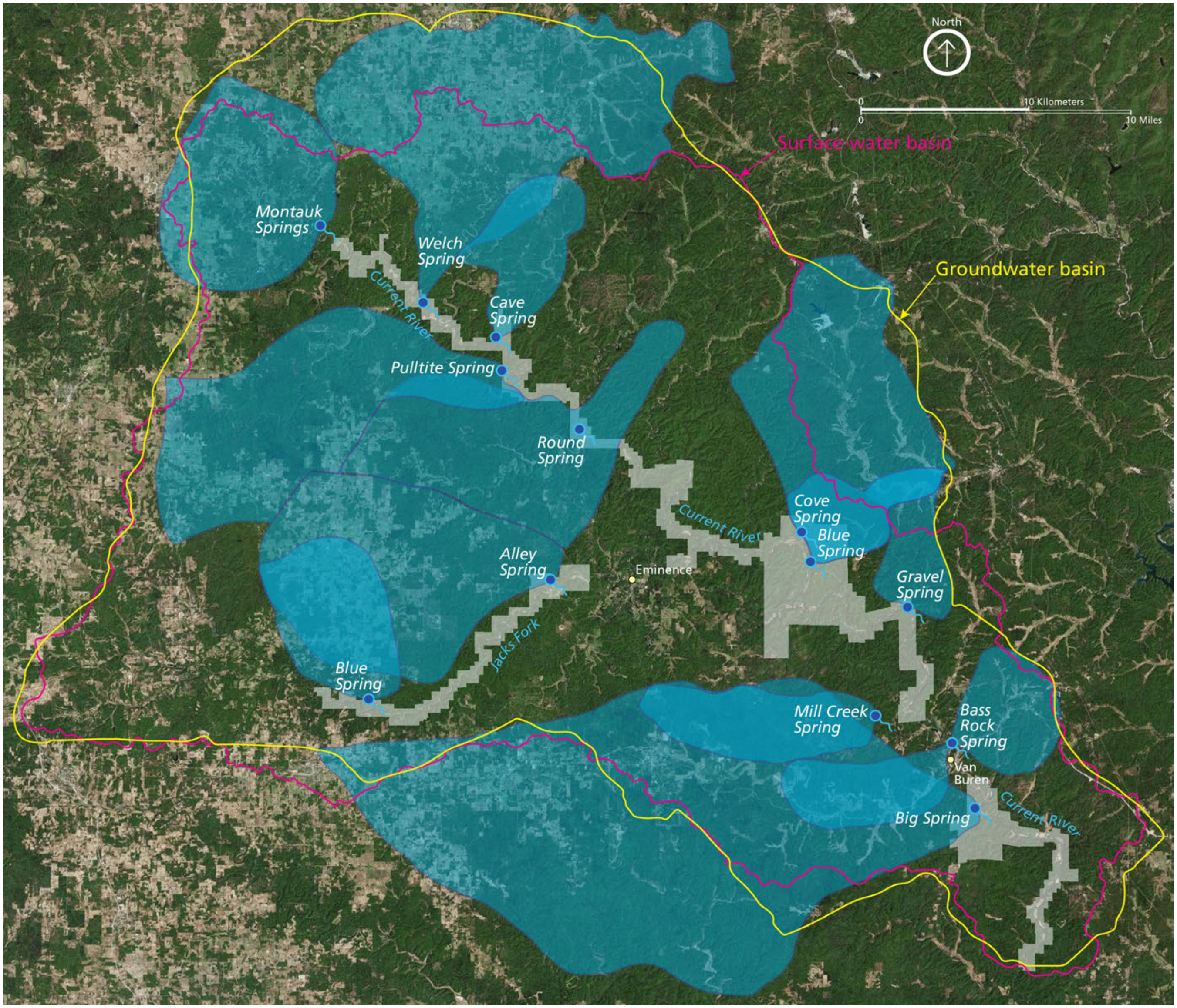


Figure 13. Map of spring recharge areas over the surface-water and groundwater basins of the Current River and Jacks Fork. Spring recharge areas (blue polygons) for the major springs of Ozark National Scenic Riverwaysare complex, overlap, and cross both the groundwater basin (yellow outline, defined by water-well measured potentiometric surface) and the surface-water basin (pink outline). Recharge areas that cross the potentiometric groundwater basin are examples of interbasin transfers of groundwater. The park is the white translucent areas. Much of the recharge areas are well beyond park boundaries. Graphic by Trista Thornberry-Ehrlich (Colorado State University) redrafted after figure 23 in Mugel et al. (2009) using ESRI World Imagery basemap (accessed 8 October 2015).

travels from as far as 80 km (50 mi) away and takes up to 14 days to flow from the surface to Big Spring (fig. 13; Imes and Kleeschulte 1995; Kleeschulte 2000). Geologists estimate that 55 m^3 (1,950 ft^3) of dissolved carbonate rock flows out of Big Spring every day (Imes et al. 2007; National Park Service 2015). This means the total volume of cave passages increases by 224,000 m^3 (7,920,000 ft^3) per year (Harrison et al. 1997).

The water flowing out of the park's springs is not merely meteoric water trickling downward through the bedrock. At Alley Spring, along the Jacks Fork, the source of water is from a lower cave passage (fig. 14). Artesian pressure causes the upward movement of groundwater from cavernous bedrock beneath the dissolution-resistant sandstone layers.

Sinkholes

A sinkhole, or doline, is a depression that has no natural external surface drainage—when it rains, all of the water

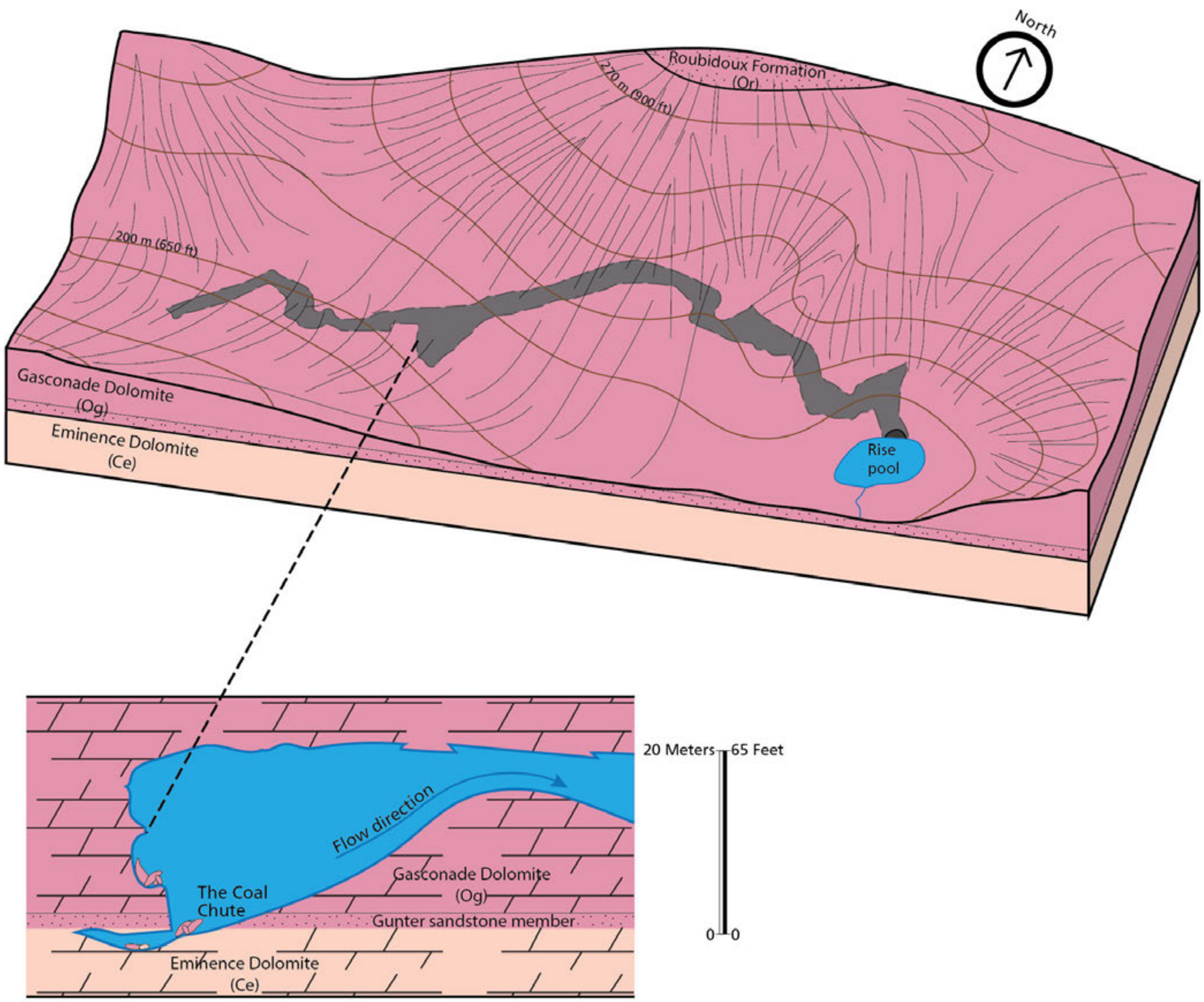


Figure 14. Illustration of Alley Spring conduit system. Brown contour lines are 15 m (50 ft) intervals with the highest contour at 270 m (900 ft) elevation and the lowest at 200 m (650 ft). Hydrostatic pressure caused from confining sandstone layers in the overlying bedrock pushes water from below the surface upwards toward the rise pool of Alley Spring. Prominent sandstone layers occur within the Roubidoux Formation (geologic map unit Or), Gasconade Dolomite (Og), and Eminence Dolomite (Ce). Graphic by Trista Thornberry-Ehrlich (Colorado State University) redrafted after figure 6 in Orndorff et al. (2006).

stays inside the sinkhole and typically drains into the subsurface. In general, sinkholes can vary from a few square meters to hundreds of hectares in area and from less than one to hundreds of meters deep. Some are shaped like shallow saucers or bowls with gently sloping walls whereas others have vertical walls; some hold water indefinitely and form natural ponds (Kaufman 2007). Sinkholes typically form at least in part by collapse or slow subsidence of dissolved bedrock fragments into an underground conduit or void (e.g., cover-subsidence, and cover-collapse sinkholes; figs. 15 and 16). The bottom conduits ("throat") of the park's sinkholes are often blocked by debris and other material (Lowell et al. 2010). Where dissolution creates a large enough void beneath a capping sandstone layer, the surface collapses to form a sinkhole. Sinkholes in the park are commonly rimmed with sandstone or chert blocks suggesting bedrock collapse of sandstone into dissolution voids below (Weary and Orndorff 2001; Orndorff et al. 2006). Sinkholes mapped on the lower part of the Roubidoux Formation collapsed through the basal sandstones into caves of the underlying

Gasconade Dolomite. Sinkholes in the lower part of the Jefferson City Dolomite are collapsed into caves beneath the upper sandstone of the Roubidoux Formation.

Sinkhole collapse may be more common during times of flooding or other high water or high flow events but it can happen anytime. Human activity may also trigger sinkhole collapse. For example, groundwater pumping can lower the water table thereby reducing

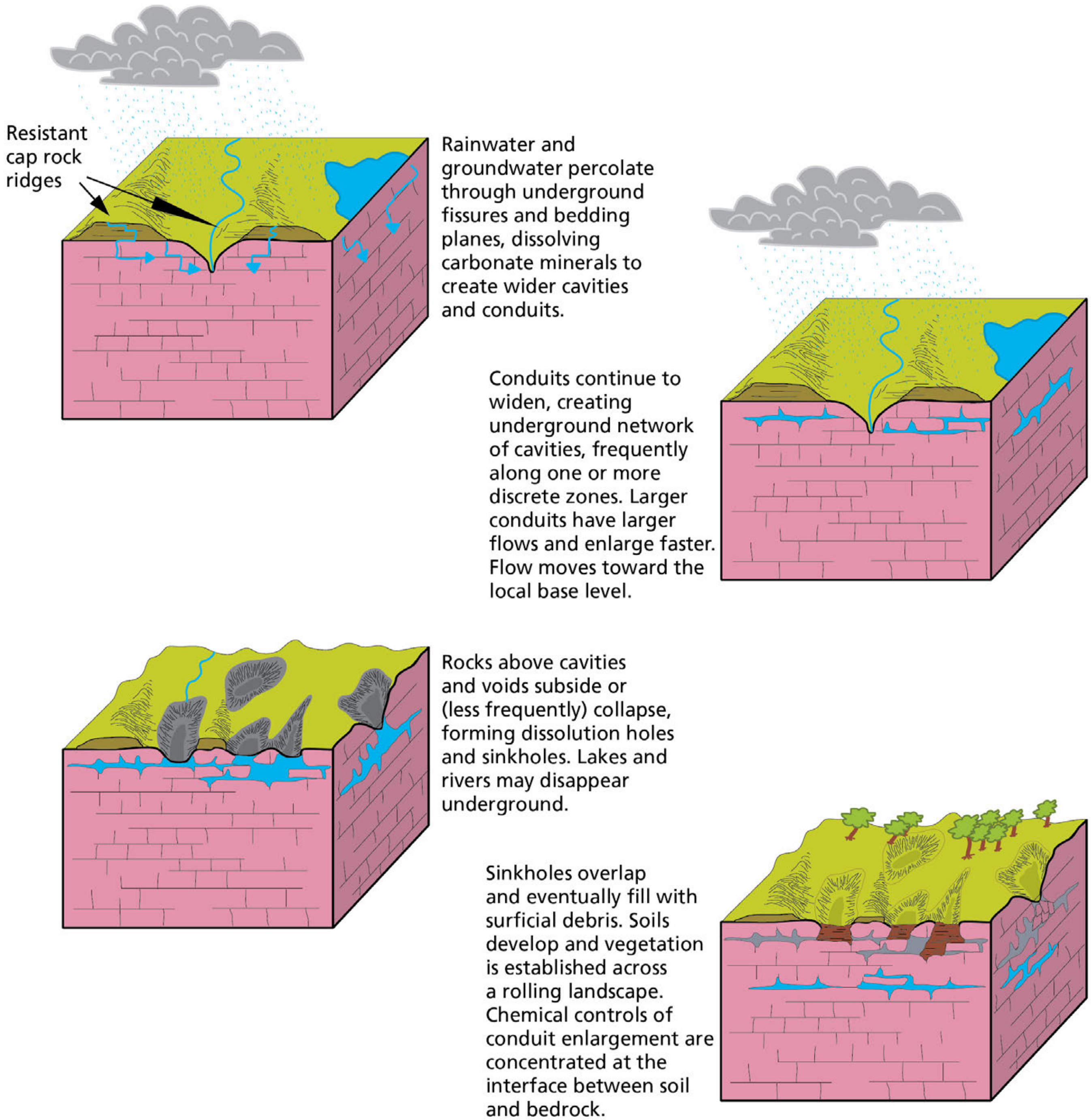


Figure 15. Three-dimensional illustration of karst landscape formation. Resistant cap rocks such as sandstone layers in the Roubidoux Formation (Or) overlie caves and sinkhole plains. Sinkholes are common throughout the area of Ozark National Scenic Riverways, where karst landscapes dominate and continue to develop today in the Ordovician and Cambrian dolomite and limestone (geologic map units Cp, Ce, Og, Or, and Ojc). Graphic by Trista L. Thornberry-Ehrlich (Colorado State University), created using information from Hack (1974).

buoyant support of the overlying rock which may lead to subsidence or collapse into a sinkhole. Refer to the "Geologic Resource Management Issues" chapter for additional information.

Sinkholes in the Roubidoux Formation, Jefferson City Dolomite, Gasconade Dolomite, Eminence Dolomite, and Potosi Dolomite (geologic map units **Or**, **Ojc**, **Og**, **Ce**, and **Cp**, respectively) are mapped in the "Hazard

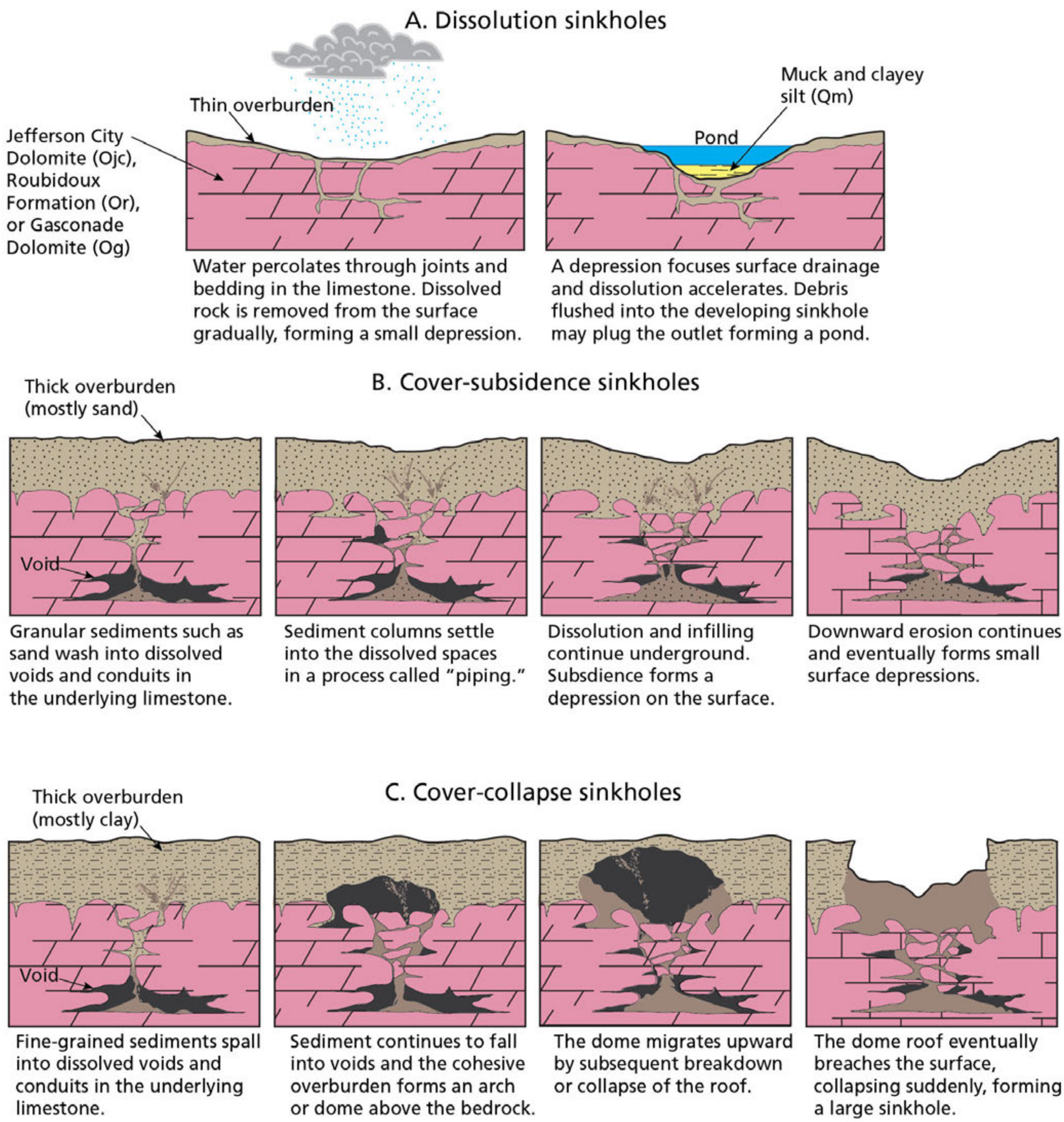


Figure 16. Illustration of sinkhole types. Dissolution, cover-subsidence, and cover-collapse sinkholes develop from dissolution and downward erosion of unconsolidated material into the underlying cavities. Sinkholes can be a combination of the three types or may form in several overlapping phases. The type of sinkhole that forms is controlled in part by the thickness and type of overburden and the local hydrology. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after figures by Tihansky (1999:126–127).

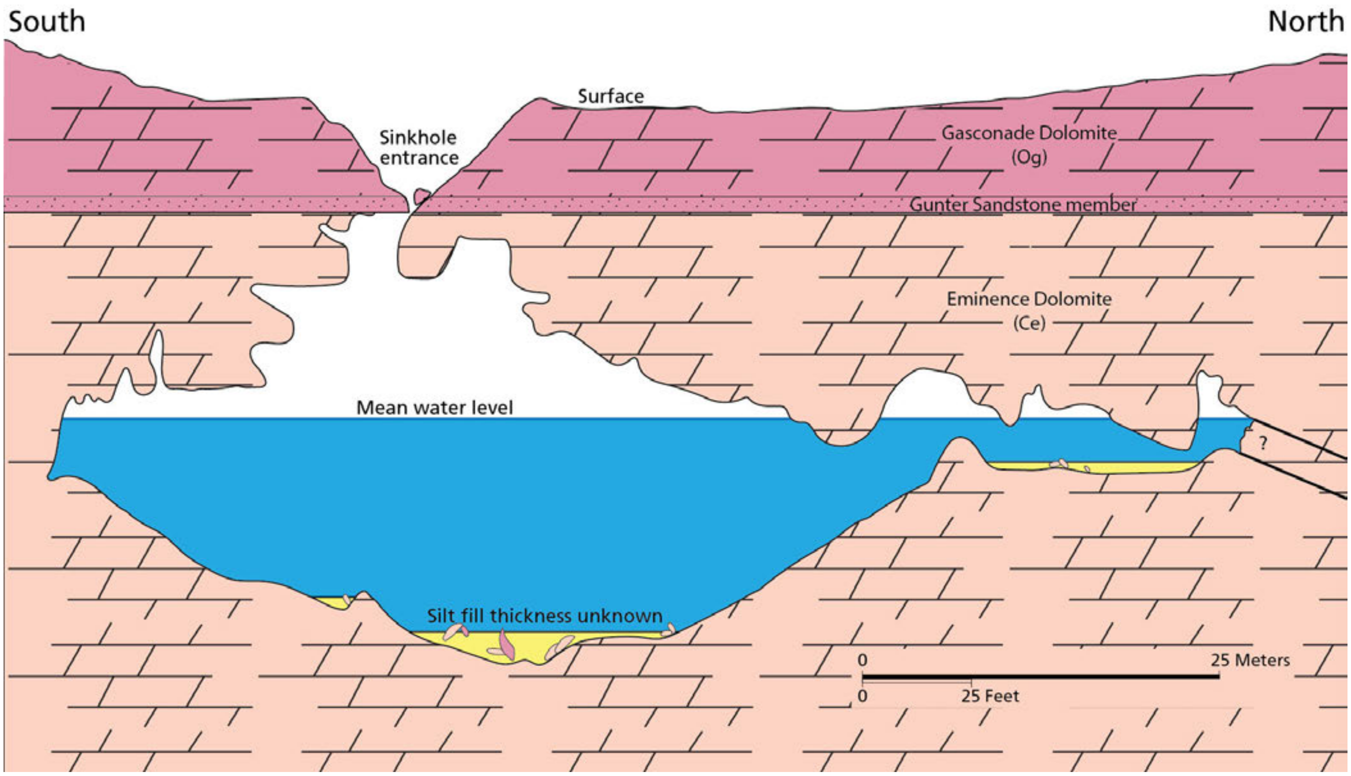


Figure 17. Cross-sectional illustration of Devils Well sinkhole and subterranean lake. The conduit system is forming within the Eminence Dolomite (Ce) beneath the Gunter Sandstone member of the Gasconade Dolomite (Og). Devils Well formed where a large chunk of the roof collapsed beneath the sandstone. Future collapse is possible. Graphic by Trista Thornberry-Ehrlich (Colorado State University) redrafted after figure 4.2 in Lowell et al. (2010).

Area Features" layer within the GRI GIS data. Muck (**Qm**) accumulated in many sinkholes when they were filled with water (Vana-Miller 2007; Weary et al. 2016). In the park, sinkholes occur near Blue Spring, Rymers, Horse Camp, and Shawnee Creek on the Jacks Fork, and near Akers, Devils Well, Bee Bluff, Blue Spring, Big Spring, and Cataract Landing along the Current River (Weary et al. 2016). High concentrations of sinkholes are located in areas of "weak" rock such as rocks adjacent to major fault zones and in areas underlain by the fractured or deformed Roubidoux Formation and Jefferson City Dolomite (see "Faults and Fractures" section; Orndorff et al. 2006).

At least 339 sinkholes occur in the Big Spring recharge area, 312 occur within the recharge area for Alley Spring, and 284 are within the recharge area for Welch Spring (Mugel et al. 2009; Dave Weary, US Geological Survey, geologist, written communication, 21 June 2016). The Devils Well sinkhole formed when the roof (supported by the Gunter Sandstone member of the Gasconade Dolomite) of a large cavern within the Eminence Dolomite containing a subterranean lake collapsed (fig. 17; Lowell et al. 2010; Weary et al. 2014). A 24 m- (80 ft-) deep lake is now visible through the sinkhole and is about 30 m (100 ft) below the viewing platform; a small natural bridge of the Gunter Sandstone member of the Gasconade Dolomite is just above the viewing platform (Lowell et al. 2010; National Park Service 2015). Many sinkholes are filled or covered by residuum (e.g., **QTr**, **QTtrc**, and **QTrr**) left from intense weathering of the bedrock (Lowell et al. 2010).

Losing Streams

Losing or "sinking" streams are karst features wherein surficial drainage sinks relatively rapidly underground to flow through the subterranean conduits and caves. Sinking streams seem to disappear. Some streams may flow along the surface of an insoluble caprock until reaching a layer of karst rock, at which point the drainage almost entirely flows underground. Within the Current River watershed, 340 km (211 mi) of streams are designated losing streams—those which distribute 30% or more of their flow through permeable geologic materials into a bedrock aquifer within 4 km (2 mi) distance downstream of an existing discharge (Missouri

Department of Natural Resources 1999). Within the Jacks Fork watershed, 13 km (8 mi) of streams are designated losing streams (Missouri Department of Conservation 2016).

Cave Habitats

According to Baker et al. (2015), caves support many aquatic and terrestrial habitats defined by a variety of environmental parameters, including

- zonation (the level within the cave; e.g., entrance zone, twilight zone, and deep cave or phreatic and vadose zones above and below the water table, respectively)
- available light (any light allows some plant species to exist)
- humidity (deep cave levels routinely exceed 99%)
- temperature
- gases (e.g., carbon dioxide, hydrogen sulfide, methane, and radon)
- water in cave streams, drips, drip pools, and seeps
- morphology of the cave passage (i.e., abundance of ledges or ceiling cracks, ceiling height, domes)
- substrate (e.g., dry rock areas to shelter spiders or drip pools supporting tiny ostracods)
- connectivity (connections with the surface can introduce nutrients.

The "Geologic Setting and Significance" chapter lists some of the endemic or significant cave flora and fauna that inhabit caves in the park. Cave habitats are particularly sensitive to changing conditions and take a long time to recover from disturbance.

Surficial Geologic Map Units

Unlike bedrock units that are typically described and mapped by age and rock type, surficial deposits are described and mapped ("**Q**" and "**QT**" units) primarily by their process of deposition and resulting geomorphology. Surficial deposits cover nearly all (about 95%) of the drainage basins in the Ozarks area including the Current River and Jacks Fork valleys (Weary et al. 2014). The surficial deposits mapped within the park resulted from the following processes (see the Map Unit Properties Table for more information):

- flowing water (**Qa**, **Qt**, and **QTg**)
- standing water (**Qm**)
- blowing wind (**Ql** and **Qtl**)
- slope movements (**Qc** and **Qls**)
- and frost weathering or deep weathering (**QTtrc**, **QTr**, and **QTrr**).

Alluvium and terrace deposits (**Qa** and **Qt**, respectively) are the most common surficial units by area (Weary et al. 2016). **Qm** is further discussed in the "Sinkholes" subsection. **Ql** and **Qtl** figure prominently in the "Periglacial Features" section. **Qc** and **Qls** collect at the bases of slopes (see "Slope Movements" section). For a discussion about **QTtrc**, **QTr**, and **QTrr**, see "Bedrock Weathering and Residuum Formation" section.

Bedrock Weathering and Residuum Formation

Carbonate minerals make up the majority of the Paleozoic bedrock. While those minerals and rocks dissolve to create karst features, insoluble components of the bedrock, such as chert, sand, and clay, are left behind. These "leftovers" can accumulate to great depths and are called "residuum." Residuum in the park area is commonly red or reddish-orange sandy clay and includes all sizes of particles from small clays up to cobbles and boulders up to 1.8 m (6 ft) in diameter (Weary et al. 2014). Of all the surficial units mapped by Weary et al. (2014), they consider residuum as the greatest surficial deposit volumetrically with some deposits more than 30 m (100 ft) thick although it is typically about 12 m (40 ft) thick in the park (Weary et al. 2014).

