National Park Service
US Department of the Interior

Natural Resource Stewardship and Science

# Hot Springs National Park

## *Geologic Resources Inventory Report*

Natural Resource Report NPS/NRSS/GRD/NRR—2013/741

**ON THE COVER**
View from the top of the display spring down to the Arlington Lawn within Hot Springs National Park.

**THIS PAGE**
Gulpha Creek flows over Stanley Shale downstream from the Gulpha Gorge Campground.

Photographs by Trista L. Thornberry-Ehrlich (Colorado State University)

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*Geologic Resources Inventory Report*

Natural Resource Report NPS/NRSS/GRD/NRR—2013/741

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

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

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# Executive Summary

*The Geologic Resources Inventory (GRI) is one of 12 inventories funded by the National Park Service Inventory and Monitoring Program. The Geologic Resources Division held a GRI scoping meeting for Hot Springs National Park in Arkansas on 23–24 April 2007 and a follow-up conference call on 22 May 2013 to discuss geologic resources, the status of geologic mapping, and resource management issues and needs. This report synthesizes those discussions and is a companion document to the previously completed GRI digital geologic map data.*

This Geologic Resources Inventory (GRI) report was written for resource managers to assist in resource management and science-informed decision making, but it may also be useful for interpretation. The report was prepared using available geologic information. The Geologic Resources Division did not conduct any new fieldwork in association with this report. The report discusses geologic issues facing resource managers at the park, distinctive geologic features and processes within the park, the geologic history leading to the park's present-day landscape, and provides information about the GRI geologic map data produced for the park. An overview graphic (in pocket) illustrates the geologic data. The Map Unit Properties Table (in pocket) summarizes report content for each geologic map unit. This report also contains a glossary and a geologic time scale.

Hot Springs National Park was established as a unit of the National Park System in 1921, but was originally set aside for protection and preservation much earlier, in 1832. This is the oldest record of land set aside for preservation in perpetuity by the federal government. The inspiration for this reservation was the thermal waters flowing from hot springs along the southwestern slope of Hot Springs Mountain in the Zigzag Mountains of central Arkansas. The hot springs attracted human interest for centuries and continue to do so today; annual visitation to Hot Springs National Park is more than 1.3 million. Because the hot springs are the primary natural resource, the park's resource management priority is to preserve the quality and quantity of the thermal water and make it available for public use.

The rocks and structures exposed in the Zigzag Mountains record a geologic history that encompasses an ancient ocean basin; Ouachita-Mountain building and deformation; geothermal system development; the opening of the Atlantic Ocean and Gulf of Mexico; and weathering and erosion.

The source map for the GRI digital geologic data is Johnson and Hanson (2011), a map by the Arkansas Geological Survey, which was funded in part by the GRI program. The map units mapped by Johnson and Hanson (2011) can be divided into three categories: (1) Paleozoic bedrock deformed and metamorphosed during mountain building and between 500 and 323 million years old, (2) Cretaceous igneous rocks and metasedimentary rocks approximately 80 to 101 million years old, and (3) Quaternary sediments and precipitates less than 2.6 million years old.

The Paleozoic sedimentary sequence of rocks ("O", "S", "D", and "M" geologic map units) accumulated over millions of years in a longstanding marine basin along the southeastern margin of North America. These rocks are exposed throughout the park and surrounding area. The entire stack of rocks were deformed and pushed north and northwestward during the Ouachita Orogeny of the late Paleozoic. The younger Cretaceous igneous and metamorphosed rocks ("K" units) are only present as discrete dikes in the park and relate to extension of Earth's crust along the southeastern margin of the continent during the opening of the Gulf of Mexico. The youngest, unconsolidated surficial deposits reflect the processes of weathering and erosion active since the end of the Paleozoic mountain building. Associated with the hot springs are precipitated deposits of calcium carbonate, tufa (Qtufa). A blanket of tufa once covered the southwestern slope of Hot Springs Mountain.

Geologic features of particular significance for resource management at Hot Springs National Park include the following:

- Geothermal Hot Springs. The park's 47 hot springs are a mixture of older, thermal water and younger, shallow (cool) groundwater. Both are recharged from local precipitation. The thermal water is heated by Earth's normal geothermal gradient, meaning there is no "hotspot" beneath Hot Springs. Geologic structures, including fractured bedrock, a plunging fold, and a thrust fault create the specific conditions that allow the water to be heated at depth and rise rapidly to the surface. Geologists are still investigating and delineating the recharge areas for both the thermal and cold water components. Early in the history of the resort at Hot Springs, developers began controlling the flow of the springs and removing the blanket of tufa that once covered the hillside. Now, to protect the water quantity and quality of the system, the springs are in locked spring boxes and plumbed to a centralized cooling facility for distribution to the local fountains and bathhouses.
- Folds, Fractures, and Faults of the Ouachita Mountains. Geologic structures control the development and flow of the thermal system at Hot

Springs. These features formed during the intense compression associated with the Ouachita Orogeny. This part of the Ouachita Mountains contains fractured bedrock, as well as abundant, nearly parallel, overturned folds cut by thrust faults. The pattern of structures is complex. Differential erosion has caused softer shales to wear away more rapidly than harder sandstones, cherts, and novaculites. These resistant rocks (novaculite and sandstone) cap most of the ridges in the Zigzag Mountains.

- Paleontological Resources. Marine invertebrate fossils have been discovered in the Ordovician, Silurian, Devonian, and Mississippian rocks delineated on the geologic map. Some plant and vertebrate fragments are noted from the Stanley Shale (Ms). Fossil graptolites are known from the park and are housed in the park's museum collection; a formal park-wide paleontological resource survey has not yet been completed.
- Connections with Park Stories and Resources. In addition to the geologic framework being responsible for the emergence of hot springs, the area's geology has long attracted interest in its mineral wealth. The novaculite and sandstone were used by American Indians beginning thousands of years ago. Novaculite use for whetstones continues today.

Geologic issues of particular significance for resource management at Hot Springs National Park include the following:

- Geothermal Water Quantity and Quality. The primary resource-management priority at the park is protecting and preserving the thermal hot spring resource and ensuring its long term availability for visitor use. Concerns range from changes to recharge, vent sealing, and piracy of the resource. Much of the park's thermal water recharge area is currently beyond park boundaries. Climate change and increased impervious surfaces associated with home development will affect recharge. Increased development may also affect water quality. A local well began pumping water with elevated temperatures. This situation has inspired a nearly decade-long, in-depth study of the hot springs system and its connectivity with surrounding areas.
- Radon Exposure. Radon is a heavy, colorless, odorless, radioactive gas that occurs naturally within the spring waters and tufa deposits precipitated by the springs. To minimize exposure and associated long term health risks, ventilation systems have been installed, and the park continually monitors radon concentrations in all park facilities.
- Slope Movements. Within the city and the park of Hot Springs, the primary hazard is rockfall off the steep slopes. Within the City of Hot Springs, undercut slopes have failed threatening local businesses and human safety. Engineering structures were installed in variously successful attempts to mitigate the hazards. Within the park, engineering structures mitigate rock fall risk above the park's water cooling facility, as well as along sections of the West Mountain Drive.
- Disturbed Lands, Unauthorized Collecting, Vandalism, and Artificial Ponds. Disturbances on the landscape result primarily from mineral interest. Most of the novaculite, Tripoli, sandstone, and chert quarries within the park are considered historic. Extraction of novaculite and quartz crystals continues outside the park. Bedrock outcrops are marred by graffiti and vandalism. Two minor, artificial ponds are within park boundaries.
- Flooding. Many streams in the park are ephemeral and flow only after periods of high precipitation. They coalesce to form Hot Springs Creek through the center of the park, Bull Bayou on the west corner, or Gulpha Creek on the park's east side. The outlets for these waterways are narrow. During the 1880s, Hot Springs Creek was covered by "the creek arch"—a system of masonry arches that funnels the creek beneath the town of Hot Springs. During very high flows such as in 1963, 1990, and 2005 this system was overwhelmed and significant flooding occurred.

# Acknowledgements

*The GRI is administered by the Geologic Resources Division of the Natural Resource Stewardship and Science Directorate.*

The Geologic Resources Division relies on partnerships with institutions such as Colorado State University, the US Geological Survey, state geological surveys, local museums, and universities to develop GRI products.

Special thanks to Stephen Rudd (Hot Springs NP) for answering a multitude of questions and sharing his many years of experience managing the natural resources of Hot Springs NP. His comments improved the report. Doug Hanson and Angela Chandler (both of the Arkansas Geological Survey) reviewed the report and provided excellent feedback. The GRI program partially funded the Arkansas Geological Survey to complete geologic map of Hot Springs NP and the surrounding area (Johnson and Hanson 2011).

**Credits**

Source Map

Ty Johnson and Doug Hanson (Arkansas Geological Survey; Johnson and Hanson 2011)

Report Author

Trista L. Thornberry-Ehrlich (Colorado State University)

Report Review

Doug Hanson (Arkansas Geological Survey)
Angela Chandler (Arkansas Geological Survey)
Stephen Rudd (Hot Springs National Park)
Jason Kenworthy (NPS Geologic Resources Division)

Report Editing

Rebecca Port (NPS Geologic Resources Division)

GRI Digital Geologic Data Production

Jack Garner (NPS Geologic Resources Division)
Heather Stanton (Colorado State University)
Jim Chappell (Colorado State University)
Stephanie O'Meara (Colorado State University)

Geologic Map Graphic, Layout and Design

Max Jackl (Colorado State University)

Geologic Map Graphic, Review

Georgia Hybels (NPS Geologic Resources Division)
Rebecca Port (NPS Geologic Resources Division)
Jason Kenworthy (NPS Geologic Resources Division)

# Introduction

*This section briefly describes the National Park Service Geologic Resources Inventory Program and the history and regional geology of Hot Springs National Park.*

### Geologic Resources Inventory Program

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

The objectives of the GRI are to provide geologic map data and pertinent geologic information to support resource management and science-based decision making in more than 270 natural resource parks throughout the National Park System. To realize these objectives, the GRI team undertakes three tasks for each natural resource park: 1) conduct a scoping meeting and provide a scoping summary, 2) provide digital geologic map data in a geographic information system (GIS) format, and 3) provide a GRI report. These products are designed and written for nongeoscientists. Scoping meetings bring together park staff and geologic experts to review available geologic maps, develop a geologic mapping plan, and discuss geologic issues, features, and processes that should be included in the GRI report. Following the scoping meeting, the GRI map team converts the geologic maps identified in the mapping plan to digital geologic map data in accordance with their data model. Refer to the "Geologic Map Data" section for additional map information. After the map is completed, the GRI report team uses these data, as well as the scoping summary and additional research, to prepare the geologic report. This geologic report assists park managers in the use of the map and provides an overview of the park's geology, including geologic resource management issues, geologic features and process, and the geologic history leading to the park's present-day landscape.

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

For additional information regarding the GRI, including contact information, please refer to the GRI website (http://www.nature.nps.gov/geology/inventory/). The current status and projected completion dates of GRI products are available on the GRI status website (http://www.nature.nps.gov/geology/GRI_DB/Scoping/Quick_Status.aspx).

### Park Setting

Hot Springs National Park is the first example of land set aside for preservation in perpetuity by the federal government—originally designated Hot Springs Reservation on April 20, 1832. Legislation signed by President Andrew Jackson reserved "four sections of land including said [hot] springs, reserved for the future disposal of the United States [which] shall not be entered, located, or appropriated, for any other purpose whatsoever." Unfortunately, Congress did not pass legislation for administering the site and as a result, no controls over settlement and development were exerted in the area for decades (Shugart 2003). In the late 1870s, after years of land ownership dispute, government control over the reservation was reestablished (Shugart 2003). It became a unit of the National Park System as Hot Springs National Park on March 4, 1921.

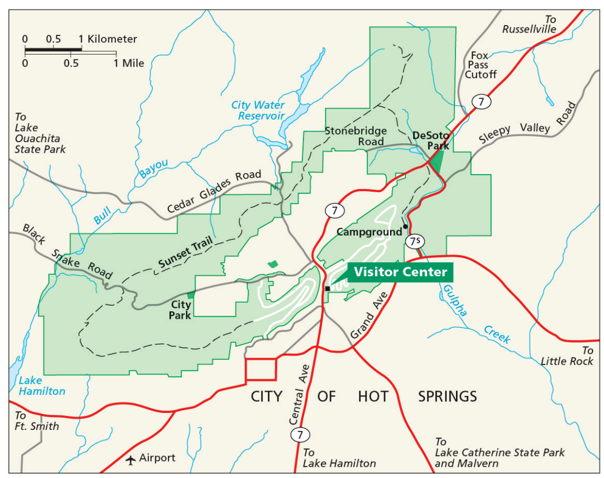



**Figure 1. Map of Hot Springs National Park and surrounding area. Refer to plate 1 for a detailed map of the park. National Park Service map, available online: http://www.nps.gov/hfc/cfm/carto.cfm (accessed 2 December 2013).**

The park encompasses approximately 2,250 ha (5,550 ac) of steep ridges and valleys in Garland County, Arkansas (fig. 1 and plate 1). The 47 natural, geothermal hot springs inspired the creation of the park—they remain the park's primary natural resource, though not preserved in a natural state. A series of pipes, flumes, and tanks are in place to collect, cool, and transport water from the springs; they allow the park to conserve and manage the production of uncontaminated hot water for public use (National Park Service 2005). Enabling mandates requiring the park to provide the thermal waters to the public, makes Hot Springs National Park the only NPS unit with a specific mission of collecting and distributing its primary natural resource (S. Rudd, Hot Springs NP, natural resource program manager, conference call, 22 May 2013).

In addition to its natural resources, the park has a rich cultural history. American Indians bathed in the hot springs and quarried local sandstone and novaculite for implement material. The first settlers of European descent reached the area in 1807 and quickly recognized the economic value of the local natural resources for a health resort. By the 1830s, rudimentary infrastructure was already in place to meet the needs of visitors to the hot springs. Land disputes, management changes, new construction, and a devastating fire are all part of the Hot Springs story, ultimately culminating in the luxury spa that was Bathhouse Row by 1923 (Shugart 2003). As part of a National Historic Landmark District, the park includes eight historically significant bathhouses along Bathhouse Row: Superior, Hale, Maurice, Fordyce, Quapaw, Ozark, Buckstaff, and Lamar (fig. 2). The park surrounds the historic downtown of the city of Hot Springs and attracted more than 1.3 million visitors in 2012.

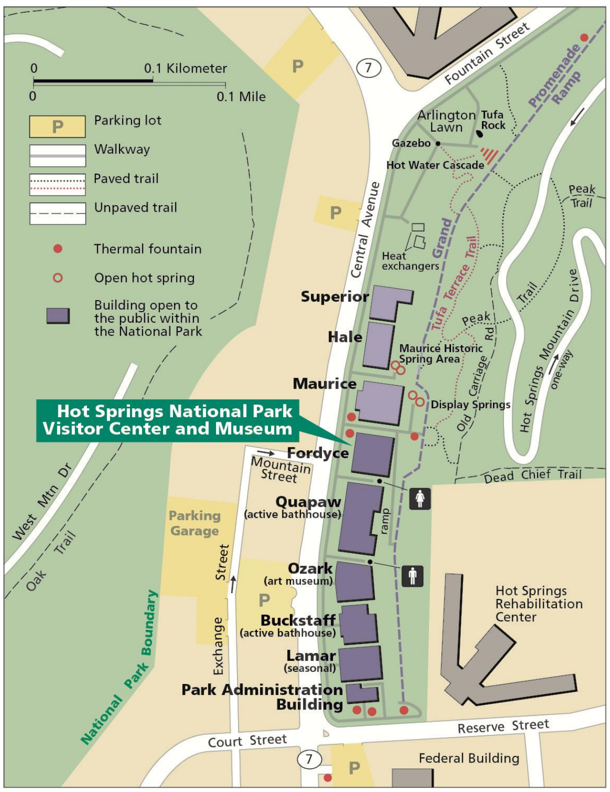



**Figure 2. Detail map of Bathhouse Row. National Park Service map, available online: http://www.nps.gov/hfc/cfm/carto.cfm (accessed 11 July 2013).**

## Geologic Setting

A geologic history involving long-term marine deposition, construction of the Ouachita Mountains, igneous intrusions, and millions of years of weathering and erosion created the geologic framework that allows the hot springs to emerge on the southwestern slopes of Hot Springs Mountain.

Arkansas is divided into two topographic regions: the Interior Highlands underlain by ancient, resistant Paleozoic bedrock; and the Gulf Coastal Plain of young,

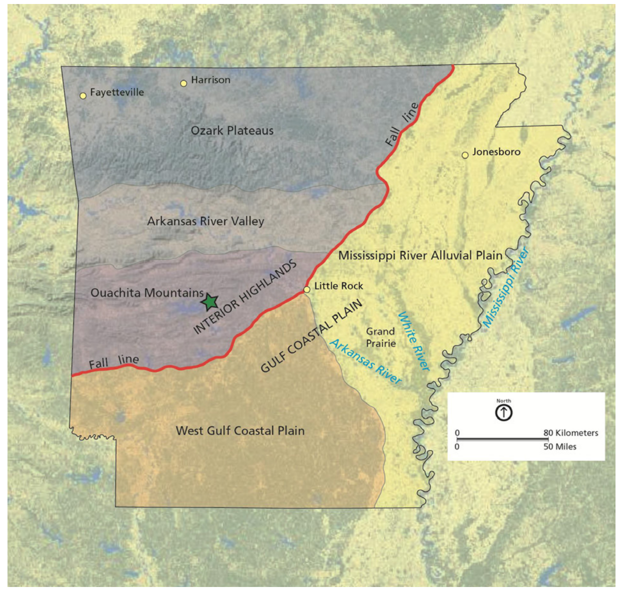



**Figure 3. Physiographic provinces of Arkansas with information from Arkansas Geological Survey (2012). Green star denotes the location of Hot Springs National Park (fig 1 and plate 1). Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) using ESRI National Geographic topographic imagery basemap layer.**

unconsolidated sediments (e.g. clay, silt, sand, and gravel). The boundary between the two regions is called the "fall line" (figs. 3 and 4). Hot Springs National Park is located within the Zigzag Mountains subsection (fig. 4) of the Ouachita Mountains physiographic province—a geologically complex area of steep, forested, east to west trending ridges and narrow valleys—that is part of the Interior Highlands region. In the park area, the Ouachita Mountains are part of an eroded, structurally complex regional arch—the Benton-Broken Bow anticlinorium (Purdue and Miser 1923; Fellowes 1967; Roberts et al. 2007). The rock patterns in the Zigzag Mountains demonstrate beautifully the complex folding within the Ouachitas (Roberts et al. 2007).

The geologic foundation of Hot Springs National Park is complex. Essentially, the remains of an ancient ocean basin was forced upwards, metamorphosed under pressure during deformation, and then weathered and eroded to produce the present landscape. Three major rock types record the geologic story of Hot Springs National Park: (1) Paleozoic bedrock deformed and pressure-metamorphosed during mountain building, (2) Cretaceous igneous rocks and metasedimentary rocks, (3) Quaternary sediments and precipitates.

