National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science

Buffalo National River

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2022/2413

ON THE COVER
Photograph of an alcove developed in Silurian limestone. Such alcoves provided shelter and may contain archeological resources. Alcoves form by spalling related to joints within the rock. The alcove pictured is adjacent to the river and therefore highly susceptible to flooding. It would have been poor shelter and any traces of human use have likely washed away.
National Park Service photograph taken by Andrea Croskrey (NPS Geologic Resources Division) in spring 2007.

THIS PAGE
Photograph of near vertical bluffs of the cherty Boone Formation sitting atop massive Silurian limestone. Outcrops like this are common along certain reaches of the Buffalo River. Slope deposits typically collect at the base of such exposures due to rockfall.
National Park Service photograph taken by Andrea Croskrey (NPS Geologic Resources Division) in spring 2007.

Buffalo National River

Geologic Resources Inventory Report

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Fort Collins, Colorado

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 and technically accurate.

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Executive Summary

Comprehensive park management to fulfill the mission of the National Park Service (NPS) requires an accurate inventory of the geologic features of a park unit, but park managers may not have the necessary information, geologic expertise, or means to complete such an undertaking; therefore, the Geologic Resources Inventory (GRI) provides information and resources to help park managers make decisions for visitor safety, planning and protection of infrastructure, and preservation of natural and cultural resources. Information in the GRI report may also be useful for interpretation.

A beautiful river, flowing unimpeded through towering bluffs and meandering across floodplains, the Buffalo River was the first national river designated in the National Park System. The Buffalo River begins in the heights of the Boston Mountains Plateau and flows 245 km (153 mi) downstream (generally east) through the Springfield Plateau until its confluence with the White River on the Salem Plateau. Approximately 135 miles of the river are within the boundaries of Buffalo National River (herein also referred to as "the park"). Featuring prominently on the park's landscape are karst features such as caves, sinkholes, sinking streams, and springs. Seasonal flows along certain stretches of the Buffalo River disappear underground only to emerge downstream. The park is attractive to a wide swath of visitor uses, such as canoeing and kayaking, horseback riding, hiking, fishing, and climbing.

The Buffalo River flows past more than 200 million years of Earth's history recorded in the rocks that comprise its valley walls. The river continues to incise these rocks, the oldest having accumulated within an intermittent marine basin that inundated the area as much as 470 million years ago. Marine, fluvial, and deltaic conditions prevailed during the deposition of most of the park's bedrock, after which it was deformed by the mountain-building processes that formed the Appalachian and Ouachita Mountains. This period of deformation is reflected in the park's faults and folds. Erosion and weathering continue to change the landscape by removing material, moving it downslope, and reworking it along the valley bottoms. This dynamic landscape makes Buffalo National River an ideal area to study fluvial processes.

This report is supported by GRI-compiled maps of the bedrock and surficial geology of Buffalo National River originally mapped as 25 separate products by the US Geological Survey and the Arkansas Geological Survey. These maps, which cover the area of the park and surrounding 7.5-minute quadrangles, are herein referred to as the "GRI GIS data". The datasets were originally compiled by the GRI in 2018 and updated in 2022. Five posters illustrate the data. The GRI GIS datasets may be updated if new, more accurate geologic maps become available or if software advances require an update to the digital format. The GRI GIS data and posters 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/. Enter "GRI" as the search text and select a park from the unit list.

Given the long, narrow nature of the Buffalo National River corridor, the park's resource managers divided the park into three broad segments based on shared geomorphology and geography: the upper ranger district from the Upper Buffalo Wilderness to Mt. Hersey; the middle ranger district from Mt. Hersey to Maumee; and the lower ranger district from Maumee to Buffalo City. This report provides geologic information that is applicable to the whole park and not necessarily to the individual segments. A table identifies the specific geologic features, processes, and resource management issues associated with each geologic map unit presented in the GRI GIS data.

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

- Fluvial Features and Processes. The Buffalo River and its tributaries are the primary resource at the park and make up the fluvial features found therein. Fluvial processes are constantly reshaping the landscape. High flows, river meandering, and streambank erosion threaten natural and cultural resources in the park. High flows and floods are anticipated to increase in severity and frequency with climate change.
- Caves and Karst. Karst features form as carbonate rocks are dissolved away by percolating water. At Buffalo National River, caves, springs, sinkholes, and sinking streams are all attributable to karst processes. Karst issues include cave safety and integrity.
- Geologic Hazards: Slope Movements and Earthquakes. Slope movements may include rockfalls, landslides, and debris flows. Triggers of slope movements include frost weathering, root wedging, water-saturated soils, undercutting by

streams, human disturbance, and rock weakening due to chemical weathering. Strong earthquakes are not common in the park area, but potential for seismicity exists. Earth shaking could trigger slope movements and damage infrastructure.

- Abandoned Mineral Lands and Disturbed Lands. Abandoned mineral lands are lands, waters, and surrounding watersheds that often contain physical and environmental hazards associated with past mineral exploration, extraction, processing, and transportation. The Buffalo River area has been associated with lead and zinc mining since as early as 1818. Disturbed lands are those park lands where the natural conditions and processes have been directly altered by development.
- Ancient Sedimentary Features. The bedrock in the park preserves features indicative of the prevailing conditions during its initial deposition, more than 300 million years ago. Examples of these features include ripple marks, cross beds, and trough structures.
- Bedrock Exposures. Sandstone, limestone, dolomite, shale, and siltstone comprise the bedrock throughout the park.
- Faults and Folds. Faults and folds form in response to stresses within Earth's crust. They indicate where rock has been compressed, stretched, sheared, or fractured and moved. Faults and folds are both mapped in the GRI GIS data.
- Paleontological Resource Inventory, Monitoring, and Protection. Paleontological resources (fossils) are nonrenewable evidence of life preserved in a geologic context. Nearly all the park's bedrock contains fossils. Fossils are a protected resource in the National Park System.

Introduction to the Geologic Resources Inventory

The Geologic Resources Inventory (GRI), which is administered by the Geologic Resources Division (GRD) of the NPS Natural Resource Stewardship and Science Directorate, 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 funded by the NPS Inventory and Monitoring Program.

GRI Products

The GRI team—which is primarily a collaboration between GRD staff and research associates at Colorado State University, Department of Geosciences and University of Alaska Museum of the North—completed three tasks as part of the GRI process for Buffalo National River: (1) conducted a scoping meeting and provided a scoping summary, (2) provided digital geologic map data in a geographic information system (GIS) and poster formats, and (3) provided a GRI report (this document).

GRI products 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/. Enter "GRI" as the search text and select a park from the unit list. Additional information regarding the GRI, including contact information, is available at http://go.nps.gov/gri.

GRI Scoping Meeting

On 26–27 April 2007, the National Park Service held a scoping meeting at Buffalo National River in Harrison, Arkansas. The scoping meeting brought together park staff and geologic experts, who reviewed and assessed available geologic maps, developed a geologic mapping plan, and discussed geologic features, processes, and resource management issues to be included in the final GRI report. A scoping summary (Thornberry-Ehrlich 2007) summarizes the findings of that meeting.

GRI GIS Data and Poster

Following the scoping meeting, the GRI team compiled the GRI GIS data for Buffalo National River from 20 source maps (see "Geologic Map Data"). Geologic map posters illustrate these data. The datasets were originally compiled by the GRI in 2018 and updated in 2022. These data may be updated if new, more accurate geologic maps become available or if software advances require an update to the digital format. Because these data are the principal deliverable of the GRI, a more detailed description of the product is provided in the "Geologic Map Data" section.

GRI Report

On 17 April 2019, the GRI team hosted a follow-up conference call for park staff and interested geologic experts. The call provided an opportunity to get back in touch with park staff, introduce "new" (since the 2007 scoping meeting) staff to the GRI process, and update the list of geologic features, processes, and resource management issues for inclusion in the final GRI report. In 2021, several additional conference calls were held with park staff to address questions that came up during report writing.

This report is a culmination of the GRI process. It synthesizes discussions from the scoping meeting in 2007, the follow-up conference calls in 2019 and 2021, and additional geologic research. The selection of geologic features was guided by the previously completed GRI map data, and writing reflects the data and interpretation of the source map authors. Information from Buffalo National River's foundation document (National Park Service 2018) was also included as applicable to Buffalo National River's geologic resources and resource management.

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.

Geologic Map Data

A geologic map is the fundamental tool for depicting the geology of an area. A geologic map in GIS format is the principal deliverable of the GRI program.

Introduction to Geologic Maps

Geologic maps are two-dimensional representations of the three-dimensional geometry of rock and sediment at or beneath the land surface (Evans 2016). The colors on a geologic map represent the locations of different rocks or deposits and commonly indicate their ages. On the geologic map for the park, pink colors represent the oldest rocks, which are from the Ordovician Period, whereas yellow colors represent the youngest deposits, which are from the Quaternary Period. In

addition to color, map unit symbols identify the rocks or deposits on geologic maps. Usually, a map unit symbol consists of uppercase letters indicating age (e.g., **O** for Ordovician, **S** for Silurian, **M** for Mississippian, **PN** for Pennsylvanian, and **Q** for Quaternary) followed by lowercase letters indicating the rock formation's name or the type of deposit (e.g., **Mbu** for the Mississippian age Boone Formation, undivided). Other symbols on geologic maps depict the contacts between map units or structures such as faults or folds. Some map units, such as landslide deposits, delineate locations of past geologic hazards, which may be susceptible to future activity. Geologic maps also may show human-made features, such as wells or mines.

Geologic maps are generally one of two types: bedrock or surficial. Bedrock geologic maps display older, typically more consolidated sedimentary, metamorphic, or igneous rocks. Bedrock map units are generally differentiated based on age and rock type. Surficial geologic maps typically present deposits that are unconsolidated and formed during the past 2.6 million years (Quaternary Period). Geomorphic surfaces, geologic process, or depositional environment differentiate surficial geologic map units. The GRI GIS data for the park includes bedrock and some surficial geologic data.

Source Maps

The GRI team does not conduct original geologic mapping. Scoping participants and the GRI team identify the best available geologic maps for a park unit. Determinations are made based on coverage (extent or area mapped), map scale, date of mapping, and compatibility of the mapping to the current geologic interpretation of an area. The GRI team then compiles and converts digital data to conform to the GRI GIS data model and digitizes paper maps. The GRI GIS data for Buffalo National River was originally compiled in 2018 and updated in 2022. These data may be updated if new, more accurate geologic maps become available or if software advances require an update to the digital format.

The GRI team may compile multiple source maps to cover a park boundary or provide a greater extent as needed for resource management. The sources also provided information for this report. The following 20 maps were compiled into the GRI GIS data for Buffalo National River (fig. 1), herein referred to collectively as "GRI GIS source data,":

- Geologic map of the Big Flat Quadrangle (Chandler et al. 2011a);
- Geologic map of the Boxley Quadrangle (Hudson and Turner 2007);
- Geologic map of the Buffalo City Quadrangle (Chandler et al. 2011b);
- Geologic map of the Cozahome Quadrangle (Ausbrooks et al. 2012);
- Geologic map of the Eula Quadrangle (Braden and Ausbrooks 2003a);
- Geologic map of the Harriet Quadrangle (Smart and Hutto 2008);
- Geologic map of the Hasty Quadrangle (Hudson and Murray 2004);
- Geologic map of the Jasper Quadrangle (Hudson et al. 2001);
- Geologic map of the Marshall Quadrangle (Hutto and Smart 2008);
- Geologic map of the Maumee Quadrangle (Turner and Hudson 2010);
- Geologic map of the Mt. Judea Quadrangle (Braden and Ausbrooks 2003b);
- Geologic map of the Murray Quadrangle (Hudson and Turner 2016);
- Geologic map of the Osage SW Quadrangle (Turner and Hudson 2018);
- Geologic map of the Parthenon Quadrangle (Braden and Ausbrooks 2003c);
- Geologic map of the Ponca Quadrangle (Hudson and Murray 2003);
- Geologic map of the Rea Valley Quadrangle (Ausbrooks et al. 2011);
- Geologic map of the St. Joe Quadrangle (Hudson and Turner 2009);
- Geologic map of the Snowball Quadrangle (Braden and Ausbrooks 2003d);
- Geologic map of the Western Grove Quadrangle (Hudson et al. 2006); and
- Geologic map of the west-central Buffalo National River region (Hudson and Turner 2014).

GRI Geodatabase Model and Data Set

The GRI team standardizes map deliverables by using a data model. The GRI GIS data for Buffalo National River was compiled using data model version 2.3, 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.

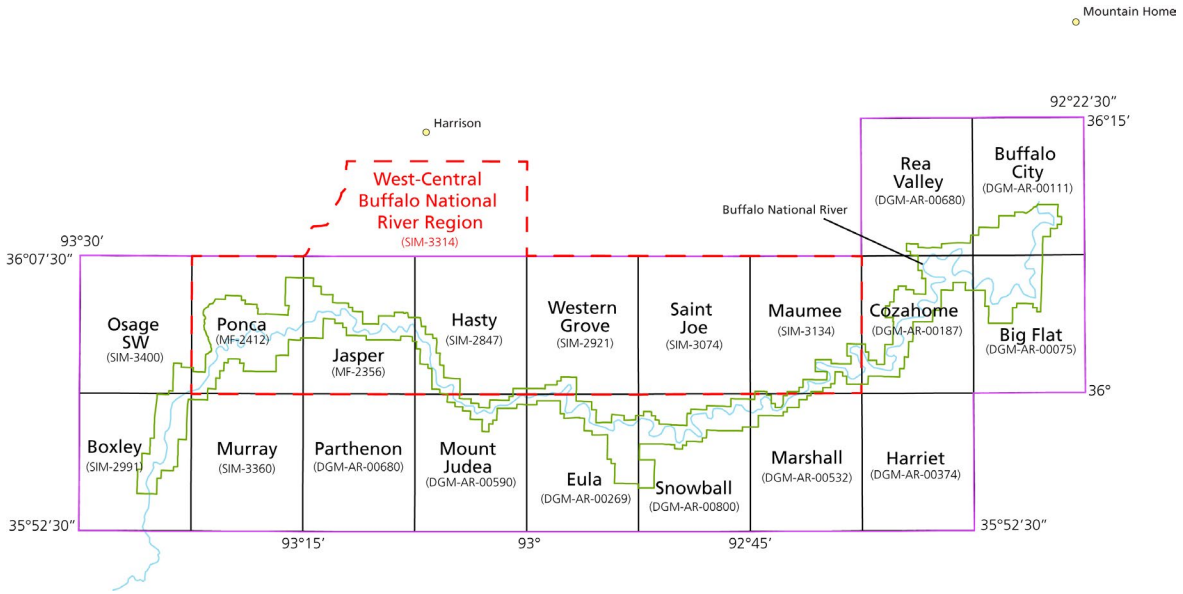

Figure 1. Index map of the GRI GIS data.
The index map displays the full extent of the GRI GIS data for Buffalo National River which includes 19 quadrangles. The extent (pink) and name (map series in parentheses) of each 7.5-minute quadrangle source map is labeled. The dashed red outline represents the extent of the West-Central Buffalo National River Region source map. See "Geologic Map Data" for references to individual source maps.The boundary of the park is outlined in green, Graphic by James Winter (Colorado State University).

The GRI GIS Data are available on the GRI publications website http://go.nps.gov/gripubs and through the IRMA portal https://irma.nps.gov/. Enter "GRI" as the search text and select a park from the unit list.

The following components are part of the 2022 GRI GIS data for the park:

- A GIS readme file (buff_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 1);
- Federal Geographic Data Committee (FGDC)–compliant metadata;
- An ancillary map information document (buff_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 (buff_geology.mxd) that displays the GRI GIS data; and
- A version of the data viewable in Google Earth (buff_geology.kmz).

GRI Geologic Map Posters

Posters (5 sheets) illustrate the GRI GIS data draped over a shaded relief image of the park and surrounding area. The posters are not a substitute for the GIS data but are supplied as helpful tools for office and field use and for users without access to ArcGIS. Not all GIS feature classes are included on the posters (table 1). 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.

The posters are available on the GRI publications website http://go.nps.gov/gripubs and through the IRMA portal https://irma.nps.gov/. Enter "GRI" as the search text and select a park from the unit list.

Use Constraints

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

Table 1. GRI GIS data layers for Buffalo National River.

Data Layer	On Poster?
Faults	Yes
Folds	Yes
Geologic Cross Section Lines	No
Geologic Measurement Localities	No
Geologic Observation Localities	Yes
Geologic Point Features	Yes
Geologic Sample Localities	No
Hazard Area Feature Boundaries	Yes
Hazard Area Features	Yes
Linear Geologic Units	Yes
Point Geologic Units	Yes
Structure Contour Lines, Base of Boone Formation (**Mbmb**)	No
Structure Contour Lines, Base of Middle Bloyd Sandstone, Bloyd Formation (**PNbm**)	No
Structure Contour Lines, Top of Boone Formation (**Mbmb**)	No
Mine Point Features (sensitive)	No
Geologic Sample Localities (sensitive)	No
Geologic Attitude and Observation Localities	No
Geologic Contacts	Yes
Geologic Units	Yes

Acknowledgements

The GRI team thanks the participants of the 2007 scoping meeting and 2019 follow-up conference call for their assistance in this inventory. The lists of participants reflect the names and affiliations of these participants at the time of the meeting and call. Melissa Trenchik from Buffalo National River was a vital source of park resource management information. Because the GRI team does not conduct original geologic mapping, we are particularly thankful for the Arkansas Geological Survey and US Geological Survey for their maps of the area. Thanks also to Angela Chandler and Richard Hutto from the Arkansas Geological Survey for their thoughtful reviews. This report and accompanying GIS data could not have been completed without them. Thanks to Katie KellerLynn for developing standard report content and organization. Thank you to the NPS Geologic Resources Division staff for reviews of sections of this report, specifically Vince Santucci and Justin Tweet for their assistance with the paleontology content, Pat Seiser with caves and karst, and Sarah Russell with abandoned mineral lands.

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Geologic Heritage of Buffalo National River

The Buffalo River flows freely through a deep valley, set between steep bluffs and cliffs showcasing millions of years of Earth's history preserved in their rocks. This chapter highlights the significant geologic features, landforms, landscapes, and stories of Buffalo National River preserved for their heritage values. It also draws connections between geologic resources and other park resources and stories.

Park Background and Establishment

The Buffalo River represents one of the last, pristine, free-flowing rivers in the conterminous US. The river cuts a winding course through gently undulating, relatively undeformed sedimentary bedrock. The stunning geology along its 218.47-km (135.75-mi) length within national river boundaries is a highlight for the more than 1.4 million annual visitors to this corner of northern Arkansas (Ziesler and Spalding 2021). Authorized by Congress on 1 March 1972, Buffalo National River, herein referred to as "the park," was the first designated national river in the National Park System (National Park Service 2018). The park will celebrate its 50th anniversary in 2022. Per its enabling legislation (P.L. 92-237), the park was established "for the purposes of conserving and interpreting an area containing unique scenic and scientific features and preserving as a free-flowing stream an important segment of the Buffalo River." The park's purpose statement presented in the foundation document (National Park Service 2018) is "to preserve a free-flowing river and to conserve and interpret the combination of natural, scenic, cultural, and scientific features characterized by deep valleys, towering bluffs, wilderness, and landscapes of the Ozark Mountains." Among the geologic features highlighted in the park's significance statements are waterfalls, steep bluffs, clear water, wooded canyons, caves, and riparian corridor (National Park Service 2018). Buffalo National River includes more than 38,000 ha (94,000 ac) of which 15,000 ha (36,000 ac) is designated wilderness (fig. 2).

The park extends in a narrow tract from the Upper Buffalo Wilderness area roughly northeastward to the confluence with the White River at Buffalo City, Arkansas. Only 11% of the Buffalo River watershed is within the park, 23% is held by other state and federal agencies, and the remaining 66% is privately owned (Panfil and Jacobson 2001). In addition to the Little Buffalo River, large tributaries include Middle, Big, Clabber, Water, Tomahawk, Brush, Bear, Calf, Richland, Davis, Mill, Cave, Cove, and Wells Creeks. The Buffalo River's tributaries typically have great relief, steep slopes, and streamside bluffs (Panfil and Jacobson 2001).

Buffalo National River is managed in three broad geographic areas (see fig. 2): the upper ranger district from the Upper Buffalo Wilderness to Mt. Hersey; the middle ranger district from Mt. Hersey to Maumee; and the lower ranger district from Maumee to Buffalo City (National Park Service 2010b). These areas roughly correspond to the upper, middle, and lower drainage basins as defined by their characteristic geology and landscape. Relatively young sandstone and shale underlie the rugged topography of the Boston Mountains in the upper drainage basin. Elevation here averages about 610 m (2,000 ft) above sea level. Chert-bearing limestone is more easily eroded resulting in relatively lower relief in the middle drainage basin. The oldest park rocks, comprising dolomite and sandstone, underlie the lower drainage basin and characteristically form rolling hills. The confluence with the White River is within the lower drainage basin; here the elevation is about 150 m (500 ft) above sea level (Hofer et al. 1995; Panfil and Jacobson 2001).

Geologic Setting and History

Present-Day Geologic Setting

The Buffalo River drains part of the southern flank of the Ozark Dome—an uplift originally formed by Precambrian volcanic activity that was reactivated as a late Paleozoic uplift developed in the foreland of the Ouachita Mountains which stretch from northwestern Arkansas into eastern Oklahoma and southern Missouri (Hudson et al. 2011; Richard Hutto, Arkansas Geological Survey, geologist, written communication, 23 April 2021). The portion of the Ozark Dome in Arkansas has eroded to form a series of plateau surfaces which consist of, from south to north, the Boston Mountains Plateau, the Springfield Plateau, and the Salem Plateau (fig. 3; Panfil and Jacobson 2001; Hudson et al. 2011). The Boston Mountains are a steeply dissected area with high relief and rugged mesa-like sandstone uplands, whereas the Springfield and Salem Plateaus are dominated by expansive rolling uplands and carbonate rocks (Panfil and Jacobson 2001). All three regions are part of the Ozark Plateaus province.

The Ozark Plateaus are a broad, uplifted region of about 130,000 km^2 (50,000 mi^2) that extends from northern Arkansas to central and southern Missouri,

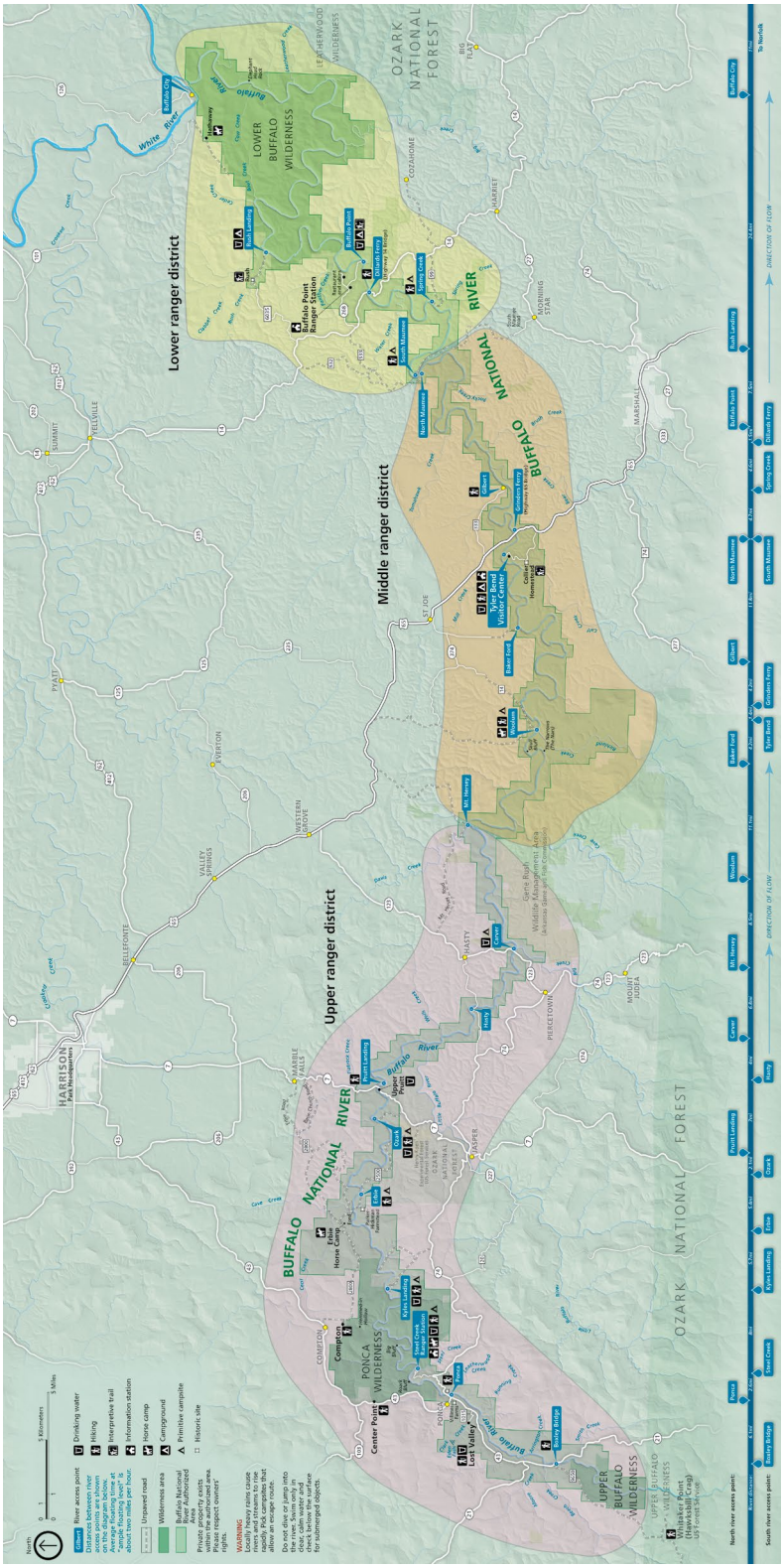

Figure 2. Map of Buffalo National River.
Park headquarters is in Harrison, Arkansas. The national river stretches from the Upper Buffalo Wilderness northeastward through the Ponca Wilderness before flowing south to Woolum. Then, it flows northeastward again through the Lower Buffalo Wilderness and its confluence with the White River. The three ranger districts are identified as the "Upper" (pastel pink), "Middle" (orange), and "Lower" (yellow) ranger districts. National Park Service maps are available at www.nps.gov/carto.

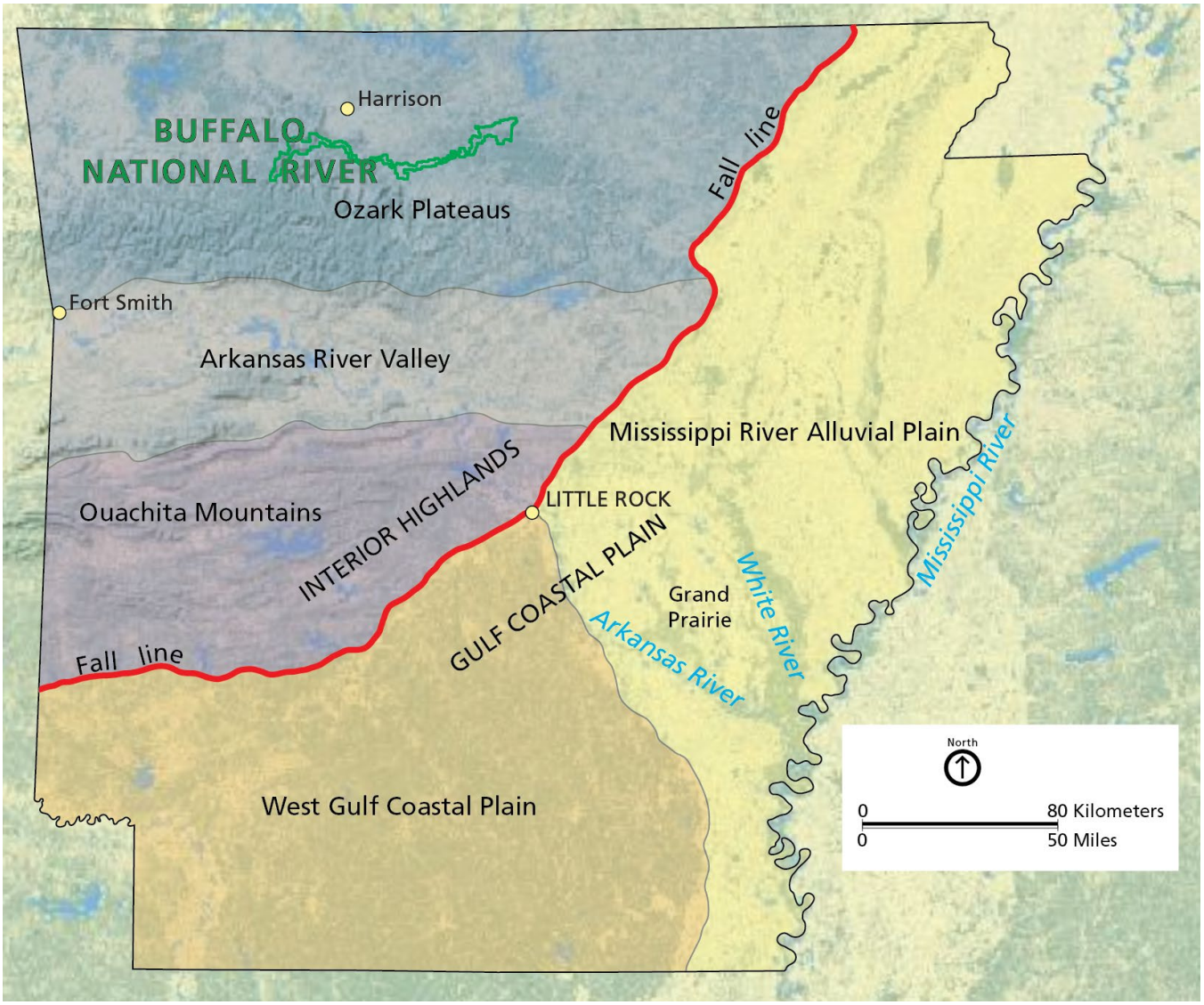

Figure 3. Map of physiographic provinces of Arkansas.
Buffalo National River (green-bordered area) is located within the Ozark Plateaus province, which contains river-dissected plateaus of undeformed rocks primarily Ordovician to Pennsylvanian in age. The Boston Mountains Plateau, Springfield Plateau, and Salem Plateau are the physiographic regions within the Ozark Plateaus province. Where the Springfield and Salem Plateaus are characterized by expansive rolling uplands and carbonate rocks, the Boston Mountains Plateau is an area with high relief and mesa-like sandstone uplands. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) using Bing Maps aerial imagery and information from the Arkansas Geological Survey (2012) and Panfil and Jacobson (2001).

southeastern Kansas, and northeastern Oklahoma. Thick sequences of Paleozoic limestone and dolomite underlie a significant portion of the province. The weathering of these rocks has resulted in steep-bluffed valleys, large springs, and cave networks.