Most of the residuum was derived from the Roubidoux Formation (**Or**) and was mapped as **QTrr** although unmapped Roubidoux residuum occurs nearly everywhere the formation was found (Weary et al. 2014). The Peck Ranch unit (**QTr**) is also a residuum unit but was only mapped outside the park, south of Rocky Falls. Some residuum is also present in map unit **QTrc**, mapped near Rock Falls and south of Roberts Field. Residuum units were mostly mapped on ridge tops; being clay rich, they are rather "sticky" (Dave Weary and Randy Orndorff, US Geological Survey, conference call, geologists, 20 October 2015).

Slope Movements

Steep slopes, which increase the potential for slope movements, characterize the bluffs and cliffs adjacent to the park's rivers, streams, and tributaries. Colluvium (**Qc**) and landslide deposits (**Qls**) are part of the GRI

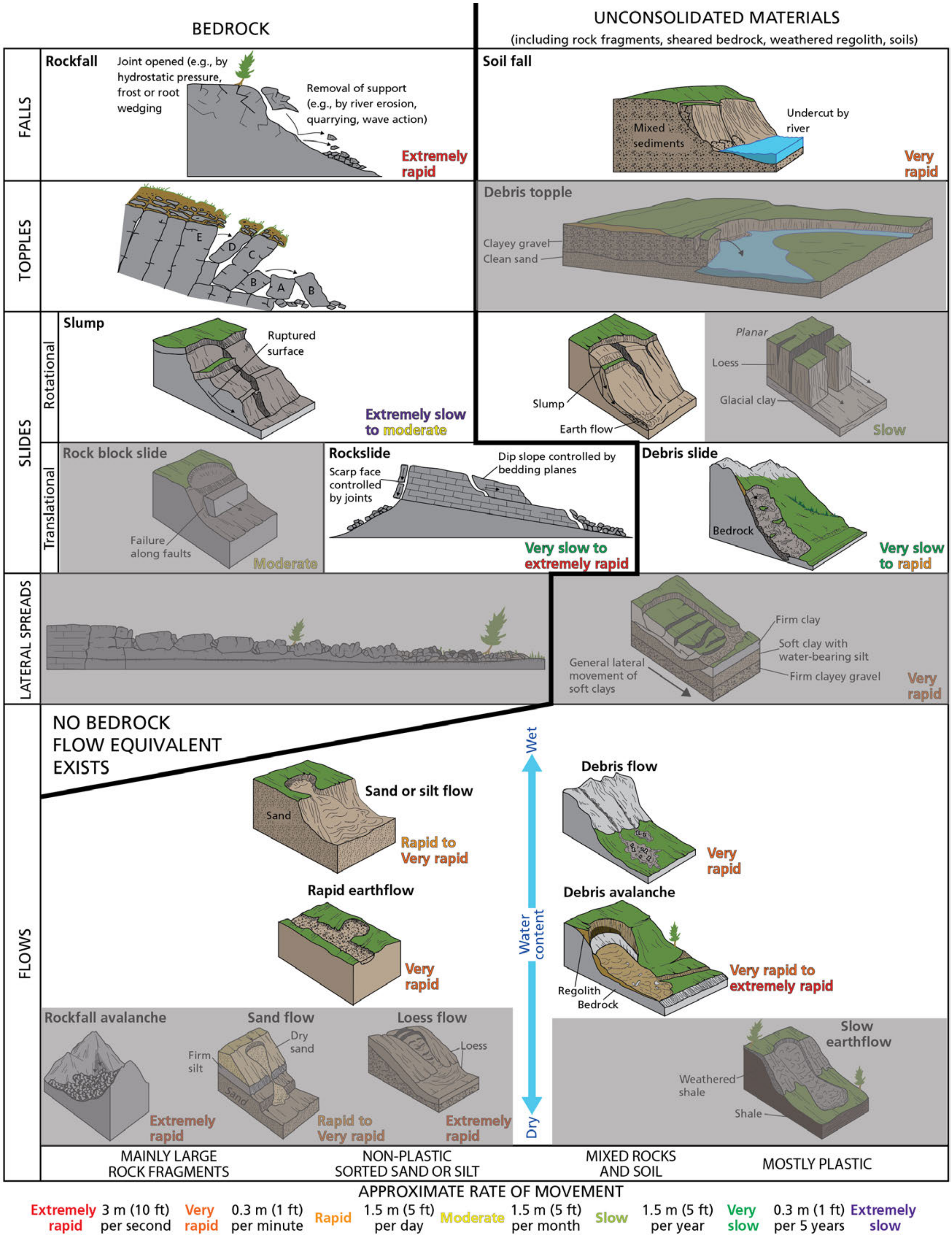


Figure 18. Illustrations of slope movements. Different categories of slope movement are defined by material type, nature of the movement, rate of movement, and moisture content. Grayed areas represent conditions that may not exist at Ozark National Scenic Riverways. Graphic by Trista Thornberry-Ehrlich (Colorado State University) redrafted after a graphic and information in Varnes (1978).

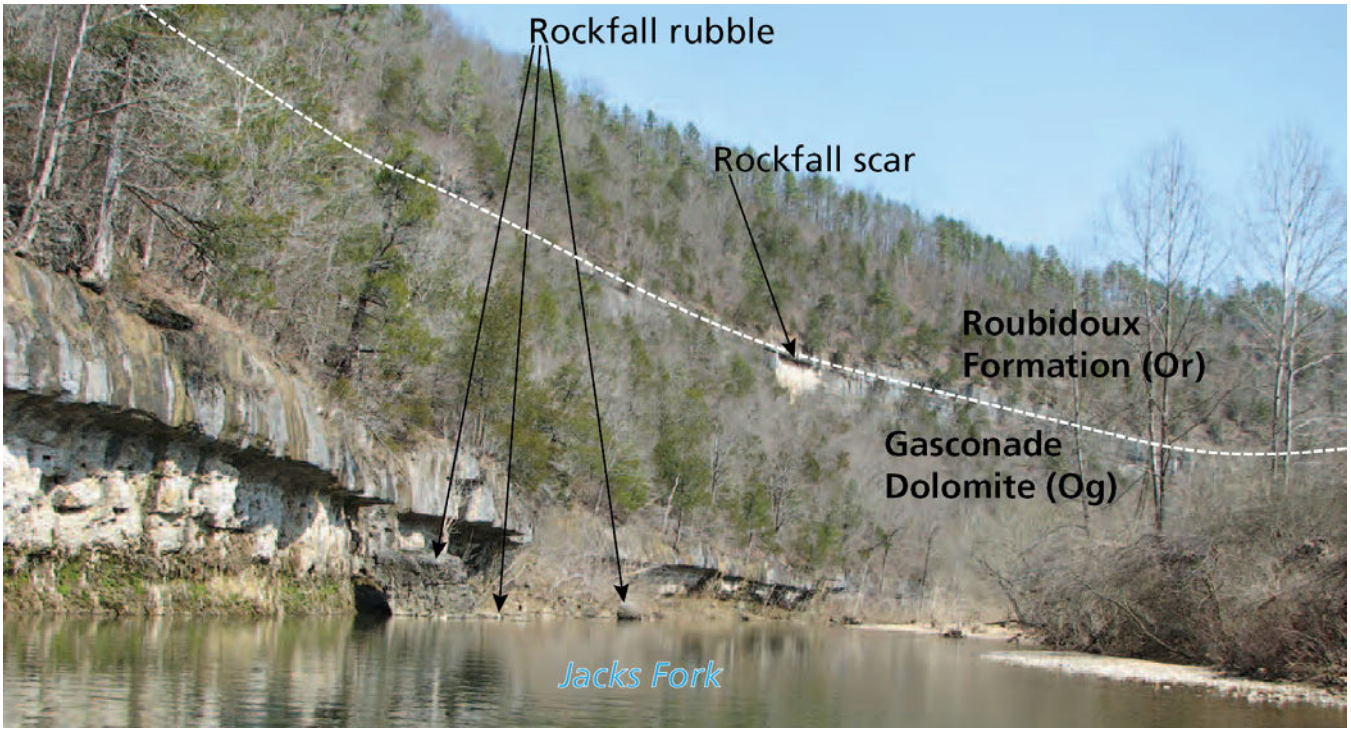


Figure 19. Photograph looking downstream along Jacks Fork east of Jam Up Cave. Differential weathering in the Gasconade Dolomite (lower portion of bluff) and Roubidoux Formation (upper portion of bluff) creates cliffs, ledges, and overhangs that are susceptible to slope movements, particularly rockfall. A relatively fresh rockfall "scar" is visible. Approximate contact between the two units is shown as a white dashed line. National Park Service photograph by Victoria Grant (Ozark National Scenic Riverways), March 2007. Cover photograph from Weary et al. (2014).

GIS data (see the Map Unit Properties Table for more details; Weary et al. 2014). Soil creep, rockfalls, debris flows, and avalanches are common types of slope movement (fig. 18). 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. Refer to figure 18 for illustrations of slope movements. Hazards and risks associated with slope movements in the park are described in the "Geologic Resource Management Issues" chapter.

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 the local climate. For example, a coarse-grained, well-cemented, quartz-rich sandstone is much more resistant to erosion than a weakly cemented shale or soluble limestone or dolomite. Differential weathering created the steep slopes and unconsolidated material, which are susceptible to slope movements, at the park.

In areas where the Gunter Sandstone member of the Gasconade Dolomite (part of **Og**) is exposed, its resistance to erosion produces benches on hillsides (fig. 19), small waterfalls, and streams that are "perched" on the sandstone. Dissolution and erosion removes the soluble carbonate rocks above and below this and other thick sandstone layers (e.g., those within the Roubidoux Formation [**Or**]) (Lowell et al. 2010). This situation may result in increased likelihood for rockfall (see fig. 19) which creates hazards where trails or the river pass near the ledges. Large chunks of sandstone are wedged apart by processes such as frost weathering and tree-root wedging and tumble downslope.

Periglacial Features

Repeated glaciations (ice ages) during the Pleistocene Epoch (2 million to approximately 20,000 years ago) scoured and reshaped the landscape of the northeastern United States and northern Missouri. The great continental ice sheets did not reach the park; their maximum southern extent was the Missouri River (see fig. 2). However, the cold global climates associated with the glacial events (and to a lesser extent, modern winters) altered the Ozark landscape. The term "periglacial" describes features that were never buried by glaciers, but were subject to cold climates and associated frost weathering. Frost weathering occurs via the freezing and thawing of water within rocks or minerals.

Apart from cores taken in the fluvial terraces to understand paleogeomorphology, the periglacial features at the park have yet to be comprehensively inventoried, described, or mapped (Joe Gilman, Missouri Geological Survey, geologist, conference call, 20 October 2015). The GRI GIS data include colluvium (**Qc**) and landslide deposits (**Qls**) that date to the Holocene and Pleistocene, the bulk of both units could have formed via periglacial processes (Weary et al. 2014; Joe Gilman, Missouri Geological Survey, geologist, conference call, 20 October 2015). Loess (**Ql**) and loess-covered terrace deposits (**Qtl**) also record periglacial environments. Loess forms as fine, winnowed, wind-blown silt that accumulates in ridges and layers when vegetation is sparse and sediment is abundant, such as during a glacial retreat. It can be derived from the floodplains of glacial braided outwash rivers that carried large volumes of glacial meltwater and sediments from the melting glaciers. Loess covers terrace deposits (**Qtl**) just upstream from Van Buren, Missouri. Another loess deposit (**Ql**) is mapped atop rhyolite of Shut-In Mountain (**Ysi**) near Rocky Falls beyond park boundaries. Loess is an aeolian feature. Aeolian processes refer to wind-blown erosion, transportation, and deposition of sediments (Lancaster 2009). The NPS Geologic Resources Division Aeolian Resource Monitoring website, http://go.nps.gov/monitor_aeolian, provides additional information. The field study of periglacial features at the park would be a potential project for the Geoscientists-in-the-Parks program (http://go.nps.gov/gip).

Sedimentary Rock Features

The vast majority of rocks in Ozark National Scenic Riverways are sedimentary. They comprise the cliffs in the park and host the caves and karst features. At the park, the sedimentary rocks are mostly either clastic or chemical. Clastic sedimentary rocks are the products of weathering, erosion, transportation, and deposition of rock fragments called "clasts." Clastic sedimentary rocks are named after the size of clasts (table 1). High-energy depositional environments, such as fast-moving streams, leave behind larger (heavier) clasts while transporting smaller (lighter) clasts. Where water moves slowly or is stagnant, such as in lakes, the water cannot transport even the smallest clasts and they are deposited. Wind also transports and deposits sand-sized or smaller clasts (table 1). Chemical sedimentary rocks form when ions (microscopic particles of rock dissolved during chemical weathering) precipitate out of water. For example, carbonate rocks, such as limestone (calcium) or dolomite (calcium and magnesium) have a carbonate (CO_3^{2-}) ion.

In the park, clastic and chemical sedimentary rocks are commonly interbedded, such as with the dolomite, quartz sandstone, and chert-rich layers of the Eminence Dolomite (geologic map unit **Ce**), Roubidoux Formation (**Or**), and Jefferson City Dolomite (**Ojc**) (Weary et al. 2014). The Gasconade and Potosi dolomites (**Og** and **Cp**) are mostly dolomite; these units contain the greatest degree of karst development (see "Cave and Karst Features and Processes" section; Weary et al. 2014).

Table 1. Clastic sedimentary rock classification and characteristics.

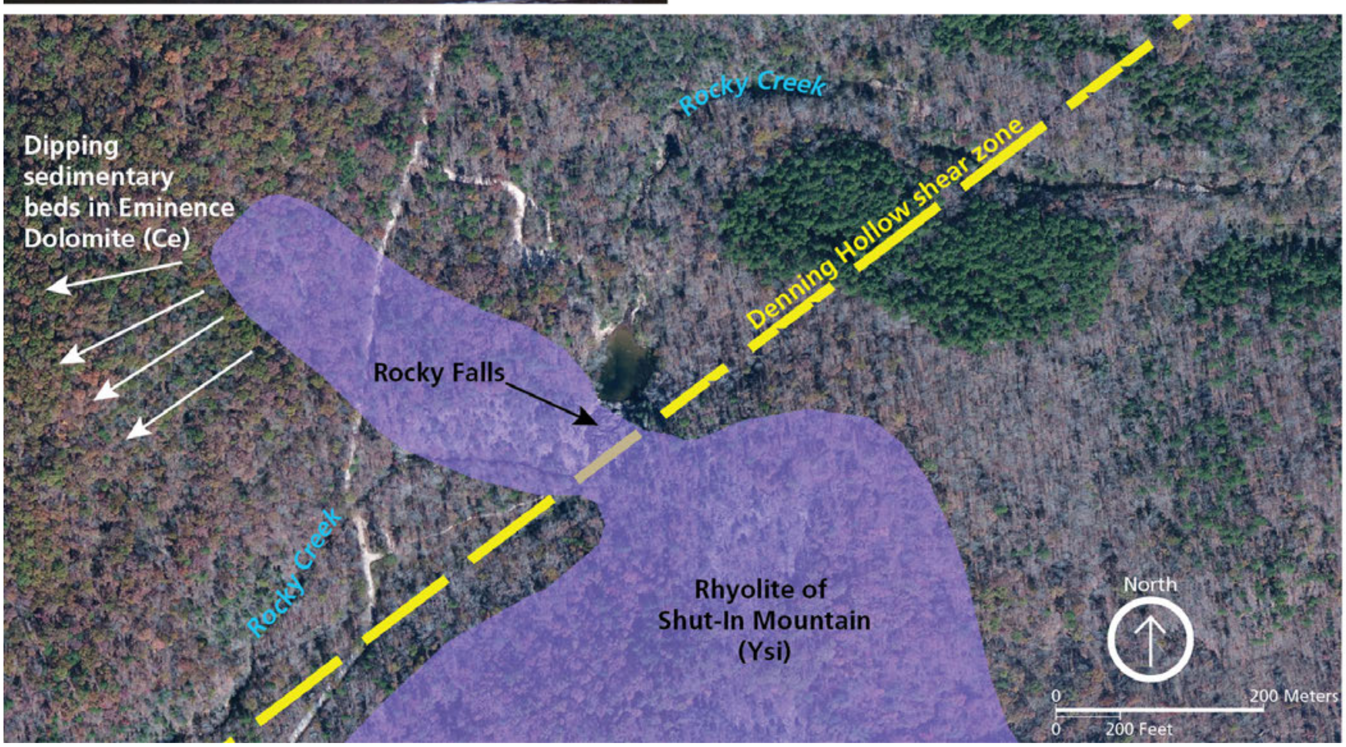
Rock Name	Clast Size	Depositional Environment	Park Examples
Conglomerate (rounded clasts) or Breccia (angular clasts)	>2 mm (0.08 in) [larger]	The relative energy levels in the depositional environments ranges from higher energy (conglomerate and breccia) to lower energy (claystone).	Lamotte Sandstone (buried at the park)
Sandstone	1/16–2 mm (0.0025–0.08 in)		Roubidoux Formation (Or); Gunter Sandstone member of the Gasconade Dolomite (Og); layers in the Eminence Dolomite (Ce)
Siltstone	1/256–1/16 mm (0.00015–0.0025 in)		Bonneterre Formation (buried at the park)
Claystone	<1/256 mm (0.00015 in) [smaller]		Not prominent in park area rocks

Note: Claystones and siltstones can also be called "mudstone," or if they break into thin layers, "shale."

Dolomite is a carbonate rock (has a CO_3^{2-} ion) with a high percentage of magnesium in addition to calcium. Limestone is another common carbonate but has nearly no magnesium. Carbonate rocks are indicative of deposition in relatively shallow seas, often in equatorial areas. Those conditions are inferred for the park and much of the southeast during the Paleozoic Era (see "Geologic History" chapter).

Features within the sedimentary rocks provide additional information about their depositional environment and history. Marine invertebrate fossils are common in many of the layers as discussed in the "Paleontological Resources" section. Particularly noteworthy is the *Cryptozoon* chert layer in the Gasconade Dolomite (see fig. 4). As chert, the layer is hard, extremely dense or compact, microcrystalline, quartz-rich rock, composed of the remains of primitive reef life (fossil algae). Also within the Gasconade Dolomite are layers of oolites or rocks composed of spherical grains of ooliths that formed as layer upon layer of minerals adhered to a central nucleus, typically in shallow water with oscillating waves. The orthoquartzite sandstone layers in the Eminence Dolomite, Gasconade Dolomite, and Roubidoux Formation are almost pure quartz; other original mineral constituents either dissolved or were carried away during deposition. The Potosi Dolomite has vugs or cavities lined with druse or crusts of quartz crystals. "Vuggy" dolomite is also part of the Gasconade Dolomite (Weary et al. 2014).

Figure 20. Illustration of Rocky Falls over rhyolite of Shut-In Mountain. Sedimentary layering (bedding) within the Eminence Dolomite (Ce) adjacent to a Mesoproterozoic knob of rhyolite of Shut-In Mountain (Ysi) dips away from the knob. The knob was an island during original deposition of the dolomite. The Denning Hollow shear zone crosses through the Rocky Falls. It may have provided a zone of weakness across the resistant igneous rock. Top photograph by Sid Covington (NPS Geologic Resources Division) taken in February 2002. Graphic by Trista Thornberry-Ehrlich (Colorado State University using GRI map data from Weary et al. (2016) and ESRI World Imagery basemap (accessed 8 October September 2015).



Most of the sedimentary layers are nearly horizontal, little disturbed since deposition. The regional average is just 3° of dip to the southeast. The gradient of the Current River follows this regional geological incline. Contrary to the overall trend are the much steeper, radially dipping beds formed near the "knobs" of very old volcanic rock (see "Volcanic Rocks and the Eminence Caldera" section and "Geologic History" chapter) where sediments accumulated and covered the knobs (Weary et al. 2014). This is visible along the west side of Rocky Creek along a stretch of the Current River section of the Ozark Trail where the Eminence Dolomite (**Ce**) was deposited on the flank of the rhyolite of Shut-In Mountain (**Ysi**). Here, the dip of the sedimentary layers is away from the summit of the mountain in a radial pattern (fig. 20; Lowell et al. 2010). Strike (orientation of rock layers) and dip (degree of tilt) measurements are included in the GRI GIS data "Geologic Attitude Observation Localities" layer.

Paleontological Resources

Paleontological resources (fossils) are any evidence of life preserved in a geologic context (Santucci et al. 2009). All fossils are nonrenewable. Body fossils are any remains of the actual organism such as bones, teeth, shells, or leaves. Trace fossils are evidence of biological activity; examples include burrows, tracks, or coprolites (fossil dung). Fossils in NPS areas occur in rocks or unconsolidated deposits, museum collections, and cultural contexts such as building stones or archeological resources. As of August 2016, 263 parks, including Ozark National Scenic Riverways, had documented paleontological resources in at least one of these contexts. The park contains examples of all three. Resource management issues are documented in that chapter of this report.

Hunt et al. (2008) provided a summary of the paleontological resources for the entire Heartland Inventory and Monitoring Network, which includes the park. See the Map Unit Properties Table for more details. The NPS Fossils and Paleontology website, http://go.nps.gov/fossils_and_paleo, provides more information.

Bedrock Fossils

Fossils have been discovered within the Eminence Dolomite, Gasconade Dolomite, and Roubidoux Formation (geologic map units **Ce**, **Og**, and **Or**, respectively) within the boundaries of the park. The fossils include stromatolites (fossil algae), gastropods, brachiopods, trilobites, cephalopods, conodonts, and some crinoid fragments all of which are common in rocks from Paleozoic Era shallow seas (see "Geologic History" chapter) (Repetski et al. 2000; Weary and Schindler 2004). Fossils have been discovered outside the park within the Potosi Dolomite (**Cp**), as well as in unconsolidated surficial deposits ("**QT**" and "**Q**" map units) suggesting that such fossils might also be found in those units in the park.

According to Justin Tweet (NPS Geologic Resources Division, guest scientist, written communication, 24 August 2016), two nautiloid species and three monoplacophoran species were named from specimens found within the park. Three additional nautiloid species, two trilobite species, and a gastropod species were named from specimens potentially found within the park.

Cave Fossils

Ozark National Scenic Riverways is one of at least 35 NPS units that preserve fossils within caves. Santucci et al. (2001) described how fossils in caves occur in two contexts: (1) as part of the bedrock in which the cave is formed, or (2) as Pleistocene and/or Holocene remains of organisms that died in or were transported into the cave. 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, or humans. If the remains were transported into the cave by humans, they may also be considered cultural resources. With more than 402 known caves (see "Cave and Karst Features and Processes" section), the park has abundant cave fossil resources and the potential for future discoveries is excellent (Hunt et al. 2008). Oscar "Oz" Hawksley, of Central Missouri State University, collected many of fossils between the 1950s and 1980, which are now curated in the Illinois State Museum Vertebrate Paleontology Collection. Examples of notable fossil animals from park caves include the following, as reported by Santucci et al. (2001):

- American black bear (*Ursus americanus*) (Tucker 1984)
- short-faced bear (*Arctodus simus*)
- jaguar (*Panthera onca*)
- stilt-legged deer *Sangamona* (or *Odocoileus*)
- beaver (*Castor canadensis*)

- dire wolf (*Canis* (*Aenocyon*) *dirus*) (Galbreath 1964)
- parts of a giant armadillo carapace.

All Pleistocene vertebrate fossils from the caves of Missouri are Wisconsinan (last major glaciation, culminating 50,000 years ago) or younger (Reams 1968; Weary and Schindler 2004).

Fossils in Museum Collections

Fossils from the park are in the collections of the following museums or institutions as reported by Hunt et al. (2008):

- Ozark National Scenic Riverways
- NPS Midwest Archeological Center
- College of the Ozarks
- Illinois State Museum
- Smithsonian Institution, National Museum of Natural History
- University of Michigan Museum of Paleontology
- University of Missouri-Columbia
- US Geological Survey.

Fossils in Cultural Contexts

Fossils discovered in archeological settings are considered cultural as well as natural resources. For example, a Nodena arrow point was discovered embedded in the pelvis of black bear (*Ursus americanus*) remains. A fossil snail was collected during excavation of a late prehistoric feature at a site, clearly anthropogenically brought to this area about 1000-1100 CE (D. Bringelson, Archeologist, Midwest Archeological Center [MWAC], personal communication from May 2008 as reported in Hunt et al. 2008). Another fossil shell was collected from the surface of an archeological site in Dent County (M. Lynott, MWAC, archeologist, personal communication from June 2008 as reported in Hunt et al. 2008). Fossils are associated with at least 14 MWAC catalog numbers (Justin Tweet, NPS Geologic Resources Division, guest scientist, written communication, 24 August 2016). Kenworthy and Santucci (2006) provided an overview of NPS paleontological resources in cultural resource contexts.

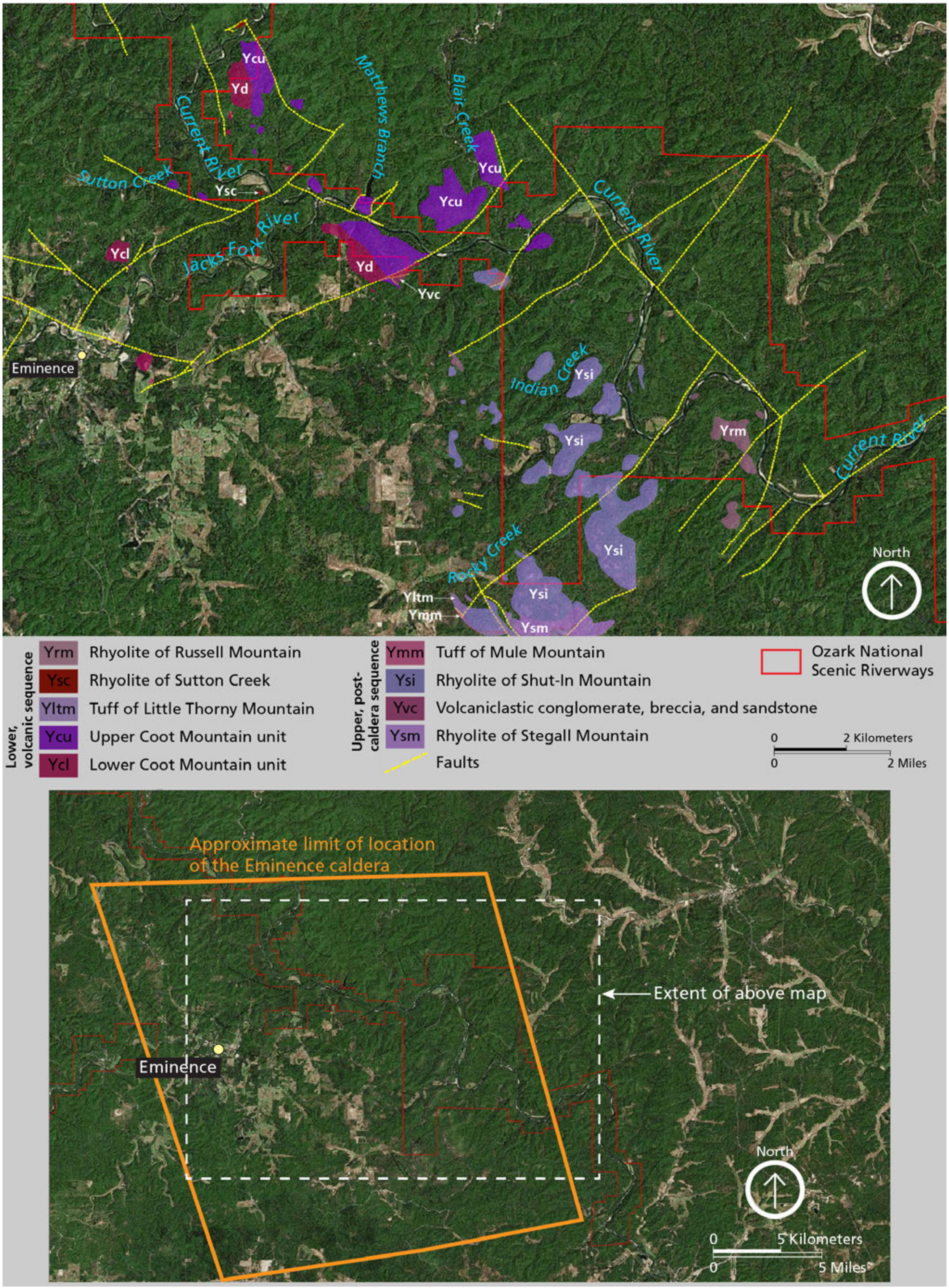
Volcanic Rocks and the Eminence Caldera

By far the oldest rocks in the park, and some of the oldest rocks in Missouri, are igneous rocks more than 1.4 billion years old (1,400,000,000 years; "**Y**" geologic map units). The vast majority of them erupted from a chain of caldera-forming volcanos that extended from Michigan to southeastern Missouri and included the Eminence Caldera. The St. Francois Mountains to the northeast are similar in age and composition. Igneous rocks are those that formed from molten material. Where molten material erupts from volcanoes, cools and solidifies at the Earth's surface, extrusive ("volcanic") igneous rocks form. Where molten material cools beneath the surface, intrusive ("plutonic") igneous rocks form. See table 2 for a simple classification of igneous rocks.

Table 2. Volcanic rocks classification and relative characteristics.

