National Park Service
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Natural Resource Stewardship and Science

Chickasaw National Recreation Area

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2015/1008

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

The Natural Resource Report Series is used to disseminate comprehensive information and analysis about natural resources and related topics concerning lands managed by the National Park Service. The series supports the advancement of science, informed decision-making, and the achievement of the National Park Service mission. The series also provides a forum for presenting more lengthy results that may not be accepted by publications with page limitations.

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

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

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Executive Summary

The Geologic Resources Inventory (GRI) is one of 12 inventories funded by the National Park Service (NPS) Inventory and Monitoring Program. The Geologic Resources Division of the NPS Natural Resource Stewardship and Science Directorate administers the GRI. This report synthesizes discussions from a scoping meeting for Chickasaw National Recreation Area (Oklahoma) on 17-18 October 2007 and a follow-up conference call on 12 March 2014, which were held by the Geologic Resources Division to determine geologic resources, the status of geologic mapping, and geologic resource management issues and needs. It is a companion document to previously completed GRI digital geologic map data.

Chickasaw National Recreation Area preserves historic freshwater and mineral springs, extensive park infrastructure constructed by the Civilian Conservation Corps in the 1930s, and the entire Lake of the Arbuckles. Believed to have healing properties, the mineral springs near Sulphur, Oklahoma became a popular destination in the late 1890s. To protect the springs along Travertine and Rock Creeks from uncontrolled use, the Chickasaw and Choctaw Nations ceded all of the springs and 260 ha (640 ac) to the Department of the Interior in 1902, and the area became the Sulphur Springs Reservation. In 1906, Congress re-designated the reservation as Platt National Park, named for the Connecticut senator who introduced the 1902 legislation that preserved the springs. Under President Roosevelt's New Deal, work by the Civilian Conservation Corps in Platt National Park became one of the most cohesive and intensive programs of master planning and landscape conservation carried out in the national parks. In 1976, Platt National Park was combined with the Arbuckle National Recreation Area and re-designated the Chickasaw National Recreation Area in honor of the Chickasaw Nation.

Groundwater discharging from the springs flows from the Arbuckle-Simpson aquifer. This aquifer provides water for public supply, farms, mining, wildlife conservation, recreation, and the scenic beauty of springs, streams, and waterfalls. East of the recreation area, the Cambrian–Ordovician carbonate rocks of the Arbuckle-Simpson aquifer are 910 m (3,000 ft) to as much as 1,200 m (4,000 ft) thick. The aquifer is exposed on the surface east of the recreation area but confined beneath the conglomerate and shale of the Pennsylvanian Period Vanoss Formation in Chickasaw National Recreation Area. The springs in the recreation area mark the transition between fresh water and saline sections of the Arbuckle-Simpson aquifer.

In Chickasaw National Recreation Area, Travertine Creek flows into Rock Creek, which empties into Lake of the Arbuckles. Lake of the Arbuckles includes 58 km (36 mi) of shoreline and is the principal water supply reservoir for the cities of Ardmore and Davis, Oklahoma. The recreation area also contains the smaller Veterans Lake.

At the 2007 GRI scoping meeting and 2014 conference call, participants identified the following geologic features and processes in Chickasaw National Recreation Area:

- Freshwater and Mineral Springs. Chickasaw National Recreation Area contains five named springs and spring groups. These include two freshwater springs (Buffalo and Antelope springs) and three mineral springs and groups (Black Sulphur springs group, Hillside spring, and Pavilion springs group). Buffalo and Antelope springs are the main water sources for Travertine Creek, the principal tributary to Rock Creek. The mineral springs discharge into Rock Creek, the largest stream entering the recreation area.
- Vendome Artesian Well. Mineral-rich groundwater flowed from Vendome artesian well at an estimated 9,500 liters (2,500 gallons) per minute when the well was drilled in 1922. In 1935, the Civilian Conservation Corps connected this popular tourist site to Travertine Creek via an artificial waterway that included two wading pools and a waterfall. In 1998, a new Vendome Well was drilled about 6 m (20 ft) west of the original well.
- Travertine Creek and Travertine Island. Groundwater flowing from Antelope and Buffalo springs contains dissolved calcium carbonate, which precipitates out of solution to form the

porous limestone known as travertine. Impressive travertine deposits are exposed along Travertine Creek and on Travertine Island. In 1934, the Civilian Conservation Corps used local blocks of Vanoss Conglomerate to build a rock picnic table and rock benches on Travertine Island.

- Paleontological Resources. Fossils of marine invertebrates are found primarily in the Ordovician (485 million to 444 million years ago) and Devonian (419 million to 359 million years ago) rocks in Chickasaw National Recreation Area. They record a vibrant ecosystem and extent of an inland sea that covered present-day southern Oklahoma during the Paleozoic Era.
- Sedimentary Features in the Vanoss Formation. Features in the Vanoss conglomerate (**PNvc**) and overlying Vanoss shale (**PNvs**) provide evidence of Late Paleozoic tectonics, as well as regional depositional environments. These features include upward-fining cycles of sediment, parallel laminations, trough cross-bedding, ripple marks, fenestrae, mud cracks, rip-up clasts, and varves.
- Folds and Faults. During the Pennsylvanian Period, tectonic forces compressed, folded, faulted, and uplifted the strata of southern Oklahoma. Paleozoic rocks in and adjacent to Chickasaw National Recreation Area document this deformation. From north to south, regional folds include the broad Hunton anticline (A-shaped fold), Sulphur syncline (U-shaped fold), Belton anticline, Mill Creek syncline, Tishomingo anticline, and the Dougherty anticline. The folds are bordered by high-angle normal, reverse, and strike-slip faults.
- Cave and Karst Features. The Arbuckle-Simpson aquifer is a massive karst feature mapped east, south, and west of the recreation area. Small dissolution caves are found in the exposed travertine banks of Travertine Island, and caves created by fractures in the Vanoss Formation occur on the cliff at Bromide Hill. However, no significant caves or karst features are documented in Chickasaw National Recreation Area. Poorly understood circular hills that occur as distinct knobs just outside the borders of the recreation area have been interpreted as collapse features associated with ancient karst topography.
- Rock Creek Drainage Basin. Part of Chickasaw National Recreation Area is in the Rock Creek drainage basin. Rock Creek cut a V-shaped valley into the dense, erosion-resistant Vanoss Formation, but over the years, the valley has widened laterally as less-resistant layers of sandstone and shale have been eroded at a faster rate than the underlying, resistant conglomerate layers. Features associated with the meandering Rock Creek include point bars and cutbanks.
- Bromide Hill. This steep cliff composed of Vanoss conglomerate rises 43 m (140 ft) above Rock Creek. Bromide Hill is the most recognizable topographic feature in Chickasaw National Recreation Area. Its summit offers panoramic views of the Arbuckle Mountains and the Washita River Valley.

The following two issues were identified as the primary geologic resource management issues at the 2007 GRI scoping meeting:

- The Need for a Geologic Map of the Recreation Area. Since the meeting, a geologic map of the area has been completed, and it was used as the source map for the GRI GIS data.
- Groundwater Use and Spring Discharge Monitoring. Because of growing demand for water, increased groundwater pumping, and unregulated discharge outside of the recreation area, a systematic monitoring program for the springs was needed. Chickasaw National Recreation Area staff members developed a systematic, comprehensive monitoring program.

A follow-up conference call in 2014 identified the following geologic resource management issues:

- Water Quality. Springs in the recreation area flow water from the Arbuckle-Simpson aquifer and thus are susceptible to contamination from activities outside the recreation area. Surface water quality is monitored in Chickasaw National Recreation Area and park staff members work closely with the city of Sulphur to monitor and repair occasional manhole overflows and sewer-line blockages. Natural asphalt seeps may occur in Veterans Lake and Lake of the Arbuckles. The seeps are most notable when lake levels are low.
- Flooding and Debris Flows. During wet years, campgrounds, parking lots, and other nearshore infrastructure may be flooded. Floods may also cause sewage spills and other pollution, transport silt to the upper end of Lake of the Arbuckles, and cause debris to accumulate behind bridges. Flash floods may impact the Travertine Nature Center,

which is built on a floodplain. Climate change may increase intense rainfall events in southern Oklahoma resulting in higher risks of flooding.

- Rockfall. Large portions of the cliff at Bromide Hill have fallen into Rock Creek although no accidents or injuries from falling rock have been reported in Chickasaw National Recreation Area.
- Lakeshore Erosion. Fluctuations of the shoreline of Lake of the Arbuckles are minor, but these fluctuations may cause erosion. Dense vegetation helps stabilize the banks, but erosion may threaten archeology sites along the shoreline.
- Paleontological Resource Inventory, Monitoring, and Protection. Paleozoic rocks in Chickasaw National Recreation Area contain abundant exposures of marine invertebrate fossils. Park staff members are developing a paleontological research plan that will address a paleontological inventory and assessment of fossils in the recreation area, as well as methods to prevent illegal collecting.
- External Mineral Exploration and Development. Although no mining is allowed in the park, extraction of hydrocarbons occurs in the surrounding area by means of modern horizontal drilling techniques and hydraulic fracturing (fracking). Fluid injection wells associated with the production of hydrocarbons have triggered earthquakes in Oklahoma, the largest of which occurred approximately 110 km (70 mi) north of Chickasaw National Recreation Area in 2011. East of the recreation area, quarries mining construction aggregate have been developed in the aquifer outcrop, and groundwater that fills deep pits in these quarries must be removed. Such large withdrawals of water from the aquifer threaten stream and spring flow in Chickasaw National Recreation Area.
- Abandoned Mineral Lands. Chickasaw National Recreation Area contains two surface mines that may require action to mitigate hazards.

The rock units, fossils, unconsolidated sediments, and subdued topography in Chickasaw National Recreation Area reflect a dynamic evolution of the Arbuckle Mountains and southern Oklahoma that involves four major geological events:

- Rifting of the Craton. Tectonic rifting, the oldest event, pulled apart the crust of present-day southern Oklahoma in the Early and Middle Cambrian (541 million to 500 million years ago).
- Shallows Seas Flood the Craton. Sea level rise spread shallow seas over most of the continent, including present-day Oklahoma, from the Late Cambrian to the Pennsylvanian Periods (500 million to 323 million years ago).
- Uplift and Deformation. Intense folding and faulting caused by the collision of ancestral North America with South America during the Pennsylvanian Period (323 million to 299 million years ago) led to the rise of the Arbuckle Mountains.
- Erosion Shapes the Modern Landscape. Subtle uplift, regional tilting, and erosion over millions of years resulted in the modern landscape.

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

Products and Acknowledgments

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

GRI Products

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

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

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

Additional information regarding the GRI, including contact information, is available at http://go.nps.gov/gri. The current status and projected completion dates of products are available at http://go.nps.gov/gri_status.

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Geologic Setting and Significance

This chapter describes the regional geologic setting of Chickasaw National Recreation Area, summarizes connections among geologic resources and other park resources, and discusses the establishment of the recreation area.

Park Setting

Chickasaw National Recreation Area is south of Sulphur, Oklahoma, about midway between Oklahoma City and Dallas, Texas (fig. 1). The recreation area's 4,005.83 ha (9,898.63 ac) preserve historic freshwater and mineral springs that discharge into Rock Creek and its principal tributary, Travertine Creek (plate 1). Rock Creek is the largest stream entering Chickasaw National Recreation Area and receives mineral-rich water from Black Sulphur, Pavilion, and Hillside springs and Vendome Well (Hanson and Cates 1994). Travertine Creek depends on fresh groundwater flowing primarily from Buffalo and Antelope springs (fig. 2). Calcium carbonate precipitates out of the water and forms the sedimentary rock, travertine, for which the creek is named. Travertine Creek flows into Rock Creek near Lincoln Bridge, a stone bridge built in 1909 to connect Sulphur to the mineral springs south of the creek (see cover).

The recreation area also includes Veterans Lake, fed by Wilson Creek, and Lake of the Arbuckles (fig. 3). Following a drought in the 1950s that seriously depleted water supplies in the area, the US Bureau of Reclamation designed and built the Arbuckle Dam, which was completed in 1966. The 950 ha (2,350 ac) Lake of the Arbuckles includes 58 km (36 mi) of shoreline and is the primary water supply reservoir for the cities of Ardmore and Davis, Oklahoma. In addition to supplying municipal and industrial water to surrounding communities, the lake supports recreational activities and provides flood control (US Bureau of Reclamation 2012). The smaller, 27 ha (67 ac) Veterans Lake filled in 1933 and offers 5 km (3 mi) of shoreline.

The gently rolling hills and stream-cut ravines of Chickasaw National Recreation Area are erosional remnants of the Arbuckle Mountains. The elevation ranges from about 378 m (1,240 ft) above sea level southeast of the park to 259 m (850 ft) above sea level in Rock Creek at the southwest corner of the recreation area (Hanson and Cates 1994). Bromide Hill, a vertical bluff that rises 43 m (140 ft) above Rock Creek, is a dominant physical feature within the recreation area, offering panoramic views from its summit.

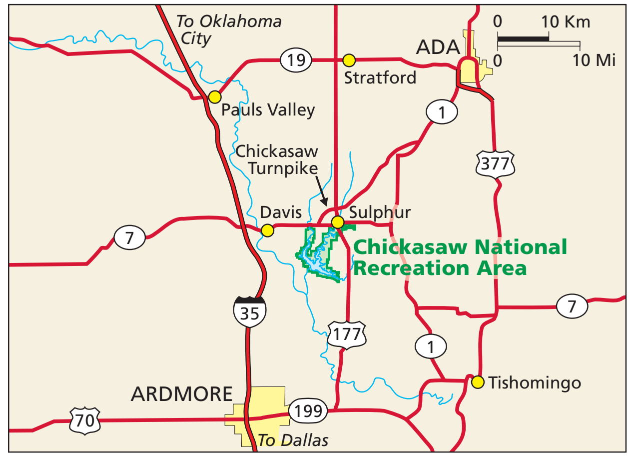

Figure 1. Location map of Chickasaw National Recreation Area. See plate 1 (in pocket) for detailed park map. National Park Service map, available at http://www.nps.gov/hfc/cfm/carto-detail.cfm?Alpha=CHIC (accessed 15 June 2015).

Figure 2. Buffalo Spring in Chickasaw National Recreation Area. Freshwater from Buffalo Spring flows into Travertine Creek. The CCC built the stonework in the 1930s. National Park Service photograph, available at http://www.nps.gov/chic/learn/photosmultimedia/photogallery.htm (accessed 15 June 2015).

The recreation area is within the Arbuckle Uplift

Figure 3. Lake of the Arbuckles in Chickasaw National Recreation Area. The lake is the primary water supply for Ardmore, Oklahoma, and a popular recreation spot for park visitors. This photo is looking to the north and includes only one arm of the lake. It was taken during a time of relatively high water. The Buckhorn boat ramp is in the lower right. The conglomerate facies of the Vanoss Formation (PNvc) underlies the forested hills that border the lake. National Park Service photograph, available at http://www.nps.gov/chic/learn/photosmultimedia/photogallery.htm.

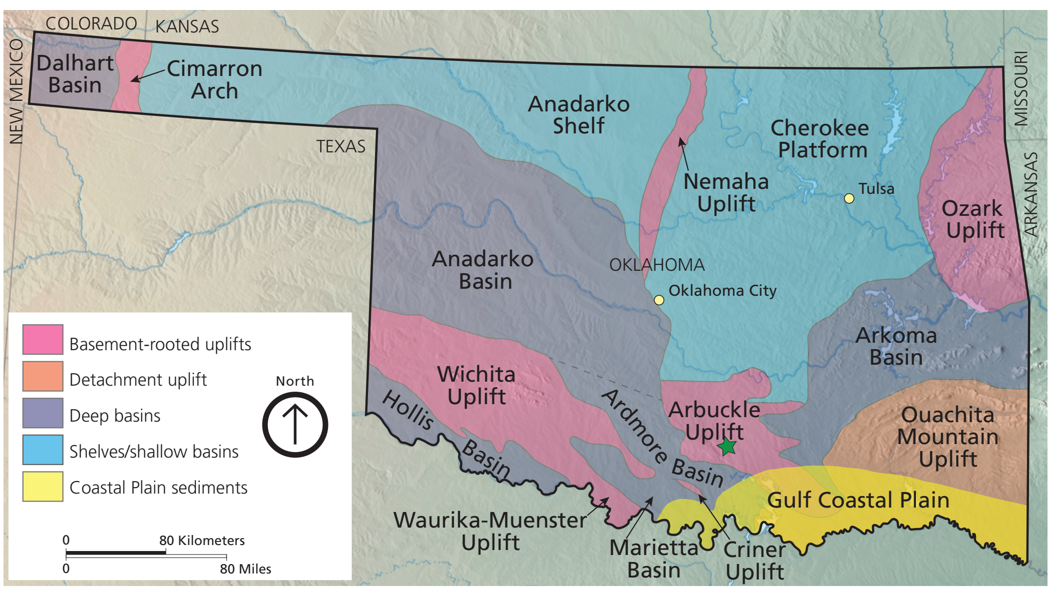

Figure 4. Geologic provinces of Oklahoma. Chickasaw National Recreation Area (green star) lies within the Arbuckle Uplift, which contains some of the thickest accumulations of Paleozoic sedimentary rock in the central United States. Map by Trista Thornberry-Ehrlich (Colorado State University) after an Oklahoma Geological Survey diagram, available at http://www.ogs.ou.edu/MapsBasic/Provinces.jpg (accessed 4 March 2014) and comments from Neil Suneson (Oklahoma Geological Survey, written communication, 24 November 2014). Basemap by Tom Patterson (National Park Service), available at http://www.shadedrelief.com/physical/index.html (accessed 15 October 2014).

physiographic province (fig. 4). The uplift is just south of the Cherokee Platform, which is part of the vast interior plains of North America. The geographic location, underlying geologic formations, hot and humid summers, and relatively mild winters support both prairie and forest ecosystems.