Geologic History

The geologic story of Buffalo National River began more than 470 million years ago and reveals a long record of landform development and change starting when global sea level was high and shallow seas inundated much of southeastern North America. The geologic map units captured in the GRI GIS data fall into two broad categories representing vastly different periods in Earth's history (figs. 4, 5, and 6):

(1) Bedrock that is about 480 to 300 million years old (Ordovician through Pennsylvanian periods in table 2; "**O**", "**S**", "**M**", and "**PN**" map units). At least 490 m (1,600 ft) of relatively flat-lying sedimentary rocks, such as dolomite, limestone, sandstone, and chert, are

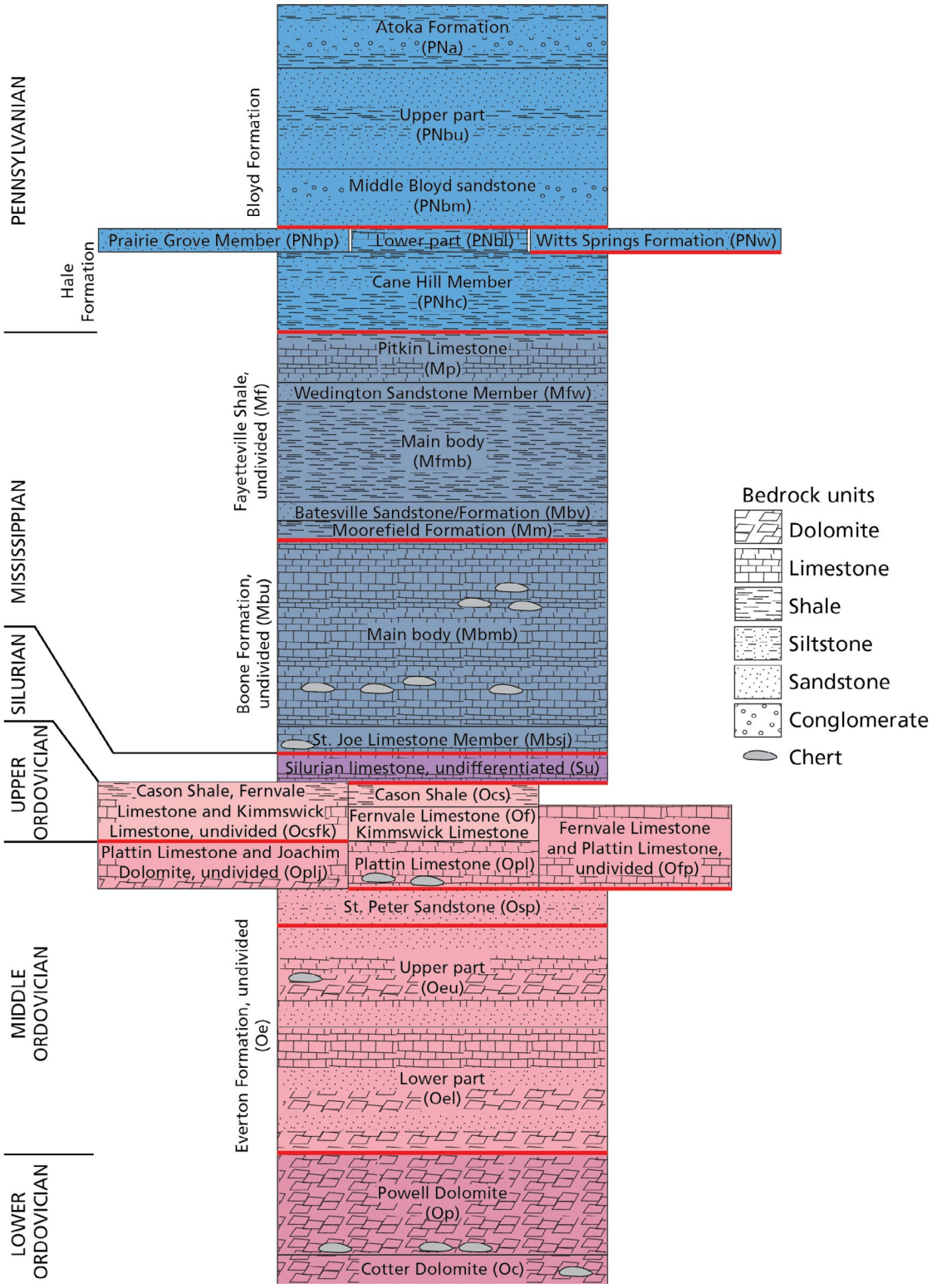

Figure 4. Schematic diagram of a stratigraphic column.
The bedrock at Buffalo National River contains a geologic record dating back to the Ordovician, more than 470 million years ago. The youngest bedrock exposed within the park boundaries is Pennsylvanian, which is more than 300 million years old. Periods of erosion or non-deposition between units are depicted as bold red lines. Thickness of units varies across the map area, generalized thicknesses are represented here. Unit colors conform to US Geological Survey standard geologic time colors. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) using GRI GIS source data.

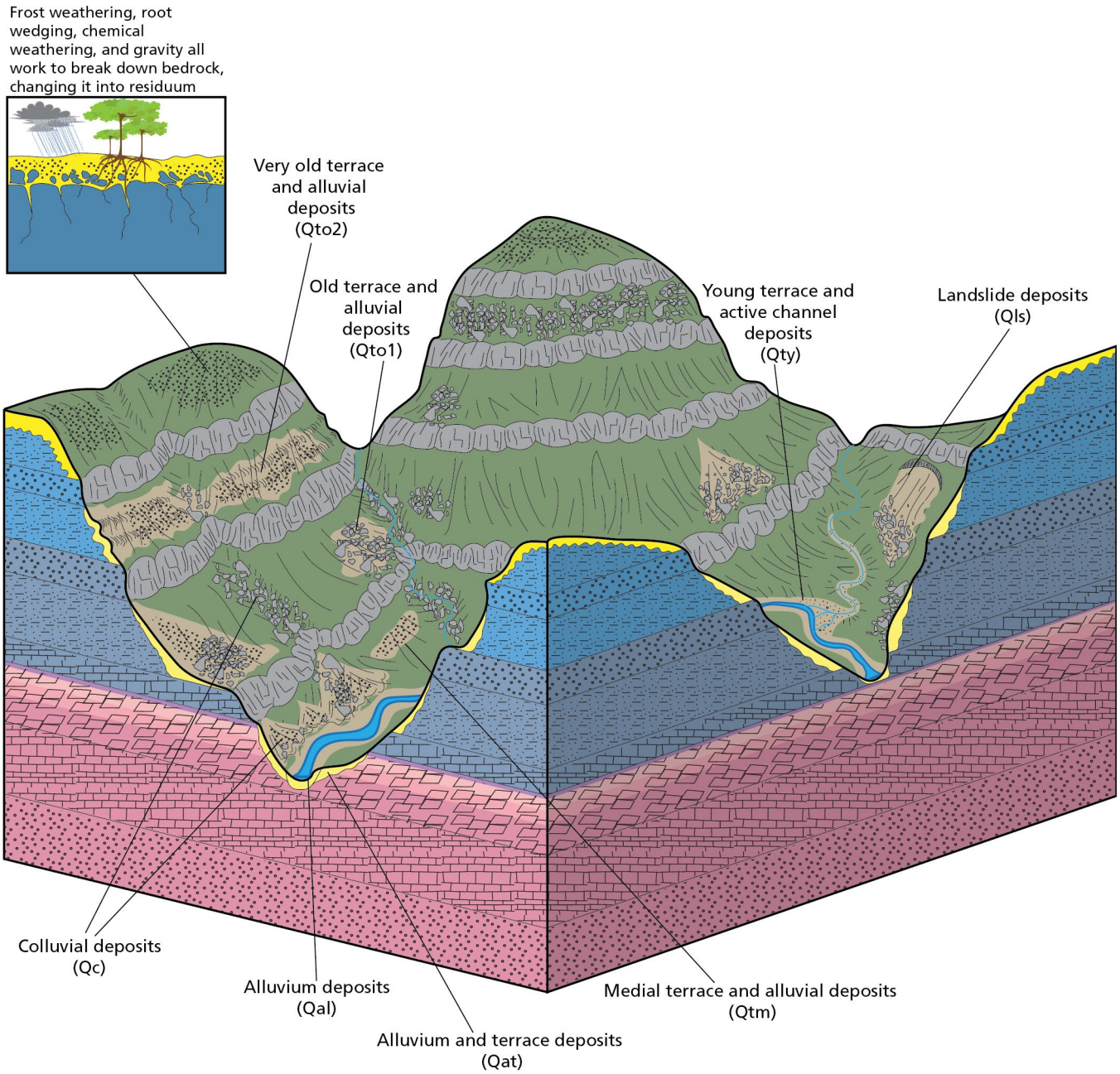

Figure 5. Diagram of the park's landscape with surficial units.
Buffalo River is cutting down through ancient bedrock to form a large valley. Throughout this process, the ancient river left terraces perched high above the modern floodplain. Slope deposits accumulate at the base of valley slopes. Unit colors conform to US Geological Survey standard geologic time colors. Diagram is not drawn to scale. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) using GRI GIS source data.

exposed in the park. Dolomite is both a mineral and a rock (also referred to as dolostone). Dissolution of the dolomite and limestone (carbonates) formed the caves, sinkholes, springs, and other karst features.

(2) Much younger unconsolidated surficial deposits and accumulations of material derived from deeply weathered older bedrock (Quaternary period in table 2; "**Q**" map units). These rocks and deposits mostly formed in the past few tens to hundreds of thousands of years. Some are actively forming along park streams, rivers and slopes.

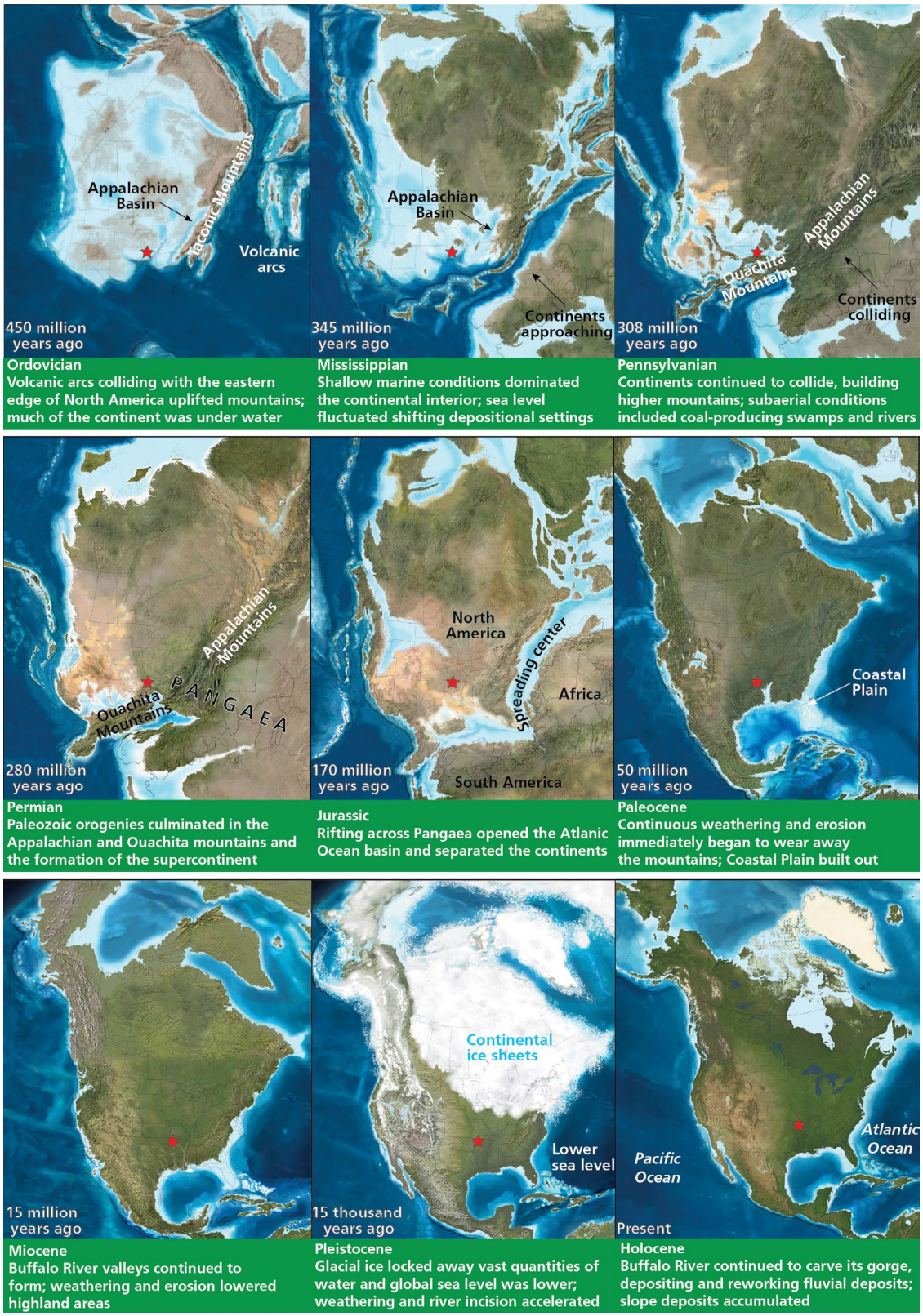

Figure 6. Paleogeographic maps of North America.
The red star indicates the approximate location of Buffalo National River. Graphic complied by Trista L. Thornberry-Ehrlich (Colorado State University). Base paleogeographic maps created by Ron Blakey and used under license (North American Key Time Slices © 2013 Colorado Plateau Geosystems Inc.), additional information is available at https://deeptimemaps.com/.

Table 2. Geologic time scale.

The geologic time scale puts the divisions of geologic time in stratigraphic order, with the oldest divisions at the bottom and the youngest at the top. GRI map abbreviations for each time division are in parentheses. Only geologic units mapped within the park are included here. The Quaternary Period and Tertiary time are part of the Cenozoic Era. The Triassic, Jurassic, and Cretaceous Periods are part of the Mesozoic Era. The periods from Cambrian through Permian are part of the Paleozoic Era. Boundary ages are millions of years ago (MYA) and follow the International Commission on Stratigraphy (Cohen et al. 2013).

Geologic Time	MYA	Geologic Map Units	Geologic Events
Quaternary Period (Q): Holocene Epoch (H)	0.0117–today	**Qal**, **Qat**, **Qty** deposited **Qc** and **Qls** formed	Fluvial meandering, incision, and deposition; slope processes
Quaternary Period (Q): Pleistocene Epoch (PE)	2.6–0.0117	**Qtm**, **Qto1**, and **Qto2** deposited	Ice age glaciations; glacial outburst floods; river courses modified; weathering and incision accelerated
Tertiary (T): Neogene Period (N)	23.0–2.6	Any units deposited during this time were eroded away	Fluctuating sea levels; meandering rivers
Tertiary (T): Paleogene Period (PG)	66.0–23.0	Any units deposited during this time were eroded away	Ongoing erosion and weathering
Cretaceous Period (K)	145.0–66.0	Any units deposited during this time were eroded away	**Global mass extinction** at end of Cretaceous (dinosaurs extinct)
Jurassic Period (J)	201.3–145.0	Any units deposited during this time were eroded away	Ongoing erosion and weathering
Triassic Period (TR)	251.9–201.3	Any units deposited during this time were eroded away	**Global mass extinction** at end of Triassic Breakup of Pangaea begins; Atlantic Ocean opened; sediments began building out the coastal plain
Permian Period (P)	298.9–251.9	Any units deposited during this time were eroded away	**Global mass extinction** at end of Permian. Supercontinent Pangaea intact. Appalachians may have rivaled height of modern Himalayas.
Pennsylvanian Period (PN)	323.2–298.9	**PNhc**, **Pnhp**, **Pnw**, **PNbl**, **PNbm**, **PNbu**, **PNa** deposited	Alleghany (Appalachian) Orogeny; some terrestrial depositional settings
Mississippian Period (M)	358.9–323.2	**Mbsj**, **Mbmb**, **Mbu**, **Mm**, **Mbv**, **Mf**, **Mfmb**, **Mfw**, **Mp** deposited	Open marine to fluctuating nearshore settings
Devonian Period (D)	419.2–358.9	None mapped	**Global mass extinction** at end of Devonian; Appalachian Basin collected sediment and subsided
Silurian Period (S)	443.8–419.2	**Su** deposited	Ongoing marine sedimentation Neoacadian Orogeny
Ordovician Period (O)	485.4–443.8	**Ocsfk**, **Of**, **Ocs**, **Oel**, **Oeu**, **Oe**, **Osp**, **Oplj**, **Ofp**, **Oc**, and **Op** deposited	**Global mass extinction** at end of Ordovician; deeper marine settings Sea level fluctuations; marine and nearshore settings Taconic Orogeny; open marine settings
Cambrian Period (C)	538.8–485.4	None mapped	Extensive oceans covered most of proto-North America (Laurentia)

Table 2, continued. Geologic time scale.

Geologic Time	MYA	Geologic Map Units	Geologic Events
Proterozoic Eon: Neoproterozoic Era (Z)	1,000–538.8	None mapped	Supercontinent Rodinia rifted apart
Proterozoic Eon: Mesoproterozoic Era (Y)	1,600–1,000	None mapped	Formation of early supercontinent; Grenville Orogeny
Proterozoic Eon: Paleoproterozoic Era (X)	2,500–1,600	None mapped	None reported
Archean Eon	~4,000–2,500	None mapped	Oldest known Earth rocks
Hadean Eon	4,600–4,000	None mapped	Earth formed about 4.6 billion years ago.

Paleozoic Era

More than 470 million years ago, during the Early Ordovician, thick, marine carbonate sediments accumulated on the seafloor to become the Cotter and Powell dolomite (geologic map units **Oc** and **Op**, respectively; fig. 7A and 7B)—the oldest rocks mapped within the park (GRI GIS source data; Lowell et al. 2010; Schaper 2015). Carbonate sediments commonly accumulate in depositional environments that range from tidal flats to deepwater basins and most carbonate sediments originate on a shallow-water platform, shelf, or ramp and are transported landward and basinward by waves and currents. By the Middle Ordovician, dropping sea level caused depositional environments to shift toward more nearshore or terrestrial settings. The Everton Formation (**Oe**, **Oeu**, and **Oel**) was deposited in barrier island and tidal flat (nearshore) environments with abundant sand (Hudson and Murray 2003). From the Middle to Late Ordovician varying nearshore to marine shelf depositional settings predominated, punctuated by periods of erosion and/or nondeposition. During this time the St. Peter Sandstone (**Osp**), Joachim Dolomite (**Oplj**), Plattin Limestone (**Opl**, **Oplj**, and **Ofp**), Kimswick Limestone (**Of** and **Ocsfk**), Fernvale Limestone (**Of**, **Ocsfk**, and **Ofp**), and Cason Shale (**Ocs** and **Ocsfk**) accumulated.

During the Silurian Period there was either not much deposition or a lot of erosion. This is evidenced by the very thin Silurian limestone (**Su**) unit on the geologic map. Similarly, non-deposition/erosion during the Devonian left little to no record of that period, so Mississippian units ("**M**" map units) directly overlie the Silurian limestone. By the end of the Devonian, sea level was starting to rise again, and deposition of deeper water sediments began.

In the early Mississippian, a longstanding carbonate depositional environment is recorded by the St. Joe Limestone Member of the Boone Formation (**Mbsj**) and the interbedded limestones and chert of the Boone Formation, main body (**Mbmb**; Hudson and Turner 2016). The Batesville Sandstone (**Mbv**) contains eroded fragments from the underlying Boone Formation indicating a period of erosion and reworking. Toward the south, the Batesville Sandstone thins and the proportion of limestone cement in the rock increases slightly. This suggests a decreasing sand supply and an open marine setting instead of nearshore (Hudson and Turner 2007). Eventually, the carbonate shelf transitioned into a southward deepening muddy shelf that accumulated the black muds of the Fayetteville Shale (**Mf**, **Mfmb**, **Mfw**). This shelf shoaled upward (became shallower) during the deposition of the Pitkin Limestone as sea level dropped (**Mp**; Hudson and Murray 2003).

At the beginning of the Pennsylvanian, sediments that would become the sandstone and siltstone of the Hale Formation (**PNhc** and **PNhp**) were deposited in tidal flat and shoreface environments as sea level began to rise again. Sea level continued to rise during the deposition of the lower part of the Bloyd Formation (**PNbl**) in an open-marine platform setting. Relative sea level then dropped and the Middle Bloyd sandstone (**PNbm**) was laid down by terrestrial braided streams (fig. 7C; Hudson and Murray 2003) draining toward the basin to the south. Marine settings with fluctuating sea levels returned to the area during deposition of what would become the alternating sandstone and shale of the Atoka Formation (**PNa**; Hudson and Turner 2007).

Bedrock younger than the Pennsylvanian Period is not present at Buffalo National River (fig. 8A; GRI GIS source data). Whatever rocks were deposited atop the Atoka Formation (**PNa**) have since been removed by erosion. During the late Paleozoic Era, mountains were forming across much of eastern, southern, and western North America. About 100 km (60 mi) south of Buffalo National River, the Ouachita Mountains uplifted, and

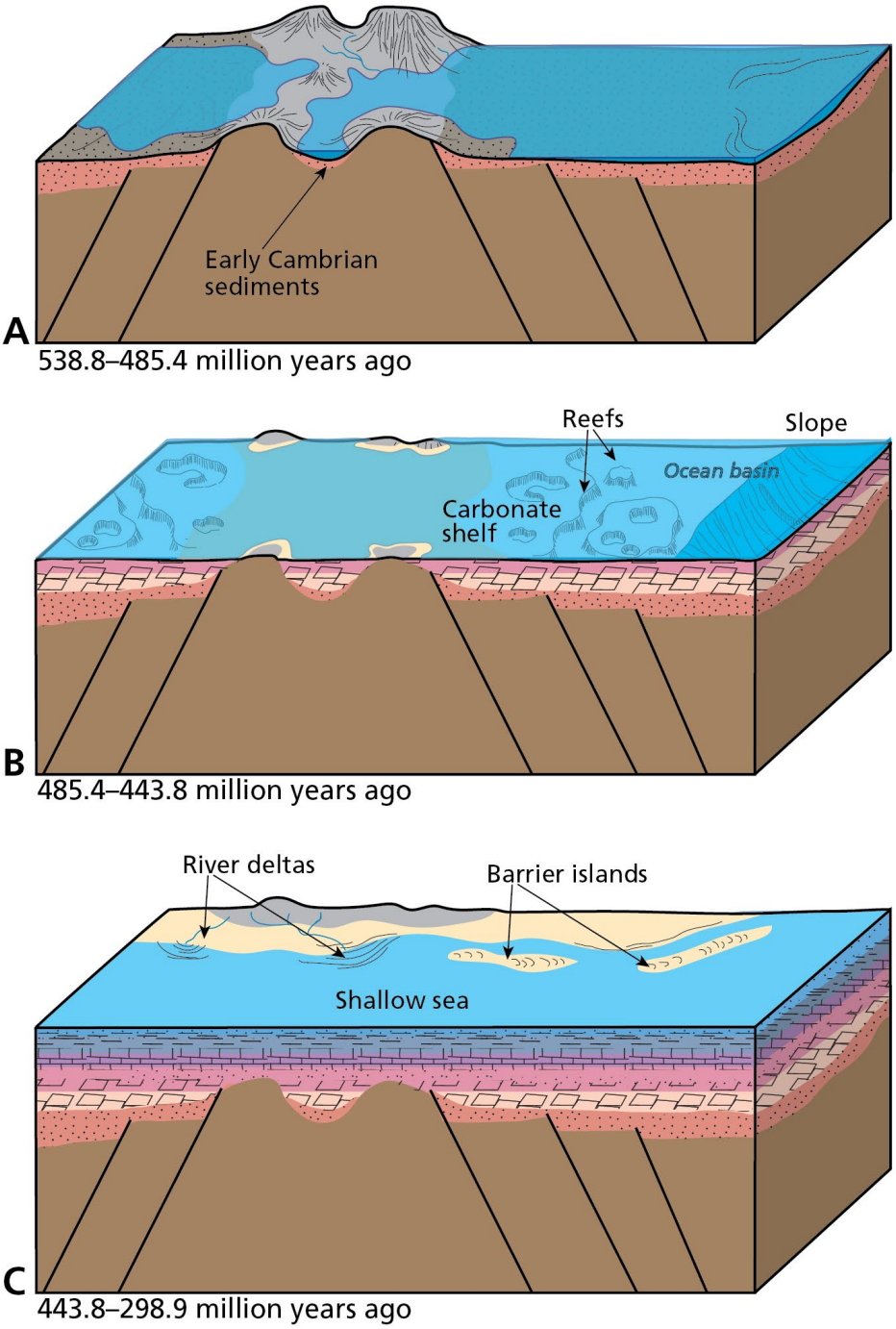

Figure 7. Illustration of the evolution of the landscape and geologic foundation of Buffalo National River. During the Cambrian Period, shallow seas inundated northern Arkansas as erosion continued to weather away older volcanic uplifts and coarse sediments were reworked. (B) During the Ordovician Period, fluctuating, shallow seas and limited terrestrial sediment caused thick carbonate deposits ("O" map units) to accumulate, punctuated periodically by erosional surfaces or deposition of sand as sea level lowered. (C) In the middle Paleozoic Era, shallow marine environments continued to dominate throughout the Silurian, Mississippian, and Pennsylvanian Periods. Marine deposition was punctuated by periods of low sea level and subsequent terrestrial deposition by streams and rivers. "S", "M", and "PN" units were deposited. Continued on figure 8. Graphics are not to scale. Colors conform to US Geological Survey standards and indicate different time periods on geologic maps. They correspond to the colors used on the geologic time scale (table 2). Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) with information from Lowell et al. (2010), Weary et al. (2014), and GRI GIS source data.

in their foreland the preexisting Ozark Dome uplifted further (Hudson 2000; Hudson et al. 2011; Richard Hutto, Arkansas Geological Survey, geologist, written communication, 23 April 2021). During this time, the Appalachian Mountains also completed their rise and the Ancestral Rocky Mountains formed. These tectonic forces likely folded and fractured rocks in the park and moved them along normal and strike-slip faults that correspond to the mapped faults in the GRI GIS data. During the late Paleozoic Ouachita Orogeny, briny, mineral-laden fluids flushed through the local bedrock, leaving heavy metal ore deposits along faults and fractures (Lowell et al. 2010).

Mesozoic Era

There are no rocks from the Mesozoic Era mapped within Buffalo National River, however, geologic events during this time 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 (see fig. 6). 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 Atlantic Ocean, which is still widening today. 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. As the gulf expanded, the Earth's crust between the southern Appalachians and Ouachita Mountains subsided, deepening an already low-lying area caused by Precambrian rifting and forming the Mississippi Embayment (Angela Chandler, Arkansas Geological Survey, geologist, written communication, 7 May 2021). The topographically low Mississippi Embayment was inundated by waters from the Gulf of Mexico when sea levels were high (Unkelsbay and Vineyard 1992; Levin 1999; Schaper 2015). Sediments eroded from the Ouachita Mountains collected within the embayment. Weathering, erosion, and fluvial incision were the dominant geologic processes operating in the park by the end of the Mesozoic Era and the Ozark Plateaus continued to be an area of erosion and weathering throughout the following Cenozoic Era (Unkelsbay and Vineyard 1992; Schaper 2015).

Cenozoic Era

Throughout the early Cenozoic Era (see table 2 and fig. 6), periodic incursions from the Gulf of Mexico inundated the lower Mississippi Embayment, depositing thick layers of marine sediment that would eventually fill the embayment during the Paleocene and Eocene Epochs (Saucier 1994). When sea level rises, the base level to which erosion can occur also rises, resulting in less incision by rivers. Therefore, incursions from the Gulf of Mexico reduced the rate of net incision by upstream rivers of the Mississippi River system, including the Buffalo River. By contrast, when sea level is lowered or the upstream land uplifted, the drop in base level increases river incision and causes river-channel entrenchment. Throughout these fluctuations, Buffalo River has incised or cut down through approximately 300 m (1,000 ft) of sandstone, shale, limestone, and dolomite (National Park Service 2018) leaving behind fluvial geologic deposits (e.g., **Qtm**, **Qto1**, and **Qto2**) "perched" above the modern floodplain. These stranded terrace deposits are a record of ancient river levels (GRI GIS source data).

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. Even though glacial ice never reached farther south than central Missouri (see fig. 6), the glaciations affected temperature and vegetation globally and were the single most significant geologic process to affect the modern geomorphology and geologic history of the lower Mississippi River system (Saucier 1994). Lower temperatures and less vegetation at Buffalo National River during the Pleistocene ice ages caused accelerated weathering and accumulation of slope deposits, such as landslides (**Qls**) and colluvium (**Qc**; GRI GIS source data).

Ice advance and retreat rearranged the preexisting drainages in the midcontinent. By the end of the Pleistocene, 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 during interglacial periods, funneling immense quantities of glacial meltwater and outwash sediments to the Gulf of Mexico (Saucier 1994).

During glaciations, 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 (Buffalo) Rivers formed during the most recent glaciation—the Wisconsinan (Fisk 1944; Waterways Experiment Station 1951).