The sediments that now compose the Paleozoic bedrock of the park and surrounding areas date back to the Cambrian and Ordovician through Mississippian periods, or approximately 500 to 323 million years ago (fig. 5). They include shales (geologic map units Om, Ow, Opc, SOu, Sm, and Ms), sandstones (Ob, Sb, and Mshs), chert (Obf), and novaculite (MDa) (fig. 6) (see "Map Unit Properties Table" and "Geologic Map Graphic") (King 1937; Johnson and Hanson 2011). The Ouachita Orogeny (mountain-building event) deformed and fractured the bedrock into the folds and faults that are

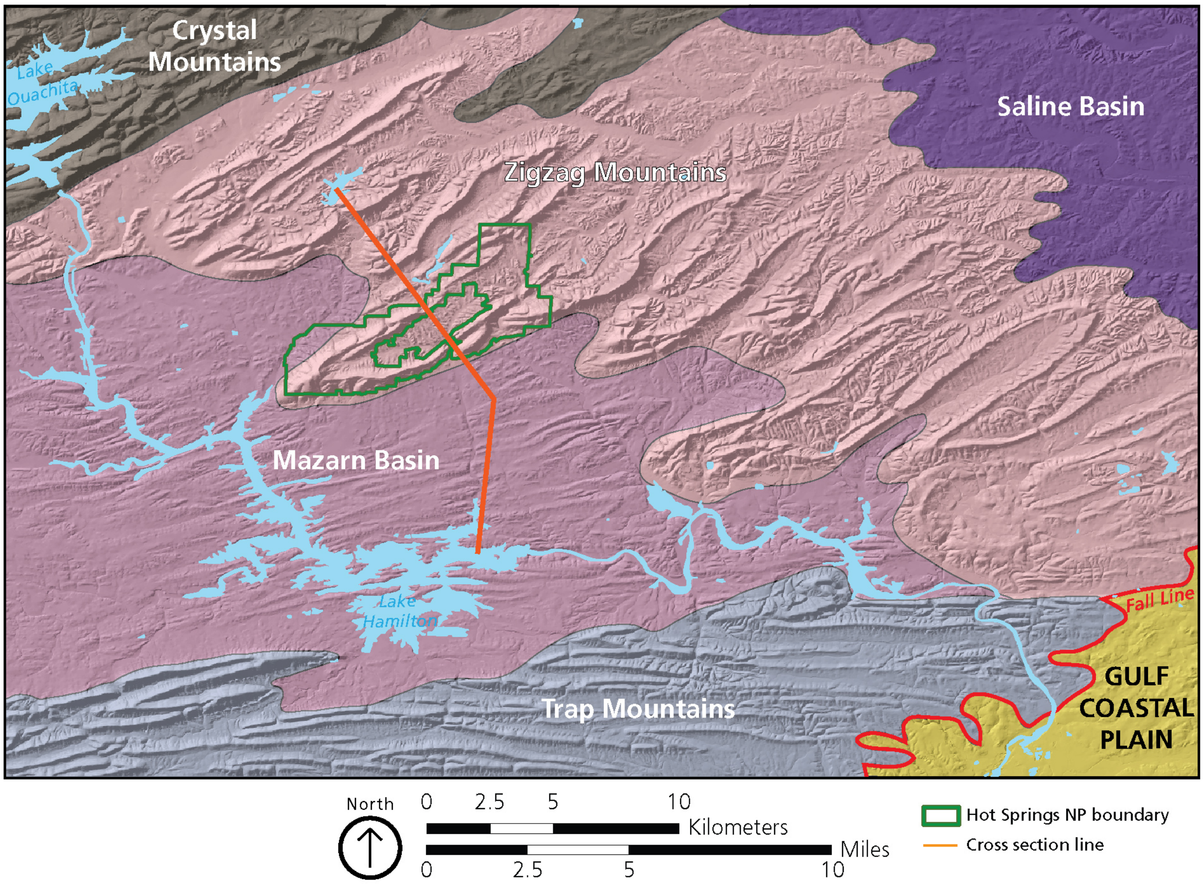



**Figure 4. Physiographic subsections and landscape around Hot Springs National Park. Orange line denotes the location of the cross section of plate 2. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) using ESRI hillshade imagery with assistance from Georgia Hybels (NPS Geologic Resources Division).**

the natural plumbing for the geothermal system at Hot Springs National Park.

During the Cretaceous, 145 to 65 million years ago, a series of igneous rocks intruded the local bedrock as large plutons and smaller dikes and sills (Ki, Kia, Kil, Kid, and Kis). The heat of this molten rock "cooked" the adjacent bedrock producing an "aureole" of hornfels and quartzite (Kms) rocks adjacent to the intrusive bodies (Johnson and Hanson 2011).

Beginning about 2 million years ago, Earth's climate became intermittently colder and great glacial ice sheets advanced from the Arctic during repeated ice ages. These vast glaciers never reached as far south as central Arkansas, but the colder climate contributed to local erosion and weathering. Units from this time include terrace deposits (Qt) left perched above modern floodplains (Qal) when rivers incised lower channels. The youngest geologic units in the park area are the travertine and tufa (Qtufa) deposits precipitated as the geothermal springs emerge at approximately 62°C (143°F) and calcium-carbonate-saturated waters "de-gas" when they reach the surface (Johnson and Hanson 2011).

Steep, forested hills separated by narrow valleys characterize the landscape in the park (plate 1). Notable local landforms include Hot Springs, North, Indian, Sugarloaf, West, and Music mountains. The slopes of Music Mountain rise from less than 210 m (700 ft) above sea level to more than 425 m (1,400 ft) over a short distance. Hot Springs Creek runs through the center of the park and Gulpha Creek carves a steep gorge along the park's eastern side separating Indian Mountain from North and Hot Springs mountains. Smaller, ephemeral streams flow down the slopes of other ridges including Whittington Creek between West Mountain and Sugarloaf and Music mountains.

The hot springs cluster on the southwest slope of Hot Springs Mountain where geologic structures such as faults, folds, and fractures and sedimentary bedding channel groundwater to great depths where it is heated via the natural geothermal gradient and then rises quickly back to the surface.

Roberts et al. (2007) prepared a geologic excursion tour guide that details the geologic features, processes, and history across various locations within Hot Springs National Park.

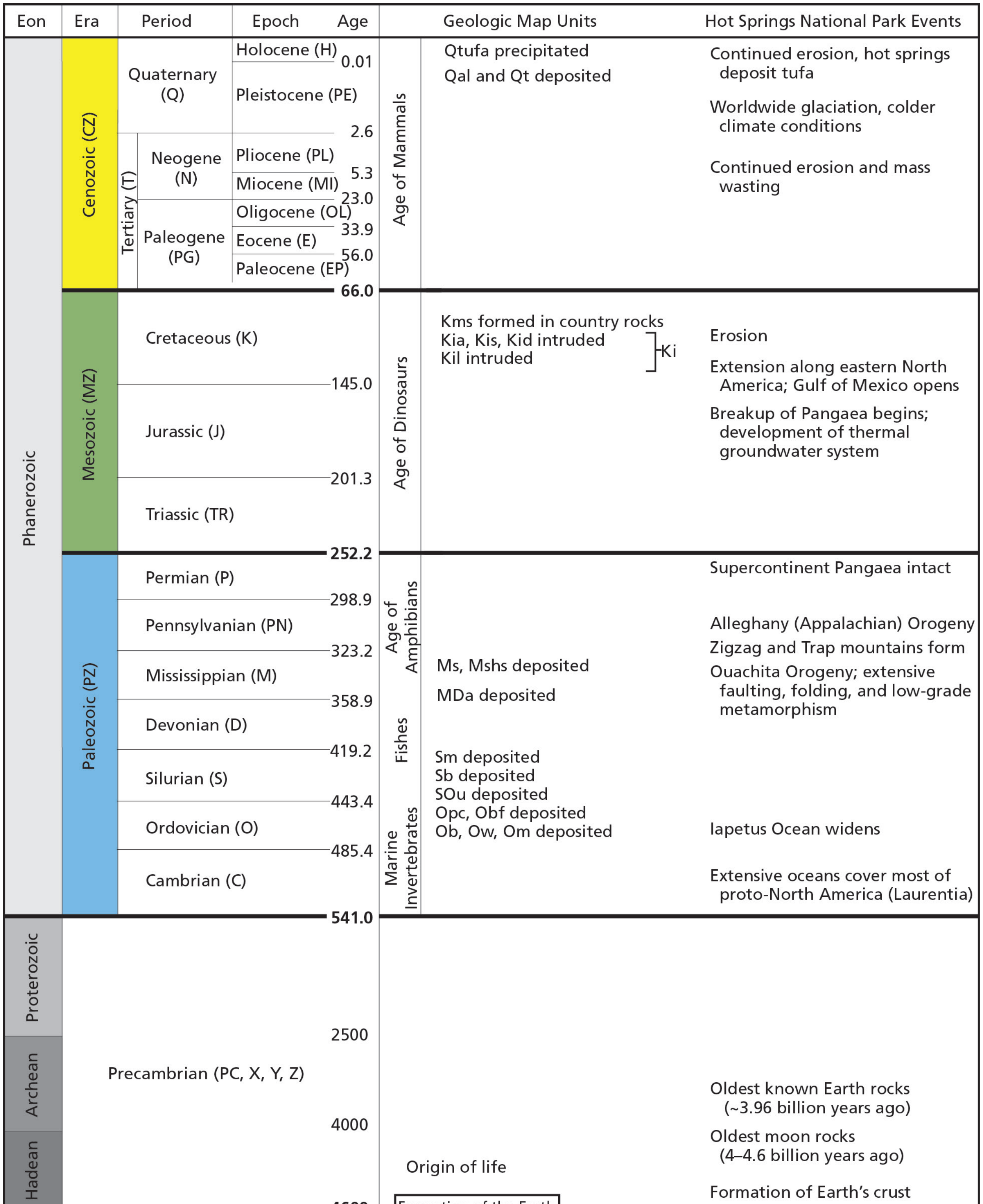
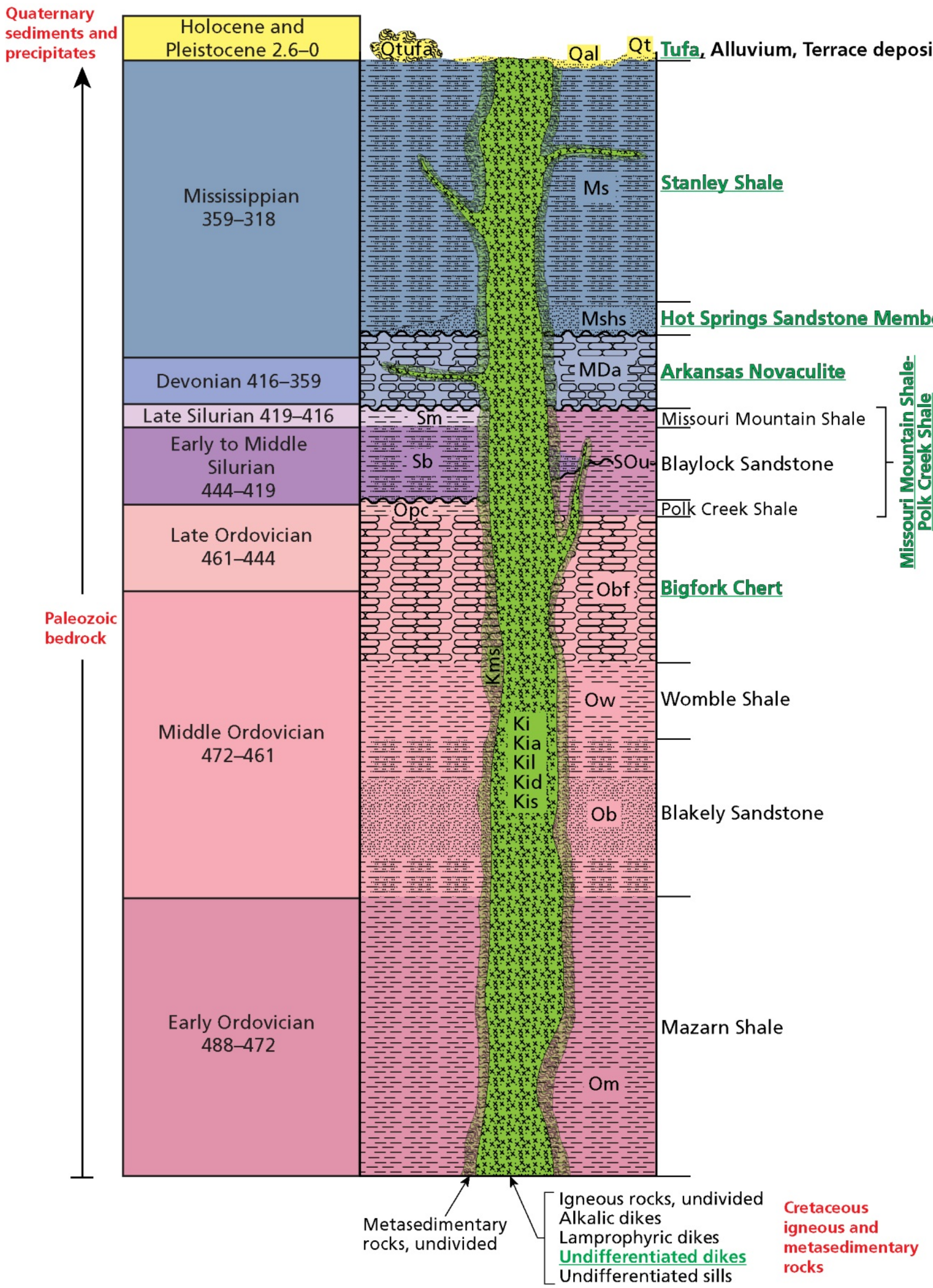



**Figure 5. Geologic time scale. The divisions of the geologic time scale are organized stratigraphically, with the oldest at the bottom and youngest at the top. GRI map abbreviations for each geologic time division are in parentheses. Boundary ages are in millions of years. Bold lines indicate major boundaries between eras. Major life history and tectonic events affecting the Hot Springs National Park area are included. The geologic map units for Hot Springs National Park are also listed stratigraphically. Graphic design by Trista Thornberry-Ehrlich (Colorado State University) and Rebecca Port (NPS Geologic Resources Division), using dates published by the International Commission on Stratigraphy (http://www.stratigraphy.org/index.php/ics-chart-timescale; accessed 23 September 2013).**




***Age is in millions of years before present and indicates the time spanned by associated epoch or period. Rock/sediment units associated with those epochs or periods may not encompass the entire age range.***

**Figure 6. Stratigraphic column for Hot Springs National Park. Colors are standard colors approved by the US Geological Survey to indicate different time periods on geologic maps; they also correspond to the colors on the Map Unit Properties Table. Green, underlined unit names indicate units that occur within Hot Springs National Park. Red text refers to the three major map unit categories. See the Map Unit Properties Table for more detail. Graphic by Trista L. Thornberry-Ehrlich after the stratigraphic column included in Johnson and Hanson (2011).**

# Geologic Features and Processes

*Geologic resources underlie park ecosystems and geologic processes shape the landscape of every park. This section describes the most prominent and distinctive geologic features and processes in Hot Springs National Park.*

Discussions during a 2007 scoping meeting (Thornberry-Ehrlich 2007) and a 2013 follow-up call identified geologic features and processes present in the park, including:

- Geothermal Hot Springs
- Folds, Fractures, and Faults of the Ouachita Mountains
- Geologic Connections to Park Stories and Resources
- Paleontological Resources

### Geothermal Hot Springs

A hot spring is an emergence of groundwater at elevated temperatures relative to its surroundings or other springs of average groundwater temperature in the region. The heat source for hot springs can be either the Earth's natural geothermal gradient (temperature increases with depth below the surface) or igneous activity (the presence of molten material near the surface). The water at Hot Springs National Park achieves an elevated temperature of 62°C (143°F) from a normal geothermal gradient rather than via an igneous source, meaning there is no "hotspot" beneath the park. The average natural geothermal gradient, or rate of change of temperature with depth, is 25°C/km (15°F/1,000 ft). Of the 16 units in the NPS with significant geothermal resources, Hot Springs National Park is the only one not associated with igneous activity (S. Rudd, Hot Springs NP, natural resource program manager, conference call, 22 May 2013).

The park's hot springs occur along a narrow, oval-shaped area about 460 m (1,500 ft) long and 120 m (400 ft) wide, along the southwestern slopes of Hot Springs Mountain (fig. 7). They emerge near the axis of the anticlinal ("A"-shaped) fold between two thrust faults (Bedinger et al. 1979; Sniegocki 1996). In 2007, there were 47 thermal springs documented within the park; however this number is not fixed in time or space (table 1) (Thornberry-Ehrlich 2007). Early records indicate as many as 72 springs (Bedinger et al. 1970). In 1878, there were 56 identified springs (Van Cleef 1878). Older springs have naturally stopped when precipitated carbonate minerals clog the spring. New springs develop where thermal water exploits another outlet through the tufa (Qtufa) (Hanor 1980). Throughout history, developers have buried, secured, destroyed, or diverted spring flows to maximize recreational access as described in the "Anthropogenic Modifications to the Hot Springs" section (Yeatts 2006).

The mechanics of the geothermal system at the park, including its recharge area, are still being studied. The most comprehensive studies of the origin and nature of the hot springs at the park were by Bedinger et al. (1970, 1979). More recent work was undertaken in response to geothermal water appearing in a well outside the park in 2006 as described in the "Understanding the Geothermal System" section. Geochemical data, flow measurements, and geologic structure in the region support the concept that essentially all of the water emerging at the hot springs originated as local precipitation (Bedinger et al. 1970; Sniegocki 1996). In addition to the deep, thermal-water component, the springs' discharge includes a shallow, cold-water component ranging from 0% to 16% of total flow. That amount increases sharply after rainfall to between 21% and 31% (Noguchi 1982a, 1982b; Bell and Hays 2007; Hays et al. 2008).

Because the local Paleozoic bedrock is not porous, joints, fractures, and separations along bedding planes host and transport groundwater flow (Kresse and Hays 2009). These fractures formed primarily during the Ouachita Orogeny (see "Folds Fractures and Faults of the Ouachita Mountains" section).

From precipitation at the recharge surface area of approximately 330 m (1,100 ft) in elevation, the water is funneled downward along faults, fractures, and bedding planes. Crucial to the system, a southwest-tilted, overturned anticlinal fold structure slowly directs the groundwater to great depths where it is heated. The water travels downward about 30 cm (12 in) per year (Hanor 1980). At least four or five other anticlinal structures in the area have similar geothermal potential, but there is another factor that is responsible for the emergence of the hot springs within the park rather than elsewhere—a thrust fault.

A thrust fault separates Hot Springs and West mountains. Central Avenue is roughly aligned with the fault trace. The fault creates a barrier to groundwater flow that causes the hot springs to emerge on the southwestern slopes of Hot Springs Mountain. They emerge at approximately 190 m (630 ft) in elevation—a difference of about 140 m (470 ft) from the recharge area on Indian, North, and Hot Springs mountains (fig. 8 and Geologic Map Graphic). During the Ouachita Orogeny, the thrust fault transported impervious rocks (possibly Precambrian crystalline basement rocks) toward the surface, juxtaposing them against the fractured Paleozoic bedrock. This impervious rock blocks further downdip groundwater flow and the fractured zone associated with the fault provides outlets for the water (S. Rudd, conference call, 22 May 2013).