Geologic Significance and Connections

In the 1940s and 1950s, William E. Ham and his colleagues began mapping the geology of the Arbuckle Mountains, and in 1954, Ham and McKinley produced a 1:72,000-scale geologic map of the Arbuckle Mountains that is considered by many to be the most accurate geologic map of the Arbuckle region (Ham and McKinley 1954; Blome et al. 2013). Ham (1955) later published this map in an Oklahoma Geological Survey guidebook, and Ken S. Johnson (1990) later revised the Ham and McKinley map. A 1990 Oklahoma Geological Survey Circular on the hydrology of the Arbuckle Mountains contains both the Johnson (1990) map and the original Ham and McKinley (1954) map (Fairchild et al. 1990).

The evolution of the Arbuckle Mountains involves four major geological events: (1) rifting, (2) deposition in shallow seas, (3) uplift and deformation, and (4) major erosion (see "Geologic History" chapter; Donovan and Butaud 1993; Tapp 1995; Blome et al. 2013). During the Early and Middle Cambrian (fig. 5), tectonic rifting pulled apart the crust along the southern margin of the ancestral North American continent, forming enormous rift valleys, similar to those in eastern Africa today. This rifting phase was followed by a long period of Late Cambrian through Middle Mississippian (fig. 5) deposition, subsidence, and sea level rise. Shallow marine sediments, primarily limestone and dolomite, accumulated in the rift basins as shallow seas inundated the continental margin, which included present-day south-central Oklahoma.

Intense folding and faulting occurred during the Pennsylvanian and Permian periods (fig. 5) when all the major land masses on the globe were coming together to form the supercontinent Pangaea. Tectonic compression resulted in the Arbuckle, Ouachita, and Wichita mountains of southern Oklahoma. From north to south, significant folds in the Chickasaw National Recreation Area include the Hunton anticline, Sulphur syncline, Belton anticline, Mill Creek syncline, Tishomingo anticline, and the Dougherty anticline. Anticlines are convex, A-shaped folds that resemble upside-down canoes. Synclines are just the opposite. They are concave, U-shaped folds. Faults in the region include the Sulphur fault, South Sulphur fault, Mill Creek fault zone, and the Reagan fault (Blome et al. 2013). The axes of the folds and faults are oriented northwest–southeast, and are described in more detail in the "Geologic Features and Processes" chapter of the report.

The folded and faulted rocks in the Arbuckle Uplift represent some of the thickest accumulations of Paleozoic rocks in the central United States. Rock units in Chickasaw National Recreation Area span the Ordovician to Pennsylvanian periods (figs. 5 and 6; see the Map Unit Properties Table). The Pennsylvanian Vanoss Formation (geologic map units **PNvs** and **PNvc**) is the primary rock unit exposed in the recreation area (Hanson and Cates 1994; Scheirer and Scheirer 2006; Blome et al. 2013). It consists of two major "facies," which are lithologically distinct, sedimentary units deposited in different places at the same time: the shale facies (**PNvs**) and the conglomerate facies (**PNvc**) (Blome et al. 2013). The Vanoss Formation thickens from east to west and is approximately 100 m (330 ft) thick in Vendome Well.

Significantly, the tightly cemented limestone, conglomerate, shale, and sandstone of the Vanoss Formation act as a confining layer over the underlying Arbuckle-Simpson aquifer (fig. 6). An aquifer may be thought of as an underground reservoir of water. Water percolating from the surface fills any open spaces in subsurface rock units. If the pore spaces in the rock are connected and sufficient groundwater moves through the pore spaces (known as "permeability"), the rock unit becomes an aquifer (fig. 7).

The outcrop portion of the Arbuckle-Simpson aquifer in south-central Oklahoma is about 1,300 km^2 (520 mi^2), but the aquifer also extends into the subsurface in some areas, such as under Chickasaw National Recreation Area. The eastern Arbuckle-Simpson aquifer was designated a "Sole Source Aquifer" by the US Environmental Protection Agency (EPA) in 1989 in order to protect drinking water supplies in this area with limited water supply alternatives (Oklahoma Water Resources Board 2003; Christenson et al. 2011). The aquifer consists of rocks of the Cambrian–Ordovician Arbuckle (**Owk** and **Ow**) and Simpson (**Obm** and **Ooj**) groups (fig. 8). The Simpson Group is as much as 700

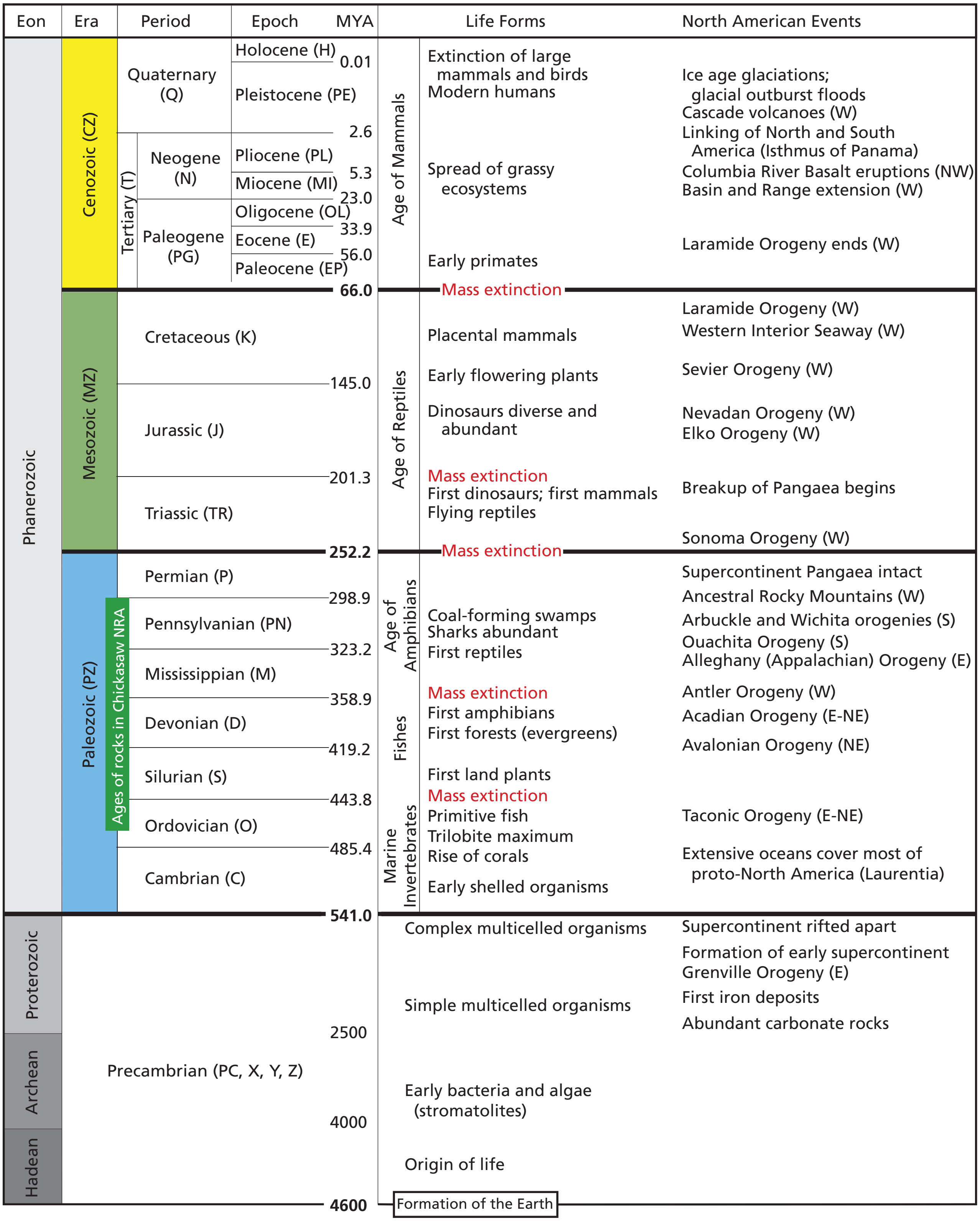

Figure 5. Geologic time scale. The divisions of the geologic time scale are organized stratigraphically, with the oldest divisions at the bottom and the youngest at the top. Exposures in Chickasaw National Recreation Area include Ordovician through Pennsylvanian rocks (green bar in "Era" column). GRI map abbreviations for each time division are in parentheses. Compass directions in parentheses indicate the regional locations of events. Boundary ages are millions of years ago (MYA). National Park Service graphic using 2015 ages from the International Commission on Stratigraphy. (http://www.stratigraphy.org/index.php/ics-chart-timescale; accessed 7 May 2015).

Age	Stratigraphic Unit (map symbol)			Aquifer Unit	Rock Description
Quaternary	Artificial fill (af)			Unconsolidated sediment	Fill for dams and other projects.
Quaternary	Alluvium (Qal)			Unconsolidated sediment	Unconsolidated sand, silt, clay and gravel.
Permian (lower)	Pontotoc Group	Stratford Formation (Ps)		Upper confining unit ("post-Simpson" unit)	Shale and sandstone
Pennsylvanian (Upper)	Pontotoc Group	Vanoss Formation	Shale facies (PNvs)	Upper confining unit ("post-Simpson" unit)	Primarily green, gray, and red shale and silty shale.
Pennsylvanian (Upper)	Pontotoc Group	Vanoss Formation	Conglomerate facies (PNvc)	Upper confining unit ("post-Simpson" unit)	Limestone boulders, cobbles, and pebbles in a calcareous matrix.
Pennsylvanian (Middle)	Deese Group (PNd)			Upper confining unit ("post-Simpson" unit)	Sandstone, shale, limestone conglomerate, limestone.
Pennsylvanian (Middle) / Pennsylvanian (Lower)	Atoka and Wapanucka Formations (PNaw)			Upper confining unit ("post-Simpson" unit)	Unfossiliferous sandstone and brown to gray shale.
Pennsylvanian (Lower) / Mississippian (Upper)	Springer Formation (PNMs)			Upper confining unit ("post-Simpson" unit)	Black, fissile shale separated by thin beds of sandstone and limestone.
Mississippian (Middle)	Caney Shale (Mc)			Upper confining unit ("post-Simpson" unit)	Black, fissile shale with phosphatic concretions.
Mississippian (Middle) / Mississippian (Lower) / Devonian (Upper)	Sycamore Limestone, Welden Limestone, Woodford Shale (MDsw)			Upper confining unit ("post-Simpson" unit)	Shale, cherty to silty limestone, black bituminous shale.
Devonian (Lower)	Hunton Group (DSOh)	Upper part (Dhu)		Upper confining unit ("post-Simpson" unit)	Blue to white shale and argillaceous limestone.
Silurian / Ordovician (Upper)	Hunton Group (DSOh)	Lower part (SOhl)		Upper confining unit ("post-Simpson" unit)	Fossiliferous to massive to argillaceous limestone.
Ordovician (Upper)	Sylvan Shale and Viola Group (Osv)	Sylvan Shale (Os)		Upper confining unit ("post-Simpson" unit)	Soft, green to gray, fissile shale.
Ordovician (Upper)	Sylvan Shale and Viola Group (Osv)	Viola Group (Ov)		Upper confining unit ("post-Simpson" unit)	Fossiliferous and cherty limestone.
Ordovician (Middle)	Simpson Group	Bromide, Tulip Creek, McLish Formations (Obm)		Arbuckle-Simpson aquifer	Sandstone, shale, and limestone.
Ordovician (Middle)	Simpson Group	Oil Creek and Joins Formations (Ooj)		Arbuckle-Simpson aquifer	Basal conglomerate layer overlain by sandstone, limestone, and shale.
Ordovician (Lower)	Arbuckle Group (upper part)	West Spring Creek and Kindblade Formations (Owk)		Arbuckle-Simpson aquifer	Mostly limestone that grades eastward into dolomite with sandstone and shale.
Ordovician (Lower)	Arbuckle Group (upper part)	West Spring Creek Formation (Ow)		Arbuckle-Simpson aquifer	Limestone that grades eastward into dolomite with sandstone and shale.

Figure 6. Schematic stratigraphic column for Chickasaw National Recreation Area. Age 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. Gray rows indicate units not mapped within the recreation area. Modified from Blome et al. (2013).

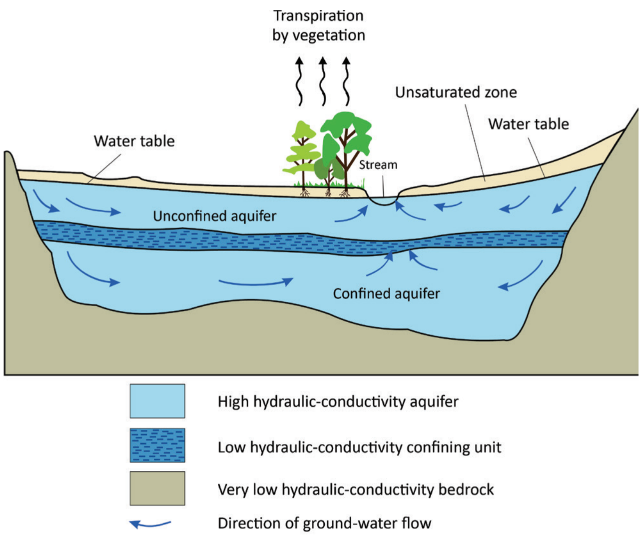

Figure 7. Schematic of an aquifer. Water percolating through the unsaturated zone of unconsolidated sediments or porous rock forms an unconfined aquifer. If a rock layer does not have sufficient porosity or permeability, it forms a barrier to groundwater flow. Groundwater below this confining layer becomes part of a confined aquifer. The Arbuckle-Simpson aquifer has properties resembling both a confined and unconfined aquifer. Hydraulic conductivity is a measure of how easily groundwater flows through pore spaces in the rock unit. Diagram by Hans Hillewaert (Creative Commons Attribution-Share Alike 3.0 Unported license), available online at http://en.wikipedia.org/wiki/Aquifer (accessed 6 May 2014).

m (2,300 ft) thick in the western Arbuckle-Simpson aquifer, but generally thins to less than 300 m (1,000 ft) thick in the eastern Arbuckle-Simpson aquifer (Barthel 1985; Hanson and Cates 1994; Christenson et al. 2011). Because the upper part of the Arbuckle Group has been eroded, its thickness varies. Regionally, the unit is as much as 1,200 m (4,000 ft) thick, but its total thickness beneath Chickasaw National Recreation Area is unknown (Barthel 1985; Hanson and Cates 1994).

The Arbuckle-Simpson aquifer can be divided into three distinct outcrop regions (fig. 8). The largest and most significant region is the eastern Arbuckle-Simpson aquifer, which is exposed east of Chickasaw National Recreation Area. West of the eastern outcrop region, the rock units dip below the surface, and the groundwater becomes more saline. The mineral springs in Chickasaw National Recreation Area are evidence of this transition from fresh to saline groundwater (Christenson et al. 2011).

Beneath Chickasaw National Recreation Area, the confined groundwater in the Arbuckle-Simpson aquifer is under a great amount of pressure. Where that pressure is released, groundwater rises naturally to a level of hydrostatic equilibrium in what is known as "artesian flow" (fig. 9). If that equilibrium level is higher than the ground surface, the water will flow onto the surface. Artesian flow is responsible for many freshwater and mineral springs in Chickasaw National Recreation Area.

Where a well, such as Vendome Well, penetrates through the confining layer, groundwater flows upward naturally, without pumping, and the well is known as an "artesian well." Artesian wells can produce an abundant amount of groundwater. When Vendome Well was drilled in 1922, it produced an estimated 9,500 liters (2,500 gallons) of water per minute and was the largest artesian well in Oklahoma (Gould and Schoff 1939; Hanson and Cates 1994).

Most of the Paleozoic rocks older than the Vanoss Formation in Chickasaw National Recreation Area are exposed south of Lake of the Arbuckles in the Tishomingo anticline (Blome et al. 2013). The anticline is cored by the limestones of the Viola Group (**Ov**). Younger rocks are exposed on the flanks of the fold and include the Ordovician Sylvan Shale (**Os**), the Silurian and Upper Ordovician Lower Hunton Group (**SOhl**), Lower Devonian Upper Hunton Group (**Dhu**), and the Devonian–Lower Mississippian undifferentiated Sycamore Limestone, Welden Limestone, and Woodford Shale (**MDsw**) (fig. 6; Blome et al. 2013).

Since the end of the Paleozoic Era, approximately 252 million years ago, erosion has removed any post-Paleozoic strata that once occurred in the region. Erosion smoothed the mountainous landscape, and regional tilting resulted in southeast flowing streams (Christenson et al. 2011). The topography of Chickasaw National Recreation Area reflects the diversity of rock types and their susceptibility to erosion. Erosion-resistant limestone conglomerate of the Vanoss Formation forms the high points in the recreation area, such as the Bromide Hill Overlook. Valleys have been carved into finer-grained, less-resistant shales and siltstones.