The Earth is now experiencing an interglacial period; however, geologic processes are still changing the

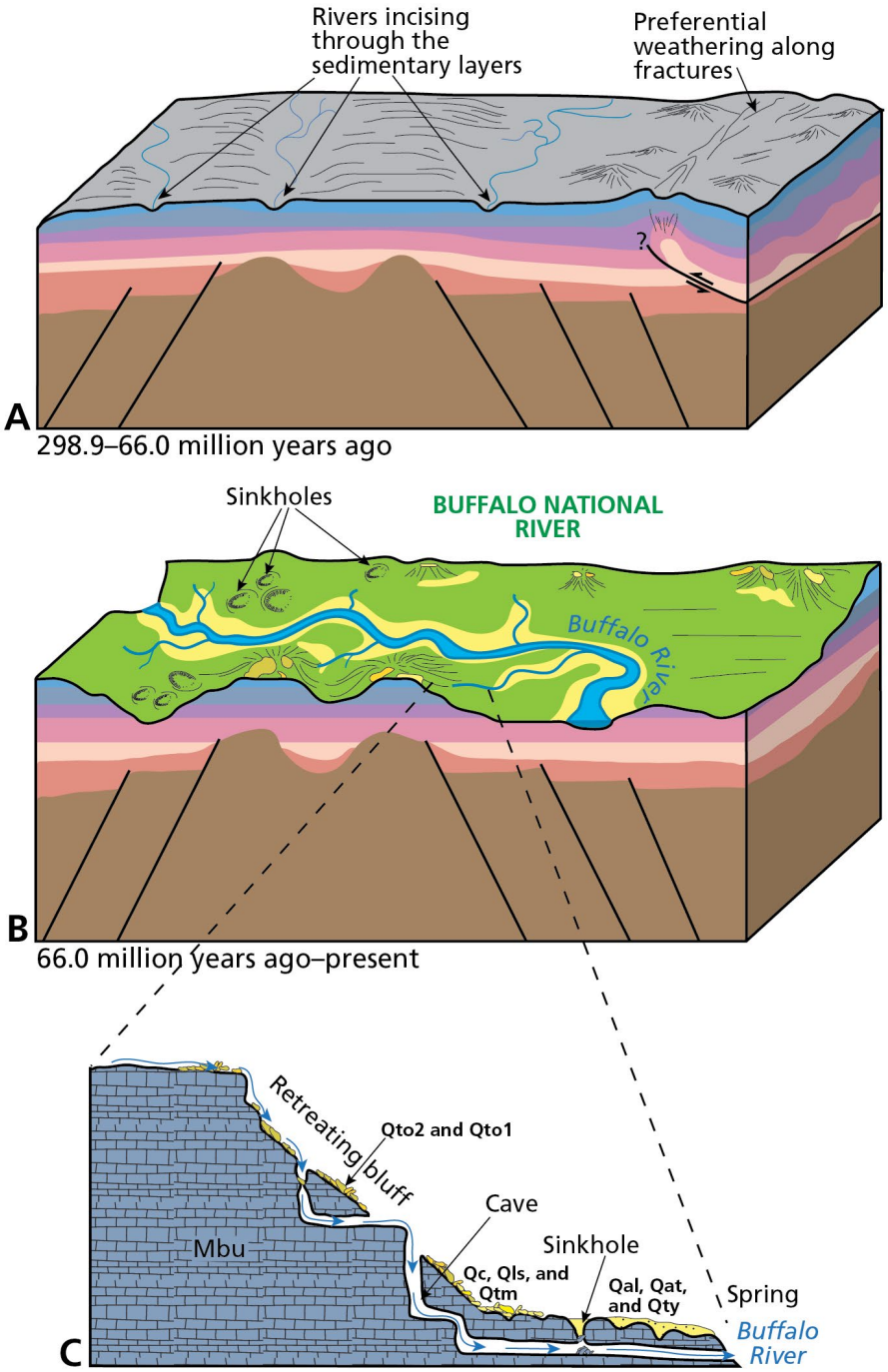

Figure 8. Illustration of the continuing development of the landscape and geologic foundation of Buffalo National River.

Continued from figure 7. (A) During the late Paleozoic and Mesozoic Eras, mountain building to the east and south caused some faulting and deformation. Pangaea rifted apart and erosion continued to mute the landscape and weather away the geologic units. B) In the Cenozoic Era up to the present day, rivers continue to meander and incise their channels, carving valleys down to the Ordovician dolomite. C) Groundwater dissolved vast conduits through the soluble bedrock, forming caves and springs. Surficial deposits accumulated and are reworked on the landscape. Graphics are not to scale. Colors are standard colors approved by the US Geological Survey to indicate different time periods on geologic maps. 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), Weary et al. (2014), and GRI GIS source data.

landscape at Buffalo National River (fig. 8B). The Buffalo and White Rivers and their tributaries continue to incise their channels and deposit mantles of alluvium and terrace deposits (**Qal**, **Qat**, **Qty**, and **Qtm**; GRI GIS source data). Slope deposits, such as landslide and colluvium (**Qls** and **Qc**, respectively), continue to accumulate at the base of slopes and cliffs (GRI GIS source data). Karst dissolution of the carbonate bedrock is ongoing, enlarging conduits and caves, causing riverside bluffs to retreat, and forming sinkholes (fig. 8C; see "Karst Features and Processes").

Geologic Heritage and Connections

Geologic Heritage encompasses the significant geologic features, landforms, and landscapes characteristic of our nation which are preserved for the full range of values that society places on them, including scientific, aesthetic, cultural, ecosystem, educational, recreational, tourism, and other values. The NPS also identifies geologic heritage aspects of museum collections, soils, and scientific data sets.

Geoheritage sites are conserved so that their lessons and beauty will remain as a legacy for future generations. Such areas generally have great potential for scientific studies, use as outdoor classrooms, and enhancing public understanding and enjoyment. Geoheritage sites are fundamental to understanding dynamic earth systems, the succession and diversity of life, climatic changes over time, evolution of landforms, and the origin of mineral deposits. Currently, there is no comprehensive national registry that includes all geoheritage sites in the United States.

The human story at Buffalo National River and its mosaic of cultural landscapes—significance statements presented in the foundation document (National Park Service 2018)—are tied to the park's geologic resources and landscape. Valuable references regarding the park's human history include Adams et al. (1904), McKnight (1935), Pitcaithely (1989), Catton (2008), and cultural landscape inventory reports such as Rusch (2013) and National Park Service (2010a). Stretching at least 12,000 years back, the story began with Indigenous hunters and gatherers who established temporary camps in caves and small villages on river terraces (National Park Service 1999; Panfil and Jacobson 2001). Alcoves that were used as shelters at Buffalo National River may contain archeological resources (Thornberry-Ehrlich 2007). Notable sites include Cob Cave and Indian Rockhouse (National Park Service 2018). More than 700 known sites within the park include cave shelters, bluff shelters, open sites (e.g., flint-knapping workshops), structures (e.g., baking ovens), and objects (National Park Service 1999; National Park Service 2018). Lithic scatters (places where rocks were knapped) are present across the entire park (Suika Rivett, Buffalo National River, archeologist, conference call, 17 April 2019). Habitation sites are concentrated along ridge tops and terraces (Catton 2008). Bluff shelters were possibly used for specialized foraging activities, storage, and sometimes for bird trapping (Catton 2008). Bluff shelters were also used for habitation. The river provided transportation of goods for trade (Catton 2008). Prior to European contact, the Osage, and possibly the Quapaw and others, hunted in the area of the Buffalo River. In the protohistoric to historic period (1650 to about 1940), Osage and Cherokee were just two of the groups who hunted and settled in the area until land treaties changed around 1830 and Anglo settlers forced them off the land (National Park Service 2010a).

In the 18th century, fur traders were likely the first Europeans to explore the Arkansas Ozarks—ultimately establishing Arkansas Post on the Arkansas River (Catton 2008; see Thornberry-Ehrlich 2013 GRI report for Arkansas Post National Memorial). When European settlers arrived in the 1820s, they cleared valley bottoms for pasture and cut timber from the valley slopes (National Park Service 1999; Catton 2008). Because the rich alluvial soils of the floodplain made for the best crop land these areas were quickly claimed. New-coming settlers had to stake claims on hillsides and rolling prairies between drainages where soil was thin and rocky and vulnerable to drought—intensified by the karst drainage in these upland areas (Catton 2008).

Major battles of the American Civil War took place at nearby Pea Ridge and Prairie Grove. Local skirmishes occurred at Cave Mountain, Boxley Mill, and Richland Valley. Park caves provided hideouts for guerilla warfare and produced saltpeter for the Confederate Army (National Park Service 1999; Catton 2008). Later, some shelters, caves, small creeks, and alcoves were used to produce and hide illicit corn whiskey (Catton 2008).

The river provided local transportation at places such as Grinders Ferry and Dillards Ferry (National Park Service 1999). The railroad expansions of the 1870s brought increased logging—for both commercial uses (logs floated down the river to mills) and the construction of the railroad—and a population surge which lasted until about 1920; the railroad reached Harrison in 1901 (Scott and Hofer 1995; Panfil and Jacobson 2001; Catton 2008; National Park Service 2010a). A bridge spanned the river by 1903 (Catton 2008). Major milling sites and tie slides (where railroad ties were slid down steep slopes to the river to raft floating timber) were concentrated near Gilbert's railhead (National Park Service 1999).

According to Catton (2008), by the late 1920s, the Ozark region became a hotbed for proposed hydroelectric development. In 1936, 73 dams were planned for the White and Arkansas River basins. Lone Rock Dam was proposed for the Buffalo River, but this plan was interrupted by the outbreak of World War II. The Buffalo River's tourism possibilities made it ideal for addition into the state park's program in 1938 as an "attractive place to visit, recreate, and preserve" (Catton 2008, p. 259). Civilian Conservation Corps (CCC) era infrastructure in the park dates to this time, using local materials such as those quarried at Buffalo Point. More dams (for flood control as well as hydroelectric power) were proposed in the early 1960s, including one near Gilbert, but by this time, fishing clubs and conservation organizations were strongly opposed and the Kennedy administration's commitment to preserving the nation's remaining free-flowing streams eventually gave rise to the first "national river".

Mining History

The presence of zinc and lead ores in the Buffalo National River area were reported as early as 1818. Confederate forces obtained lead from the region during the American Civil War, particularly in the upper Cave Creek drainage, which joins the Buffalo River near the Erbie access point (Catton 2008). Zinc mining reached a peak between 1914 and 1917, but deposits were irregular and never matched the magnitude of the Tri-State mining region of southern Missouri (McKnight 1935; Catton 2008). The Rush mining district, in the lower ranger district of Buffalo National River, produced zinc ore primarily from the 1890s to the mid-1930s and was entered on the National Register of Historic Places in 1987 (Burghhardt 1992). Ponca, in the upper ranger district of the park, was another area of extensive lead and zinc mining (National Park Service 1999). Most mining interest in the area was over by World War II. Lasting mining impressions at Buffalo National River include mine tunnels, shafts, open cuts, mill ruins, mill tailings and piles of waste rock, and deserted buildings (Catton 2008). The abandoned mines are bat habitat now; pipestrelle and little brown bats were noted in one park cave (Burghardt 1992). Mining is a component of the park's geologic heritage. A thorough examination of the park's mining history is beyond the scope of this report, but such information could contribute to understanding and interpretation of the park's history.

Geologic Ecosystem Connections

In addition to the historical connections briefly presented here, geologic features and processes are fundamentally connected with vegetation patterns, many animal habitats, soils, and water resources. According to the park's foundation document, part of its significance is due to the topographical diversity and geographic setting combined with the convergence of northern, southern, and western ecosystems to form the ecological background of the park (National Park Service 2018).

Geology gives rise to soil formation. Soil resources are beyond the scope of this report and the subject of another natural resource inventory in the National Park Service. Soil resources inventory products for Buffalo National River were updated in 2013 and are available at https://irma.nps.gov/DataStore/Reference/Profile/1048825.

The park fosters distinctive biodiversity within its boundaries. Rare glades and relic species (e.g., beech forests and goat prairie communities) are highlights of this system (National Park Service 2018). Insignificant looking seeps can harbor very dynamic habitats and cultural features (GRI conference call participants, conference call, 17 April 2019). The Buffalo River ecosystem is a fundamental resource of the park. Aquatic and riparian habitats (e.g., native river cane communities and habitat for rare freshwater mussels), shaped by free-flowing water, are listed among the park's fundamental resources and values (National Park Service 2018). The NPS Heartland Network has inventoried and is currently monitoring natural resources in Buffalo National River; reports and natural resource updates are available at https://www.nps.gov/im/htln/buff.htm.

Because of the park's narrow corridor, land-use practices within the watershed and upstream of the park can strongly impact the ecosystem within the park. Agriculture adjacent to park boundaries tends to result in cleared lands, impounded drainages (farm ponds), and animal waste (Panfil and Jacobson 2001). Housing and other suburban developments typically involve an increase in impervious surfaces such as buildings, parking lots, streets, and sidewalks. Impervious surfaces cause runoff to flow quickly into the groundwater system rather than to slowly infiltrate through soil. Impervious surfaces cause stormwater runoff, local erosion, sedimentation, stream channelization, and degradation of stream habitat and biodiversity (Panfil and Jacobson 2001; Greco 2001). The carbonate bedrock underlying much of the park and surrounding area exacerbates these effects by way of dissolved underground conduits which rapidly funnel any runoff directly to the Buffalo River system (see "Abandoned Mineral Lands" and "Disturbed Lands"; Panfil and Jacobson 2001; Ryan and Meiman 1996). The Buffalo National River Science Symposium proceedings (inaugural meeting held in Harrison on April 23, 2019,

and another planned for 2022) intended to provide a forum for scientists, landowners, land managers, and other stakeholders to share data and information about many of the water-related issues on the Buffalo National River. Reports presented are available from the Buffalo River Watershed Alliance at https://buffaloriveralliance.org/Science (accessed 23 August 2021). Additional information regarding the park's water resources is available from the NPS Water Resources Division (http://go.nps.gov/waterresources)

Predicted climate change trends will impact the ecosystem at Buffalo National River. In comparing recent climate values within the context of historical conditions, temperatures are increasing and overall precipitation is decreasing at Buffalo National River (Monahan and Fisichelli 2014). Recent climatic conditions are already shifting beyond the measured, historical range of variability and extreme climate events are increasing in severity and frequency. The park is already noting an increase in the frequency and severity of flood events as well as intermittent drought conditions (National Park Service 2018). According to Monahan and Fisichelli (2014), ongoing and future changes in climate will affect all aspects of park management including natural resource protection, park operations, and visitor experience. Understanding the causes and effects of these changes is crucial to protecting the natural and cultural resources at the park. Schuurman et al. (2020) provides guidance for natural resource managers using the resist-accept-direct framework. The NPS Climate Change Response Program (https://www.nps.gov/orgs/ccrp/index.htm) can provide more assistance.

Geologic Features and Processes

Geologic resources, including the karst-dominated watershed, free-flowing river, and lead and zinc ore mineralization, are fundamental resources and intrinsic values of Buffalo National River. The geologic features and processes highlighted in this chapter are significant to the park's landscape and history. Selection of these features and processes was based on input from scoping and conference-call participants, analysis of the GRI GIS data, and research of the scientific literature and NPS reports. Each is discussed in this chapter and on table 3 in the context of relevant geologic map units.

Table 3. Geologic map units and associated features and processes in Buffalo National River.

Detailed descriptions of each unit per source-map quadrangle, including composition, thickness, and correlation with other units are in the buff_geology.pdf in the GRI GIS data (see "GRI Products"). Bold subheadings correspond to sections of this chapter (e.g., "Fluvial Features and Processes"). See figure 1 for a map of quadrangle locations.

Geologic Unit (map symbol)	Features and Processes	Location
Alluvium and terrace deposits (**Qat**)	**Fluvial Features and Processes** **Qat** is unconsolidated clay, silt, sand, and gravel being deposited, eroded, and reworked by modern rivers and streams. One or more low-lying terraces are commonly part of **Qat**. **Faults and folds** Three joint measurement stations are located in **Qat** as part of the GRI GIS data.	**Qat** lines the Buffalo River channel and is mapped along larger tributaries, such as Bear and Brush creeks. **Qat** is mapped in Big Flat, Buffalo City, Cozahome, Rea Valley, Eula, Harriet, Mt. Judea, Parthenon, Marshall, and Snowball quadrangles.
Alluvium deposits (**Qal**)	**Fluvial Features and Processes** **Qal** is unconsolidated clay, silt, sand, and gravel being deposited, eroded, and reworked by modern rivers and streams. Local alluvium includes grainsizes from silt and clay to boulders. Organic content commonly relatively high.	**Qal** is within the active river channel and sandy/gravel point bar deposits. It is also mapped along larger tributaries, including Sweden, Tomahawk, Dry, Water, Henson, Crooked, and Mill creeks. **Qal** is mapped in Boxley, Cozahome, Maumee, Murray, Rea Valley, St. Joe, and Western Grove quadrangles.
Young terrace and active channel deposits (**Qty**)	**Fluvial Features and Processes** **Qty** is unconsolidated clay, silt, sand, and gravel being deposited, eroded, and reworked by modern rivers and streams. Terrace deposits provide a record of valley incision.	**Qty** commonly comprises the lowest terrace above the river and the gravel bars and sandy point bar deposits along Buffalo River and its larger tributaries. **Qty** is mapped in Big Flat, Boxley, Buffalo City, Cozahome, Eula, Hasty, Jasper, Marshall, Maumee, Murray, Mt. Judea, Snowball, Osage SW, Ponca, Rea Valley, and Western Grove quadrangles.
Colluvial deposits (**Qc**)	**Qc** may include unconsolidated, subrounded to angular blocks as large as 6 m (20 ft) in diameter. **Qc** is commonly deposited in fan-shaped lobes that may cover or obscure underlying geology.	**Qc** is commonly deposited in fan-shaped lobes extending downslope from valley walls toward river channels. **Qc** is mapped in Boxley, Jasper, Murray, Osage SW, Ponca, and St. Joe quadrangles.

Table 3, continued. Geologic map units and associated features and processes in Buffalo National River.

Geologic Unit (map symbol)	Features and Processes	Location
Landslide deposits (**Qls**)	**Qls** includes blocks of many different types of bedrock, including limestone, sandstone, and shale. **Qls** locally starts as semi-coherent blocks of bedrock (Toreva blocks) slide downslope, but typically break up mid-slide to become a jumbled mass of rocks. .	**Qls** is mapped in Boxley, Cozahome, Eula, Snowball, Hasty, Maumee, Mt. Judea, Parthenon, and Murray quadrangles.
Medial terrace and alluvial deposits (**Qtm**)	**Fluvial Features and Processes** **Qtm** was deposited, eroded, and reworked by a precursor to the modern Buffalo River and its tributaries. Unconsolidated clay, silt, sand, gravel, and cobbles compose **Qtm** and line the valleys some 12 m (40 ft) above the active channel, typically at the edge of the riparian zone along the river. A rusty brown "patina" is indicative of its older age relative to modern terraces developing along the corridor.	**Qtm** is mapped in Big Flat, Buffalo City, Cozahome, Eula, Hasty, Marshall, Maumee, Mt. Judea, Ponca, Rea Valley, Snowball, and Western Grove quadrangles.
Old terrace and alluvial deposits (**Qto1**)	**Fluvial Features and Processes** **Qto1** was deposited, eroded, and reworked by a precursor to the modern Buffalo River and its tributaries. Unconsolidated sand and gravel compose **Qto1**. Weathered, rusty brown surfaces are indicative of its older age relative to modern terraces developing along the corridor. A paleomagnetism sample locality is part of the GRI GIS data for **Qto1** in park boundaries.	**Qto1** lines valleys some 24 to 30 m (80 to 100 ft) above the active channel, on ridges above the river. **Qto1** is mapped in Boxley, Eula, Jasper, Marshall, Maumee, Mt. Judea, Murray, Ponca, Rea Valley, and Snowball quadrangles.
Very old terrace and alluvial deposits (**Qto2**)	**Fluvial Features and Processes** **Qto2** was deposited, eroded, and reworked by an ancient, topographically higher precursor to the modern Buffalo River and its tributaries. Poorly exposed, unconsolidated sand and gravel (largely rounded chert and sandstone clasts) compose **Qto2**. Weathered, rusty brown surfaces are indicative of its older age relative to modern terraces developing along the corridor.	**Qto2** lines valleys some 60 m (200 ft) above the active channel, on ridges above the river. **Qto2** is mapped in Big Flat, Buffalo City, Hasty, Marshall, Maumee, Mt. Judea, Osage SW, and Snowball quadrangles.
Atoka Formation (**PNa**)	Exposures of **PNa** include shale, siltstone, and sandstone. **Ancient Sedimentary Features** **PNa** likely deposited in alternating shallow to deep open basin conditions. Cross stratification and ripple laminations are common. **Bedrock Exposures** Sandstone intervals within **PNa** stand out as prominent topographic ledges. **Paleontological Resources** **PNa** contains horizontal and vertical invertebrate burrow and was bioturbated.	**PNa** caps the highest hills. **PNa** is mapped in Boxley, Murray, Osage SW, Parthenon, and Ponca quadrangles.
Bloyd Formation, Upper part (**PNbu**)	**PNbu** is predominantly sandstone with some shale and limestone l. **Caves and Karst** Resistant units such as **PNbu** may function as caprock over conduit-forming limestone. **Ancient Sedimentary Features** **PNbu** includes prominent crossbedding and trough features formed by deposition in flowing water. Other sedimentary features include loading, soft-sediment deformation, and ball and pillow structures. **Bedrock Exposures** **PNbu** forms prominent cliffs and ledges in the higher reaches of Buffalo National River. **Paleontological Resources** Upper portion is often heavily bioturbated with horizontal and radiating invertebrate burrows. Sandstone beds contain fragmentary remains of fossil lycopods (*Lepidodendron*) and other plants. Plant fossils exposed in ceilings within alcoves. A few crinoids are reported within some limestone lenses.	PNbu forms prominent cliffs and ledges. **PNbu** is mapped in Boxley, Eula, Hasty, Jasper, Mt. Judea, Murray, Osage SW, Parthenon, Ponca, and St. Joe quadrangles.

Table 3, continued. Geologic map units and associated features and processes in Buffalo National River.

Geologic Unit (map symbol)	Features and Processes	Location
Bloyd Formation, Middle Bloyd sandstone (**PNbm**)	**PNbm** is mostly reddish to brown sandstone. **Caves and Karst** Resistant units such as **PNbm** may function as caprock over cave-forming limestone. **Ancient Sedimentary Features** Depositional features include crossbeds and pebble clast conglomerates indicating high-energy environments. **Bedrock Exposures** **PNbm** forms a prominent bluff separating **PNbu** and **PNbl**. **Paleontological Resources** **PNbm** contains terrestrial plant fossils including lycopods.	PNbm forms a prominent bluff along river valleys. **PNbm** is mapped in Eula, Mt Judea, Parthenon, and Snowball quadrangles.
Bloyd Formation, Lower part (**PNbl**)	**PNbl** is predominantly black shale and siltstone interbedded with thin-bedded units of sandstone and limestone. **Caves and Karst** 10% of known cave openings in the park are present in **PNbl**. Springs commonly emerge from the base of this unit. **Ancient Sedimentary Features** **PNbl** was likely deposited in alternating shallow to deep open basin conditions. Individual layers have ripple laminations formed by moving water. **Bedrock Exposures** In general, **PNbl** is poorly exposed. **Paleontological Resources** **PNbl** is bioturbated. Carbonate units are fossiliferous, but deeply weathered.	PNbl is poorly exposed on moderate to steep slopes. **PNbl** is mapped in Boxley, Eula, Hasty, Jasper, Mt. Judea, Murray, Osage SW, Parthenon, Ponca, and St. Joe quadrangles.
Witts Springs Formation (**PNw**)	**PNw** is mostly sandstone and interlayered clay shale. **Caves and Karst** Carbonate cementation in the sandstone is prone to dissolution, making weathered portions of this unit friable. **Ancient Sedimentary Features** Units commonly display ripple laminations formed by moving water. **Bedrock Exposures** **PNw** commonly forms prominent bluffs. **Paleontological Resources** **PNw** contains plant fragments and fossiliferous sandstone.	**PNw** commonly forms prominent bluffs. **PNw** is mapped in Eula, Marshall, Osage SW, and Snowball quadrangles.
Hale Formation, Prairie Grove Member (**PNhp**)	**PNhp** consists of calcite-cemented sandstone with interbedded limestone. **Caves and Karst** Limestone units and carbonate cementation are prone to dissolution and karst formation. **Ancient Sedimentary Features** **PNhp** has crossbeds, some of which have bi-directional dips indicating tidal influence multiple flow directions. **Bedrock Exposures** **PNhp** forms steep hillslopes and ledges. Honeycomb weathering (pitted surfaces) common. **Paleontological Resources** **PNhp** contains some pure limestone lenses or pockets that have produced an abundance of crinoids, corals, bryozoans, brachiopods, mollusks, crinoids, and possible algae (Konett et al., 2018).	**PNhp** forms steep hillslopes and ledges. **PNhp** is mapped in Boxley, Eula, Hasty, Jasper, Mt. Judea, Murray, Osage SW, Parthenon, Ponca, and St. Joe quadrangles.

Table 3, continued. Geologic map units and associated features and processes in Buffalo National River.

Geologic Unit (map symbol)	Features and Processes	Location
Hale Formation, Cane Hill Member (**PNhc**)	**PNhc** is interbedded shale, siltstone, and sandstone. **Ancient Sedimentary Features** **PNhc** has soft-sediment deformation features such as slumps and folds. **PNhc** also has trough crossbeds and ripple laminations recording deposition via flowing water. **Bedrock Exposures** **PNhc** is stained orange brown and has some iron nodules and limonitic boxwork. **Paleontological Resources** **PNhc** contains invertebrate trace fossils, wood fragments, and crinoid-bearing limestone clasts in conglomeratic zones.	**PNhc** forms moderately steep slopes. **PNhc** is mapped in Boxley, Eula, Harriet, Hasty, Jasper, Marshall, Mt. Judea, Murray, Osage SW, Parthenon, Ponca, St. Joe and Snowball quadrangles.
Pitkin Limestone (**Mp**)	**Mp** consists of gray limestone and black shale units. **Caves and Karst** **Mp** is prone to karst dissolution. **Ancient Sedimentary Features** Fossils and ooids (rounded limestone grains) indicate **Mp** accumulated in a nearshore marine environment. **Bedrock Exposures** Petroliferous odor is common for fresh surfaces of **Mp**. **Paleontological Resources** **Mp** is fossiliferous with corals, bryozoans (*Archimedes*), nautiloids, gastropods, and crinoids common.	Mp forms steep slopes. **Mp** is mapped in the Boxley, Eula, Harriet, Hasty, Jasper, Marshall, Mt. Judea, Murray, Osage SW, Parthenon, Ponca, St. Joe, and Snowball quadrangles.
Fayetteville Shale, Undivided (**Mf**)	**Mf** is black shale with significant sandstone and limestone units. **Caves and Karst** Limestone units and carbonate cementation are prone to dissolution and karst formation. **Ancient Sedimentary Features** The fine-grained nature of **Mf**, as well as its thin laminations indicate quiet water depositional settings in a deep basin. **Bedrock Exposures** **Mf** is poorly exposed on low slopes but does crop out instreams and gullies. **Mf** may contain septarian concretions nearly 0.6 m (2 ft) in diameter.	**Mf** forms gentle slopes and is poorly exposed at the surface due to vegetation and overlying sediment and soil. **Mf** is mapped in Boxley, Eula, Harriet, Marshall, Mt. Judea, Murray, Osage SW, Parthenon, and Snowball quadrangles.
Fayetteville Shale, Wedington Sandstone Member (**Mfw**)	**Mfw** is predominantly calcite-cemented sandstone and siltstone with local limestone interbeds. **Caves and Karst** Carbonate cementation is prone to dissolution making weathered portions of this unit friable. **Ancient Sedimentary Features** Sedimentary features include low-angle crossbeds and ripples indicating deposition in gently flowing water. **Bedrock Exposures** **Mfw** commonly forms a topographic bench within the otherwise gently sloping **Mf**. **Paleontological Resources** **Mfw** is bioturbated.	**Mfw** is present as a resistant bench within **Mf**. **Mfw** is mapped in Hasty, Jasper, Maumee, Ponca, and St. Joe quadrangles.

Table 3, continued. Geologic map units and associated features and processes in Buffalo National River.

Geologic Unit (map symbol)	Features and Processes	Location
Fayetteville Shale, Main body (**Mfmb**)	**Mfmb** is mostly black shale with thin-bedded, interbedded siltstone. **Ancient Sedimentary Features** The fine-grained nature of **Mfmb**, as well as its thin laminations indicate quiet water depositional settings in a deep basin. **Bedrock Exposures** **Mfmb** is poorly exposed on low slopes but crop out along streams and gullies. **Mfmb** may contain septarian concretions nearly 0.6 m (2 ft) in diameter.	**Mfmb** is poorly exposed on low slopes. **Mfmb** is mapped in Hasty, Jasper, Maumee, Ponca, and St. Joe quadrangles.
Batesville Sandstone/ Formation (**Mbv**)	**Mbv** is predominantly calcite- or iron-cemented sandstone with interbedded limestone and shale units. At its base is the Hindsville Limestone member. **Caves and Karst** Limestone units are prone to karst dissolution. **Mbv** may host sinkholes formed by collapse into cavities in underlying **Mbu**. **Ancient Sedimentary Features** Sedimentary features include low-angle crossbeds and ripples indicating deposition in gently flowing water. **Bedrock Exposures** **Mbv** commonly contains disseminated pyrite framboids that oxidize to reddish spots. Topographic surfaces of **Mbv** are typically flat (plateau-like), except for sinkholes and local ledges. **Paleontological Resources** Limestone units in **Mbv** preserve remains of rugose corals, bryozoans, brachiopods, and crinoids.	**Mbv** is mapped in Big Flat, Boxley, Eula, Harriet, Hasty, Jasper, Marshall, Maumee, Mt. Judea, Murray, Osage SW, Parthenon, Ponca, St. Joe, Snowball, and Western Grove quadrangles.
Moorefield Formation (**Mm**)	**Mm** is clay to silty shale. **Bedrock Exposures** **Mm** forms a gentle slope below **Mbv**. **Paleontological Resources** **Mm** contains trace fossils	**Mm** is mapped in Big Flat, Harriet, and Marshall quadrangles.
Boone Formation, Undivided (**Mbu**)	**Mbu** is characterized by limestone interbedded with chert and locally, a basal sandstone and limestone (in some areas broken out as the St. Joe Limestone **Mbsj**). **Mbu** corresponds to the Springfield karst aquifer. **Fluvial features and processes** Conduits in **Mbu** locally capture low flows of the Buffalo River. **Caves and Karst** Karst conduits at Boxley Valley and Woolum funnel the seasonal low flow of the Buffalo River, creating a sinking stream. **Mbu** has a perched aquifer above the river baseline. 75% of known cave openings are in **Mbu**. Springs commonly emerge from the base of this unit (see **Mbsj**). Sinkholes are also present in **Mbu**—best developed where **Mbu** is overlain by **Mbv**. **Ancient Sedimentary Features** Bedding in **Mbu** undulates due to settling during sedimentation into older karst features such as sinkholes. **Bedrock Exposures** Boone County is the type locality for **Mbu**. Ridges of **Mbu** form the surface of the karstic Springfield Plateau. Deep weathering has produced a regolith composed of red-brown residual clay and angular chert gravel which covers nearly the entire surface. **Paleontological Resources** **Mbu** contains crinoid columnals and brachiopod fossils. Some conodonts are present in the basal unit.	The Boone Formation is the most widespread unit within the Buffalo River drainage. The topography of **Mbu** features steep, relatively flat-topped ridges incised by ravine-like drainages. **Mbu** is mapped in Big Flat, Eula, Harriet, Marshall, Mt. Judea, Parthenon, and Snowball quadrangles.