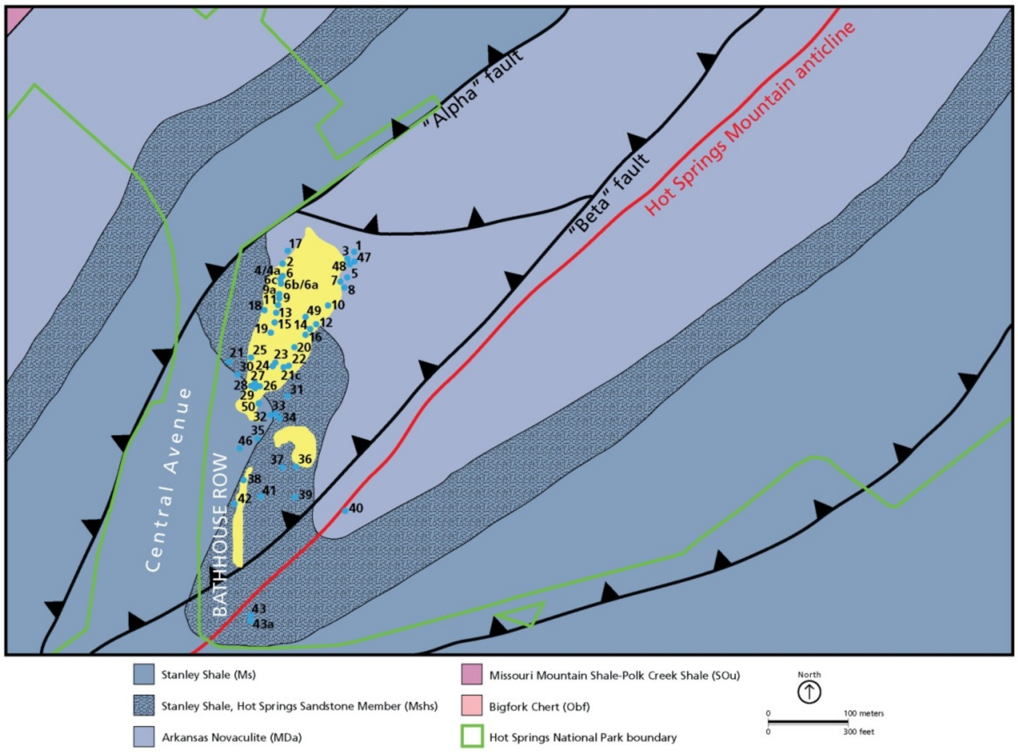



**Figure 7. Thrust faults and hot spring locations within Hot Springs National Park. Bold black lines are thrust faults with sawteeth on the leading edge. Bold red line is the axis of Hot Springs Mountain anticline. Green line is the park boundary. Note the hot spring locations are almost entirely clustered between thrust faults. Spring numbers correspond to those listed on table 1. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) with information from figures 3 and 6 in Yeatts (2006).**

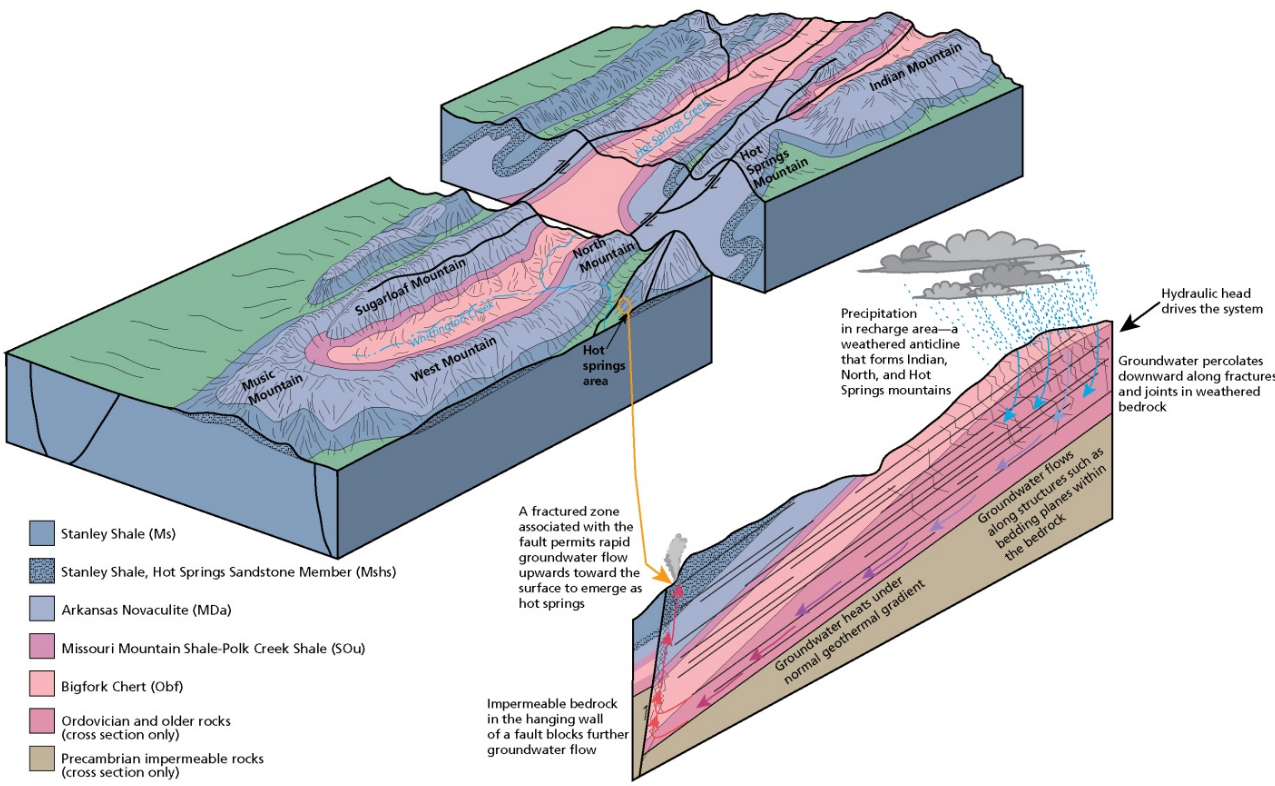



**Figure 8. Cross section through Hot Springs Mountain and adjacent hills. Surface exposures of the Stanley Shale (Ms) are tinted green for clarity. Other colors are standard USGS colors. Bold black lines are faults. Geologic structures control the thermal water system that supplies the hot springs at Hot Springs National Park. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after an unnumbered figure in Bedinger (1974).**

**Table 1. List of named springs within Hot Springs National Park.**

| # | Spring Name | Condition as of 2006 | Use of Water |
|---|---|---|---|
| 1 | Egg | Reconstructed 1980 | Collection system |
| 2 | Arsenic South | Reconstructed 1977 | Collection system |
| 3 | Arlington | Reconstructed 1980 | Collection system |
| 4 | Cliff | Reconstructed 1977 | Collection system |
| 4a | Cliff New | Constructed 1977 | Collection system |
| 5 | Avenue | Reconstructed 1980 | Collection system |
| 6 | Boiler House North | Reconstructed 1977 | Collection system |
| 6a | Cooler North | Reconstructed 1977 | Collection system |
| 6b | Cooler South | Reconstructed 1977 | Collection system |
| 6c | Boiler House South | Constructed 1977 | Collection system |
| 7 | Imperial North | Reconstructed 1980 | Collection system |
| 8 | Crystal | Reconstructed 1980 | Collection system |
| 9 | Rector | Reconstructed 1977 | Collection system |
| 9a | Rector North | Constructed 1977 | Collection system |
| 10 | Cave | Covered with fill | Drains to creek arch |
| 11 | Little Iron North | Reconstructed 1977 | Collection system |
| 12 | Little Geyser | Abandoned | Not collected |
| 13 | Little Iron South | Reconstructed 1977 | Collection system |
| 14 | Ral | Abandoned | Not collected |
| 15 | Big Iron | Reconstructed 1977 | Collection system |
| 16 | Imperial South | Abandoned | Not collected |
| 17 | Arsenic North | Reconstructed 1977 | Collection system |
| 18 | Hitchcock | Abandoned | Not collected |
| 19 | Superior Bath | Reconstructed 1977 | Collection system |
| 20 | Superior North | Abandoned | Not collected |
| 21 | Alum | Abandoned | Not collected |
| 21c | Alum East | Constructed 1980 | Collection system |
| 22 | Superior South | Reconstructed 1980 | Collection system |
| 23 | Twin North | Reconstructed 1980 | Collection system |
| 24 | Twin South | Reconstructed 1980 | Collection system |
| 25 | Hale Bath | Reconstructed 1980 | Collection system |
| 26 | Palace | Reconstructed 1980 | Collection system |
| 27 | Tunnel | Display tunnel | Drains to creek arch |
| 28 | Maurice | Covered | Drains to creek arch |
| 29 | Dripping | Display fountain | To fountain and creek arch |
| 30 | Arch | Abandoned | Not collected |
| 31 | Haywood | Reconstructed 1980 | To fountain and creek arch |
| 32 | Noble | Display spring | Drains to creek arch |
| 33 | Lamar | Display spring | Drains to creek arch |
| 34 | Wiley | Display spring | Drains to creek arch |
| 35 | Hardin | Abandoned | Not collected |
| 36 | Eisele | Abandoned | Not collected |
| 37 | Stevens | Abandoned | Not collected |
| 38 | Horseshoe | Reconstructed 1980s | Collection system |
| 39 | Army and Navy | Drilled and cased | Drains to creek arch |
| 40 | W.J. Little | Abandoned | Not collected |
| 41 | Mud | Abandoned | Not collected |
| 42 | Quapaw Bath | Reconstructed 1980s | Collection system |
| 43 | Reservoir North | In collection reservoir | Collection system |
| 43a | Reservoir South | In collection reservoir | Collection system |
| 46 | Fordyce Bath | Reconstructed 1980s | Collection system |
| 47 | New North | Reconstructed 1980 | Collection system |
| 48 | New South | Reconstructed 1980 | Collection system |
| 49 | USGS | Reconstructed 1980 | Collection system |
| 50 | Maurice Bath | Reconstructed 1980s | Drains to creek arch |

***The numbers refer to locations on figure 7. Data are from Yeatts (2006). Reconstruction involved re-excavating the springs to their bedrock emergence points, replumbing the collection systems with polycarbonate liners (to reduce clogging mineral precipitation), and replacing the lock boxes. Regular maintenance includes replacing valve bodies and cleaning reservoirs (S. Rudd, Hot Springs NP, natural resource program manager, conference call, 7 August 2013).***

The hydraulic head generated by the relatively high elevation of Indian Mountain drives the system. The groundwater descends to estimated depths of 1,300 to 2,300 m (4,400 to 7,500 ft) below the surface and is heated under a normal geothermal gradient (Bell and Hays 2007). When the water is heated, it is less dense and rises rapidly to the surface along a narrow "escape route" of fracture zones in the Hot Springs Sandstone member of the Stanley Shale (Mshs) to emerge as artesian geothermal hot springs. The hot water retains much of its geothermal energy (Bedinger et al. 1979; Hanor 1980; Sniegocki 1996; Johnson and Hanson 2011; S. Rudd, conference call, 22 May 2013). Analyses of silica in the thermal spring water reveal that the maximum temperature reached by the water is no more than a few degrees higher (66.6°C [151.9°F]) than the temperature at which the springs emerge (62°C [143°F])—meaning it rises quickly to the surface to discharge (Bedinger et al. 1979; Sniegocki 2001; Bell and Hays 2007).

The probable thermal-water recharge area is north and east of the park where heavily fractured exposures of Bigfork Chert (geologic map unit Obf), Hot Springs Sandstone member of the Stanley Shale (Mshs), and the Arkansas Novaculite (MDa) are exposed. This outcrop of the Bigfork Chert is approximately 93 $km^2$ (36 $mi^2$) and the area of the Arkansas Novaculite is approximately 34 $km^2$ (13 $mi^2$) (National Park Service 2005). Recent studies, described in the "Geothermal Issues" section, narrows the source area to a 31 to 39 $km^2$ (12 to 15 $mi^2$) area, much of which is outside the boundaries of the park and all east of Central Avenue, as part of a weathered anticline that forms Indian, North, and Hot Springs mountains (S. Rudd, conference call, 22 May 2013). Yeatts (2006, 2008) quantified the recharge area for the shallow, cold-water component to be a mere 0.3 to 0.5 $km^2$ (0.1 to 0.2 $mi^2$) upgradient of the hot springs about 300 m (1,000 ft) east of Central Avenue on Hot Springs Mountain.

Isotope dating with tritium ($^3H$) and radiocarbon ($^{14}C$; "carbon-14") indicates the thermal water emerging from the springs is approximately 4,400 years old, whereas the cold water component is approximately 20 years old (Bedinger et al. 1979; Sniegocki 1996, 2001). As described further in the "Climate Change and Spring Flow" section, the springs discharge water at a varying rate, but in recent years has averaged between 2,480,000 and 2,700,000 L/24 hrs (655,000 and 710,000 gal/24 hrs), emerging at a temperature of 62°C (143°F), a pH between 7.1 and 7.5, and dissolved solids between 175 to 200 mg/L (National Park Service 2005; Thornberry-Ehrlich 2007; Allen et al. 2000; Sniegocki 1996, 2001; S. Rudd, conference call, 22 May 2013). Dyes released just upgradient from the hot springs on Hot Springs Mountain in the suspected cold water recharge area took 1 to 3 weeks to emerge in the cold water component at hot-water recovery sites; flow was along the contact between the Hot Springs Sandstone member of the Stanley Shale (Mshs) and the Stanley Shale (Ms) as well as along northeast-trending joints, fractures, and faults (Yeatts 2006, 2008).

### Anthropogenic Modifications to the Hot Springs

Beginning hundreds if not thousands of years ago, humans bathed in the hot springs for medical reasons or relaxation. Certain springs were thought to alleviate specific ailments. People soaked their feet in "Corn Hole Spring" to relieve corns, bunions, and other foot ailments, or they bathed in Alum Springs to help sore eyes (Bedinger 1974). Initially, bathers would simply sit in natural shallow pools in the bed of Hot Springs Creek. There, the thermal water mixed with the stream water and created various temperatures. Desiring more predictable, consistent conditions, early developers staked claims on particular springs and modified them to control their flow, temperature, and water quality. Prior to the city's incorporation in 1876, raw sewage was also dumped into Hot Springs Creek (S. Rudd, conference call, 7 August 2013). In the 1830s, the first bathhouses were simple brush huts or log cabins placed over excavations where thermal water flowing from the springs was transported by wooden troughs (Van Cleef 1878; Hanor 1980). Elaborate bathhouses soon followed and developers removed more of the calcium carbonate (tufa) "blanket" on the hillside to further control thermal water flow (Hanor 1980; Yeatts 2006).

Later, springs were lined with masonry. Rounded pea gravel was layered with perforated cast iron pipes in spoke patterns to form a lens and direct water to larger catchment structures for distribution to the bathhouses and fountains (Allen et al. 2000; Thornberry-Ehrlich 2007). Because the geothermal water is saturated with dissolved minerals, such as carbonate, aragonite, and manganese and iron oxides and hydroxides that precipitate when the water emerges, the cast iron system was frequently clogged (Jacquess and Hagni 1988; Allen et al. 2000).

By 1901, most of the hot springs were covered and/or being diverted. Some of the concrete vaults that are still in use in the park were installed in the 1920s (S. Rudd, conference call, 7 August 2013). In 1931, in an effort to support the eight bathhouses constructed between 1912 and 1922 (now part of the park), some springs were deepened and the collection system reconstructed. From the collection tanks, pumps pushed the water uphill to 3 buried reservoirs on the hillside above Bathhouse Row (S. Rudd, conference call, 7 August 2013). Other major changes to the springs and spring distribution system occurred in the Arlington Lawn area in 1976, the upper promenade in 1979, and the lower promenade in 1981. Park staff installed various upgrades to the plumbing system including replacement of cast iron pipes with PVC, which is less susceptible to mineral precipitation. Currently there are 26 lock boxes within the park collecting water from 33 springs (fig. 9). Approximately 10 additional springs drain directly to Hot Springs Creek (Yeatts 2006). The present collection system transports thermal water through 5- to 15-cm (2- to 6-in) pipes that lead to the collection main in the creek arch. The main then carries the thermal water to the central collection system reservoir (Yeatts 2006). The park uses a 1,080,000 L (285,000 gal) concrete tank located beneath the Park Administrative Building to mix and cool the thermal

**Figure 9. Locked spring boxes within Hot Springs National Park. Imperial Spring is in the foreground of the top image, Crystal Spring is in the lower image. All hot springs emerge on the southwestern slopes of Hot Springs Mountain. Photographs by Trista L. Thornberry-Ehrlich (Colorado State University), taken in 2007.**

water to a safer temperature of approximately 39°C (101–102°F) before distributing to bathhouses or thermal fountains (Yeatts 2006; Thornberry-Ehrlich 2007). After storage reservoirs are filled (approximately 3,000,000 L [8000,000 gallons] total), any overflow goes into the creek arch (S. Rudd, conference call, 7 August 2013).

Vestiges of the tufa (Qtufa) blanket that once covered the southwestern slope of Hot Springs Mountain are still visible at De Soto Rock, the cliffs behind Bathhouse Row, the steep bluff at Arlington Lawn, and near the north gates to the Rehabilitation Center above the Promenade (Hanor 1980). Invasive species such as kudzu cover many of the tufa exposures (S. Rudd, conference call, 7 August 2013). The "display springs" behind Maurice Bathhouse are reproductions of the hot springs' appearance prior to the construction of the collection systems (fig. 10 and cover photo). They are natural seeps at full temperature with constructed tufa arches (S. Rudd, conference call, 7 August 2013). Blue-green algae is abundant in the springs. Local residents and visitors are allowed and encouraged to collect the world-renowned spring water from various spigots and fountains along Bathhouse Row (National Park Service no date). The primary resource management goal is to maintain a consistent volume and quality of water in the spring system (Thornberry-Ehrlich 2007).

**Figure 10. Hot Water Spring Cascade. The park supports a 12 to 15 m (40 to 50 ft) flowing display spring at Arlington Lawn to demonstrate how much of the entire hillside might have appeared if the hot springs were still flowing freely. The feature is plumbed to mix hot and warm waters to a safe temperature, and blocks of tufa were put in place to resemble a natural flowing hot spring. Photograph by Trista L. Thornberry-Ehrlich, taken in 2007.**

### Cold-Water Springs

There are also many cold springs throughout the area, including Arsenic Spring and the sources of Gulpha Creek (Roberts et al. 2007). These typically discharge at temperatures of 15 to 27°C (59 to 79°F) (Sniegocki 1996). With the exception of lower silica content, the chemical composition of the cold-water springs is similar to the thermal water springs (Sniegocki 2001). The cold-water springs tend to emerge along contacts between the Bigfork Chert (Obf) and less fractured formations such as shales. For example, Whittington Spring and some of the "jug fountains" emerge at the contact between Bigfork Chert and the Polk Creek Shale (Opc and SOu). Other cold-water springs, including Happy Hollow Spring (located at the end of Fountain Street), are located along fractures in the Arkansas Novaculite (MDa) (National Park Service 2005; Yeatts 2006; Roberts et al. 2007; Johnson and Hanson 2011). Flow from these springs can be strongly correlative with local precipitation. In a year of high rainfall such as 2009, (200 cm [80 in]), springs appeared across the park's landscape, and then the following year when precipitation was lower (about 80 cm [30 in]), many disappeared (S. Rudd, conference call, 22 May 2013). Average annual precipitation for the park is approximately 150 cm (58 in). Immediately following even moderate rainfall events is the emergence of hundreds of short-lived cold water springs. These flow for several hours until the local recharge is exhausted (S. Rudd, conference call, 7 August 2013).

Water from some cold-water springs, including the classic shallow aquifer system at Happy Hollow Spring, is very young; however, some springs also feature water older than that emerging at the hot springs. At Whittington Spring on West Mountain, the water is 6,000 years old. It is unclear whether this water was ever geothermally heated or just takes so long to get to the surface that it cools in response to contact with the bedrock (S. Rudd, conference call, 7 August 2013).

#### Folds, Fractures, and Faults of the Ouachita Mountains

Paleozoic bedrock was deformed and/or fractured during the Ouachita Orogeny that created the distinctive structures of the Zigzag Mountains. The rocks folded until the stress was so great that they fractured to create joints or slid past each other along faults (fig. 11). Different rocks respond differently to applied stress. "Softer", weaker shales may accommodate more folding than "harder" sandstones or novaculites, which tend to fracture. As described in the "Geothermal Hot Springs" section, folded, fractured, and faulted bedrock created the plumbing that fuels the hot springs geothermal system.

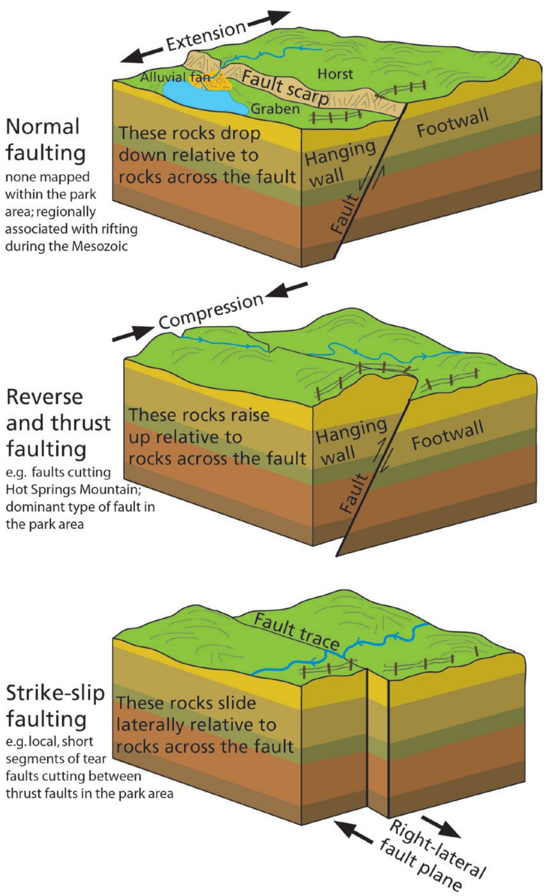



**Figure 11. Schematic illustrations of fault types. Footwalls are below the fault plane and hanging walls are above. In a normal fault, crustal extension (pulling apart) moves the hanging wall down relative to the footwall. In a reverse fault, crustal compression moves the hanging wall up relative to the footwall. A thrust fault is similar to a reverse fault, but has a dip angle of less than 45°. In a strike-slip fault, the relative direction of movement of the opposing plate is lateral. When movement across the fault is to the right, it is a right-lateral (dextral) fault, as illustrated above. When movement is to the left, it is a left-lateral (sinistral) fault. A strike-slip fault between two plate boundaries is called a transform fault. Graphic by Trista Thornberry-Ehrlich (Colorado State University).**

There are two primary types of folds: anticlines (convex, "A"-shaped folds) and synclines (concave, "U"-shaped folds). Both are mapped within and surrounding the park. Most of the folds are plunging which means that their axes are tilted. Many of these folds are overturned, meaning they were folded beyond vertical (fig. 12). The Zigzag Mountains contain a series of plunging folds on the southern limb of a larger structure, the east-west trending Benton-Broken Bow anticlinorium (regional fold composed of smaller folds with the overall shape of an anticline), which forms the core of the Ouachita Mountains in this region (Purdue and Miser 1923; Fellowes 1967). Among these folds are the Hot Springs Mountain anticline, the Park anticline, and the North Mountain syncline (Arndt and Stroud 1952).