Water plays the major role in shaping the landscape of Chickasaw National Recreation Area. Surface runoff and spring water formed Rock Creek that today cuts

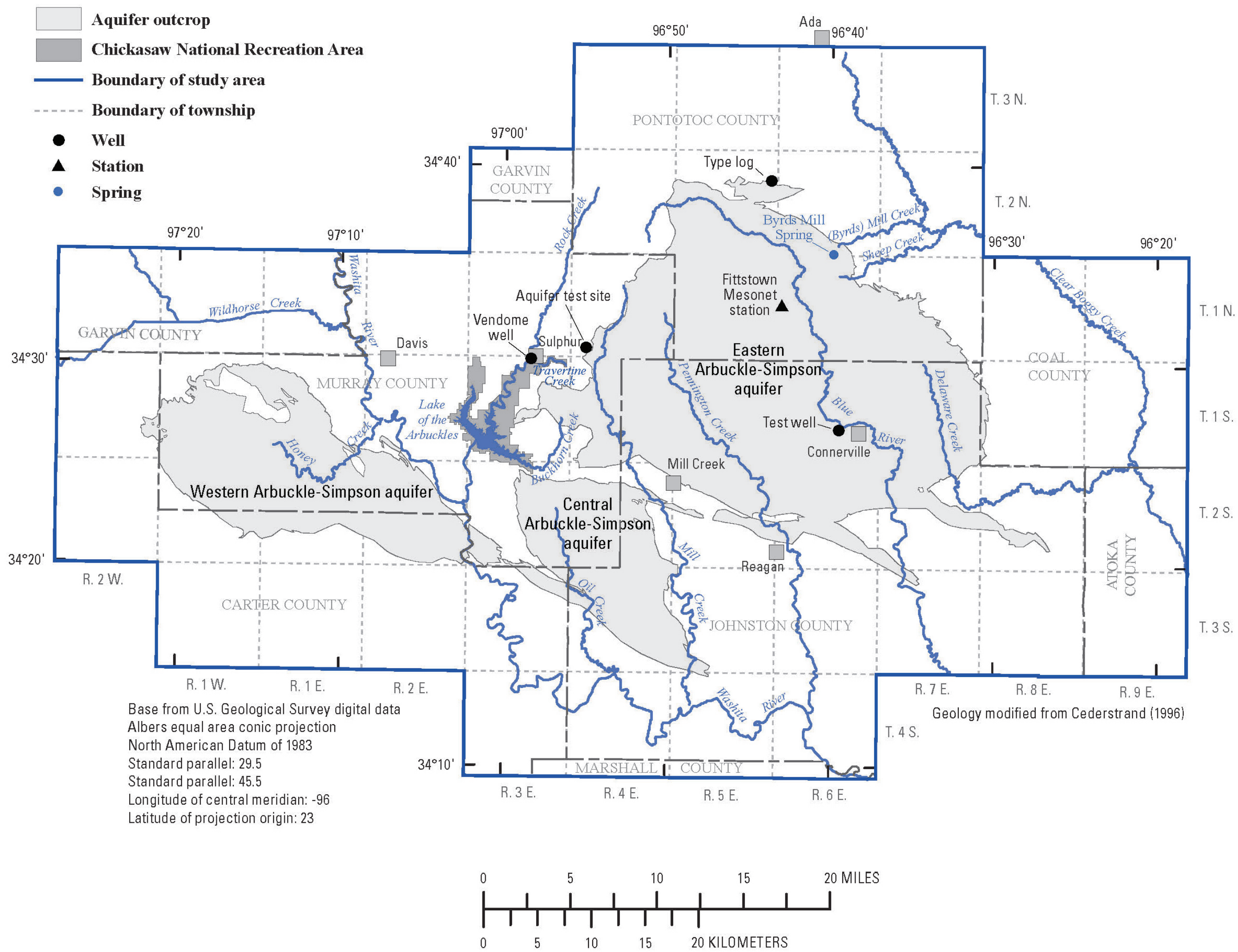

Figure 8. Regional extent of the Arbuckle-Simpson aquifer outcrop in south-central Oklahoma. The aquifer is the main water source for approximately 39,000 people that currently live in the region. Chickasaw National Recreation Area is part of the Eastern Arbuckle-Simpson aquifer. US Geological Survey figure extracted from Christenson et al. (2011, figure 2), available at http://pubs.usgs.gov/sir/2011/5029/ (accessed 4 March 2014).

across the Vanoss Formation and continues to cut a V-shaped valley. Lateral erosion by Rock Creek continues to undercut Bromide Hill, eroding less-resistant sandstone and shale layers. Undercutting results in rock overhangs that may collapse into the creek.

Groundwater also plays a role in shaping the landscape. The slightly acidic groundwater dissolves carbonate rock, and if dissolution takes place near the surface, the surface collapses, creating a sinkhole. Although not present in Chickasaw National Recreation Area, several sinkholes are mapped east of the park (Blome et al. 2013). These sinkholes now stand as circular hills above the surrounding topography. When the sinkholes formed, circulating fluids tightly cemented the carbonate rock fragments that had collapsed into the openings. Subsequent erosion removed the less-resistant limestone that surrounded the sinkhole and left the more-resistant carbonate breccia. The result of this differential erosion is today's inverse topography wherein those features that were once low areas now appear elevated.

Establishment of Chickasaw National Recreation Area

Groundwater in Chickasaw National Recreation Area contains abundant calcium and magnesium dissolved

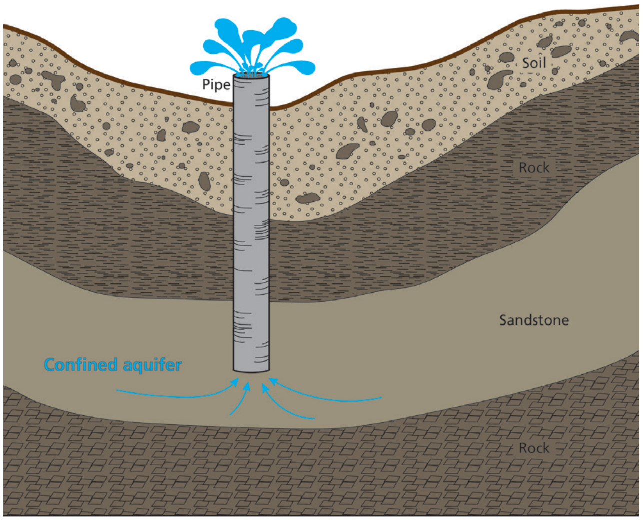

Figure 9. Schematic of an artesian well. Hydraulic pressure in a confined aquifer causes groundwater to rise to a point where hydrostatic equilibrium is reached. An artesian well or artesian flowing spring results if that equilibrium point is above the ground surface. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after a public domain image created by Pearson Scott Foresman and available at http://en.wikipedia.org/wiki/Artesian_aquifer (accessed 6 May 2014).

from the limestone and dolomite through which it flows. A number of the springs, such as Hillside, Pavilion, Black Sulphur, and Bromide springs also contain abundant sulphur, bromide, and other minerals. In the late 1890s, thousands of visitors flocked to Sulphur, Oklahoma, because of the therapeutic and medicinal properties that were attributed to these springs.

Fearing the region would suffer due to the uncontrolled use of the springs, the Chickasaw and Choctaw nations ceded all of the springs and 260 ha (640 ac) to the Department of the Interior in 1902 to create the Sulphur Springs Reservation. In 1906, it was renamed Platt National Park for Senator Orville Platt of Connecticut, who backed the park's legislation.

In 1976, Platt National Park and Arbuckle National Recreation Area were combined and, in honor of the Chickasaw Nation, Congress re-designated the area as Chickasaw National Recreation Area. Prior to the re-designation, Platt National Park experienced a remarkable transformation. During the Great Depression of the 1930s, President Franklin D. Roosevelt inaugurated the Civilian Conservation Corps (CCC) to put men back to work. Between 1933 and 1942, more than three million men built structures, planted trees, prevented soil erosion, and conserved natural resources in America's national parks and forests. In the Platt Historic District, the CCC used natural limestone from the area to build a number of landscape features, which included a new cistern and basin for Hillside Spring, the Bromide Pavilion, an artificial creek and two wading pools from Vendome Well to Flower Park, and a waterfall on Travertine Creek (cover and fig. 10). They also planted 800,000 trees (National Park Service 2014a). This collaboration between the National Park Service (NPS) and the CCC during the New Deal era reflects one of the most cohesive and intensive programs of master planning and landscape conservation carried out in the national parks. To honor this accomplishment, Platt National Park Historic District was designated a National Historic Landmark in 2011.

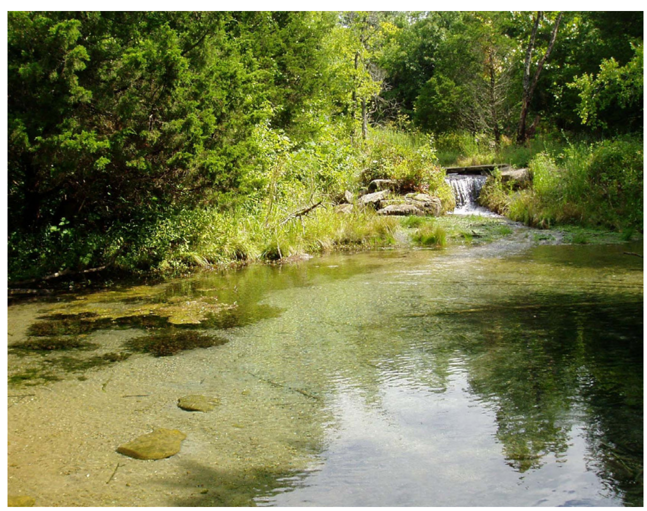

Figure 10. Structures built by the Civilian Conservation Corps in the 1930s. Top: Bromide Pavilion. Spring water was piped across Rock Creek to the pavilion. Bottom: Antelope Spring waterfall. National Park Service photographs, available at http://www.nps.gov/chic/learn/photosmultimedia/photogallery.htm (accessed 15 June 2015).

Geologic Features and Processes

This section describes noteworthy geologic features and processes in Chickasaw National Recreation Area.

During the 2007 scoping meeting (see Graham 2008) and 2014 conference call, participants (see Appendix A) identified the following geologic features and processes in Chickasaw National Recreation Area:

- Freshwater and Mineral Springs
- Vendome Artesian Well
- Travertine Creek and Travertine Island
- Paleontological Resources
- Sedimentary Features in the Vanoss Formation
- Folds and Faults
- Cave and Karst Features
- Rock Creek Drainage Basin
- Bromide Hill

Freshwater and Mineral Springs

Protection of the freshwater and mineral springs was the primary reason that the Sulphur Springs Reservation was established in 1902. Over the years, several of the springs have been modified, and many of the springs and seeps do not carry official names. Today, Chickasaw National Recreation Area contains five named springs and spring groups (plate 1, and poster, in pocket). Antelope and Buffalo springs are considered to be freshwater springs, and Black Sulphur, Hillside, and Pavilion are considered mineral springs. The Pavilion Springs group consists of seven springs, and the Black Sulphur Springs group (originally known as Beach Springs) consists of three springs (Gould and Schoff 1939). All of these springs were among the 33 original springs identified by Charles Gould of the US Geological Survey prior to the establishment of Sulphur Springs Reservation (Gould 1906; Water Resources Division 1997; Muncrief 2006). The mineralized springs contain high concentrations of sodium and chloride, which gives the water a salty taste, and hydrogen sulfide, which imparts a sulfuric, rotten-egg odor. In the early years of the 20th century, the spring water was considered to have medicinal qualities and many thousands of visitors and local residents came annually to drink the salty water, especially the Bromide Springs water (see below) (Gould 1906).

Spring Geochemistry

Chemical analyses of Antelope, Hillside, Pavilion, and Black Sulphur springs (Buffalo Spring did not have a comparable suite of analyses) indicate that groundwater flowing from these springs contains similar concentrations of the same major elements except for sodium, chloride, sulphur, and hydrogen sulfide (table 1; Water Resources Division 1997; Christenson et al. 2009). Concentrations of sodium and chloride in Bromide and Medicine springs are significantly higher than in any of the other springs or Vendome Well, and Bromide Spring contains the highest sulfate concentration (table 1). Specific conductance, a measure of the ionic content in the groundwater, is only slightly higher in the mineral springs. Hillside, Pavillion, and Black Sulphur springs also contain higher concentrations of the trace elements boron, lithium, and strontium than does Antelope Spring.

Hydrogen sulfide, which is also present at Vendome Well (see below), is a by-product of reducing environments, which are common in the presence of petroleum. The hydrogen sulfide in the groundwater emerging from the springs in Chickasaw National Recreation Area may have migrated from the oil and gas accumulations west of the park (Christenson et al. 2009; Bob Schulz, Chevron Corporation, chemical engineer-retired, personal communication, 29 July 2014; see "External Mineral Exploration and Development" section). Several oil and gas wells have been drilled in northwestern Murray County, and groundwater from one producing oil well near the northwestern boundary of the recreation area was sampled in 2009 as part of a US Geological Survey Arbuckle-Simpson aquifer study (Christenson et al. 2009, sample 31). The oil well sample was typical of a concentrated brine solution derived from the evaporation of seawater, but hydrogen sulfide was not part of the sampling criteria.

The Springs and the Arbuckle-Simpson Aquifer

Although the springs in Chickasaw National Recreation Area are west of the mapped area of the Arbuckle-Simpson aquifer (fig. 8), they are supplied by water from the aquifer. As described by Christenson et al. (2011), water that recharges the aquifer flows west

Table 1. Chemical analysis for the springs and Vendome Well in Chickasaw National Recreation Area. See notes on facing page.

Element	Mineral Springs					Freshwater Spring		Vendome Well (2)
	Hillside Spring (1)	Pavilion Spring (1)	Black Sulphur Spring (1)	Bromide Spring (3)	Medicine Spring (3)	Antelope Spring		
						(1)	(2)	
Specific conductance	676.333	734.24	893.182	Not analyzed		568.207	635	2,100
Average Concentrations Measured in milligrams/liter (MG/L). These are the major ions.								
Alkalinity (as $CaCO_3$)	296.9	303.5	308.778	Not analyzed		324.21	315	278
Bicarbonate (as HCO_3)	363	371	385			418	384	339
Bromide	0.25*	0.25*	0.25*			1.56	0.04	2.08
Calcium	111	68.4	64.5	50	68	68.3	79.1	86.6
Chloride	74	93	152	2,000	2,370	3	3.35	558
Magnesium	49.2	31	29.6	30	36	30.6	35.4	37.4
Nitrogen, ammonia	0.125	0.176	16	Not analyzed		0.03	<0.04	0.43
Phosphorus	0.025*	0.025*	0.025*			0.025*	<0.02	<0.02
Potassium	9.4	3.9	5.2			3.8	1.48	9.60
Sodium	333	78.6	121	1,300	1,490	76	3.37	316
Sulphur (as sulfate)	22.7	19.4	25	48	14	17.7	16.9	35.1
Sulphur as H2S	0.54	0.935	1.075			0	Not analyzed	
Average Concentrations Measured in micrograms/liter (UG/L). These are considered to be trace elements.								
Antimony	11*	11*	11*	Not analyzed		25	<0.20	<0.20
Aluminum	191	104	28.5*			83	<2	
Arsenic	11*	11*	11*			11*	E.1	0.5
Barium	133	162	156			162	171	202
Beryllium	0.45*	0.25*	0.25*			0.25*	<0.06	<0.06
Boron	319	98	181			82	18	496
Cadium	4	2	7			2	E.03	<0.04
Chromium	3	2	3			2	<0.8	<0.8
Cobalt	2*	2*	2*			2*	0.177	0.310
Copper	17*	17*	17*			17*	0.4	1.2
Germanium	23*	22.5*	22.5*			22.5*	Not analyzed	
Lead	7.5*	7.5*	7.5*			19	0.93	<0.08
Lithium	60	16	22			18	1.4	66.2
Manganese	57.5	8.5	6			40.4	E.2	2.2
Mercury	24.5*	24*	24*			24.5*	Not analyzed	
Molybdenum	3	4	2			4	2.9	<0.4
Nickel	8*	5*	2*			14	1.85	1.57
Selenium	16	6.5	14			40	0.8	2.5
Silver	8.9*	2.6*	2.6*			8.7	<0.2	<0.2
Strontium	6850	1960	3090			1900	84.0	6,860
Tellurium	16.5*	16.5*	16.5*			44	Not analyzed	
Thallium	5.5*	17	5.5*			5.5*	0.09	<0.04
Titanium	7*	7*	7*			7*	Not analyzed	
Uranium	Not analyzed						1.67	<0.04
Vanadium	13	5.5*	5.5*	Not analyzed		14	0.2	<0.1
Zinc	10	11	4.5*			39	6.4	0.6

Notes for Table 1 (facing page):

(1) Average concentrations are from WRD baseline water quality report for Chickasaw National Recreation Area (1997). Asterisks (*) mark concentrations that were "Computed with 50% or more of the total observations as values that were half the detection limit," thus, their values should be used with caution (WRD 1997, p. 12). See the WRD report for a more complete analysis.

(2) Values from the Arbuckle-Simpson aquifer study by Christenson et al. (2009, their Appendix 1). E: estimated. See Christenson et al. (2009) for a more complete analysis.