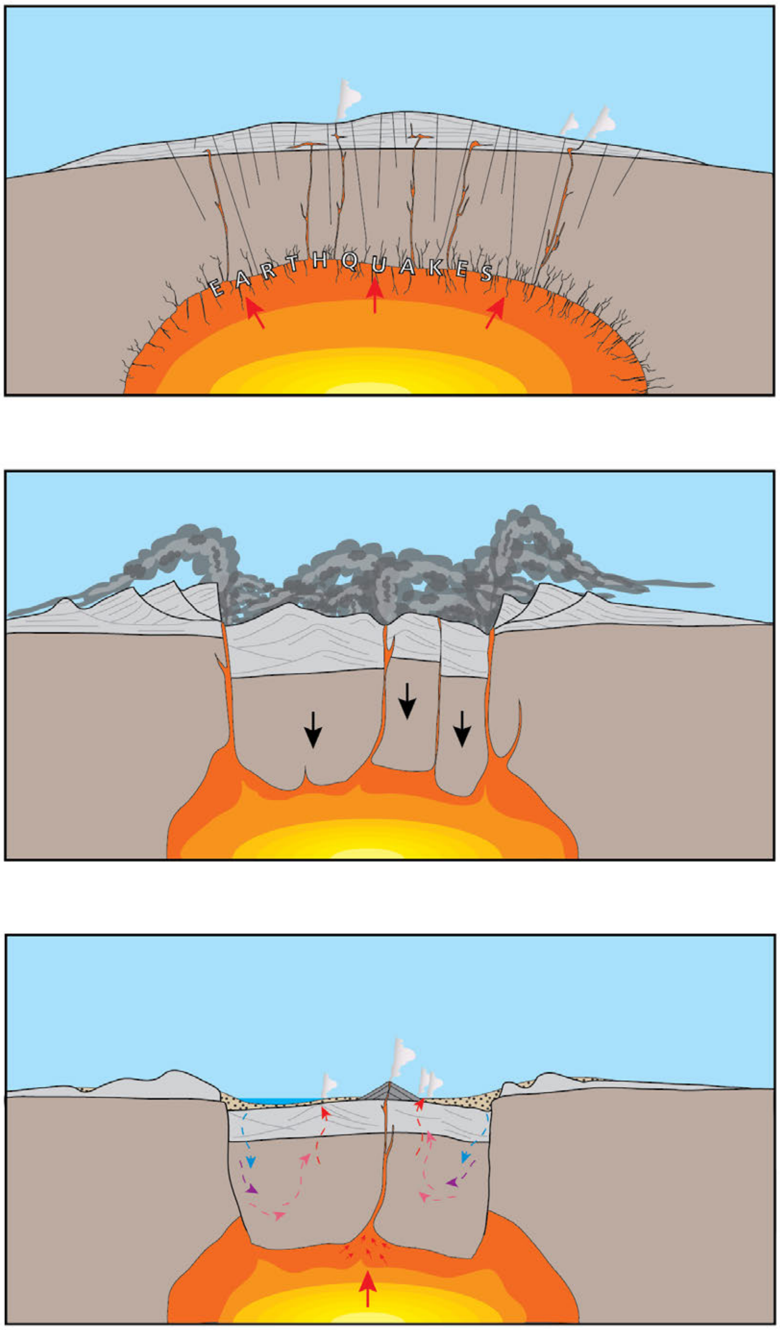
Rock Name:	Rhyolite	Rhyodacite	Dacite	Andesite	Basaltic Andesite	Basalt
Silica (SiO_2) content*	≥72%	68%–72%	63%–68%	57%–63%	52%–57%	≤52%
Color	Color ranges from lighter (for silica-rich rhyolite) to darker (for lower silica basalt)					
Viscosity of magma	Viscosity ranges from high (thicker) for rhyolite to low (more fluid) for basalt.					
Typical style of eruption	Eruption style ranges from explosive for rhyolite to effusive for basalt.					
Park Examples	Lower and Upper Coot Mountain units (Ycl and Ycu); Rhyolites of Shut-In Mountain (Ysi), Sutton Creek (Ysc), and Russell Mountain (Yrm)	Rhyolite of Russell Mountain (Yrm)	Not mapped in park.	Not mapped in park.	Not mapped in park.	Not mapped in park.

* from Bacon (2008).



Ycu
Yd
Current River
Matthews Branch
Blair Creek
Ycu
Ycu
Sutton Creek
Ysc
Jacks Fork River
Ycl
Yd
Yvc
Current River
Eminence
Indian Creek
Ysi
Ysi
Yrm
Current River
Ysi
Rocky Creek
Yltm
Ymm
Ysi
Ysm
North
Lower, volcanic sequence
Yrm Rhyolite of Russell Mountain
Ysc Rhyolite of Sutton Creek
Yltm Tuff of Little Thorny Mountain
Ycu Upper Coot Mountain unit
Ycl Lower Coot Mountain unit
Upper, post-caldera sequence
Ymm Tuff of Mule Mountain
Ysi Rhyolite of Shut-In Mountain
Yvc Volcaniclastic conglomerate, breccia, and sandstone
Ysm Rhyolite of Stegall Mountain
Faults
Ozark National Scenic Riverways
0 2 Kilometers
0 2 Miles
Approximate limit of location of the Eminence caldera
Extent of above map
Eminence
North
0 5 Kilometers
0 5 Miles

Figure 21 (facing page). Map of Mesoproterozoic Era map units near the confluence of the Jacks Fork and Current rivers. Tuff of little Thorny Mountain (Yltm), the rhyolite of Russell Mountain (Yrm), the rhyolite of Sutton Creek (Ysc), and the upper and lower Coot Mountain units (Ycu and Ycl, respectively) compose the lower, volcanic sequence in the area, whereas the other units are part of the upper sequence after the caldera collapse. Lower map shows the approximate extent of the Eminence caldera. Graphic by Trista Thornberry-Ehrlich (Colorado State University) redrafted after figure 8.3 in Lowell et al. (2010) using GRI map data from Weary et al. (2016) and ESRI World Imagery basemap (accessed 29 September 2015). Caldera extent from figure 3 in Weary et al. (2014).



As large volumes of magma accumulate a few miles below Earth's surface, the ground swells, fractures and faults rupture, and earthquakes occur.

As the volcano erupts, the caldera collapses. Immense ash falls and pyroclastic flows are produced.

After the caldera forms, the following take place almost simultaneously: caldera walls slough downward into the depression, slope movements occur on adjacent slopes, a lake or lakes develop in the caldera depression from rain and snowmelt, and small lava domes and lava flows erupt into the lake or lakes. Also, as groundwater interacts with hot rock, hydrothermal activity occurs.

Figure 22 (above). Illustration of caldera formation. The volcanic geologic map units associated with the Eminence Caldera demonstrate both concurrent and post-caldera collapse features (e.g., tilted flow layering juxtaposed with more-or-less horizontal layering). Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after Smith and Bailey (1968, figure 5).

With the exception of the Big Spring Granite (**Yg**) mapped between Big Spring and Van Buren, the igneous rocks at the park are volcanic rocks. They are mapped between Logyard to the southeast and Eminence to the west in the area of the confluence of the Current River and Jacks Fork (fig. 21; see GRI poster; Weary et al. 2014, 2016). See the Map Unit Properties Table for more details. Rocky Falls flows over the Rhyolite of Shut-In Mountain (**Ysi**).

Geologists use silica (silicon dioxide, SiO_2) content as a means for classifying volcanic rocks (table 2). The percentage of silica influences many properties of magma, including viscosity and explosiveness. In general, lavas with more silica are more viscous and explosive (table 2). The volcanic rocks at the park are primarily rhyolites (**Yrm**, **Ysc**, and **Ysi**) and ash-flow or air-fall tuffs (**Ysm**, **Ymm**, **Yltm**, **Ycu**, and **Ycl**) of broadly rhyolitic composition. The type of magma that forms rhyolite is very viscous and can erupt during the most explosive type of eruptions—caldera forming eruptions. For comparison, Yellowstone National Park is atop a massive caldera (a "supervolcano") and a caldera eruption formed the crater at Crater Lake National Park (see GRI report by KellerLynn 2013). A caldera is a volcanic feature that forms as a large, basin-shaped depression that collapsed during a massive eruption (fig. 22). In the geologic record, these are marked by faults that surround volcanic rocks.

The Eminence caldera erupted 1.48 billion years ago. Today, the caldera is denoted by faults oriented to the northeast and northwest (see "Faults and Fractures" section). More than 50 isolated "knobs" of ignimbrite (the deposit of an explosive volcanic flow) and lava—relatively hard rocks compared to the surrounding sedimentary rocks—are all that remains of the caldera (Lowell 2000; Weary et al. 2014). Sedimentary layers in younger, adjacent rocks, tilt away from these knobs indicating that they were a topographic high and probably formed islands when the area was underwater during the Paleozoic Era (see fig. 20 and "Geologic History" chapter). In general, the volcanic rocks do not show any sign of being buried more than a few kilometers or of other extensive deformation so they have likely been high points for more than 500 million years (Weary et al. 2014).

Steeply dipping, rotated blocks of depositional flow-banding are characteristic of caldera eruptions. The volcanic rocks have a banded texture called "foliation" that was created while the rocks erupted, as well as postdepositional deformation (Weary et al. 2014). The bands formed because the lava was heterogeneous and the different materials flowed, were ejected, and/or cooled in different ways. Successive eruptions created repeated layers of banded material. Molten material associated with these volcanoes that cooled slowly beneath the surface but did not erupt, formed granite plutons. Where these buried masses are juxtaposed with Paleozoic sedimentary rocks (e.g., Bonneterre Formation) are favorable sites for finding minerals such as those mined from the Viburnum Trend (see "External Mineral Development" section) which accumulated as saturated, geothermal fluids percolated through the rocks in the late Paleozoic (Lowell et al. 2010).

Radiometric Ages

In geology, radiometric dating methods compare the abundance of a naturally occurring radioactive isotope of a mineral with the abundance of its decay products, which form at a known constant rate of decay (Boltwood 1907). Radiometric dating is now the principal source of information about the absolute age of rocks and other geological features. Igneous rocks and volcanic ash layers are prime candidates for radiometric dating because they contain the necessary radioactive minerals. Sedimentary rocks rarely contain the appropriate minerals and are often dated relatively—based on their relationship with other rocks. The ages of several igneous rock units in the park have been determined via radiometric dating techniques. The GRI GIS data include uranium-lead ages for the Big Spring quad granite (**Yg**) and the Rhyolite of Shut-In Mountain (**Ysi**) (Weary et al. 2014). Dates are reported on the Map Unit Properties Table. Additional radiometric dating could reveal more about the complicated history of the igneous rocks of the area and constrain the timing of the Eminence caldera's eruption and collapse.

Faults and Fractures

A fault is a fracture along which rocks have moved. At the park, faults are commonly obscured by vegetation and residuum (e.g., **QTr**, **QTtrc**, and **QTrr**). Their presence is inferred from vertical offset of strata and cataclastic (severely, brittlely deformed) bands observed in outcrop or in blocks of sandstone (Lowell et al. 2010). The three primary types of faults are normal faults, reverse faults, and strike-slip faults. They are

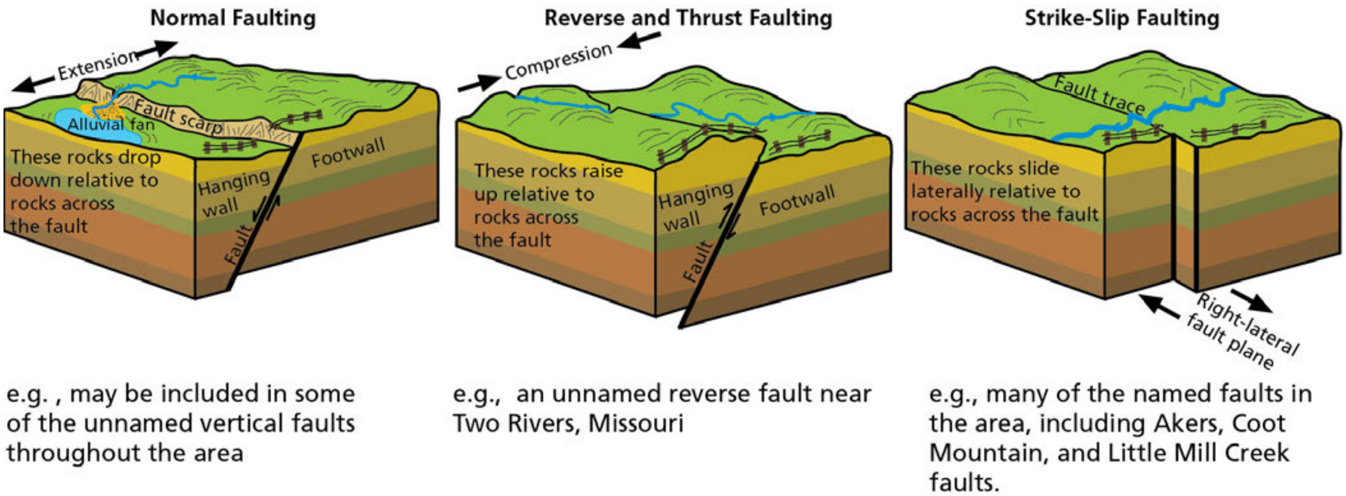


Figure 23. Illustrations of fault types. Movement occurs along a fault plane. Footwalls are below the fault plane and hanging walls are above. In a normal fault, crustal extension (pulling apart) moves the hanging wall down relative to the footwall. In a reverse fault, crustal compression moves the hanging wall up relative to the footwall. A thrust fault is similar to a reverse fault, but has a dip angle of less than 45°. In a strike-slip fault, the relative direction of movement of the opposing plate is lateral. When movement across the fault is to the right, it is a right-lateral (dextral) fault, as illustrated above. When movement is to the left, it is a left-lateral (sinistral) fault. A strike-slip fault between two plate boundaries is called a transform fault. Graphic by Trista Thornberry-Ehrlich (Colorado State University).

classified based on motion of rocks on either side of the fault plane as described in fig. 23. Reverse and vertical faults of unknown offset/displacement (probably strike-slip) are mapped in GRI GIS data (Weary et al. 2014a). The GRI GIS data include 29 named faults; typically these faults are named for their geographic location and are probably strike-slip faults (see posters, in pocket).

Regionally, the faults are oriented along two dominant strikes: northeast and northwest (Lowell et al. 2010). The faults are divisible into three broad age groups corresponding to periods of volcanism, mountain building, and other regional-scale deformation (see "Geologic History" section): (1) those showing evidence of only being active in the Mesoproterozoic Era, (2) those that were active at one or more times prior to the deposition of the Ordovician sedimentary rocks, and (3) those that were active at one or more times in the Phanerozoic Eon and probably during the Proterozoic Eon (Weary et al. 2014).

In the early 1800s, movement along faults in the New Madrid Seismic Zone southeast of the park were responsible for some of the largest earthquakes ever recorded in North America. Smaller magnitude earthquakes occasionally shake the region, including one in October 2015 while this report was being written. See the "Seismic Activity Hazards and Risk" section.

The Denning Hollow and Mud Spring Hollow shear zones are linear areas of deformation, possibly active as left-lateral strike-slip zones during the Proterozoic Eon and later reactivated. They are characterized by features such as closely spaced fractures, mineralized veins, a foliation or banded appearance, and reduced grain-size (Weary et al. 2014). The two zones are roughly parallel, striking northeast to southwest, and are about 2.3 km (1.4 mi) apart in the vicinity of Roberts Field campground. The western Denning Hollow shear zone forms a contact between the Eminence and Potosi dolomites (**Ce** and **Cp**). An unnamed, northwest to southeast striking, vertical fault truncates the Denning Hollow shear zone; this fault is in turn truncated by the Mud Spring Hollow shear zone.

Vertical joints, or fractures along which movement has not occurred, are oriented north-south and east-northeast (National Park Service 2007). These joints formed during the buckling of Earth's crust associated with the Ouachita orogeny, and possibly the Alleghany orogeny, that constructed mountains to the south in Pennsylvanian–Permian time (Cox 1995; Weary and Orndorff 2001). The joint sets are oriented parallel to the direction of the sedimentary layering (bedding planes), and because most of the park's bedrock is soluble (see "Caves and Karst Features and Processes" section), the joints are enlarged by surface and groundwater dissolution (Weary and Orndorff 2001).

Fractures, joints, faults, and fault zones such as the Wilderness-Handy fault zone provide permeable and/or porous substrates which facilitate groundwater movement. Rocks along large deformation zones are intensely silicified and brecciated with almost complete carbonate dissolution. In the past, mineral-laden fluids flowing through these permeable and porous zones deposited valuable ores including lead (e.g., the Mississippi Valley-type mineralization; see "External Mineral Development" section) (Lowell et al. 2010).

Folds

Despite being difficult to locate due to lack of exposure and extensive vegetative cover, small folds are mapped in the park. Folds are curves or bends in originally flat structures, such as rock strata, bedding planes, or foliation. The two primary types of folds are anticlines which are "A-shaped" (convex) and synclines which are "U-shaped" (concave). Both types of folds can be overturned or tilted past vertical. Folds can "plunge" meaning the fold axis tilts. As bedrock is compressed, anticlines and synclines form adjacent to each other like wrinkles in a blanket. A monocline is a local steepening of rock layers in an otherwise uniform gentle dip. Small-scale anticlines, synclines, and monoclines are identified in the GRI GIS data (see posters, in pocket). Adjacent and parallel synclines and anticlines deform the Gasconade and Eminence dolomites (geologic map units **Og** and **Ce**, respectively) in the northwesternmost corner of the park near Baptist Access on the Current River where the fold axes are only about 100 m (330 ft) apart. Several fold axes occur in the southernmost reach of the park near Kelley Bluff. A monocline occurs just northwest of park boundaries in the Waymeyer area. In general, gentle, open folds formed during compression near faults and in subsidence features related to large dissolution (karstic) voids (see "Cave and Karst Features and Processes" section).

Geologic Resource Management Issues

Some geologic features, processes, or human activities may require management for human safety, protection of infrastructure, and preservation of natural and cultural resources. The NPS Geologic Resources Division provides technical and policy assistance for these issues.

During the 2001 scoping meeting (see National Park Service 2001) and 2015 conference call, participants (see Appendix A) identified the following resource management issues.

- Flooding and Fluvial Geomorphology
- Climate Change Impacts
- Caves and Associated Landscape Management
- Ozarks Aquifer and Springs Protection
- Erosion
- Paleontological Resource Inventory, Monitoring, and Protection
- Slope Movement Hazards and Risks
- Seismic Activity Hazards and Risks
- Abandoned Mineral Lands
- External Mineral Development

Management Resources

The Additional References section and Appendix B list resources available to park managers to support science-informed decision making. The park's Water Resources Foundation Document (Vana-Miller 2007) and Cave Management Guide (National Park Service 2010) are primary sources of information for resource management within the park. The park's foundation document is forthcoming. Cultural landscape restoration and management are also addressed in a number of publications.

Flooding, slope movements (including rockfall along cliffs or in caves), and earthquakes are examples of geologic hazards—a natural or human-caused geologic condition or process that may impact park 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 Missouri Department of Natural Resources lists information about geologic hazards (e.g., abandoned mines, earthquakes, landslides, and karst), mineral resources, and geologic maps at their geologic resources section website (http://dnr.mo.gov/geology/geosrv/geores/index.html).

The Heartland Network is monitoring land-cover changes at the park. More information about the network's vital signs monitoring program is available at: http://science.nature.nps.gov/im/units/htln/monitor/index.cfm.

The American Geosciences Institute maintains a critical issues program website (http://www.americangeosciences.org/critical-issues) with information on topics including climate, energy, hazards, mineral resources, and water. The US Geological Survey's Columbia Environmental Research Center maintains a robust website (http://www.cerc.usgs.gov/) with information about water quality, climate change, energy development, environmental chemistry, the Ozark Highlands, and ecosystem health.

Resource managers may find *Geological Monitoring* (Young and Norby 2009; http://go.nps.gov/geomonitoring) useful for addressing 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, suggested methods of monitoring, and case studies.

The Geoscientists-in-the-Park and Mosaics in Science programs are internship programs to place scientists (typically undergraduate students) in parks to complete geoscience-related projects that may address resource management issues. Projects at Ozark National Scenic Riverways have included (as of August 2016):

- Cave/karst inventory and monitoring (1997, 1998, 2000, 2002)
- Cave/karst research (2001)
- Hydrology inventory and monitoring (2002).

Projects are listed on the GIP website: http://go.nps.gov/gip_products. Products created by the program participants may be available on that website or by contacting the Geologic Resources Division. Refer to the programs' websites at http://go.nps.gov/gip and https://www.nps.gov/subjects/youthprograms/mosaics.htm for more information.

Flooding and Fluvial Geomorphology

The fluvial resources associated with the Current River and Jacks Fork are the major natural-resource features at Ozark National Scenic Riverways. The park was established in part to preserve the Current River and Jacks Fork as free-flowing rivers. Their courses are largely unimpaired by dams or other control methods and flow is dependent on rainfall and input from the karst subterranean network (e.g., from springs; see "Caves and Associated Landscape Management" section). Average annual precipitation is 114 cm (45 in) for Eminence, Missouri (Jacobson and Pugh 1992; US Climate Data 2016). Following heavy rainfall, rapid surface runoff on the steep valley slopes and subterranean recharge contributes to flash flooding (Alexander 1990). Water levels in the Current River and Jacks Fork can rise as fast as 0.6 m/hour (2 ft/hour) (Wilson 2001).

Streamflow is the most fundamental variable for understanding physical, chemical, and biological dynamics in the riverine ecosystem (Covington 2002). Streamflow data are collected at seven sites within the Current River's and Jacks Fork's drainages: (1) Montauk State Park, (2) Highway 17 near Mountain View, (3) Alley Spring, (4) Eminence, (5) Akers Ferry, (6) Van Buren, and (7) Doniphan (south of the park) (Vana-Miller 2007). A stage-only gage was established on the Powdermill Bridge in 2015. The highest flows occur from April to May (fig. 24). Floods are least common from late August to early September. Floods typically last at least 2 to 3 days (Wilson 2001). Since record keeping began at Van Buren in 1921, 25-year floods (flows greater than about 24,900 m^3/sec [87,800 ft^3/sec]) happened in 1935 and 1993. A 50-year flood (a discharge that has a 2% chance of being equaled or exceeded in any given year with discharge of more than 3,000 m^3/sec [105,000 ft^3/sec]) has not occurred (Alexander 1990; Vana-Miller 2007). Flood discharge for a 100-year flood (a 1% chance of being equaled or exceeded in any given year) for the Current River drainage area would be over 3,500 m^3/sec (123,000 ft^3/sec). Compare those flows to the Current River's average annual discharge of about 56 m^3/sec (2,000 ft^3/sec) at Van Buren (US Geological Survey 2016a). Higher in the watershed, above Akers, Missouri, the normal flow is about 14 m^3/sec (500 ft^3/sec) (Alexander 1990; Vana-Miller 2007; US Geological Survey 2015, 2016b). Because park boundaries and infrastructure closely border most of the river corridor, large floods could cause safety issues and damage infrastructure. Floods of the 25-year magnitude have caused major damage to park infrastructure (Wilson 2001).

The shape or morphology of a stream channel is integral to the fluvial and riparian ecosystem, which depends on the size, shape, and bottom characteristics of the channel and its change through time (Jacobson et al. 2001; Covington 2002). Riparian zones affect slope movements (e.g., interplay of alluvium **Qal**, landslide deposits **Qls**, and colluvium **Qc**; see "Slope Movements" sections) and channel morphology (Vana-Miller 2007). Changes to the rivers' channels are mostly a natural result of meandering; however, human modifications

Figure 24. Photographs of flood conditions. Floods may occur rapidly after heavy precipitation. Floods are an important natural process in maintaining the diversity and health of the riparian zones flanking the rivers. Photographs by Victoria Grant (NPS Ozark National Scenic Riverways) taken in April 2011.

to the streambanks and floodplain areas have altered the system affecting discharge, sediment supply, and erosional resistance of the banks (see "Erosion" section). As channel morphology changes, spatial and temporal distributions of depth, velocity, substrate, and alluvial deposits within the stream itself also change. Aquatic plants and animals (e.g., mussels) that cannot migrate with the changing habitats are negatively impacted (Jacobson and Primm 1997; Covington 2002).

Riparian zones, underlain by alluvium, terrace, and slope deposits (**Qa**, **Qls**, **Qc**, **Qt**, and **Qtl**) are among the most disturbed ecosystems in the park; disturbance is accelerated by land clearing, logging, and overuse (Vana-Miller 2007). Current land-use stressors to the Current River's and Jacks Fork's drainage basins include the effects of tailing disposal, increased recreational use, poorly engineered road crossings, renewed timber clearing, land conversion to grazing, and channel gravel mining (Jacobson and Primm 1997; Covington 2002; Vana-Miller 2007). Analysis of drainage-basin variables such as channel morphology, bottom sediment type, and indicators of channel stability demonstrated connections among geology, physiography, and land-use patterns (Panfil and Jacobson 2001). Cleared land area is negatively correlated with drainage-basin average slope. Bankfull (the point at which the flow begins to enter the active floodplain) channel geometry, residual pool (the depth that, if flow were reduced to zero, water would fill pools just up to their rims) dimensions, and bottom sediment particle size correlate positively with drainage area and topographic relief (Panfil and Jacobson 2001). Channels are shallower with finer-grained bedloads in the less rugged, western basins of the Current River tributaries, than in the steeper, middle and eastern basins (Panfil and Jacobson 2001).

Park infrastructure and recreational-use areas are also at risk for loss or damage when streams change their courses or flooding inundates low areas. Channel engineering (e.g., boat ramps, bridge abutments, and levees) and river crossings, such as in Eminence on the Jacks Fork and Van Buren on the Current River, have changed the local flow of the rivers and, consequently, their channel morphology by creating scouring in some areas and gravel deposits in others (Covington 2002). While planning for streambank infrastructure, the park should consult NPS planning documents including Director's Orders 77-1 (Wetland Protection) and 77-2 (Floodplain Management), as well as the other laws, regulations, and policies listed in Appendix B and available at https://www.nps.gov/applications/npspolicy/index.cfm.

For areas within the park with flooding concerns or other potential changes to channel morphology, additional study and monitoring protocols may be needed. The protocols used by Panfil and Jacobson (2001) identified subtle land-use impacts on channel morphology and sediment characteristics in Current River tributaries. Jacobson and Pugh (1997) outlined stream restoration guidelines that show where inherent instability is likely to overwhelm restoration activities; these guidelines are now being used by the State of Missouri (Covington 2002). McKenney (2001) defined spatial and temporal controls on the creation and degradation of stream habitats, based in part on monitoring data from Jacobson and Pugh (1997) from the Ozarks. Park resource managers can contact the Heartland I&M network and/or consult existing standard operating procedures such as those defined in the *Geological Monitoring* chapter about fluvial geomorphology by Lord et al. (2009). They 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.

Covington (2002) noted the need to (1) inventory the status and vulnerability of campgrounds to flooding, (2) incorporate stream-profile data into the park's GIS, (3) use historical aerial photographs to measure changes in stream morphology through time, and (4) study the impacts of levees, bridge abutments, and armoring to channel morphology.

Additional data sources and methodologies include:

- US Geological Survey's existing stream-gauge network provides a record of aggradation, degradation, and morphology changes (Jacobson 1995). This could be expanded to include more gages on tributary streams. Real-time water resources data are available at http://mo.water.usgs.gov/.

- Low-altitude aerial photography and LiDAR, particularly useful to document the spatial distribution of gravel bars (fig. 25) and sediment routing (Jacobson and Gran 1999).
- Establish a network of monitored cross sections throughout the park with resurvey/monitor to provide rates of erosion, deposition, and habitat alteration (McKenney and Jacobson 1996).
- Continue and expand Global Change network surveys (McKenney and Jacobson 1996) to include tributaries and downstream parts of the Jacks Fork and Current rivers. Two sites are already benchmarked on the Jacks Fork (Victoria Grant, Ozark National Scenic Riverways, natural resources program manager, conference call, 20 October 2015).

Surface water quality, impacted by runoff, increased surrounding urbanization, and mining can have effects on the park ecosystem (see "Ozarks Aquifer and Springs Protection" section; Covington 2002). Water quality discussions are beyond the scope of this report. Vana-Miller (2007) presented the water resources report for the park. Schmitt et al. (2008) presented protocol for heavy-metal monitoring at the park. Davis and Barr (2006) detailed possible sources of microbiological contamination of the park's water column and streambed sediment. The NPS Water Resources Division (http://www.nature.nps.gov/water/) can provide technical and regulatory assistance to resource managers at the park regarding water-related issues.