**Figure 12. Photograph of overturned folds. The folded bedrock is Bigfork Chert (geologic map unit Obf) along Promise Land Road. White line delineates the general fold pattern. Photograph by Trista L. Thornberry-Ehrlich (Colorado State University), taken in 2007.**

There are four types of faults identified in the GIS data: thrust faults, overturned thrust faults, detachment faults ("décollements"), and tear faults. All of these are associated with compressional forces. Along thrust faults, rocks above the fault (hanging wall) are pushed, or thrust, over rocks below the fault and the fault angle is less than 45°. Overturned thrust faults are tilted past vertical. Detachment faults are thrust faults with displacement on the kilometer or tens of kilometers scale. Tear faults are smaller faults associated with thrust faults, but are often oriented at right angles or oblique to the principal thrust fault. The extreme compression during the Ouachita Orogeny was accompanied by thrust faulting (figs. 7 and 11) and pervasive fracturing in the more resistant units (e.g. cherts, sandstones, and novaculites) (Fellowes 1967). Many of the thrust faults trend southwest-northeast and are parallel with the folds (see "Geologic Map Graphic") (Purdue and Miser 1923; Arndt and Stroud 1952).

Faults cut Hot Springs Mountain and provide both a dam to further downward groundwater flow and a fracture conduit for the water to emerge at the hot springs (Hanor 1980). Two thrust faults define the northern and southern limits of the hot springs discharge area (see fig. 7). The southern fault, sometimes referred to as the "Beta" fault, extends northeastward approximately 2,700 m (9,000 ft) along the axis of the Hot Springs Mountain anticline and dips 44° north. The northern, "Alpha", fault extends nearly parallel to Fountain Street extending northeastward about 2,800 m (9,200 ft) onto the southeast flank of North Mountain. A natural ravine, eroded into fractured rocks, marks the location of a small fault that splits away from the Beta fault, trending west to connect with the Alpha fault (Bedinger 1979; Yeatts 2006; Johnson and Hanson 2011). Smaller-scale fractures, also called joints, occur where the rock has been broken, but no movement (as defines a fault) has occurred. Fractures are exposed perpendicular to sedimentary layering in the Arkansas Novaculite (MDa) on top of West Mountain (fig. 13) (Hanor 1980).

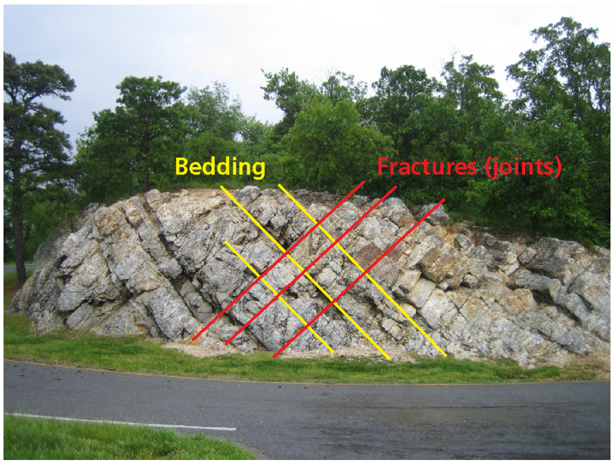



**Figure 13. Fractured Arkansas Novaculite. Exposures of the Arkansas Novaculite (geologic map unit MDa) atop West Mountain have fractures (red lines) perpendicular to bedding (yellow lines). Photograph by Trista L. Thornberry-Ehrlich (Colorado State University), taken in 2007.**

Differential erosion (i.e. more rapid erosion of weaker units versus resistant units) of the folded and faulted rock sequence has caused the "zigzag" ridges. Shales, particularly sheared shales, weather rapidly and thus often underlie valleys. The Stanley Shale (Ms) is mapped throughout the valleys within and surrounding Hot Springs National Park's south and west sides.

Mountains and ridges are supported by more erosion-resistant rocks such as Arkansas Novaculite (geologic map unit MDa) and Hot Springs Sandstone (Mshs) (Arndt and Stroud 1952). Remnants of more resistant rock, such as Goat Rock on Hot Springs Mountain or Balanced Rock on Sugarloaf Mountain, may persist as pinnacles when surrounding rock erodes away (Hanor 1980).

### Geologic Connections to Park Stories and Resources

#### American Indian History

The hot and cold springs have attracted people to Hot Springs for thousands of years (Hanor 1980). American Indians considered this "Valley of the Vapors" neutral ground and different groups came to hunt, trade, and bathe (Bedinger 1974; National Park Service 2005).

In addition to the springs, local rocks were also of value. For as many as 10,000 years, American Indians have quarried rock for constructing tools. There are more than 120 quarry sites in the Hot Springs Sandstone Member of the Stanley Shale (geologic map unit Mshs) and Arkansas Novaculite (MDa) (National Park Service 2005). American Indians sought the hard, dense, fine-grained novaculite, "Hard Arkansas", from the lower layers of Arkansas Novaculite (MDa), that produces a glass-like, scalloped fracture pattern and razor-sharp edges when broken or chipped (figs. 14 and 15) (Bedinger 1974; Hanor 1980).


**Figure 14. Fine-grained Arkansas Novaculite. The hard, brittle, almost pure silica content of the Arkansas Novaculite made it an ideal stone tool material and today continues to supply whetstones. Note the sharp fractures. Photograph by Trista L. Thornberry-Ehrlich (Colorado State University), taken in 2007.**

William Henry Holmes, noted explorer, archeologist, and geologist, described one novaculite quarry in Garland County as a series of large pits, exposed rock faces, and a massive area of knapping debris—the "Great Workshop". This site was likely worked for thousands of years (at least during the Woodland period, ca. 650 BCE to 950 CE) and the morphology of the novaculite ridge crest was altered (Arkansas Archeological Survey 2013). Stream-worn cobbles of Hot Springs Sandstone member of the Stanley Shale (Mshs) were used to break apart the novaculite (Roberts et al. 2007). American Indians removed some 10,000 tons of material from local quarries (Thornberry-Ehrlich 2007). Tools made from novaculite are found associated with archeological sites as old as 10,500 BCE in the Paleoindian Period and as far away as Texas, Louisiana, Mississippi, and Missouri (Arkansas Archeological Survey 2013). By the late 19th century, miners were using many of the American Indian quarries to extract novaculite for use as whetstones, metal blade sharpeners. In fact the term "novaculite" stems from "nova cula", Latin for "sharp knife" (Roberts et al. 2007).

The industrial mineral Tripoli, weathered novaculite, was mined from one location on Indian Mountain (S. Rudd, conference call, 22 May 2013). This mineral material is friable microcrystalline silica. The friability stems from the dissolution of tiny grains of interstitial carbonate (Hanor 1980) and the rock's "triple-point"

**Figure 15. American Indian quarries and blocks of Arkansas Novaculite. The fine-grained white novaculite was most prized by tool makers. Worked chips and fragments are common at these sites. National Park Service photographs by Stephen Rudd (Hot Springs National Park).**

texture developed by low grade pressure metamorphism (D. Hanson, geologist, Arkansas Geological Survey, written communication, 23 September 2013). It has applications to a wide range of industries, such as polishing and buffing compounds, filler agent in paints, and as mild abrasives. Tripoli is still mined regionally (American Tripoli 2002).

### Early European History and Park Establishment

According to Hanor (1980), Europeans first visited the area as early as 1541. French trappers and hunters followed the Spanish into Arkansas territory. Many features in the park, including Hot Springs Creek and Gulpha Creek, originally had French names—Bayou des Sources Chaudes and Fourche à Calfat, respectively.

Following the Louisiana Purchase in 1803, President Jefferson sent the Dunbar-Hunter expedition to explore the area. At Hot Springs, they found a steaming hillside covered with a blanket of calcium carbonate (tufa). Expedition leaders surmised chemical reactions "in the bowels of the hill" involving sulfur, clay, and bitumen were the thermal source. Following the expedition report, interest in the hot springs increased dramatically. The first permanent residents arrived in 1807 (Bedinger 1974; Hanor 1980). In 1832 the federal reserve was created at the hot springs and surrounding area.

Following a devastating fire in 1878, Hot Springs was rebuilt as a spa city and constructed elegant brick and stucco (fire-resistant) Victorian bathhouses between 1912 and 1923. These are now interpreted as Bathhouse

Row (fig. 2) as detailed by Shugart (2003). Following a decline in spa visitation during the 1960s, most of the bathhouses closed and fell into disrepair. Hot Springs is known as the "Spa City" and in the time since 2007, the bathhouses within the park were renovated, leased, and made operational—once again a vital part of the area's economy and story. The current lessee of Superior Bathhouse even uses geothermal water to brew beer (S. Rudd, conference call, 7 August 2013).

The area's valuable rock resources, already utilized by American Indians for thousands of years, were also extracted by European settlers. Novaculite mining for the whetstone industry began in the early 1800s at many of the same quarries established by American Indians. It continues today (Arkansas Archeological Survey 2013). The area also attracts visitors interested in mineralogical specimens because the Ouachita Mountains of Arkansas is America's most prolific source of clear, hexagonal quartz crystals (Jones 2009). During the Ouachita Orogeny, the rocks were extensively fractured and faulted. During the last phases of the orogeny, silica-saturated hydrothermal solutions flowed through the openings, precipitating the quartz crystals (fig. 16) in the pockets in a setting not unlike the geothermal hot springs today (Roberts et al. 2007; Jones 2009). Hot Springs is often incorrectly assumed to be the source of the quartz


**Figure 16. Quartz veins in bedrock. Exposures of white quartz veins within bedrock are common throughout the park area. At the end of the mountain building events, silica-saturated fluids migrated through the deformed rock leaving precipitates of quartz throughout the area and some were in turn deformed. Notable examples include the famous quartz crystals of Arkansas. Photograph by Trista L. Thornberry-Ehrlich (Colorado State University), taken in 2007.**

crystals because of all the tourist interest, but the major source areas are at Mount Ida, 34 km (21 mi) west of Hot Springs and Jessieville, 12 km (7 mi) north of Hot Springs. Though present in a variety of morphologies, the local specimens are textbook examples of quartz with perfectly formed hexagonal prisms and pointed terminations (Jones 2009). Many commercial and visitor-accessible quarries exist today, including Mount Ida, Colemans (northwest of the park on State Highway 7), Stanley Mine (east of Mount Ida off US Highway 270), Starfire Mine, and Crystal Pyramid Mine (Jones 2009).

### Connections with Microbiology and Astrobiology

The thermal waters emerging from the hot springs of the park are enriched with respect to certain minerals and naturally safe to drink (National Park Service no date). Once thought to be sterile water, the National Aeronautics and Space Administration chose this water to hold moon rocks while performing experiments to detect signs of life. Modern microscopes have revealed the presence of microbes in the water. Therefore purity is staunchly protected at the park with locked coverings over the springs and constant monitoring (National Park Service 2005).

Biomarkers, chemical or physical signatures of living organisms (primarily microbes), occur within the carbonate tufa (Qtufa) deposits of hot springs at the park. Biomarkers included mineralized microbial forms, biofilms, mineral spheres (amorphous mineralized life forms), and biologically weathered crystals (Allen et al. 1998, 2000). Microbe morphology varied among rods, spirals, spherical bodies, and elongate forms (Allen et al. 1998). Recent studies have focused on using the biomarkers present in the hot springs deposits as proxies for evidence of life in Martian hot spring deposits. Given the extreme environment supporting life at Hot Springs, it is possibile that microorganisms adapted to dark, anaerobic conditions in the subsurface could exist on Mars (Allen et al. 2000).

Researchers from the University of Oklahoma's aquatic microbiology department identified a bacterial genus and species unique to the geothermal springs at Hot Springs National Park—*Fontimonas thermophile* (proposed name) (Losey et al. 2013). This bacterial system has been evolving since the geothermal system became intact and functioning. The date when the hot springs first appeared is not known. The system has likely been functioning since at least the Quaternary (D. Hanson, written communication, 23 September 2013). Some researchers propose it may be much older, dating back to the Paleozoic, over the past 230 million years. If this is true, then these organisms have survived and evolved through several mass extinction events of Earth's history (S. Rudd, conference call, 22 May 2013).

## Paleontological Resources

Hot Springs National Park is one of at least 243 NPS areas that preserve paleontological resources (fossils). All paleontological resources are non-renewable and subject to science-informed inventory, monitoring, protection, and interpretation as outlined by the 2009 Paleontological Resources Preservation Act. Regulations associated with the Act are still (November 2013) being developed. As described in detail in the "Map Unit Properties Table," Hunt et al. (2008), and Johnson and Hanson (2011), the Ordovician to Mississippian bedrock geologic units in the Hot Springs area contain some fossils, although—with the exception of graptolites in the Polk Creek Shale (Opc)—they are uncommon. Fossils in the area include marine invertebrates, sponges, radiolarians, conodonts, spores, graptolites, brachiopods, trilobites, crinoids, as well as occasional plant fossils and vertebrates (Johnson and Hanson 2011; D. Hanson, written communication, 23 September 2013). Interestingly, during the Paleozoic, turbidity currents (submarine landslides) carried many of these now fossilized remains from nearshore to deeper water depositional environments (Johnson and Hanson 2011).

As of the writing of this report, the only fossils discovered within the park are graptolites from the Polk Creek Shale (geologic map units SOu and Opc) (McFarland 2004; Hunt et al. 2008). Graptolites are small colonial organisms. In morphology, some resemble saw blades. Globally, graptolites are important biostratigraphic and biochronologic index fossils. There are Polk Creek Shale graptolites in the park's museum collections, although they were apparently not collected within the park (Hunt et al. 2008). The limestones used in the construction of Bathhouse Row are from Alabama and Arkansas and may display fossil resources. This cultural resource context would provide interesting interpretive "exposures" of fossils (Hunt et al. 2008; Kenworthy and Santucci 2006). The Arkansas Geological Survey website contains basic information about fossils in the state (http://www.geology.ar.gov/geology/fossils.htm, accessed 2 December 2013).

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

# Geologic Issues

*Geologic issues described in this section may impact park resources or visitor safety and could require attention from resource managers. Contact the Geologic Resources Division for technical and policy assistance.*

During the 2007 scoping meeting (summarized by Thornberry-Ehrlich 2007) and 2013 conference call, the following geologic resource management issues were identified:

- Geothermal Water Quantity and Quality
- Radon Exposure
- Slope Movements
- Disturbed Lands, Unauthorized Collecting, Vandalism, and Artificial Ponds
- Flooding

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

#### Geothermal Water Quantity and Quality

The hot springs are the primary natural resource at the park. Therefore protecting them, their watershed, their source of heat, and maintaining consistent quantity and quality of spring water are resource management priorities. The concerns with regards to thermal water discharge are significant at Hot Springs National Park, for example: (1) changes to recharge, (2) vent sealing, and (3) "piracy" of the geothermal resource. In addition to these concerns, there is a major effort underway to better understand and characterize the recharge area and processes responsible for the hot springs in the park to provide better information for resource management.

As described in the "Geothermal Hot Springs" section, hydraulic head drives the geothermal spring system so any changes to pressure or flow paths in the recharge area, in addition to alterations to the amount of recharge (described in "Climate Change and Spring Flow" section), can rapidly affect discharge at the hot springs. Minerals (e.g. geologic map unit Qtufa) precipitate rapidly from solution when the springs emerge to atmospheric conditions. This raises the question of whether the geothermal hot springs will flow indefinitely or will the overall system eventually seal itself with mineral precipitates. Dating of tufa deposits (geologic map unit (Qtufa) in the park area would help to determine the history of spring discharge (Thornberry-Ehrlich 2007).

There is also concern of "piracy" of the park's geothermal resource by drilling outside the park. In 1832, Congress made it against the law to drill for geothermal water in the Hot Springs Reservation. In the 1880s, Congress held hearings regarding the construction of the creek arch and use of explosives and drilling to "enhance flow" (S. Rudd, Hot Springs NP, natural resource program manager, conference call, 7 August 2013). The 1970 Geothermal Steam Act (as amended in 1988) provides additional protection for the park's hot springs. The Act prohibited geothermal leasing in national park units, but it authorized the Secretary of the Interior to issue geothermal development and utilization leases on non-NPS lands administered by the Department of the Interior, on lands administered by the Department of Agriculture, or on lands that are not federally-owned but are subject to a federal reservation for geothermal resources. This authority has been delegated to the Bureau of Land Management (BLM). BLM implements the Act through the regulations contained in 43 Code of Federal Regulations Part 3200. See also Appendix B.

The Act required the NPS to maintain a monitoring program for significant thermal features within units of the National Park System, including a research program in cooperation with US Geological Survey (USGS) to collect and assess data on the geothermal resources in park units containing significant thermal features. The Act directed the NPS to begin such data collection near areas of current, proposed, and potential geothermal development.

The Act then required the Secretary of the Interior to determine, upon receipt of an application for a lease, whether geothermal exploration or development is reasonably likely to result in adverse effects on significant thermal features in park units. If adverse effects on a park's significant thermal features are determined to be reasonably likely, the Secretary must include protective stipulations in leases and drilling permits. The Act also prohibits the Secretary from issuing a lease if the geothermal exploration or development is reasonably likely to result in significant adverse effects on significant thermal features in park units. In addition, the Secretary of Agriculture is required to consider the effects on significant NPS thermal features in determining whether to consent to the Secretary of the Interior's issuance of leases on national forest lands.

NPS Management Policies (2006) § 4.8.2.3 reiterate that parks must monitor their significant thermal features. In addition, it is NPS policy to:

- protect, preserve and manage thermal resources in parks as a critical component of park natural resource systems, and for public education, interpretation, and scientific research;
- strive to maintain the natural integrity of thermal systems in parks;
- work to prevent unacceptable impacts caused by the development of thermal resources; and
- work closely with federal, state, and tribal agencies to delineate the full extent of thermal resources, and protect those that occur within parks using the authority of the Geothermal Steam Act and other laws.

Drilling laws do not currently control wells in the recharge area (Thornberry-Ehrlich 2007; S. Rudd, conference call, 22 May 2013).Thermal water throughout the Ouachita Mountains tends to occur in similar geologic settings—the nose of plunging anticlines and closely aligned thrust faults (Kresse and Hays 2009).

#### Understanding the Geothermal System

Despite nearly two centuries of scientific and commercial interest in the springs, their recharge area and hydrologic connections to adjacent areas were not well defined. This issue came to the attention of park staff and local geologists in February–March 2006 when a shallow water well (the "Bratton well"), located 10 km (6 mi) east of the park, began discharging geothermal water at a temperature of 34°C (93°F). Mean local groundwater temperature is 17°C (63°F) for a shallow well (Kresse and Hays 2009). This event was coincident with blasting associated with a nearby highway bypass expansion project and the construction of the Crossgate Baptist Church complex (Thornberry-Ehrlich 2007). An early hypothesis was that shockwaves from the blasting extended down into the fractured subsurface with the potential to disturb geothermal systems (Rudd 2008). In examining the associated environmental assessments performed by the highway department, the park was able to have the highway project postponed for further research (Greco 2006; S. Rudd, conference call, 22 May 2013). Because, at that time, the Bratton well area was considered outside the thermal water recharge zone and the connection between that well and the park's geothermal hot springs was not understood, the park embarked on a cooperative research effort with the US Geological Survey and University of Arkansas among others to develop an accurate recharge model by the end of 2015 (S. Rudd, conference call, 22 May 2013). This may help determine if the water quantity will be sufficient to supply the bathhouses and park needs in the future.

The goals of the research projects are:

- determine if the newly produced water in Bratton well is from a different source than the water in the park
- perform geophysical logging and water sampling from Bratton well and other important cold water sites to understand the nature and origin of their cold groundwater components
- produce a detailed water level map and determine connectivity between the park's hot springs and local wells
- obtain strontium and other isotope geochemical information to act as flow tracers
- research and define the recharge area for Hot Springs National Park
- perform hydraulic and discharge monitoring to determine patterns in hydraulic head variations, preferably on a spring by spring basis.

Results from these studies are already providing excellent information about the geothermal system. Bolyard et al. (2008) used strontium and carbon isotopes as tracers to delineate flow paths, determine groundwater residence time, and determine the thermal water recharge area. These isotopes are effective because of the distinctive isotopic signatures of groundwater coming into contact with specific geologic units. Using geochemical signatures, Kresse and Hays (2009) determined approximately 40% of the thermal water emerging at the hot springs in prolonged contact with shale formations (i.e. Stanley Shale [Ms]) at depth and 60% was in contact with the quartz formations (i.e. Bigfork Chert [Obf]). They also noted key chemical differences between thermal waters emerging in domestic wells and the thermal waters emerging from the hot springs. Across the distance between the park's springs and the Bratton well are a surficial watershed, three anticlines, and several large thrust faults through fractured rock (Kresse and Hays 2009). They are likely not hydraulically connected, but the Bratton well does occur on a similar geologic structure as the hot springs—at the nose of a southwest plunging anticline along a major thrust fault. Changes in the domestic wells may serve as analogs to understand potential effects of landuse changes on the Hot Springs National Park thermal system; the Bratton well has a monitor (Kresse and Hays 2009; S. Rudd, conference call, 7 August 2013).