Table 3, continued. Geologic map units and associated features and processes in Buffalo National River.

Geologic Unit (map symbol)	Features and Processes	Location
Boone Formation, Main body (**Mbmb**)	**Mbmb** is interbedded limestone and chert. **Caves and Karst** Springs, caves, and sinkholes are common in **Mbmb**. **Ancient Sedimentary Features** **Mbmb** does have some undulatory bedding and channel fills indicating deposition in flowing water from shallow to deep marine. **Bedrock Exposures** Deep weathering has produced a regolith composed of red-brown residual clay and angular chert gravel which covers nearly the entire surface. **Faults and folds** Quartz mineralization in **Mbmb** is common near faults running through the unit. **Paleontological Resources** Corals, bryozoans, brachiopods, mollusks, ostracods, and crinoids (calyxes and ossicles) are documented in the upper portions of **Mbmb**, Some conodonts are present in the basal layers.	**Mbmb** is mapped in Boxley, Buffalo City, Cozahome, Hasty, Jasper, Maumee, Murray, Osage SW, Ponca, Rea Valley, St. Joe, and Western Grove quadrangles.
Boone Formation, St. Joe Limestone Member (**Mbsj**)	**Mbsj** is typically thin-bedded limestone and interbedded shale with a basal sandstone present locally. **Caves and Karst** Karst features are common in this unit. Fitton and Yardelle Springs emerge from **Mbsj**. **Ancient Sedimentary Features** Scant wavy beds indicate some moving water during deposition, but the unit is characteristically thin bedded and flat lying. **Bedrock Exposures** The type locality for **Mbsj** is on the St. Joe quadrangle, on Mill Creek. **Paleontological Resources** Bryozoans, brachiopods, crinoids, and conodonts are common in **Mbsj**.	**Mbsj** is mapped in Boxley, Buffalo City, Cozahome, Hasty, Jasper, Maumee, Murray, Osage SW, Ponca, Rea Valley, St. Joe, and Western Grove quadrangles.
Silurian limestone, undifferentiated (**Su**)	**Su** is entirely limestone. **Caves and Karst** **Su** is likely too thin for vast cave development but is prone to karst dissolution. **Ancient Sedimentary Features** Abundant fossils and massive bedding indicate deposition in a calm, shallow marine setting. **Bedrock Exposures** **Su** forms broad domes and troughs with underlying units. Weathered outcrops are rounded along streams, but blocky on hillsides. Vugs (cavities) may be filled with crystalline calcite. **Paleontological Resources** **Su** is fossiliferous with remains of corals, bryozoans, brachiopods, cephalopods, ostracods, trilobites, and crinoids.	**Su** is mapped in Cozahome, Harriet, Marshall, Maumee, and Snowball quadrangles.

Table 3, continued. Geologic map units and associated features and processes in Buffalo National River.

Geologic Unit (map symbol)	Features and Processes	Location
Cason Shale (**Ocs**)	**Ocs** is shale and siltstone with local dolostone or limestone. **Ancient Sedimentary Features** **Ocs** has cone-in-cone structures formed after burial during diagenesis into solid rock. **Bedrock Exposures** **Ocs** contains phosphate nodules and pebbles as well as oxidized pyrite framboids. **Paleontological Resources** **Ocs** preserves rugose corals, tabulate corals, and crinoids.	**Ocs** is mapped in Cozahome, Maumee, and St. Joe quadrangles.
Cason Shale, Fernvale Limestone and Kimmswick Limestone, undivided (**Ocsfk**)	See descriptions for **Ocs**, **Ofp**, and **Of**. **Caves and Karst** **Ocsfk** is likely too thin for vast cave development but is prone to karst dissolution. **Bedrock Exposures** **Qcsfk** is not well exposed but is commonly present as moss-covered masses. **Paleontological Resources** Fossils present in the limestone, include barrel-shaped crinoid columnals, nautiloids, and brachiopods.	**Ocsfk** is mapped only in Marshall quadrangle.
Fernvale Limestone (**Of**)	**Of** is coarse-grained limestone. See descriptions for **Ocsfk** and **Ofp**. **Caves and Karst** Karst dissolution is common in this unit. **Ancient Sedimentary Features** **Of** is bioclastic, formed in a shallow open-water area once teeming with life. **Bedrock Exposures** **Of** is present in isolated exposures, often as moss-covered mounds and boulders. **Of** has calcite-filled vugs and pyrite inclusions. **Paleontological Resources** **Of** preserves bryozoans, brachiopods, nautiloids and crinoid columnals (barrel-shaped).	**Of** is mapped in Big Flat, Boxley, Cozahome, Hasty, Jasper, Maumee, Murray, Osage SW, Ponca, Rea Valley, St. Joe, and Western Grove quadrangles.
Fernvale Limestone and Plattin Limestone, undivided (**Ofp**)	**Caves and Karst** Karst dissolution is common in this unit. **Bedrock Exposures** **Ofp** has calcite-filled vugs and pyrite inclusions, as well as stylolites. Many beds have a sugary texture. **Paleontological Resources** **Ofp** preserves rugose corals, brachiopods, nautiloids, crinoids, and conodonts.	**Ofp** is mapped in Eula, Mt. Judea, Parthenon, and Snowball quadrangles.
Plattin Limestone (**Opl**)	**Opl** is dense micritic limestone interbedded with calcarenite and dolostone. **Caves and Karst** Springs are abundant at the contact between **Opl** and **Osp** (where intervening units are absent). **Ancient Sedimentary Features** Unit is fine-grained and dense, this may indicate deposition in quiet, marine conditions. **Bedrock Exposures** **Opl** is so dense and fine grained, it displays conchoidal fracture when freshly broken.	**Opl** is mapped in Buffalo City, Cozahome, Harriet, Hasty, Marshall, Maumee, Rea Valley, and St. Joe quadrangles.

Table 3, continued. Geologic map units and associated features and processes in Buffalo National River.

Geologic Unit (map symbol)	Features and Processes	Location
Plattin Limestone and Joachim Dolomite, undivided (**Oplj**)	**Oplj** is limestone overlying dolostone. **Caves and Karst** Springs are abundant at the contact between Oplj and Osp where the Joachim Dolomite is absent. **Ancient Sedimentary Features** Unit is mostly thin to medium bedded with intervals of sandstone that may indicate nearshore (tidal flat?) depositional settings. **Bedrock Exposures** Unit including the Joachim Dolomite is sporadically exposed.	**Oplj** is mapped only in Big Flat quadrangle.
St. Peter Sandstone (**Osp**)	**Osp** is sandstone interbedded with siltstone and shale with scant dolostone. **Caves and Karst** Springs are abundant at the contact between **Opl** and **Osp** (where intervening units are absent). Carbonate cementation is prone to dissolution making weathered portions of this unit friable. **Ancient Sedimentary Features** Mixture of rock types suggest myriad depositional environments across a platform during accumulation of **Osp**. **Bedrock Exposures** **Osp** is a ledge forming sandstone in the lower reaches of the Buffalo River valley. **Faults and folds** A joint measurement station is located in **Osp** as part of the GRI GIS data. **Paleontological Resources** **Osp** preserves ostracods and is bioturbated with *Skolithos* and other invertebrate burrows.	**Osp** forms ledges in the lower reaches of the Buffalo River valley. **Osp** is mapped in Big Flat, Buffalo City, Cozahome, Eula, Harriet, Hasty, Marshall, Maumee, Mt. Judea, Rea Valley, St. Joe, Snowball, and Western Grove quadrangles.
Everton Formation, Undivided (**Oe**)	**Oe** is primarily interbedded dolostone, sandy dolostone, and sandstone with sparse chert. **Caves and Karst** Impermeable beds in **Oe** act as aquitards or barriers to groundwater percolation or flow. Springs are common in **Oe**. Mitch Hill Spring is the park's largest spring discharging from **Oe**. **Oe** is part of the Ozark aquifer. 20% of known cave openings are in **Oe** in the park. **Ancient Sedimentary Features** **Oe** has planar and crinkly laminations and mudcracks. It was likely deposited in a low-energy, shallow marine environment that was intermittently exposed. **Faults and Folds** Three joint measurement stations are located in **Oe** as part of the GRI GIS data. **Paleontological Resources** Local limestone bed within **Oe** contains stromatolites (fossil algae mounds). Other fossils preserved in **Oe** include bivalves, gastropods, nautiloids, trilobite, gastropods, ostracodes, trilobites and a variety of invertebrate trace fossils (burrows and pellets). Oncolites also documented in **Oe**.	**Oe** is mapped in Big Flat, Boxley, Buffalo City, Cozahome, Eula, Harriet, Hasty, Jasper, Marshall, Mt. Judea, Murray, Parthenon, and Rea Valley quadrangles.

Table 3, continued. Geologic map units and associated features and processes in Buffalo National River.

Geologic Unit (map symbol)	Features and Processes	Location
Everton Formation, Upper part (**Oeu**)	**Oeu** is interlayered dolostone, sandstone, and limestone. See **Oe** description. **Caves and Karst** Karst dissolution is common in **Oeu**. **Paleontological Resources** **Oeu** is locally fossiliferous.	**Oeu** is mapped in Maumee, Osage SW, Ponca, St. Joe, and Western Grove quadrangles.
Everton Formation, Lower part (**Oel**)	**Oel** is interbedded sandstone, limestone, and dolostone. See **Oe** description. **Caves and Karst** Springs commonly emerge from the base of this unit. Paleokarst, now filled by cemented breccias formed long ago by collapse of overlying sandstone into large cavities in carbonate-rich units. **Ancient Sedimentary Features** **Oel** has planar to wavy laminations indicating quiet water depositional settings. **Faults and Folds** A fault at Horseshoe Bend creates a conduit structure that funnels the flow of Buffalo River underground as a sinking stream during seasonal low flow. **Paleontological Resources** **Oel** includes stromatolitic hemispheres as large as 0.3 m (1 ft) in diameter.	**Oel** is mapped in Maumee, Osage SW, Ponca, St. Joe, and Western Grove quadrangles.
Powell Dolomite (**Op**)	**Op** is dolostone with interbedded siltstone and shale. **Fluvial Features and Processes** **Op** crops out in some of the deepest reaches of the Buffalo River valley. **Caves and Karst** Dolostone is susceptible to karst dissolution. **Ancient Sedimentary Features** **Op** includes mudcracks indicating some subaerial exposure during its deposition. **Bedrock Exposures** The **Op** dolostone contains quartz geodes. A prominent chert layer in **Op** (Black Ledge Chert) forms small glades locally. **Faults and Folds** The Cane Branch monocline exposes **Op** to erosion where it would otherwise be buried. A joint measurement station is located in **Op** as part of the GRI GIS data. **Paleontological Resources** **Op** preserves bivalves, gastropod. trilobites, conodonts, and stromatolites.	**Op** is mapped in Buffalo City, Hasty, Jasper, Ponca, Rea Valley, and Western Grove quadrangles.
Cotter Dolomite (**Oc**)	**Oc** is dolostone and sparse chert. **Fluvial Features and Processes** The Oc crops out in the deepest reaches of the valley. **Caves and Karst** Dolostone is susceptible to karst dissolution. **Ancient Sedimentary Features** **Oc** is thinly laminated, likely deposited in quiet water settings. **Bedrock Exposures** Chert nodules in **Oc** show concentric colored bands. **Oc** also has vugs or cavities filled with drusy quartz. Only the upper portions of **Oc** crop out in the valley.	**Oc** is mapped in Buffalo City, Ponca, and Rea Valley quadrangles.

Fluvial Features and Processes

Fluvial features are those which are formed by flowing water. Fluvial processes both construct (e.g., deposition of alluvial geologic map units **Qat**, **Qal**, and **Qty**) and erode (e.g., the Buffalo River valley) landforms. The Buffalo River and its tributaries form the fluvial features at Buffalo National River. According to the park's foundation document significance statements, the Buffalo River is an exceptional example of a free flowing, Ozark-mountain river as it is undammed and protected for its entire length within the Ozark Plateaus (National Park Service 2018). The Buffalo River is the central element of the whole array of natural and historical features; its characteristic flow is through quiet pools separated by short riffles (National Park Service 1999; Mott and Lauraas 2004).

Fluvial features occur on many scales in the park ranging from the large river valleys to the smallest streams. Examples of the park's fluvial features include meandering river channels, gravel bars and islands, riffles, point bars, floodplains, waterfalls (e.g., Hemmed-in-Hollow), and terraces (fig. 9). River channels are the perennial course of the flowing water. As water flows around curves, the flow velocity (and thus erosive energy) is greatest on the outside of a bend and least on the inside of a bend. The river therefore erodes its bank on the outside and leaves point bar deposits—crescent-shaped ridges of sand, silt, and clay—on the inside of its bends. As the process continues, the outside of the bend retreats while the inside migrates laterally, thus creating migrating meanders. Meandering reaches its extreme when the narrow neck of land between two bends is breached, leaving an oxbow lake or abandoned meander (fig. 9). Meanders along the Buffalo River are entrenched into the bedrock with minimal (or very slow) lateral migration (Richard Hutto, Arkansas Geological Survey, geologist, written communication, 23 April 2021).

Very recent terrace deposits are part of the active floodplain flanking the river and positioned at slightly higher elevations (**Qat**, **Qty**). The fluvial terraces perched above the modern floodplain are a clear record of stream incision and are listed among the park's significance statements presented in the foundation document (National Park Service 2018). The first, and youngest mapped perched terrace (**Qtm**) is 12 m (40 ft) above the river on the edge of the active floodplain. The second, older terrace (**Qto1**), is 24 to 30 m (80 to 100 ft) above the river. The third, older terrace (**Qto2**) is 60 m (200 ft) above the river. The fourth, and oldest terrace, is much higher and harder to recognize (GRI GIS source data; Thornberry-Ehrlich 2007).

Local bedrock can have a strong influence on the type of fluvial features forming along the Buffalo River and its tributaries. In some reaches, the river is confined by narrow valleys and shear bluffs as much as 150 m (500 ft) high, whereas in other areas, it meanders across alluvial bottoms (Mott and Lauraas 2004; National Park Service 2018). During seasonal low-flow, geologic structures and dissolved carbonate bedrock conduits funnel flow underground and the river becomes a sinking stream, leaving the channel dry at locations such as Horseshoe Bend, Boxley Valley, and Woolum (Thornberry-Ehrlich 2007).

Bedrock may also affect the river's bedload, which in turn impacts aquatic habitats. The Buffalo River tributaries flowing through carbonate-rich bedrock have shallower channels, better-sorted, gravel-rich substrate, and more eroding banks than those flowing through abundant sandstone bedrock. Along the Buffalo River's main stem, gravel bar accumulations were greatest within 1 km (0.6 mi) of carbonate bedrock-rich tributary junctions (Panfil and Jacobson 2001). Local land-use patterns also affect fluvial geomorphology; shallow channels with gravel-rich bedloads and eroding banks tend to flow through cleared land areas. Knowledge of underlying natural trends will help in targeting areas to study this phenomenon.

Flooding, wherein the river's flow crests over the banks and inundates typically dry areas, is common along the Buffalo River and its tributaries at any time of the year. Narrow channels are overwhelmed when heavy rains funnel through the drainages, resulting in flash floods. During peak flows which occur on average every 50 to 65 years, the river can rise up to 20 m (60 ft) above normal levels (Thornberry-Ehrlich 2007). Floods are the primary geomorphological agents shaping the fluvial environment and have an important role in controlling the pattern of riparian vegetation along channels and floodplains. During high flows or floods, a river deposits natural levees of sand and silt along its banks. These deposits represent the relatively coarse-grained component of a river's suspended sediment load and form a high area on the alluvial land surface. Flooding along the Buffalo River and its larger tributaries also recharges riverine wetlands adjacent to their channels. Flooding is a natural process, but it becomes a resource management issue when flooding is caused or exacerbated by human activities and/or when significant cultural or natural resources are threatened.

Caves and Karst

Karst is a landscape that forms through the dissolution of soluble rock, most commonly carbonates such as limestone or dolomite. Caves, sinkholes (dolines), sinking or losing streams, springs, conduits, pits,

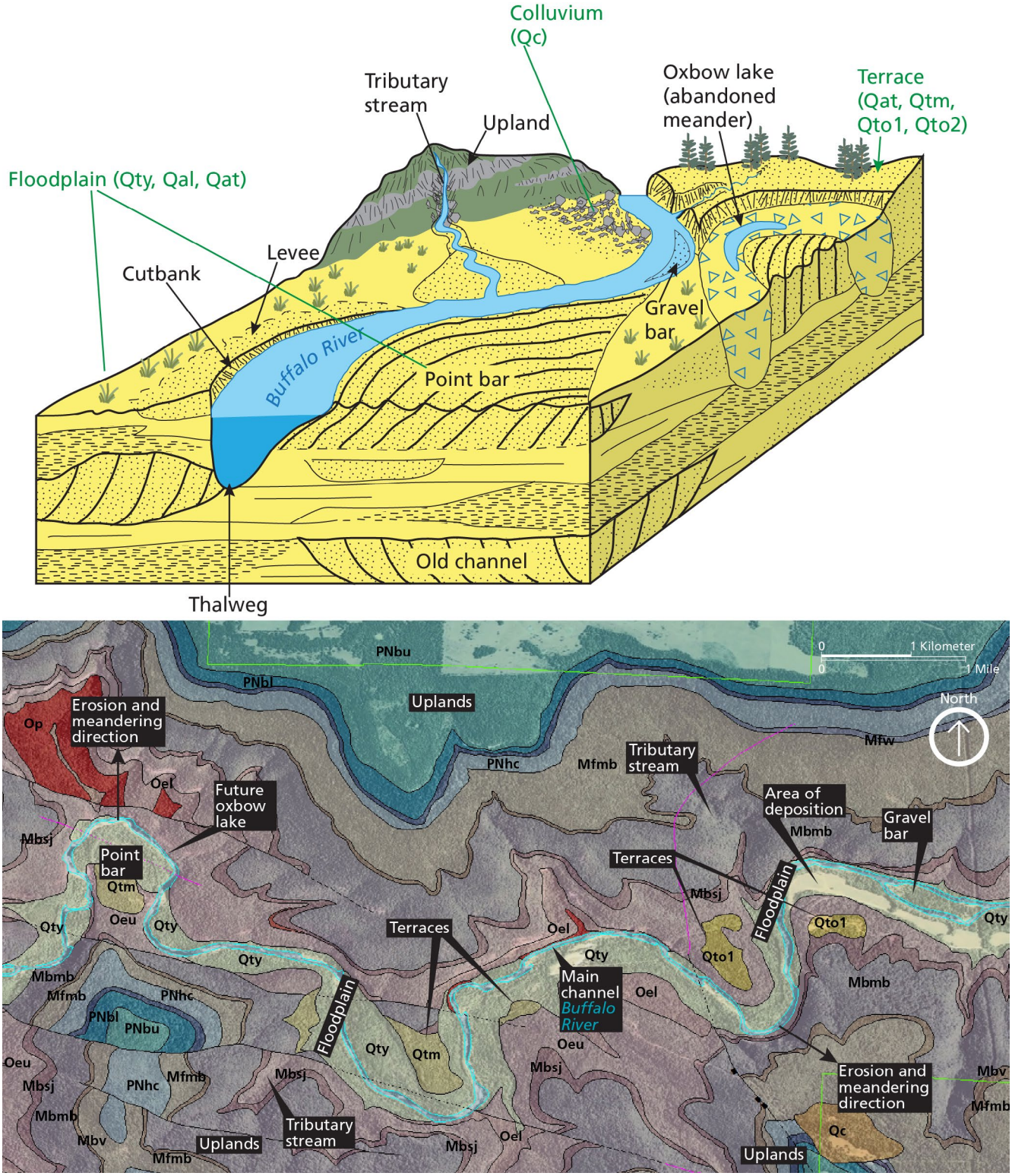

Figure 9. Diagram and map of fluvial features and depositional settings for alluvium.
The Buffalo River cuts down through bedrock to carve deep gorges. Diagram on top depicts how myriad fluvial features are formed along its length as the river meanders across its floodplain depositing alluvium in some areas and scouring the valley floor in others. Green text identifies local examples and relevant geologic map units present in the park. Diagram is not to scale. Map below shows geologic map units (colored areas) over aerial imagery with fluvial features labeled. Graphics by Trista L. Thornberry-Ehrlich (Colorado State University) using GRI GIS data and ESRI World Imagery basemap.

alcoves, karst aquifers, paleokarst, and internal drainage are characteristic features of karst landscapes (fig. 10; Toomey 2009). Caves and karst features require four geologic conditions to form: suitable, soluble rocks (e.g., the carbonate or carbonate-cemented sandstone at the park); flowing groundwater (as a solvent); hydrogeologic framework (hydraulic gradient); and time. The groundwater must be acidic enough (due to addition of carbon dioxide from the atmosphere and soil detritus) for chemical dissolution to occur. Flowing groundwater adds a mechanical component to cave and karst formation by removing materials loosened by the chemical dissolution process (Pat Seiser, National Cave and Karst Research Institute, NPS Cave and Karst program coordinator, written communication, 19 April 2021).

Caves are naturally occurring underground voids that are large enough for human entry and extend into a dark zone where no natural light is visible. Many types of caves exist, and they vary in size, origin, and appearance. They include solution caves (commonly associated with karst), volcanic or lava tubes, sea caves, talus caves (voids among collapsed boulders), regolith caves (formed by soil piping), and glacier (ice-walled) caves (Palmer 2007; Toomey 2009). Caves and bedrock crevices may provide habitat for bats and other animals. Cave features are nonrenewable resources.

A significance statement presented in the park's foundation document (National Park Service 2018) declared "Buffalo National River contains a dense array of karst features, including hundreds of caves and thousands of sinkholes, sinking streams, springs, and other natural features formed by the complex interplay of groundwater and surface water." The need to update the park's cave and karst management plan, dating from 1984, was identified as a high priority. An updated plan would provide a consistent framework for managing Buffalo National River's substantial subterranean systems. It is also needed to protect sensitive resources—particularly those related to visitation and research, as well as above-ground activities which have the potential to impact cave and karst resources. The plan could also address how park staff can provide sustainable public enjoyment and education.

Caves

191 NPS units, including Buffalo National River, contain or potentially contain caves, karst, and/or pseudokarst (Land et al. 2013). Buffalo National River has at least 360 and likely more than 500 cave openings (Kayla Sapkota, Cave Research Foundation, Vice President, email communication to Pat Seiser, National Cave and Karst Research Institute, NPS Cave and Karst Program coordinator, 11 April 2021; see fig. 10), including Fitton Cave—the longest known cave in Arkansas at 24 km (15 mi; Thornberry-Ehrlich 2007; Soto 2014). Fitton Cave, which includes cave passages at six levels spanning 120 m (393 ft) of elevation, was mapped entirely within the Boone Formation (geologic map units **Mbsj**, **Mbmb** and **Mbu**). Fitton Cave was mapped by the Cave Research Foundation (Thornberry-Ehrlich 2007; Hudson et al. 2011). The passages of Fitton Cave reveal it short-circuited streams at different topographic levels in the past (Thornberry-Ehrlich 2007). Fitton Spring is the discharge point for the cave (Aley and Aley 1999; Hudson et al. 2011). Caves such as Fitton Cave are noteworthy in part because of their spectacular cave formations, or speleothems—mineral formations that grow on cave walls—and locally include gypsum needles, angel hair, crystalline pendants; mirabilite needles; and calcite or aragonite flowstone, dripstone, rimstone dams, cave rafts, cave popcorn, and cave coral (fig. 11; National Park Service 2018). Other caves, such as John Eddings Cave, are characterized by having broad avenue-like passages. In August 2020, park staff discovered criminals had forced their way into a secure entrance to Fitton Cave and damaged, vandalized, and removed many cave formations, such as stalagmites and draperies (Branstetter 2020).

Karst

According to the Park Atlas for Buffalo National River (National Park Service 2010b), karst rock types underlie 43% of the park area. Karst was a major factor in the establishment of the national river (Chuck Bitting, Buffalo National River, natural resource manager, conference call, 17 April 2019). Karst features at Buffalo National River include underground drainage, springs, sinkholes (dolines), and alcoves and overhangs (fig. 12). In the Buffalo River area, groundwater watersheds do not correspond with the surficial (topographic) drainage basin divides. Groundwater is able to flow from one basin to another (e.g., from Crooked Creek basin into the Buffalo River basin), commonly emerging as springs. For instance, the water feeding Dogpatch Spring can flow beneath a surficial divide and emerge at a topographic low in a neighboring basin because flow is facilitated at depth by a fault surface. At Mitch Hill, dye traces and mapping revealed an upwelling of a lower spring into an uncommon karst "window" (Thornberry-Ehrlich 2007). A "window" forms where localized geologic structures, weathering, and erosion expose rocks at the surface that are stratigraphically much lower. Margaret White Springs delivers so much water to the middle section of the Buffalo River that it lowers the river's temperature and is vitally important for the aquatic life there and downstream (Chuck Bitting, Buffalo National River, natural resource manager, conference call, 17 April 2019).

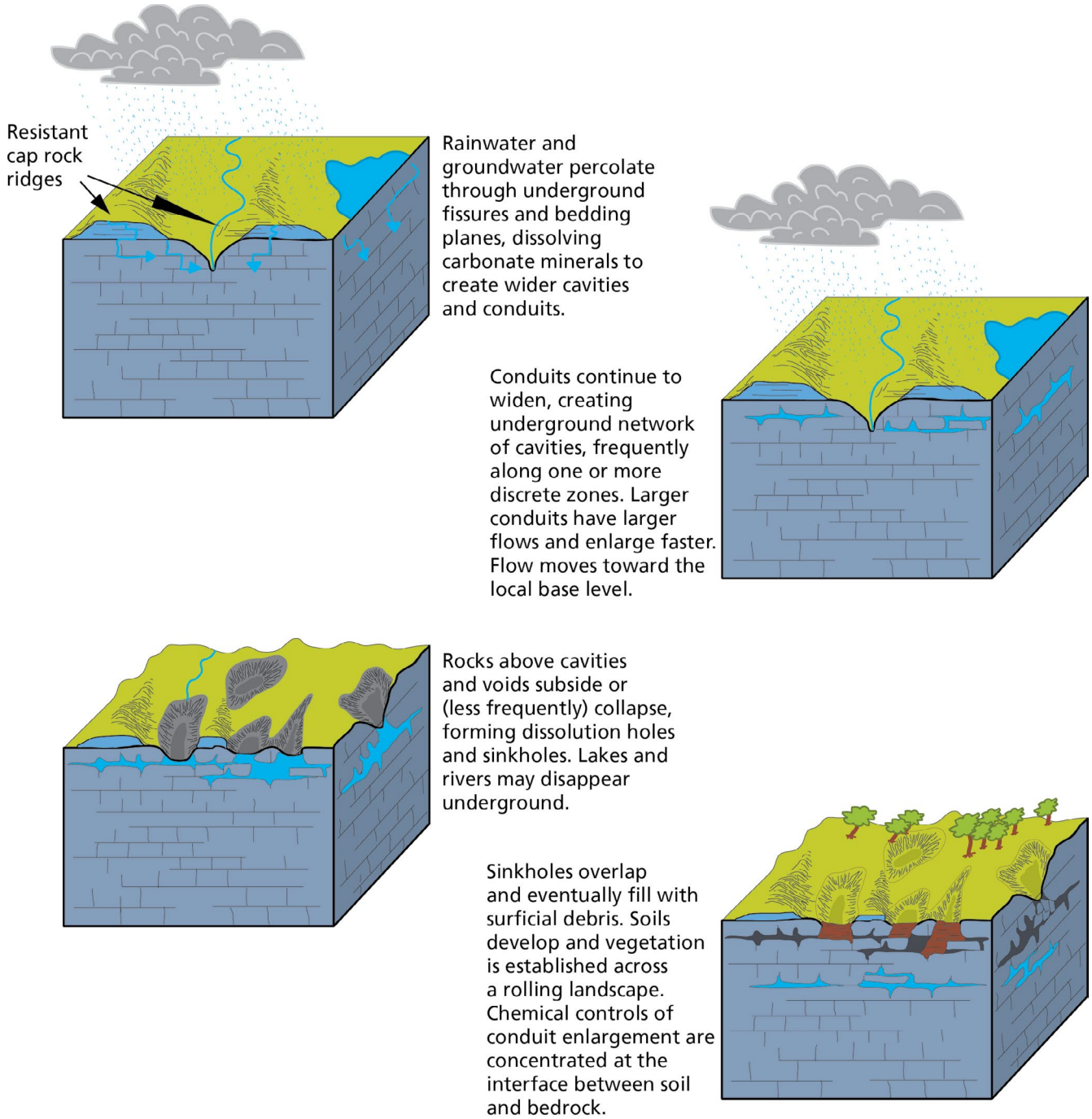

Figure 10. Three-dimensional illustration of karst landscape formation.
Resistant cap rocks, such as sandstone layers within the Bloyd Formation (PNbl, PNbm, PNbu), overlie caves and sinkhole plains. Caves, sinkholes, and other karst features also develop readily in areas without cap rocks. Sinkholes are common throughout the area of Buffalo National River, where karst landscapes dominate and continue to develop today in the Mississippian and Ordovician dolomite and limestone. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) created using information from Hack (1974).