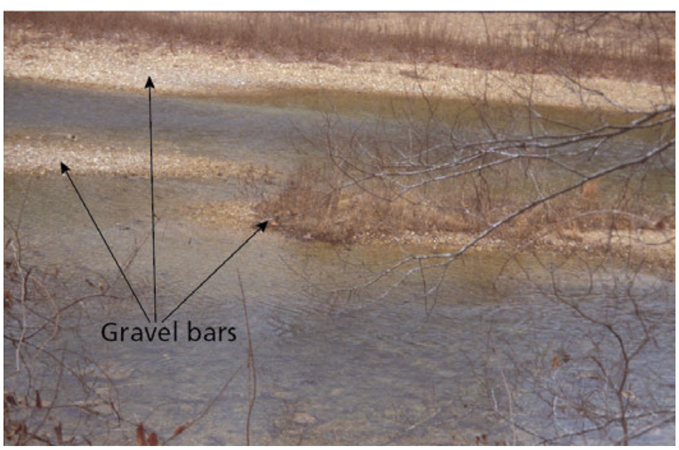


Figure 25. Photograph of gravel bars in the Jacks Fork. Finer grained material is washed away downstream leaving the coarsest material behind in the river channel. This changes the morphology of the channel and the fluvial habitat. If the bars persist above the water level long enough, vegetation stabilizes the feature. Photograph by Sid Covington (NPS Geologic Resources Division) taken in February 2002.

Stream Sediment Storage and Load

In addition to their dissolved minerals (see "Caves and Karst Features and Processes" section), the streams and rivers at the park transport clastic material from fine clays to coarse gravels. As noted in the "Erosion" section, fine sediment can remain in suspension, causing turbidity and clouding the water which adversely affects riverine ecosystems (Covington 2002). Human use stirs up the bottom sediments, resuspending them and facilitating downstream transport (see "Erosion" section; Covington 2002; Vana-Miller 2007).

Stream bottom sediments are changing from finer grained to more gravel-rich, chert sediments because bank erosion removes the finer-grained components while the gravels remain (Vana-Miller 2007). Finer sediment sizes are "easier" for streams to transport. Gravel moves the most during high energy flow such as storms and flooding. Additionally, because chert does not dissolve like the carbonate bedrock, it is "left behind" and forms much of the gravel in park stream beds (Panfil and Jacobson 2001).

Increased gravel content can lead to shallower streams because base flow moves more easily through gravel than finer sediments (Panfil and Jacobson 2001). A three-year study to better understand the geomorphic drivers of best habitat for mussel restoration should develop or update models of gravel transport (time frame of decades to centuries after human land disturbance) within the major rivers. This will help park resource managers understand how fast the gravel is moving through the system and address future issues (Victoria Grant, Ozark National Scenic Riverways, natural resources program manager, conference call, 20 October 2015).

To understand the changes in sediment storage and load and to predict future trends, park resource managers need an understanding of sediment influx (e.g., from breached or leaking tailings ponds, natural bank erosion, agriculture runoff) (Covington 2002). Stream flow regime models may help to determine why sediment loads are changing within the park. Sediment-load monitoring data (suspended and bed loads), though widely variable over space and time, are vital to understanding stream ecosystem dynamics.

Climate Change Impacts

Historical climate data trends in the park vicinity are highly variable, both seasonally and annually (Fisichelli 2013). Climate projections by Fisichelli (2013) for mid-century (2041–2070) suggest:

- a 2.6°C (4.7°F) rise in temperature compared to 1971–2000 average,
- a 3-week longer frost-free period, and
- strong interannual and seasonal variability for precipitation, including a 20% increase in the annual number of >2.5 cm (1-in) rain events.

Potential impacts of climate change to natural and cultural resources at the park are pervasive and far-reaching. Increasing temperatures will cause certain species to shift their range northward. The populations of some park species may decline because of limited dispersal abilities and specific habitat requirements (Fisichelli 2013). Because the park has been a refuge for relict species from ice age glaciations, these species may be especially sensitive to changing parameters (Fisichelli 2013). Fisichelli (2015) summarizes forest vulnerability to different climate-change scenarios.

More variable precipitation will cause both increased drought and flooding and in turn cause more frequent erosional disturbance to aquatic and streambank communities, as well as potential degradation of cultural resources (see "Flooding and Fluvial Geomorphology" and "Erosion" sections; Fisichelli 2013). Stretches of the river near springs with relatively consistent flow and cool temperatures (such as near source springs) will increasingly function as refugia or vital habitat for sensitive species (Fisichelli 2013).

If storm flows increase, bottom sediment will be more frequently mobilized. Peak discharges may be more erosive and likely to destabilize stream banks. If this causes stream widening, the channel sinuosity would be reduced and overall canopy cover may be affected. Increased storm flows would also disturb benthic habitats; a shallower and warmer benthic habitat with lower diversity would be expected (Panfil and Jacobson 2001).

Climate-change could also affect visitation at the park (Fisichelli 2013). Temperature strongly predicts visitation at the park and explained 99% of the variation in monthly visitation (Fisichelli and Ziesler 2015). Based on mid-century temperature projections, annual park visitation could potentially increase as much as 46% (Fisichelli and Ziesler 2015). This increase in visitation could produce a correlative increase in land-use disturbances and negatively impact park natural resources and strain the capacity of park infrastructure.

Case studies detailing how archeology can reveal paleoenvironmental data and illustrating ways in which archeological studies can advance efforts to better understand and respond to climatic shifts are ongoing at the park (Bringelson 2013). These studies integrate archeological and paleoclimate data sets to understand how environmental change has affected the human past (Dempsey and Bringelson 2013). The studies require thorough knowledge of late Quaternary landscape evolution in order to predict where people were at different times and what they were doing, as well as how climate change has influenced where the archeological resources may be preserved (Dempsey and Bringelson 2013). If the park is interested in studying past change, understanding how the river corridors have changed along with shifting climates through time is an important component. This will increase understanding of the human-landscape interactions of the past, which may serve as a proxy for developing strategies to understand modern climate change (Dempsey and Bringelson 2013). Refer to the NPS Climate Change website for additional information: https://www.nps.gov/subjects/climatechange/index.htm.

Caves and Associated Landscape Management

Cave features are nonrenewable resources and, with 402 known caves, they are a fundamental component of the Ozarks landscape. See the "Cave and Karst Features and Processes" section. With the exception of guided tours in Round Spring Cavern, all caves in the park are closed to recreational access to minimize the spread of white-nose syndrome. Primary management issues associated with caves include the following concerns that are summarized below:

- sinkhole flooding and collapse,
- cave breakdown,
- slippery surfaces, precipitous drops, and drowning,
- radon,
- vandalism and dumping, and
- white-nose syndrome.

The Federal Cave Resources Protection Act of 1988 requires the identification of "significant caves" in NPS areas, 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 FOIA request (see also Appendix B). Documentation of caves provides a baseline for future management planning. Many park caves were only recently discovered and have yet to be surveyed; mapping of park caves continues (House 2015).

The regional karst features also contribute to the Ozarks aquifer (geologic map units **Cp**, **Ce**, **Og**, **Or**, and **Ojc**), which represents nearly 42% of Missouri's usable groundwater (Orndorff et al. 2006; Vana-Miller 2007) and thus are important for groundwater quantity and quality considerations (see "Ozarks Aquifer and Springs Protection" section. Even slight disturbances can cause major impacts to the delicately balanced cave-aquatic and cave-terrestrial ecosystems. Damage or distortion to cave ecosystems can come from varied sources, close by (e.g., artificial lighting or groundwater pumping) or far away (e.g., acid rain or air pollution).

Sinkhole Flooding and Collapse

Sinkholes occur throughout the park; sinkholes are part of the GRI GIS data, mapped as "Hazard Area Features" (Weary et al. 2016). Sinkhole flooding is a natural hydrologic process that occurs during intense rainfall when the quantity of storm water flowing into the sinkhole exceeds its capacity to drain into underlying conduits. The presence of muck and clayey silt (geologic map unit **Qm**), deposited in intermittently ponded sinkholes, attest to this process. The flow of water into and out of a sinkhole may change its morphology, potentially widening and/or deepening it.

Most sinkholes form slowly through solution and subsidence and thus can be identified and avoided. The Jefferson City Dolomite and Roubidoux Formation (**Ojc** and **Or**, respectively) have the highest concentration of sinkholes in this part of Missouri. Most are closed-throat sinkholes; however, collapses have occurred historically (Orndorff et al. 2006). For example, a collapse created the opening to Devils Well and therefore, another large collapse is possible there (Lowell et al. 2010). 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). Lowering of the water table may also contribute to sinkhole formation. Aley and Creath (1989) described instances of mine-related pumping contributing to "litters of sinkholes" forming.

Geologists suspect many more unrecorded sinkholes exist in the park's forests. The current data only include those that were identified on 6-m (20-ft) contour maps and fieldwork discoveries. There is a need to acquire bare-earth LiDAR to accurately identify and better characterize sinkhole areas in the park (Dave Weary, US Geological Survey, geologist, written communication, 21 June 2016).

Cave Breakdown

The term "cave breakdown" refers to the collapse of a cave ceiling or wall, or to the debris accumulated through such collapse. Collapse chambers exist at Round Spring Cavern (Lowell et al. 2010). The caves at the park continue to change over time. 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.

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 can be slowed in some cave areas by the installation of roof bolts into the cave roof and walls. These bolts anchor loose slabs to the adjacent intact rock in an attempt to stabilize the cave ceiling. Detailed cave mapping and assessment of potential hazards would help resource managers identify areas at particular risk. Refer to the "Slope Movement Hazards and Risk" section for additional information.

Slippery Surfaces, Precipitous Drops, and Drowning
Slippery surfaces and drowning dangers attest to the omnipresent dripping, flowing, and standing water in many of the park caves. Unauthorized cave use, particularly in closed caves, continues to be an issue for resource managers at the park (see "White-Nose Syndrome" subsection).

Radon
Radon (^{222}Rn) is a colorless, odorless, radioactive gas that naturally 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 park bedrock. Airflow can concentrate or transport radon throughout caves. Airflow in caves is a function of interior cave and exterior ambient temperatures and of the cave's configuration. Temperature gradients produce pressure differences between the cave interior and exterior, causing air to move (Yarborough 1980, 1981).

Uranium-enriched granites and rhyolites, and residuum developed on carbonate rocks in the Ozark Plateau Province are likely to produce radon and the province has a "moderate" overall radon potential according to a preliminary US Geological Survey assessment (Schumann 1993). According to the park website, elevated levels of radon occur in the park at Round Spring Cavern. Although this is perfectly normal in a limestone cave, the health effects, if any, are not currently known and therefore the park "discourages babies and pregnant women from participating" in the tour (see https://www.nps.gov/ozar/learn/education/visiting.htm). Field (2007) discussed risks to cave workers (e.g., "tour guides") from exposure to radon and noted that many NPS caves, including Round Spring Cavern, had elevated radon measurements. If concerns do arise, managers can contact the NPS Geologic Resources Division or the Missouri Geological Survey for assistance in developing a radon study plan. Information about residential exposure to radon in Missouri is available at the state's Department of Health and Senior Services website (http://health.mo.gov/living/environment/radon/index.php). Radon exposure is monitored at many NPS areas in the Midwest Region, including Hot Springs National Park in Arkansas (see GRI report by Thornberry-Ehrlich 2013) and Mammoth Cave National Park in Kentucky (see GRI report by Thornberry-Ehrlich 2011).

Vandalism, Visitor Access, and Dumping
Cave formations, or speleothems, are commonly fragile, and easily damaged by intentional vandalism or unintentional damage by humans. Touching the cave formations introduces lint and oils from the body and alters the character of the cave-formation system (Covington 2002). Speleothems and other features in the park have been broken and vandalized, and cultural resources in the cave have been stolen or damaged, and graffiti is an additional concern (Kimberly Houf, Ozark National Scenic Riverways, terrestrial ecologist, email, 16 December 2015). Other cave-use issues include trampling, muddy tracks on cave formations, littering, and bat disturbance (White 1985). The cave environment is slow to recover from damage and damaged speleothems many never "recover." The Springfield Plateau Grotto (SPG), a chapter of the National Speleological Society (NSS) and the Cave Research Foundation (CRF) have been active in the park reattaching at least 78 speleothems in Shannon County (Jonathan Beard, SPG of the NSS, secretary/treasurer, written communication, 10 July 2016).

Social trails lead to the most popular caves and cause erosion, vegetation deterioration, and soil compaction (see also "Erosion" section; White 1985). Caves are also popular climbing destinations and park staff members working with the CRF continue to remove illegally-installed climbing gear from park caves, as well as identify and monitor cultural resources within the caves (House 2015). Looters have dug illegally at several park caves and many of these areas were refilled by volunteers from the SPG and CRF (Jonathan Beard, SPG of the NSS, secretary/treasurer, written communication, 10 July 2016).

In the mid-1980s, park resource managers gated some cave entrances and installed educational signs to promote responsible cave behavior and talk about the importance and fragility of the cave ecosystem (White 1985). Today, even though the majority of caves are closed to the general public, the park continues this style of educational management with closure postings throughout the park and at several well-known cave entrances.

Sinkholes and caves throughout the region have historically been used as garbage dumps. Sinkholes are also the sites of some septic systems discharge (Covington 2002). Graffiti removal, trash collection, and trail marking and restoration are all projects in which volunteers with the SPG and CRF engage at Ozark National Scenic Riverways; as many as 13 park caves have experienced some restoration or improvements (Jonathan Beard, SPG of the NSS, secretary/treasurer, written communication, 10 July 2016).

White-Nose Syndrome

White-nose syndrome (WNS) is a disease in bats caused by the fungus *Pseudogymnoascus destructans*. Discovered in the winter of 2006–2007 in a cave in New York, WNS has devastated hibernating bat colonies throughout the eastern United States and Canada. WNS has killed over 6 million bats within various species including Indiana and gray bats. WNS was discovered in gray bats in Shannon County, Missouri in May 2010. With this discovery, park managers closed all caves to recreational activities, except for guided trips into Round Spring Cave. While bats themselves are the primary way this fungus is spread, the closure of caves helps to ensure that people do not accidently transfer the fungus to new locations. (Castle and Cryan 2010; National Park Service 2012). See also http://nature.nps.gov/biology/WNS/index.cfm and http://www.whitenosesyndrome.org/.

Once bats in a hibernating colony contract WNS, the colony usually suffers a 90% or greater loss in bat numbers. The disease thrives in colder temperatures such as those found in a hibernaculum and causes skin infections that prematurely awakens hibernating bats. This uses their stored reserves sooner than needed and the bats die of starvation. Since its discovery, research has helped biologists better understand this disease, but there is still much to know and there are no easy solutions to this problem. (Castle and Cryan 2010; National Park Service 2012). Over the winter of 2014–2015, members of the Cave Research Foundation noted that most of the caves visited in the park showed multiple species with obvious signs of fungus. As the disease spreads, bats are moving from known locales to other caves for hibernation (House 2015). To help prevent the spread of the disease and to better educate the public, visitors' shoes are treated after Round Spring cave tours and more interpretive and educational signs, posters, and pamphlets are being developed (House 2015).

Cave and Karst Management

A park-specific cave management plan was completed for the park in 1988 and revised in 2010 to reflect the cave closures associated with WNS (National Park Service 1988, 2010).

The cave management plan provided strategies to achieve the following management goals (National Park Service 1988):

- Complete an inventory, evaluation and classification of caves in the park and develop a resource database integrated with information from cooperating agencies and organizations.
- Establish guidelines for restrictions, access and use of popular caves for recreational, interpretive and scientific purposes that will assure resource preservation.
- Assure the preservation of identified rare and endangered cave species and their habitat.
- Provide opportunities for recreational cave use and integrate park interpretive programs and materials with resources protection, visitor safety and resource management concerns.
- Evaluate existing problems of vandalism, over-use, impact on cave biota, safety hazards and information needs identified in current surveys and implement corrective actions.
- Establish a long-term monitoring system for cave resources and visitor use which will document impact and indicate need for management response.
- Cooperate with other agencies, educational institutions and organizations to increase public awareness and appreciation of cave resources.
- Encourage investigations and scientific research which will improve existing knowledge of Ozark Riverways' cave resources and further the park's management objectives for preservation, use and interpretation.

As reported in the plan's environmental assessment (National Park Service 1988), the preferred approach to the plan was to

- extend basic inventory and classification to all park caves;
- conduct comprehensive biological survey on major and significant caves;
- increase cave ecology research;
- increase visitor information program;

- establish monitoring system; and
- establish an advisory cave management team.

For a servicewide perspective on cave management, refer to Land et al. (2013). That publication was part of a National Cave and Karst Research Institute (http://www.nckri.org/) effort to compile survey results from NPS park units with cave and karst resources to help identify and prioritize research, remediation, interpretation, and other activities to best understand and manage cave and karst resources. As part of their goal to "identify the most critical needs in cave and karst research, management, and education/interpretation and provide recommendations on a general park-wide level and for specific parks", they noted that Ozark National Scenic Riverways had (1) threatened and/or endangered species, but critical habitats have not yet been identified; and (2) have recreational use of caves, but possess neither general nor cave-specific safety and rescue plans. They recommended having the US Fish and Wildlife Service (http://www.fws.gov/endangered/) establish critical habitat for the threatened and endangered species found within the park, as well as establishing a general safety and rescue plan for all caves regardless of size (Land et al. 2013).

Baker et al. (2015) produced a guide to assist NPS cave managers in deciding what to inventory and monitor in caves and provides ways to do this work in a nationwide, cohesive manner. Their recommendations take into account the rare and/or cryptic nature of cave species, as well as the complex logistics often involved with the cave environment. They stress the importance of completing an inventory of cave resources before embarking on a monitoring plan.

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.

Ozarks Aquifer and Springs Protection

The Ozarks aquifer provides nearly 42% of Missouri's usable groundwater (Vana-Miller 2007). The aquifer extends from the buried Cambrian confining unit below the Potosi Dolomite (geologic map unit **Cp**) to the surface including the Potosi Dolomite, Eminence Dolomite (**Ce**), Gasconade Dolomite (**Og**), Roubidoux Formation (**Or**), and Jefferson City Dolomite (**Ojc**) in the park (Aley and Creath 1989). This aquifer is unconfined and supplies water for domestic use and to the park's springs; local surface waters are supplied in large part by groundwater springs (Aley and Creath 1989; Lowell et al. 2010). Groundwater at the park has been measured to travel up to 5 km (3 mi) per day (Vana-Miller 2007). Because of the characteristically high infiltration rates and permeability of karst landscapes (i.e., large subterranean conduits), as well as the presence of faults, little to no adsorption of any surficial contaminants occurs. This means that contaminants are readily transported through the system.

Missouri's noted thunderstorms introduce water and pollutants into the hydrogeologic system in "slugs" via discrete recharge zones (42% of the recharge to springs), losing streams (11% of the recharge to springs), sinkholes (10% of the recharge to springs), and other solution openings (Aley and Aley 1987; Aley and Creath 1989; Vana-Miller 2007). These contaminants flow quickly through the karst conduit system, emerge at springs, and into the Jacks Fork and Current rivers' watersheds. Dye-tracing studies have also revealed complex and vast groundwater flow patterns crossing surface drainage divides and crisscrossing flow paths commonly far beyond park boundaries (see fig. 13; Aley and Creath 1989; Covington 2002; Mugel et al. 2009; Lowell et al. 2010). This lends an added element of unpredictability to the system's response to contamination or adjacent land-use change. It also makes the management and protection of springs and rivers, whose flow emanates largely from springs, a resource management challenge at the park (Aley and Creath 1989).

Land-use practices, especially land clearing, mining, and associated increases in sediment and nutrient loads, as well as other point and nonpoint discharges, present the greatest long-term threat to springs in the Ozarks (Bowles et al. 2011). Other threats to the spring ecosystem include disrupted stream channel geomorphology (see "Flooding and Fluvial Geomorphology" section), increased sediment deposition and bank erosion (see "Erosion" section), increased light penetration and water temperature, nutrient loading, and decreased leaf litter and woody debris. Dewatering of local aquifers, even the deepest ones, due to urbanization, mining operations, or agricultural use can cause loss of spring flow in the park and may contribute to sinkhole formation (see "Caves and Associated Landscape Management" section) Aley and Creath 1989; Covington 2002).

Mugel et al. (2009) provided quantitative landscape characteristics of areas within the spring, groundwater, and surface-water recharge areas. The recharge areas with the most open land and the least forest land per unit recharge area are Blue Spring (on Jacks Fork), Welch Spring, and Alley Spring. Similarly, the recharge areas with the least amount of publicly owned land per unit recharge area are Blue Spring (on Jacks Fork), Cave Spring, Welch Spring and the spring complex at Pulltite Spring. These areas may be more at risk for contamination or misuse.

The Heartland Network commissioned a land-use study in an effort to inventory and monitor land-use change. A resulting report by Hansen and Gryskiewicz (2003) presented (1) a characterization of the current landscape surrounding the park, (2) a summary of patterns of land-use change over time, (3) conceptual models showing links between ecological functioning within the park and land-use change, and (4) indicators and methods for monitoring landscape changes in the future. For the park, their study reinforced the idea that ecological functioning within the park depends heavily on the maintenance of surrounding habits. Conversion to urban (disturbed) landscapes may be a significant threat to park ecosystems. The most relevant land-use changes to monitor are those which reduce functional ecosystem size or eliminate unique habitats outside of park boundaries (Hansen and Gryskiewicz 2003). Land-cover change source data include the National Land Cover Dataset (available at: http://landcover.usgs.gov/landcoverdata.php); Landsat satellite imagery, park-specific mapping with frequent updates; and the US Census Bureau (available at: http://www.census.gov/).

As mentioned in the "Geologic Significance and Connections" section, the many springs at the park are vital water sources for the park's rivers and harbor special habitats for specific species. These small and delicate ecosystems are more sensitive to disturbance than the adjacent waterways (National Park Service 2015). Wading, swimming, and fishing, which may dislodge aquatic plants and disturb sediments, are prohibited in the park's springs and spring branches. A list of laws and regulations protecting Ozark springs is available at: http://www.nps.gov/ozar/learn/nature/spring-laws.htm. There is relatively little information on the physical and biological impacts of contaminated groundwater within springs or within surface water fed by springs (Bowles et al. 2011).

Lowell et al. (2010) presented a method using water-table data, detailed geologic mapping, and dye tracing to create a regional potentiometric surface and improve understanding about the flow towards Big Spring. Their approach showed the irregular nature of the groundwater flow, particularly in areas near prominent regional faults (e.g., the Wilderness Handy fault zone) that can act as highly permeable zones. A similar approach could be applied to other springs within the park to understand the source area and nature of groundwater flow.

Audio-magnetotelluric (AMT) data, collected at Alley Spring, helped delineate the actual path of groundwater flow and could be collected for other park springs as well (Pierce and Weary 2009; Weary and Pierce, 2009). AMT soundings consist of electric and magnetic field measurements over a range of frequencies to identify the electromagnetic signature of a conduit and to map its location. Karst conduits are relatively low-resistivity areas in the AMT data (Weary and Pierce, 2009).

Bowles et al. (2008, 2011) detailed the methodology of the Heartland Inventory and Monitoring Network's spring monitoring program collecting data on aquatic vegetation, aquatic invertebrates, fish, habitat, and water quality from six large springs at the park. Using detailed geologic map data (e.g., GRI GIS data) with groundwater flow data and spring monitoring data could yield quantitative measures on the influence of geology and habitats at the park's major springs.

Expanding the monitoring to other key springs would increase the scope of understanding along the river corridors.

The Missouri Geological Survey is involved in a multi-year project to redefine the recharge areas of springs across the state. Within the park, work was done on Big Spring, Mammoth, and Greer springs. Future projects focus on Alley and Welch springs. Publications on their results are forthcoming (Joe Gilman, Missouri Geological Survey, geologist, conference call 20 October 2015).

Erosion

Erosion is an ongoing natural weathering process on the landscape at the park. On average, 43% of all streambanks (alluvium and low terraces; geologic map units **Qa**, **Qt**, and **Qtl**) in a study of the Current and Buffalo rivers are moderately or severely eroding; cutbanks and protruding roots denote areas of erosion (see "Flooding and Fluvial Geomorphology" section; Panfil and Jacobson 2001).

Human activities can impact erosion rates throughout the park. Examples of such activity in the Ozark region include the construction of roads, trails, parking lots, and other infrastructure; logging of forests with subsequent agricultural development; and human impacts from foot traffic, vehicles, domestic animals, river fords, and watercraft access points or put-in areas (Panfil and Jacobson 2001; Covington 2002; Greco 2002). These activities increase erosion in three ways (1) Land surface disturbances can remove stabilizing vegetation (2) When impervious or compacted surfaces (e.g., roads and parking lots) are installed, they cause increased runoff and sheet flow which may form rills or channels on the sides of the structure. (3) Increased river erosion (meandering) and formation of gravel bars.

Erosion contributes to the sediment load of the rivers and streams. During very high precipitation, compacted, unpaved roads become sources of sediment and gravel roads can contribute 100 times more sediment than paved or abandoned roads (Panfil and Jacobson 2001; Covington 2002; Greco 2002; Vana-Miller 2007).

Access points for canoes, rafts, and boats can be areas of high soil and sediment erosion because of human foot traffic, vehicles and trailers, and putting the watercraft into the river (fig. 26). Up to 20 fords are used in the park and, in many reaches, shallow depths permit crossings (Greco 2002). Unofficial roads and fords were created in some areas and contribute to local erosion (fig. 27; Greco 2002). Riparian land use also leads to increased gravel influx which homogenizes the aquatic habitat and fills in pools and interstices among cobbles (Covington 2002). Cobble and gravel beds are fish nesting sites and residences for aquatic insects and certain species of fish (e.g., darters) (Greco 2002).

Where the stream banks become destabilized by human activity, stream meandering can increase, causing additional erosion and the formation of gravel bars. As the fine-grained material is carried away downstream in suspension and the gravel remains in the channel (see fig. 25; Covington 2002). Excessive sediment loads in rivers and streams can have negative impacts on the ecosystem (see the "Flooding and Fluvial Geomorphology" section) and impact the cave and karst system within the park.

Covington (2002), Greco (2002), and GRI conference call participants, suggested the following action items for management of erosion at the park:

- Map and inventory roads and trails (active and abandoned). This would supplement a 1991 roads and trails study and environmental assessment.
- Use GPS to identify locations on drainages, hillslopes, and other natural and cultural resources impacted by erosion along roads and trails.
- Use GPS locations in a GIS to categorize and rank road and trail locations based on impacts.
- Perform repeat photography at designated photo points to monitor changes (see http://go.nps.gov/grd_photogrammetry for information about using photogrammetry for resource management).
- Develop a reclamation program for abandoned roads and trails, including road closures, paving high-use roads, upgrading artificial drainages, reconstructing stream crossings, placing culverts or water bars in strategic locations.

As detailed in the "Geologic Setting and Significance" section, land-use practices within and adjacent to the park have a controlling influence on the park's ecosystem These landscape-scale changes have the potential to affect larger areas than the localized impacts also discussed in this section (see "Ozarks Aquifer and Springs Protection" section).

Figure 26. Photographs of eroded streambanks at unauthorized access points. Human use at these areas can accelerate erosion and stream bank degradation. Photographs by Deanna Greco (NPS Geologic Resources Division) taken in April 2002.

Figure 27. Photographs of erosion along roads and social trails. Some areas are crisscrossed with trails and further use widens areas of impact along the streambanks. Photographs by Deanna Greco (NPS Geologic Resources Division) taken in April 2002.

Paleontological Resource Inventory, Monitoring, and Protection

Fossils are common in Ozark National Scenic Riverways and are found in the rocks of the park, within caves, and associated with cultural resources. There are fossils in park and outside repository museum collections. Refer to the "Paleontological Resources" section for more information.

All paleontological resources are nonrenewable 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 2016, National Park Service regulations associated with this act had been signed. Regulations for other agencies in the Department of Interior were awaiting signatures.

Similar to cave formation damage and theft, fossil theft is an issue of concern for park resource managers (Victoria Grant, Ozark National Scenic Riverways, natural resources program manager, conference call, 20 October 2015). Formal paleontological resource monitoring is not occurring within the park; however, current cave-focused archeological monitoring would detect fossil-resource disturbances in cave sediments and cave forming units (e.g., in the Eminence Dolomite, Gasconade Dolomite, and Jefferson City Dolomite [**Ce**, **Og**, and **Ojc**]).

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 a park-specific survey has not yet been completed for the park, a variety of publications and resources provide park-specific or servicewide information and paleontological resource management guidance.

- The GRI source map Weary et al. (2016) and published map (Weary et al. 2014) summarized fossil content in geologic units mapped in the park and surrounding area.
- Santucci et al. (2001) compiled information about fossils in caves in 35 parks, including Ozark National Scenic Riverways.
- Hunt et al. (2008) summarized paleontological resources for Ozark National Scenic Riverways and other parks in the Heartland Inventory and Monitoring Network and provided the following

preliminary recommendations for paleontological resource management:

- ◻ Conduct field inventories for paleontological resources to more fully document in situ and karst (cave and overhang) occurrences of fossils. Consider a formal site documentation and condition assessment for significant fossil localities. Monitor significant sites at least once a year in the future.
- ◻ Have park staff members observe exposed cliffs, other erosional bedrock, rivers and streams (especially during times of low water levels) and karst features for fossil material while conducting their usual duties. Document any observations with photographs using a common item (e.g., pencil) for scale. Fossils and their associated geologic context (surrounding rock material) should be documented but left intact. Except for permitted scientific research, paleontological resources should remain in situ unless they are subject to imminent threats by artificially accelerated earth surface processes or anthropogenic impacts.
- ◻ Contact the NPS Geologic Resources Division for paleontological resource management or interpretation 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.