Kresse and Hays (2009) noted that blasting activities were likely not responsible for an increase in thermal water in local wells. Propagation of new fractures near blasting sites is of limited extent—potentially less than 100 m (300 ft). Rather changes in recharge rates including long-standing droughts were allowing thermal water components to increase in percentage compared to the cold-water contribution (S. Rudd, conference call, 7 August 2013). Likewise, wet-season surges in recharge were hydraulically pushing thermal waters into some wells. Some sites showed changes in sealed fractures allowing thermal water percentage to increase in some wells.

Kresse and Hays (2009) and Bell and Hays (2007) determined that any changes in the recharge/runoff ratio in the recharge area could affect discharge and temperature at the hot springs. Changes could include differences in surface and subsurface physical properties of hydraulic conductivity, porosity, storage, and fracture connectivity. Changes to these parameters cause changes in hydraulic head and pressure. Land-use changes, as they affect hydraulic characteristics, will result in rapid changes to the flow of the hot springs. This is described further in "Climate Change and Spring Flow" and "Land Use Changes". Because hydraulic head powers the thermal water system, this will result in discharge changes. A decrease in the thermal water component would be accompanied by a corresponding increase in the cold-water recharge, lowering overall hot spring temperature.

#### Climate Change and Spring Flow

Heavy summer precipitation events, mild winters, and high humidity characterize the warm, wet climate of central Arkansas. The hot springs are recharged from meteoric water (precipitation) and any change in precipitation patterns will impact spring flow. Thus, continuing climate change will likely affect the availability and quantity of the park's primary resource. Karl et al. (2009) presented climate models that project continued warming and an increase in the rate of warming through the year 2100. The number of days per year with temperatures over 30°C (90°F) may eventually reach more than 135 (about 4.5 months) in central Arkansas compared with just 75 days (2.5 months) observed between 1961 and 1979 (Karl et al. 2009). Climate models also suggest a decrease in precipitation in winter and spring and thus the frequency, duration, and intensity of droughts are likely to continue to increase (Karl et al. 2009). Sea surface temperatures are also rising and this correlates with an increase in hurricane power (i.e. peak wind speeds and rainfall intensity) (Karl et al. 2009; Loehman and Anderson 2010). Hurricanes that travel inland from the Gulf of Mexico bring abundant precipitation to central Arkansas. According to the National Flood Insurance Program (2011), Arkansas is particularly vulnerable to severe flooding over a broad area from hurricanes. Notable examples of destructive storms causing widespread flooding in Arkansas include Hurricane Katrina in 2005 and Hurricane Ike in 2008.

By monitoring the flow rates of the geothermal hot springs, park staff have made a more accurate connection between precipitation patterns and hot spring response. Prior to this monitoring, the exact response delay of the springs was unknown, but was thought to be between one and five years. However, during a recent drought from approximately 2009 through 2012, the monitored flow rates dropped from 2,700,000 L/day (710,000 gal/day) to a low of 2,480,000 L/day (655,000 gal/day) over just six to eight weeks (S. Rudd, conference calls, 22 May 2013; 7 August 2013). Now, park resource managers estimate the delay between changes in recharge (precipitation) and the flow response of the springs is on the order of less than a few months. Response time to drought conditions is rapid and the system is still recovering average flow after prolonged precipitation events in 2013 (S. Rudd, conference call, 22 May 2013).

The NPS Climate Change Response Program (CCRP, based in Fort Collins, Colorado) facilitates Servicewide climate change science, adaptation, mitigation, and communication (CCRP 2010). The CCRP developed a climate change response strategy and climate change action plan for the NPS. Refer to their website (http://www.nature.nps.gov/climatechange/index.cfm) for additional information and to download the plans. Karl et al. (2009) summarizes climate data, projections, as well as regional impacts across the United States. A new (the third) National Climate Assessment report (Karl et al. 2009 was the second) will be published in early 2014 and will be available at the website for the U.S. Global Change Research Program (http://globalchange.gov/resources/reports, accessed 2 December 2013).

#### Land Use Changes

As described in the "Geothermal Hot Springs" section, the recharge area for the hot springs is being more accurately defined as a forested hogback north and east of the park on Indian, North and Hot Springs mountains—all part of the same weathered anticline (S. Rudd, conference call, 7 August 2013). A large percentage (perhaps as much as half) of that recharge area is not within park boundaries, presenting challenges to monitoring and maintaining adequate recharge area to sustain the spring water quantity and quality mandated by the park's enabling legislation (S. Rudd, conference call, 7 August 2013). The surrounding forest ridges that comprise the recharge area have been used as tree farms or hunting grounds but are now potential home sites for developers moving away from the crowded shores of Lake Hamilton (S. Rudd, conference call, 22 May 2013). Continuing urban and suburban expansion will include increased municipal infrastructure and building or extension of major roadways (Kresse and Hays 2009). Park resource management is concerned that an increase in impervious surfaces such as paved roads and driveways, the construction of stormwater diversion structures such as sewers and culverts, blocking of surface fractures, and the removal of vast tracts of soil and vegetation will have negative impacts on the recharge area available to the geothermal system (Kresse and Hays 2009; S. Rudd, conference call, 22 May 2013). As detailed in the "Climate Change and Spring Flow" section, this system responds rapidly to changes in precipitation and thus recharge. Maximizing recharge area while rapid regional development continues will be a challenge. Development that would maximize recharge area could include large home plots (1 to 2 ha [3 to 5 ac]), a minimum of impervious surfaces, and land clearing practices that account for the natural condition of the landscape (S. Rudd, conference call, 22 May 2013). As described in the "Geothermal Hot Springs" section, the Bratton well may serve as an analog to potential impacts on the hot springs geothermal system if development continues closer to park boundaries (Thornberry-Ehrlich 2007).

The water emerging from the hot springs is approximately 4,400 years old. This means it takes thermal recharge water approximately that long to cycle through the system. High precipitation in the recharge area "pushes" (via hydraulic head) more water through the system causing higher flow rates. However, this is not the same water that fell as precipitation a few months prior. Recent studies indicate little change in water chemistry has occurred in the springs since the late 1800s (Bell and Hays 2007; Hays et al. 2008). It is unknown how contaminants introduced to the thermal water recharge area during development and land use will affect water quality later. The younger, shallower local groundwater component to the hot springs flow has a much faster response time to changes in recharge water quantity and quality. Because this water can account for more than 30% of the hot springs discharge (after a storm event), the potential for contamination of the flows is a concern (Bell and Hays 2007).

Expansion of surrounding development may also negatively impact the fluvial system in the area. Increases in impervious surfaces decrease the area available for groundwater recharge while also increasing surficial runoff. This can hasten erosion and cause gullying or channel incision. In addition, vegetation clearing changes the nature of the surficial cover type. A lack of stabilizing vegetation leads to increased erosion. The eroded sediment then flows into local streams, increasing sediment load and turbidity. This in turn may change channel morphology (Thornberry-Ehrlich 2007).

#### Monitoring the Geothermal Resource

Understanding the major processes and controls affecting the origin, flow, and thermal and chemical transport of the park's hot springs has been the subject of much recent study and ongoing monitoring. Heasler et al. (2009)—the chapter in *Geological Monitoring* about geothermal systems—described the following methods and vital signs for understanding geothermal systems and monitoring hydrothermal features: (1) thermal feature location; (2) thermal feature extent; (3) temperature and heat flow; (4) thermal water discharge; and (5) fluid chemistry. Brahana (2008) described how geochemical, particularly stable-isotopic and radionuclide analyses are key to understanding water source and relative age, particularly for a setting such as that at Hot Springs National Park, where old thermal waters mix with young, cold groundwater.

### Radon Exposure

Radon is a heavier-than-air, colorless, odorless, radioactive gas. It is a natural decay product from also naturally occurring uranium and thorium in the bedrock and tufa beneath the park. Long term exposure to elevated levels of radon creates an increased risk for lung cancer. Refer to the Environmental Protection Agency (EPA) radon website for additional information: http://www.epa.gov/radon/. Radon naturally accumulates in caves, basements, and other subterranean cavities. Limited air circulation in these spaces concentrates radon gas to levels appreciably higher than outside. The Environmental Protection Agency's (EPA) recommended maximum level of radon gas concentration is 4 picocuries per liter (pCi/L) (EPA 2013). Hot Springs National Park infrastructure is particularly susceptible to elevated radon levels. The hot springs themselves create natural vents for the gas. In addition the spring water also contains high levels (820pCi/L) of radon in solution, although the amount varies greatly between springs and is dependent on temperature and flow rates (Kuroda et al. 1954; Epperson and Rhodes 1990). Bathhouses constructed near the springs further concentrate the gas in their confined spaces. The basement of Hale Bathhouse is one example of bathhouse construction creating additional radon hazards. Waters of Wall Spring contact the foundation of Hale Bathhouse and react with the concrete and oxygen to precipitate radium carbonate. This precipitation has occurred to such an extent that the foundation wall is now radioactive. The park restricts access to this portion of the bathhouse and monitors the radon levels (S. Rudd, conference call, 22 May 2013). Because radon is naturally occurring and is relatively easy to mitigate, remediation of the threat requires monitoring and ventilation.

Bathhouses and the park headquarters have measured elevated levels of radon gas and are monitored regularly by park staff. To reduce radon concentrations, ventilation systems were installed during restoration of the bathhouses between 2007 and 2013. Bathhouse lessees are required to monitor and maintain the ventilation systems (S. Rudd, conference call, 22 May 2013). For example, a failure of the ventilation system in the Ozark Bathhouse temporarily led to radon levels of 29 pCi/L, more than seven times the EPA recommended maximum level.

### Slope Movements

The steep slopes within and surrounding Hot Springs National Park are prone to movement via landslides, rockfalls, and slumps (fig. 18) (Thornberry-Ehrlich 2007). Talus, or blocks of rock, at the base of slopes are evidence of past slope movements (fig. 17) (Hanor 1980). The resistant bedrock that caps the highest slopes is naturally fractured, faulted, and folded. Fracturing is further enhanced by tree roots (fig. 19) and frost weathering. These processes wedge the exposed blocks of bedrock apart and allow them to tumble down steep slopes.

**Figure 17. Blocks of talus at the base of steep slopes. Talus blocks derived from Hot Springs Sandstone Member of the Stanely Shale (geologic map unit Mshs) Photograph by Trista L. Thornberry-Ehrlich (Colorado State University), taken in 2007 on the north side of the Arlington parking lot landslide.**

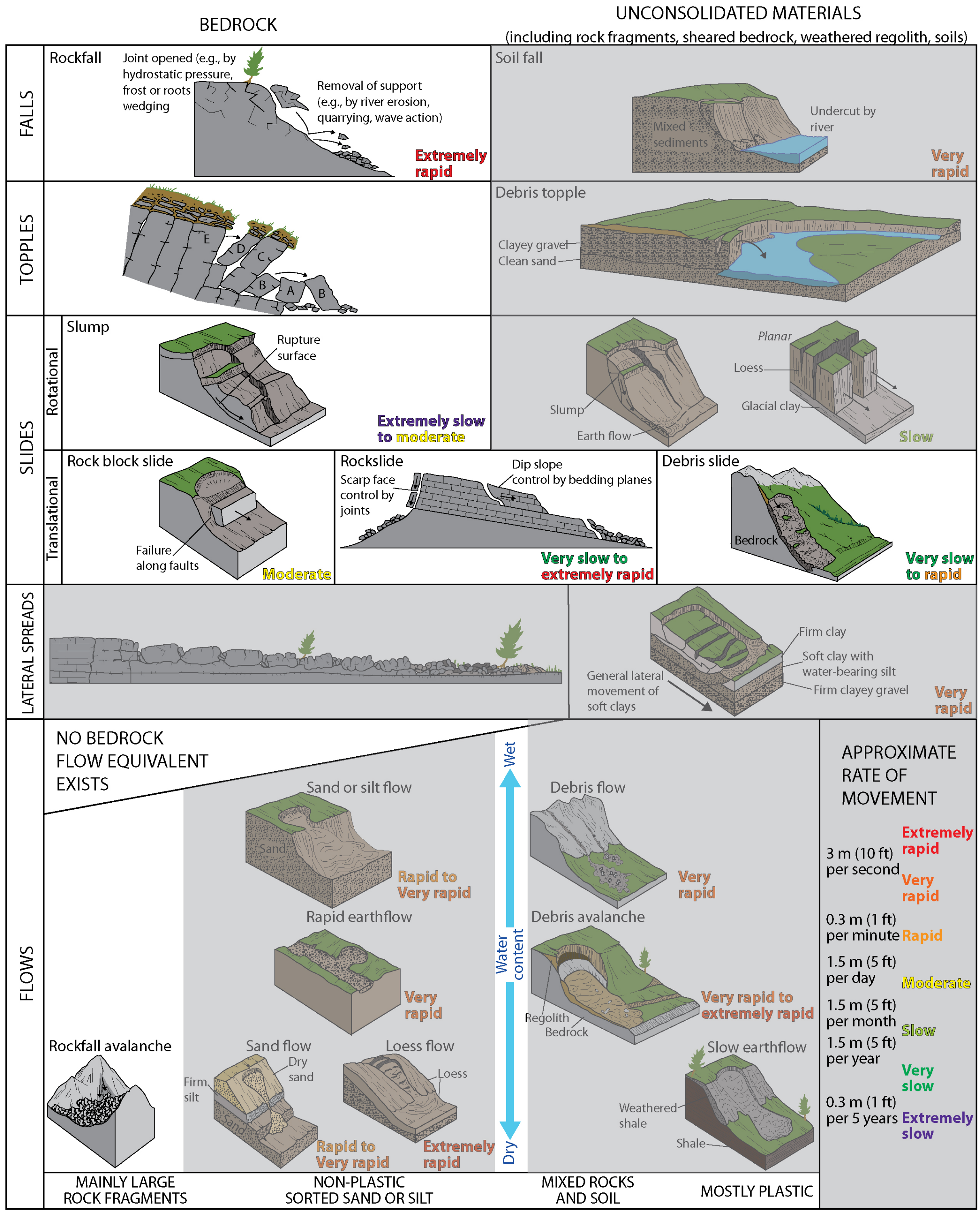



**Figure 18. Types of slope movements. Grayed areas depict conditions that are not likely to exist within Hot Springs National Park. Graphic by Trista Thornberry-Ehrlich (Colorado State University) redrafted after a graphic and information in Varnes (1978).**

The fractured rocks and narrow, steep valley between Hot Springs and West mountains created slope movement hazards that were exacerbated by historic development aimed at maximizing access to the springs and associated businesses. During the early construction of the historic town of Hot Springs, developers excavated the "toes" of several slopes to create stable, level ground for building. Van Cleef (1878) described how in many places the mountainside was "blasted away to make room for the buildings and other

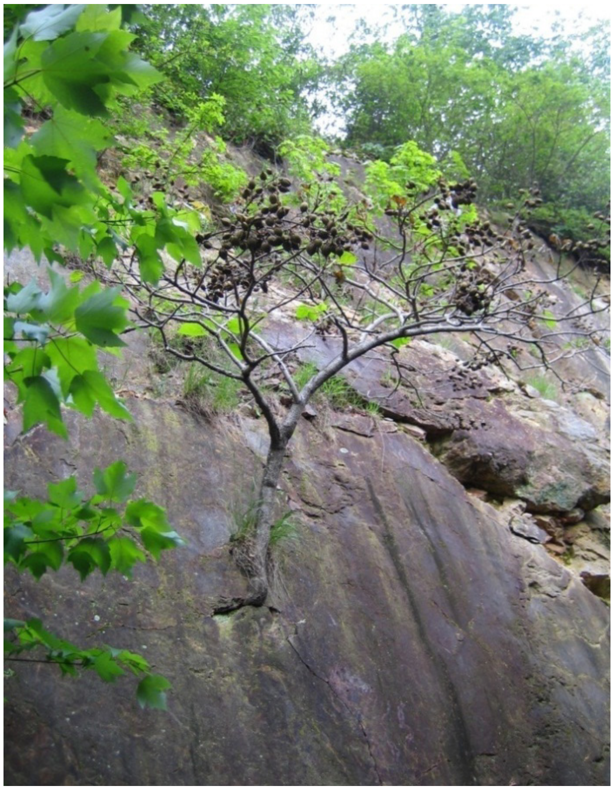


**Figure 19. Tree growing out of a near vertical bedrock outcrop. Fractures in the bedrock permit frost weathering, but also plant and tree root growth. The roots wedge apart the rocks and may even serve to chemically weather the rocks through acid-producing decay. Photograph by Trista Thornberry-Ehrlich (Colorado State University), taken in 2007**

improvements." In doing so, developers undercut the slopes creating "highwalls" nearly 30 m (100 ft) high in very close proximity to many businesses. Some walls also exposed unstable slope talus and colluvium, creating even more slope movement hazards below the near vertical cliffs of the valley walls. According to a study conducted for the Federal Emergency Management Agency (FEMA), significant rockfall hazards exist on the slopes of North and West mountains (Woodward-Clyde Consultants 1997). The problem is largely confined to specific areas beyond park boundaries and is exacerbated by anthropogenic activities. In the past, landslides have buried cars, inundated the lower floors of local hotels and even claimed the life of a local resident. For example a 1984 landslide at the Arlington Hotel buried 13 cars and the lower deck of the parking garage. In 1995, one person was killed and two were injured when a landslide partially destroyed the Hot Springy Dingy store (S. Rudd, conference call, 22 May 2013; Arkansas Geological Survey 1984, 1995).

Within the park, there are two significant areas of concern. The first is on Hot Springs Mountain upslope of the facility the park constructed to cool geothermal water for bathhouses and fountains. At this location, the slopes are steep and the tufa deposits (Qtufa) are weathered, friable, and fractured. The site has a history of rockfall activity, and in the late 1990s, appeared unstable—the potential for future hazardous rockfall occurrences at the site is a serious concern (Chleborad 1999). A rockfall there would threaten both park staff safety and the cooling facility itself. Because access to the geothermal water is the park's primary mission, the cooling facility is an important piece of park infrastructure. The second area is along West Mountain Drive where excavations created the potential for slope movement, particularly after large rain events. Despite the previous construction of retaining walls, landslides occur along the road toward the dead-end loop of Summit Drive (S. Rudd, conference call, 7 August 2013). A landslide in 2007 or 2008 dislodged a large block of folded rock near the junction of West Mountain Summit Drive and West Mountain Drive (as indicated in the GRI GIS data), destroyed a gate, and flowed across the roadbed, leaving 5 m (15 ft) of debris (S. Rudd, conference calls, 22 May 2013; 7 August 2013).

### Managing and Monitoring Slope Movements

Remediation efforts against slope movements include building retaining walls (fig. 20); installing high tensile nets, rockfall catch fences, and/or anchor bolts, as well as plastering the exposed rock faces with concrete and installing drain pipes (fig. 21) (Woodward-Clyde Consultants 1997). These techniques have mixed results. The natural spring discharge in the areas with concrete plastering make rockfall prevention nearly impossible as the seeping water dissolves the concrete coating from the inside out. It becomes friable and fails (fig. 21). Within the park, wire rope nets and bolts were installed to contain the fractured tufa (geologic map unit Qtufa) deposit above the park's geothermal cooling towers (S. Rudd, conference call, 22 May 2013). Thus far, these structures have prevented tufa spalling off the slope (Thornberry-Ehrlich 2007; S. Rudd, conference call, 22 May 2013). A wall was constructed along the problematic stretch of West Mountain Road to minimize the risk of future slope movements. Scoping participants noted a need to map landslide areas within the park (Thornberry-Ehrlich 2007). Chleborad (1999) recommended steep areas within the park be inspected on a regular basis for surface indications of slope failure including through- going cracks, hummocky land

**Figure 20. Retaining wall. Structures are placed at the bases of slopes whose toes were excavated to make more room in the narrow valley in the early history of Hot Springs, Arkansas. Photograph by Trista Thornberry-Ehrlich (Colorado State University), taken in 2007.**

**Figure 21. Slope movement mitigation measures. Concrete sprayed against bedrock with drains installed is one type of structure to keep spalling rocks in place on steep slopes. These systems have largely failed due to seeping water undermining the integrity of the concrete, which then dissolves and fractures (left image) from the outside in, becoming a falling hazard itself (right image). Photographs by Trista Thornberry-Ehrlich (Colorado State University), taken in 2007 from a parking lot adjacent to the old Medical Arts building across Central Avenue from the Arlington Hotel.**

surface, and new movements along cracks. Park staff frequently remove kudzu from the hillslope near the cooling tower and assess signs of slope movements (S. Rudd, conference call, 7 August 2013).