(3) Values from water samples analyzed in 1987 from Andrews and Burrough (2000, their table 1).

under the "post-Simpson" unit (fig. 6) and then up through the "post-Simpson." The chemistry of the groundwater indicates that the freshwater and mineral springs at Chickasaw National Recreation Area mark the freshwater/saline transition zone at the edge of the Arbuckle-Simpson aquifer's freshwater flow system (Christenson et al. 2009, 2011). In general, the eastern Arbuckle-Simpson aquifer, exposed east of the park, is unconfined and is recharged by precipitation. Rock units in this unconfined portion of the Arbuckle-Simpson aquifer are fractured and highly permeable. Groundwater flows relatively rapidly through an extensive fresh groundwater zone (Christenson et al. 2011). At least 100 springs discharge fresh water from the aquifer, including Antelope and Buffalo springs in the recreation area and Byrd Mill Spring, the largest spring and primary source of drinking water for Ada (Oklahoma Water Resources Board 2003).

The water-bearing units (fig. 6) thicken from east-to-west, and where they are buried beneath Chickasaw National Recreation Area, they are confined by the overlying conglomerate facies (geologic map unit **PNvc**) and shale facies (**PNvs**) of the Vanoss Formation (Christenson et al. 2011). Groundwater emerging from the freshwater springs is relatively young (post-1950s), indicating that groundwater moves quickly from recharge areas to stream and spring discharge areas (Christenson et al. 2009). Groundwater collected from Antelope Spring had an apparent age of calendar year 1962 (Christenson et al. 2009).

The higher concentrations of sodium, chloride, and sulfate in groundwater emerging from the mineral springs of Chickasaw National Recreation Area suggest a mixture of fresh water from the Arbuckle-Simpson aquifer and saline water from a deeper, regional source (Christenson et al. 2009). Groundwater age analyses were not conducted for Hillside, Pavilion, and Black Sulphur springs, but groundwater sampled from Vendome Well was approximately 10,500 years old (see "Vendome Artesian Well" section; Christenson et al. 2009).

Freshwater Springs

Buffalo Springs and Antelope Springs, in the eastern end of the Platt Historic District, are the primary freshwater springs in Chickasaw National Recreation Area (fig. 2 and plate 1). They are the principal source of water for Travertine Creek, and in average years, the two springs have a combined flow of about 19 million liters (5 million gallons) of water a day (National Park Service 2014b). Droughts and pumping of groundwater may lower the water level in the aquifer, which, in turn, will reduce the flow from the springs (see "Groundwater Use and Spring Discharge Monitoring" section).

Water from Buffalo and Antelope springs contains an abundant amount of dissolved calcium carbonate (Water Resources Division 1997). Calcium carbonate precipitates, forming the buff-colored, porous travertine deposits. Travertine terraces have formed along the length of Travertine Creek (see "Travertine Creek and Travertine Island" section).

The landscape surrounding Antelope and Buffalo springs was modified in the 1930s by the CCC (National Park Service 2014a). Antelope Spring, which emerges from the Vanoss Formation (**PNvs** and **PNvc**), was uncovered when some soil and rock were removed. In other areas, the CCC modified slopes in order to expose boulders and rock outcrops. At Buffalo Spring, the CCC used native stone to enclose the pool that visitors see today (fig. 2).

Mineral Springs

The CCC also used native stone to construct features such as pavilions and enclosures around the mineral springs in Chickasaw National Recreation Area (fig. 10). The main sulphur-rich springs are Hillside Spring, Pavilion Springs, Black Sulphur Springs, Bromide Spring, and Medicine Spring (plate 1; National Park Service 2014c). Bromide and Medicine springs are not mapped on plate 1 but are located at the base of Bromide Hill. Sulphur water also flows from Vendome Well (fig. 11).

Before the CCC built a new cistern and basin for Hillside Spring, the spring flowed from a rock wall below the present-day Platt District Ranger Station (Leeper House). In 1935, the CCC removed the old pavilion structure at Hillside Spring and built a retaining wall into the hillside (Hohmann and Grala 2004). The sulphur-rich water flows at a rate of about 300 liters (80 gallons) per minute (National Park Service 2014c). Believed to brighten eyes and improve complexions, Hillside Spring was also known as "Beauty Spring." Currently, high bacteria counts make the water unsafe to drink (Water Resources Division 1997; National Park Service 2014c). A warning has been posted over the Hillside Spring fountain for many years (Noel Osborn, NPS Chickasaw National Recreation Area, Chief of Resource Management, written communication, 6 August 2014).

Named for the number of pavilion structures built over the springs beginning in the 1890s, Pavilion Springs received a permanent structure in the 1930s. In the early days of the recreation area, the best known of the seven Pavilion Springs was "Big Tom," which flowed at 150 liters (40 gallons) per minute (National Park Service 2014c). As of 1997, the main fountain in the pavilion was still the main source of water for many local residents, even though samples from the main fountain showed thallium concentrations of 17 micrograms per liter, which was in excess of the EPA drinking water criterion of 2 micrograms per liter (Water Resources Division 1997).

Black Sulphur Springs consists of a group of four sulphur-rich springs (plate 1). The original Black Sulphur Spring, which cannot be found today, was on the old trail that went up the side of the cliff (National Park Service 2014c). These springs were originally known as "Beach Springs" because they bubbled up from the sandy beach along Rock Creek just upstream from its confluence with Travertine Creek. Up until at least 1997, water from the springs collected in a basin, and upon demand, the water was pumped through a chlorinator and piped to a spigot in the Black Sulphur Pavilion (Water Resources Division 1997). The pavilion was built in 1929, and the original neoclassical structure still stands (National Park Service 2014c). Water no longer flows from the fountain in the pavilion because mineralization has plugged the chlorination equipment (Noel Osborn, NPS Chickasaw National Recreation Area, Chief of Resource Management, written communication, 6 August 2014). The water coming directly from the springs is not safe to drink (National Park Service 2014c).

Sulphur, Medicine, and Bromide springs trickle from the base of Bromide Hill about 1.6 km (1 mi) southwest of Pavilion Springs. Medicine and Bromide springs are the main bromide-containing springs and the most mineralized springs in Chickasaw National Recreation Area. Water from both springs was piped across Rock Creek to the Bromide Pavilion (fig. 10). Flow from these springs has always been marginal (Andrews and Burrough 2000). Gould (1906) initially recorded a flow of 4 liters (1 gallon) per minute for Bromide Spring and 2 liters (0.5 gallon) per minute for Medicine Spring. At some time before 1939, the spring water was routed into underground vaults before being piped to the pavilion (Gould and Schoff 1939). National Park Service officials discontinued piping spring water to the pavilion in the 1970s due to low water yields from the springs, periodic detection of fecal coliform bacteria in the water, inundation of the vaults by Rock Creek, perceived liability of providing spring water to the public, costs and labor associated with chlorinating the water, or a combination of these factors (Andrews and Burrough 2000; Noel Osborn, NPS Chickasaw National Recreation Area, Chief of Resource Management, written communication, 6 August 2014).

The loss of Bromide Spring has been considered the greatest resource loss at Chickasaw National Recreation Area (National Park Service 2014c). Bromide Spring was arguably the most popular spring at the turn of the 20th century. Bromide water had the reputation of being able to cure every disease known to mankind, especially stomach diseases (Muncrief 2006). The crowd at the spring with their water jugs would often consist of at least 700 visitors. They would wait in line for hours to get their water. The superintendent of Sulphur Springs Reservation had to hire a watchman because the water from Bromide Spring was stolen at night and sold in area saloons. In December 1907, 8,050 visitors took away 17,730 liters (4,683 gallons) of water. The following month, 7,017 visitors collected 16,010 liters (4,230 gallons) of Bromide water. In 1908, the Oklahoma Legislature requested a daily shipment of water from the park to include 40 liters (10 gallons) of Antelope Spring water, 40 liters (10 gallons) of Sulphur water, and 20 liters (5 gallons) of Bromide water (Muncrief 2006).

In 1907, a springhouse was built over Bromide Spring, and in 1908, a swinging bridge over Rock Creek allowed easier access to Bromide and Medicine springs. This bridge was washed away by a flood in 1916 and was replaced by a steel structure known as "Rainbow Bridge." In 1933, the CCC replaced the springhouse with the Bromide Pavilion (fig. 10). The new pavilion eliminated the need for Rainbow Bridge, which was dismantled in 1942.

In the 1990s, park officials expressed interest in resuming piping mineralized spring water to Bromide Pavilion and in restoring the pavilion as a visitor attraction. A hydrology and water quality study in 2000, however, showed that water flowed into the Bromide Spring vault at a rate of less than 0.40–0.79 liters (0.1–0.21 gallons) per minute and into Medicine Spring vault at a rate of less than 0.04–0.91 liters (0.01–0.24 gallons) per minute, so providing a sufficient amount of potable water would be difficult (Andrews and Burrough 2000). In addition, *Escherichia coli* (*E. coli*), fecal coliform, and fecal streptococcal bacteria were detected in some samples from the springs. Intermittent inundation of the springs by Rock Creek and seepage of surface water into the vaults was also found to pose a threat of contamination. Potential contamination, low flow, and the added physical hazard of an unstable cliff overhanging the vaults made re-establishing spring flow to Bromide Pavilion problematic (Andrews and Burrough 2000). Currently, city water is piped to the Bromide Pavilion (National Park Service 2014c).

Vendome Artesian Well

Vendome Well is an artesian well drilled at the boundary of the freshwater and saline water zones in the confined part of the Arbuckle-Simpson aquifer (Christenson et al. 2009). When drilled in 1922, Vendome Well produced 9,500 liters (2,500 gallons) of water per minute from the aquifer, making it the largest artesian well in Oklahoma (fig. 11; Gould and Schoff 1939; National Park Service 2014d).

Located only a block away from the railroad depot and about 2.4 m (8 ft) outside the main entrance to what was then Platt National Park, Vendome Well soon became the icon of the city of Sulphur, featured on post cards and souvenirs. Vendome Well water was available for drinking and was also channeled into a heated medicinal pool for visitors hoping to cure a variety of ailments. Visitors would also take mud baths

Figure 11. Vendome Well and Flower Park in Chickasaw National Recreation Area. When drilled in 1922, Vendome Well became the largest artesian well in Oklahoma, producing 9,500 liters (2,500 gallons) of water per minute. The water is 99% fresh and 1% brine. Note the drinking fountain that allows visitors to drink from the well. National Park Service photograph, available at http://www.nps.gov/chic/learn/photosmultimedia/photogallery.htm (accessed 15 June 2015).

in the outflow stream from the well (Noel Osborn, NPS Chickasaw National Recreation Area, Chief of Resource Management, written communication, 6 August 2014).

In 1935, the CCC redesigned the channel into an artificial creek that included two wading pools and a waterfall, which emptied into Travertine Creek (National Park Service 2014d). Chickasaw National Recreation Area acquired the well property in 1979, and in 1998, a new Vendome Well with a steel casing to resist corrosion was drilled about 6 m (20 ft) west of the original well. Today, water from the new Vendome Well is piped to the historic enclosure (National Park Service 2014d).

Sodium and chloride are the major ions in the water discharging from Vendome Well (table 1). Water samples in 2009 had a dissolved solids concentration of 1,250 milligrams/liter (mg/l) and a chloride concentration of 558 mg/l (Christenson et al. 2009). These concentrations exceeded the secondary maximum contaminant levels (SMCLs) for dissolved solids (500 mg/l) and chloride (250 mg/l). Because SMCLs are associated with aesthetic considerations (taste, color, and odor) and are not considered a hazard to human health, visitors may safely drink from the well.

The well water has a brine component of about 1%. Samples from the well have the highest concentrations of specific conductance, dissolved solids, potassium, chloride, fluoride, bromide, iodide, ammonia, arsenic, boron, lithium, and strontium of the two deep wells sampled in the 2009 Arbuckle-Simpson aquifer study (table 1; Christenson et al. 2009; National Park Service 2014d). The chloride-to-bromide mass ratio suggests that the brine is a product of evaporated seawater, which suggests an origin quite different from the freshwater recharged wells on the aquifer outcrop to the east (Christenson et al. 2009). Vendome Well water also has the distinct aroma of hydrogen sulfide.

In addition to water chemistry, the age, recharge temperature, and the presence of terrigenic (land-based) helium in Vendome Well water also distinguish it from the aquifer's freshwater. Carbon-14 dating indicates that groundwater flowing from Vendome Well is about 10,500 years old, which is much older than the relatively recent age of the freshwater flowing from springs and wells on the unconfined outcrop portion of the Arbuckle-Simpson aquifer (Christenson et al. 2009, 2011).

Christenson et al. (2009) also measured the concentrations of dissolved argon, neon, and xenon in water samples to determine the temperature of the water when it recharged to the aquifer. Typically, recharge temperatures reflect the air temperature at the time of recharge. The mean annual temperature at Ada, Oklahoma, is 16°C (61°F). Recharge temperatures of most freshwater samples averaged 14.2°C (57.6°F), which suggests that recharge occurred during the cooler months of the year (Christenson et al. 2009). However, recharge temperatures from Vendome Well samples were 6.6°C (44°F), indicating that recharge took place during an earlier, cooler time period.

The presence of abundant helium in Vendome Well water provides further evidence of old age. The helium in the well water represents a terrigenic source rather than atmospheric helium. Terrigenic helium derives from internal production in the aquifer, external input of helium to the aquifer, mixing with water that is enriched in helium (e.g., oilfield brine), or a combination of these. Regardless of how it formed, terrigenic helium suggests that groundwater flowed deep into the aquifer to pick up crustal helium before discharging from the well (Christenson et al. 2009).

Travertine Creek and Travertine Island

Spring water in the Arbuckle-Simpson aquifer is saturated with calcium carbonate ($CaCO_3$) and supersaturated in carbon dioxide (CO_2) with respect to the atmosphere. Carbon dioxide is released to the atmosphere when water discharges from the springs, and calcium carbonate precipitates onto streambed materials to become the porous, freshwater limestone known as travertine (Chafetz and Folk 1984). In addition to Travertine Creek in Chickasaw National Recreation Area, many other spring-fed streams in the region contain travertine deposits, including Turner Falls on Honey Creek, Price Falls at Fall Creek, Blue River, Pennington Creek, and Delaware Creek (Osborn et al. 2006).

The most spectacular travertine deposits in the area occur at Turner Falls, the 23 m (77 ft) high waterfall on Honey Creek, located on the Arbuckle anticline in the western portion of the aquifer (Emig 1971; Love 1985; Utech 1998). Turbulence may be the primary factor contributing to the precipitation of travertine at Turner Falls (Love 1985). Turbulence aerates the water, which promotes the growth of algae and mosses. Algae and mosses provide an absorbent, porous substrate upon which travertine accumulates. Precipitation of travertine builds up waterfalls and increases turbulence, and the cycle continues (Love 1985).

Turbulence, temperature, and the nature of the substrate are three factors that influence the rate of travertine precipitation. Precipitation of travertine increases during the summer months when temperature and photosynthesis increase. In 1985, the average summer rate of precipitation of travertine at waterfalls in Honey Creek was 2 mm/month (0.08 in/month) (Love 1985).

Travertine Creek receives its water primarily from Antelope and Buffalo springs. Travertine Creek flows over 75 natural rock falls and 6 CCC-constructed dams on its 4.0 km (2.5 mi) course from Travertine Nature Center to Pavilion Springs (fig. 12). The water in the creek averages 18°C (65°F) year round. Travertine Island, within Travertine Creek, is one of the more exceptional geologic features in Chickasaw National Recreation Area. Reached by the Travertine Creek Trail, the island contains impressive deposits of travertine (fig. 13). In 1934, the CCC used native blocks of Vanoss Formation to build a long, slab rock picnic table and

Figure 12. Travertine Creek flows over Little Niagara Falls, located in the northeastern portion of the Platt Historic District of Chickasaw National Recreation Area. National Park Service photograph, available at http://www.nps.gov/cultural_landscapes/snp/850145.html (accessed 1 May 2014).

Figure 13. Travertine cliffs on Travertine Island. Travertine forms the foundation of Travertine Island. Note the vugs (holes) and small caves that have formed due to dissolution of the limestone. Photograph by the author.

rock benches on the island (fig. 14). Travertine deposits were identified as a geologic resource for assessment via the Natural Resource Condition Assessment (see "Geologic Resource Management Issues" chapter; Noel Osborn, Chickasaw National Recreation Area, Chief of Resource Management, email, 8 June 2015).

Figure 14. Picnic table on Travertine Island. The table was built by the Civilian Conservation Corps in the 1930s using blocks of the Vanoss Formation conglomerate. Photograph by the author.

Paleontological Resources

Paleontological resources (fossils) are any evidence of life preserved in a geologic context (Santucci et al. 2009). All fossils are non-renewable. Body fossils are any remains of the actual organism such as bones, teeth, shells, or leaves. Trace fossils are evidence of biological activity; examples include burrows, tracks, or coprolites (fossil dung). Fossils in NPS areas occur in rocks or unconsolidated deposits, museum collections, and cultural contexts such as building stones or archeological resources. As of July 2015, 260 parks, including Chickasaw National Recreation Area had documented paleontological resources in at least one of these contexts. The NPS Geologic Resources Division Paleontology website provides more information (National Park Service 2014e). While this report was in production, an updated paleontological resource summary was published as Tweet et al. (2015). Recreation area staff should consult that report for updated paleontological resource information.