Slope Movement Hazards and Risks

As described in the "Slope Movements" section, slope processes—primarily rockfalls—occur at the park. Slope deposits such as colluvium and landslide deposits (geologic map units **Qc** and **Qls**, respectively), as well as residual and colluvial material on terrace-like landforms (**QTtrc**) attest to areas of past slope movement; these areas could experience future slope movements (Weary et al. 2014). Landslide scars attest to long-past slope movements where there has been no sizeable movement in recent years (Dave Weary and Randy Orndorff, US Geological Survey, conference call, geologists, 20 October 2015). Slope movements, typically in the form of small slumps, and rockfalls are an ongoing item of concern for park resource managers (Conference call participants, 20 October 2015). Slope movements also affect caves (e.g., cave breakdown or sinkhole slumping; see "Caves and Associated Landscape Management" section).

These processes are natural elements of landscape change. They become hazards when visitors hike or boat near the base of cliffs or in caves (see "Caves and Associated Landscape Management" section). Particularly hazardous areas are those with visible cracks, loose material, or overhangs.

There are many options that park managers can consider to reduce risk associated with slope movement hazards. One is visitor and staff education regarding the potential risks. Verbal warnings by park rangers, or signs and other written notices posted at visitor centers, trailheads, and/or websites is one option to educate visitors. Another option is limiting access to potentially hazardous sites via fencing, ropes, or other barriers. These options should be assessed by NPS staff with regards to impacts to the natural experience, fiscal limitations, visitor access, and maintenance requirements.

If funding permits, resource managers could consider obtaining quantitative information to assess the frequency and magnitude of rockfall and other slope movements in high visitation areas. A photomonitoring program is one possibility. The Geoscientist-in-the-Parks program (http://go.nps.gov/gip) is an option to support such a project. The NPS Geologic Resources Division Photogrammetry website (http://go.nps.gov/grd_photogrammetry) provides examples of how photographic techniques support structural analysis of rockfall areas.

The following references provide additional background information, suggested vital signs, and resources for assessing and documenting slope movements:

- Weary et al. (2014) provided park-specific examples and photographs of rockfall and other hazards.
- 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.

- US Geologic Survey publication *The landslide handbook—A guide to understanding landslides* (Highland and Bobrowsky 2008).
- US Geological Survey landslides website (http://landslides.usgs.gov/).
- NPS Geologic Resources Division Geohazards website (http://go.nps.gov/geohazards).
- NPS Geologic Resources Division Slope Movement Monitoring website (http://go.nps.gov/monitor_slopes).

Seismic Activity Hazards and Risks

Faults crisscross much of the park (see "Faults and Fractures" section). The majority of these faults are ancient structures and no longer active (Dave Weary, US Geological Survey, geologist, written communication, 21 June 2016). Earthquakes are ground vibrations or 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 urbanized areas and alteration of the landscape(table 3). The "Richter magnitude" is a measure of the energy released by an earthquake. Earthquakes can damage park infrastructure such as bridges, roads, and building foundations directly or trigger other hazards, such as slope movements on the steep bluffs along Current River or Jacks Fork or ceiling collapse within park caves, which may impact park 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.

Large earthquakes are not common in south-central Missouri; however, the region—and most of the eastern United States—shook during epic earthquakes 200 years ago. From 1811–1812, the largest earthquakes ever recorded in the continental United States (approximately magnitude 8.0) occurred along the New Madrid fault. The massive earthquakes were felt throughout an area of 130,000 km^2 (50,000 mi^2). The New Madrid Seismic Zone (red and orange area on fig. 28) is centered along the Mississippi River valley where Arkansas, Missouri, Illinois, Kentucky, and Tennessee converge, about 150 km (93 mi) southeast of the park. Intra-plate seismic zones such as the New Madrid Seismic Zone are far from plate boundaries, which are the typical locations of earthquakes (Chapman et al. 2002). The US Geological Survey created a variety of general interest publications marking the bicentennial of the New Madrid earthquakes (e.g., Williams et al. 2010, 2011). See also http://earthquake.usgs.gov/earthquakes/states/events/1811-1812.php and the earthquakes page by the Missouri Geological Survey http://dnr.mo.gov/geology/geosrv/earthquakes.htm.

Table 3. Seismic scale and list of notable earthquakes that affected the park and surrounding area.

Notable Local Earthquakes	Modified Mercalli Scale
none reported	**I:** Detectable only by sensitive instruments (**Imperceptible shaking**)
none reported	**II:** Detectable by few persons at rest, especially on upper floors; suspended objects may swing
none reported	**III:** Detectable noticeably indoors, but not always recognized as earthquake; standing autos rock slightly; vibration like passing machinery
June 18, 2002	**IV:** Detectable indoors by many persons, outdoors by few; at night, some may awaken; dishes, windows, doors disturbed, autos rock noticeably
June 10, 1987 November 9, 1968 1976	**V:** Detectable by most people; some breakage of dishes, windows, and plaster; disturbance of tall objects
January 4, 1843 October 31, 1895	**VI:** Detectable by everyone, many frightened and run outdoors; falling plaster and chimneys, minor damage
December 16, 1811 January 23, 1812 February 7, 1812	**VII:** Everyone runs outdoors; damage to buildings varies depending on quality and material of construction; noticed by auto drivers
none reported	**VIII:** Panel walls thrown out of frames; fall of walls, monuments, chimneys; sand and mud ejected from ground; auto drivers disturbed
none reported	**IX:** Buildings shifted off foundations, cracked, thrown out of plumb; ground fractured; underground pipes broken
none reported	**X:** Most masonry and frame structures destroyed; ground fractured, rails bent, landslides triggered
none reported	**XI:** Few structures remain standing; bridges destroyed; ground fissures, pipes broken, landslides, rails bent
none reported	**XII:** Total damage; waves seen on ground surface, lines of sight and level distorted, objects thrownup in air (**Catastrophic destruction**)

The Modified Mercalli scale details the physical effects of different earthquake magnitudes. The 1811 and 1812 earthquakes were the major New Madrid earthquakes. Information from Johnston and Schweig (1996), and Williams et al. (2011).

The US Geological Survey's earthquake probability maps indicate that the probability of a moderate (magnitude-5.0) or greater earthquake within 100 years in this area is 2% to 10% (fig. 28; Petersen et al. 2008).

More recent earthquakes have been much smaller. On Friday, 16 October 2015, a magnitude 3.4 earthquake was felt at the park. It shook park headquarters building, rattled windows, and was felt by people throughout the area. The epicenter was 40 km (25 mi) away from the park (Larry Johnson, Ozark National Scenic Riverways, superintendent, conference call, 20 October 2015). The US Geological Survey event page for the earthquake provides additional information: http://earthquake.usgs.gov/earthquakes/eventpage/nm60119416#general_region.

A US Geological Survey emeritus geologist (John Tinsley) is currently studying caves in the central and eastern United States for evidence of ancient earthquakes ("paleoseismicity") contained in cave formations (e.g., breakage and "healing" or new growth of speleothems). Caves in the Ozarks have revealed a 500-year recurrence interval for "large" (magnitude >6) earthquakes (Tinsley 2014; Dave Weary and Randy Orndorff, US Geological Survey, geologists, conference call, 20 October 2015).

For parks interested in monitoring earthquakes and understanding seismic history, the Geological Monitoring chapter about earthquakes and seismic activity 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 (Braile 2009). Missouri-specific information is available at http://earthquake.usgs.gov/earthquakes/states/?region=Missouri. The Missouri Geological Survey's website http://dnr.mo.gov/geology/geosrv/earthquake.htm is another resource for information about seismicity in Missouri.

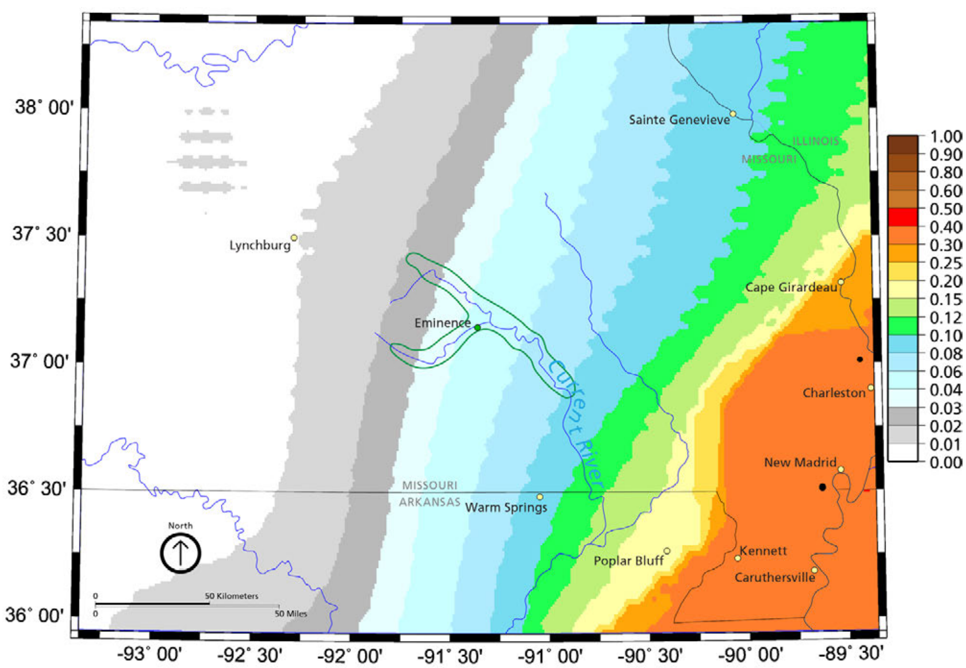


Figure 28. Probability map of the occurrence of earthquakes with magnitudes greater than 5.0. This probability assumes a 100-year timespan and a 50-km (30-mi) radius around Eminence, Missouri. Ozark National Scenic Riverways is northwest of the New Madrid Seismic Zone (warm colors to the east), whose recent (> 5.0 magnitude) epicenters are the solid black circles. Graphic was generated by the US Geological Survey's Probabilistic Seismic Hazards Assessment (PSHA) mapping program (https://geohazards.usgs.gov/eqprob/2009/index.php).

Abandoned Mineral Lands

According to the NPS abandoned mineral lands (AML) database (accessed 14 July 2015) and Burghardt et al. (2014), the park contains one AML feature at one site. The Partney quarry was a surface mine for dolomite building stone; it was approximately 90 m (300 ft) long and 30 m (100 ft) wide. This quarry was used by the Civilian Conservation Corps during construction of infrastructure at Big Spring in the 1930s. This quarry could provide replacement stone if repair of historic structures was needed. Big Spring Granite (geologic map unit **Yg**) was quarried locally south and east of Van Buren, Missouri, about 100 m (330 ft) north of the park boundary on Brown Road (Lowell et al. 2010). There are numerous prospecting pits and some mine workings in areas within and near the park typically around the periphery of the igneous rock outcrops. Most of these are pre-World War II prospects for iron, copper, and manganese (Grawe 1943; Dave Weary, US Geological Survey, geologist, written communication, 21 June 2016).

Abandoned mineral lands are lands, waters, and surrounding watersheds that contain facilities, structures, improvements, and disturbances associated with past mineral exploration, extraction, processing, and transportation, including oil and gas features and operations, for which the NPS takes action under various authorities to mitigate, reclaim, or restore in order to reduce hazards and impacts to resources.

AML features and disturbed lands include adits, prospects, shafts, structures, open pits, tunnels, waste rock piles, mills, wells, and landform modifications such as service roads, drainage diversions, and drill pads. AML features pose a variety of resource management issues such as visitor and staff member safety and environmental quality of air, water, and soil. AML features can also provide habitat for bats and other animals, some of which may be protected under the Endangered Species Act or state species listings.

Resource management of AML features requires an accurate inventory and reporting. All AML features should be recorded in the Servicewide AML Database (the NPS Geologic Resources Division will provide assistance). An accurate inventory identifies human safety hazards and contamination issues, and facilitates 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. No AML features within the park have been mitigated and no additional features at the site are in need of mitigation (Burghardt et al. 2014). The NPS AML website, http://go.nps.gov/aml, provides more information. The Missouri Geological Survey's website (http://dnr.mo.gov/geology/geosrv/index.html) offers "GeoSTRAT"—a geosciences technical resource assessment tool with features such as the locations of springs, mines, and sinkholes on an interactive map. Their website also includes an oil and gas database with permit locations for more than 12,000 wells.

External Mineral Development

Ozark National Scenic Riverways is immediately south of the world's largest lead and zinc mining district—the Viburnum Trend (see fig. 2). Mining in this "New Lead Belt" began in the early 1950s. Tailings from past mining and potential future exploration or development are possible sources of contamination and other impacts to the park's river and karst ecosystems (see also the "Ozarks Aquifer and Springs Protection" section; Schmitt et al. 2008; Schumacher 2008).

Mining and oil and gas extraction is conducted adjacent to dozens of National Park Service areas. The National Park Service works with adjacent land managers and other permitting entities to help ensure that National Park System resources and values are not adversely impacted by external mineral exploration and development. Potential impacts include groundwater and surface water contamination, erosion and siltation, introduction of exotic plant species, reduction of wildlife habitat, impairment of viewsheds and night skies, excessive noise, and diminished air quality. Visitor safety and overall degradation of the visitor experience are particular concerns. The NPS Geologic Resources Division Energy and Minerals website, http://go.nps.gov/grd_energyminerals provides additional information.

In the Viburnum Trend, mine waste (tailings) is held in large ponds impounded by earthen dams. Complete or partial failure of those structures could cause vast amounts of toxic sediment containing lead, zinc, cadmium, cobalt, and nickel, acidic water, and mineral-extraction chemicals to be introduced into the surface waters, and through the karst system into the groundwater (Covington 2002; Vana-Miller 2007).

Karst systems are particularly susceptible to the introduction and transportation of contaminants because rock is fractured and has rapid connections between surface and subsurface water. Sinkholes, conduits, and springs are probably facilitating the transport of mine-related contaminants from runoff and discharge (Schmitt et al. 2008). Abandoned tailings from historic mining are already making their way into park streams. They are differentiated from natural, local-sourced sediment by their size, shape, composition, and quality. These tailings are either leaking from beneath the tailing ponds impoundment or from ponds that have been breached (Covington

2002). Dye-tracing in 2008 revealed a subsurface connection between a losing reach of Logan Creek, downstream from the active Sweetwater Mine, and Blue Spring, 16 km (10 mi) to the southwest, on the Current River. Discharge from the mine complex composes as much as 68% of the discharge into upper Logan Creek, which eventually resurges at Blue Spring. This is changing water chemistry within Blue Spring and also the mineralogy and concentrations of trace elements in streambed sediments in Blue Spring and downstream in Current River (Schumacher 2008). Sediments are enriched in cobalt and nickel, as well as galena and cerrusite minerals. Three breaches from the Sweetwater Mine tailings pile in 1977 and 1978 released mine waste into the karst system. Increased turbidity from these releases extended more than 64 km (40 mi) downstream in Logan Creek and into Blue Spring on the Current River (Schumacher 2008).

Mining can also involve significant groundwater pumping that, because of the complicated, interconnected, karstic groundwater system at the park, could impact flow at the major springs and consequently within the rivers themselves (see "Ozarks Aquifer and Springs Protection" section; Aley and Creath 1989).

Areas around the park are being explored for potential mining (National Park Service 2015). Future mining potential needs to remain an issue of attention for park resource managers (Joe Gilman, Missouri Geological Survey, geologist, conference call 20 October 2015). More than 300 exploration holes were drilled for lead and zinc in the Mark Twain National Forest west of Big Spring. Most of these holes are in the spring's recharge area and could introduce toxic drilling fluids into the karst conduit system (Covington 2002; Schmitt et al. 2008). Lead and zinc exploration is occurring in the Eleven Point River area, just south of the park. A company formerly interested in prospecting there has withdrawn their proposal; however, many leases may become active again with changes in the mineral economy (Dave Weary, US Geological Survey, geologist, conference call, 20 October 2015). There may be economically viable lead, zinc, copper, and cobalt deposits on Missouri Department of Conservation lands within the recharge areas for major springs on the Current River upstream of the confluence with Jacks Fork and elsewhere (Vana-Miller 2007; Joe Gilman, Missouri Geological Survey, geologist, conference call, 20 October 2015). Orndorff et al. (2006) and Weary et al. (2010) performed detailed mapping to show how cave, spring, and sinkhole formation in the Ozarks occurs within the geologic framework (see "Cave and Karst Features and Processes" section). Those publications provide important information about the potential effects of land-use decisions (including mining) in a karstic terrain. Schmitt et al. (2008) presented protocols for monitoring mining-related metals in the park's river system. In 1989, a Sole Source Aquifer designation was pursued for the Big Spring recharge area to protect the aquifer from mineral leases and mining permits (Aley and Creath 1989). The Environmental Protection Agency denied the petition in 1992 based on the questionable conclusion that alternative sources of domestic water supplies were available (Chilman et al. 1996).

Regionally, the lead and zinc deposits occur in the Cambrian Bonneterre Formation (not mapped in the GRI GIS data as the unit is not exposed at the surface within the park; however, the unit is shown on cross-sections through throughout the park area; see Weary et al. 2014, sheet 2). Mineralization occurred in the Bonneterre near the buried Proterozoic igneous rocks (igneous knobs; "**Y**" geologic map units) throughout the area because of a contrast in permeability between the igneous protrusions and overlying sedimentary rocks during the injection of mineral-laden fluids in the late Paleozoic (Lowell et al. 2010; Mouat and Clendenin 1975). Weary et al. (2014) show the proposed prospecting-permit-applications area in Mark Twain National Forest.

The Missouri Geological Survey's website (http://dnr.mo.gov/geology/geosrv/index.html) offers "GeoSTRAT"—a geosciences technical resource assessment tool. Relevant to external mineral development are the locations of drill areas, oil and gas wells, wells, mines, prospects, and metallic mineral waste management areas.

Geologic History

This chapter describes the chronology of geologic events that formed the present landscape.

The geologic foundation of the park reveals a long history of landform development and change spanning more than 1.5 billion years. The oldest rocks in Ozark National Scenic Riverways were created when calderas erupted as an ancient supercontinent was pulled apart. Hundreds of millions of years later, shallow seas inundated the area. Over millennia, thick stacks of fossiliferous sedimentary rocks accumulated atop and adjacent to the volcanic rocks. In more recent history, erosion, weathering, and slope movements shaped the river valleys of the park. Trickling groundwater dissolved vast conduits in the soluble carbonate rocks to form the characteristic karst features of southeastern Missouri. Today, slope deposits collect at the base of slopes and the Current River and Jacks Fork continually modify their channels and adjacent floodplain areas. Water continues to dissolve bedrock, enlarging caves, forming sinkholes, and flowing from springs.

Mesoproterozoic Era (1.6–1.0 billion years ago): Building the Ozark Dome, Volcanism, Deformation, and Erosion

Basement rocks across southern Missouri record tectonic events that occurred more than 1.5 billion years ago along the southern margin of the North American craton. At this time, a continental rift began to form as the ancient supercontinent of Rodinia began to break apart. Rocks from this time period are found in a northwest-oriented, 12–20 km- (7–20 mi-) thick wedge of granite, rhyolite, and clastic sedimentary rocks across southern Missouri (Lowell et al. 2005; Darnell et al. 1995). The Mesoproterozoic igneous rocks exposed within the park ("**Y**" geologic map units) were likely associated with massive volcanoes that erupted along the edges of that rift (fig. 29A; Lowell et al. 2010; Weary et al. 2014). Within the Current River basin, a cluster of about 50 rhyolite and two granite knobs (fig. 30) protrude to the surface through the adjacent Paleozoic sedimentary rocks; many other knobs likely remain buried. These make up the Eminence-Van Buren volcanic field which is part of the core of the Ozark dome—an asymmetrical structure in which the center is high and the rock layers slope (dip) away from the center (Lowell et al. 2010; Weary et al. 2014). The volcanic field erupted more or less contemporaneously with movement along strike-slip faults about 1.48 and 1.38 million years ago (Lowell and Clendenin 2003; Lowell et al. 2010). The oldest geologic structures in the park, the faults that only deform the Mesoproterozoic rocks, are additional evidence of these cataclysmic events (Weary et al. 2014).

The Eminence caldera erupted violently because of its high silica content, and eventually amassed an expansive lava plateau with some peaks (Unklesbay and Vineyard 1992; Schaper 2015). Volcanic rocks on the surface cooled as fine-grained or porphyritic (conspicuous crystals in a fine-grained or glassy matrix) rhyolite lava, tuff, and breccia (**Yrm**, **Yvc**, **Ysc**, **Ysi**, **Ysm**, **Ymm**, **Yltm**, **Ycu**, and **Ycl**; Weary et al. 2014; Schaper 2015). Molten rocks which cooled below ground between eruptions formed shallow bodies of granite (**Yg**; Weary et al. 2014; Schaper 2015). Caldera eruptions blew away entire mountaintops and fractured surrounding rocks where additional volcanoes erupted. Following eruptions, the caldera subsided or collapsed incrementally (Lowell 2000). This left subsurface plutons of granite closer to the surface than before (Unklesbay and Vineyard 1992; Schaper 2015). The Coot Mountain units (**Ycl** and **Ycu**, tuff of Little Thorny Mountain (**Yltm**), rhyolite of Russell Mountain (**Yrm**), and rhyolite of Sutton Creek (**Ysc**) are associated with these eruptions, caldera formation, and collapse (Lowell et al. 2010; Weary et al. 2014). The rocks were rotated and steeply inclined, about 65°–90°, when the caldera collapsed (Lowell et al. 2010). Contemporaneous, steep-walled domes of granitic rock (e.g., Big Spring quad granite; **Yg**) intruded the volcanic rocks about 1.47 billion years ago (Lowell et al. 2010; Weary et al. 2014). The rhyolite of Shut-In Mountain and the Mule Mountain tuff (**Ysi** and **Ymm**, respectively) were erupted onto an intra-caldera surface after rotation and collapse so they remain, nearly horizontal (Lowell et al. 2010). Post-collapse, volcaniclastic (sedimentary rocks made up of clasts of volcanic rocks) unconformably overlie the volcanic rocks elsewhere in Missouri but are not mapped in the GRI GIS data. The boundary is marked by a distinct air-fall tuff unit (Lowell et al. 2010). After about 100 million years of intense volcanic activity, weathering and erosion proceeded for at least a few hundred million years and there are no rocks from this time period mapped in the GRI GIS data (Schaper 2015; Weary et al. 2016).

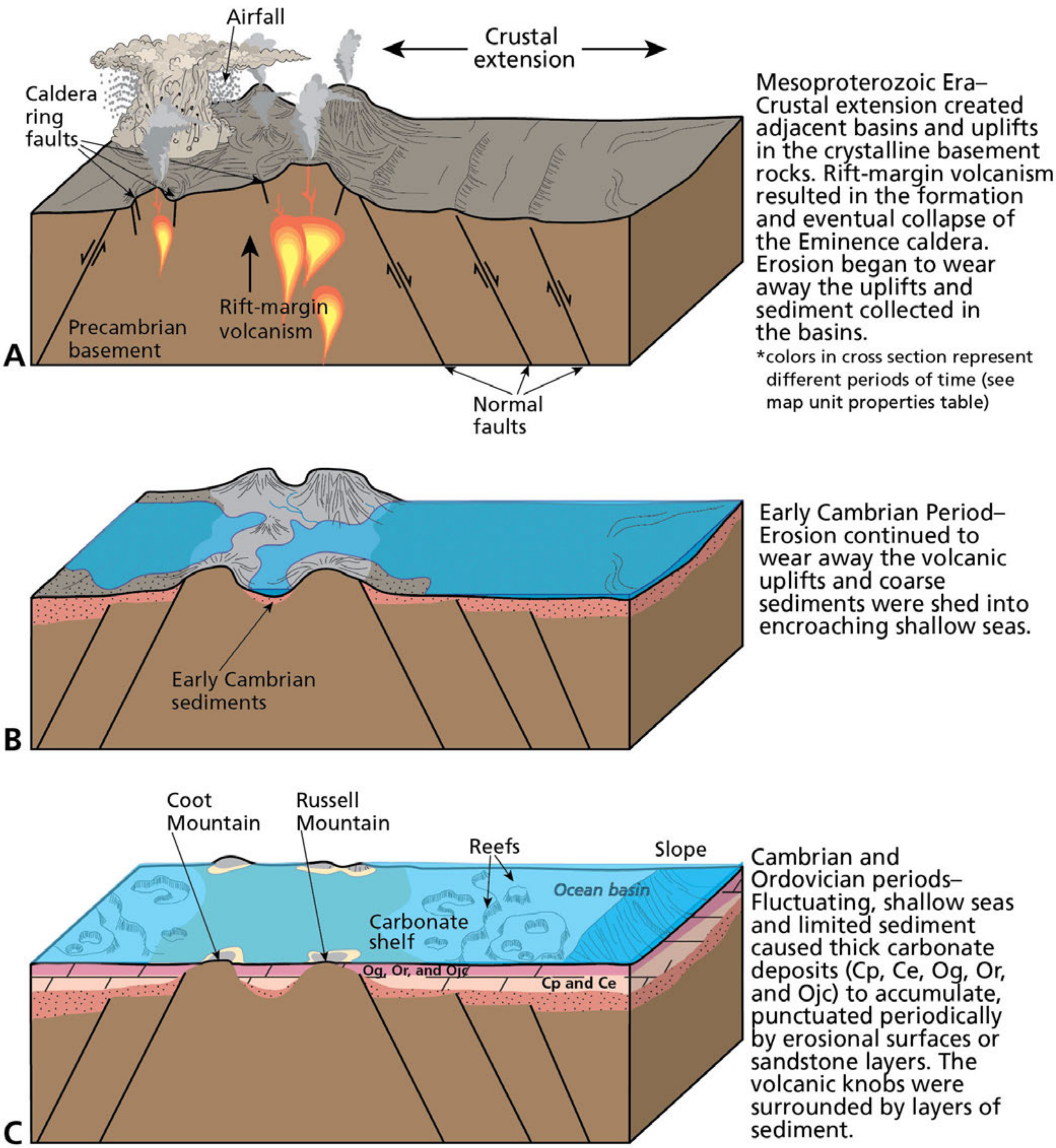


Figure 29A–C. Illustration of the evolution of the landscape and geologic foundation of Ozark National Scenic Riverways. Continued on next page. Graphics are not to scale. Colors are standard colors approved by the US Geological Survey to indicate different time periods on geologic maps, and correspond to the colors on the Map Unit Properties Table. Map symbols are included for the geologic map units mapped within the park. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) with information from Lowell et al. (2010) and Weary et al. (2014).