FEMA rates the hazards of a given area by the following criteria: slope height; distance of a feature of interest from the toe of the slope; occupancy frequency for structures at the toe of the slope; existing mitigation measures; rockfall history; water pressure estimates based on visual observations; location of observed joints relative to each other and to the slope face; and kinematic stability analysis. Their hazard level rankings ranged from low to high for sites on North and West mountains (Woodward-Clyde Consultants 1997).

Wieczorek and Snyder (2009)—the chapter in *Geological Monitoring* about mass wasting—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) assessing landslide hazards and risks. For additional information refer to the Arkansas Geological Survey landslides website (http://www.geology.ar.gov/geohazards/landslides.htm), Highland and Bobrowsky (2008), and the US Geological Survey landslides website (http://landslides.usgs.gov/).

### Disturbed Lands, Unauthorized Collecting, Vandalism, and Artificial Ponds

Disturbed lands are those where natural conditions and processes were impacted by human development or agriculture. Humans have long utilized the natural resources of the Hot Springs area. As described in the "Connections with Park Stories" section, American Indians were the first to extract minerals from the park area. They sought sandstone and novaculite for tools and other implements from the Hot Springs Sandstone Member of the Stanley Shale (geologic map unit Mshs) and Arkansas Novaculite (MDa) (Johnson and Hanson 2011). There are some historic prehistoric quarries within park boundaries on North and Indian mountains within the park. Numerous worked novaculite chips are collected (S. Rudd, conference call, 7 August 2013). In order to minimize impacts to the sites, access trails have been closed. The park is not planning to remediate or otherwise alter the quarries as they are now considered cultural resources (S. Rudd, conference call, 22 May 2013). According to the NPS Geologic Resources Division Abandoned Mineral Lands (AML) database, there are no AML sites or features documented within Hot Springs National Park (database accessed 15 July 2013). Refer to Burghardt et al. (2013) for additional Servicewide AML information.

Rock collecting is a popular regional activity, although collecting is illegal within Hot Springs National Park (and all NPS areas). Nevertheless, incidents of rock theft or vandalism have occurred within the park. For example, material was collected from Arkansas Novaculite (MDa) outcrops along Gorge Road within the park. During large storms, when trees are uprooted, arrowheads and worked rocks within the root balls are subject to theft (S. Rudd, conference call, 7 August 2013).

Graves Pit, excavated in outcrops of Bigfork Chert (Obf) provided sand and gravel material for road construction. The 7-ha (17-ac) pit is now part of the park and is fenced. There are also several abandoned aggregate quarries north of the park. Park resource managers have some concern about the possible future development of quarries. Prospectors drilled several exploratory wells for oil and gas development in the 1920s beyond park boundaries. These wells were all abandoned and not considered for future development (Thornberry-Ehrlich 2007; S. Rudd, conference call, 7 August 2013).

As part of a long-standing issue, park staff members have noted an increase in graffiti and vandalism on park bedrock outcrops, particularly at pull-outs, Mountain Tower, and near the Pagoda (Roberts et al. 2007; S.

Rudd, conference call, 7 August 2013). This damages the outcrop appearance, as well as mosses, ferns, and slow-growing lichens that live on the outcrops (Roberts et al. 2007). Processes to removing the graffiti, such as sandblasting or soda, are difficult, time-consuming, and also degrading to the rock surface (S. Rudd, conference call, 7 August 2013). The park may develop a bedrock outcrop management plan to assess, monitor, and potentially restore outcrops. Shenandoah National Park developed such a plan (summarized by Thornberry-Ehrlich 2013).

There are two small, artificial lakes in the park; Ricks Pond, and an unnamed pond in Sleepy Hollow. These are only 1 and 0.8 ha (2.5 and 2 ac), respectively, in area (Petersen and Justus 2005; Thornberry-Ehrlich 2007). The lakes are both infilling with sediment. There is a dam in Sleepy Valley. These lake features are considered historic and not likely to be removed (S. Rudd, conference call, 22 May 2013).

#### Flooding

Flooding is the primary fluvial issue at Hot Springs National Park. The ridges in the park border narrow valleys with typically short, ephemeral stream runs. The four largest streams are Bull Bayou, and Hot Springs, Gulpha, and Whittington creeks—all part of the Ouachita River Basin (Petersen and Justus 2005). The steep terrain and narrow, bowl-shaped watershed surrounding the historic town of Hot Springs rapidly funnels runoff from Whittington and Hot Springs creeks toward the basin's outlet—the 60-m (200-ft) wide gap between Hot Springs and West mountains. This gap is also the location of Central Avenue and Bathhouse Row. Gulpha Creek flows through the novaculite ridges at a water gap between North and Indian mountains. The steep ridges and narrow valleys have a limited capacity for flow and thus during seasonal storms or occasional hurricanes (e.g. a storm in 1963, a microburst in 1990, and Hurricane Rita in 2005) the system is overwhelmed and floods. Bull Bayou flows across a broad valley underlain by shale of the Stanley Shale (Ms), not within a gorge. Only about 0.8 km (0.5 mi) flows through park land. Its outlet into Lake Hamilton is southwest of Music Mountain, southwest of the park. It does not experience the same level of flash flooding as the restricted drainages.

In an effort to contain the channel and increase area for development, a tunnel was built to carry Hot Springs Creek beneath the city of Hot Springs. Major excavation and reconstruction to contain and cover the creek occurred in 1882–83 (Shugart 2003). The 5-m (16-ft) diameter masonry tunnel, known as "the creek arch", below Park Avenue/Central Avenue extends for about 1,400 m (4,600 ft) through the gap between Hot Springs Mountain and West Mountain (fig. 22) (Yeatts 2006). Although the creek arch has sufficient volume to contain 3-year recurrence interval stormflows, it is incapable of handling higher flows to avoid flooding (US Army Corps of Engineers 1993). The dense development and associated impervious surfaces (buildings, roads, parking structures) create significant runoff into the system.

Flooding of the buried Hot Springs Creek occurs along Bathhouse Row when flow exceeds the creek arch's capacity. Notable examples were in July 1963, when Bathhouse Row was flooded and a 1990 microburst (Gilstrap and Christensen 1964; Bedinger et al. 1970).

**Figure 22. Creek Arch over Hot Springs Creek. The structure channels stream and spring flow beneath the gap between West and North Mountain and Bathhouse Row. The system cannot handle very high flows and floods. Ten hot springs drain into the creek causing steam at the end of the arch. Photograph by Trista Thornberry-Ehrlich (Colorado State University), taken in 2007.**

The 33 cm (13 in) of rain within a few hours during a microburst in 1990 caused a catastrophic flood in Hot Springs. The rain centered on the eroded core of West, Music, and Sugarloaf mountains, which are the headwaters of Whittington Creek. Floodwaters were 1 m (2-4 ft) deep on Central Avenue and exceeded the 100-year recurrence-interval discharge on Gulpha Creek (Southard 1992). The greater the recurrence interval is, the more unusual the event. The 1990 flood washed away vehicles, damaged or destroyed homes, culverts, bridges, dams, roads, and other public facilities (Southard 1992). Most of the damage was on the city side of Central Avenue, but water did enter the basements of the buildings on Bathhouse Row (S. Rudd, conference call, 7 August 2013). The park installed valve complexes to prevent high flows from entering the buildings through street drains (S. Rudd, conference call, 7 August 2013). The park also installed one-way valves on sump pumps to minimize water backflowing into the bathhouses (S. Rudd, conference call, 22 May 2013).

The US Geological Survey maintains a flood warning and information website for the City of Hot Springs: http://ar.water.usgs.gov/hotsprings/. In the 1990s, the US Army Corps of Engineers proposed construction of a channel through the deformed bedrock of the "snout" of West Mountain to divert the flow of Whittington Creek past the narrow gap between West and Hot Springs mountains. It involved excavating a 33-m (100-ft) deep canal or concrete vault along West Mountain behind the Hot Springs commercial district. However, the project was not approved and the search continues for a viable flood-prevention solution—possibilities include a larger, more open creek arch, and a perforated (grate-like) road surface (S. Rudd, conference call, 7 August 2013).

Lord et al. (2009)—the chapter in *Geological Monitoring* about fluvial geomorphology—described methods for inventorying and monitoring geomorphology-related vital signs, including: (1) watershed landscape (vegetation, land use, surficial geology, slopes, and hydrology); (2) hydrology (frequency, magnitude, and duration of stream flow rates); (3) sediment transport (rates, modes, sources, and types of sediment); (4) channel cross-section; (5) channel planform; and (6) channel longitudinal profile.

# Geologic History

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

Three main groups of rocks reflect the geologic history in the park: (1) Paleozoic bedrock deformed and metamorphosed during mountain building, (2) Cretaceous igneous rocks and adjacent metasedimentary rocks, and (3) Quaternary sediments and precipitates. The geologic history of Hot Springs National Park involves long-term marine deposition, construction of the Ouachita Mountains, igneous intrusions, and millions of years of weathering and erosion. These events and the resulting rocks formed the geologic framework that allows the hot springs to emerge on the southwestern slopes of Hot Springs Mountain. The rocks within and around the park span from the Ordovician (approximately 480 million years ago) to the present (see figs. 5 and 6).

**Paleozoic Era (541–252 million years ago): Building the Ouachita Mountains, Assembling Pangaea, Developing the Geothermal System**

Throughout much of the Paleozoic Era, a marine basin inundated Arkansas (fig. 24). This basin collected hundreds to thousands of meters of sediment that later became shales, limestones, cherts, and sandstones. A shallow shelf to the north and east, now recorded in rocks of the modern Ozark Mountains, was analogous to the present-day Bahamas. This shelf provided a source of sediments to the deeper water environments recorded in the rocks of the Ouachita Mountains (Cebull et al. 1976; Dokka et al. 2003). Changing sea levels, reflected in the various depositional environments recorded in the Paleozoic bedrock were influenced by global tectonic events, such as mountain-building orogenies along the eastern edge of North America, or global climatic shifts, such as ice ages.

As the sediments collected on the edge of the shelf, they were prone to submarine mass wasting processes. Masses of sediment slumped and slid down the shelf face forming submarine landslide deposits (turbidites) that spread over the deep ocean floor (fig. 23). Pelagic settling (slow sedimentation of fine particles in the deep ocean), turbidity currents, and other mass flow mechanisms formed much of the off-shelf, deep-water (slope to abyssal plain) deposits exposed in the rocks throughout the park area (Purdue and Miser 1923; Lowe 1989; Dokka et al. 2003). Submarine fans collected the coarser, siliciclastic components (Lowe 1989; Dokka et al. 2003). A deepwater depositional setting, including occasional submarine landslides, prevailed during the deposition of the Mazarn Shale (geologic map unit Om), Blakely Sandstone (Ob), Womble Shale (Ow), and Bigfork Chert (Obf) (fig. 25A). These units are all conformable, representing a predominantly continuous depositional setting, from one unit to the next (Johnson and Hanson 2011).

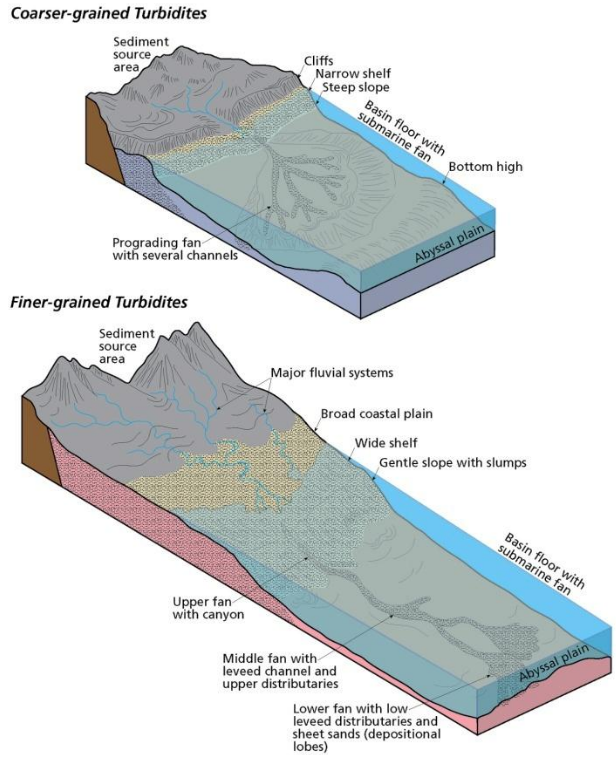



**Figure 23. Schematic models for coarse and fine-grained turbidites. Both types are prevalent in the deep marine sedimentary rocks exposed in the Hot Springs National Park area. The finer-grained turbidites (lower graphic) are common in Ordovician rocks whereas the coarser, siliceous turbidites (upper graphic) are more common in the later Paleozoic. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after figure 12 in Dokka et al. (2003).**

The Blakely Sandstone (Ob) formed as a series of upper and middle submarine fan channel deposits derived from submarine scarps and slopes. The Womble Shale (Ow) records a large sedimentary slurry deposit mixing shallow-water and deepwater materials (Dokka et al. 2003). It is conformable with the siliceous sediments of the Bigfork Chert (Obf) recording more or less continuous deposition (Johnson and Hanson 2011). Pulses of mixed, mud-rich sediments collected in the deep-water basin during the deposition of the Polk Creek Shale (Purdue and Miser 1923).

A period of erosion or non-deposition, marked by an unconformable contact, separates the Polk Creek Shale (Opc and SOu) from the overlying Blaylock Sandstone (Sb) or Missouri Mountain Shale (Sm and/or SOu) (Johnson and Hanson 2011). After the period of erosion, deposition rates increased and the basin was subsiding; basin subsidence created more space to accommodate

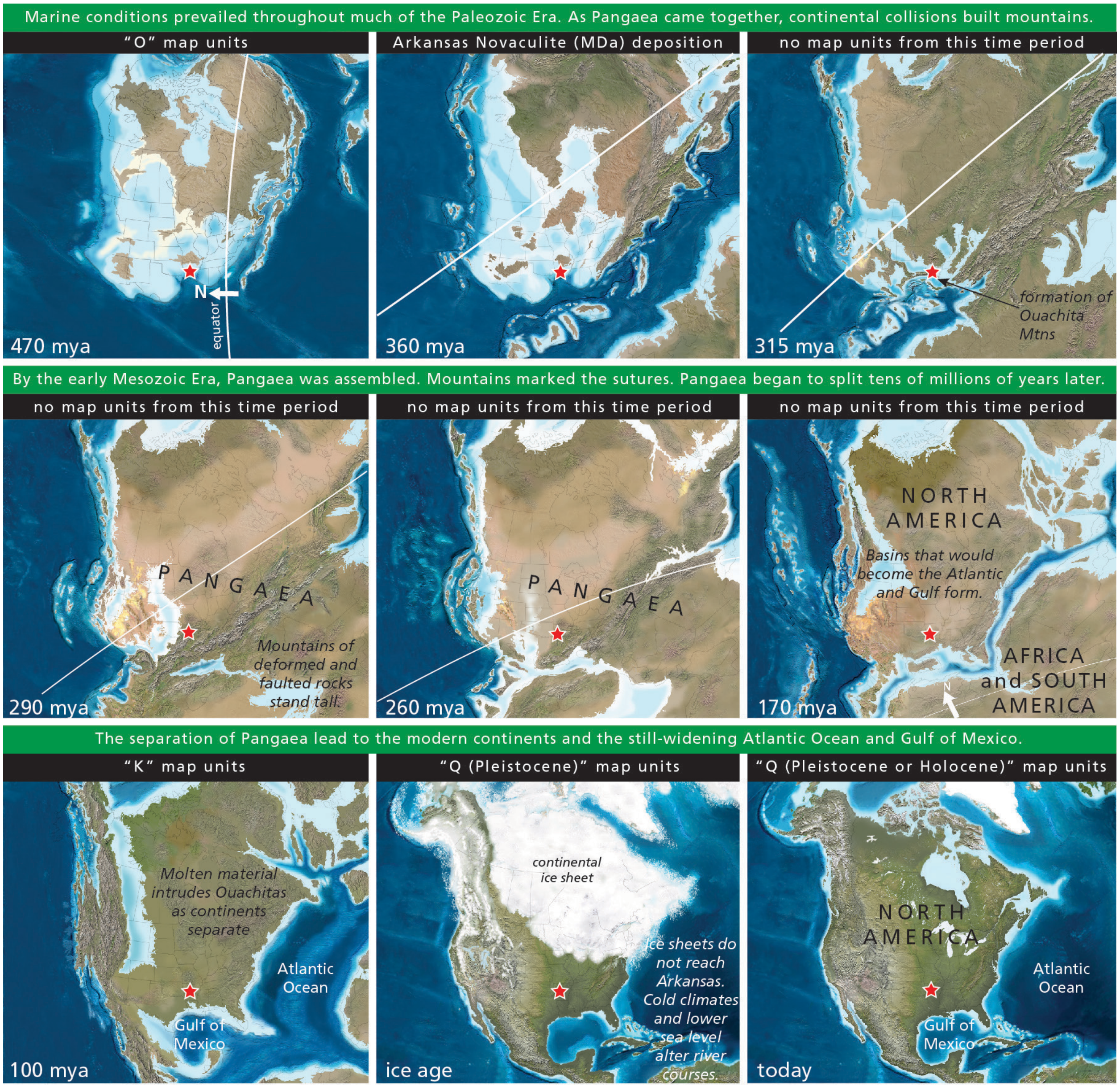
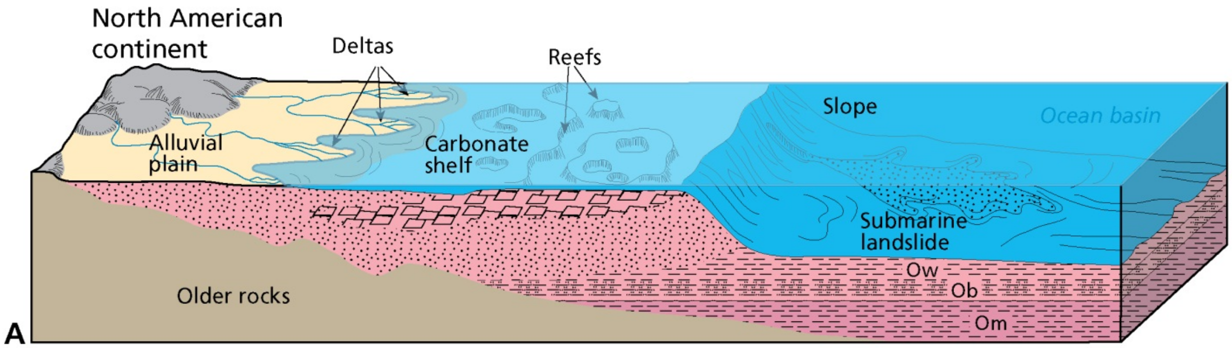


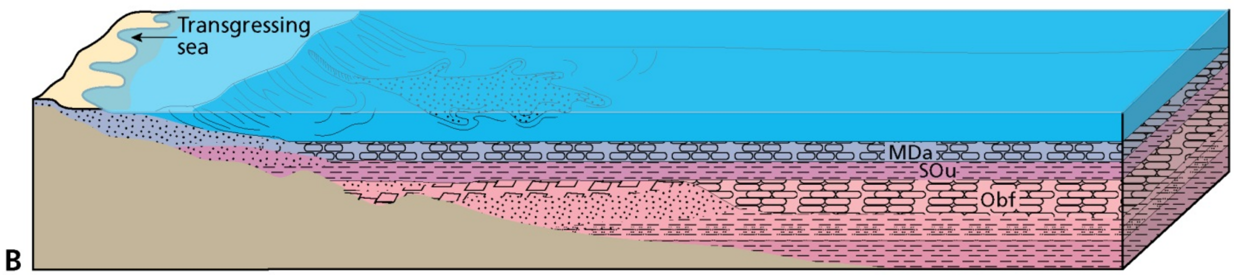

**Figure 24. Paleogeographic maps for Hot Springs National Park. The geologic history of the park encompasses the longstanding deposition in a marine basin, uplift of an ancient mountain, crustal extension (pulling apart of Earth's crust) and igneous activity, the formation and evolution of a fluvial system, and emergence of hot springs. The red stars represent the approximate location of Hot Springs National Park during various points in geologic time. The white lines across the graphics represent the approximate location of the equator. "mya" = million years ago. Graphic complied by Jason Kenworthy (NPS Geologic Resources Division). Base paleogeographic maps created by Ron Blakey (Colorado Plateau Geosystems, Inc.), which are available at http://cpgeosystems.com/index.html (accessed 10 July 2013).**

added sediments (Purdue and Miser 1923). Sea transgressions accompanied the beginning of the deposition of the Missouri Mountain Shale (Sm and/or SOu)

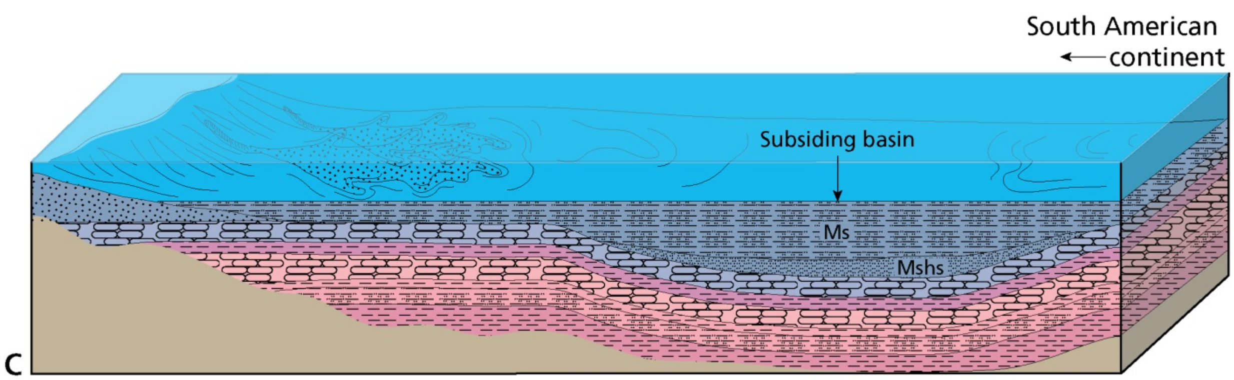
The Arkansas Novaculite (MDa) likely formed in a marine environment (fig. 25B) 30 degrees south of the equator (S. Rudd, Hot Springs NP, natural resource program manager, conference call, 22 May 2013). A period of erosion or non-deposition preceded and followed the deposition of the novaculite (Johnson and Hanson 2011). The Arkansas Novaculite (MDa) is enigmatic because of the purity of its composition, nearly all silica dioxide, which is uncommon. Siliceous sedimentation must have proceeded with very little other sedimentary input. The pure siliceous nature of the novaculite stems from two likely sources: (1) a cyclic introduction of aeolian (wind-blown) detritus into the depositional basin, (2) siliceous sediments (potentially fossil remains from radiolarian and sponges) from the marine shelf to the north being rapidly deposited downslope as turbidity currents (Purdue and Miser 1923; Lowe 1977; Hanor 1980; Dokka et al. 2003). Geologists refer to the environment in which the novaculite collected as a "starved basin" where very slow accumulation of siliceous sediment occurred (Roberts et al. 2007). Beds of novaculite pebbles and sandstone atop




Early through Middle Ordovician: a shallow carbonate shelf developed at the edge of the continent (now recorded as rock units in the Ozark Mountains) and further offshore, a deep ocean basin accumulated mixtures of clays, muds, silts, and sands of the Mazarn Shale (Om), Blakely Sandstone (Ob), and Womble Shale (Ow).