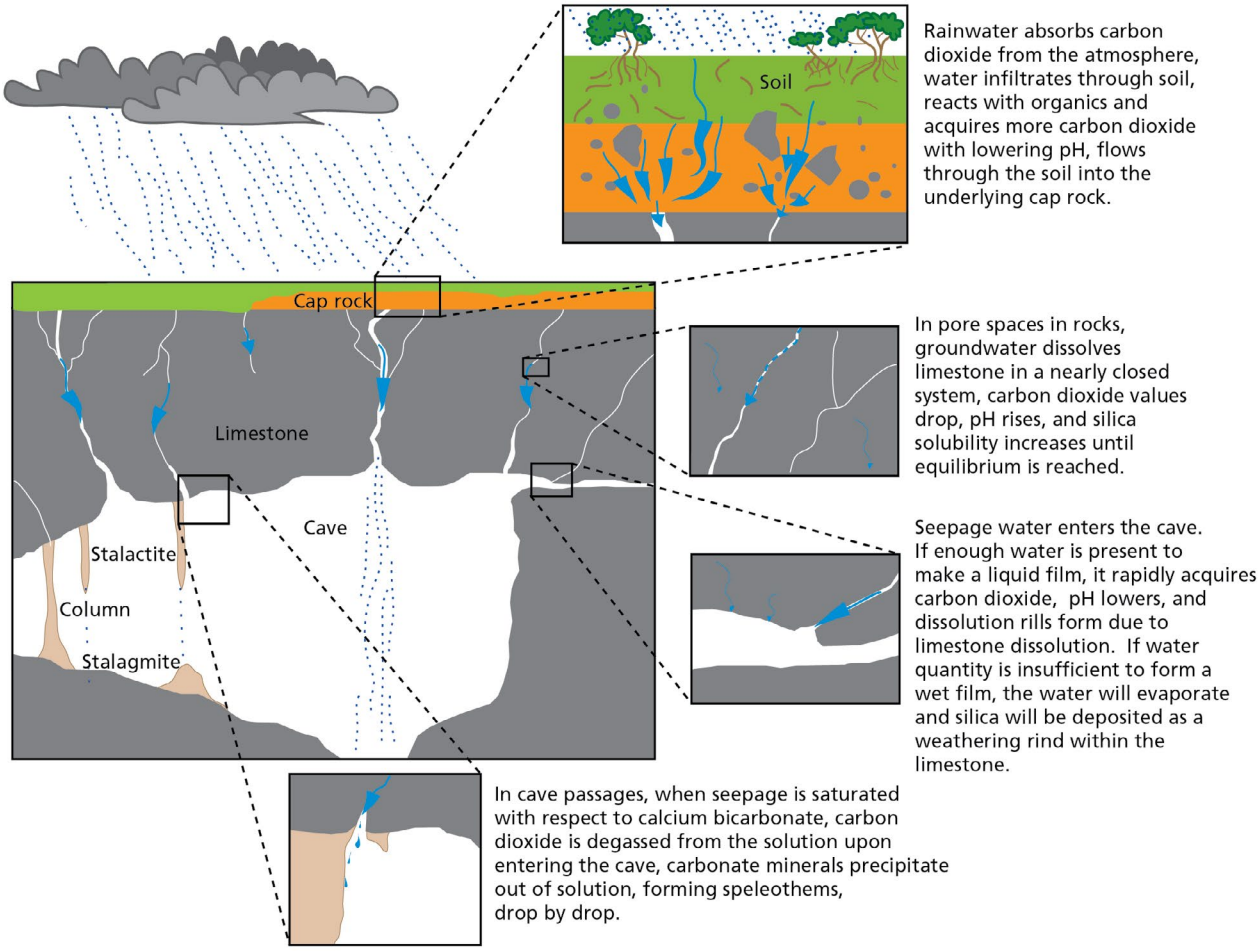

Figure 11. Generalized diagram of speleothem development.
Cap rock may include sandstone and/or shale. Rainwater percolates through the soil and gains carbon dioxide, which in turn lowers the pH. The now acidic groundwater will dissolve limestone it seeps through, lowering carbon dioxide, and increasing pH. When this seepage solution enters a cave and is exposed to air, carbon dioxide values increase again, pH lowers, and minerals come out of solution. If the seepage is saturated with respect to calcium bicarbonate, carbonate minerals precipitate, forming speleothems drop-by-drop. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University), after information provided in Palmer and Palmer (2003).

Sinkholes

Sinkholes form when carbonate rocks dissolve. Several types of sinkholes exist and are visible at Buffalo National River. Solution sinkholes are abundant at the park and form as concave round or funnel shaped holes in carbonate in the top of the Boone Formation (geologic map units **Mbsj**, **Mbmb** and **Mbu**) where it is exposed at the surface. Collapse sinkholes form when a rock type such as sandstone, that is not susceptible to dissolution, collapses into a void dissolved in the underlying limestone or dolomite. These types of sinkholes form in the Everton Formation (**Oe**) and where the Batesville Sandstone (**Mbv**) collapses into the underlying Boone Formation (Angela Chandler, Arkansas Geological Survey, geologist, written communication, 7 May 2021).

Several geologic controls establish the distribution of sinkholes in the Buffalo National River area. Most form in the Boone Formation (**Mbsj**, **Mbmb** and **Mbu**) or the contact between the Boone Formation and the Batesville Sandstone (**Mbv**; Chenoweth 1997). Areas with a resistant sandstone caprock, like the Batesville, tend to form subjacent collapses that have an orthogonal joint-controlled distribution. The orientation and frequency of joints are the major geologic controlling factors influencing the morphology

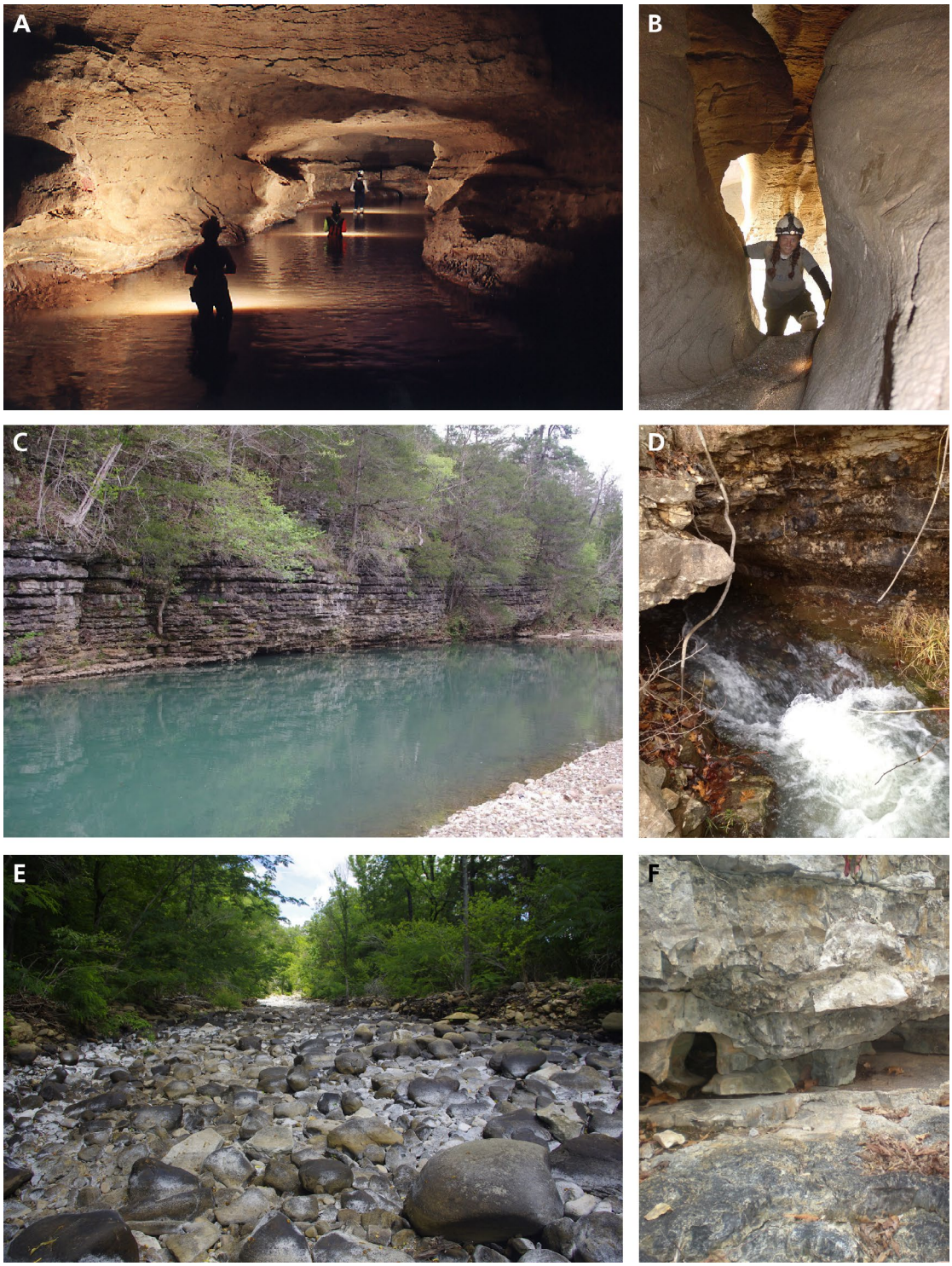

Figure 12. Photographs of karst features at Buffalo National River.
(A) John Eddings Cave which is formed in the limestone of the Boone Formation (Mbu, Mbmb), the Fernvale Limestone (Ocsfk, Ofp, Of), and the Plattin Limestone (Oplm, Oplj, Ofp). (B) A side passage to Fitton Cave—the longest cave in Arkansas. (C) Riverside outcrop of the Boone Formation wherein dissolution along bedding planes and joints creates significant permeability for groundwater movement. (D) Rapid flow from a spring indicates poor filtering of any contaminants. (E) A dry or sinking stream segment of Big Creek below reaches that were flowing on the surface. Note the white, evaporative crust on the cobbles. (F) Conduits along bedding indicates seasonal or past rapid flow. Photographs A and B are courtesy of Chuck and Carol Bitting. Photographs C–F are from Brahana (2013).

and distribution of sinkholes (Chenoweth 1997). Joints parallel to formational contacts can result in a linear cluster of sinkholes. Where two joints intersect, a sinkhole with an associated short cave is commonly present. The intersection of three or more joints forms deep, vertical shafts. At Buffalo National River, sinkhole formation and type are intrinsically related to stratigraphic setting, topography, and joint orientation and frequency (Chenoweth 1997).

Alcoves as Sandstone Karst

An alcove is a large deep niche formed in a precipitous face of rock. Alcoves form curved recesses created by the collapse of curved joints or by the upward propagation of slab failures below rock ledges (Young and Young 1992; Angela Chandler, Arkansas Geological Survey, geologist, written communication, 7 May 2021). Where carbonate rocks are present, dissolution may contribute to the formation of alcoves. Alcove formation is a product of cliff weathering processes, which can include but is not limited to karst dissolution, and eventually leads to the formation of arches and natural bridges (Angela Chandler, written communication, 7 May 2021).

Slope Movements

Slope movements, also called "mass movements" or referred to generally as "landslides", have happened and will continue to happen in the park (figs. 13 and 14). Landslides were noted among the park's significance statements presented in the foundation document and were noted during field mapping (see scanned field books in "Regional Geologic Information" section) (National Park Service 2018; Angela Chandler, Arkansas Geological Survey, geologist, conference call, 17 April 2019). Slope movements are the downslope transfer of material (e.g., soil, regolith, and/or rock). Slope movements can occur rapidly (e.g., debris flows or rockfall) or over long periods of time (e.g., slope creep).

Gravity, frost and plant-root wedging, erosion, swelling clays, shaly layers providing slip surfaces, and karst dissolution are primary causes of slope instability at Buffalo National River. The magnitude of slope failures depends on slope, aspect, soil type, and geology. Within the park, much of the landscape is moderately to steeply sloping and includes near vertical cliffs and bluffs. Toreva blocks—stratified and backward tilted slump blocks—of Ordovician to Upper Mississippian and Pennsylvanian units, slid downslope initially as a semi-coherent mass before breaking up into a jumbled earth flow (Thornberry-Ehrlich 2007).

Abandoned Mineral Lands

Abandoned mineral lands (AML) 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. The NPS acts under various authorities to mitigate, reclaim, or restore AML to reduce hazards and impacts to resources. According to the NPS AML database and Burghardt et al. (2014), Buffalo National River contains 361 AML features at 47 sites and ore mineralization was noted among the park's significance statements presented in the foundation document (National Park Service 2018). Park staff believe these numbers to need a thorough review and update (Melissa Trenchik, Buffalo National River, chief of Resources Stewardship, Science, Interpretation and Education, conference call, 17 August 2021). The GRI GIS data recorded 6 mine features in the park; these included quarries, adits, mines, and shafts, some of which provided aggregate for local roadway construction (Thornberry-Ehrlich 2007). Mississippi Valley-type lead and zinc mineralization along structural features in north Arkansas, especially faults, led to the development of several mining areas, beginning in the 1880s, in and around the Buffalo National River. The historic Rush mining district (Rea Valley, Buffalo City, and Big Flat quadrangles) overlaps with park land (see fig. 1). Other nearby mining operations included the Ponca lead mines, the Mt. Hersey area mines, and the Dogpatch mines (fig. 15). Mining operations ceased before 1960.

In the 1990s, the park embarked on a series of mine-opening closures including blocked access and gates; at that time, 43 openings needed work (Burghardt 1992; Burghardt and Higgins 1993). These hazardous openings were typically large, irregularly shaped, and commonly located beneath unstable cliffs or bluffs (Burghardt 1992). In addition to the large openings, the mineralized area was riddled with shallow exploratory pits, trenches, and subsidence zones (Burghardt 1992). Park staff estimate there are likely thousands of small pits and prospect holes throughout the park (Chuck Bitting, Buffalo National River, natural resource manager, conference call 17 April 2019). In 2007, it was noted that the park owned all mineral interests except for five tracts; however, it was also noted that no valid claims existed in park boundaries (Thornberry-Ehrlich 2007). As of 2021, park needs related to AML include addressing concerns about mineral looting, identification of tract numbers, and further review of the status of claims and mineral interests (Melissa Trenchik, conference call, 17 August 2021). These could be potential Scientist-in-the-Parks (SIP) projects (see "Guidance for Resource Management").

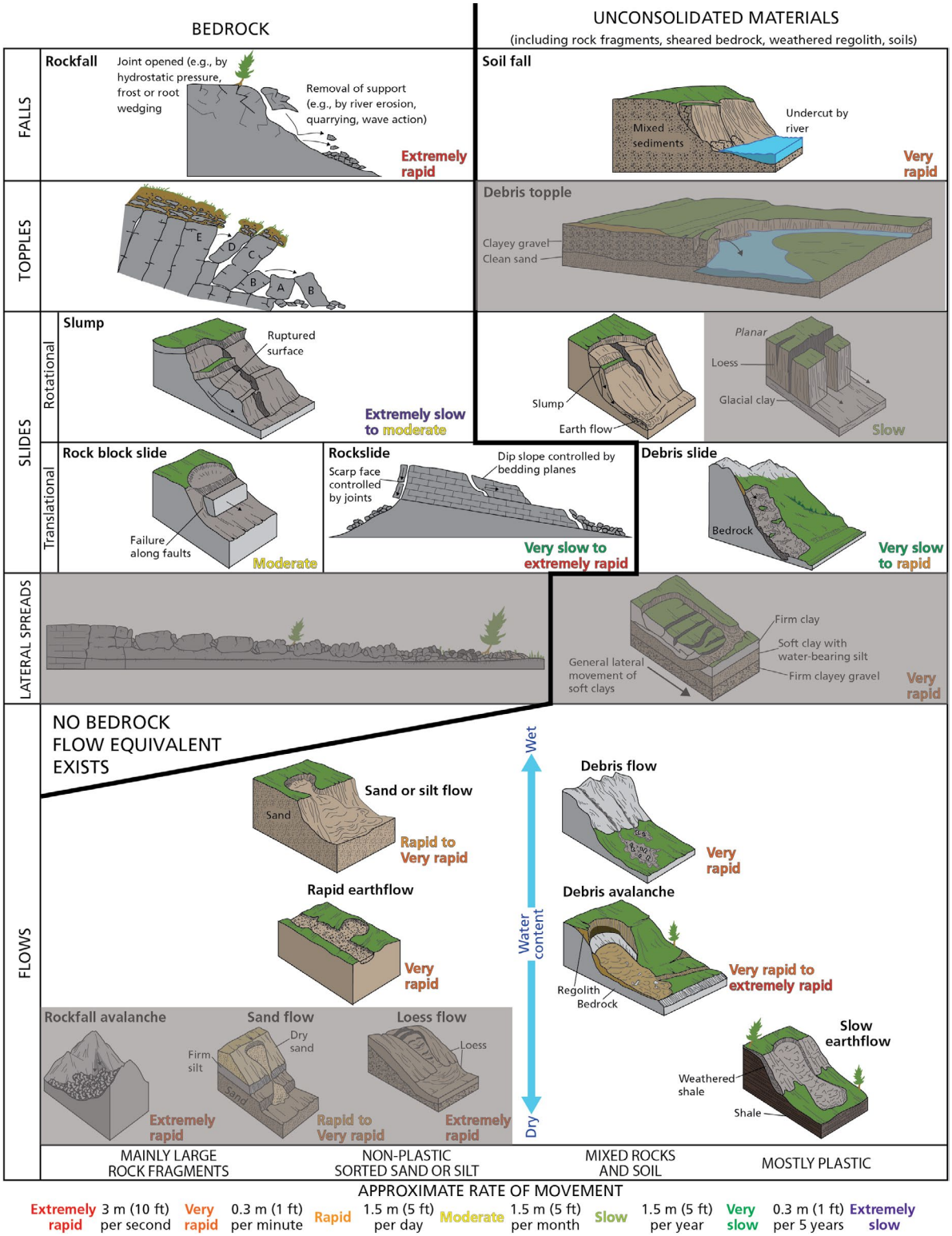

Figure 13. Illustrations of slope movements.
Slope movement categories are defined by material type, nature of the movement, rate of movement, and moisture content. Shaded areas depict conditions unlikely to exist at Buffalo National River. The abundant vegetation in the park stabilizes some slopes, but slope issues could be exacerbated by factors such as natural or anthropogenic removal of vegetation and climate change. Graphic by Trista Thornberry-Ehrlich (Colorado State University) redrafted after a graphic and information in Varnes (1978) and Cruden and Varnes (1996).

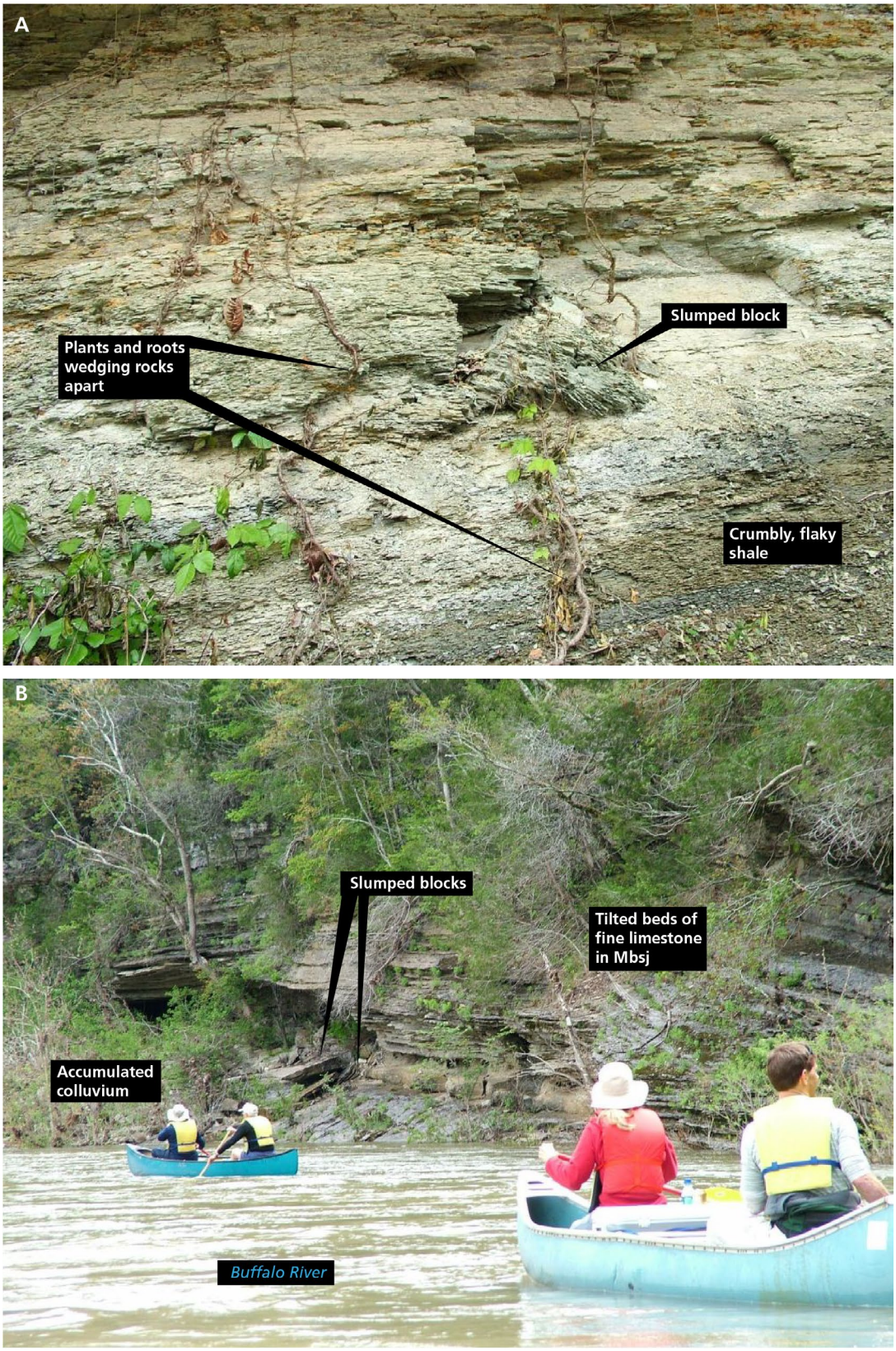

Figure 14. Photographs of slope movements at Buffalo National River.
Steep slopes throughout much of the park are susceptible to mass wasting or slope failure. These movements range in scale from huge blocks of rock to small flakes of shale shed downslope during rainfall. Photographs by Andrea Croskrey (NPS Geologic Resources Division) taken in spring 2007.

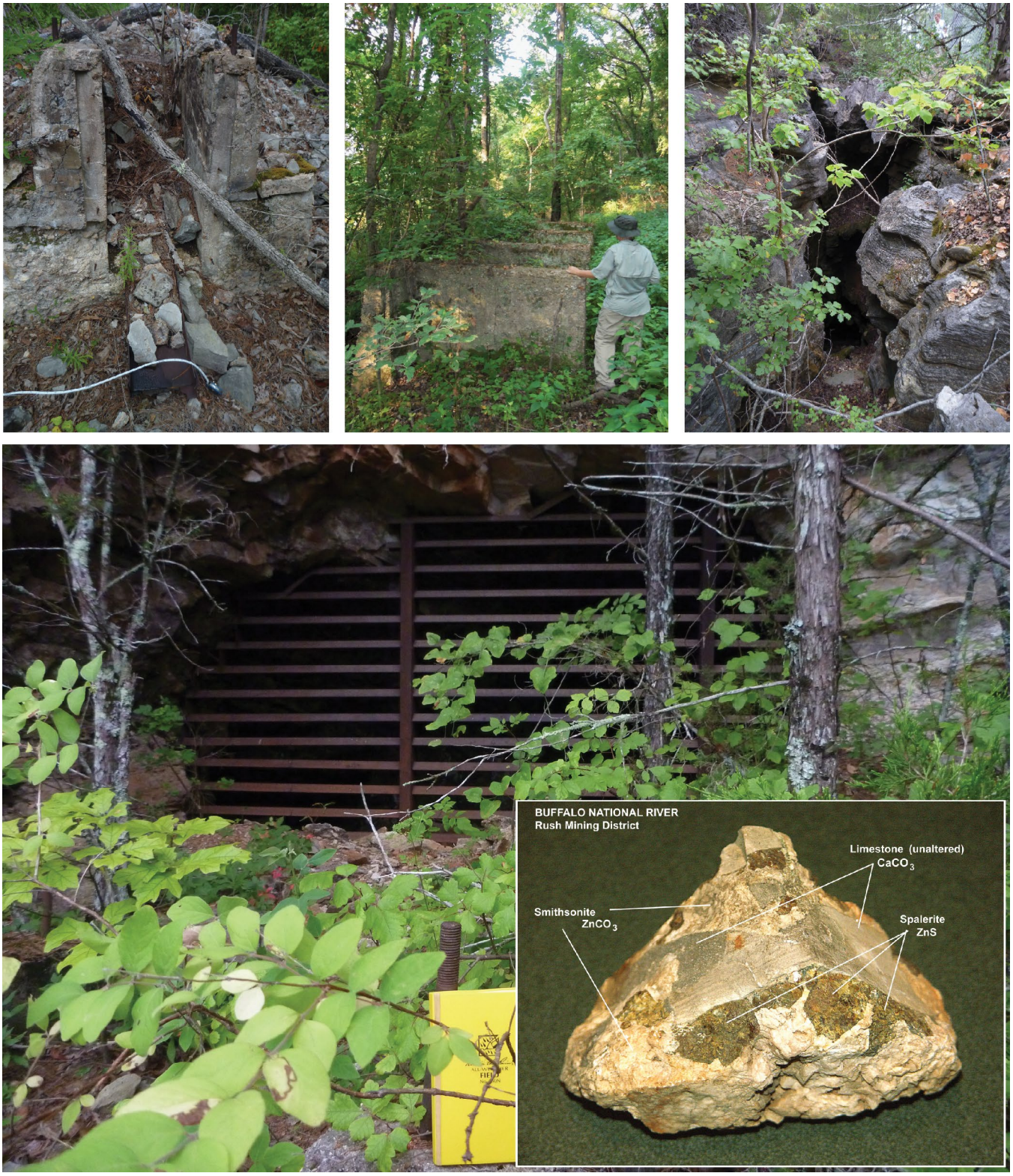

Figure 15. Photographs of abandoned mineral lands in Buffalo National River.
Lead and zinc ore was mined historically in the park area. Many features are left to weather naturally into the landscape. Some pose safety issues, such as mine openings, but also provide habitat for bats and other animals. Top left and middle photographs are building foundations. Upper right and bottom photographs are mine openings. NPS field photographs by Brandy Henderson (US Forest Service) taken in 2011. Inset photograph is an NPS photograph.

Disturbed Lands

Disturbed lands are those where the natural conditions and processes have been directly impacted by development. These include facilities, military bases, roads, dams, and abandoned campgrounds; agricultural activities such as farming, grazing, timber harvest, and abandoned irrigation ditches; overuse; or inappropriate use (fig. 16). Usually, lands disturbed by natural phenomena such as landslides, earthquakes, floods, and fires are not considered for restoration unless influenced by human activities. Restoration activities return a site, watershed, or landscape to some previous condition, commonly some desirable historic baseline.

Arkansas Department of Transportation highway standards require 40% silica (e.g., chert) in road surface aggregate. Quarrying for sand, gravel, and clay is ongoing near the park for local construction including chert deposits in the Buffalo River's tributaries. Ground and vegetation disturbances along these tributaries increases sedimentation rates which eventually impacts the Buffalo River (Thornberry-Ehrlich 2007). Other ground surface disturbances include grazing and logging. Buffalo National River permits cattle grazing in some areas with only about six active permits remaining (Melissa Trenchik, Buffalo National River, chief of Resources Stewardship, Science, Interpretation and Education, conference call, 17 August 2021). Adjacent logging activities left behind abandoned access roads through park lands, which are targets for potential reclamation and restoration in the park to achieve a return to natural conditions (Thornberry-Ehrlich 2007).

As local population increases, especially in the Harrison, Arkansas area, park resource managers are concerned about negative impacts on natural resources, particularly from land-use changes (Panfil and Jacobson 2001; Thornberry-Ehrlich 2007). In the Buffalo River area, about 11% of the drainage basin was converted from forest to pasture between 1965 and 1992 and there has been a trend toward the clearing of steeper, more erodible lands (Panfil and Jacobson 2001). There are very few regulations on housing or urban development. Development trends seem likely to focus on the northern and western sides of the park over the next 10–12 years. Park staff remain vigilant as to new proposed highway changes (e.g., Highway 7) and adjacent developments (Melissa Trenchik, conference call, 17 August 2021). Development increases the amount of impermeable surfaces such as roads, parking lots, roofs, and driveways which will increase surface runoff. Other potential negative impacts of adjacent development include overuse of the park's facilities, increased erosion and sediment loads, and water contamination. Groundwater aquifer systems through carbonate-rich bedrock are particularly vulnerable to contamination because any input is quickly funneled through the conduit system with little if any natural filtering or sorption (Ryan and Meiman, 1996).

Roads are a primary contributor to harmful sediment influxes to local streams (Greco 2001). Local roads concentrate flows and increase erosional processes in an area where steep topography already funnels precipitation rapidly into the Buffalo River. Approximately 172 km (107 mi) of roads are located within park boundaries; these are impervious surfaces with an overall lack of cross drains to accommodate runoff (Greco 2001). Lack of road drainage structures, ditchline interception of ephemeral drainages, routing of ditches directly into streams, and overwidening of roadbeds are all exacerbating the problem of harmful sediment influxes to streams at the park (Greco 2001).

Ancient Sedimentary Features

Sedimentary rocks—all the bedrock in the park—are particularly useful as records of geologic history. Certain depositional environments yield characteristic features in sedimentary rocks as evidence of their setting. The present (e.g., unconsolidated surficial deposits) provides clues to the past (e.g., solid bedrock) and vice versa. High energy depositional environments, such as fast-moving streams, deposit larger (heavier) clasts while transporting smaller (lighter) clasts. The larger sand- and gravel-sized clasts settle out to eventually lithify (solidify) into sandstone or conglomerate, respectively. Where water moves slowly or is stagnant, such as in inland seas, the water cannot transport even the smallest clasts and they are deposited as clay layers, which become shale. Wind also transports and deposits sand-sized or smaller clasts.

In addition to grain size, sedimentary processes are recorded in the rock fabric and layering features. The type and condition of sediments (e.g., rounding, sorting, bedding, and composition) can record the prevailing depositional environment. Some of the most common sedimentary features in park rocks include crossbeds, troughs, planar bedding, mudcracks, load features, and ball and pillow structures. Each provides clues as to where and how they were deposited.

Crossbeds and ripples indicate deposition in flowing water or wind. Geologists can determine current direction by measuring the crossbeds. The direction the beds are dipping, or tilting indicates paleocurrent or the rough direction of sediment transport. Examples of crossbeds in park rocks include the Atoka Formation (geologic map unit **PNa**), Hale Formation (**PNhp** and **PNhc**), Bloyd Formation (**PNbu**), sandstone layers in the Fayetteville Shale (**Mfw**), and Batesville Sandstone (**Mbv**) (Hudson and Murray 2004; Hudson and Turner 2007).

Figure 16. Photograph of garbage dumped at Gilbert Spring.
Prior to the establishment of the park, natural depressions (e.g., sinkholes) were used as local landfills. Gilbert Spring is a karst feature at the park, emerging where water, percolated through dissolution joints and fractures, intersects the top of an impermeable layer and flows laterally. NPS photograph by Andrea Croskrey taken in spring 2007.