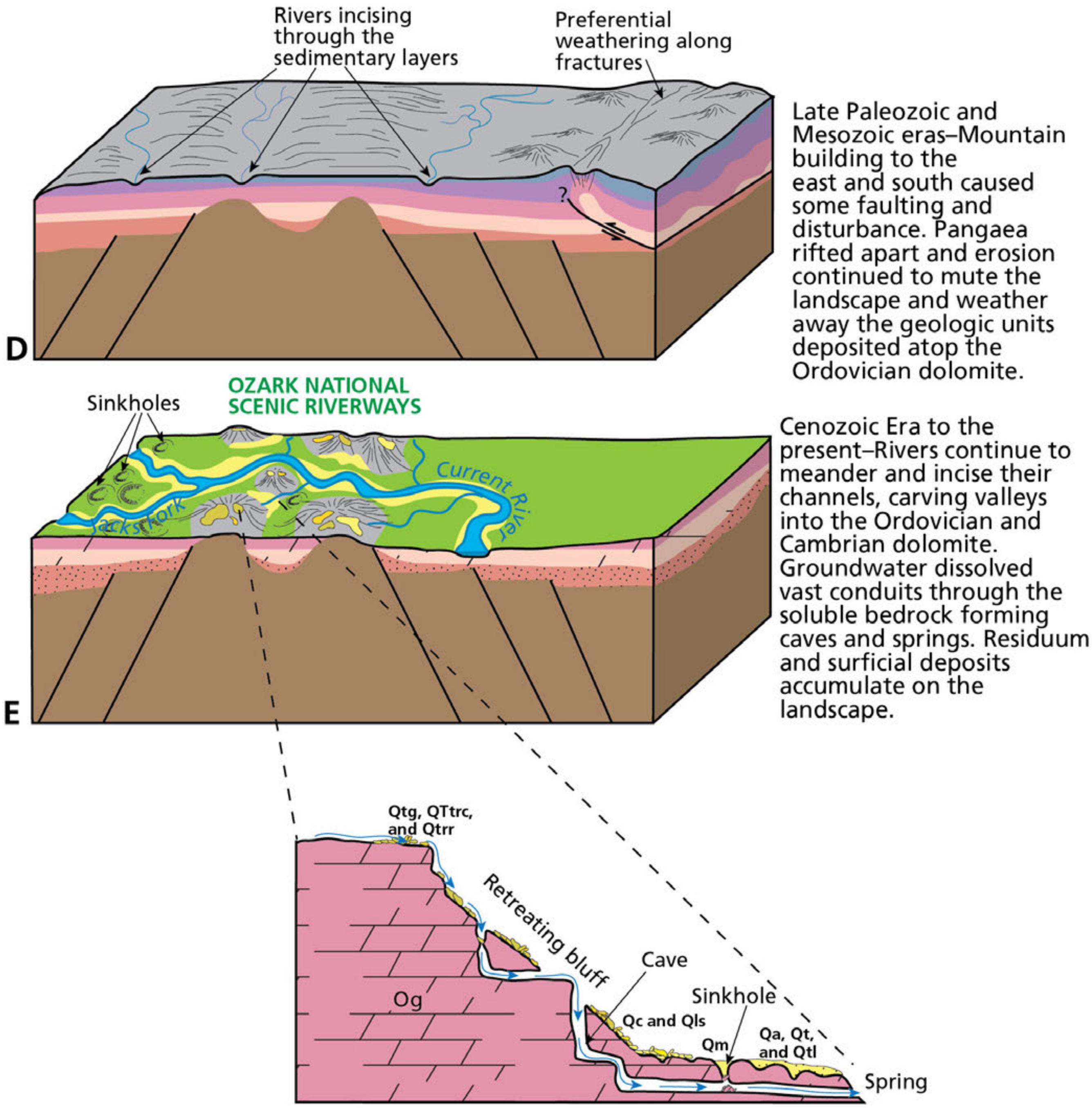


Figure 29D–E. Illustration of the evolution of the landscape and geologic foundation of Ozark National Scenic Riverways. Continued from previous page. Graphics are not to scale. Colors are standard colors approved by the US Geological Survey to indicate different time periods on geologic maps, and correspond to the colors on the Map Unit Properties Table. Map symbols are included for the geologic map units mapped within the park. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) with information from Lowell et al. (2010) and Weary et al. (2014).

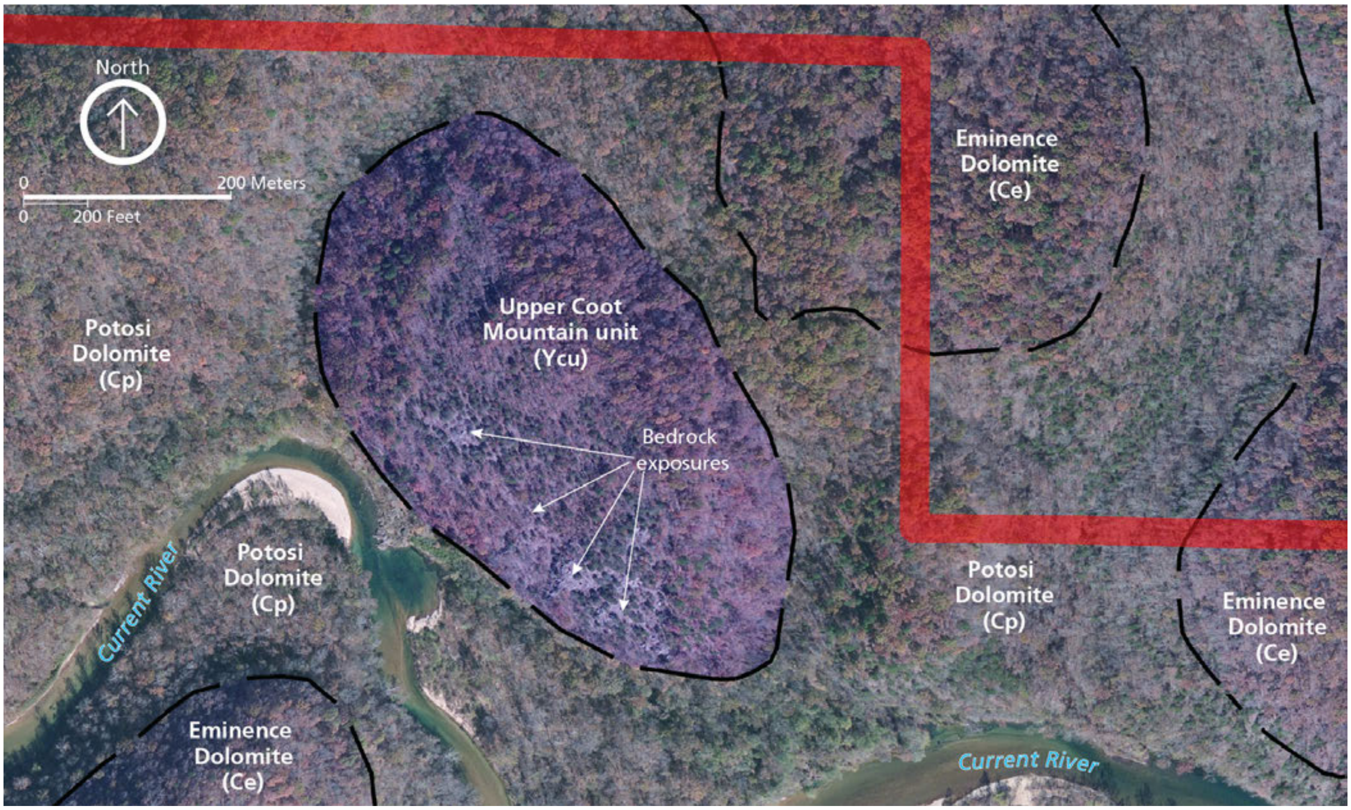


Figure 30. Aerial image of Mesoproterozoic rhyolite knob of the Upper Coot Mountain unit (Ycu) surrounded by Cambrian dolomites. Image is near the confluence of Current River and Jacks Fork. Bedrock exposures are more common on the igneous knobs and vegetation is qualitatively sparser. Bold red line is the boundary of Ozark National Scenic Riverways. Dashed black lines are contacts between the geologic map units. Graphic by Trista Thornberry-Ehrlich (Colorado State University) using GRI map data from Weary et al. (2016) and ESRI World Imagery basemap (accessed 9 May 2016).

Paleozoic Era (541–252 million years ago): Marine Inundation, Deposition, and Erosion, Assembling Pangaea

More than 500 million years ago, global sea level rose and shallow seas inundated much of southeastern North America. Thick marine carbonates (dominantly limestone and minor amounts of terrestrial (sandy) sediments were deposited on the seafloor and in valleys surrounding the topographic highs formed by the Mesoproterozoic rocks (figs. 29B and 31; Lowell et al. 2010; Schaper 2015).This irregular surface resulted in great variations in the thicknesses and distributions of contemporaneous Cambrian units (Lowell et al. 2010). It also represents a tangible time-gap in the geologic rock record that can be spanned with a human hand—at the unconformable contact between older, volcanic rocks and marine sedimentary rocks hundreds of millions of years younger (fig. 32; Unklesbay and Vineyard 1992; Thompson 1995; Schaper 2015).

By the late Cambrian, most of North America was very near Earth's equator (Levin 1999; Unklesbay and Vineyard 1992; Schaper 2015). Shallow, tropical seas still covered the park and the open ocean was only a few hundred kilometers away, near what is now central Arkansas (fig. 29C; Unklesbay and Vineyard 1992; Thompson 1995; Schaper 2015). Terrestrial sediment sources were scarce and shallow-water carbonate deposition piled up layers that eventually became the upper Cambrian Potosi Dolomite (**Cp**) and Eminence Dolomite (**Ce**), and the lower Ordovician Gasconade Dolomite (**Og**), Roubidoux Formation (**Or**), and Jefferson City Dolomite (**Ojc**) (Repetski et al. 1998; Lowell et al. 2010; Weary et al. 2014). A second group of faults in the park were active at one or more times prior to the deposition of the Ordovician Gasconade Dolomite (**Og**), Roubidoux Formation (**Or**), and Jefferson City Dolomite (**Ojc**) (Weary et al. 2014). These deformed the Cambrian and older rocks (**Ce**, **Cp**, and "**Y**" units). Fossil trilobites, gastropods,

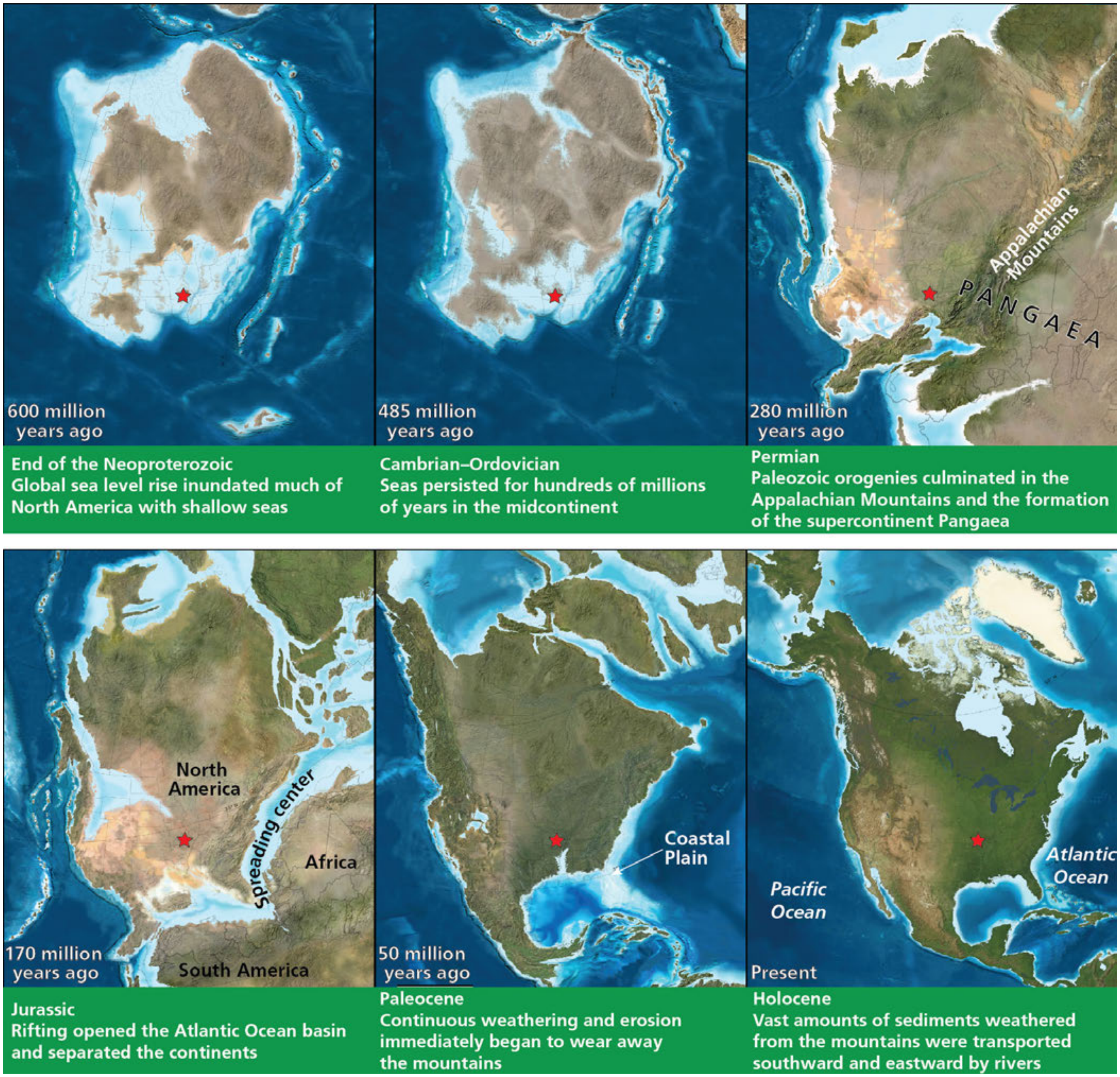


Figure 31. Paleogeographic maps of North America. The red star indicates the approximate location of Ozark National Scenic Riverways. Graphic complied by Trista L. Thornberry-Ehrlich (Colorado State University). Base paleogeographic maps created by Ron Blakey (Colorado Plateau Geosystems, Inc.), which are available at http://cpgeosystems.com/index.html.

and other mollusks in the Cambrian and Ordovician rocks record the new types of ecosystems that followed the "Cambrian explosion" of new groups of marine organisms that evolved in the early Cambrian (Thompson 1995; Hunt et al. 2008; Schaper 2015).

The Potosi Dolomite and Eminence Dolomite circle knobs of Mesoproterozoic rock, indicating that these knobs were likely islands jutting above the sea. Quartz-rich sandstone layers and lenses within the Eminence Dolomite indicate periods of marine regression, when the seas retreated and nearshore, beach-like depositional environments prevailed (Lowell et al. 2010). The exposed Mesoproterozoic igneous rocks may have provided a terrestrial sediment source for these layers. Following longstanding limestone and

Figure 32. Photograph of unconformity. Thick beds of dark gray Eminence Dolomite (in background) dip off of a knob of lighter-colored Mesoproterozoic rhyolite (foreground) along Rocky Creek, about 14 km (9 mi) east-southeast of the town of Eminence. The contact between the two rock units is significantly unconformable, with about 980 million years of missing record between them. This locality is described in Lowell and others (2010) as field trip stop 7. US Geological Survey photograph by Richard Harrison, taken in 1998. Caption and photo courtesy David Weary (US Geological Survey).

dolomite deposition, was a period of nondeposition or erosion. During this period, the top of the Eminence Dolomite was weathered into an irregular surface prior to the deposition of the Gasconade Dolomite. At this time, North America was moving north, away from the equator (Unklesbay and Vineyard 1992; Levin 1999; Schaper 2015).

The Gunter Sandstone member of the Gasconade Dolomite (lower part of **Og**) was the first Ordovician unit deposited atop the erosional surface of the Eminence Dolomite. It signals a period of relatively rapid transgressive-regressive sea level changes with multiple unconformities within **Og** (periods when no rocks were deposited, or were subsequently eroded away) (Repetski et al. 2000; Lowell et al. 2010). Sands accumulated in high energy, nearshore, subtidal environments (Lowell et al. 2010). Eventually, deeper water settings returned and deposition of limestones (dolomites) and siliceous cherts resumed forming the rest of the Gasconade Dolomite. Sea level fluctuations and shifting environments alternately deposited sandstone, chert, and dolomite of the Roubidoux Formation and the more dolomite-rich Jefferson City Dolomite (Thompson 1995; Lowell et al. 2010; Weary et al. 2014; Schaper 2015). Mud cracks within the Roubidoux Formation formed during periods of exposure when sea level dropped (Lowell et al. 2010).

Bedrock units younger than the early Ordovician Period are not mapped at the park (Weary et al. 2014, 2016). Whatever units were deposited atop the Jefferson City Dolomite (**Ojc**) have since been removed by erosion. There is no evidence in the Cambrian and Ordovician rocks that they were ever buried by more than about 1,500 to 2,700 m [5,000 to 9,000 ft] of rocks (Epstein et al. 1977; Repetski et al. 1998; Lowell et al. 2010). This is despite major tectonic events occurring as close as a few hundred kilometers of the park (fig. 29D; Cox 1995; Lowell et al. 2010). During the late Paleozoic

Era, mountains were forming across much of eastern, southern, and western North America. About 200 km (124 mi) south of the park, the Ouachita Mountains were uplifted. At the same time, the Appalachian Mountains rose during the final Appalachian orogeny. Ancestral Rocky Mountains were also forming at this time. These tectonic forces likely fractured rocks in the park and moved them along strike-slip faults that correspond to the third and youngest group of faults mapped in the GRI GIS data (Weary et al. 2016). In the late Paleozoic Era, mineral-saturated, geothermal fluids flowed upward from deep below Earth's surface to deposit lead-rich minerals along fractures and within pores that would later become mining areas such as the Viburnum Trend (Lowell et al. 2010). During this same event, other geothermal fluids altered the limestones that had been deposited earlier in the park to dolomite—the bedrock formations seen today. Heavy mineral deposition occurred at the interface between the Mesoproterozoic volcanic rocks and the adjacent Paleozoic sedimentary rocks.

Mesozoic Era (252 million–66 million years ago): Pangaea Separation, Local Erosion, and Mississippi Embayment Subsidence

There are no rocks from the Mesozoic Era mapped within the park, however geologic events during the time period played a role in shaping the southeastern United States. At the dawn of the Mesozoic Era, all landmasses on Earth were assembled into the supercontinent Pangaea (fig. 31). Just a few tens of millions of years later, during the Triassic and Jurassic periods, rifting began to pull apart Pangaea. Africa and South America separated from North America, forming the still-widening Atlantic Ocean. This rifting also opened the Gulf of Mexico basin in the late Triassic or early Jurassic (Saucier 1994). The Gulf of Mexico continued to widen through the Cretaceous Period. During the Cretaceous, global sea level rose to the extent that the North American continent was divided by the Western Interior Seaway that stretched from the Gulf of Mexico to the Arctic Ocean. As the gulf expanded, the Earth's crust between the southern Appalachians and Ouachita Mountains subsided creating the Mississippi Embayment. The topographically low Mississippi Embayment was inundated when sea levels were high (Unkelsbay and Vineyard 1992; Levin 1999; Schaper 2015). As sea levels fluctuated during the Late Cretaceous, the embayment alternated between shallow marine and fluvial environments. Sediments eroded from the Ouachita Mountains collected within the embayment. Although the waters of the embayment did not reach what is now the park, they did extend to near Cape Girardeau, Missouri, 120 km (75 mi) east of Eminence. Marine and near-marine sands, sandstones and clay were deposited across southeastern Missouri. Weathering, erosion, and fluvial incision were the dominant geologic processes operating in the park by the end of the Mesozoic Era, and the Ozarks continued to be an area of erosion and weathering continuing throughout the Cenozoic Era which followed (Unkelsbay and Vineyard 1992; Schaper 2015).

Cenozoic Era (the past 66 million years): River Valley Evolution and Ice Age Glaciation

Throughout the early Cenozoic Era (fig. 29E), periodic incursions from the Gulf of Mexico inundated the lower Mississippi Embayment, depositing thick layers of marine sediments that would eventually fill the embayment during the Paleocene and Eocene epochs (Saucier 1994). This had impacts on the development of the entire Mississippi River system, including Current River and Jacks Fork. Higher sea levels yield higher base levels and overall less incision by rivers upstream. By contrast, when sea level is lowered or the upstream land uplifted, the drop in base level causes incision and river-channel entrenchment. Fluvial geologic units (e.g., **QTg** and **Qt**) "perched" as terrace deposits above the modern floodplains record prior river levels (Weary et al. 2014a) that occurred when the base level was higher.

At the beginning of the Pleistocene Epoch, the system experienced a major change. Ice age glaciation was the single most significant geologic process to affect the modern geomorphology and geologic history of the lower Mississippi River valley (Saucier 1994). During repeated continental glaciations (ice ages) of the Pleistocene Epoch (between 2.6 million years ago and approximately 12,000 years ago) thick sheets of ice advanced and retreated over much of North America. Glacial ice never reached farther south than central Missouri (see fig. 2), but the global effects of their presence are recorded in the geologic units in the Ozarks. Weathering was accelerated in the colder, less vegetated settings causing more accumulation of slope deposits such as landslides (**Qls**) and colluvium (**Qc**). A cover of Pleistocene, wind-blown loess (**Qtl** and **Ql**) of varying thicknesses extends over all of the park area except for the highest parts of the Ozarks (Bunker et al.

1988; Weary et al. 2014; Schaper 2015). In some places, ancient soil horizons are buried beneath the loess, representing a warmer period 75,000 and 125,000 years ago (Weary et al. 2014).

Ice advance and retreat rearranged the preexisting drainages in the midcontinent, and the Mississippi, Ohio, and Missouri rivers emerged as the continent's major drainage systems (Fisk 1944; Saucier 1994). The Mississippi River valley repeatedly functioned as a sluiceway, funneling immense quantities of glacial meltwater and outwash sediments to the Gulf of Mexico (Saucier 1994). During glacial intervals, vast amounts of water were entrained as ice, resulting in a lower global sea level. Erosional processes dominated the exposed landscape, causing breaks in the stratigraphic record (Saucier 1994). Rivers carved canyons into the continental shelves. The entrenched valleys of the Mississippi, Arkansas, and White rivers formed during the most recent glaciation—the Wisconsinan (Fisk 1944; Waterways Experiment Station 1951).

Geologic processes are still changing the landscape at Ozark National Scenic Riverways. Since the Mesozoic Era, residuum (**QTrr**, **QTtrc**, and **QTr**), otherwise known as soil, clay, and rock fragments, has weathered from exposed (and subsurface) bedrock (Bunker et al. 1988; Weary et al. 2014; Schaper 2015). This process continues to wear away the bedrock and slowly mute the relief. The Current River, Jacks Fork, and their tributaries continue to incise their channels and deposit mantles of alluvium (**Qal**) along their courses (Weary et al. 2014a, 2014b). Gravity, wind, and flowing water move this residuum, depositing it in graded layers (Bunker et al. 1988; Schaper 2015). Slope deposits such as landslide and colluvium (**Qls** and **Qc**, respectively) continue to accumulate at the base of slopes and cliffs. Muck and clayey silt are slowly filling undrained karst sinkholes within the Roubidoux Formation (**Or**) and the Jefferson City Dolomite (**Ojc**) at the park (Weary et al. 2014).

Geologic Map Data

A geologic map in GIS format is the principal deliverable of the GRI program. GRI GIS data produced for the park follows the source maps listed here and includes components described in this chapter. Posters (in pocket) display the data over imagery of the park and surrounding area. A Map Unit Properties Table (in pocket) summarizes report content for each map unit. Complete GIS data are available at the GRI publications website: http://go.nps.gov/gripubs.

Geologic Maps

A geologic map is the fundamental tool for depicting the geology of an area. Geologic maps are two-dimensional representations of the three-dimensional geometry of rock and sediment at or beneath the land surface (Evans 2016). Colors and symbols on geologic maps correspond to geologic map units. The unit symbols consist of an uppercase letter indicating the age (see fig. 3) and lowercase letters indicating the formation's name. Other symbols depict structures such as faults or folds, locations of past geologic hazards that may be susceptible to future activity, and other geologic features. 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.americangeosciences.org/environment/publications/mapping, provides more information about geologic maps and their uses.

Geologic maps are typically one of two types: surficial or bedrock. Surficial geologic maps 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. GRI produced a bedrock map with surficial units for Ozark National Scenic Riverways.

Source Maps

The GRI team does not conduct original geologic mapping. The team digitizes paper maps and compiles and converts digital data to conform to the GRI GIS data model. The GRI GIS data set includes essential elements of the source maps such as map unit descriptions, a correlation chart of units, a map legend, map notes, cross sections, figures, and references. These items are included in the ozar_geology.pdf. The GRI team used data from Weary et al. (2014) clipped to the park and immediate vicinity to craft the GRI GIS product for the park. Seamless digital data are now available digitally as Weary et al. (2016). Map sheets and pamphlet are published as Weary et al. (2014). These maps provided information for the report as well.

GRI GIS Data

The GRI team standardizes map deliverables by using a data model. The GRI GIS data for the park was compiled using data model version 2.1, which is available is available at http://go.nps.gov/gridatamodel. This data model dictates GIS data structure, including layer architecture, feature attribution, and relationships within ESRI ArcGIS software. The GRI Geologic Maps website, http://go.nps.gov/geomaps, provides more information about the program's map products.

GRI GIS data are available on the GRI publications website http://go.nps.gov/gripubs and through the NPS Integrated Resource Management Applications (IRMA) portal https://irma.nps.gov/App/Portal/Home. 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 (ozar_gis_readme.pdf) that describes the GRI data formats, naming conventions, extraction instructions, use constraints, and contact information.
- Data in ESRI geodatabase GIS format;
- Layer files with feature symbology (table 4);
- Federal Geographic Data Committee (FGDC)–compliant metadata;
- An ancillary map information document (ozar_geology.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 (ozar_geology.mxd) that displays the GRI GIS data; and
- A version of the data viewable in Google Earth (ozar_geology.kmz; table 4).

Table 4. GRI GIS data layers for Ozark National Scenic Riverways (ozar_geology.mxd; ozar_geology.kmz).

Data Layer	On Poster?	Google Earth Layer?
Geologic Attitude and Observation Localities (strike and dip)	No	No
Folds	Yes	Yes
Faults	Yes	Yes
Hazard Area Feature Boundaries (sinkholes)	Yes	Yes
Hazard Area Features (sinkholes)	Yes	Yes
Surficial Contacts	Yes	Yes
Surficial Units	Yes	Yes
Bedrock Contacts	Yes	Yes
Bedrock Units	Yes	Yes

GRI Map Posters

Three posters of the GRI GIS draped over a shaded relief image of the park and surrounding area are included with this report. Not all GIS feature classes are included on the posters (table 4). The posters also include photographs of the park's landscape and historic resources. A cross section from Weary et al. (2014) is provided on the "Jacks Fork to Two Rivers" sheet. Geographic information and selected park features have been added to the posters. Digital elevation data and added geographic information are not included in the GRI GIS data, 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 poster. Based on the source map scale (1:24,000) and US National Map Accuracy Standards, geologic features represented in the geologic map data are expected to be horizontally within 12 m (40 ft) of their true locations.

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Additional References

These references, resources, and websites may be of use to resource managers. Refer to Appendix B for laws, regulations, and policies that apply to NPS geologic resources. The US Geological Survey compiled a glossary for geologic terms (http://geomaps.wr.usgs.gov/parks/misc/glossarya.html).

NPS Geologic Resources Division

The Geologic Resources Division (http://go.nps.gov/geology) provides technical and policy support for geologic resource management issues in three emphasis areas:

- geologic heritage,
- active processes and hazards, and
- energy and minerals management.

Contact the division for assistance with resource inventories, assessments and monitoring; impact mitigation, restoration, and adaptation; hazards risk management; law, policy, and guidance; resource management planning; data and information management; and outreach and youth programs (Geoscientists-in-the-Parks and Mosaics in Science).

Park staff can formally request assistance via https://irma.nps.gov/Star/.

Geology of NPS Areas

- NPS Geologic Resources Division Education Website: http://go.nps.gov/geoeducation
- NPS Geologic Resources Inventory: http://go.nps.gov/gri
- NPS Geoscientists-In-the-Parks (GIP) internship and guest scientist program: http://go.nps.gov/gip
- 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://go.nps.gov/views

NPS Resource Management Guidance and Documents

- Management Policies 2006 (Chapter 4: Natural resource management): http://www.nps.gov/policy/mp/policies.html
- 1998 National parks omnibus management act: http://www.gpo.gov/fdsys/pkg/PLAW-105publ391/pdf/PLAW-105publ391.pdf
- 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://go.nps.gov/geomonitoring
- NPS Technical Information Center (TIC) (Denver, Colorado; repository for technical documents): https://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://www.globalchange.gov/home
- Intergovernmental Panel on Climate Change: http://www.ipcc.ch/

Geological Surveys and Societies

- Missouri Geological Survey: http://dnr.mo.gov/geology/
- The Geology of Missouri: http://members.socket.net/~joschaper/geo.html
- Missouri Watershed Inventory and Assessment: http://mdc.mo.gov/your-property/greener-communities/missouri-watershed-inventory-and-assessment
- US Geological Survey: http://www.usgs.gov/
- Geological Society of America: http://www.geosociety.org/
- American Geophysical Union: http://sites.agu.org/
- American Geosciences Institute: http://www.americangeosciences.org/
- Association of American State Geologists: http://www.stategeologists.org/

US Geological Survey Reference Tools

- Geologic glossary (simplified definitions): http://geomaps.wr.usgs.gov/parks/misc/glossarya.html
- National geologic map database (NGMDB): http://ngmdb.usgs.gov/ngmdb/ngmdb_home.html
- Geologic names lexicon (GEOLEX; geologic unit nomenclature and summary): http://ngmdb.usgs.gov/Geolex/search
- Geographic names information system (GNIS; official listing of place names and geographic features): http://gnis.usgs.gov/
- GeoPDFs (download 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://pubs.usgs.gov/imap/i2720/

Appendix A: Scoping Participants

The following people attended the GRI scoping meeting, held on 5–6 December 2001, or the follow-up report writing conference call, held on 20 October 2015. 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.