Late Ordovician through early Mississippian: following deep-water deposition of the Bigfork Chert (Obf), a pulse of muddy sediment collected as the Missouri Mountain Shale and Polk Creek Shale (SOu). Sea level rose as a transgression occurred and starved basin conditions led to the deposition of the siliceous sediments of the Arkansas Novaculite (MDa) with occasional pulses of other sediment types.

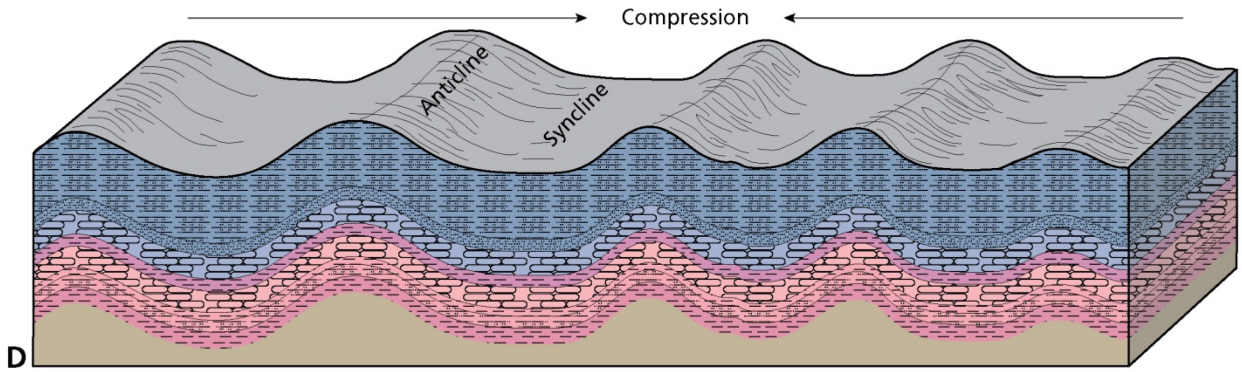



Mississippian into Pennsylvanian: the deep ocean basin began to shrink and subside as Earth's crust was warping in advance of the approach of the South American continent to the west at the onset of the Ouachita Orogeny. The Stanley Shale (Ms) and the Stanley Shale, Hot Springs Sandstone Member (Mshs) collected as thick turbidite deposits reflecting increased sediment input and basin subsidence.

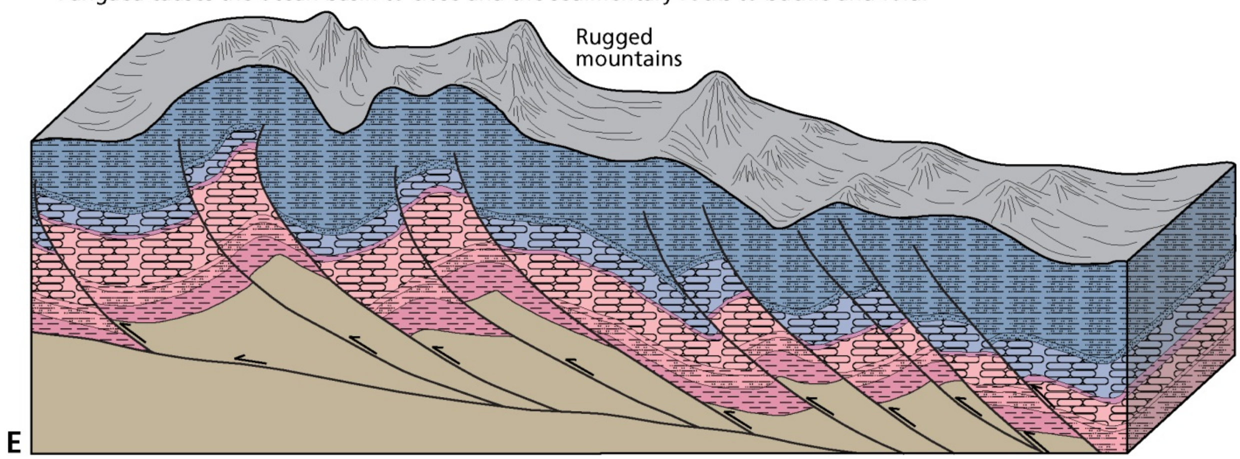
**Figure 25. Evolution of the landscape in the area of Hot Springs National Park. Figure continues on the next page. Panels A through C encompass the Ordovician Period through the Pennsylvanian Period, approximately 460 million to 300 million years ago. Graphic by Trista L. Thornberry-Ehrlich with information from Purdue and Miser (1923), Bedinger et al. (1979), and Johnson and Hanson (2011). Drawings not to scale.**

the Arkansas Novaculite signal subaerial exposure at some point after deposition (Purdue and Miser 1923).

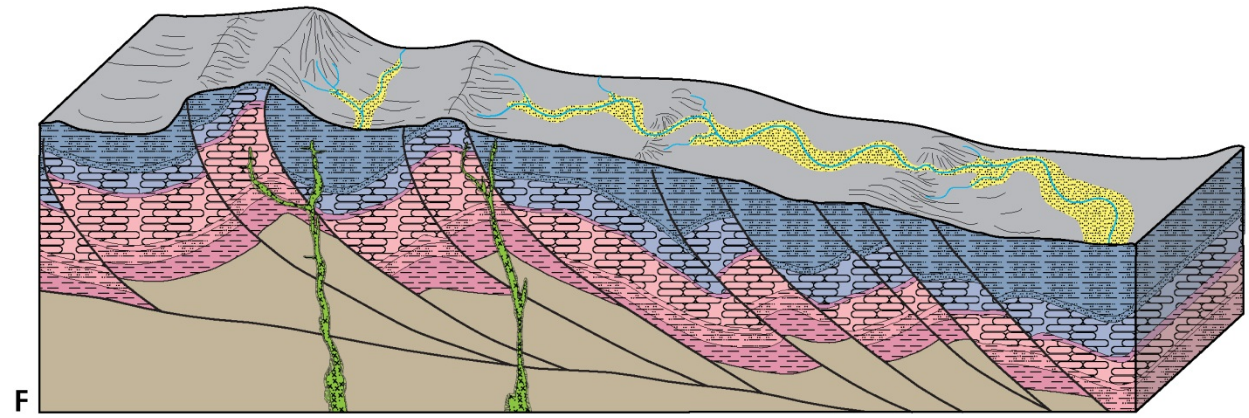
Following a period of erosion or non-deposition, the shale, sandstone, tuff, and siliceous shale of the Mississippian Stanley Shale (Ms and Mshs) collected as turbidites and sedimentation rates increased (fig. 25C) (Dokka et al. 2003; Johnson and Hanson 2011). The Hot Springs Sandstone Member of the Stanley Shale (Mshs) formed in a limited part of the basin and is not present throughout the Ouachita Mountains (Purdue and Miser 1923). The sandstone collected as high-energy turbidity currents swept down into the ocean basin (Roberts et al. 2007). Tuff (volcanic ash) layers in the Stanley Shale indicate volcanic activity in the area. Along with an increase in sedimentation rates, the volcanism signaled the onset of the Ouachita Orogeny as subduction-plate collision began to close the basin and push rocks to the north and northwest (Arbenz 1989; Dokka et al. 2003). The Stanley Shale is the youngest Paleozoic unit present in the park area (Johnson and Hanson 2011).




Pennsylvanian into Permian: contintental collision associated with the construction of the supercontinent Pangaea causes the ocean basin to close and the sedimentary rocks to buckle and fold.




Pennsylvanian into Permian: contintental collision continues. As deformation proceeds, the rocks break and slide atop one another on thrust faults to accomodate extreme shortening. Shale units such as the Stanley Shale (Ms) can accomdate more flexure than can brittle units such as the Bigfork Chert (Obf) or Arkansas Novaculite (MDa). It is possible the overturned anticline of Hot Springs Mountain was developing the geothermal resource.




Mesozoic into Cenozoic: contintental collision ceased and the supercontinent rifted apart. Local igneous activity, possibly associated with continental extension, caused the intrusion of magma bodies, dikes, and sills (Ki, Kia, Kil, Kid, and Kis). Heat from these intrusions also caused contact metamorphism of the adjacent bedrock (Kms). Weathering and erosion are continually beveling the landscape, wearing away the softer shales differentially from the harder cherts, sandstones, and novaculites. Surficial deposits accumulate on the landscape (e.g. Qal, Qt). When sufficient erosion exposed the faulted southwestern flank of Hot Springs Mountain, the heated water emerged as hot springs.

**Figure 25. Evolution of the landscape in the area of Hot Springs National Park, continued from previous page. Panels D through F encompass the Pennsylvanian Period through the Cenozoic Era, approximately 300 million years ago to the past 2.6 million years. Graphic by Trista L. Thornberry-Ehrlich with information from Purdue and Miser (1923), Bedinger et al. (1979), and Johnson and Hanson (2011). Drawings not to scale.**

During the Pennsylvanian and into the Permian, South America and Africa collided with North America, destroying the Ouachita basin and culminating in the final assembly of the supercontinent Pangaea. The Ouachita Mountains were just one of three major mountain chains, the others being the Appalachians and the Marathons that formed along the southern and eastern edges of North America during the collision (Dokka et al. 2003). Sediments deposited in the Ouachita basin were pushed northwestward onto the North American continent. The pile of rocks eventually folded (fig. 25E) and faulted over themselves (fig. 25F) accordion-style into an immense lop-sided pile that now form the core of the Benton-Broken Bow Uplift (Hanor 1980; D. Hanson, geologist, Arkansas Geological Survey, written communication, 23 September 2013).

Pennsylvanian and Permian rock units do not appear on the map, having either never been deposited in the area, or eroded away following uplift during the Ouachita Orogeny.

#### Mesozoic Era (252–66 million years ago): Pangaea Separation, Ouachita Mountains Erosion, and Igneous Intrusion

Pangaea was not to last. During the Triassic and Jurassic periods, rifting pulled what would become Africa and South America apart from North America forming the Atlantic Ocean and Gulf of Mexico. Intrusions of molten magma forced upwards through the deformed rocks of the Ouachita Mountains (Hanor 1980). Cretaceous igneous plutons, dikes, and sills occur throughout the map area (Kms, Kia, Kil, Kid, and Kis) (Hanor 1980; Johnson and Hanson 2011). Where these igneous magmas were thick enough, they heated the adjacent country rocks to the extent that the minerals within those rocks recrystallized to form metamorphic rocks such as metaquartzite and hornfels (Johnson and Hanson 2011). This forms an "aureole" of contact metamorphism in the bedrock surrounding the igneous plutons. Mineral-laden fluids associated with these intrusions are also responsible for many of the local mineral deposits (S. Rudd, conference call, 7 August 2013).

Erosion and weathering processes were continually reducing the heights of the Ouachita Mountains throughout the Mesozoic (fig. 25F). Continental rifting formed many basins along eastern and southern North America at the base of the mountains. Steeply dipping normal faults formed the boundaries of these basins, which quickly filled with sediment eroded from the surrounding highlands. Great portions of the once Alps-like Ouachita Mountains slowly lowered and were buried by younger, sediments of the Gulf Coastal Plain (Hanor 1980). The Gulf Coastal Plain continues to accumulate sediment today.

Weathering and erosion dominate the geologic history of the park area throughout the Mesozoic and most of the following Cenozoic Era. Rivers transported sediments worn from the highlands to build the Coastal Plain towards the Gulf of Mexico. Because various types of rocks are more or less resistant to erosion, some areas eroded faster than others. Low-lying areas, such as Mazarn Basin or the narrow valley in which the city of Hot Springs is located, are underlain by softer shales such as the Stanley Shale (Ms). Alternatively, the ridges of the ZigZag Mountains are supported by resistant Arkansas Novaculite (MDa) and Hot Springs Sandstone Member of the Stanley Shale (Mshs) (Purdue and Miser 1923; Bedinger et al. 1979; Johnson and Hanson 2011).

Depending on when groundwater began to percolate to great depths beneath Hot Springs Mountain, it is possible the thermal-hydrologic system has been intact and functioning for an extensive period, possibly as much as 230 million years, of geologic time (S. Rudd, conference call, 22 May 2013). When weathering removed enough overburden, the thermal waters were at last able to find an outlet, emerging as hot springs on the southwestern slope of Hot Springs Mountain. The timing of this event is unknown (S. Rudd, conference call, 7 August 2013).

#### Cenozoic Era (the past 66 million years): Ouachita Mountains Erosion and Surface Processes

Fluvial systems continued evolving on the landscape throughout the Cenozoic. Streams carved gaps, such as Gulpha Gap or the one through which Central Avenue runs, through the resistant ridges, typically along areas weakened by faults or folds in the bedrock. Terrace deposits (Qt) perched above the modern floodplain record prior river levels (Johnson and Hanson 2011).

Repeated, continental-scale glaciations (ice ages) during the Pleistocene Epoch (between 2.6 million years ago and approximately 12,000 years ago) recorded global climate changes at that time. Thick sheets of ice repeatedly advanced and retreated over northern North America. Glacial ice did not reach as far south as Arkansas; however, colder climates played a role in accelerated weathering of the landscape. The highest points of the Ouachita Mountains may have experienced periglacial conditions that included discontinuous permafrost, tundra-like vegetation, and frost weathering. Frost weathering wedged untold numbers of boulders from the bedrock to form talus at the base of slopes. Areas such as the east side of Hot Springs Mountain above Gulpha Gorge within the park, and Blowout Mountain in the park vicinity, are areas with abundant talus (Hanor 1980).

Pleistocene and Holocene deposits include alluvium (Qal) collecting along creeks, streams, and rivers. Although not dated with certainty, one of the youngest geologic units within the park is the calcium carbonate (travertine or tufa; Qtufa) being precipitated as thermal waters emerge from underground at the park's famous hot springs (Johnson and Hanson 2011; D. Hanson, written communication, 23 September 2013). Humans removed large portions of the tufa (Qtufa) once present as a mantle on the slopes of Hot Springs Mountain (fig. 26) to control and regulate hot spring flow. Their modifications developed the hot springs of the eponymous town and park (Hanor 1980).

**Figure 26. Lithograph showing landscape of the Hot Springs Reservation. Note the extensive tufa deposits on the hill to the right. Lithograph originally published in 1844 by William Clowes and Sons of London. It was used as the frontispiece of English geologist G.W. Featherstonhaugh's "Excursion through the Slave States, Volume II." Image in the collections of Hot Springs National Park.**

# Geologic Map Data

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

### Geologic Maps

Geologic maps facilitate an understanding of an area's geologic framework and the evolution of its present landscape. Using designated colors and symbols, these maps portray the spatial distribution and relationships of rocks and unconsolidated deposits. Geologic maps can be divided into two primary types: surficial and bedrock. Surficial geologic maps typically encompass deposits that are unconsolidated and formed during the past 2.6 million years (the Quaternary Period). Surficial map units are differentiated by geologic process or depositional environment. Bedrock geologic maps encompass older, typically more consolidated sedimentary, metamorphic, and/or igneous rocks. Bedrock map units are differentiated based on age and/or rock type. The geologic map for Hot Springs National Park includes surficial and bedrock map units.

Geologic maps often depict geomorphic features, structural interpretations (such as faults or folds), and locations of past geologic hazards that may be prone to future activity. Anthropogenic features such as mines or quarries, as well as observation or collection locations, may be indicated on geologic maps.

### Source Maps

The GRI team converts digital and/or paper geologic source maps to GIS formats that conform to the GRI GIS data model. The GRI digital geologic map product also includes essential elements of the source maps, including unit descriptions, map legend, map notes, references, and figures. The GRI team used the following source map to produce the digital geologic data for Hot Springs National Park This source map also provided information for the "Geologic Features and Processes," "Geologic Issues," and "Geologic History" sections of this report.

Johnson, T. C. and W. D. Hanson. 2011. Geologic Map of the Hot Springs North, Hot Springs South, Fountain Lake and Lake Catherine 7.5; Quadrangles, Garland, Hot Spring and Saline Counties, Arkansas (scale 1:24,000). DGM-HSR-003. Arkansas Geological Survey, Little Rock, Arkansas, USA. http://www.geology.ar.gov/geologic_maps/dgm_hsr003.htm accessed 25 September 2013.

### Geologic GIS Data

The GRI team implements a GIS data model that standardizes map deliverables. The data model is included on the enclosed CD and is also available online (http://science.nature.nps.gov/im/inventory/geology/GeologyGISDataModel.cfm). This data model dictates GIS data structure, including layer architecture, feature attribution, and relationships within ESRI ArcGIS software. The GRI team digitized the data for Hot Springs National Park using data model version 2.1.

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

The following components and geology data layers are part of the data set:

- Data in ESRI geodatabase GIS format
- Layer files with feature symbology (table 2)
- Federal Geographic Data Committee (FGDC)–compliant metadata
- A help file (hosp_geology.pdf) document that contains all of the ancillary map information and graphics, including geologic unit correlation tables, and map unit descriptions, legends, and other information captured from source maps.
- An ESRI map document file (hosp_geology.mxd) that displays the digital geologic data
- A KML/KMZ version of the data viewable in Google Earth. Not all data layers may be represented in the Google Earth data.

**Table 2. Geology data layers in the Hot Springs National Park GIS data.**

| Data Layer | Data Layer Code | On Map Graphic? | Google Earth Layer? |
|---|---|---|---|
| Geologic Cross Section Lines | SEC | No | No |
| Geologic Attitude Observation Localities (strike and dip) | ATD | No | No |
| Geologic Observation Localities (joint measurement) | GOL | No | No |
| Hazard Point Features (landslide and debris flows) | HZP | No | No |
| Mine Point Features | MIN | No | No |
| Map Symbology | SYM | Yes | No |
| Folds | FLD | Yes | Yes |
| Faults | FLT | Yes | Yes |
| Linear Dikes | DKE | Yes | Yes |
| Alteration and Metamorphic Area Boundaries | AMAA | No | Yes |
| Alteration and Metamorphic Areas | AMA | No | Yes |
| Geologic Contacts | GLGA | Yes | Yes |
| Geologic Units | GLG | Yes | Yes |

#### Geologic Map Graphic

The Geologic Map Graphic displays the GRI digital geologic data draped over a shaded relief image of the park and surrounding area. For clarity, not all GIS feature classes may be visible (table 2). Geographic information and selected park features have been added to the overview. Digital elevation data and added geographic information, are not included with the GRI GIS data for the park, but are available online from a variety of sources.