Trough features in sedimentary rocks may record flow in channelized conditions such as those found in streams, tidal channels, or interdunal areas. Troughs occur in the Atoka Formation (geologic map unit **PNa**), Hale Formation (**PNhp** and **PNhc**), and Bloyd Formation (**PNbu**) (Hudson and Murray 2003; Hudson and Turner 2007).

Planar bedding may occur in instances of planar flow wherein the flow velocity is too fast to form ripples in fine and very fine sand. Basically, planar bedding indicates intense sediment transport over a flat-lying bed which is characterized in detail by a system of low, linear ridges, a few grain diameters high, which align parallel to flow direction. Planar bedding is visible in park bedrock, including the Atoka Formation (geologic map unit **PNa**), Hale Formation (**PNhp** and **PNhc**), Bloyd Formation (**PNbu**), sandstone layers in the Fayetteville Shale (**Mfw**), Batesville Sandstone (**Mbv**), Boone Formation (**Mbu**), and the Everton Formation (**Oeu**) (Hudson et al. 2006; Hudson and Turner 2007; Turner and Hudson 2018).

Mudcracks commonly indicate conditions wherein water-saturated mud, is exposed to subaerial conditions and dries out, causing the characteristic polygonal areas separated by cracks. Later, other sediments may settle into the open cracks, sealing the surface. Mudcracks occur in the Everton Formation (**Oe**) and Powell Dolomite (**Op**) (Smart and Hutto 2008; Chandler et al. 2011a).

Load features and ball and pillow structures are examples of soft-sediment deformation—features that form prior to lithification or consolidation of the sediments. Load features (or load casts) are bulges, lumps, and lobes that form at the separations between layers of sedimentary rocks. Uneven distribution of coarse and fine sediments causes the more dense sediments to press down into underlying less dense sediments leaving a protrusion of the overlying coarse material extending downward into the finer grained or softer sediments. When loading within soft sediments becomes extreme and/or a shock (e.g., earthquake) is applied, ball and pillow structures may form. A shock ruptures and destabilizes the sediments causing individual lobes of the load feature to break off and settle downward into the underlying layers. Ball and pillow structures are commonly present at the contact between a sandstone bed and an underlying mudstone bed and take on a hemispherical or kidney shape. Load features and ball and pillow structures are present in the Bloyd Formation (**PBbu**) (Braden and Ausbrooks 2003a, b, c).

Detailed descriptions of the bedrock map units are available in the ancillary map information document (buff_geology.pdf) in the GRI GIS data. In addition to sedimentary features, fossils are found in many of the bedrock map units within the park (see "Paleontological Resources").

Bedrock Exposures

"Bedrock" is the solid, unweathered rock that underlies unconsolidated surficial deposits and residuum. Bedrock is dramatically exposed along much of the Buffalo River's course (fig. 17). Only sedimentary rocks are present in bedrock outcrops in the park. Sedimentary rocks accumulate from reworked rock fragments, precipitate chemically, or form as a hybrid of both processes (table 4).

The three main types of sedimentary rocks are clastic, chemical, and organic. Clasts are the products of weathering, erosion, transportation, and deposition of rock fragments which eventually lithify. Chemical sedimentary rocks form by dissolution and reprecipitation of minerals during diagenesis or weathering. Organic sedimentary rocks are composed of organic remains (e.g., coal) or were produced by the physiological activities of an organism (e.g., secretion of calcium carbonate to form limestones of coral reefs). The bedrock within Buffalo National River includes strata of all three major sedimentary rock types.

A geologic formation is named for a geographic feature, such as a stream, road, or town located near the place the rock formation is best displayed or first described, known as the "type locality." Typically, a particular outcrop in that area is designated to represent the lithology and character of the entire formation, including its upper and lower contacts, and is referred to as a "type section." Type localities and type sections have scientific, historical, and educational significance. Many of the formations on the geologic map of Buffalo National River were named for geographic features in north Arkansas, and many are very well exposed in the park (Mark Hudson, US Geological Survey, geologist, written communication, 3 May 2019; Thornberry-Ehrlich 2007). Information about formally named geologic units may be found at the USGS Geolex service: https://ngmdb.usgs.gov/Geolex/search.

Faults and Folds

Faults and folds are present where rocks have been compressed, stretched, sheared, or fractured and moved. They are common structural features in areas of mountain building, such as the Ouachita Mountains. A fault is a fracture along which rocks on one side have moved relative to rocks on the other side. The three primary types of faults are normal faults, reverse faults,

Figure 17. Photographs of bedrock exposures in Buffalo National River.
(A) An alcove created where a softer, less erosion-resistant layer weathered beneath a more resistant layer. Such alcoves were commonly used as shelters. (B) Steep, near vertical bluffs of the Boone Formation tower above the Buffalo River. (C) Sharp contact between the Cason Shale (bottom) and St. Joe Limestone member of the Boone Formation (top). The shale is less resistant to erosion and weathers away more readily leaving overhangs. (D) Silurian limestone characteristically weathering to a smooth, massive bluff on the outside of the meander bend at Shine Eve. Photographs by Andrea Croskrey (NPS Geologic Resources Division) taken in spring 2007.

Table 4. Sedimentary rock classification and characteristics.

* Claystone and siltstone can also be called "mudstone," or if easily splits into thin layers, "shale."

**Carbonate classification is based on Dunham's textural classification scheme (Dunham 1962).

Sedimentary Rock Type	Rock Name	Texture	Depositional Environment	Buffalo National River Examples
Inorganic Clastic	Conglomerate (rounded clasts)	Clast size: >2 mm (0.08 in)	High energy (e.g., swift river currents, strong winds)	Layers in **PNa, PNbm**, and **PNw**
Inorganic Clastic	Breccia (angular clasts)	Clast size: >2 mm (0.08 in)	High energy (e.g., talus accumulation at a cliff base)	Layers in **Mbv** and **Oel**
Inorganic Clastic	Sandstone	Clast size: 1/16–2 mm (0.0025–0.08 in)	Less energy than conglomerate (e.g., forearc basins)	Layers in **Mbv**, **Mf**, and **Osp**
Inorganic Clastic	Siltstone*	Clast size: 1/256–1/16 mm (0.00015–0.0025 in)	Less energy than sandstone (e.g., deltas, glacial deposits)	Layers in **PNa**, **PNbu**, and **PNhp**
Inorganic Clastic	Claystone*	Clast size: <1/256 mm (0.00015 in)	Low energy (e.g., floodplains, lagoons, lakes)	Clasts in **Qal**
Carbonate Clastic**	Fossiliferous Limestone	Generic name for carbonate rock containing fossils	Primarily marine	Layers in **Mp**, **Mbv**, **Mb**, **Su**, **PNhg**
Carbonate Clastic**	Crystalline	Crystal supported; no fossil fragments, carbonate grains, or carbonate mud	No depositional features can be recognized	Layers in **Su**, **Mb**, and **Mbv**
Carbonate Clastic**	Boundstone	Composed entirely of fossils, fossil fragments, or carbonate mud fragments cemented together	High energy; bound together during deposition (e.g., reefs)	None identified in mapping
Carbonate Clastic**	Grainstone	Grain (e.g., fossil fragments) supported with no carbonate mud	Less energy than boundstone; original components bound together following deposition	None identified in mapping
Carbonate Clastic**	Packstone	Grain (e.g., fossil fragments) supported with some carbonate mud	Less energy than grainstone; original components bound together following deposition	None identified in mapping
Carbonate Clastic**	Wackestone	Carbonate mud supported with more than 10% grains and less than 90% carbonate mud	Less energy than packstone; original components bound together following deposition	None identified in mapping
Carbonate Clastic**	Mudstone	Carbonate mud supported with less than 10% grains and more than 90% carbonate mud	Low energy; original components bound together following deposition	None identified in mapping
Chemical	Limestone (carbonate mud)	Generic name. Formed by the precipitation of calcium (Ca) and carbonate (CO_3^{2-}) ions from water	Freshwater (e.g., lakes) or marine environments	Layers in **Mp**, **Mbu**, **Su**, **Ocsf**, **Of**, and **Opl**
Chemical	Travertine	Precipitation of calcium (Ca) and carbonate (CO_3^{2-}) ions from freshwater	Terrestrial springs	At springs in **Osp** and **Oe**
Chemical	Dolomite	Precipitation of calcium (Ca), magnesium (Mg), and carbonate (CO_3^{2-}) ions from water	Post-depositional alteration of limestone by Mg-rich groundwater or direct precipitation in shallow marine environments	Layers in **Oc**, **Ou**, and **Op**
Chemical	Evaporites (e.g., gypsum)	Precipitation of salts to form evaporite minerals	Hot and dry	None identified in mapping

Table 4, continued. Sedimentary rock classification and characteristics.

Sedimentary Rock Type	Rock Name	Texture	Depositional Environment	Buffalo National River Examples
Chemical	Oolite	Precipitation of calcium carbonate in thin spherical layers around an original particle (e.g., fossil fragment)	Shallow marine; particles are rolled back and forth by constant motion of tides or waves	Layers in **Mb** and **Mbsco**
Organic	Coal	Peat (partly decomposed plant matter) buried, heated, and altered over time	Lagoon, swamp, marsh	Layers in **PNbu** and **PNa**

and strike-slip faults (fig. 18). All three fault types are mapped in Buffalo National River. Faults are classified based on the type of relative movement across the fault plane as described in figure 18. Faulting was noted among the park's significance statements presented in the foundation document (National Park Service 2018). Within park boundaries, the GRI GIS data identifies at least 14 major, named faults, including the Compton, Kyles Landing, St. Joe, Stringtown Hollow, Confederate, White Hollow, North Rocky Creek, Spring Creek, Water Creek, Rock Creek, Hickory Creek, Climax, Fish Trap, Ducks Head, and Hathaway Mountain faults. Myriad small faults (not necessarily mapped) are visible in rocks all along the river (fig. 19).

Folds are curves or bends that form in response to compression of originally flat-lying rock strata. The two primary types of folds are anticlines, which are "A-shaped" or convex, and synclines, which are "U-shaped" or concave (fig. 20). Another type of fold, called a monocline, is a curved step-like structure consisting of a steeply dipping zone between areas of relatively horizontal strata. The fold axis is a line that runs along the points of maximum curvature in a fold. The fold axis commonly tilts or plunges along its length. Folds identified within park boundaries include named folds such as the Cliff Hollow, Kimball Creek, and Jones Hollow anticlines, the Grogins Hollow, Rock Creek, and Panther Creek synclines, and the Adds Creek, Hanner Point, Bee Bluff, Web, Sawmill, Ingram Creek, Caney Hollow, Silver Hollow, and Monte Cristo monoclines. Smaller folds (not necessarily mapped) are visible in bedrock exposures along the river.

Faults and folds disrupted and deformed the Paleozoic bedrock of the park in three phases: 1) latest Mississippian to earliest Pennsylvanian faulting and folding; 2) west to west-northwest trending faulting and monoclinal folding in the middle to late Pennsylvanian; and 3) a reactivation of preexisting structures in the late Pennsylvanian to early Permian (Hudson 2000; Hudson et al. 2011). The faults and folds of the final phase diverted deep mineralizing fluids upsection during the Late Pennsylvanian and early Permian (Hudson 2000; Hudson et al. 2011), and thus were crucial in the emplacement of the lead/zinc mineralization associated with the Ouachita Orogeny (see "Abandoned Mineral Lands"). Movement along faults may result in earthquakes (see "Geologic Hazards"). They also play a role in karst development; the fractured rock providing conduits for percolating groundwater to dissolve and enlarge openings (see "Caves and Karst"; Hudson et al. 2011).

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 feces). Fossils in NPS areas occur in rocks or unconsolidated deposits, museum collections, and cultural contexts such as building stones or archeological resources. As of April 2022, 283 parks had documented paleontological resources in at least one of these contexts.

The first park-specific paleontological resource inventory for Buffalo National River was undertaken in 2018 (Konett et al. 2018). Fossils are among the park's significant statements presented in the foundation document and paleontological deposits are fundamental resources and values (National Park Service 2018). Nearly all the bedrock units at the park are known to contain fossils (figs. 21 and 22; Konett et al. 2018). Some sections of limestone consist of up to 90% crinoid ("sea lily") fragments (fig. 23; Konett et al. 2018). Hunt et al. (2008) presented a literature-based inventory of fossils in the park's bedrock and the other Heartland Network parks.

Pleistocene and Holocene vertebrate fossils, including ursids, peccaries and other mammal taxa are documented from caves within Buffalo National

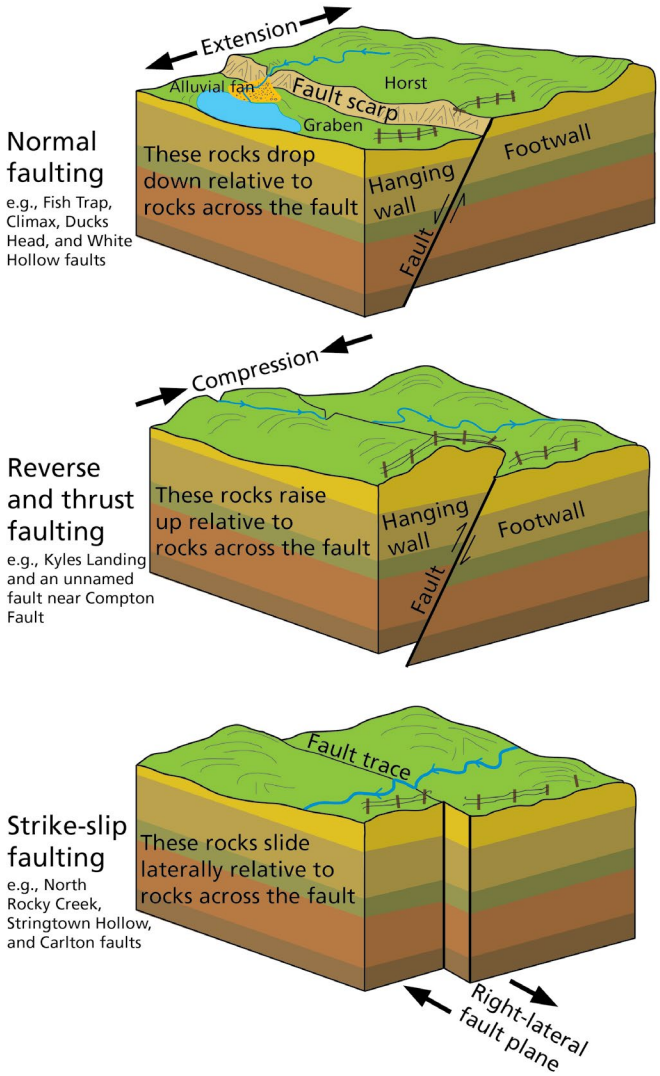

Figure 18. Illustrations of fault types. Footwalls are below the fault plane and hanging walls are above. In a normal fault, crustal extension (pulling apart) moves the hanging wall down relative to the footwall. In a reverse fault, crustal compression moves the hanging wall up relative to the footwall. A thrust fault is similar to a reverse fault, but the fault plane 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. All three major fault types are recorded in the GRI GIS data for Buffalo National River. Graphic by Trista Thornberry-Ehrlich (Colorado State University).

River (Santucci et al. 2001; Thornberry-Ehrlich 2007). A famous deposit of Pleistocene vertebrate fossils is located just outside park boundaries in an area known as the Conard Fissure. The Conard Fissure is a geologic structure (collapsed sinkhole), which created a small natural trap for vertebrate fossil remains washed in by the Buffalo River. The Conard Fissure is an important Irvingtonian (North American Land Mammal Age) mammal locality, excavated during the beginning of the 20th century by a field crew from the American Museum of Natural History under the supervision of paleontologist Barnum Brown. There is a good potential for similar fossil deposits in the caves and other karst features throughout Buffalo National River.

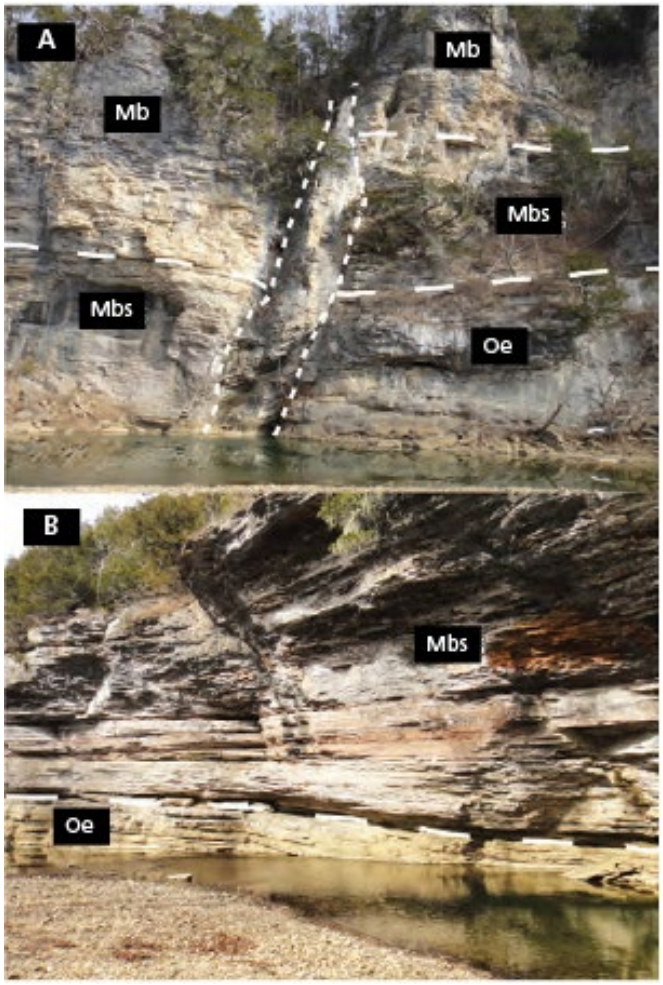

Figure 19. Photographs of faults exposed along Buffalo River. Image A (top) is looking east toward the South Braden Mountain fault zone where two faults (finely dashed white lines) drop the contact (coarsely dashed white lines) between the St. Joe Limestone Member of the Boone Formation (geologic map unit Mbsj) and the Everton Formation (Oe) to the north. Image B (bottom) shows the gently southeast-dipping layers in the hanging wall north of the fault zone. Graphic modified from figure 13 in Hudson et al. (2011).

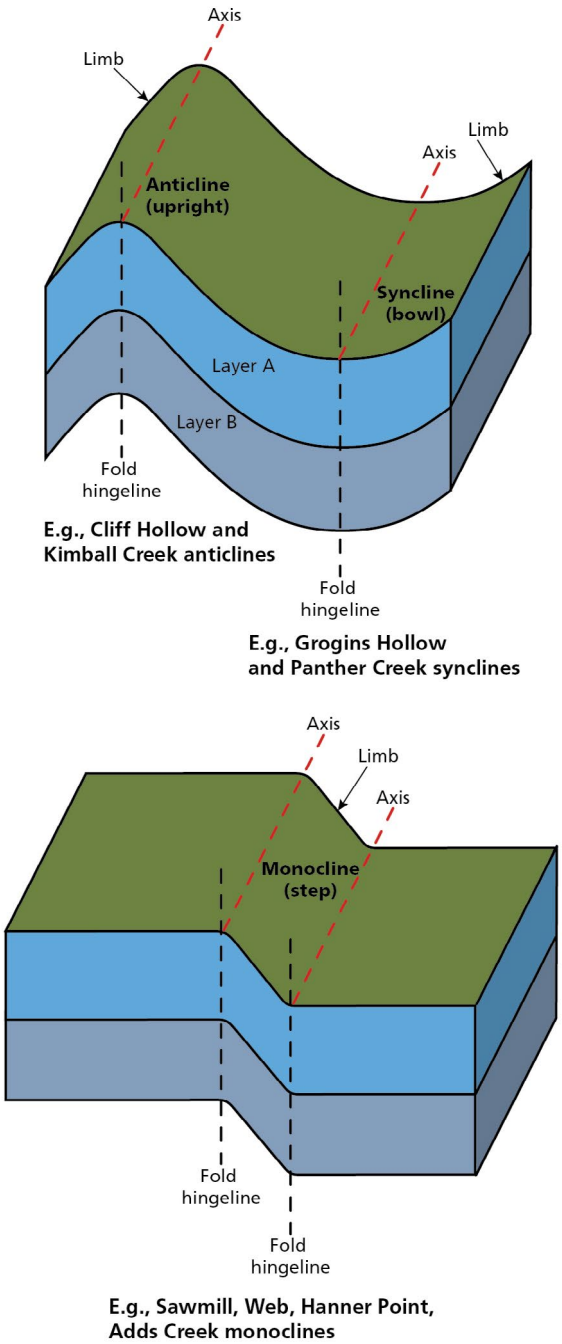

Figure 20. Illustrations of fold types.
Folds accommodate stress within rocks without fracture (faulting). All three major fold types (synclines, anticlines, and monoclines) are recorded in the GRI GIS data for Buffalo National River. Folds are typically oriented perpendicular to the tectonic stress that is forcing the rock layers to buckle. The Buffalo River cuts through folded strata in the park, giving some outcrops a tilted appearance. Folds also influenced where economic accumulations of minerals precipitated in the bedrock. Graphic by Trista Thornberry-Ehrlich (Colorado State University).

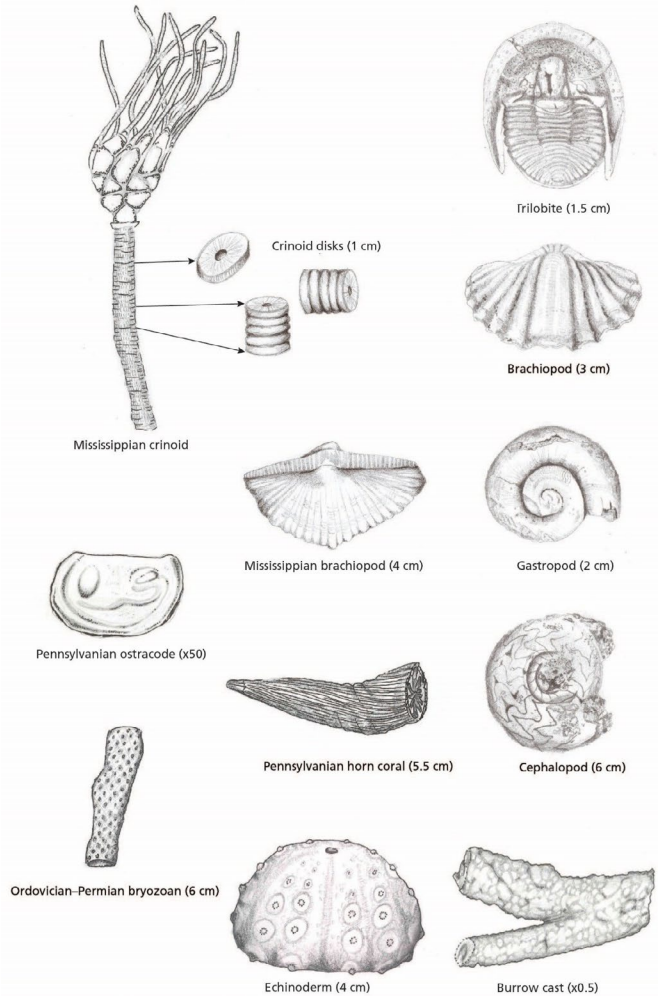

Figure 21. Fossil sketches.
The limestone, dolomite, sandstone, siltstone, and shale in the park are commonly fossiliferous. These sketches are representative of some of the fossil types and ages that may be present in the park's geologic units. Fossils are at risk of burial or degradation by natural and anthropogenic slope processes, as well as theft. Sketches by Trista L. Thornberry-Ehrlich (Colorado State University).

Figure 22. Photograph of an orthoconid nautiloid fossil.
The fossil is in Silurian limestone (geologic map unit Su). Such fossils are abundant in the park's bedrock. National Park Service photograph taken by Andrea Croskrey (NPS Geologic Resources Division) taken in spring 2007.

Figure 23. Photograph of a crinoid -rich sample of the St. Joe Limestone Member of the Boone Formation. This is geologic map unit Mbsj. Many of the fragments are sections of the creature's "stem" known as columnals. Fossiliferous rocks such as this are testament to the seas teeming with life in the area during the Mississippian Period. Figure was presented as figure 8 in Konett et al. (2018).

Geologic Resource Management Issues

This chapter highlights issues (geologic features, processes, and human activities affecting or affected by geology) that may require management for human safety, protection of infrastructure, or preservation of natural and cultural resources. Each is discussed in this section and on table 5 in the context of relevant geologic map units. The NPS Geologic Resources Division provides technical and policy assistance for these issues (see "Guidance for Resource Management").

Table 5. Resource management issues in the context of associated geologic map units.

Resource management issues correspond to sections of this chapter (e.g., "Flooding, Erosion, and other Fluvial Issues"). See table 3 for a description and location of geologic map units.

Resource Management Issue	Geologic Map Units	Description of Potential Issue
Flooding, Erosion, and other Fluvial Issues	**Qat**, **Qal**, **Qty**	These alluvial deposits line the Buffalo River channel and its tributaries and is found on all floodplains in the park. River meandering through these sediments may threaten natural and cultural features, such as archeological sites, along the river.
Flooding, Erosion, and other Fluvial Issues	**Mbv, Mbu, Mbmb**	Sinkholes, sinking streams, and karst conduits in these units may funnel surface water rapidly into the subsurface, contributing to high flows and increasing contamination risk.
Flooding, Erosion, and other Fluvial Issues	**Osp**	**Osp** is a confining unit to groundwater flow resulting in springs emerging at its contact with overlying units.
Cave and Karst-related issues	**Mbu, Mbmb, Su, Ocsfk, Of, Ofp, Opl, Oplj, Oe, Op, and Oc**	Karst conduits, faults, and other geologic structures in these units may rapidly transmit contaminants into regional aquifers.
Geologic Hazards: Slope Movements	**Qc, Qls**	These units are the product of past slope movements. Scars along the slopes and bluffs adjacent to the river and its tributaries attest to many ancient rockfalls and landslides. Colluvial fans occur at the base of many slopes and bluffs along the river and its tributaries. Landslide deposits may form hummocky or irregular terrain.
Geologic Hazards: Slope Movements	**Qto1, Qto2**	Perched above the river valley on ridges, older terrace deposits may be prone to slope processes.
Geologic Hazards: Slope Movements	**PNa, PNbu, PNbm, PNbl, PNw, PNhp, PNhc, Mp, Mfw, Mbv. Mm, Su, Osp**	• Resistant units such as **PNa, PNbu, PNbm, PNw, PNhp, PNhc, Mbv**, and **Osp** weather to form Toreva blocks that slid downslope as a semi-coherent unit before breaking up into a jumbled earthflow deposit (**Qls**). • **PNhc** and the basal sandstone of **PNbu** is a source of the large, massive blocks in **Qc** and **Qls**. • **PNhp**, **Mp**, and the sandstone of **Mfw** is a source of some of the material in **Qls**. • **PNbm** forms prominent bluffs in the park and may be prone to rockfall or landslides. • **PNbl** is exposed on moderate to steep slopes. The fissile nature of this unit may cause it to slide or slump. • **PNhp**, being on steep slopes or ledges, is prone to rockfall. • **Mm** develops a gentle slope beneath the more resistant **Mbv**; this creates a rockfall-prone setting. • **Su** is prone to rockfall and slides if exposed on steep slopes. • Slumped sandstone blocks of **Osp** are common on slopes. • Earthquakes may trigger slope movements in these units.

Table 5, continued. Resource management issues in the context of associated geologic map units.

Resource Management Issue	Geologic Map Units	Description of Potential Issue
Geologic Hazards: Slope Movements	**Mf, Mfmb, and Ocs**	**Mf** and **Mfmb** act as regional slip surfaces and are present at the toe of many landslides (**Qls**) in the park. Both units are susceptible to landslides. Shale such as **Ocs** may function as a regional or local slip surface but is limited in extent.
Geologic Hazards: Slope Movements	**Mbu, Mbmb**	**Mbu** and **Mbmb** is prone to karst dissolution, sinkhole collapse, and rockfalls along the Buffalo River and its tributaries. Thick, persistent deposits of chert may be undercut by dissolution and pose serious rockfall hazards. Bus-sized blocks of Boone Formation rock have fallen in recent history. Earthquakes may trigger slope movements in these units.
Geologic Hazards: Earthquakes	**Qat, Qal, Qty, Qtm**	Seismic shaking in unconsolidated units could cause considerable instability and damage infrastructure built on these units.
Abandoned Mineral Lands and Disturbed Lands	**Qat, Qal, Qty**	Alluvium from these units is mined for sand and gravel by local developers.
Abandoned Mineral Lands and Disturbed Lands	**Mbv, Mbsj, Ofp, Oe, Oel, Op**	There are likely thousands of small pits and prospect holes throughout the park resulting from mineral exploration in the area in these units. However, no valid claims currently exist in park boundaries. The units were of interest due to the following qualities: • **Mbv** breaks into thin, flat blocks, ideal for flagstone or building material. • A phosphate pebble layer is present in some locations at the base of **Mbsj**. • The GRI GIS data records a quarry in **Ofp** within park boundaries. The material of interest is not reported. • Most local zinc prospects are in **Oe**. A shaft exists within **Oe** inside park boundaries as part of the GRI GIS data, as well as three adits and one mine. • Zinc carbonate ore was extracted at Old Granby mine from **Oel** as early as 1875. • The Black Ledge Chert within **Op** was historically mined for decorative stone.
Paleontological Resources Inventory, Monitoring, and Protection	**PNbu, PNbm, PNw, PNhp, PNhc, Mp, Mbv, Mbu, Mbmb, Mbsj, Mf, Mfw, Mfmb, Su, Ocs, Ocsfk, Of, Ofp, Opl, Oplj, Osp, Oe, Oeu, Oel, Op**	Fossils may be targeted by thieves. A paleontological age-date locality is present in **Op** within park boundaries.

Flooding, Erosion, and other Fluvial Issues

A clean, free-flowing river is one of the park's fundamental resources and values (see "Fluvial Features and Processes"); this includes the features associated with the river, such as its riparian zone, hydrologic system, and habitats (National Park Service 2018). A hydrological survey is a high-priority management need identified in the foundation document (National Park Service 2018). National Park Service (1999) stated a management goal was to "manage riparian lands to protect or restore a minimum of one-hundred-foot forested riparian corridor on either side of Buffalo River". This requires a watershed-wide approach to management, but the park only contains 11% of that watershed, making such an approach challenging. Mott and Lauraas (2004) stressed the need to work with adjacent landowners to establish riparian buffers, soil conservation practices, riparian bank restoration, and building fences to keep livestock out of tributary streams and rivers.