Most of the fossils found in Chickasaw National Recreation Area come from Ordovician and Devonian strata (table 2; Koch and Santucci 2003; Blome et al. 2013). These fossils include brachiopods, echinoderms, trilobites, pelecypods, bryozoans, graptolites, and ostracodes (fig. 15). Fossils provide information regarding the depositional environment, age, water depth, submarine structure, and shoreline geometry at a time when present-day Oklahoma was covered by an extensive inland sea. For example, Ordovician trilobites from the Viola Group (**Ov**) were restricted

Table 2. Fossils documented in Chickasaw National Recreation Area.

Age	Rock Unit (map symbol)	Invertebrate Fossils
Upper Mississippian–Lower Pennsylvanian	Springer Formation (PNMs)	brachiopods, bryozoans, bivalves
Middle Pennsylvanian	Deese Group (PNd)	crinoids, endothyrids, brachiopods, mollusks
Lower Mississippian	Caney Shale (Mc)	Conodonts, pelecypods, gastropods, ostracodes, goniatites, cephalopods
Lower Devonian	Upper part Hunton Group (DSOh, Dhu)	Haragan Formation: brachiopods, trilobites, corals, gastropods, bivalves, sponges, anthozoans, straight cephalopods (*Rhinoceras* sp.), goniatites (ammonites), crinoids
Silurian; Upper Ordovician	Lower part Hunton Group (SOhl)	anthozoans, conodonts, crinoids, brachiopods, gastropods, crustaceans, foraminifers, ostracodes
Upper Ordovician	Sylvan Shale (Os)	graptolites, chitinozoans
Upper Ordovician	Viola Group (Ov)	trilobites (*Crytolithus trilos*, *Isotelus*), graptolites
Middle Ordovician	Bromide Formation (Simpson Group) (Obm)	brachiopods, trilobites, bryozoans, graptolites, pelecypods, ostracodes, echinoderms

Fossil lists from Koch and Santucci (2003) and Blome et al. (2013). See updated information in Tweet et al. (2015).

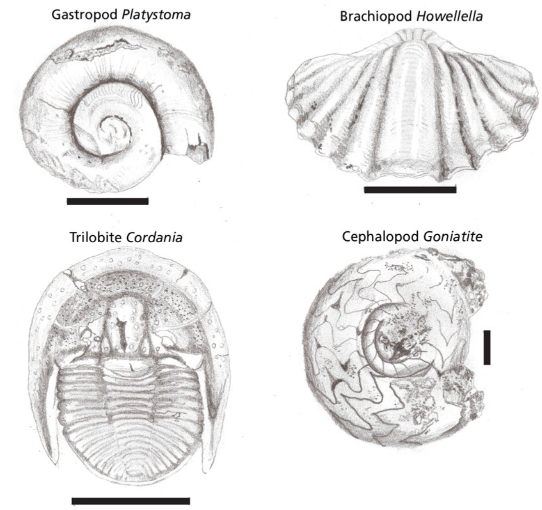

Figure 15. Common Paleozoic marine invertebrate fossils found in Oklahoma. The black bar is 1 cm (0.4 in) long. Sketches by Trista Thornberry-Ehrlich (Colorado State University) after specimens from the Sam Noble Museum (2015), available at: http://commonfossilsofoklahoma.snomnh.ou.edu/ (accessed 24 April 2014).

to relatively cool marine water on continental shelves that were approximately 30 m (100 ft) deep (Shaw 1991). Mixing of two previously distinct genera in Oklahoma suggest that sea level rose, causing a marine transgression and the elimination of the biogeographic boundary separating the two genera. Reefs constructed from Ordovician bryozoans have been discovered just south of the recreation area and southeast of the city of Sulphur (Cuffey and Cuffey 1994).

Fossils from the Bromide Formation (**Obm**) have been well-studied. In addition to the discovery of bryozoan reefs, researchers have discovered new genera and species of ostracod; documented eight different species of the bivalve genus *Conocardium*; discovered a new genera of tubular bryozoan; and reported on many trilobite genera, including *Calliops*, *Dolichoharpesi*, *Encrinuroides*, *Homotelus*, *Lonchodomas*, and *Pandaspinapyga* (Sutherland and Amsden 1959; Levinson 1961; Esker 1964; Frederickson 1964; Branson 1966; Farmer 1975; Cuffey and Cuffey 1994).

Deep-marine fauna are found in the Upper Ordovician Sylvan Shale (**Os**) and Viola Group (**Ov**). Shale beds in both units contain graptolites, an extinct group of organisms that flourished in the Ordovician Period, and the Viola Group contains the deep-water trilobite *Crytolithus trilos* (Koch and Santucci 2003; Blome et al. 2013).

The upper part of the Hunton Group (**Dhu**) consists of two formations: (1) the Haragan Formation, which is very fossiliferous and crops out in the Goddard Youth Camp, and (2) the Bois d'Arc Formation, which is not exposed in Chickasaw National Recreation Area (Blome et al. 2013). The thin-bedded argillaceous limestone and mudstone of the Haragan Formation have produced numerous trilobites, brachiopods, corals, gastropods, and bivalves. A new trilobite species has been described from the Haragan Formation, and graptolites have been found at a site near Dougherty, Oklahoma (Koch and Santucci 2003). In addition to the invertebrate fossils listed in table 2, shark teeth and gastroliths (stomach stones) have also been recovered from Devonian strata.

See "Paleontological Resource Inventory, Monitoring, and Protection" section and Tweet et al. (2015) for information on managing the paleontological resources of the recreation area.

A variety of marine invertebrates are found in the Lower Mississippian Caney Shale, which is mapped south of the Reagan Fault in the southeastern part of the recreation area. The fauna reflect the advance of open-marine environments into the region during a continent-wide marine transgression (rise of sea level).

Although not found in Chickasaw National Recreation Area, fossil logs of the Late Devonian plant, *Archaeopteris*, have been discovered in the Upper Devonian-Lower Mississippian Woodford Shale (**MDsw**) of southern Oklahoma (Cardott 2001). Archaeopteris grew more than 20 m (66 ft) tall with trunks measuring several feet in diameter (Sam Noble Museum 2015). Because there are no Devonian terrestrial sedimentary rocks in Oklahoma, the source of these logs that floated out to sea to be petrified in the anoxic black marine shale of the Woodford Shale has not been identified.

Basins in southern Oklahoma subsided in the Late Mississippian and Early Pennsylvanian Periods (Johnson 2008). Fauna in the Upper Mississippian-Lower Pennsylvanian Springer Formation (**PNMs**) lived in open marine environments that existed in the subsiding basins, which began receiving sediments eroded from emerging highlands.

The Middle Pennsylvanian Deese Group crops out along the northern shore of Lake of the Arbuckles in southeastern Chickasaw National Recreation Area. Fossiliferous gray to white limestone beds in the unit contain crinoids, endothyrids, brachiopods, and mollusks. These invertebrates lived in a marine environment which occurred in the structural basin that formed between the Tishomingo and Hunton anticlines (Blome et al. 2013).

Sedimentary Features in the Vanoss Formation

The Pennsylvanian Vanoss Formation is the most extensive rock unit in Chickasaw National Recreation Area. Features in the Vanoss conglomerate (**PNvc**) and overlying Vanoss shale (**PNvs**) provide evidence of Late Paleozoic tectonics, as well as the regional depositional environments. Exceptional exposures of the Vanoss Formation occur along Travertine Creek and near Rock Creek Campground (fig. 16).

Figure 16. The Vanoss conglomerate facies in Chickasaw National Recreation Area. The upper photo illustrates the outcrop pattern of the unit with ledges of sandstone and conglomerate and slopes of shale. Physical weathering may cause blocks of conglomerate to break away and cascade down the slope. The lower photo illustrates the size and roundness of the clasts in the conglomerate. Pencil is 14 cm (5.5 in) long for scale. The roadcut is opposite the turn into the Rock Creek Campground. Photographs by the author.

In general, coarse-grained conglomerate is the dominant rock in the Vanoss Formation. The Vanoss conglomerate consists of rock sequences that begin with conglomerates and transition upward into beds (layers) of finer-grained sandstones and siltstones (Donovan and Butaud 1993). These upward-fining sequences reflect a cyclic decrease in stream energy (table 3). When energy was high, the stream was able to transport and deposit the coarser-grained pebbles,

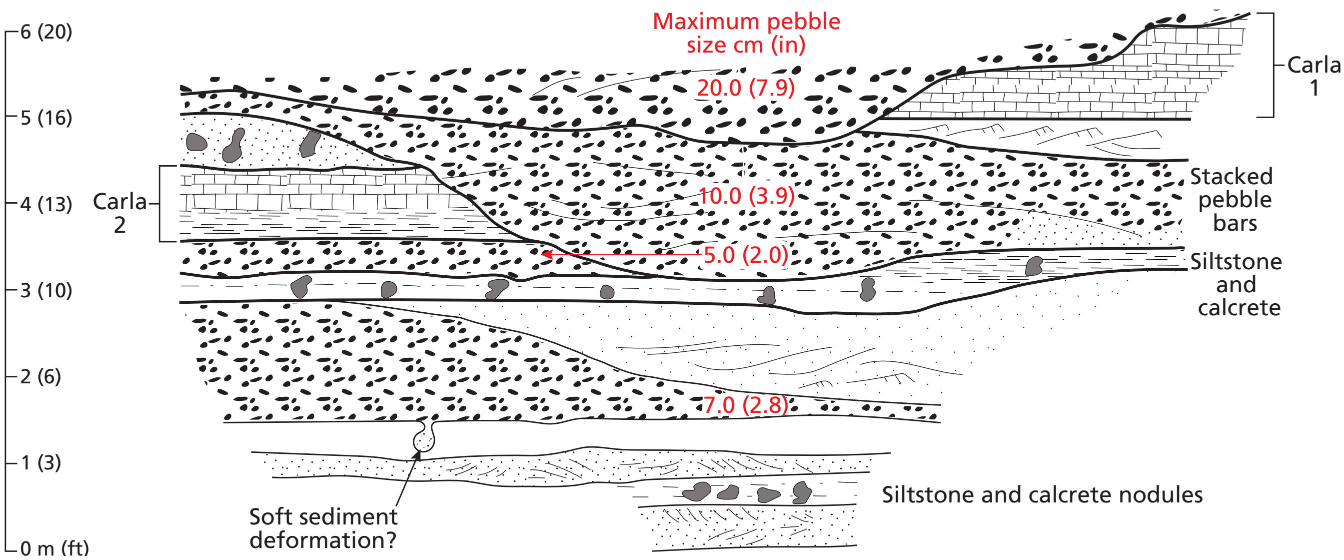

Figure 17. Sketch of the Vanoss Formation near the top of Bromide Hill. The vertical scale is exaggerated approximately three times. The cross-section illustrates the complex relationship between rock type and process. The "Carla" is a lacustrine limestone. The "stacked pebble bars" unit is younger than the limestone, siltstone, and calcrete into which it has incised. Diagram redrafted by Trista Thornberry-Ehrlich (Colorado State University) after Donovan and Butaud (1993, figure 10).

cobbles, and boulders resulting in the conglomerate; when energy was low, primarily finer-grained sand and silt particles were deposited resulting in the sandstone and siltstone.

Individual conglomerate beds in the Vanoss Formation range from 3 cm (1 in) to 3 m (10 ft) thick (Donovan and Butaud 1993). Clasts (individual grains or fragments of rock) in the conglomerate are well-rounded, which is a feature characteristic of fluvial processes (fig. 16). Originally, clasts weathered out of strata have sharp, angular edges. As they rolled and tumbled along a stream bed, the edges became rounded.

Sandstone beds composed of fine-grained quartz are thinner, ranging from 1 cm (0.4 in) to 1 m (3 ft) thick, and are interbedded with siltstone, shale, and thin limestone beds (fig. 17). Features in the sandstones include parallel laminations, small-scale trough cross-bedding, symmetrical ripple marks, and erosive bases above limestone beds (table 3; Donovan and Heilen 1988; Donovan and Butaud 1993).

The Vanoss Formation represents deposition in an alluvial-fan system (Ham 1973; Donovan and Heilen 1988; Donovan and Butaud 1993). Alluvial fans commonly form when stream gradients abruptly decreases. For example, when a stream flows from the mouth of a steep canyon and onto a relatively flat valley floor, its channel velocity decreases, as does its capacity to transport boulders, cobbles, and other coarse sediment. At this point the coarse material is deposited, filling the stream channel and causing it to migrate laterally. As the stream migrates back-and-forth, it eventually forms the typical fan-shaped feature known as an alluvial fan. The conglomerate unit in the

Table 3. Stratigraphic features and depositional processes in the Vanoss Formation

Stratigraphic Feature	Associated Process
Upward-fining (coarse- to fine-grained) cycles	Decrease in stream velocity
Parallel laminations	High energy, consistent stream flow
Trough cross-bedding	Channel filling
Symmetrical ripple marks	Lower energy, bi-directional flow (e.g., lake shoreline)
Mudstone (shale)	Low energy environment
Limestone	Carbonate sedimentation
Fenestrae (holes)	Escape of gas from partly lithified sediment
Mud cracks	Desiccation of sediment
Rip-up clasts	High energy flow
Varves	Seasonal or cyclic deposition
Nodular limestone	Ancient soil development (calcrete)

Vanoss Formation (**PNvc**) was deposited near the mouth of a canyon where the gradient of the stream abruptly decreased and the alluvial fan formed.

Conglomerate beds in the Vanoss Formation that contain mostly pebbles may represent periods of sheet-like flooding across the alluvial fan. These sheet floods may have also been responsible for the sandstone beds in Chickasaw National Recreation Area, especially those exposed at Bromide Hill. The sandstones are laterally persistent, and the parallel laminations suggest a high-energy flow regime common to flooding. The absence of coarser sediment suggests that the sand-sized sediment was deposited farther out on the alluvial fan than the conglomerates. The siltstone and shale beds also suggest deposition on the distal (far) end of an alluvial fan where silt and clay filled abandoned channels on the fan surface (Donovan and Butaud 1993).

The thinly-bedded sandstone and limestone beds near the top of Bromide Hill suggest a low-energy lacustrine depositional environment. Symmetrical ripple marks in the fine-grained sandstone formed from the bi-directional influence of waves on a shoreline. During storms, partly lithified sandstone was ripped up and re-deposited to form the rip-up clasts found in the sandstone beds. As lake levels rose, algal photosynthesis led to carbonate precipitation, and as lake levels fell and the limestone dried, mud cracks formed. Escaping gas from decaying algae created fenestrae (holes) in the limestone. Carbon- and oxygen-isotope data indicate that the limestone formed in a freshwater environment (Donovan and Butaud 1993).

Varves (genetically related paired sedimentary layers) in the thinly-bedded limestone may record annual cyclic deposition. These sedimentary couplets are commonly deposited in still water. If this is the case, the number of varves suggests that the lake system at the top of the Vanoss Formation existed for approximately 1,000 years (Donovan and Heinlen 1988; Donovan and Butaud 1993).

Limestone nodules in the upper part of the Vanoss shale suggest near-surface formation of calcrete (Donovan and Butaud 1993). Modern calcretes form as a result of the accumulation of calcite in soil horizons, usually under evaporative, semi-arid conditions. Calcretes in the Vanoss Formation have similar paleogeographic and paleoclimatic implications. They record the increased aridity on the midcontinent as the Pennsylvanian transitioned into the Permian Period.

These sedimentary features offer clues to the evolving Pennsylvanian landscape of south-central Oklahoma. Alluvial-fan environments developed at the base of the newly-formed Arbuckle Mountains. Braided streams emerging from the mountains deposited 3–4 m (3–13 ft) thick cycles of conglomerates and sandstones. As stream discharge decreased and channels migrated across the alluvial fans, finer-grained silts and clays capped the coarser-grained deposits. Calcrete soil horizons attest to semi-arid conditions in the region, although the presence of lake deposits suggests that higher water tables may have occurred from time to time (Donovan and Butaud 1993).

In addition, the contact between the Vanoss Formation and the underlying strata provide critical evidence for the timing of the Arbuckle Orogeny, a major mountain-building episode in the Pennsylvanian Period (fig. 5). The Arbuckle Orogeny (the term 'orogeny' means 'mountain-building event') deformed the older strata beneath the Vanoss Formation, tilting the beds at high angles to the topographic surface. In contrast, the Vanoss Formation strata are relatively undeformed (Ham and McKinley 1954; Ham 1973; Blome et al. 2013). Post-Pennsylvanian regional uplift tilted the Vanoss Formation, but the beds dip less steeply than the older strata. This type of contact where the dip angles of the overlying and underlying beds are in contrast to one another is known as an "angular unconformity." The angular unconformity at the base of the Vanoss Formation indicates that the Arbuckle Orogeny had ended by the Late Pennsylvanian Period (Blome et al. 2013). The strike and dip angles included in the GRI GIS data illustrate the different orientations of the rock layers, which resulted primarily from deformation caused by the Arbuckle Orogeny.

Folds and Faults

During an orogeny, rock layers are typically folded and faulted. The two common types of fold are anticlines, which are convex A-shaped folds, and synclines, concave U-shaped folds, and both are mapped within the GRI GIS data for Chickasaw National Recreation Area (plate 2). Both types of folds can be overturned—tilted past vertical—by continued or future tectonic forces. Folds frequently "plunge" meaning the fold axis tilts. A fault is a fracture along which rocks have moved.