2001 Scoping Meeting Participants

Name	Affiliation	Position
Zelda Bailey	NPS National Cave and Karst Research Institute	not recorded
Tim Connors	NPS Geologic Resources Division	Geologist, GRI maps coordinator
Sid Covington	NPS Geologic Resources Division	Geologist
Bill Duley	Missouri Geological Survey	not recorded
Victoria Grant	NPS Ozark National Scenic Riverways	Resource management
Deanna Greco	NPS Geologic Resources Division	Geologist
Bruce Heise	NPS Geologic Resources Division	Geologist, GRI program coordinator
Bob Higgins	NPS Geologic Resources Division	Geologist
Scott House	NPS Ozark National Scenic Riverways	Resource management
Jeff Imes	USGS Water Resources Division	Hydrologist
Robert Jacobsen	US Geological Survey	Geologist
Ron Kerbo	NPS Geologic Resources Division	Cave Specialist
Dennis M. Meinert	DRS Soil and Water Conservation Program	not recorded
Mark Middendorf	Missouri Geological Survey	not recorded
Bill O'Donnell	NPS Ozark National Scenic Riverways	not recorded
Randall Orndorff	US Geological Survey	Geologist
James Price	NPS Ozark National Scenic Riverways	Archeologist
Charles Putnam	NPS Ozark National Scenic Riverways	Resource management
Chris Ward	NPS Ozark National Scenic Riverways	not recorded

2015 Conference Call Participants

Name	Affiliation	Position
Joe Gilman	Missouri Geological Survey	State geologist, survey director
Victoria Grant	NPS Ozark National Scenic Riverways	Natural resource program manager
Larry Johnson	NPS Ozark National Scenic Riverways	Superintendent
Jason Kenworthy	NPS Geologic Resources Division	Geologist, GRI reports coordinator
Randall Orndorff	US Geological Survey	Geologist
Trista L. Thornberry-Ehrlich	Colorado State University	Geologist, author, and graphic designer
Dave Weary	US Geological Survey	Geologist

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 National Park Service 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 2016. Contact the NPS Geologic Resources Division for detailed guidance.

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 CFR § 2.1(a)(1)(iii)** prohibits destroying, injuring, defacing, removing, digging or disturbing paleontological specimens or parts thereof. **Prohibition in 36 CFR § 13.35** applies even in Alaska parks, where the surface collection of other geologic resources is permitted. Regulations in association with 2009 PRPA are being finalized (August 2016).	**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 (including rock and mineral resources), unless otherwise authorized by law.	**36 CFR § 2.1** prohibits possessing, destroying, disturbing mineral resources… in park units. **Exception: 36 CFR § 13.35** allows some surface collection of rocks and minerals in some Alaska parks (not Klondike Gold Rush, Sitka, Denali, Glacier Bay, or 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.	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; and -NPS must evaluate use of external quarries. Any deviation from this policy requires a 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 United States not authorized by congress or approved by the USACE. **Clean Water Act 33 USC § 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 the 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.
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 Freedom of Information Act (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.	**36 CFR § 2.1** prohibits possessing/ destroying/disturbing…cave resources…in park units. **43 CFR 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
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 for 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 CFR Parts 610 and 611** are the US Department of Agriculture regulations for the Natural Resources Conservation Service. 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; and -develop/follow written prescriptions (instructions).

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Climate Change	**Secretarial Order 3289** (Addressing the Impacts of Climate Change on America's Water, Land, and Other Natural and Cultural Resources) (2009) requires DOI bureaus and offices to incorporate climate change impacts into long-range planning; and establishes DOI regional climate change response centers and Landscape Conservation Cooperatives to better integrate science and management to address climate change and other landscape scale issues. **Executive Order 13653** (Preparing the United States for the Impacts of Climate Change) (2013) outlines Federal agency responsibilities in the areas of supporting climate resilient investment; managing lands and waters for climate preparedness and resilience; providing information, data and tools for climate change preparedness and resilience; and planning. **Executive Order 13693** (Planning for Federal Sustainability in the Next Decade) (2015) established to maintain Federal leadership in sustainability and greenhouse gas emission reductions. **President's Climate Action Plan** (2013), http://www.whitehouse.gov/sites/default/files/image/president27sclimateactionplan.pdf	None applicable.	**Section 4.1** requires NPS to investigate the possibility to restore natural ecosystem functioning that has been disrupted by past or ongoing human activities. This would include climate change, as put forth by Beavers et al. (in review). **NPS Climate Change Response Strategy** (2010) describes goals and objectives to guide NPS actions under four integrated components: science, adaptation, mitigation, and communication. **Policy Memo 12-02** (Applying National Park Service Management Policies in the Context of Climate Change) (2012) applies considerations of climate change to the impairment prohibition and to maintaining "natural conditions". **Policy Memo 14-02** (Climate Change and Stewardship of Cultural Resources) (2014) provides guidance and direction regarding the stewardship of cultural resources in relation to climate change. **Policy Memo 15-01** (Climate Change and Natural Hazards for Facilities) (2015) provides guidance on the design of facilities to incorporate impacts of climate change adaptation and natural hazards when making decisions in national parks. **DOI Manual Part 523, Chapter 1** establishes policy and provides guidance for addressing climate change impacts upon the Department's mission, programs, operations, and personnel. **Revisiting Leopold: Resource Stewardship in the National Parks** (2012) will guide US National Park natural and cultural resource management into a second century of continuous change, including climate change. **Climate Change Action Plan** (2012) articulates a set of high-priority no-regrets actions the NPS will undertake over the next few years **Green Parks Plan** (2013) is a long-term strategic plan for sustainable management of NPS operations.

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 614/134533, September 2016

National Park Service
U.S. Department of the Interior

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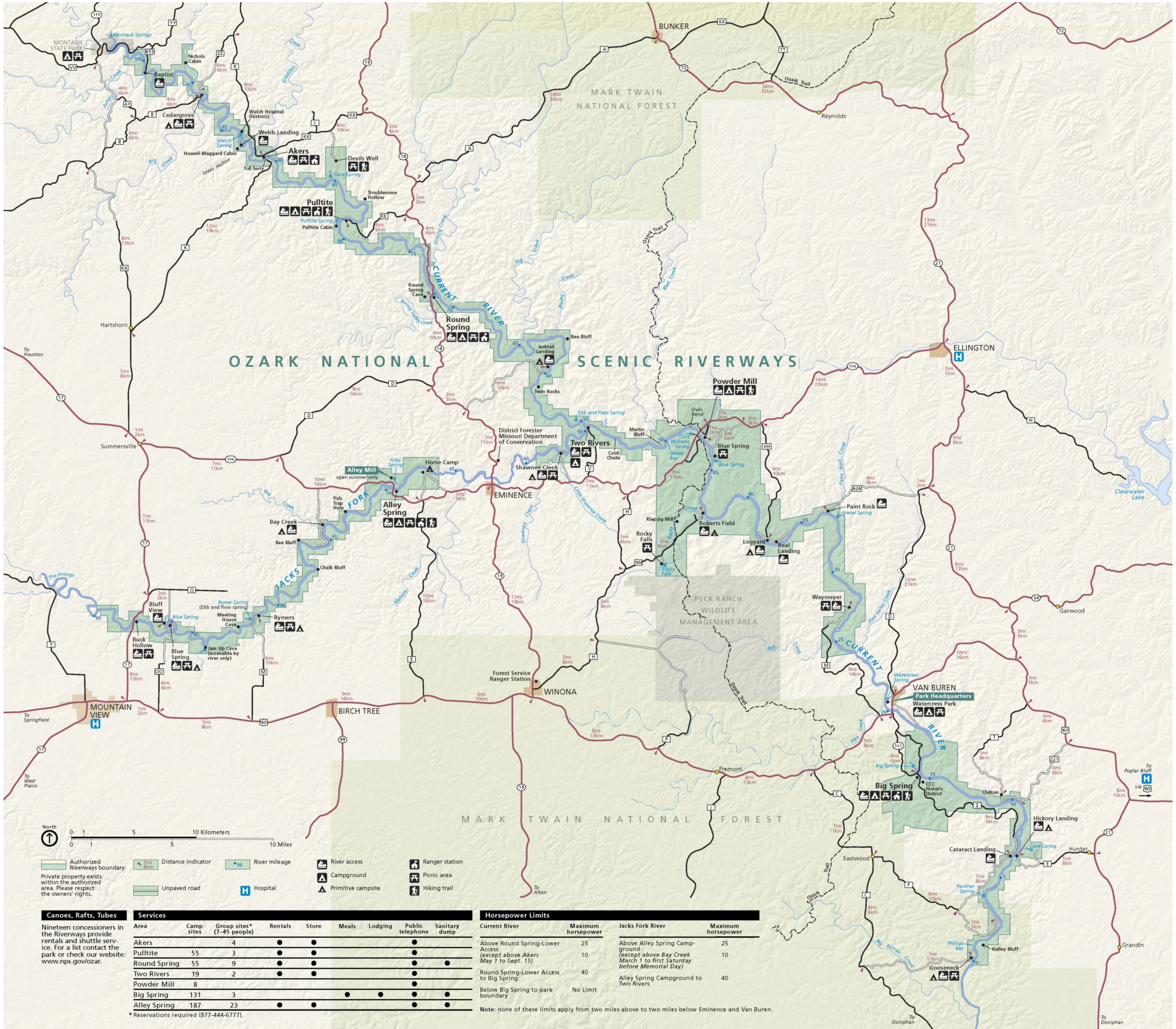


Services

Area	Camp sites	Group sites* (7–45 people)	Rentals	Store	Meals	Lodging	Public telephone	Sanitary dump
Akers		4	●	●			●	
Pulltite	55	3	●	●			●	
Round Spring	55	9	●	●			●	●
Two Rivers	19	2	●	●			●	
Powder Mill	8						●	
Big Spring	131	3			●	●	●	●
Alley Spring	187	23	●	●			●	●

* Reservations required (877-444-6777).

Horsepower Limits

Current River	Maximum horsepower	Jacks Fork River	Maximum horsepower
Above Round Spring-Lower Access	25	Above Alley Spring Campground	25
(except above Akers May 1 to Sept. 15)	10	*(except above Bay Creek March 1 to first Saturday before Memorial Day)*	10
Round Spring-Lower Access to Big Spring	40	Alley Spring Campground to Two Rivers	40
Below Big Spring to park boundary	No Limit		

Note: none of these limits apply from two miles above to two miles below Eminence and Van Buren.

Figure 1. Map of Ozark National Scenic Riverways. The Current River and Jacks Fork cut into the Ozark Plateaus in south-central Missouri. National Park Service map available at https://www.nps.gov/hfc/cfm/carto.cfm

Geologic Map of Ozark National Scenic Riverways

Missouri

National Park Service
U.S. Department of the Interior

Geologic Resources Inventory
Natural Resource Stewardship and Science

Current River North of Twin Rocks

Wallace Barn at Devils Well. National Park Service photograph.

Current River. National Park Service photograph.

Welch Spring and Hospital Ruins. National Park Service photograph.

Round Spring. National Park Service photograph.

NPS Boundary

Infrastructure

- Point of interest
- Road
- River

Folds

- Anticline, approximate
- Syncline, approximate

Faults

- Unknown offset/displacement, approximate

Sinkholes

- Karst sinkhole (filled with Quaternary sediments)

Geologic Contacts

- Approximate

Surficial Units

- Qa — Alluvium (Holocene)
- Qm — Muck and clayey silt (Holocene and Pleistocene?)
- Qls — Landslide deposits (Holocene and Pleistocene?)
- Qc — Colluvium (Holocene and Pleistocene)
- Qt — Terrace deposits (Holocene and Pleistocene?)
- Qtl — Loess-covered terrace deposits (Pleistocene?)
- Ql — Loess (Pleistocene)
- QTrr — Residuum derived from Roubidoux Formation (Quaternary and Tertiary)
- QTr — Peck Ranch unit (Quaternary and Tertiary, and Mesozoic?)
- QTtrc — Residual and colluvial material on terrace-like landforms (Quaternary and Tertiary)
- QTg — Upland gravel deposit (Quaternary and Tertiary)

Bedrock Units

- Ojc — Jefferson City Dolomite (Lower Ordovician)
- Or — Roubidoux Formation (Lower Ordovician)
- Og — Gasconade Dolomite (Lower Ordovician)
- Ce — Eminence Dolomite (Upper Cambrian)
- Cp — Potosi Dolomite (Upper Cambrian)
- Yg — Big Spring quad granite (Mesoproterozoic)
- Yrm — Rhyolite of Russell Mountain (Mesoproterozoic)
- Yvc — Volcaniclastic conglomerate, breccia, and sandstone (Mesoproterozoic)
- Ysc — Rhyolite of Sutton Creek (Mesoproterozoic)
- Ysi — Rhyolite of Shut-In Mountain (Mesoproterozoic)
- Ysm — Rhyolite of Stegall Mountain (Mesoproterozoic)
- Ymm — Tuff of Mule Mountain (Mesoproterozoic)
- Yltm — Tuff of Little Thorny Mountain (Mesoproterozoic)
- Ycu — Upper Coot Mountain unit (Mesoproterozoic)
- Ycl — Lower Coot Mountain unit (Mesoproterozoic)

This map was produced by Chase Winters and Georgia Hybels (Colorado State University) in September 2016. 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.

This sheet displays geologic data from Weary et al. (2014, 2016) clipped to the park and immediate vicinity. Seamless digital data are available digitally as Weary et al. (2016). Map sheets and pamphlet are published as Weary et al. (2014).

Weary, D. J., R. W. Harrison, R. C. Orndorff, R. E. Weems, J. S. Schindler, J. E. Repetski, and H. A. Pierce. 2014. Bedrock geologic map of the Spring Valley, West Plains, and parts of the Piedmont and Poplar Bluff 30' x 60' quadrangles, Missouri, including the upper Current River and Eleven Point River Drainage basins (scale 1:100,000). Scientific Investigations Map 3280. US Geological Survey, Reston, Virginia. http://pubs.er.usgs.gov/publication/sim3280

Weary, D. J., R. C. Orndorff, R. W. Harrison, and R. E. Weems. 2016. Digital geologic map data for the Ozark National Scenic Riverways and adjacent areas along the Current River and Jacks Fork, Missouri. Data Release. US Geological Survey, Reston, Virginia. http://dx.doi.org/10.5066/F7CJ8BKB

As per source map scale and US National Map Accuracy Standards, geologic features represented here are expected to be 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.

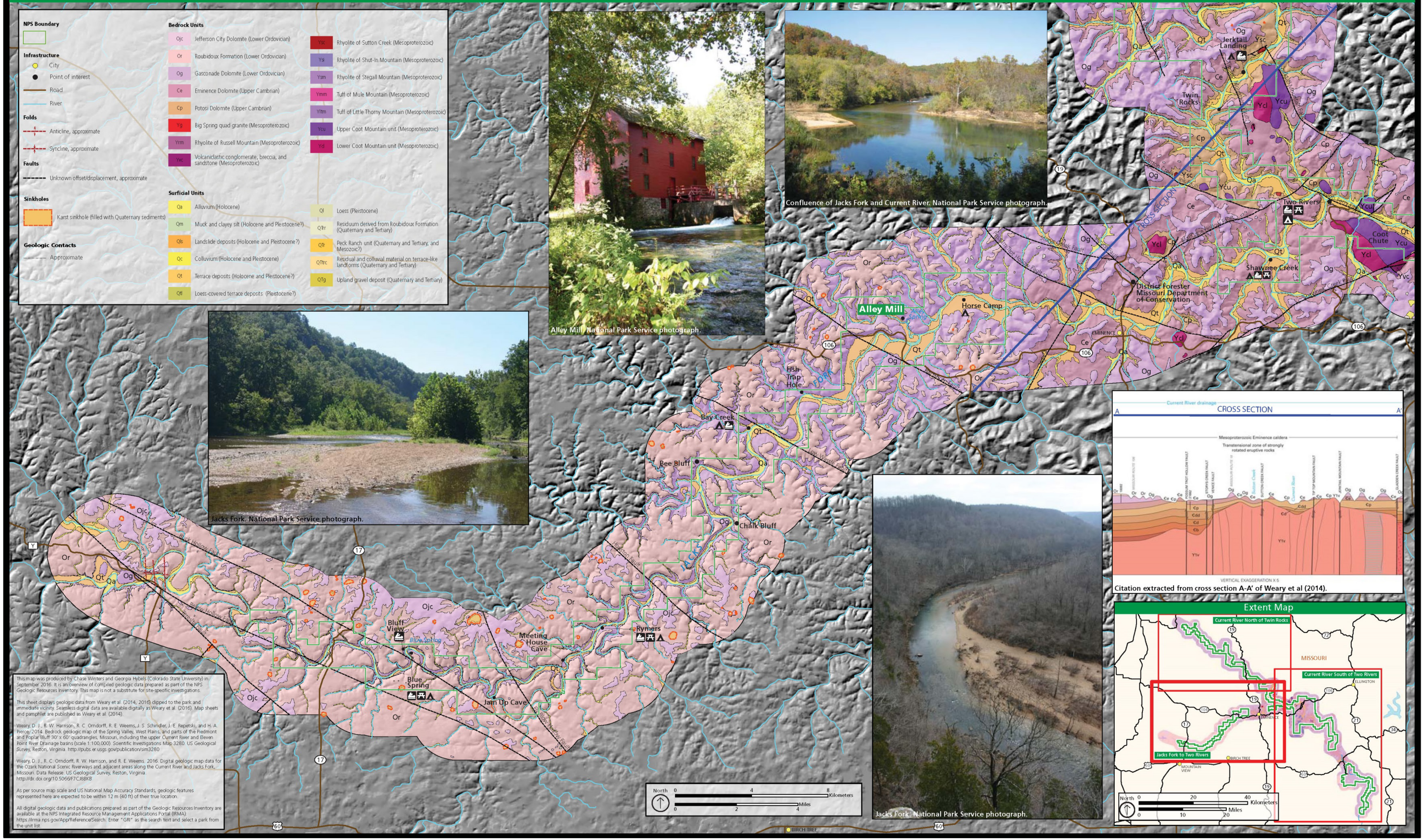
Geologic Map of Ozark National Scenic Riverways

Missouri

National Park Service
U.S. Department of the Interior

Geologic Resources Inventory
Natural Resource Stewardship and Science

Jacks Fork to Two Rivers



Alley Mill. National Park Service photograph.

Confluence of Jacks Fork and Current River. National Park Service photograph.

Jacks Fork. National Park Service photograph.

Jacks Fork. National Park Service photograph.

Citation extracted from cross section A-A' of Weary et al (2014).

Extent Map

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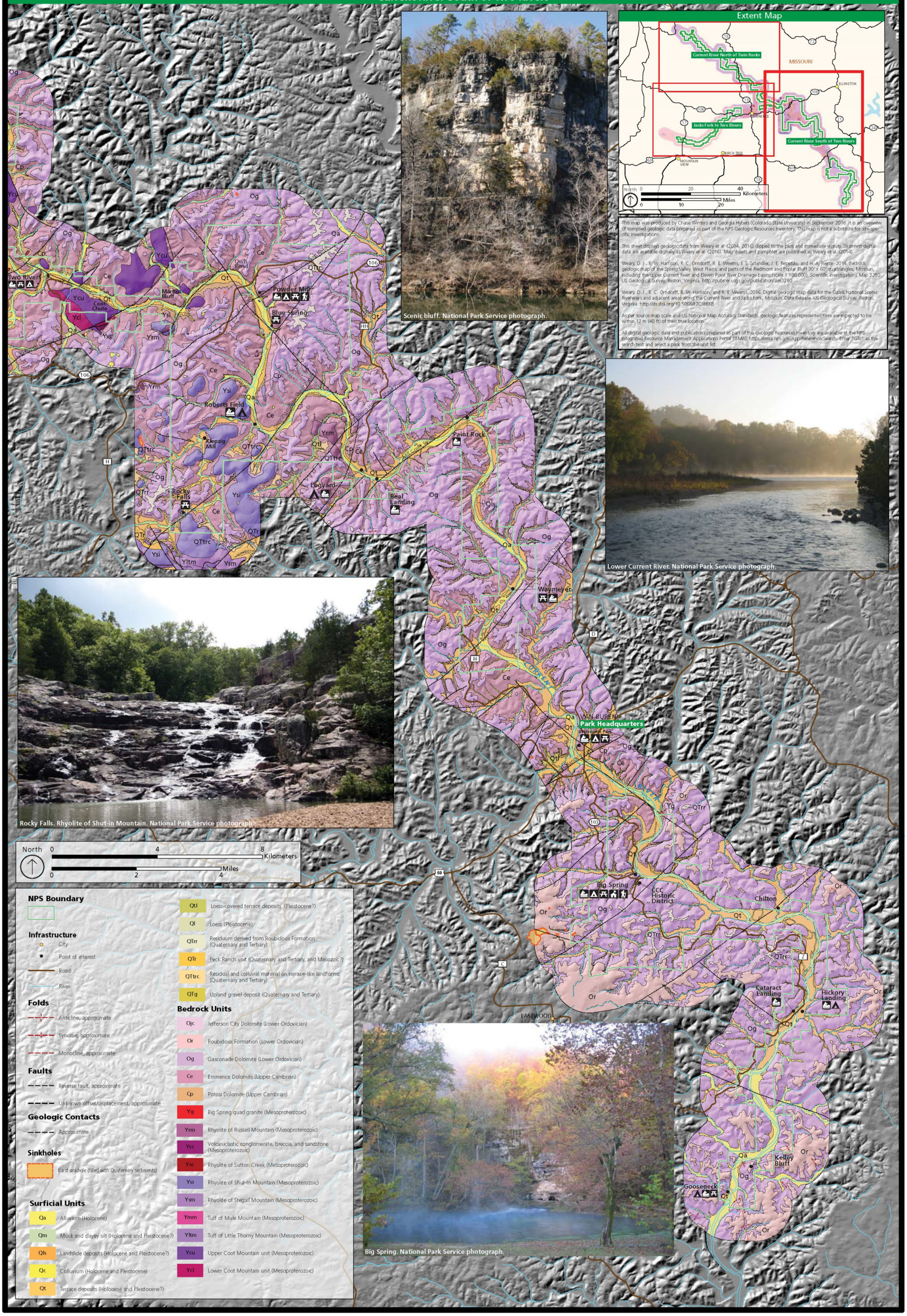
Geologic Map of Ozark National Scenic Riverways

Missouri

National Park Service
U.S. Department of the Interior

Geologic Resources Inventory
Natural Resource Stewardship and Science

Current River South of Two Rivers



Scenic bluff. National Park Service photograph.

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Lower Current River. National Park Service photograph.

Rocky Falls. Rhyolite of Shut-in Mountain. National Park Service photograph.

North 0 4 8 Kilometers
0 2 4 Miles

NPS Boundary

Infrastructure

- City
- Point of interest
- Road
- River

Folds

- Anticline, approximate
- Syncline, approximate
- Monocline, approximate

Faults

- Reverse fault, approximate
- Unknown offset/displacement, approximate

Geologic Contacts

- Approximate

Sinkholes

- Karst sinkhole (filled with Quaternary sediments)

Surficial Units

Qa	Alluvium (Holocene)
Qm	Muck and clayey silt (Holocene and Pleistocene?)
Qls	Landslide deposits (Holocene and Pleistocene?)
Qc	Colluvium (Holocene and Pleistocene)
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Og	Gasconade Dolomite (Lower Ordovician)
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Cp	Potosi Dolomite (Upper Cambrian)
Yg	Big Spring quad granite (Mesoproterozoic)
Yrm	Rhyolite of Russell Mountain (Mesoproterozoic)
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Ysc	Rhyolite of Sutton Creek (Mesoproterozoic)
Ysi	Rhyolite of Shut-In Mountain (Mesoproterozoic)
Ysm	Rhyolite of Stegall Mountain (Mesoproterozoic)
Ymm	Tuff of Mule Mountain (Mesoproterozoic)
Yltm	Tuff of Little Thorny Mountain (Mesoproterozoic)
Ycu	Upper Coot Mountain unit (Mesoproterozoic)
Ycl	Lower Coot Mountain unit (Mesoproterozoic)

Big Spring. National Park Service photograph.

Surficial Map Unit Properties Table: Ozark National Scenic Riverways

Gray-shaded map units are not mapped within Ozark National Scenic Riverways. Bold text refers to sections in report.

Age (millions of years ago)	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
QUATERNARY PERIOD Pleistocene and Holocene epochs (2.6–present)	Alluvium (Qa)	Alluvium is deposited by water along streams, floodplains, riparian areas, and alluvial plains. **Qa** consists of gravel, sand, silt, and clay. The larger clasts are slightly rounded chert, sandstone, and quartzite, mostly derived from the Paleozoic Era bedrock. Deposits of **Qa** range from 0 to 6 m (0 to 20 ft) in thickness. **Qa** is mapped along the channels of nearly every river, stream, and smaller tributaries at Ozark National Scenic Riverways.	**Surficial Geologic Map Units**—**Qa** occurs along channels and adjacent floodplains of modern streams.	**Flooding and Fluvial Geomorphology**—**Qa**, **Qt**, and **Qtl** are associated with modern fluvial systems at Ozark National Scenic Riverways. These and slope deposits (**Qls** and **Qc**) are integral to riparian zones and floodplains. **Erosion**—stream crossings and riparian areas are among the most disturbed ecosystems in the park. Increased erosion contributes to increased river meandering, increased suspended sediment load in park streams, and formation of gravel bars as the channel migrates.	**River Valley Evolution and Ice Age Glaciation—Qa** is among the youngest geologic map units occurring on the landscape at Ozark National Scenic Riverways. These units reflect the ongoing processes of weathering and erosion within the Ozark Mountains, which create sediments for river transportation and deposition. Rivers transport sediments downslope toward the Coastal Plain.
QUATERNARY PERIOD Pleistocene and Holocene epochs (2.6–present)	Muck and clayey silt (Qm)	**Qm** is fine-grained silt, reworked loess (**Ql**), clay, and organic-rich muck of unknown thickness. **Qm** is intermittently water laden. **Qm** occurs in mapped karst sinkholes within **Or** and **Ojc** in the Blue Spring to Chalk Bluff area along the Jacks Fork River. Some of these sinks, such as Tupelo Pond and Cupola Pond, support unique floral and possibly faunal communities.	**Cave and Karst Features and Processes**—**Qm** accumulates in deep sinkholes.	**Caves and Associated Landscape Management—Qm** collects in sinkholes that are plugged and intermittently flooded.	**River Valley Evolution and Ice Age Glaciation—Qm** is slowly filling sinkholes and may contain fossil pollen records of past climate conditions.
QUATERNARY PERIOD Pleistocene and Holocene epochs (2.6–present)	Landslide deposits (Qls)	**Qls** consists of a jumbled mix of dolomite, chert, sandstone, and quartzite clasts in a finer-grained matrix of clay and silt. Deposits of **Qls** range from 6 to 30 m (30 to 100 ft) thick. **Qls** is only mapped in the Van Buren North quadrangle near Waymeyer, but similar deposits occur in other areas of steep topography.	**Bedrock Weathering and Residuum Formation**—**Qls** accumulates as large landslides and large-scale slumps with hummocky surface topography. **Qls** occurs in areas of steep slopes.	**Flooding and Fluvial Geomorphology**—**Qa**, **Qt**, and **Qtl** are associated with modern fluvial systems at Ozark National Scenic Riverways. These and slope deposits (**Qls** and **Qc**) are integral to riparian zones and floodplains. **Slope Movement Hazards and Risks**—**Qls** indicates areas of past slope movement. Future movement is also possible, creating hazards for infrastructure or recreation.	**River Valley Evolution and Ice Age Glaciation—** formation of **Qc** and **Qls** was likely accelerated during the colder, periglacial conditions of the Pleistocene glaciations.
QUATERNARY PERIOD Pleistocene and Holocene epochs (2.6–present)	Colluvium (Qc)	Colluvium consists of clast-supported, rather angular to slightly rounded cobbles and boulders that collect at the bases of slopes. **Qc** contains boulders, cobbles, and pebbles of sandstone from weathering **QTrr** (derived from **Or**) in deposits about 1 m (3 ft) thick. **Qc** is only mapped in the Powder Mill Ferry quadrangle near Two Rivers, but occurs in other areas of steep topography.	**Bedrock Weathering and Residuum Formation**—**Qc** accumulates as gravity-creep deposits on steep slopes in the upper part of **Og** below **QTrr**.	**Flooding and Fluvial Geomorphology**—**Qa**, **Qt**, and **Qtl** are associated with modern fluvial systems at Ozark National Scenic Riverways. These and slope deposits (**Qls** and **Qc**) are integral to riparian zones and floodplains. **Slope Movement Hazards and Risks**—**Qc** indicates areas of past slope movement. Future movement is also possible, creating hazards for infrastructure or recreation.	**River Valley Evolution and Ice Age Glaciation—** formation of **Qc** and **Qls** was likely accelerated during the colder, periglacial conditions of the Pleistocene glaciations.

Gray-shaded map units are not mapped within Ozark National Scenic Riverways. Bold text refers to sections in report.