A primary resource management concern at the park is the riverbank and head-cutting erosion by the Buffalo River and its tributaries. This is a natural process, but is accelerated by gravel mining, concentrated overgrazing, land clearing along riparian zones, livestock stream access, and alteration of stream channels and consequent bank destabilization (Mott and Lauraas 2004; National Park Service 2018). Channel instability is

a chronic problem on the upper part of the river above Boxley Bridge to below Ponca where old gravel mining operations destabilized slopes. Lateral erosion created 6-m- (20-ft-) tall bluffs in alluvial sand, which does not provide much resistance to erosion during high flows (Chuck Bitting, Buffalo National River, natural resource manager, conference call, 17 April 2019). Lateral migration of the river is also causing channel widening in some areas. Wider channels increase the amount of sunlight penetrating the water which causes enhanced algal growth thereby threatening aquatic systems. LiDAR data from 2011 and 2016 may help quantitatively identify channel change and help managers target specific areas for erosion mitigation (GRI conference call participants, conference call, 17 April 2019).

High flows and floods are increasing in frequency and severity at Buffalo National River, and this is having adverse effects on the river corridor, which in turn may require stabilization (National Park Service 2018). The Buffalo River's steep channel contributes to instability of its banks during high flows (Thornberry-Ehrlich 2007; National Park Service 2018). In 1982, a severe flood covered one of the larger bridges crossing the river (Thornberry-Ehrlich 2007). In stretches of the river flanked by floodplains composed of unconsolidated material, lateral river migration can be aggressive during high-flow events. Efforts to engineer the river corridor or stabilize shorelines include rip rap, some artificial channelization (formerly by bulldozers), short-term cedar tree revetments, and rock vanes to protect canoe launch sites (fig. 24). For example, at Woolum, riprap protects a park road and cedar revetments are in place to maintain the current shoreline.

The bedrock along the river is a driver for recreation management on the Buffalo River. River mapping with a Doppler instrument, intended to look for sediment loading as it pertains to mussel habitat and streambank stabilization, is providing data that will be vital in managing river access points (e.g., boat launches). Access points need to be redesigned and/or relocated to areas least prone to flooding. Straight launches have been problematic because they allow access roads to deliver excess sediment directly to the river when flooded. Areas where the streambank is apt to fail should be avoided. The North Maumee and South Maumee launches are damaged nearly every time it rains substantially because the increased river flow hits adjacent bedrock bluffs and refracts to directly hit the launch with force. Other strategies to manage river access include requiring permits, using shuttles, and paving dispersed access roads to encourage use along the entire corridor as opposed to concentrating use at only about six convenient sites (Melissa Trenchik, Buffalo National River, chief of Resources Stewardship, Science, Interpretation and Education, conference call, 17 August 2021).

High flows also threaten infrastructure and archeological resources (Chuck Bitting, conference call 17, April 2019). The NPS Midwest Archeological Center monitors the length of the river every few years (GRI conference call participants, conference call 17 April 2019). A photomonitoring project could supplement this effort. The Scientists in Parks (SIP) program is an option to support such a project (see "Guidance for Resource Management"). The NPS Geologic Resources Division photogrammetry website (http://go.nps.gov/grd_photogrammetry) provides examples of how photographic techniques support analysis of quantitative landscape change.

The upper Buffalo River corridor of federal land is managed with a scenic easement on private lands. The Buffalo National River enabling legislation contains protection language that provides specific guidance regarding instream work on the river and its tributaries and an emphasis on free-flowing condition, scenery, and the values for which the river was designated. Park efforts combined with efforts of the Buffalo River Conservation Committee (BRCC), a committee established by executive order of Arkansas Governor Asa Hutchinson, are aligned to address some of the internal and external influences on the river (Melissa Trenchik, written communication, 16 November 2021). The four pillars of the BRCC are tourism and tourism activities, agriculture production/uses, unpaved (gravel) roads, and septic systems and sewage treatment. More information about this committee is available from the Arkansas Department of Agriculture at https://www.agriculture.arkansas.gov/buffalo-river-conservation-committee/. In collaboration with the Natural Resources Conservation Service (NRCS), the park is engaged in a collective effort to help private landowners maintain their land in a way that preserves the integrity of the Buffalo River watershed and aligns with the four pillars of the BRCC (Melissa Trenchik, conference call, 17 August 2021). Park managers are investigating ways to put 30 m (100 ft) buffer zones around areas of concern and use flumes to determine if nutrients and sediment are being mitigated by the buffer zones (Melissa Trenchik, conference call, 17 August 2021).

Upland erosion (fig. 25) is another resource management concern because it impacts fluvial processes by contributing sediment to river channels, leading to braided (sediment choked) channels in some reaches, which in turn may degrade aquatic habitats. Human activities that increase upland erosion include deforestation on adjoining lands, as well as horse and

Figure 24. Photographs of shoreline-loss control structures along the Buffalo River. Photographs show the concrete retaining wall and geotech meshing, used to mixed success to maintain the gravel bar at the Tyler Bend launch point. The river tends to erode around the structures and wash them away or render them useless. Top photograph is looking upstream from the launch. Bottom photograph is looking downstream approaching the launch. Photographs by Andrea Croskrey (NPS Geologic Resources Division) taken in spring 2007.

Figure 25. Photographs of deep erosional features along park roadways. Impervious surfaces and lack of stormwater management create situations where erosion removes vast amounts (see park staff in photographs for scale) of sediment adjacent to roadways. The sediment ultimately washes into depressions, caves, and streams and rivers. Photographs by Deana Greco (NPS Geologic Resources Division) taken 1 November 2000.

human trail crossings (Thornberry-Ehrlich 2007). Land-use impacts were determined for 19 tributary drainages of the Buffalo River using fluvial system data including bedrock type (i.e., carbonate versus sandstone), drainage area, drainage basin shape, average slope, elevation range, bluff area, cleared land area, steep cleared land area, and road density (Panfil and Jacobson 2001). The data indicated that the Buffalo River tributaries with larger proportions of carbonate bedrock and cleared land had overall shallower channels, better-sorted, gravel-rich bed loads, and more bank erosion than those with little cleared land and more sandstone bedrock. Additionally, gravel-bar areas on the Buffalo River's main stem were also larger within 1 km (0.6 mi) downstream of tributary junctions where the tributary flowed through carbonate-rich bedrock. Geology and cleared land were found to be correlative; a relatively large proportion of cleared land exists in the Buffalo River drainage on steep slopes (>15 degrees). This means relationships between anthropogenic and natural factors can often not be separated. Similar studies could provide a comprehensive update for the entire river system and help analyze evolving land-use trends on system conditions and predict future responses to land-use changes and climate change.

Other management goals related to water at the park include delineating groundwater drainage basins (e.g, mapping boundaries and calculating areas), feeding springs, and surface streams (National Park Service 1999). The park has a springs inventory database which has several hundred entries in an Excel spreadsheet (Aley and Aley 1999; Melissa Trenchik, conference call, 17 August 2021). This is likely a very low estimate of the

actual number of springs in the park, but that depends on how strictly spring is defined (e.g., cave entrances, seeps in alluvium or bedrock, springs modified for agricultural use, bubbling up in streambeds, or water emerging at bedrock contacts could all be considered springs). Information recorded in the database includes location, elevation, nearest town, owner, anthropogenic changes and uses, history, flora and fauna, and other notes. Some entries appear to be from water quality reports. This database was being updated in the summer of 2019 by a Geoscientist-in-the-Parks participant. Continued updates and distribution of this sensitive information is a need which could be addressed with a SIP project (Chuck Bitting, conference call 17, April 2019; Melissa Trenchik, conference call, 17 August 2021; see "Guidance for Resource Management").

Further resources for flooding, erosion, and other fluvial issues include:

- Assessment of streambank stabilization and riparian restoration efforts: https://irma.nps.gov/DataStore/Reference/Profile/658012
- Buffalo River Watershed Plan in partnership with the Arkansas Natural Resource Commission (https://www.anrc.arkansas.gov/): https://www.adeq.state.ar.us/water/planning/integrated/303d/list.aspx
- GIS point data with spring locations by the Arkansas Geological Survey (Angela Chandler, Arkansas Geological Survey, geologist, written communication, 7 May 2021).
- Mott and Lauraas (2004) described in detail the water resources at Buffalo National River, identified gaps in information, made recommendations for future action, and provided a basis for future project development. The geologic issues addressed in their water resources management plan include watershed management, riparian zone and bank erosion, gravel mining, reservoirs and impoundments, and groundwater and karst geology.

Projects for flooding, erosion, and other fluvial issues:

- The Mapping Suitable Habitat of Threatened and Endangered Freshwater Mussels in Buffalo National River is a National Park Foundation funded (money awarded in 2021), ongoing project.
- In 2023, a Project Management Information System (PMIS) project (MWRO 317936) in collaboration with Ozark National Scenic Riverways will focus on habitat restoration of native mussels with additional opportunities for river mapping.

Research needs for flooding, erosion, and other fluvial issues:

- National Park Service (2018) stated the need to continue closing gravel bars to vehicular traffic, enlarging the riparian buffer between agricultural lands and the river, and minimizing development of park infrastructure within floodplains and riparian corridors (e.g., move restroom facilities farther away from the river).
- National Park Service (2018) identified a comprehensive river use management plan and a strategy for adaptation to climate change as high-priority planning needs. Data needs for these efforts include a comprehensive Buffalo River watershed study, streambank erosion mapping (high-priority data need), and dye tracing on Big Creek on the upper Buffalo.
- Determine which geologic units are going to require the most maintenance as a roadbed for unpaved roads (i.e., require the most imported gravel). This will help illuminate which roads are supplying excessive sediment to the river and could be paved or closed. This may require multidisciplinary work combining geology, surficial geologic mapping, soil science, slope mapping, and water-quality data.

Cave and Karst-related Issues

Research and Protection

Cave resources (see "Caves and Karst") are protected by a variety of laws (see "Geologic Resource Laws, Regulations, and Policies"). Specific to caves, the Federal Cave Resources Protection Act of 1988 (16 U.S.C. § 4301 et seq.) directs the Department of the Interior to inventory and list "significant" caves on federal lands. All caves on NPS lands are considered significant. This act recognizes that significant caves are an invaluable and irreplaceable part of our natural heritage, and that caves may be threatened by improper use and increased recreational demand. The purpose of the act is to secure and protect significant caves on federal land for the benefit and enjoyment of all people while fostering increased cooperation and information exchange among those who use caves for scientific, educational, or recreational purposes. The act also specifically addresses confidentiality of information regarding the nature and location of caves to ensure their protection, including exemptions for cave location information from the Freedom of Information Act (FOIA).

A protection strategy for caves hosting bat populations is a resource management goal. At least four threatened and endangered bat species are present in the park.

White-nose syndrome is confirmed in the park and poses a serious threat to bat populations which thereby affects cave invertebrate populations (National Park Service 1999; National Park Service 2018; Chuck Bitting, Buffalo National River, natural resource manager, conference call, 17 April 2019). All caves in the park are closed to prevent the spread of white-nose syndrome, in accordance with US Fish and Wildlife Service recommendations. Park managers want to keep caves free of gates and fences to protect the natural environment and habitat the caves provide. However, caves without gates may be at risk for vandalism, archeological looting, and speleothem (cave formation) theft. To this end, the park seeks to keep visitors out of caves at Buffalo National River; cave locations and maps are considered confidential information in order to protect sensitive resources (Thornberry-Ehrlich 2007).

Development of a cave management plan is a PMIS project slated for 2025 that is in the process of securing funding (Melissa Trenchik, Buffalo National River, chief of Resources Stewardship, Science, Interpretation and Education, conference call, 17 August 2021). Pertinent questions include whether any caves should be open to the public, how to protect ungated caves, and how to maintain or upgrade the existing barriers to visitor access. An inventory of the status of caves is a data need (e.g., gated or ungated, GPS locations, photographs, condition descriptions). This would be an ideal SIP project (see "Guidance for Resource Management"). Monitoring could be part of a cave management 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.

Visitor Safety

Cave and karst features may pose hazards to visitor safety at Buffalo National River. Sinkholes may form in areas of significant dissolution (fig. 26). Steep pits, some of which drop hundreds of feet, may be difficult to see at the surface. Some caves are long enough to cause people entering to get lost or injured. Gates and fences can be used to keep visitors out of caves, but these structures may have negative impacts on the natural cave environment and limited success in preventing human entry (see previous section "Research and Protection"). The park contains a mixture of gated and ungated cave entrances. Park managers intend to study cave access in a transparent process and in compliance with the National Environmental Policy Act (NEPA).

Figure 26. Photographs of sinkholes developed in the Batesville Sandstone.
The Batesville Sandstone (Mbv) has sufficient strength to overlay caverns in the underlying Boone Formation until they enlarge enough to cause collapse, forming large sinkholes. The pattern of sinkhole formation is commonly controlled by local joint orientations focusing dissolution along these pre-existing fracture pathways. Photograph is part of figure 9 in Hudson et al. (2011).

Karst Hydrology and Water Quality

Karst drainage poses risks to water quality because conduits in carbonate bedrock can quickly route water and contaminants over large distances instead of the natural adsorption of contaminants typical of water percolating slowly through the subsurface. Karst drainage characterizes all park streams that are underlain by the Boone Formation (geologic map units **Mbu**, **Mbmb**, **Mbsj**), the most widespread unit in the park. These streams are "sinking streams" (even if the stream has perennial flow)—much of their water is funneled underground through karst (Aley and Aley 1999). To further complicate the risks to water quality, karst drainage may facilitate interbasin transfer of groundwater and associated contaminants to streams beyond the topographic watershed (Mott and Lauraas 2004). Interbasin recharge negatively impacts water quality (e.g., increased nutrient loads) in the Buffalo River (Mott et al. 2000).

Knowledge of groundwater movement and land-use in the park and surrounding watershed can help park managers understand the degree and extent of the potential for water quality issues in the park. A study was conducted by Aley (1982) which characterized groundwater movement and contamination hazards in the park with particular attention paid to current human use and livestock grazing. They determined some contamination from human sewage was present. An update of this study would provide timely information for park resource managers because many of the septic systems installed or inherited by the park are now more than 50 years old or were unpermitted in the first place. Failing septic systems cannot always be replaced due to the potential for karst drainage, floodplain concerns, or the presence of other resources (archeological sites). Electrical resistivity studies were conducted in October 2020 by the US Geological Survey at Kyle's Landing and Ozark campgrounds to detect underground voids and determine if leach fields would introduce gray water into karst conduits. In these locations, the septic tanks will be replaced with vault/pit toilets that will require regular pumping (Melissa Trenchik, Buffalo National River, chief of Resources Stewardship, Science, Interpretation and Education, conference call, 17 August 2021). More karst and groundwater studies in locations across the park (e.g., Steel Creek where *E. coli* bacteria was detected) like the electrical resistivity study could reveal similar situations where park infrastructure needs to be changed to accommodate both visitor needs and water quality concerns.

Dye tracing in karst landscapes is a technique wherein dyes are added to an upland groundwater recharge area and traced to outlets (e.g., springs) to study the movement of groundwater. Dye tracing can be used to isolate leakage/contamination problems from adjacent areas; Mott and Lauraas (2004) detailed how to use this technique. Soto (2014) provided a summary of dye tracing studies at the park which included Mitch Hill Spring area; Fitton Cave and Van Dike Spring recharge area; Springs in the Mill Creek topographic basin; Dogpatch Springs topographic basin; Davis Creek topographic basin; John Eddings Cave/Elm Spring recharge area; Gilbert Spring and the Gilbert community; Tomahawk Creek area; and Big Creek area. Aley and Aley (1999) inventoried karst hydrology features and delineated groundwater recharge areas in the Fitton Cave and Fitton Spring area using dye tracing. Aley and Aley (2000) provided the final project report on the inventory and delineation of karst features at the park. The application of this technique to other areas would further refine the understanding of the groundwater system. A comprehensive guide to dye tracing procedures and interpretations was presented in Aley (2019) for the Ozark Underground Laboratory. The guidance therein applies to the setting at Buffalo National River.

In 2012, a 6,500-head swine Confined Animal Feeding Operation (CAFO) was approved by the Arkansas Department of Environmental Quality to be located on Big Creek, a tributary of the upper section of the Buffalo River, in an area of well-developed karst [e.g., John Eddings cave is approximately 8 km (5 mi) away]. This was the first time a farming operation of this magnitude had been situated within the Buffalo River watershed and only 5 km (3 mi) upstream from the park boundary (Brahana et al. 2014; Stone 2015). Scientific data for the Big Creek watershed such as dye tracing, resistivity studies, flow-gage data, and flora and fauna surveys, were largely lacking with no groundwater assessment, no karst assessment, no surface water assessment, and no biological assessment being performed (Brahana et al. 2014). The CAFO operated for six years before the state of Arkansas, in 2019, announced an agreement to cease operations and obtain a conservation easement on the land (Repanshek 2019).

The absence of data to understand the potential impacts of such operations led park managers to conduct several studies (Melissa Trenchik, written communication, 16 November 2021). Those studies include:

1. Big Creek Project, NPS-BUFF
    - In 2013, the park initiated the Big Creek Project. *E. coli* was measured at three sites (Big Creek and upstream and downstream of Big Creek on the Buffalo River).
    - Between 2014 and 2020, the three sites increased to six sites to capture regional effects, such as variations in geology and watershed characteristics.
    - Project goal, as described in the 2013 project plan: "Characterize *E. coli* concentrations for base-flow conditions when water-based recreation is likely to occur in response to permitted CAFO."
2. US Geological Survey (Ben Miller, hydrologic technician) project using seepage runs and dye tracing to understand base flow behavior within the Big Creek watershed, Newton County, AR. The final report is pending as of 2022.

Geologic Hazards

A geologic hazard ("geohazard") is a natural or human-caused geologic condition or process (e.g., volcanic eruption, earthquakes, landslides) that may impact park resources, infrastructure, or visitor and staff safety. In the context of naturally occurring hazards, it is important to understand the distinction between "hazard" and "risk". The level of "hazard" (low, medium, high) refers to the likelihood that an event will

occur. "Risk" refers to the consequences of the hazard event (Holmes et al. 2013). Identifying geologic hazards, assessing the likelihood of occurrence, and defining potential risks to infrastructure or people can assist the National Park Service with the management of these hazards (Schaller et al. 2014). The primary geologic hazards identified at Buffalo National River are slope movements, earthquakes, and climbing hazards.

Slope Movements

Park resource managers seek to make visitors aware of the potential for slope hazards such as rockfalls and to warn them about active slide and rockfall areas (see "Slope Movements" in the "Geologic Features and Processes" chapter; Thornberry-Ehrlich 2007). Areas where slope movements have occurred in the past can indicate where they may occur again. Areas in and near the park with a history of slope movements include Boxley Valley, roads near Ponca, and roads at Jasper. Carlton Branch, a stream near Jasper (outside the park boundary), is a major slide hazard area. Following every rain, reactivation of slide material releases sediment causing the stream to become very cloudy, like milk of magnesia in appearance (fig. 27; Chuck Bitting, Buffalo National River, natural resource manager, conference call, 17 April 2019).

Predicting potential slope hazard locations is a primary objective for risk management. This is difficult to do because, often, several factors combine to create slope instability and movement, and these factors may be difficult to identify and/or quantify. For example, at "The Barns," a combination of drought conditions, which reduced stabilizing vegetation, followed by heavy rainfall, which caused clays to swell in fractures, resulted in the failure of a bus-sized block of bedrock. The Barns is the local name for two bluff shelters that are exposed for over a quarter mile just upstream from and continuous with Margaret White Bluff. They are accessible from pastures located in the adjacent floodplain and were large enough to store hay in the past (Richard Hutto, Arkansas Geological Survey, geologist, written communication, 23 April 2021). Digital elevation models that identify steep slopes could be used to assess the potential for slope movements, but this method has not yet been applied to Buffalo National River (Chuck Bitting, Buffalo National River, natural resource manager, conference call, 17 April 2019).

Resource managers could consider obtaining information to assess the frequency and magnitude of rockfall (and other slope movements) in high visitation areas. A photo-monitoring project is one possibility. The SIP program is an option to support such a project (see "Guidance for Resource Management"). 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 Unstable Slopes Management Program (https://usmp.info/client/credits.php) is a cooperative effort between the National Park Service, Federal Highways, University of Montana, and others working to create a central database of unstable slopes with ranking systems. This database will support an unstable slope management tool to allow prioritization of mitigation to reduce slope hazard risks along transportation corridors. The slopes of Buffalo National River would be ideal candidates for inclusion in the effort (contact the NPS Geologic Resources Division at https://www.nps.gov/orgs/1088/contactus.htm). 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 landslides, (2) landslide causes and triggers, (3) geologic materials in landslides, (4) measurement of landslide movement, and (5) assessment of landslide hazards and risks. The Arkansas Geological Survey's website (https://www.geology.arkansas.gov/geohazards/landslides.html) discusses local landslides and other geologic hazards.

Earthquakes

Earthquakes are ground vibrations—shaking—that occur when rocks suddenly move along a fault (see "Faults and Folds"), releasing accumulated energy (Braile 2009). Earthquake intensity ranges from imperceptible by humans to destruction of developed areas and alteration of the landscape. The "Richter magnitude" is a measure of the energy released by an earthquake. Earthquakes can directly damage park infrastructure or trigger other hazards such as slope movements that may impact park resources, infrastructure, or visitor safety. Figure 28 shows the predicted earthquake hazard for the next 50 years for Buffalo National River. The park is not located near a known active seismic zone; however, earthquakes with magnitudes between 2 and 3 are not uncommon. A 4.0 earthquake was recently felt near Murray on the Little Buffalo River (Mark Hudson, US Geological Survey, geologist, conference call, 17 April 2019).

Areas in the Buffalo River region have the potential for earthquakes because basement faults are oriented perpendicular to the extensional force direction of the modern plate tectonic stress field (or forces within Earth's crust). In 2019 and 2020, the US Geological Survey flew high-resolution magnetic and radiometric surveys over northwest Arkansas in the upper Buffalo and Little Buffalo River areas (McCafferty and Brown

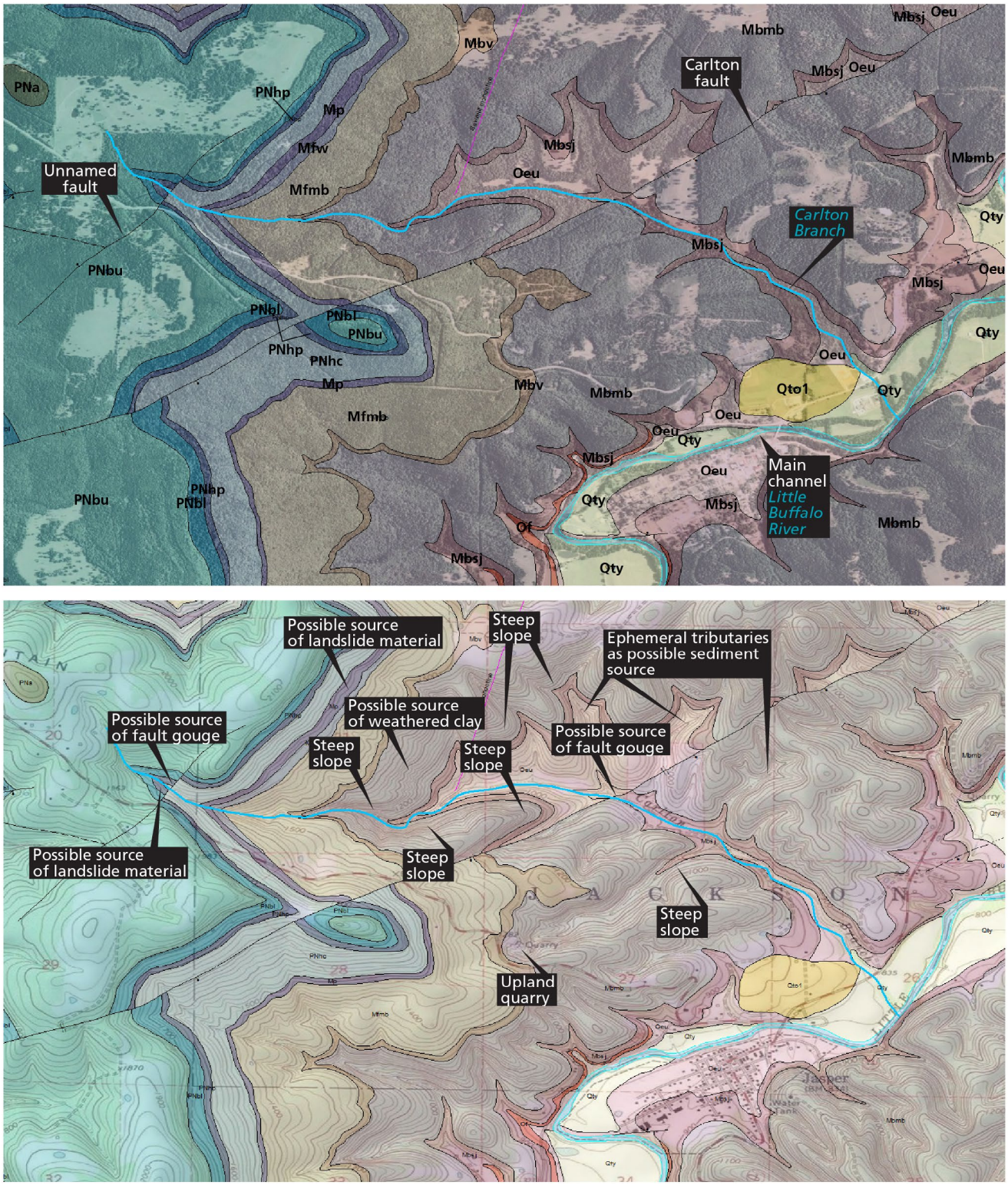

Figure 27. Geologic maps of the Carlton Branch area.
The top graphic shows mapped geologic formations over aerial imagery; the bottom graphic shows the geologic formations over a topographic map. Following precipitation events, Carlton Branch runs a milky white color for several days. The source of the suspended sediment is unclear but could stem from crosscutting faults or deeply weathered bedrock. Carlton Branch is located near Jasper, beyond park boundaries. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) using GRI GIS data, ESRI World Imagery, and USA topo base maps.

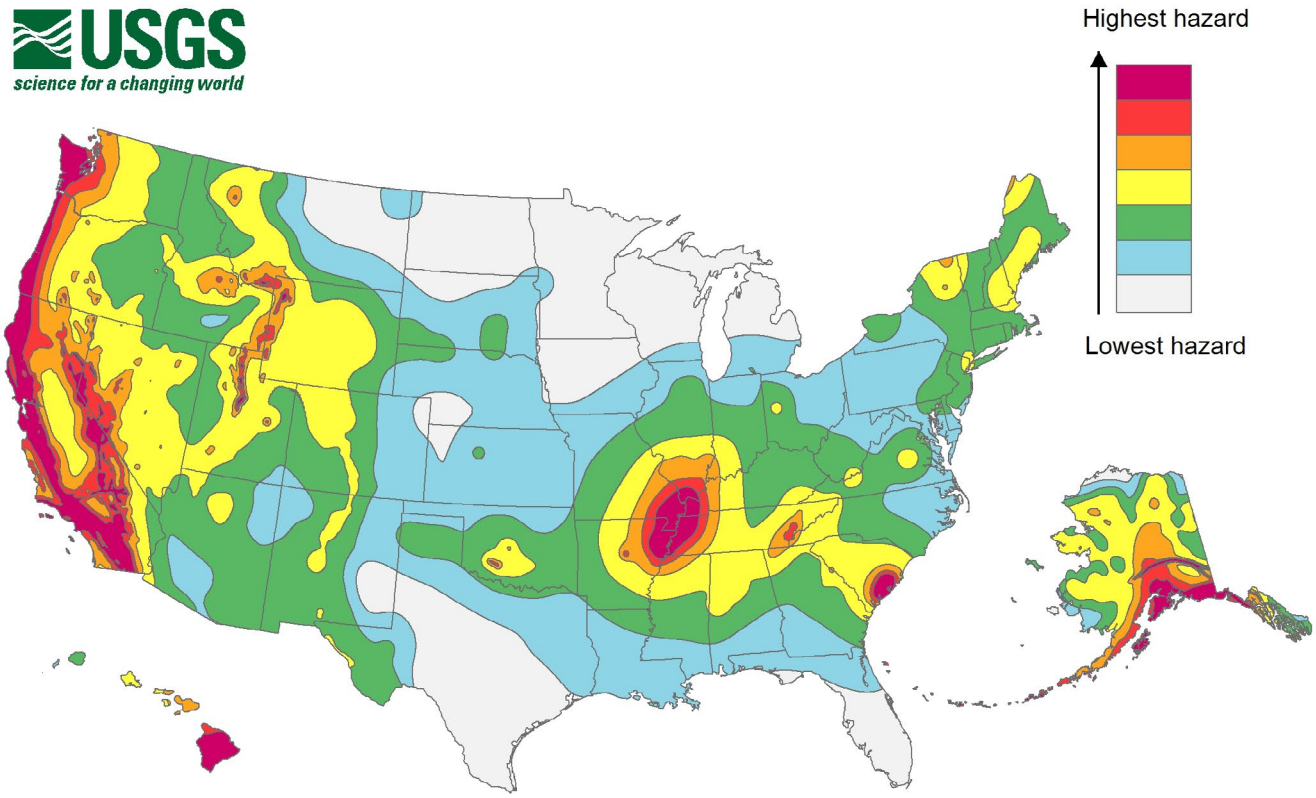

Figure 28. Seismic hazard map.
The map shows predicted earthquake hazards across the United States for the next 50 years based on the 2018 update of the National Seismic Hazard Models (https://www.usgs.gov/programs/earthquake-hazards/science/introduction-national-seismic-hazard-maps). Northern Arkansas is near the New Madrid Seismic Zone and has moderate probability of seismicity. Locally, the hazard may be greater than shown because site geology (particularly unconsolidated sediment) may amplify ground motions. Graphic by the US Geological Survey.

2020). The survey was flown to improve the geologic framework for research related to mineral resource, energy resource, and geologic hazards studies in the area. Results will aid in understanding concealed geology and may detect active faults. The low-flying planes presented a good opportunity to educate the public on active science in the park (Mark Hudson, conference call, 17 April 2019).