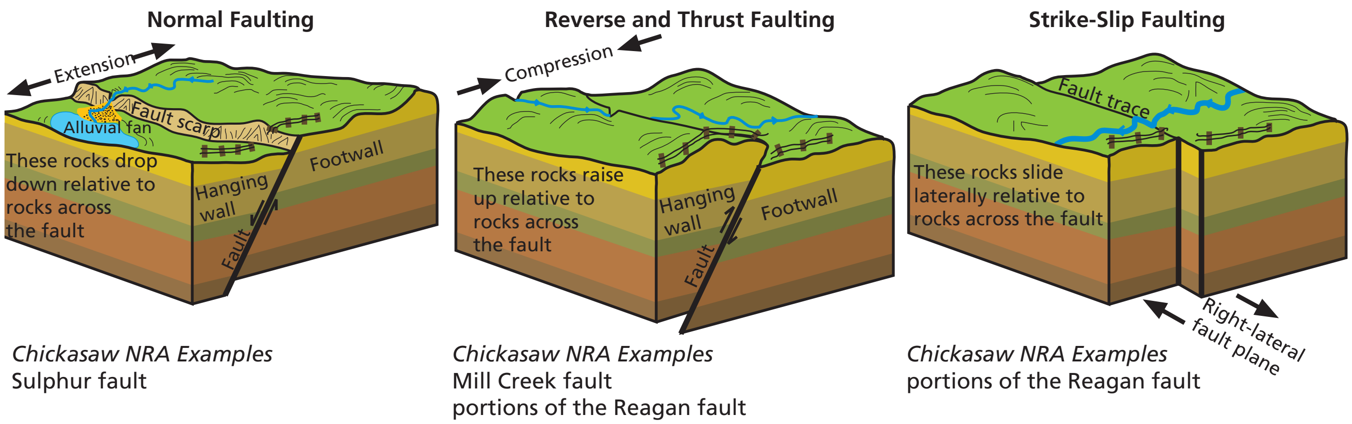

Figure 18. Schematic illustrations of three general fault types. In a fault, movement occurs along a fault plane. "Footwalls" are below the fault plane and "hanging walls" are above it. In a normal fault, crustal extension (pulling apart) moves the hanging wall down relative to the footwall. In a reverse 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 degrees. In a strike-slip fault, the relative direction of movement of the opposing plate is lateral. When movement across the fault is to the right, it is a right-lateral (dextral) fault, as illustrated above. When movement is to the left, it is a left-lateral (sinistral) fault. All three types are present in the Arbuckle Mountains; the Sulphur fault is a normal fault, Mill Creek fault is a reverse fault and movement along the Reagan fault incorporates both reverse and strike-slip motion. Graphic by Trista Thornberry-Ehrlich (Colorado State University).

The three primary types of faults are normal faults, reverse faults, and strike-slip faults (fig. 18). All three are mapped within the recreation area (Blome et al. 2013).

During the Pennsylvanian Period, the strata of southern Oklahoma were compressed, folded, faulted, and uplifted as a result of the Wichita and Arbuckle orogenies (fig. 5). In general, strata were folded into regional, northwest–southeast oriented anticlines and synclines separated by high-angle normal, reverse, and strike-slip faults (fig. 18; Christenson et al. 2011; Blome et al. 2013).

These structural features are mapped primarily in the Paleozoic rocks to the east and along the southern border of Chickasaw National Recreation Area (fig. 19). From northeast-to-southwest, the folds include the broad Hunton anticline, Sulphur syncline, Belton anticline, Mill Creek syncline, Tishomingo anticline, and the Dougherty anticline (table 4; Christenson et al. 2011; Blome et al. 2013). The faults listed in table 4 separate these folds. In some cases, such as the Mill Creek syncline and the Belton anticline, the folds appear to be part of extensive fault blocks rather than individual folds and faults (Blome et al. 2013). Some of these structural features extend into the subsurface beneath the Vanoss Group in Chickasaw National Recreation Area (Scheirer and Scheirer 2006).

Table 4. Folds and faults in the Chickasaw National Recreation Area vicinity.

List of Folds	List of Faults (fault type)
Hunton anticline	Sulphur (normal)
Sulphur syncline	South Sulphur (normal)
Belton anticline	Mill Creek (reverse/thrust)
Mill Creek syncline	Reagan (thrust, strike-slip)
Tishomingo anticline	
Dougherty anticline	

Folds and faults are listed from north to south. Locations are indicated on figure 19 and the geologic map poster (in pocket). See plate 2 for cross-section illustration of these features.

The broad Hunton anticline formed during the Wichita Orogeny and was further deformed during the younger, more intense Arbuckle Orogeny (Cardott and Chaplin 1993; Allen 2000; Blome et al. 2013). Strata of the Arbuckle and Simpson groups are exposed in the core of the anticline. The Clarita and Franks fault zones cut the Hunton anticline on the east and northeast, and the Sulphur fault zone truncates the southern flank of the anticline (Christenson et al. 2011).

The Sulphur syncline is between the steeply-dipping Sulphur fault and the South Sulphur fault and contains primarily Simpson Group strata (plate 2). Subsurface gravity data suggest that the Sulphur syncline does

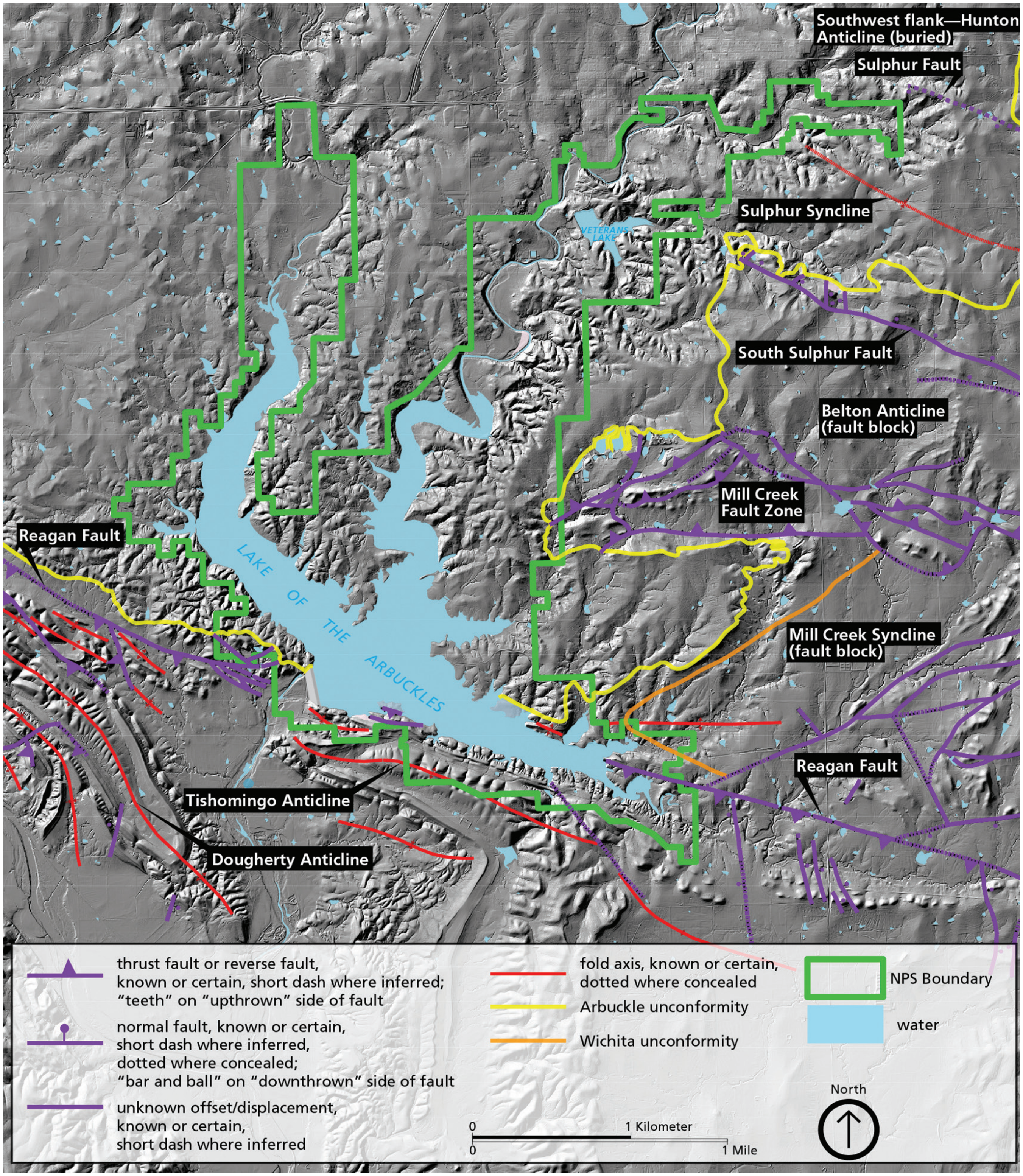

Figure 19. Map showing the structural features and related Pennsylvanian angular unconformities in and near Chickasaw National Recreation Area. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Blome et al. (2013, figure 6), using GRI GIS data.

Figure 20. Tishomingo anticline. The beds of the Hunton Group (DSOh) dip gently on either side of the crest of the anticline. View is to the east-southeast. Photograph is from Blome et al. (2013).

not extend beneath Chickasaw National Recreation Area (Scheirer and Scheirer 2006). The Sulphur fault bends to the southwest and terminates into the South Sulphur fault about 2 km (1.2 mi) east of Chickasaw National Recreation Area (Scheirer and Scheirer 2006; Christenson et al. 2011; Blome et al. 2013).

The Belton anticline is bracketed by the South Sulphur fault and the Mill Creek fault zone, a series of thrust faults that form the northern border of the Mill Creek syncline (plate 2; Christenson et al. 2011; Blome et al. 2013). The anticline appears to be an up-thrown fault block rather than a simple fold, and because of this structural complexity, it is not possible to define a fold axis (Blome et al. 2013).

The narrow Mill Creek syncline consists of more than 2,400 m (8,000 ft) of folded and faulted Paleozoic strata (plate 2; Blome et al. 2013). The syncline is a graben (down-thrown fault block), but unlike typical grabens that are bounded by normal faults, the Mill Creek syncline is bounded by reverse and thrust (low-angle reverse) faults and contains a series of anticlines and synclines. The fault block is also a remnant of a Pennsylvanian basin that formed between the Tishomingo and Hunton uplifts during the Wichita Orogeny (Cardott and Chaplin 1993; Blome et al. 2013). Sediments eroded from these uplifts became the Deese Group (**PNd**).

During the Arbuckle Orogeny, the Deese Group, along with older strata, was folded and faulted, and the entire basin was displaced as a single fault block. In some exposures east of Chickasaw National Recreation Area, the Mill Creek fault zone juxtaposes Ordovician Arbuckle strata (**Owk** and **Ow**) of the Belton Anticline against Pennsylvanian Deese Group (**PNd**) in the Mill Creek syncline, a displacement of approximately 1,500 m (5,000 ft) (Ham 1945; Christenson et al. 2011; Blome et al. 2013).

Two significant unconformities in the Mill Creek Syncline put time constraints on each orogeny. The Wichita unconformity separates the Middle Pennsylvanian (Desmoinesian stage, about 309 million to 305 million years old) Deese Group (**PNd**) from more steeply dipping older rocks. The older strata had been folded and tilted to the southwest during the Wichita Orogeny. After the Deese Group was deposited, the strata were intensely deformed during the Arbuckle Orogeny. The Arbuckle unconformity separates deformed Deese Group (**PNd**) and older rock units from the overlying and relatively undeformed conglomerate facies of the Vanoss Group (**PNvc**), and it marks the end of the Arbuckle Orogeny (plate 2; Blome et al. 2013).

The Reagan fault, which contains both reverse and thrust (low-angle reverse) faults and strike-slip movement, separates the Mill Creek syncline from the Tishomingo and Dougherty anticlines (fig. 19). In contrast to the Mill Creek syncline and Belton anticline, the Tishomingo and Dougherty anticlines are relatively simple folds so their fold axes can be shown on a geologic map (fig. 19; poster [in pocket]; Blome et al. 2013). The oldest rocks of the Tishomingo anticline in the recreation area are along its axis, and belong to the Ordovician Viola Group (**Ov**). Farther to the southeast, the anticline is cored by the entire sequence of Arbuckle Group units and Middle Proterozoic granitic rocks (Ham and McKinley 1954; Johnson 1990; Blome et al. 2013). Near Mill Creek, southeast of the recreation area, stratigraphic displacement along the Reagan fault is at least 2,300 m (7,500 ft) (Christenson et al. 2011).

Part of the relatively tightly-folded Tishomingo anticline forms the southern border of Chickasaw National Recreation Area (Blome et al. 2013). The fold of the Tishomingo anticline is exposed in an abandoned quarry just south of the recreation area boundary (fig. 20). Algal laminations, snail fragments, and small brachiopod shells are exposed on bedding surfaces of the folded carbonate strata in this quarry.

Smaller faults and folds throughout the region terminate into these major northwest–southeast oriented faults. The smaller faults have more diverse orientations, smaller displacements, and shorter lengths (Scheirer and Scheirer 2006; Christenson et al. 2011; Blome et al. 2013). The major and minor faults and fractures contribute significantly to the permeability of the Arbuckle-Simpson aquifer (Blome et al. 2013). In contrast, the relative lack of faults and fractures in the overlying Vanoss Formation contributes to its ability to seal the underlying Arbuckle-Simpson aquifer beneath Chickasaw National Recreation Area.

Cave and Karst Features

Karst is a landscape that forms through the dissolution of soluble rock, most commonly carbonates such as limestone or dolomite (Toomey 2009). Caves, sinkholes, streams whose channels lie above the water table ("losing streams"), springs, and internal drainage are characteristic features of karst landscapes. As of February 2015, cave or karst resources are documented in 153 NPS parks including Chickasaw National Recreation Area. The NPS Geologic Resources Division Cave and Karst Resources website provides more information (National Park Service 2014f).

Chickasaw National Recreation Area contains 9% karst (Land et al. 2013; Weary and Doctor 2014). However the Arbuckle-Simpson Aquifer is a massive karst feature more than 80 km (50 mi) across that is mapped east, south, and west of the recreation area (fig. 8). The eastern Arbuckle-Simpson aquifer is of particular importance to the recreation area as flow from the aquifer supplies the springs of Chickasaw National Recreation Area (Christenson et al. 2011). The Eastern portion of the aquifer encompasses four surface watersheds and seven subsurface watersheds (fig. 21). Those watersheds are primarily outside the recreation area. Therefore development or contamination (e.g., oil or other hazardous material spills) in the Rock Creek surface and subsurface watersheds (Dale Pate, NPS Geologic Resources Division, Cave and Karst Program Lead, email, 15 June 2015; see "Water Quality" section). Note that the Rock Creek subsurface watershed extends east of Rock Creek and underlies Mill Creek north of Travertine Creek (fig. 21).

Weathering of the carbonates in the Arbuckle Group (**Owk** and **Ow**) produced features indicative of karst development, such as dissolution cavities in limestone, collapse breccias, dissolution-enlarged fractures, and vuggy porosity (Christenson et al. 2011). Fracturing and brecciation create additional voids in the rock, increasing the natural permeability in the Arbuckle Group.

Because the Arbuckle-Simpson limestones are buried under the Vanoss Formation and other post-Simpson formations, Chickasaw National Recreation Area does not contain any documented caves or sinkholes, and no significant caves (Noel Osborn, NPS Chickasaw National Recreation Area, Chief of Resource Management, written communication, 13 August 2014). Most of the caves and sinkholes occur where the Arbuckle-Simpson aquifer is mapped on the surface to the west and south of the recreation area on the Arbuckle and Tishomingo anticlines.

Small dissolution caves have formed in the travertine that lines the banks of Travertine Island (fig. 13), and small caves associated with fractures in the Vanoss conglomerate (**PNvc**) have formed in the cliff at Bromide Hill.

The poorly-understood, circular hills that occur as distinct knobs just outside the borders of Chickasaw National Recreation Area and in other parts of the Arbuckle Mountains have been interpreted as collapse

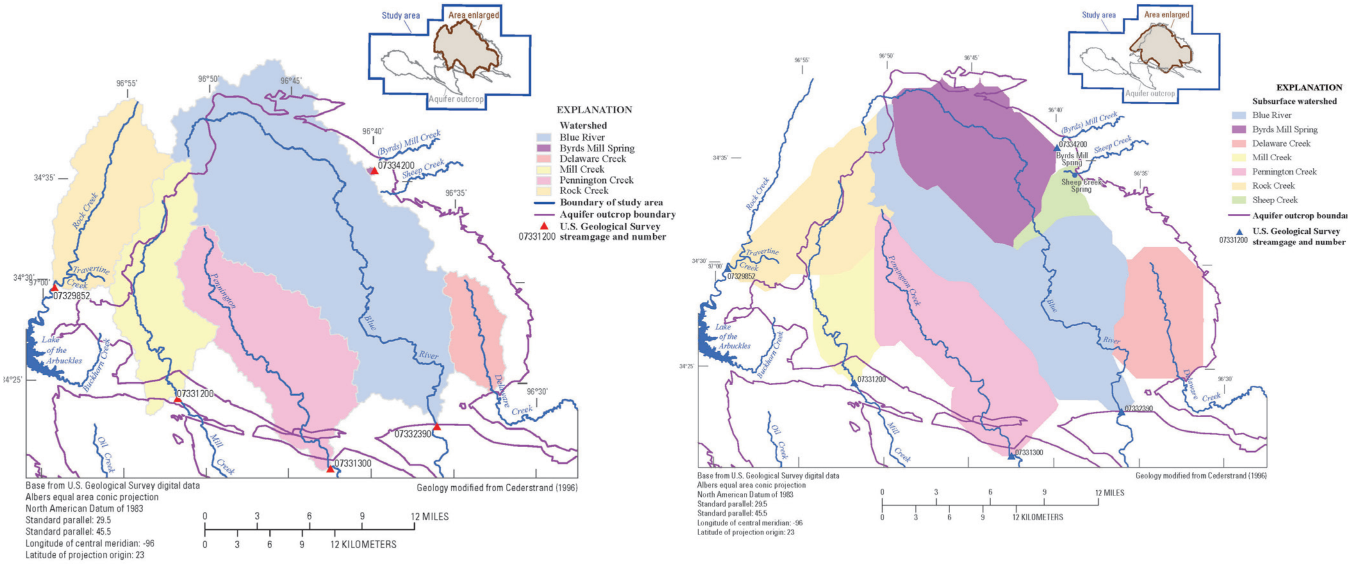

Figure 21. Maps of surface (left) and subsurface watersheds (right) of the Arbuckle-Simpson aquifer. The national recreation area is at the far left of the maps (Lake of the Arbuckles). US Geological Survey maps extracted from Christenson et al. (2011, figures 21 and 22).