#### Map Unit Properties Table

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

#### Use Constraints

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

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

# Glossary

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

**absolute age.** The geologic age (in years) of a fossil, rock, feature, or event; commonly refers to a radiometrically determined age. See "radiometric age."

**abyssal plain.** A flat region of the deep ocean floor, usually at the base of the continental rise.

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

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

**alkalic.** Describes a rock that is enriched in sodium and potassium.

**alluvium.** Stream-deposited sediment.

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

**anticline.** A convex ("A"-shaped) fold. Older rocks are found in the center. Compare with "syncline."

**anticlinorium.** A large, regional feature with the overall shape of an anticline. Composed of many smaller folds.

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

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

**ash (volcanic).** Fine material ejected from a volcano. Also see "tuff."

**aureole.** A zone surrounding an igneous intrusion in which the country rock shows the effects of contact metamorphism from high-temperature (molten) material.

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

**base flow.** Streamflow supported by groundwater; flow not attributed to direct runoff from precipitation or snow melt.

**basement.** The undifferentiated rocks, commonly igneous and metamorphic, that underlie rocks exposed at the surface.

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

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

**bed.** The smallest sedimentary stratigraphic unit, commonly ranging in thickness from about 1 cm (0.4 in) to 1 to 2 m (39.4 to 78.7 in) and distinguishable from beds above and below.

**bedding.** Depositional layering or stratification of sediments.

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

**block (fault).** A crustal unit bounded completely or partially by faults.

**bioturbation.** The reworking of sediment by organisms.

**Bouma cycle.** A fixed, characteristic succession of five intervals that makes up a complete sequence of a turbidite. One or more intervals may be missing. The five intervals are, from bottom to top (oldest to youngest): a) graded, b) lower parallel laminations, c) current ripple laminations, d) upper parallel laminations, and e) pelitic. Named after Arnold Bouma, Dutch sedimentologist. Also see "turbidite."

**brittle.** Describes a rock that fractures (breaks) before sustaining deformation.

**calcareous.** Describes rock or sediment that contains the mineral calcium carbonate ($CaCO_3$).

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

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

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

**cementation.** Chemical precipitation of material into pores between grains that bind the grains into rock.

**chemical sediment.** A sediment precipitated directly from solution (also called "nonclastic").

**chemical weathering.** Chemical breakdown of minerals at Earth's surface via reaction with water, air, or dissolved substances; commonly results in a change in chemical composition providing more stability in the current environment.

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

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

**clastic.** Describes rock or sediment made of fragments of pre-existing rocks (clasts). Also see "epiclastic."

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

**colluvium.** A general term for any loose, heterogeneous, and incoherent mass of soil material and/or rock fragments deposited through the action of surface runoff (rainwash, sheetwash) or slow continuous downslope creep. Usually collects at the base of a gentle slope or hillside.

**concordant.** Describes a stratum with contacts parallel to the orientation of adjacent strata.

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

**conodont.** One of a large number of small, disjunct fossil elements assigned to the order Conodontophorida, phosphatic in composition and commonly tooth-like in form, but not necessarily in function.

**contact metamorphism**. Changes in rock as a result of contact with an igneous body.

**continental rifting.** Process by which a region of crust undergoes extension (pulling apart), resulting in the formation of many related normal faults, and often associated with volcanic activity.

**convergent boundary.** A plate boundary where two tectonic plates collide.

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

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

**crossbedding.** Uniform to highly varied sets of inclined sedimentary beds deposited by wind or water that indicate flow conditions, such as water flow direction and depth.

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

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

**cryptocrystalline.** Describes a rock texture in which very small individual crystals cannot be recognized or distinguished with an ordinary microscope. Compare with "holocrystalline" and "microcrystalline."

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

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

**décollement**. A markedly displaced (kilometers to tens of kilometers), shallowly dipping to subhorizontal fault or shear zone. See "detachment fault."

**deformation**. A general term for the processes of rock faulting, folding, and shearing as a result of various Earth forces, such as compression (pushing together) and extension (pulling apart).

**detachment fault.** Synonym for décollement used widely to describe a regionally extensive, gently dipping normal fault that is commonly associated with extension in a metamorphic core complex.

**detritus.** A collective term for loose rock and mineral material that is worn off or removed by mechanical processes.

**differential erosion.** Erosion that occurs at irregular or varying rates due to differences in the resistance and hardness of surface material.

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

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

**dip-slip fault.** A fault with measurable offset in which the relative movement is parallel to the dip of the fault. Compare with "strike-slip fault."

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

**discordant.** Describes a contact between strata that cuts across or is set at an angle to the orientation of adjacent rocks.

**divergent boundary.** An active boundary where tectonic plates are moving apart (e.g., a spreading ridge or continental rift zone).

**dolomite.** A carbonate sedimentary rock containing more than 50% of the mineral dolomite (calcium-magnesium carbonate)by weight or by areal percentage under the microscope.

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

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

**extension.** A type of strain resulting from "pulling apart" forces. Opposite of compression.

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

**feldspar.** A group of abundant (comprising more than 60% of Earth's crust), light-colored to translucent silicate minerals found in all types of rock. Usually white and gray to pink. May contain potassium, sodium, calcium, barium, rubidium, and strontium, along with aluminum, silica, and oxygen.

**floodplain.** The surface or strip of relatively smooth land adjacent to a river channel and formed by the river. Covered with water when the river overflows its banks.

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

**foliation.** A preferred arrangement of crystal planes in minerals. In metamorphic rocks, the term commonly refers to a parallel orientation of planar minerals such as micas.

**footwall.** The lower wall of a fault. Compare with "hanging wall."

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

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

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

**geology.** The study of Earth, including its origin, history, physical processes, components, and morphology.

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

**gradient.** See "slope."

**hanging wall.** The upper wall of a fault. Compare with "footwall."

**hinge line.** A line or boundary between a stable region and one undergoing upward or downward movement.

**hornfels.** A fine-grained rock composed of a mosaic of grains that are the same size in all dimensions, without preferred orientation. Typically formed by contact metamorphism, which occurs near the contact with an intrusion of molten material.

**hydraulic conductivity.** Measure of permeability coefficient (the ease with which water moves through spaces or pores in soil or rock).

**hydrogeologic.** Describes geologic influences on groundwater and surface water composition, movement, and distribution.

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

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

**incision.** The process whereby a downward-eroding stream deepens its channel or produces a narrow, steep-walled valley.

**index fossil.** A fossil that identifies and dates the strata or succession of strata in which it is found.

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

**isoclinal.** Describes a fold with parallel limbs.

**isotopic age.** An age (in years) calculated from the quantitative determination of radioactive elements and their decay products; "absolute age" and "radiometric age" are often used in place of isotopic age but are less precise terms.

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

**lacustrine.** Describes a process, feature, or organism pertaining to, produced by, or inhabiting a lake or lakes.

**lamination.** Very thin, parallel layering.

**landslide.** Any process or landform resulting from rapid, gravity-driven mass movement.

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

**limb.** One side of a structural fold.

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

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

**lithification.** The conversion of sediment into solid rock.

**lithify.** To change to stone or to petrify; especially to consolidate from a loose sediment to a solid rock through compaction and cementation.

**lithology.** The physical description or classification of a rock or rock unit based on characteristics such as color, mineral composition, and grain size.

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

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

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

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

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

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

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

**meteoric water.** Water of recent atmospheric origin.

**microcrystalline.** Describes a rock texture consisting of crystals visible only with a microscope. Compare with "cryptocrystalline" and "holocrystalline."

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

**nonconformity.** An erosional surface preserved in strata in which crystalline igneous or metamorphic rocks underlie sedimentary rocks. Compare with "unconformity."

**normal fault.** A dip-slip fault in which the hanging wall moves down relative to the footwall. Compare with "reverse fault" and "thrust fault."

**oblique fault.** A fault in which motion includes both dip-slip and strike-slip components.

**orogeny.** A mountain-building event.

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

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

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

**Pangaea.** A supercontinent that existed during the Permian and Triassic periods and included much of Earth's continental crust. Split into Gondwana and Laurasia.

**parent material.** The unconsolidated organic and mineral material in which soil forms.

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

**passive margin.** A margin at which no plate-scale tectonism is taking place; plates are not converging, diverging, or sliding past one another. An example is the east coast of North America. Compare with "active margin."

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

**pluton (plutonic).**(Describes) a body of intrusive igneous rock that crystallized at some depth beneath Earth's surface. Compare with "stock."

**porosity.** The proportion of void space (i.e., pores or voids) in a volume of rock or sediment deposit.

**progradation.** The seaward building of land area due to sedimentary deposition.

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

**quartzite.** Metamorphosed quartz sandstone.

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

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

**recharge.** Infiltration process that replenishes groundwater.

**regolith.** General term for the layer of rock debris, organic matter, and soil that commonly forms the land surface and overlies most bedrock.

**regression.** Long-term seaward retreat of the shoreline or relative fall of sea level.

**reverse fault.** A contractional high-angle (greater than 45°) dip-slip fault in which the hanging wall moves up relative to the footwall. Compare with "normal fault" and "thrust fault."

**rift.** A region of crust where extension results in formation of many related normal faults, often associated with volcanic activity.

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

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

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

**rock fall.** The most rapid mass-wasting process in which rocks are dislodged and move downslope rapidly.

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

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

**scarp.** A steep cliff or topographic step resulting from displacement on a fault or by mass movement or erosion. Also called an "escarpment."

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

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

**shale.** A clastic sedimentary rock made of clay-sized particles that exhibit parallel splitting properties.

**silicate.** A compound whose crystal structure contains the $SiO_4$ tetrahedra.

**silicic.** Describes a silica-rich igneous rock or magma.

**siliciclastic.** Describes noncarbonate clastic rocks.

**sill.** An igneous intrusion with the same orientation as the surrounding rock.

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

**siltstone.** A variably lithified sedimentary rock composed of silt-sized grains.

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

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

**soil.** The unconsolidated mineral or organic matter on the surface of the earth that has been affected by climate (water and temperature) and organisms (macro and micro), conditioned by relief, acting on parent material over a period of time. Soil differs from the material from which it is derived in many ways.

**spring.** A site where water issues from the surface due to the intersection of the water table with the ground surface.

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

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

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

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

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

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

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

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

**subaerial.** Describes a condition or process that exists or operates in the open air on or immediately adjacent to the land surface.

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

**syncline.** A downward-curving (concave) fold with layers that dip inward; stratigraphically younger rocks are found in its core. Compare with "anticline."

**synclinorium.** A composite synclinal structure of regional extent composed of lesser folds.

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

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

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

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

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

**trace (fault).** The exposed intersection of a fault with Earth's surface.

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

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

**transgression.** Landward migration of the sea as a result of a relative rise in sea level.

**travertine.** A limestone deposit or crust, often banded, formed from precipitation of calcium carbonate from saturated waters, especially near hot springs and in caves.

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

**tufa.** A chemical sedimentary rock composed of calcium carbonate, formed by evaporation as an incrustation around the mouth of a spring, along a stream, or, exceptionally, as a thick, concretionary deposit in a lake or along its shore. It may also be precipitated by algae or bacteria. A hard, dense variety of travertine.

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

**type locality.** The geographic location where a stratigraphic unit (or fossil) is well displayed and formally defined. The place of original description, from which the unit or fossil derives its name.

**unconformity.** An erosional or non-depositional surface bounded on one or both sides by sedimentary strata. An unconformity marks a period of missing time. Compare with "nonconformity."

**uplift.** A structurally high area in the crust produced by movement that raises the rocks.

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

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

**weathering.** The physical, chemical, and biological processes by which rock is broken down.

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# Additional References

*This section lists additional references, resources, and websites that may be of use to resource managers. Web addresses are current as of November 2013. Refer to Appendix B for laws, regulations, and policies that apply to NPS geologic resources.*

#### Geology of National Park Service Areas

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

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

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

#### NPS Resource Management Guidance and Documents

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

Management Policies 2006 (Chapter 4: Natural resource management): http://www.nps.gov/policy/mp/chapter4.htm

NPS-75: Natural resource inventory and monitoring guideline: http://www.nature.nps.gov/nps75/nps75.pdf

NPS Natural resource management reference manual #77: http://www.nature.nps.gov/Rm77/

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

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

#### Geological Surveys and Societies

Arkansas Geological Survey: http://www.geology.ar.gov/home/index.htm

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

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

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

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

#### US Geological Survey Reference Tools

US Geological Survey national geologic map database (NGMDB): http://ngmdb.usgs.gov/

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

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

US Geological Survey geoPDFs (download searchable PDFs of any topographic map in the United States): http://store.usgs.gov (click on “Map Locator & Downloader”)

US Geological Survey publications warehouse (many publications available online): http://pubs.er.usgs.gov

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

# Appendix A: Scoping Meeting Participants

*The following people attended the GRI scoping meeting for Hot Springs National Park, held on 23-24 April 2007, or the follow-up report writing conference call, held on 22 May 2013. Discussions during these meetings supplied a foundation for this GRI report. The scoping summary document is available on the GRI publications website: http://go.nps.gov/gripubs.*

**2007 Scoping Meeting Participants**

| Name | Affiliation | Position |
|---|---|---|
| Leo Acosta | NPS Arkansas Post NM | Resource Management |
| Angela Chandler | Arkansas Geological Survey | Geologist |
| Jeff Connelly | University of Arkansas | Professor-Geologist |
| Tim Connors | NPS Geologic Resources Division | Geologist |
| Deanna Greco | NPS Geologic Resources Division | Geologist |
| Doug Hanson | Arkansas Geological Survey | Geologist |
| Philip Hays | US Geological Survey | Geologist |
| Bruce Heise | NPS Geologic Resources Division | Geologist |
| Mark Hudson | US Geological Survey | Geologist |
| Tim Kresse | US Geological Survey | Hydrologist |
| Bill Prior | Arkansas Geological Survey | Geologist |
| Steve Rudd | NPS Hot Springs NP | Geologist |
| Trista Thornberry-Ehrlich | Colorado State University | Geologist, GRI Report Author |
| Bekki White | Arkansas Geological Survey | State Geologist |

**2013 Conference Call Participants**

| Name | Affiliation | Position |
|---|---|---|
| Angela Chandler | Arkansas Geological Survey | Geologist |
| Tim Connors | NPS Geologic Resources Division | Geologist, GRI Maps Coordinator |
| Doug Hanson | Arkansas Geological Survey | Geologist |
| Jason Kenworthy | NPS Geologic Resources Division | Geologist, GRI Reports Coordinator |
| Steve Rudd | NPS Hot Springs National Park | Geologist |
| Trista Thornberry-Ehrlich | Colorado State University | Geologist, GRI Report Author |

# Appendix B: Geologic Resource Laws, Regulations, and Policies

*The Geologic Resources Division developed this table to summarize laws, regulations, and policies that specifically apply to National Park Service minerals and geologic resources. The table does not include laws of general application (e.g., Endangered Species Act, Clean Water Act, Wilderness Act, National Environmental Policy Act, or National Historic Preservation Act). The table does include the NPS Organic Act when it serves as the main authority for protection of a particular resource or when other, more specific laws are not available. Information is current as of November 2013. Contact GRD for detailed guidance.*

| Resource | Resource-specific Laws | Resource-specific Regulations | 2006 Management Policies |
|---|---|---|---|
| Paleontology | **National Parks Omnibus Management Act of 1998, 16 USC. § 5937** protects the confidentiality of the nature and specific location of paleontological resources and objects.<br><br>**Paleontological Resources Preservation Act of 2009**, **16 USC. § 470aaa *et seq.***, provides for the management and protection of paleontological resources on federal lands. | **36 C.F.R. § 2.1(a)(1)(iii)** prohibits destroying, injuring, defacing, removing, digging or disturbing paleontological specimens or parts thereof.<br><br>**36 C.F.R. § 13.35** prohibition applies even in Alaska parks where the surface collection of other geologic resources is permitted.<br><br>Regulations in association with 2009 PRPA are being finalized (November 2013). | **Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity.<br><br>**Section 4.8.2.1** emphasizes I & M, encourages scientific research, directs parks to maintain confidentiality of paleontological information, and allows parks to buy fossils only in accordance with certain criteria. |
| Rocks and Minerals | **NPS Organic Act**, **16 USC. § 1 *et seq.*** directs the NPS to conserve all resources in parks (which includes rock and mineral resources) unless otherwise authorized by law.<br><br>**Exception:16 USC. § 445c (c) – Pipestone National Monument enabling statute**. Authorizes Native American collection of catlinite (red pipestone). | **36 C.F.R. § 2.1** prohibits possessing, destroying, disturbing mineral resources…in park units.<br><br>**Exception: 36 C.F.R. § 7.91** allows limited gold panning in Whiskeytown.<br><br>**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. |

| Resource | Resource-specific Laws | Resource-specific Regulations | 2006 Management Policies |
|---|---|---|---|
| Geothermal | **Geothermal Steam Act of 1970, 30 USC. § 1001** *et seq.* as amended in 1988, states:<br>-No geothermal leasing is allowed in parks.<br>-"Significant" thermal features exist in 16 park units (the features listed by the NPS at 52 Fed. Reg. 28793-28800 (August 3, 1987), plus the thermal features in Crater Lake, Big Bend, and Lake Mead).<br>-NPS is required to monitor those features.<br>-Based on scientific evidence, Secretary of Interior must protect significant NPS thermal features from leasing effects.<br><br>**Geothermal Steam Act Amendments of 1988, Public Law 100- 443** prohibits geothermal leasing in the Island Park known geothermal resource area near Yellowstone and outside 16 designated NPS units if subsequent geothermal development would significantly adversely affect identified thermal features. | None Applicable. | **Section 4.8.2.3** requires NPS to:<br>-Preserve/maintain integrity of all thermal resources in parks.<br>-Work closely with outside agencies.<br>-Monitor significant thermal features. |
| Nonfederal minerals other than oil and gas | **NPS Organic Act, 16 USC. §§ 1 and 3**<br><br>**Surface Mining Control and Reclamation Act of 1977, 30 USC § 1201** ***et. seq.*** prohibits surface coal mining operations on any lands within the boundaries of a NPS unit, subject to valid existing rights. | **NPS regulations at 36 C.F.R. 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.<br><br>**SMCRA Regulations at 30 C.F.R. Chapter VII** govern surface mining operations on Federal lands and Indian lands by requiring permits, bonding, insurance, reclamation , and employee protection. Part 7 of the regulations states that National Park System lands are unsuitable for surface mining. | **Section 8.7.3**states that operators exercising rights in a park unit must comply with 36 CFR Parts 1 and 5. |

| Resource | Resource-specific Laws | Resource-specific Regulations | 2006 Management Policies |
|---|---|---|---|
| Park Use of Sand and Gravel | **Materials Act of 1947, 30 USC. § 601** does not authorize the NPS to dispose of mineral materials outside of park units.<br><br>**Exception:** 16 USC. §90c 1(b) the non-wilderness portion of Lake Chelan National Recreation Area, where sand, rock and gravel may be made available for sale to the residents of Stehekin for local use as long as such sale and disposal 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:<br>- Only for park administrative uses.<br>- After compliance with NEPA & other federal, state, and local laws, and a finding of non-impairment.<br>- After finding the use is park's most reasonable alternative based on environment and economics.<br>- Parks should use existing pits and create new pits only in accordance with park-wide borrow management plan.<br>- Spoil areas must comply with Part 6 standards<br>- NPS must evaluate use of external quarries.<br><br>Any deviations from this policy require written waiver from the Secretary, Assistant Secretary, or Director. |

| Resource | Resource-specific Laws | Resource-specific Regulations | 2006 Management Policies |
|---|---|---|---|
| Upland and Fluvial Processes | **Rivers and Harbors Appropriation Act of 1899, 33 USC. § 403** prohibits the construction of any obstruction, on the waters of the united states, not authorized by congress or approved by the USACE.<br><br>**Clean Water Act 33USC. § 1342** requires a permit from the USACE prior to any discharge of dredged or fill material into navigable waters (waters of the US (including streams)).<br><br>**Executive Order 11988** requires federal agencies to avoid adverse impacts to floodplains. (see also D.O. 77-2)<br><br>**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.<br><br>**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.<br><br>**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.<br><br>**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<br><br>**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<br><br>**Section 4.8.1** directs the NPS to allow natural geologic processes to proceed unimpeded. Geologic processes…include…erosion and sedimentation…processes.<br><br>**Section 4.8.2** directs the NPS to protect geologic features from the unacceptable impacts of human activity while allowing natural processes to continue. |

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

NPS 128/123089, December 2013

National Park Service
US Department of the Interior

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

www.nature.nps.gov

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