Climbing Hazards

The secluded cliffs, bluffs, and rock outcrops at the park attract climbers. Park staff are noticing climbing anchors on bluffs and cliffs in designated wilderness areas where such installations are prohibited. Due to their non-friable surfaces and propensity to develop ledges and handholds, steep cliffs and bluffs of Atoka Formation (**PNa**) and St. Peter Sandstone (**Osp**) are most attractive to climbers. A climbing management plan is needed (Melissa Trenchik, Buffalo National River, chief of Resources Stewardship, Science, Interpretation and Education, conference call, 17 August 2021). Identifying the outcrop extents using GRI GIS data and onsite observations, and vertical heights of these formations inside park boundaries could be a valuable SIP project (see "Guidance for Resource Management") and help guide the climbing management plan efforts.

Abandoned Mineral Lands and Disturbed Lands

Abandoned mineral lands (AML; see "Abandoned Mineral Lands" in the "Geologic Features and Processes" chapter) are a testament to the historic lead and zinc mining in the park area. Although many mining features (e.g., Rush mining district in the lower ranger district) may be considered historic, they also pose serious safety hazards to intrepid visitors, such as unstable rock, vertical drops, poor footing, and

flooded mine workings (Burghardt 1992; Burghardt and Higgins 1993). Burghardt (1989) provided an overview of mine-related hazards. In the 1990s, many mine openings were closed with bat-friendly gates to allow bat passage, but not human (Burghardt and Higgins 1993). Burghardt (1993) presented criteria to estimate closure costs for the Rush mining district; these could be updated and applied to other mine closures in the park. High-visitation areas such as Rush and Lost Valley are of highest priority for AML hazard mitigation (Chuck Bitting, Buffalo National River, natural resource manager, conference call, 17 April 2019). As of 2021, the exact number and nature of mine openings and mitigated/gated openings within boundaries are data needs for the park; this issue is not yet in the Facility Management Software System (Melissa Trenchik, Buffalo National River, chief of Resources Stewardship, Science, Interpretation and Education, conference call, 17 August 2021). This effort may be a candidate for an SIP project (see "Guidance for Resource Management").

Road-related runoff causes erosional pulses (see fig. 25; "Disturbed Lands" in the "Geologic Features and Processes" chapter) that negatively impact park streams and rivers (see "Flooding, Erosion, and other Fluvial Issues") as well as cave resources by introducing excess sediment to these systems (Greco 2001). National Park Service (2018) stated that poor gravel road maintenance and poor stream and pasture management were threatening the clean, free-flowing river (a fundamental park resource) by increasing sediment load, adversely affecting floodplain structure, and causing normally deep pools to shallow. Aley and Aley (1999) determined that sediment derived from a local, steep service road caused adverse hydrologic impacts to Fitton Cave and Fitton Spring. Additional problem areas identified by Greco (2001) included Pruitt Crossing at Mill Creek, North River Road, a tributary to Hoskins Creek (site of a breached dam; fig. 29), Erbie Road, Kyle's Landing Road, Steele Creek Road, and Cave Springs Road. As part of a watershed-management approach, Mott and Lauraas (2004) suggest addressing roads outside the park boundary as well.

Greco (2001) suggested a roads inventory and analysis to identify problem areas. This would include identifying areas where control and prevention of road-related runoff and sediment production occur. Well-established practices to control and prevent road-generated erosion and peak flows, such as simple road decommissioning, upgrading surface type, culvert placement/replacement, and water-bars, can drastically reduce road-related impacts. A comprehensive roads management plan was identified in National Park Service (2018) as a medium-priority planning need.

Figure 29. Photographs of sediment washed downstream from a breached dam. Top image looks downstream from a previously impounded farm pond. The pond was on park-adjacent property and breached purposely to clean out the sediment. The bottom image shows the sediment washed into a tributary to Hoskins Creek at the park boundary. A sediment detention basin was constructed at the North River Road area to prevent the bulk of the sediment from washing farther into the Buffalo River. Photographs by Deana Greco (NPS Geologic Resources Division) taken on 8 December 2000.

The following are recommendations to reduce road-related erosion at the park (Greco 2001):

- Identify active roads. Using GPS technology, identify location of impacted drainages, hillslopes, and other natural and cultural resources impacted by roads. Identify type and location of road features causing impacts and determine the extent of impact. Determine road width and slope for comparison with Best Management Practices for road specifications. Identify low-water bridges as they influence stream habitat, stability, and morphology. Photo document road related impacts.

- Identify and inventory backcountry/abandoned roads with an emphasis on identifying areas causing active erosion. Determine levels of compaction and success of vegetative recovery on road surface. Photo documentation of road related impacts and determine extent of impacts.
- Input of GPS and inventory data into ArcGIS, categorize and rank roads based on impacts, and make recommendations for road system. Determine, through ranking, which roads to close or improve and upgrade.
- Determine proper culvert sizing as it relates to contributing watershed drainage as well as cross drain spacing/location. Evaluate the feasibility of redesigning culvert inlets to handle water/sediment flows and determine if redesign will accommodate sediment transport. Determine the frequency of recent rain and erosional events. Meteorological data collected by the park can be used to determine a recurrence interval for these events. The road corridor and associated drainage structures should be designed to withstand a 100-year runoff event.
- Develop a final report and findings. Synthesize field inventory and data analysis into a comprehensive document for management decisions.
- Develop cost estimates for road-related closure and upgrades and format into a funding request to appropriate funding sources.

Other potential resource-management reference materials for abandoned mineral lands and disturbed lands:

- Hofer et al. (1995)—surface geology and land-use patterns of the Buffalo River watershed.
- Burghardt (1989)—description of mines and hazards in the Rush mining district.
- McKnight (1935)—a definitive source for zinc and lead deposits and mining of northern Arkansas.
- Aley and Aley (1999)—dye tracing to delineate groundwater recharge areas.

Paleontological Resource Inventory, Monitoring, and Protection

Buffalo National River has geologic units known to be locally fossiliferous, so the potential exists for further discovery of fossils in bedrock or unconsolidated deposits (see "Paleontological Resources"). All paleontological resources are nonrenewable and subject to science-informed inventory, monitoring, protection, and interpretation as outlined by the 2009 Paleontological Resources Preservation Act.

Hunt et al. (2008) prepared a paleontological resource summary for the parks of the Heartland Network, including Buffalo National River. The summary was compiled through extensive literature reviews and interviews with park staff and professional geologists and paleontologists, but no field-based investigations. An on-the-ground paleontological survey would be an ideal SIP project. Resource-management recommendations from Hunt et al. (2008) for the park included:

- Encourage park staff to observe exposed gullies, eroded bedrock, and streambeds for fossil material while conducting their usual duties.
- Photographically document and potentially monitor the location of any paleontological resources that may be observed in situ (fig. 30).
- Consider long-term monitoring of paleontological sites.
- Contact the NPS Geologic Resources Division (https://www.nps.gov/orgs/1088/contactus.htm) for paleontological resource management assistance.

A park-specific, comprehensive paleontological review was prepared by Konett et al. (2018). This report included recommended interpretive themes (e.g., general paleontology in areas such as Lost Valley and "fossil quarry" at the Buffalo Point site, caves as time capsules for fossil resources, and National Fossil Day). Suggestions and strategies for paleontological resource management and protection included how to adhere to NPS policy, when to intervene to prevent resource loss, and condition status of specific fossil locations within park boundaries.

Construction activities may disturb paleontological resources, therefore, construction proposed in areas known to contain fossils should be assessed to determine the potential impacts. A recent construction/rehabilitation proposal for the Cave Mountain Road corridor prompted an assessment of in situ paleontological resources. Previous inventories identified paleontological resources in the area (Konett et al. 2018). To assess potential disturbance or impacts to paleontological resources due to road construction activities, staff at Buffalo National River requested the assistance of the NPS Geologic Resources Division paleontology group. A preconstruction assessment (Santucci et al. 2021) of potential impacts to any paleontological resources occurring within the construction footprint of the Cave Mountain Road Rehabilitation Project found in situ fossils. The assessment report provided recommendations and mitigation measures to reduce any potential adverse impacts to park fossils and associated geologic features

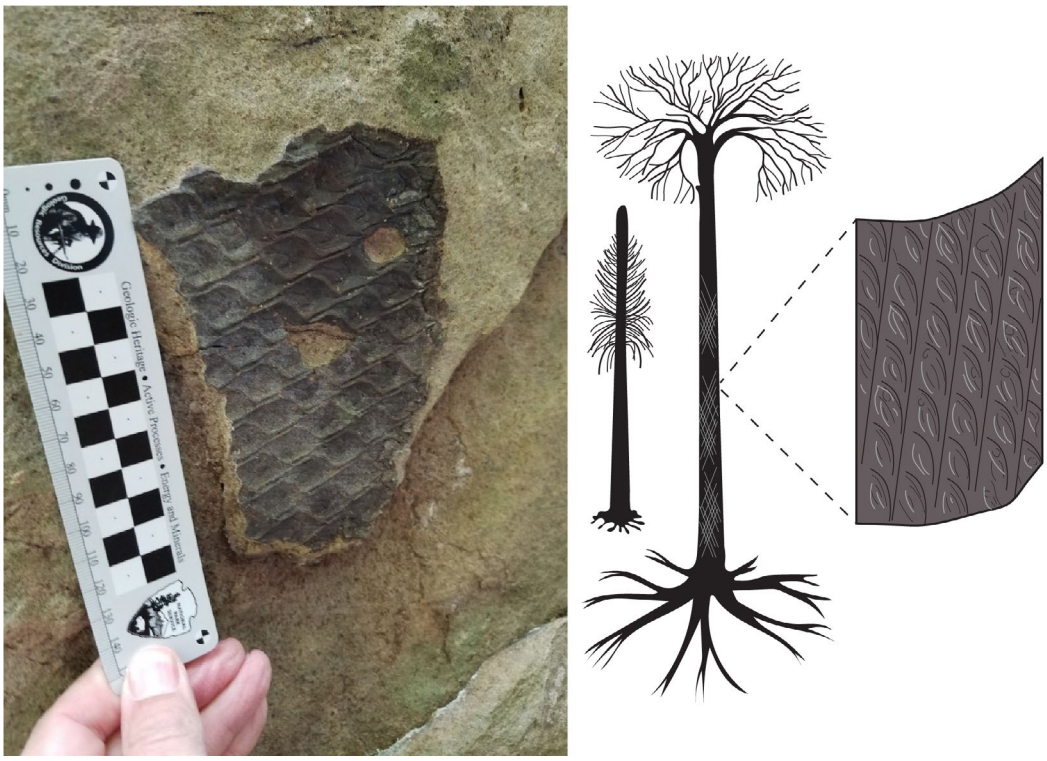

Figure 30. Photograph of Early Pennsylvanian lycopsid bark fossil with a schematic graphic showing its formation.
The fossil was originally part of a primitive vascular tree. This fossil is preserved in the Bloyd Formation (PNbu, PNbm, PNbl) on Cave Mountain within Buffalo National River. Such fossils are commonly visible in situ throughout the park. NPS photograph presented as figure 3 in Santucci et al. (2021).

and processes related to any construction related activities. Assistance with this type of assessment for future proposed projects can be requested through https://irma.nps.gov/Star/ (available on the Department of the Interior [DOI] network only).

As of April 2021, the park is investigating the potential to acquire the land around Conard Fissure. The fissure contains Pleistocene bone deposits; it was a lair for big cats and a natural trap for other fauna. The landowner is interested in selling, but negotiations continue (Chuck Bitting, Buffalo National River, natural resource manager, conference call, 17 April 2019; Justin Tweet, National Park Service, paleontologist, written communication, 5 April 2021). The Conard Fissure is also a significant historical resource. Its discovery in the early 1900s spurred various camps and digs over the years. Many specimens, including species first described from this locality, grace museums across the country (Justin Tweet, conference call, 17 April 2019).

Further Mapping and GIS Data Needs

- The park has noted an overall lack of in-house GIS expertise (GRI conference call participants, conference call, 17 April 2019).
- A GIS-based cave and karst inventory
- GPS trail surveys
- Land-use/land-cover class mapping
- Mine and cave openings inventory
- Electrical resistivity to detect underground voids in areas with septic issues or sensitive locations (e.g., Steel Creek)
- A field-based paleontological inventory (contact the NPS Geologic Resources Division at https://www.nps.gov/orgs/1088/contactus.htm)
- 1:24,000-scale geologic maps for the 39 quadrangles of interest intersecting the entire Buffalo River watershed
- Groundwater flow maps and accurate watershed mapping
- Watershed delineation using detailed terrace analysis and mapping to determine the incision history of the river
- Detailed fault mapping
- Springs inventory update
- Landscape evolution mapping
- Landslide (slope movement) area mapping

Guidance for Resource Management

Information in this chapter will assist resource managers in addressing geologic resource management issues and applying NPS policy. The compilation and use of natural resource information by park managers is called for in the 1998 National Parks Omnibus Management Act (§ 204), National Park Service 2006 Management Policies, and the Natural Resources Inventory and Monitoring Guideline (NPS-75).

Four Ways to Receive Geologic Resource Management Assistance

- Contact the NPS Geologic Resources Division (https://www.nps.gov/orgs/1088/contactus.htm). GRD staff members provide coordination, support, and guidance for geologic resource management issues in three emphasis areas: (1) geologic heritage, (2) active processes and hazards, and (3) energy and minerals management. GRD staff can provide technical assistance with resource inventories, assessments and monitoring; impact mitigation, restoration, and adaptation; hazards risk management; laws, regulations, and compliance; resource management planning; and data and information management. Park managers can formally request assistance via https://irma.nps.gov/Star/.
- Formally request assistance at the Solution for Technical Assistance Requests (STAR) webpage: https://irma.nps.gov/Star/ (available on the Department of the Interior [DOI] network only). NPS employees (from a park, region, or any other office outside of the Natural Resource Stewardship and Science [NRSS] Directorate) can submit a request for technical assistance from NRSS divisions and programs.
- Submit a proposal to receive geologic expertise through the Scientists in Parks (SIP; see https://www.nps.gov/subjects/science/scientists-in-parks.htm). Formerly the Geoscientists-in-the-Parks program, the SIP program places scientists (typically undergraduate students) in parks to complete science-related projects that may address resource management issues. Proposals may be for assistance with research, interpretation and public education, inventory, and/or monitoring. The Geologic Resources Division can provide guidance and assistance with submitting a proposal. The Geological Society of America and Environmental Stewards are partners of the SIP program. Visit the internal SIP website to submit a proposal at https://doimspp.sharepoint.com/sites/nps-scientistsinparks.
- Refer to *Geological Monitoring* (Young and Norby 2009), which 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. Chapters are available online at https://www.nps.gov/subjects/geology/geological-monitoring.htm.

Buffalo National River Documents

As of May 2022, the park has a foundation document (National Park Service 2018), but not yet a Natural Resource Condition Assessment or Resource Stewardship Strategy, all of which will be primary sources of information for resource management within the park. The foundation document listed the following fundamental resources and values, which are resource management priorities: clean, free-flowing river; physical and biological processes; aquatic and riparian habitat; geologic resources; cultural and historic resources; wilderness character; and recreational opportunities. Cultural landscape restoration and management are addressed in several publications including Campbell (1975), Neidinger (1994), Rogers (1987), Pitcaithley (1989), and National Park Service (2010a). Park staff uses LiDAR data from 2010 and 2017 (Melissa Trenchik, Buffalo National River, chief of Resources Stewardship, Science, Interpretation and Education, conference call, 17 August 2021).

The park's Resource Management Plan (National Park Service 1999) is 20 years old but contains valuable references and recommendations. Management goals described in National Park Service (1999; p. 5–7) include:

- Preserve the National River scene and maintain a free-flowing, non-polluted river.
- Manage for the perpetuation of natural and cultural resources, while providing recreation for visitors in such a manner that the impact on the environment will be minimized.
- Coordinate, encourage, and administer a viable and purposeful research program.
- Inventory and monitor park resources (this GRI report is part of that effort).
- Reintroduce extirpated species where feasible.

- Provide special protection for rare and endangered flora and fauna.
- Open fields will be maintained where scenic qualities and wildlife habitat will be restored.

The GRI scoping meeting for the park (Thornberry-Ehrlich 2007) and subsequent GRI conference calls produced the following suggestions for resource managers at Buffalo National River:

- Perform further groundwater dye trace studies to understand the flow of groundwater in the park and delineate the subterranean watershed. After the Buffalo River basin, focus on the Water Creek basin next. NPS Water Resources Division (http://go.nps.gov/waterresources) is a potential partner in this project.
- Promote a potential thesis project to obtain sediment samples looking for lead and zinc mineralization along the river corridor.
- Update the GIS presented by Hofer et al. (1995), which included quantitative surficial geology and land-use patterns (e.g., forest, agricultural, urban and barren; water and transportation; power and communication). The geology component is likely superseded by the GRI GIS data; however, the historic land-use patterns may provide a baseline inventory for comparisons with present use. This could be an SIP project.
- Perform a comprehensive paleontological inventory of the national river. Locate all vertebrate paleontological resources in pits and caves along the river. Caves with drops commonly contain these types of remains. Establish a plan to deal with potential illegal sampling and collecting. The NPS Geologic Resources Division paleontology program could assist with this project (https://www.nps.gov/orgs/1088/contactus.htm).
- Research the incision history of the river using distinguishable, dated terrace deposits, and the relationship with cave formations and faulting.
- Cooperate with the Cave Research Foundation and other agencies to perform comprehensive cave mapping at Buffalo River. Incorporate cave maps and locations into the park's GIS. The NPS Geologic Resources Division caves and karst program could assist with this project (https://www.nps.gov/orgs/1088/contactus.htm).
- Perform sedimentation and palynologic studies on largely undisturbed cave deposits and other sediments.
- Investigate the potential for cave formations (speleothems) to contain a regional record of paleoclimate.
- Compare the orientation of surficial fractures to fractures in caves. Also note local stream gradients and distance of caves to streams.
- Perform hydrogeologic modeling to determine the mechanics of the karst window and lower spring at Mitch Hill.
- Obtain results from heavy metal sampling conducted in the area by the Arkansas Geological Survey.

NPS Resource Management Guidance and Documents

- NPS Management Policies 2006 (Chapter 4: Natural Resource Management): https://www.nps.gov/policy/index.cfm
- 1998 National Parks Omnibus Management Act: https://www.congress.gov/bill/105th-congress/senate-bill/1693
- NPS-75: Natural resource inventory and monitoring guideline: https://irma.nps.gov/DataStore/Reference/Profile/622933
- NPS Natural resource management reference manual #77: https://irma.nps.gov/DataStore/Reference/Profile/572379
- Resist-Accept-Direct (RAD)—A Framework for the 21st-Century Natural Resource Manager: https://doi.org/10.36967/nrr-2283597

Regional Geologic Information

Geologic information specific to the park area is available from the following sources:

- Arkansas Geological Survey scanned field books from mapping (contact: Scott Ausbrooks).
- Bush et al. (1980) discussed regional bedrock geology.
- Hudson et al. (2011) provided a field guide to the park geology.
- Chisholm (1959) discussed park rocks in detail.
- McKnight (1935), Branner (1901), and Adams et al. (1904) discussed mineral deposits in the park area.
- Keen-Zebert et al. (2014) discussed Quaternary geology and geomorphology of the park.
- Paces et al. (2017) discussed Pleistocene cave evolution at Fitton Cave.
- Early US Geological Survey folio covering the Harrison area (Purdue and Miser 1916).

Geologic Resource Laws, Regulations, and Policies

The following table (table 6), which was developed by the NPS Geologic Resources Division, summarizes

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

Table 6. Geologic resource laws, regulations, and policies.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 NPS Management Policies
Paleontology	**Archaeological Resources Protection Act of 1979, 16 USC §§ 470aa – mm Section 3 (1) Archaeological Resource—** nonfossilized and fossilized paleontological specimens, or any portion or piece thereof, shall not be considered archaeological resources, under the regulations of this paragraph, unless found in an archaeological context. Therefore, fossils in an archaeological context are covered under this law. **Federal Cave Resources Protection Act of 1988, 16 USC §§ 4301 – 4309 Section 3 (5) Cave Resource—**the term "cave resource" includes any material or substance occurring naturally in caves on Federal lands, such as animal life, plant life, paleontological deposits, sediments, minerals, speleogens, and speleothems. Therefore, every reference to cave resource in the law applies to paleontological resources. **National Parks Omnibus Management Act of 1998, 54 USC § 100701** 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. **43 CFR Part 49** (in development) will contain the DOI regulations implementing the Paleontological Resources Preservation Act.	**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.

Table 6, continued. Geologic resource laws, regulations, and policies.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 NPS Management Policies
Caves and Karst Systems	**Federal Cave Resources Protection Act of 1988, 16 USC §§ 4301 – 4309** requires Interior/ Agriculture to identify "significant caves" on Federal lands, regulate/ restrict use of those caves as appropriate, and include significant caves in land management planning efforts. Imposes civil and criminal penalties for harming a cave or cave resources. Authorizes Secretaries to withhold information about specific location of a significant cave from a Freedom of Information Act (FOIA) requester. **National Parks Omnibus Management Act of 1998, 54 USC § 100701** protects the confidentiality of the nature and specific location of cave and karst resources. **Lechuguilla Cave Protection Act of 1993, Public Law 103-169** created a cave protection zone (CPZ) around Lechuguilla Cave in Carlsbad Caverns National Park. Within the CPZ, access and the removal of cave resources may be limited or prohibited; existing leases may be cancelled with appropriate compensation; and lands are withdrawn from mineral entry.	**36 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.
Recreational Collection of Rocks Minerals	**NPS Organic Act, 54 USC. § 100101 et seq.** directs the NPS to conserve all resources in parks (which includes rock and mineral resources) unless otherwise authorized by law. **Exception: 16 USC. § 445c (c) – Pipestone National Monument enabling statute**. Authorizes American Indian collection of catlinite (red pipestone).	**36 C.F.R. § 2.1** prohibits possessing, destroying, disturbing mineral resources…in park units. **Exception: 36 C.F.R. § 7.91** allows limited gold panning in Whiskeytown. **Exception: 36 C.F.R. § 13.35** allows some surface collection of rocks and minerals in some Alaska parks (not Klondike Gold Rush, Sitka, Denali, Glacier Bay, and Katmai) by non-disturbing methods (e.g., no pickaxes), which can be stopped by superintendent if collection causes significant adverse effects on park resources and visitor enjoyment.	**Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity.

Table 6, continued. Geologic resource laws, regulations, and policies.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 NPS Management Policies
Mining Claims (Locatable Minerals)	**Mining in the Parks Act of 1976, 54 USC § 100731 et seq.** authorizes NPS to regulate all activities resulting from exercise of mineral rights, on patented and unpatented mining claims in all areas of the System, in order to preserve and manage those areas. **General Mining Law of 1872, 30 USC § 21 et seq.** allows US citizens to locate mining claims on Federal lands. Imposes administrative and economic validity requirements for "unpatented" claims (the right to extract Federally-owned locatable minerals). Imposes additional requirements for the processing of "patenting" claims (claimant owns surface and subsurface). Use of patented mining claims may be limited in Wild and Scenic Rivers and OLYM, GLBA, CORO, ORPI, and DEVA. **Surface Uses Resources Act of 1955, 30 USC § 612** restricts surface use of unpatented mining claims to mineral activities.	**36 CFR § 5.14** prohibits prospecting, mining, and the location of mining claims under the general mining laws in park areas except as authorized by law. **36 CFR Part 6** regulates solid waste disposal sites in park units. **36 CFR Part 9, Subpart A** requires the owners/operators of mining claims to demonstrate bona fide title to mining claim; submit a plan of operations to NPS describing where, when, and how; prepare/submit a reclamation plan; and submit a bond to cover reclamation and potential liability. **43 CFR Part 36** governs access to mining claims located in, or adjacent to, National Park System units in Alaska.	**Section 6.4.9** requires NPS to seek to remove or extinguish valid mining claims in wilderness through authorized processes, including purchasing valid rights. Where rights are left outstanding, NPS policy is to manage mineral-related activities in NPS wilderness in accordance with the regulations at **36 CFR Parts 6** and **9A**. **Section 8.7.1** prohibits location of new mining claims in parks; requires validity examination prior to operations on unpatented claims; and confines operations to claim boundaries.
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 13693** (Planning for Federal Sustainability in the Next Decade) (2015) established to maintain Federal leadership in sustainability and greenhouse gas emission reductions.	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, including climate change. **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.

Table 6, continued. Geologic resource laws, regulations, and policies.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 NPS 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.
Nonfederal minerals other than oil and gas	**NPS Organic Act, 54 USC §§ 100101 and 100751**	**NPS regulations at 36 CFR Parts 1, 5, and 6** require the owners/operators of other types of mineral rights to obtain a special use permit from the NPS as a **§ 5.3** business operation, and **§ 5.7** – Construction of buildings or other facilities, and to comply with the solid waste regulations at **Part 6**.	**Section 8.7.3** states that operators exercising rights in a park unit must comply with **36 CFR Parts 1** and **5**.

Table 6, continued. Geologic resource laws, regulations, and policies.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 NPS Management Policies
Common Variety Mineral Materials (Sand, Gravel, Pumice, etc.)	**Materials Act of 1947, 30 USC § 601** does not authorize the NPS to dispose of mineral materials outside of park units. **Reclamation Act of 1939, 43 USC §387**, authorizes removal of common variety mineral materials from federal lands in federal reclamation projects. This act is cited in the enabling statutes for Glen Canyon and Whiskeytown National Recreation Areas, which provide that the Secretary of the Interior may permit the removal of federally owned nonleasable minerals such as sand, gravel, and building materials from the NRAs under appropriate regulations. Because regulations have not yet been promulgated, the National Park Service may not permit removal of these materials from these National Recreation Areas. **16 USC §90c-1(b)** authorizes sand, rock and gravel to be available for sale to the residents of Stehekin from the non-wilderness portion of Lake Chelan National Recreation Area, for local use as long as the sale and disposal does not have significant adverse effects on the administration of the national recreation area.	None applicable.	**Section 9.1.3.3** clarifies that only the NPS or its agent can extract park-owned common variety minerals (e.g., sand and gravel), and: -only for park administrative uses; -after compliance with NEPA and other federal, state, and local laws, and a finding of non-impairment; -after finding the use is park's most reasonable alternative based on environment and economics; -parks should use existing pits and create new pits only in accordance with park-wide borrow management plan; -spoil areas must comply with **Part 6** standards; and -NPS must evaluate use of external quarries. Any deviation from this policy requires a written waiver from the Secretary, Assistant Secretary, or Director.

Additional References, Resources, and Websites

Arkansas Geology

- Arkansas Geological Survey: https://www.geology.arkansas.gov/

Caves and Karst

- Cave Research Foundation: http://www.cave-research.org/index.php
- *Geological Monitoring* chapter about caves (Toomey 2009): http://go.nps.gov/geomonitoring
- National Cave and Karst Research Institute: http://www.nckri.org/
- NPS Geologic Resources Division caves and karst website: https://www.nps.gov/subjects/caves/index.htm

Climate Change Resources

- Intergovernmental Panel on Climate Change: http://www.ipcc.ch/
- NPS Climate Change Response Program Resources: http://www.nps.gov/subjects/climatechange/resources.htm
- NPS Sea Level Rise Map Viewer: https://maps.nps.gov/slr/
- NPS Climate Change, Sea Level Change website: https://www.nps.gov/subjects/climatechange/sealevelchange.htm/index.htm
- US Global Change Research Program: http://www.globalchange.gov/home

Geologic Hazards

- NPS Geologic Resources Division geohazards website: http://go.nps.gov/geohazards
- *Summary and categorization of documented geologic hazards of the National Park System* (Schaller et al. 2014)
- USGS Earthquake Hazards Program unified hazard tool: https://earthquake.usgs.gov/hazards/interactive/
- *US Geological Survey Natural hazards science strategy* (Holmes et al. 2013)

Geologic Maps

- Geologic maps of Arkansas: https://www.geology.arkansas.gov/maps-and-data/geologic-maps.html
- The American Geosciences Institute provides information about geologic maps and their uses: http://www.americangeosciences.org/environment/publications/mapping

Geological Surveys and Societies

- Arkansas Geological Survey: https://www.geology.arkansas.gov/
- US Geological Survey: http://www.usgs.gov/
- Geological Society of America: http://www.geosociety.org/
- American Geophysical Union: https://www.agu.org/
- American Geosciences Institute: http://www.americangeosciences.org/
- Association of American State Geologists: http://www.stategeologists.org/

Geology of National Park Service Areas

- NPS Geologic Resources Division (Lakewood, Colorado) Energy and Minerals; Active Processes and Hazards; Geologic Heritage: http://go.nps.gov/geology
- NPS Geodiversity Atlas: https://www.nps.gov/articles/geodiversity-atlas-map.htm
- NPS Geologic Resources Inventory: http://go.nps.gov/gri
- NPS Geoscience Concepts website: https://www.nps.gov/subjects/geology/geology-concepts.htm

Landslides and Slope Movements

- *Geological Monitoring* chapter about slope movements (Wieczorek and Snyder 2009): http://go.nps.gov/geomonitoring
- *The Landslide Handbook—A Guide to Understanding Landslides* (Highland and Bobrowsky 2008)
- *Landslide hazards and climate change* (Coe 2016)
- Unstable Slope Management Program for transportation corridor risk reduction: https://usmp.info/client/credits.php
- US Geological Survey landslides website: http://landslides.usgs.gov/

NPS Reference Tools

- NPS Technical Information Center (TIC) (Denver, Colorado; repository for technical documents): https://www.nps.gov/orgs/1804/dsctic.htm
- The GRI team collaborates with TIC to maintain an NPS subscription to GEOREF, the premier online geologic citation database, via the Denver Service Center Library interagency agreement with the Library of Congress. Multiple portals are available for NPS staff to access these records.
- GRI staff uploads scoping summaries, maps, and reports to the NPS IRMA portal (https://irma.nps.gov/DataStore/) and the GRI Publications Webpage (https://www.nps.gov/subjects/geology/geologic-resources-inventory-products.htm).

Paleontological Resources

- *A preliminary inventory of NPS paleontological resources found in cultural resource contexts* (Kenworthy and Santucci 2006)
- *Geological Monitoring* chapter about paleontological resources (Santucci et al. 2009): http://go.nps.gov/geomonitoring
- The NPS Fossils and Paleontology website: http://go.nps.gov/paleo

US Geological Survey Reference Tools

- 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): https://store.usgs.gov/map-locator
- USGS Publications Warehouse (many publications available online): http://pubs.er.usgs.gov
- Tapestry of Time and Terrain (descriptions of physiographic regions): http://pubs.usgs.gov/imap/i2720/

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