Figure 22. Circular hill east of Chickasaw National Recreation Area. These hills may represent ancient karst topography. US Geological Survey photograph from Blome et al. (2013, figure 7).

features associated with ancient karst topography (fig. 22; see map poster [in pocket]; Blome et al. 2013). The knobs range from about 60–250 m (200–800 ft) in diameter and from 15–75 m (50–250 ft) high. They are composed of undifferentiated Sylvan Shale and Viola Group units (**Osv**) or undifferentiated Bromide, Tulip Creek, and McLish formations (**Obm**). The beds of these units are chaotic and deformed, but generally dip inward toward the center of the knobs (Lidke and Blome 2010; Blome et al. 2013).

The knobs were originally interpreted as structural, deformation features rather than dissolution features. They were interpreted as “klippen,” which are isolated erosional, hanging-wall remnants of a large thrust sheet (Ham and McKinley 1954). The circular shape and inward dip of the strata, however, suggest that the knobs initially formed as large sinkholes in a Paleozoic carbonate landscape (Lidke and Blome 2010; Blome et al. 2013). Post-collapse fluids altered and cemented the strata that had collapsed into the sinkhole, making the collapsed strata more resistant to erosion than the surrounding units. Over time, erosion stripped away the less-resistant rock, inverting the topography so that the sinkholes became the circular-shaped knobs on the current landscape (fig. 22; Lidke and Blome 2010; Blome et al. 2013).

Rock Creek Drainage Basin

Chickasaw National Recreation Area is in that part of the Rock Creek drainage basin that includes Travertine Creek and drains a surface watershed of approximately 114 km^2 (44.1 mi^2). Wilson Creek flows into Veterans Lake while Rock, Buckhorn, and Guy Sandy creeks flow into Lake of the Arbuckles (plate 1).

Runoff from higher elevations north and east of Chickasaw National Recreation Area and groundwater flow from springs combined to form Rock Creek. The creek cut a V-shaped valley into the dense, erosion-resistant Vanoss Formation (**Pnvs** and **Pnvc**). The layers of sandstone and shale in the Vanoss Formation are less resistant to erosion than the conglomerate layers, so they erode at a faster rate. When Rock Creek encountered these less-resistant layers, it eroded laterally rather than vertically through the harder Vanoss conglomerate, and the valley widened in a southward direction (National Park Service 2014g).

Rock Creek, and to a lesser extent Guy Sandy Creek, develop and modify fluvial features, such as point bars and cut banks, as they meander through Chickasaw National Recreation Area (Blome et al. 2013). Meandering rivers tend to erode laterally, rather than vertically, as their thalwegs (the deepest part of a stream's current) migrate from bank to bank. Cutbanks form on the outside of a meander loop where Rock Creek cuts into rock units or unconsolidated sediments. Eroded sediment is deposited down-stream to form a point bar on the inside of a meander loop where the channel's energy decreases (fig. 24 [next page]).

The Arbuckle Dam blocked the flow of Rock Creek, and as a result, the creek's gradient and sinuosity changed. Although the dam was completed in 1966, Rock Creek continues to adjust to changes in slope, groundwater discharge, and surface flow.

Bromide Hill

Erosion and weathering processes have gradually changed the landscape of Chickasaw National Recreation Area since the Arbuckle Orogeny. Bromide Hill, the steep vertical cliff that rises 43 m (140 ft) above Rock Creek, is the most recognizable topographic feature in Chickasaw National Recreation Area (fig. 23). The cliff is composed of Vanoss conglomerate (**PNvc**). The summit offers panoramic views of the Arbuckle Mountains and the Washita River valley to the southwest. Blocks of Vanoss Formation that fall from the cliff are a potential hazard in Chickasaw National Recreation Area (see "Geologic Resource Management Issues" chapter). Vanoss Formation exposure was identified as a geologic resource for assessment via the Natural Resource Condition Assessment (see "Geologic Resource Management Issues" chapter; Noel Osborn, Chickasaw National Recreation Area, Chief of Resource Management, email, 8 June 2015).

Figure 23. Bromide Hill. Left photo is a view towards Sulphur, Oklahoma (note the water tower in the distance). Right photograph is the Vanoss Formation conglomerate facies (PNvc) that caps the cliff. Pencil is 14 cm (5.5 in) for scale. Photographs by the author.

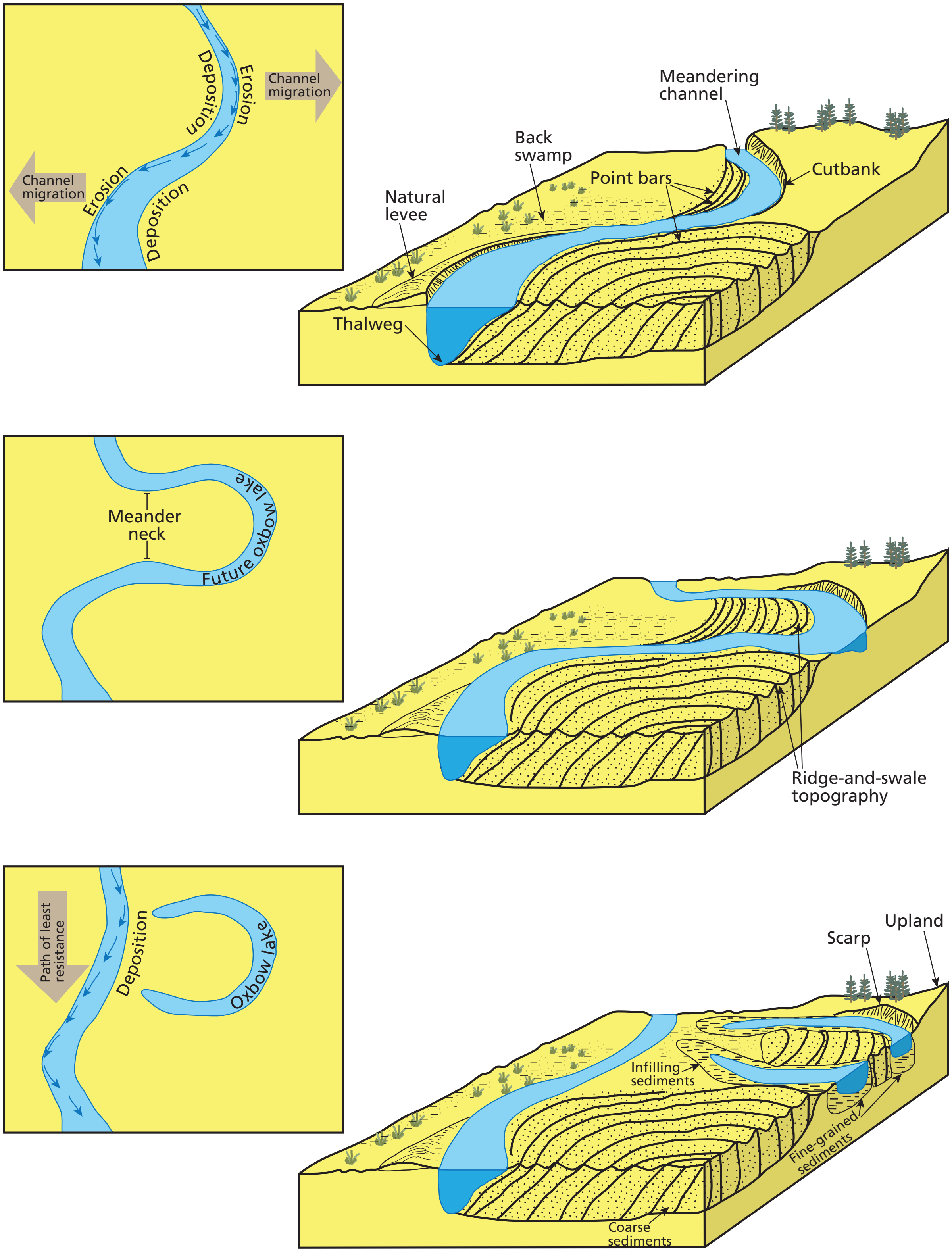

Figure 24. Schematic of the features common to a meandering river. Point bars are areas of deposition. Lateral erosion takes place at cutbanks. The thalweg is the path of greatest current velocity, represented by blue arrows within the stream. When a meander neck is cut off, an oxbow lake forms. Time progression is from upper graphic to lower graphic. Graphic by Trista Thornberry-Ehrlich (Colorado State University).

Geologic Resource Management Issues

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

Participants at the 2007 scoping meeting (see Graham 2008) identified the following two primary resource management issues affecting Chickasaw National Recreation Area:

- The Need for a Geologic Map of the Recreation Area
- Groundwater Use and Spring Discharge Monitoring

Since the meeting, a geologic map of the area has been completed (Blome et al. 2013) and was used as the GRI GIS source map. Chickasaw National Recreation Area has also developed a systematic monitoring program to address spring discharge. A follow-up conference call in 2014 identified the following additional issues:

- Water Quality
  - Sewage
  - Natural Asphalt Deposits
- Flooding and Debris Flows
- Rockfall
- Lakeshore Erosion
- Paleontological Resource Inventory, Monitoring, and Protection
- External Mineral Exploration and Development
  - Hydrocarbon Exploration and Induced Seismicity
  - Aggregate Quarries
- Abandoned Mineral Lands

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

Park staff are currently (July 2015) working on a Natural Resource Condition Assessment for Chickasaw National Recreation Area. Such assessments provide park managers an assessment and report on current conditions, critical data gaps, and selected condition influences for a subset of their park's important natural resources. A draft of that assessment incudes five geologic indicators, travertine deposits, Vanoss Formation exposure, paleontological resources, seismic risk, and disturbed lands (abandoned mineral lands). Hydrogeology of the springs will be covered in a separate portion of the report (Noel Osborn, Chickasaw National Recreation Area, Chief of Resource Management, email, 8 June 2015).

Groundwater Use and Spring Discharge Monitoring

From 1964 through 2008, the average annual reported groundwater use from the eastern Arbuckle-Simpson aquifer was 4,299 acre-feet (Christenson et al. 2011). In general, water managers plan for an annual rate of one acre-foot of water per suburban family household. The water was primarily used for water supply systems (63%). Other uses included mining (15%), power generation (14%), irrigation (7%), and recreation (1%). Power generation ceased in 1988 when use of the power plant near Sulphur was discontinued (Christenson et al. 2011).

In 2002, water managers in Canadian County, Oklahoma, which is approximately 145 km (90 mi) northwest of the recreation area, wanted to purchase water rights for the Arbuckle-Simpson aquifer. Their proposal raised concerns that large-scale withdrawals would decrease groundwater flow to rivers and springs and result in decreased water supplies, recreational opportunities, and aquatic habitat (Christenson et al. 2011). In response to these concerns, in 2003 the Oklahoma Senate imposed a moratorium on groundwater permits for municipal or public water-supply use outside of any county that overlies a "sensitive sole source groundwater basin" until a hydrological study could be completed (Oklahoma Water Resources Board 2003, p. 1; Christenson et al. 2011).

A previous groundwater study of the Arbuckle-Simpson sole source aquifer in 1994 failed to show a direct relationship between groundwater pumping and water level declines in Buffalo and Antelope springs, but it did demonstrate the need for more detailed research on the aquifer (Hanson and Cates 1994). Christenson et al. (2011) completed a comprehensive Arbuckle-Simpson aquifer study that demonstrated how increased groundwater withdrawal would result in decreased stream and spring flow. Furthermore, the study showed that increased withdrawal would result in fewer locations where groundwater would flow to streams and springs. The methodology and detailed analysis of the aquifer study is available in Christenson et al. (2011).

Chickasaw National Recreation Area developed a systematic water monitoring plan to monitor changes to spring discharge and groundwater flow. The plan includes measuring the water level at five springs (including spring groups) and Vendome Well on a weekly basis, monitoring quarterly discharge at twelve sites, and collecting water quality samples from several sites (table 5). Since 2000, water quality samples have been periodically collected from twelve sites and monitored for temperature, dissolved solids, specific conductance, and pH. Since 2005, water quality samples from ten sites have been collected every week in the summer and every month in the winter and tested for *E. coli*. Real-time discharge and water levels are currently recorded at five US Geological Survey sites, which include three stream sites and two groundwater monitoring wells (table 5; Noel Osborn, Chickasaw National Recreation Area, Chief of Resource Management, written communication, 8 December 2014).

In 2013, a US Geological Survey stream gage near Antelope Spring was moved a little farther downstream to avoid the increased traffic that had been disturbing the original site. The gage had been periodically operational since 1985. The US Geological Survey also installed a stream gage on Travertine Creek, upstream from its confluence with Rock Creek in the park. Once sufficient field discharge data have been collected to develop a rating curve, both discharge and stage measurements will be collected (Noel Osborn, Chickasaw National Recreation Area, Chief of Resource Management, written communication, 8 December 2014).

The study also showed that if groundwater withdrawals were to equal or exceed recharge to the aquifer, groundwater flow to springs and streams would eventually cease. The Arbuckle-Simpson aquifer is recharged primarily from precipitation in the outcrop areas (fig. 8). Recharge tends to be highest in January–June and lowest during July–September (Christenson et al. 2011). Because recharge is primarily from precipitation, any change in precipitation trends, such as those predicted by global climate change, may impact the Arbuckle-Simpson aquifer and the springs in Chickasaw National Recreation Area.

According to the Intergovernmental Panel on Climate Change (IPCC), an increase in global temperature has already increased the evaporation rate and moisture-holding capacity in the atmosphere, which alters the hydrological cycle and changes precipitation patterns (IPCC 2007, 2013, 2014). These changes alter streamflow, groundwater recharge, and extreme weather events. In 2011, some areas of south-central Oklahoma experienced more than 70 days of temperatures more than 38°C (100°F), and the incidence of extreme temperatures is projected to rise (Melillo et al. 2014). In 2012, severe drought (lasting more than six months) impacted southern Oklahoma.

Increased temperatures will increase evaporation and the potential for drought. In southern Oklahoma, a warming trend of 1.4°C–1.9°C (2.5°F–3.4°F) is expected to begin in 2040 and by the end of the century, temperatures are projected to have increased by 2.3°C–4.5°C (4.1°F–8.1°F) (Karl et al. 2009; Hong 2012). On average, evapotranspiration is expected to increase by as much as 8% and runoff is projected to decrease by more than 10% by the end of the 21st century (Hong 2012).

Predicting changes in precipitation patterns is not as clear as temperature. Southeastern Oklahoma may experience decreasing wet conditions from 2011 to 2050 and more severe and frequent drought after 2050 (Hong 2012). Over the last 100 years, Antelope Spring has been dry or flowed intermittently for 22 extended periods of time, especially during the 1910s, 1930s, and 1950s (Hanson and Cates 1994; National Park Service 2014b). The most recent dry period for

Table 5. Water monitoring program for Chickasaw National Recreation Area.