Age (millions of years ago)	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
QUATERNARY PERIOD Pleistocene and Holocene epochs (2.6–present)	Terrace deposits (Qt)	Terrace deposits typically contain coarser sand and gravel perched above the modern floodplain; terraces represent former stream levels. **Qt** consists of cobble- to sand-size, slightly rounded chert, sandstone, and quartzite clasts within a finer-grained matrix of sand, silt, and clay. Some of the matrix material may be reworked **Ql**. Thickness of **Qt** is typically more than 3 m (10 ft) and tends to be thicker along larger streams. **Qt** is mapped along most rivers, streams, and tributaries in Ozark National Scenic Riverways flanking deposits of **Qa**.	**Surficial Geologic Map Units**—**Qt** accumulates on relatively flat areas along modern stream valley floors and walls, but above the normal flood range, 2 to 3 m (6 to 10 ft) above stream level.	**Flooding and Fluvial Geomorphology**—**Qa**, **Qt**, and **Qtl** are associated with modern fluvial systems at Ozark National Scenic Riverways. These and slope deposits (**Qls** and **Qc**) are integral to riparian zones and floodplains. **Erosion**—Stream crossings and riparian areas are among the most disturbed ecosystems in the park. Increased erosion contributes to increased river meandering, increased suspended sediment load in park streams, and gravel bars.	**River Valley Evolution and Ice Age Glaciation—Qt** records former river levels along the Current and Jacks Fork rivers during the Holocene and possibly the Pleistocene epochs.
QUATERNARY PERIOD Pleistocene and Holocene epochs (2.6–present)	Loess-covered terrace deposits (Qtl)	**Qtl** is mostly silt with some sand and clay in windblown deposits as much as 0.3 m (1 ft) thick atop well-developed soil horizons or clay, silt, sand, and minor pebbles. **Qtl** is mapped in the Stegall Mountain and Van Buren South quadrangles.	**Surficial Geologic Map Units—Qtl** occurs on slopes above the valleys of various large streams and within a few large sinkholes. **Periglacial Features**—loess collected as winds swept across the landscape in colder climates associated with Pleistocene glaciations ("ice ages").	**Flooding and Fluvial Geomorphology**—**Qa**, **Qt**, and **Qtl** are associated with modern fluvial systems at Ozark National Scenic Riverways. These and slope deposits (**Qls** and **Qc**) are integral to riparian zones and floodplains. **Erosion**—Stream crossings and riparian areas are among the most disturbed ecosystems in the park. Increased erosion contributes to increased river meandering, increased suspended sediment load in park streams, and gravel bars.	**River Valley Evolution and Ice Age Glaciation—**buried beneath the loess is a well-developed soil horizon that is probably recording the Sangamon Geosol. **Qtl** records former river levels along the Current and Jacks Fork rivers.
QUATERNARY PERIOD Pleistocene and Holocene epochs (2.6–present)	Loess (Ql)	**Ql** consists of finely winnowed silt in deposits as much as 1 m (3 ft) thick. **Ql** is commonly mixed with residuum from plant activity and other bioturbation (i.e. burrowing). **Ql** is mapped in the Stegall Mountain quadrangle, but occurs as thin veneers in other areas including discontinuous patches on hills and ridges such as Thorny Mountain.	**Periglacial Features**—loess collected as winds swept across the landscape in colder climates associated with Pleistocene glaciations ("ice ages").	None documented.	**River Valley Evolution and Ice Age Glaciation—**buried beneath the loess is a well-developed soil horizon that is probably recording the Sangamon Geosol.
QUATERNARY PERIOD and TERTIARY (66.0–present)	Residuum derived from Roubidoux Formation (QTrr)	**QTrr** is red and reddish-orange sandy clay with abundant angular boulders of sandstone and chert. The sandstone boulders are fine- to coarse-grained, poorly sorted, and contains some ripple marks. The chert component is gray with banded, sandy, oolitic or porcelaneous (microcrystalline) varieties. Boulders can reach 2 m (6 ft) in diameter. **QTrr** is up to 12 m (40 ft) thick. **QTrr** is a widespread unit, but not mapped in all quadrangles; it occurs on hilltops where **Or** has been deeply weathered atop mapped areas of **Og**.	**Cave and Karst Features and Processes**—**QTrr** fills or covers sinkholes. **Surficial Geologic Map Units—QTrr** is a residual unit, the result of intense weathering of bedrock (**Or**). **Sedimentary Rock Features—**clasts in **QTrr** have symmetrical and asymmetrical ripple marks indicating deposition in fluvial or nearshore marine environments. Oolites in some chert boulders indicate deposition in shoreline environments. **Faults and Fractures**—**QTrr** fills or covers faults. **Folds**—**QTrr** fills or covers folds.	None documented.	**River Valley Evolution and Ice Age Glaciation—** formation of **QTrr** was likely accelerated during the colder, periglacial conditions of the Pleistocene glaciations.

Gray-shaded map units are not mapped within Ozark National Scenic Riverways. Bold text refers to sections in report.

Age (millions of years ago)	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
QUATERNARY PERIOD and TERTIARY (66.0–present)	Residual and colluvial material on terrace-like landforms (QTtrc)	**QTtrc** consists of silt, clay, sand, and gravel. Unit is only mapped in the Stegall Mountain quadrangle in terrace-like landforms adjacent to knobs of Mesoproterozoic volcanic rocks. **QTtrc** occurs in the Rocky Falls and Roberts Field areas upstream from Logyard.	**Cave and Karst Features and Processes**—**QTtrc** fills or covers sinkholes. **Surficial Geologic Map Units—QTtrc** occurs on slopes above the valleys of various large streams and within a few large sinkholes. It is gradational, in some areas, with **Qt** and **Qtl**. **Bedrock Weathering and Residuum Formation**—**QTtrc** is in part residual and colluvial in nature as it accumulates on steep slopes. **Periglacial Features**—**QTtrc** commonly has a thin mantle of loess that collected as winds swept across the landscape in colder climates associated with Pleistocene glaciations ("ice ages"). **Faults and Fractures**—**QTtrc** fills or covers faults. **Folds**—**QTtrc** fills or covers folds.	**Slope Movement Hazards and Risks**—**QTtrc** indicates areas of past slope movement. Future movement is also possible, creating hazards for infrastructure or recreation.	**River Valley Evolution and Ice Age Glaciation—** formation of **QTtrc** was likely accelerated during the colder, periglacial conditions of the Pleistocene glaciations.
QUATERNARY PERIOD and TERTIARY (66.0–present)	Upland gravel deposit (QTg)	**QTg** contains gravel deposits less than 3 m (10 ft) thick perched as high as 90 m (300 ft) above modern stream floodplains. The deposits are mostly rounded clasts of chert, sandstone, and quartzite with a silty sand matrix. Unit is mapped only on the Van Buren North quadrangle.	**Paleontological Resources—QTg** contains clasts of fossiliferous Mississippian chert. Mississippian rocks are not exposed within Ozark National Scenic Riverways.	**Paleontological Resource Inventory, Monitoring, and Protection**—fossil theft is a concern of park managers. A field-based paleontological resource survey can provide detailed, site-specific descriptions and recommendations.	**River Valley Evolution and Ice Age Glaciation—QTg** records former river levels and has remnants of geologic bedrock units no longer present on the park landscape.
QUATERNARY PERIOD, TERTIARY, and MESOZOIC ERA? (252–present)	Peck Ranch unit (QTr)	**QTr** is brown, red, and reddish-orange sandy clay with abundant angular blocks, cobbles, and pebbles of sandstone with various chert varieties similar to **QTrr**. **QTr** is at least 60 m (200 ft) thick. Unit is mapped only in the Stegall Mountain quadrangle. It occurs outside park boundaries near Rocky Falls.	**Cave and Karst Features and Processes**—**QTr** fills or covers sinkholes. **Surficial Geologic Map Units—QTr** is a residual unit, the result of intense weathering of one or more bedrock units: **Or** and **Ce**. **QTr** preserves a crude stratigraphic sequence left over from the original bedrock. **Faults and Fractures**—**QTr** fills or covers faults. **Folds**—**QTr** fills or covers folds.	None documented.	**River Valley Evolution and Ice Age Glaciation—** formation of **QTr** was likely accelerated during the colder, periglacial conditions of the Pleistocene glaciations.

Bedrock Map Unit Properties Table: Ozark National Scenic Riverways

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Age (millions of years ago)	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
LOWER ORDOVICIAN (485–470)	Jefferson City Dolomite (Ojc)	**Ojc** is light brown, medium- to fine-grained, argillaceous dolomite with lesser amounts of quartz sandstone lenses and chert beds and nodules. Bedding is thin to thick and weathered outcrops appear powdery-pale yellow. A conspicuous, ledge-forming, brown, medium-grained, siliceous, pitted-weathering dolomite occurs between 8 and 12 m (25 and 40 ft) of the base of **Ojc**—the "Quarry Ledge". **Ojc** is on average 61 m (200 ft) thick and only occurs in the park in upland areas along the upper Jacks Fork.	**Cave and Karst Features and Processes**—**Ojc** contains thick carbonate layers that are susceptible to karst dissolution. Karst sinkholes are mapped in **Ojc** and some contain deposits of **Qm**. **Bedrock Weathering and Residuum Formation**—weathered **Ojc**, that collects as the bases of exposures, tends to be more silty and less sandy than those from **Or** with residual sandstone and orthoquartzite that are less tabular in shape than those from **Or**. These characteristics help to differentiate **Ojc** and **Or** when exposures are limited. **Paleontological Resources—**sparsely fossiliferous containing trilobites and conodonts.	**Caves and Associated Landscape Management**—karst management issues include sinkhole flooding and collapse, cave breakdown or roof collapse, slippery surfaces, precipitous drops, drowning, radon, vandalism and dumping, and white-nose syndrome. Because white-nose syndrome was discovered in the park in 2010, all park caves are closed to entry except for tours of Round Spring Cavern. **Ojc** and **Or** have the highest concentration of sinkholes in this part of Missouri. Most are closed-throat sinkholes; however, collapses have occurred historically. Karst management issues include sinkhole flooding and collapse, cave breakdown, slippery surfaces, precipitous drops, drowning, radon, vandalism and dumping, and white-nose syndrome. **Ozarks Aquifer and Springs Protection**—**Ojc** is part of the Ozarks aquifer. **Paleontological Resource Inventory, Monitoring, and Protection**—fossil theft is a concern of park managers. A field-based paleontological resource survey can provide detailed, site-specific descriptions and recommendations.	**Marine Inundation, Deposition, and Erosion, Assembling Pangaea—Ojc** is the youngest Paleozoic unit exposed in the park area. It was deposited in a shallow marine basin. Sea levels fluctuated, increasing or decreasing the amount of terrestrial (noncarbonate) sediment.
LOWER ORDOVICIAN (485–470)	Roubidoux Formation (Or)	**Or** consists of white to pale orange, fine- to coarse-grained, thin- to thick-bedded, poorly sorted sandstone interbedded with medium gray, very fine- to coarse-grained, thin- to medium-bedded dolomite. Thin beds, lenses and nodules of white to medium gray chert are common. Orthoquartzite and sandy dolomite are also interlayered with the dominant sandstone and dolomite. **Or** ranges up to 76 m (250 ft) thick.	**Cave and Karst Features and Processes**—karst sinkholes are mapped in **Or** and some contain deposits of **Qm**. Sandstone layers within **Or** control the location of cave formation. **Sedimentary Rock Features—**sandstones in **Or** have symmetrical and asymmetrical ripple marks and cross beds indicating deposition in fluvial or nearshore environments. Oolites in some chert indicate deposition in shoreline environments. **Paleontological Resources—**occasional molds and impressions of the gastropod *Lecanospira*, brachiopods, cephalopods, conodonts, and crinoid fragments. Some chert contains stromatolites.	**Caves and Associated Landscape Management**—karst management issues include sinkhole flooding and collapse, cave breakdown or roof collapse, slippery surfaces, precipitous drops, drowning, radon, vandalism and dumping, and white-nose syndrome. Because white-nose syndrome was discovered in the park in 2010, all park caves are closed to entry except for tours of Round Spring Cavern. **Ojc** and **Or** have the highest concentration of sinkholes in this part of Missouri. Most are closed-throat sinkholes; however, collapses have occurred historically. **Ozarks Aquifer and Springs Protection**—**Or** is a major part of the Ozarks aquifer. **Paleontological Resource Inventory, Monitoring, and Protection**—fossil theft is a concern of park managers. A field-based paleontological resource survey can provide detailed, site-specific descriptions and recommendations.	**Marine Inundation, Deposition, and Erosion, Assembling Pangaea—Or** was deposited in a shallow marine basin. Sea levels fluctuated, increasing or decreasing the amount of sandy sediment.

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Age (millions of years ago)	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
LOWER ORDOVICIAN (485–470)	Gasconade Dolomite (Og)	**Og** is divisible into three informal units: (1) an upper unit of light gray, medium- to coarse-grained, thick-bedded, vuggy (contains cavities) dolomite; (2) a middle unit of mostly light gray, fine- to coarse-grained, medium- to thick-bedded dolomite grading downward into more chert-rich dolomite, and lower into light gray to yellowish gray, fine- to medium-grained, thin- to medium-bedded dolomite; and (3) a light gray to white sandstone, sandy dolomite, or orthoquartzite interbedded with light gray to tan, fine-grained, thin-bedded dolomite called the Gunter Sandstone Member. The lowermost, third unit ranges in thickness from 3 to 8 m (10 to 25 ft). The overall thickness of **Og** is between 45 and 235 m (148 and 770 ft).	**Cave and Karst Features and Processes**—**Og** contains thick carbonate layers susceptible to karst dissolution. **Og** is the major cave-forming unit in the park with the majority of caves in the upper reaches of the unit forming below the contact with **Ojc**. Karst sinkholes are mapped in **Og**. Sandstone layers at the base of **Og** are confining units and control the location of cave formation. **Sedimentary Rock Features—Og** chert is porcelaneous, oolitic, porous with druse, and stromatolitic. **Paleontological Resources—**white *Cryptozoon* chert layers, as well as mollusks (including planispiral gastropods), conodonts, and cephalopods.	**Caves and Associated Landscape Management**—karst management issues include sinkhole flooding and collapse, cave breakdown or roof collapse, slippery surfaces, precipitous drops, drowning, radon, vandalism and dumping, and white-nose syndrome. Because white-nose syndrome was discovered in the park in 2010, all park caves are closed to entry except for tours of Round Spring Cavern. **Og** hosts the majority of park caves. **Ozarks Aquifer and Springs Protection**—**Og** is part of the Ozarks aquifer. **Paleontological Resource Inventory, Monitoring, and Protection**—**Og** contains fossil resources that may be subject to theft or degradation. Fossil theft is a concern of park managers. A field-based paleontological resource survey can provide detailed, site-specific descriptions and recommendations.	**Marine Inundation, Deposition, and Erosion, Assembling Pangaea—Og** is the youngest unit in contact with the Mesoproterozoic igneous rocks. There is an unconformable contact with underlying **Ce** indicating a period of erosion or nondeposition.
UPPER CAMBRIAN (501–485)	Eminence Dolomite (Ce)	Dolomite, sandstone, and chert compose **Ce**. The dolomite is light gray, medium to coarse grained, massive to thick bedded, and contains stromatolites. Weathered outcrops appear bluish gray and medium gray with pitted surfaces and the unit occurs as small knobs or pinnacles. Chert stringers and nodules are common and some quartz sandstone and sandy dolomite interbeds also occur where the unit is thicker. Thickness of **Ce** ranges from 23 to 280 m (80 to 919 ft).	**Cave and Karst Features and Processes**—**Ce** contains thick carbonate layers that are susceptible to karst dissolution. **Ce** is one of the main cave-forming units in the park with the majority of caves in the upper reaches of the unit forming below the contact with **Og**. Knobs and pinnacles are left after the rest of the unit dissolves away. Karst sinkholes are mapped in **Ce**. Sandstone layers within **Ce** are confining units and control the location of cave formation. **Paleontological Resources—**fossil algae (stromatolites) in the dolomite as well as gastropods, other mollusks, and trilobites.	**Caves and Associated Landscape Management**—karst management issues include sinkhole flooding and collapse, cave breakdown or roof collapse, slippery surfaces, precipitous drops, drowning, radon, vandalism and dumping, and white-nose syndrome. Because white-nose syndrome was discovered in the park in 2010, all park caves are closed to entry except for tours of Round Spring Cavern. Extensive caves occur in **Ce**. **Ozarks Aquifer and Springs Protection**—**Ce** is part of the Ozarks aquifer. **Paleontological Resource Inventory, Monitoring, and Protection**—**Ce** contains fossil resources that may be subject to theft or degradation. Fossil theft is a concern of park managers. A field-based paleontological resource survey can provide detailed, site-specific descriptions and recommendations.	**Marine Inundation, Deposition, and Erosion, Assembling Pangaea—Ce** was deposited in a shallow marine basin. Layers of **Ce** are thinner near knobs of Mesoproterozoic rocks suggesting the indicating their presence as islands during deposition in a longstanding shallow marine basin.
UPPER CAMBRIAN (501–485)	Potosi Dolomite (Cp)	**Cp** is light brown and gray, fine- to medium-grained, massive- to thick-bedded dolomite. Vugs or cavities are filled with quartz druse. White to light gray chert nodules and stringers are common. **Cp** ranges in thickness from 15 to 175 m (50 to 575 ft).	**Cave and Karst Features and Processes**—**Cp** contains thick carbonate layers that are susceptible to karst dissolution. Minor caves and other solutional features are concentrated at or near the contact between **Cp** and **Ce**. Karst sinkholes are mapped in **Cp**. **Sedimentary Rock Features—Cp**, when freshly broken, has a fetid odor. Vugs contain in botryoidal masses of chalcedony and small quartz crystals coating the surface. **Paleontological Resources—**stromatolites, gastropods, other mollusks, and trilobites.	**Caves and Associated Landscape Management**—karst management issues include sinkhole flooding and collapse, cave breakdown or roof collapse, slippery surfaces, precipitous drops, drowning, radon, vandalism and dumping, and white-nose syndrome. Because white-nose syndrome was discovered in the park in 2010, all park caves are closed to entry except for tours of Round Spring Cavern. **Ozarks Aquifer and Springs Protection**—**Cp** is part of the Ozarks aquifer. **Paleontological Resource Inventory, Monitoring, and Protection**—fossil theft is a concern of park managers. A field-based paleontological resource survey can provide detailed, site-specific descriptions and recommendations.	**Marine Inundation, Deposition, and Erosion, Assembling Pangaea—Cp** is the oldest sedimentary unit in the Ozark National Scenic Riverways map area. Like the other Paleozoic rocks, it was deposited in a shallow marine basin.
Rocks younger than Mesoproterozoic and older than Upper Cambrian are not mapped within Ozark National Scenic Riverways. This represents a gap of nearly one billion years.					

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Age (millions of years ago)	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
MESOPROTEROZOIC ERA (1600–1000)	Big Spring quad granite (Yg)	"Granite" denotes a specific intrusive—cooled beneath the surface—igneous rock composition characterized by relatively high silica contents, rich in quartz (10 to 50%) and with more alkali feldspars than granodiorite. Other minerals include plagioclase, muscovite, biotite and/or hornblende. **Yg** is red, medium-grained with clots of altered, dark amphibole minerals with quartz and alkali feldspar. Accessory minerals include fluorite, zircon, and magnetite. **Yg** weathers to produce secondary clay, sericite and epidote. **Yg** is mapped in the Big Spring, Van Buren South, Winona, and Round Spring quadrangles.	**Radiometric Ages**—samples of **Yg** have been dated using U-Pb at: 1,461±5.5, 1,473±15, 1,480±42, and 1,473±15 million years ago.	**Abandoned Mineral Lands**—**Yg** was quarried during the CCC-era developments. **External Mineral Development**—"**Y**" units are associated with economic minerals that may be targets of exploration.	**Building the Ozark Dome, Volcanism, Deformation, and Erosion**—**Yg** formed as magma domes that rose and cooled between volcanic eruptions associated with the Eminence caldera. There is an unconformity between **Yg** and overlying **Cp** indicating more than 500 million years or erosion and/or nondeposition.
MESOPROTEROZOIC ERA (1600–1000)	Rhyolite of Russell Mountain (Yrm)	Rhyolite is an extrusive—erupted from a volcano—igneous rock with a mineralogical composition similar to granite. Textures include visible crystals in a glass to cryptocrystalline groundmass. If the alkali feldspar component decreases, rhyolite grades into rhyodacite. **Yrm** is a rhyolitic ash-flow tuff. Tuff is the consolidated or cemented form of volcanic ash and lapilli (larger volcanic ejecta). **Yrm** contains abundant crystals of pink alkali feldspar, magnetite, and hematite and is at least 1,000 m (3,000 ft) thick. **Yrm** may be correlative with **Yltm**. **Yrm** is mapped in the Stegall Mountain and Powder Mill Ferry quadrangles	**Volcanic Rocks and the Eminence Caldera**—**Yrm** is densely welded with flow-banding structures present in places. **Yrm** was erupted as multiple flows of simple and compound cooling units. Rotation of **Yrm**, reflected in the steep inclination of the banding, occurred during caldera collapse.	**External Mineral Development**—"**Y**" units are associated with economic minerals that may be targets of exploration.	**Building the Ozark Dome, Volcanism, Deformation, and Erosion**—**Yrm** formed during the rift margin volcanism associated with the Eminence caldera. **Yrm** and **Yltm** may have been part of the same eruptive event.
MESOPROTEROZOIC ERA (1600–1000)	Volcaniclastic conglomerate, breccia, and sandstone (Yvc)	A breccia is a coarse-grained rock composed of angular, broken rock fragments held together in a fine-grained matrix. In some areas of **Yvc**, the fragments are subrounded composing a conglomerate interbedded with coarse- to medium-grained sandstone and strongly silicified breccia. The 8- to 13-cm (3- to 5-in) diameter cobbles are derived from **Ysc**, **Ycu**, and other volcanic rocks. The weathered, greenish, finer-grained matrix is also volcaniclastic material. **Yvc** only occurs on the southern side of Coot Mountain, and in the Eminence and Powder Mill Ferry quadrangles.	**Volcanic Rocks and the Eminence Caldera**—**Yvc** contains fragments of **Ysc** and **Ycu** indicating these units were already in place when further eruptions exploded, incorporating the fragments into a new unit.	None documented.	**Building the Ozark Dome, Volcanism, Deformation, and Erosion**—**Yvc** was erupted and emplaced after **Ysc** and **Ycu**.
MESOPROTEROZOIC ERA (1600–1000)	Rhyolite of Sutton Creek (Ysc)	**Ysc** consists of alkali rhyolite to rhyolite with phenocrysts (large crystals) on pink feldspar in a dark pink, finer-grained matrix. **Ysc** also contains conspicuous aggregates of small pink feldspar crystals in an apple-green matrix that alter yellowish white. **Ysc** is mapped in the Eminence quadrangle and is exposed along the northwest bank of the Current River near Tip Top Mountain and near the confluence with the Jacks Fork River.	**Volcanic Rocks and the Eminence Caldera**—**Ysc** contains aggregates of crystals that may be xenoliths, or fragments derived from another rock that were incorporated into the lava of **Ysc**. Fragments of **Ysc** are part of **Yvc**. **Ysc** displays some flow banding, but is commonly not layered.	**External Mineral Development**—"**Y**" units are associated with economic minerals that may be targets of exploration.	**Building the Ozark Dome, Volcanism, Deformation, and Erosion**—**Ysc** formed during the rift margin volcanism associated with the Eminence caldera.

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Age (millions of years ago)	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
MESOPROTEROZOIC ERA (1600–1000)	Rhyolite of Shut-In Mountain (Ysi)	**Ysi** is dense rhyolite to alkali trachyte lava. With alkali feldspar and minor mafic minerals (biotite, amphibole, or pyroxene), trachyte is similar to rhyolite in composition, but with less quartz. **Ysi** is relatively crystal rich with white to pink alkali feldspar and some quartz crystals. Accessory minerals include fluorite, magnetite, and hematite, all in a light pink to maroon red matrix. **Ysi** is at least 275 m (900 ft) thick. **Ysi** is mapped in the Stegall Mountain quadrangle. Rocky Falls flows Ysi.	**Volcanic Rocks and the Eminence Caldera**—**Ysi** displays some flow banding, but is commonly not layered. **Ysi** has some small zones of hydrothermal brecciation and vesicles (original bubbles or cavities) filled with quartz and feldspar. **Ysi** possibly formed as coalesced lava flows and domes. The hydrothermal brecciation likely marks vent sites. **Radiometric Ages**—a sample of **Ysi** was been dated using U-Pb at 1,470±2.7 million years ago.	**External Mineral Development**—"**Y**" units are associated with economic minerals that may be targets of exploration.	**Building the Ozark Dome, Volcanism, Deformation, and Erosion**—**Ysi** was deposited atop **Ymm** and **Yltm** in the caldera after it collapsed and its flanks rotated.
MESOPROTEROZOIC ERA (1600–1000)	Rhyolite of Stegall Mountain (Ysm)	**Ysm** is similar in composition to **Ysi** as dense rhyolite to alkali trachyte lava. The only difference is a lower quartz-phenocryst content (0.5 to 2% versus 3 to 5%). **Ysm** is at least 61 m (200 ft) thick. **Ysm** is mapped in the Stegall Mountain quadrangle.	**Volcanic Rocks and the Eminence Caldera**—**Ysm** is genetically related to **Ysi**.	None documented.	**Building the Ozark Dome, Volcanism, Deformation, and Erosion**—**Ysm** is part of the Mesoproterozoic suite of volcanic rocks at the park. It likely erupted after the collapse of the Eminence caldera.
MESOPROTEROZOIC ERA (1600–1000)	Tuff of Mule Mountain (Ymm)	**Ymm** is air-fall tuff with dense, aphanitic (glassy to microcrystalline), finely laminated appearance. Thickness of **Ymm** ranges from 4.5 to 30 m (15 to 100 ft). **Ymm** is mapped in the Stegall Mountain quadrangle.	**Volcanic Rocks and the Eminence Caldera**—**Ymm** has rare angular quartz phenocrysts. **Ymm** has abundant accretionary lapilli or pellets of ash that formed by rainfall through a downwind ash cloud or by accretion from a moisture-laden eruption.	None documented.	**Building the Ozark Dome, Volcanism, Deformation, and Erosion**—the contact between **Ymm** and overlying **Ysm** and **Ysi** is conformable indicating a long period of volcanic eruptions. The underlying contact with **Yltm** is complex and irregular. **Ymm** was deposited in the caldera after it collapsed.
MESOPROTEROZOIC ERA (1600–1000)	Tuff of Little Thorny Mountain (Yltm)	**Yltm** is dense, dark maroon to purple, moderately crystal-rich, and quartz-poor, ash-flow tuff. Phenocrysts are almost entirely alkali feldspar with some magnetite, hematite, and fluorite. **Yltm** is at least 1,000 m (3,000 ft) thick. **Yltm** is mapped in the Stegall Mountain quadrangle.	**Volcanic Rocks and the Eminence Caldera**—**Yltm** shows fiamme (dark, glassy lenses formed by the collapse of pumice fragments) and eutaxitic (banded or layered) textures with some flow banding. Rotation of **Yltm**, reflected in the steep inclination of the banding, occurred during caldera collapse.	None documented.	**Building the Ozark Dome, Volcanism, Deformation, and Erosion**—an unconformity occurs between **Yltm** and overlying **Ymm** indicating a period of erosion and/or nondeposition between volcanic episodes. **Yltm** was synvolcanic. **Yltm** formed during the rift margin volcanism associated with the Eminence caldera. After deposition, it rotated when the caldera collapsed.
MESOPROTEROZOIC ERA (1600–1000)	Upper Coot Mountain unit (Ycu)	**Ycu** is similar in composition to **Ysm** and **Ysi** as dense rhyolite to alkali rhyolite to alkali trachyte, but is a densely welded ash-flow tuff. Sparse pink feldspar and rare quartz phenocrysts with some magnetite and fluorite. **Ycu** is mapped at the summit and northeast side of Coot Mountain, at Jerktail Mountain, and Wildcat Mountain.	**Volcanic Rocks and the Eminence Caldera**—**Ycu** shows eutaxitic (banded or layered) textures with flow layering. Vapor-phase feldspar and quartz mineralization is common in pumice fragments.	**External Mineral Development**—"**Y**" units are associated with economic minerals that may be targets of exploration.	**Building the Ozark Dome, Volcanism, Deformation, and Erosion**—**Ycu** formed during the rift margin volcanism associated with the Eminence caldera. After deposition, it rotated when the caldera collapsed.
MESOPROTEROZOIC ERA (1600–1000)	Lower Coot Mountain unit (Ycl)	**Ycl** is similar in composition to **Ycu** as alkali rhyolite to alkali trachyte to trachyte and rhyolite ash-flow tuff, air-fall tuff, and perhaps lava. **Ycl** appears dark maroon with pink feldspar phenocrysts and some magnetite. **Ycl** has some pumice-rich, poorly welded layers. **Ycl** is exposed and mapped along the southwestern side of Coot Mountain, at Jerktail Mountain, and an unnamed knob along Missouri Route 106 east of Eminence.	**Volcanic Rock Features and the Eminence Caldera**—**Ycu** has some flow-layering, but most of the original volcanic depositional (fall and flow) features have been destroyed or altered beyond recognition. Secondary quartz mineralization (veins and cavities) is common.	**External Mineral Development**—"**Y**" units are associated with economic minerals that may be targets of exploration.	**Building the Ozark Dome, Volcanism, Deformation, and Erosion**—**Ycl** formed during the rift margin volcanism associated with the Eminence caldera. After deposition, it rotated when the caldera collapsed.