Monitoring Procedure	Parameters Measured	Site(s)
Weekly (since 2006)	Water level	1. Buffalo Spring; 2. Antelope Spring; 3. Pavilion Springs (underpass) 4. Hillside Spring; 5. Black Sulphur Springs; 6. Vendome Well outflow
Quarterly (since 2004)	Discharge	1. Buffalo Spring; 2. Antelope Spring; 3. Pavilion Springs (Big Tom); 4. Pavilion Springs (underpass); 5. Hillside Spring; 6. Black Sulphur Springs 7. Travertine Creek site 1; 8. Travertine Creek site 1.5; 9. Travertine Creek site 2; 10. Travertine Creek site 4; 11. Buckhorn Creek; 12. Rock Creek at Black Sulphur Bridge
Water Quality (since 2005): Periodically (since 2000)	Temperature, pH, dissolved solids, specific conductance	1. Rock Creek (40 ft Hole); 2. Upper Guy Sandy Creek (State Ramp); 3. Travertine Creek (Cold Springs); 4. Buckhorn Creek (Hatchery); 5. Buckhorn Creek (Powerlines); 6. Rock Creek (Ballfield, discontinued in 2008); 7. Lake of the Arbuckles (Guy Sandy Arm) 8. Lake of the Arbuckles (Arbuckle Dam); 9. Lake of the Arbuckles (Buckhorn Arm); 10. Lake of the Arbuckles (Rock Creek Arm); 11. Veterans Lake; 12. Antelope Spring; 13. Buffalo Spring
Water Quality (since 2005): Summer: weekly Winter: monthly	*E. coli*	1. Travertine Creek (Little Niagara Falls); 2. Travertine Creek (Bear Falls); 3. Travertine Creek (Panther Falls); 4. Rock Creek (Black Sulphur swimming area); 5. Rock Creek (40-ft hole) 6. Veterans Lake; 7. Lake of the Arbuckles (Buckhorn D Loop); 8. Lake of the Arbuckles (Buckhorn Pavilion); 9. Lake of the Arbuckles (Buckhorn Arm); 10. Lake of the Arbuckles (Point Turnaround)
Real-time measurements (US Geological Survey sites)	Discharge	Rock Creek at Sulphur (ID 07329852): 1989–present
	Discharge	Travertine Creek north of US 177 at Sulphur (ID 073298507): 10/2013–present
	Discharge	Antelope Spring at Sulphur (ID 07329849): 1985–present (discontinuous)
	Water level	Park groundwater well 1 (West) (ID 343022096): 1972–present (discontinuous)
	Water level	Park groundwater well 2 (East) (ID 343017096): 1972–present (discontinuous)

Information provided by Noel Osborn, Chief of Resource Management, Chickasaw National Recreation Area (written communication, 8 December 2014). Note that the real-time measurements of the two park wells and Antelope Spring provide a discontinuous record.

Antelope Spring was from September 2012 to May 2015. Extended periods of no flow within that time frame include from September 20 to December 27, 2013, and from February 13, 2014 to May 3, 2015 (Noel Osborn, Chickasaw National Recreation Area, Chief of Resource Management, written communication, 15 December 2014; US Geological Survey 2015). More severe and frequent drought may decrease the amount of groundwater in the Arbuckle-Simpson aquifer and prolong these periods of no spring flow.

As this report was being finalized, approximately 58 cm (23 in) of rain fell in late spring 2015 and Antelope Spring discharge went from dry in May to 0.3 m^3/s (12 ft^3/s) in June and July (Noel Osborn, Chickasaw National Recreation Area, Chief of Resource Management, email, 8 June 2015; US Geological Survey 2015). For reference, mean July 8 discharge at Antelope Spring over the past 16 years is 0.068 m^3/s (2.4 ft^3/s) (US Geological Survey 2015).

Water Quality

The surface and subsurface watersheds that supply surface and spring water to the recreation area are primarily outside the recreation area (fig. 21). Therefore activities that are detrimental to water quality outside the recreation area (e.g., oil or hazardous material spills, other contamination, development) could affect water quality within the recreation area (Dale Pate, NPS Geologic Resources Division, Cave and Karst Program Lead, email, 15 June 2015). The Water Resources Division of the National Park Service evaluates the water quality in the National Park units and performed a baseline inventory of the surface water and spring discharge water quality in Chickasaw National Recreation Area in 1997 (Water Resources Division 1997).

Currently, Chickasaw National Recreation Area has a systematic monitoring program that monitors both water quality and water quantity as follows (Noel Osborn, Chickasaw National Recreation Area, Chief of Resource Management, written communication, 13 August 2014):

- Collecting monthly stage measurements at five springs and Vendome Well,
- Collecting periodic discharge measurements at five springs, Vendome Well, and seven sites on Travertine and Rock Creeks,
- Quarterly, monitoring water quality (temperature, dissolved oxygen, specific conductance, and pH) at six stream sites, five lake sites, and two springs (Antelope and Buffalo),
- Monitoring *E. coli* at nine swimming areas in Travertine and Rock Creeks, Lake of the Arbuckles, and Veterans Lake,
- Monitoring real-time streamflow at US Geological Survey gages at Antelope Spring, Travertine Creek, Rock Creek,
- Monitoring real-time water-level at two observation wells.

The monitoring program addresses the two water quality issues that were discussed during the scoping meeting and conference call, sewage and natural asphalt deposits.

Sewage

Prior to the construction of the Arbuckle Dam in the mid 1960s, effluent from the Sulphur sewage disposal plant drained into Rock Creek watershed (US Bureau of Reclamation 2012). As part of the dam project, the Sulphur sewage effluent pumping plant and pipeline were constructed to collect all effluent and convey it about 6 km (4 mi) to the Guy Sandy Creek watershed. The maximum capacity of the plant was 15 million liters (4 million gallons) per day. Nevertheless, Sulphur's sewage treatment holding pond would occasionally overflow into Rock Creek.

In 2007, the city installed a new, larger sewage lagoon to reduce the potential overflow problem. In 2011, Sulphur replaced an old 18-inch main pipe, constructed a new wastewater treatment system, and extended the discharge point on Guy Sandy Creek to a location farther from the recreation area. The upgrades significantly reduced sewer leaks and overflows, but problems still occasionally occur. Park staff members work closely with the city to monitor and repair occasional manhole overflows and sewer-line blockages (Noel Osborn, Chickasaw National Recreation Area, Chief of Resource Management, written communication, 13 August 2014). Rock Creek is currently sampled for *E. coli* bacteria on a monthly basis.

The city of Sulphur's water supply comes from a well field drilled into the Arbuckle-Simpson aquifer north of Chickasaw National Recreation Area, near Antelope and Buffalo springs. Chickasaw National Recreation Area staff members use data from US Geological Survey gages on Antelope Spring and two observation wells to evaluate effects of city well withdrawals on the springs. Sulphur city managers also provide daily withdrawal amounts from the well field to park staff. During times of high water levels in the past, unregulated discharge from some older wells flowed into a creek, which flowed into the park. The city of Sulphur plugged these old wells and drilled a deeper, higher capacity well, which does not flow into the tributary stream (Noel Osborn, Chickasaw National Recreation Area, Chief of Resource Management, written communication, 13 August 2014).

Natural Asphalt Deposits

Naturally-occurring asphalt seeps are found in the Rock Creek arm of Lake of the Arbuckles, especially when lake levels are low, and they may occur in Veterans Lake (fig. 25). Because of their small size and intermittent occurrences, these asphalt seeps do not require mitigation (Noel Osborn, Chickasaw National Recreation Area, Chief of Resource Management, written communication, 13 August 2014). Lake of the Arbuckles covers portions of the Vanoss Formation (geologic map units **PNvs** and **PNvc**), Deese Group (**PNd**), Caney Shale (**Mc**), undifferentiated Mississippian and Devonian rocks (**MDsw**), and possibly the Hunton Group (**DSOh**), while Veterans Lake has filled a depression in the Vanoss conglomerate (**PNvc**). The asphalt seeps have an undetermined source and appear to be random.

Natural asphalt is found in quarries south of the Arbuckle Dam in the Viola Group (**Ov**) and in quarries east of the park in sandstones within the Simpson Group (**Obm** and **Ooj**) (Noel Osborn, Chickasaw National Recreation Area, Chief of Resource Management, conference call 11 March 2014). Sandstones in the Oil Creek Formation of the Simpson Group contain about 8% asphalt and were mined for road-surfacing material from 1890 to 1962 (Ham 1973; Christenson et al. 2009).

Figure 25. Veterans Lake. Natural asphalt may seep into Lake of the Arbuckles and Veterans Lake (shown here) from subsurface formations. The seeps are not visible on the surface. As petroleum migrates to the surface, it may degrade into asphalt. "No wake" buoys, like the one in this photo, are also in Lake of the Arbuckles. National Park Service photograph, available at http://www.nps.gov/chic/photosmultimedia/photogallery.htm (accessed 8 August 2014).

Flooding and Debris Flows

Flash flooding and debris flows present a potential hazard in Chickasaw National Recreation Area. Rock Creek drains an area of 114 km^2 (44.1 mi^2), and intense rainfall events can rapidly fill the creek (Tortorelli and McCabe 2001; US Geological Survey 2014). Since a streamflow gaging station was installed at Rock Creek near Sulphur, Oklahoma, in 1989, the US Geological Survey, in cooperation with Chickasaw National Recreation Area, has kept a detailed record of Rock Creek discharge (Andrews and Burrough 2000; US Geological Survey 2014). The mean daily discharge on Rock Creek has been 0.31 m^3/s (11 ft^3/s). This average is skewed, however, by extreme discharge events that usually occur in the spring and early summer. From July to November, daily discharge in Rock Creek is often less than 0.1 m^3/s (5 ft^3/s). Following a rain event, for example, daily discharge went from 0.074 m^3/s (2.6 ft^3/s) on July 29, 2014, to 0.40 m^3/s (14 ft^3/s) on July 30, 2014. The highest documented extreme peak discharge of 294 m^3/s (10,400 ft^3/s) was recorded on April 26, 1990 (Tortorelli and McCabe 2001; US Geological Survey 2014). The estimated recurrence interval of a flood this size is once every 25 years (Tortorelli and McCabe 2001). As this GRI report was in final review—almost 25 years to the month—record discharges occurred from May through July 2015.

Figure 26. Flood waters. A paddler kayaks through a parking lot in Chickasaw National Recreation Area following the 2007 flood. National Park Service photograph, available at http://www.nps.gov/chic/photosmultimedia/photogallery.htm (accessed 23 April 2014).

In 2007, several flooding events inundated campgrounds and parking lots in Chickasaw National Recreation Area (fig. 26; US Geological Survey 2014). Rehabilitation of the campsites cost approximately $72,000 (Graham 2008). As mentioned in the "Geologic Features and Processes" chapter, high waters of Rock Creek pose a threat of contamination for Bromide and Medicine springs, but high precipitation and flooding may also contaminate other springs in the recreation area. A warning sign has been posted over the Hillside Spring fountain for many years due to intermittent bacterial contamination. In a 1968 study, bacterial counts increased at Hillside and Black Sulphur springs after significant precipitation. Contamination consisted of soil bacteria and fecal coliform and streptococci from birds and mammals native to the area (Noel Osborn, Chickasaw National Recreation Area, Chief of Resource Management, written communication, 13 August 2014). Black Sulphur Spring usually does not have bacteria contamination during dry periods. In the 1968 study, no bacterial pollution was found at Pavilion Springs.

Floods transport silt from Upper Guy Sandy Creek to the upper end of the Lake of the Arbuckles. The accumulation of silt in the reservoir decreases its holding capacity. Buckhorn and Rock Creek, the other two streams that flow through the recreation area and into the lake, have rocky channels, so they are not as silty as Upper Guy Sandy Creek. Debris carried by the floodwaters accumulates behind bridges and must be cleared. Flash floods may also impact the

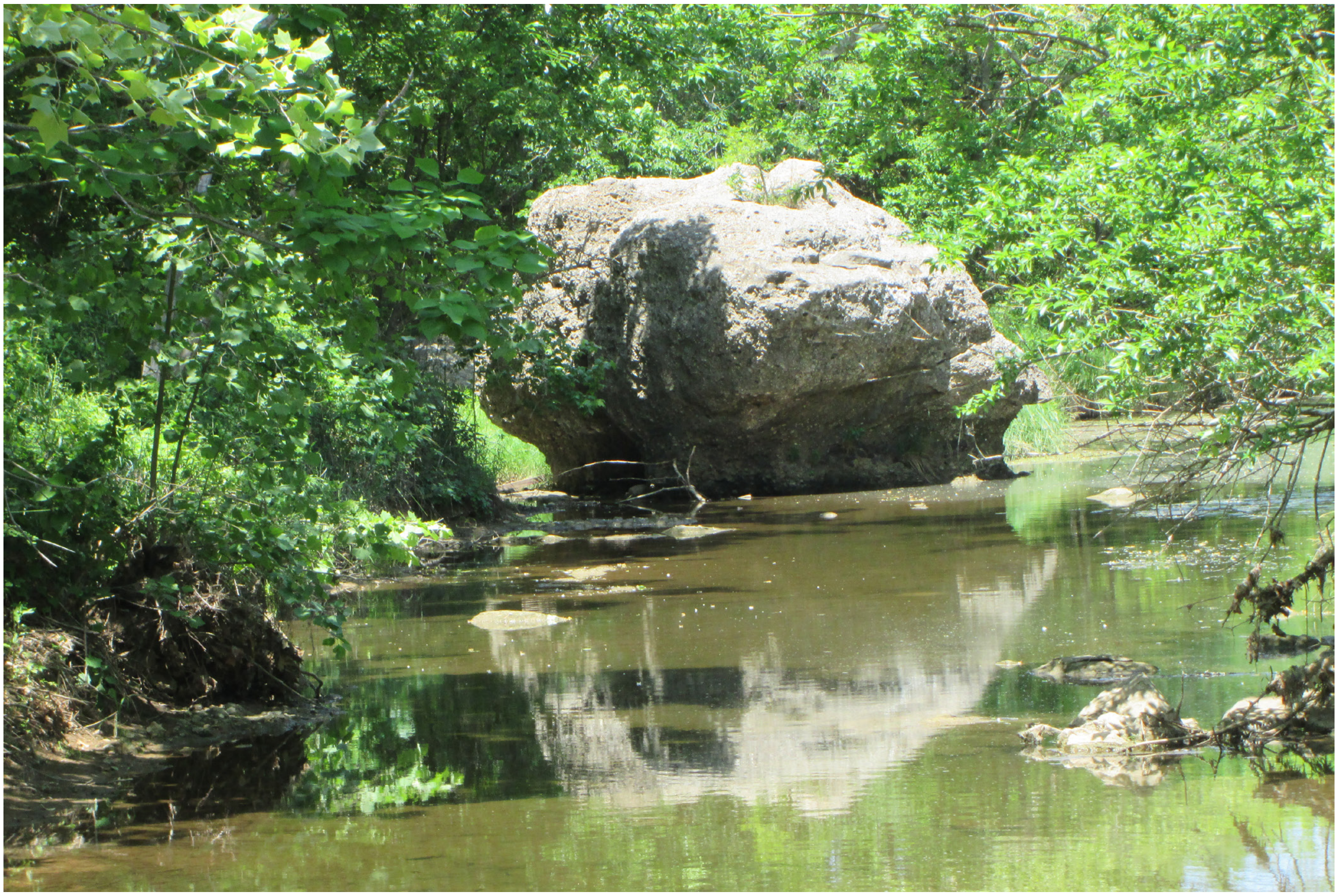

Figure 27. Rockfall from Bromide Cliff. This block of Vanoss conglomerate rests in Rock Creek about 30 m (100 ft) downstream from Bromide Spring. Photograph by the author.

Travertine Nature Center, the campgrounds, and other infrastructure that are built on the floodplain. Neither a warning system nor a response plan existed for Chickasaw National Recreation Area at the time of the GRI scoping meeting (Graham 2008).

In 2015, NPS Water Resources Division staff members completed the Riparian System Condition Assessment Report for Chickasaw National Recreation Area. Riparian areas for both Rock Creek and Guy Sandy Creek received "Proper Functioning Condition" ratings, the highest of three possible ratings. This rating indicates that both creeks have adequate vegetation and landforms to dissipate flood energy and absorb high flows without significant changes in vegetation, erosion, or channel and floodplain geomorphology (Martin et al. 2015). However, extreme flood events such as those in May through July 2015 are outside the typical flood regime and riparian conditions discussed in the Martin et al. (2015) report (Joel Wagner, NPS Water Resources Division, Wetlands Program Lead, personal communication, 8 July 2015).

Flooding and intense rainfall events may also raise the water level in Lake of the Arbuckles. During wet years, water held behind the dam may rise and flood campgrounds, boat ramps, parking lots, and other facilities along the shoreline in Chickasaw National Recreation Area, including the Buckhorn Ranger Station.

With increasing temperature and evaporation rates, the moisture-holding capacity of the atmosphere and thus, the potential for severe storms, has also increased (IPCC 2013, 2014). In southern Oklahoma, climate change may result in more intense rainfall patterns and a potentially higher risk of flooding (Hong 2012).

Rockfall

Slope movements, which are any downslope transfer of soil, regolith, and/or rock under the influence of gravity. Soil creep, rockfalls, debris flows, and avalanches are common types of slope movements. These processes and the resultant deposits are also known as "mass wasting" and commonly grouped as "landslides." Slope movements, particularly rockfall, affect parts of Bromide Hill (National Park Service 2014g). However, no accidents or injuries from falling rock have been reported in Chickasaw National Recreation Area (Graham 2008). Rock Creek undercuts the vertical cliff of Vanoss conglomerate (**PNvc**) at Bromide Hill, and the unsupported overhanging rock may eventually fall into the creek. One block about the size of a one-car garage (about 28 m^3 [1,000 ft^3]) has fallen 30 m (100 ft) downstream from the Bromide and Medicine spring vaults (fig. 27). Rockfall potential also exists along the road leading to the summit of Bromide Hill. Physical weathering may cause portions of the conglomerate benches to break away and cascade down the steep slope. Small rockfalls also occur along other sections of Rock Creek.

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

Lakeshore Erosion

Participants at the 2007 scoping meeting expressed minor concern that fluctuation of the shoreline around the Lake of the Arbuckles may cause shoreline erosion, which may subsequently threaten some archeology sites (Graham 2008). An archeological survey was completed in 1965 prior to the construction of the Arbuckle Dam. At that time, extensive archeological excavations uncovered artifacts at sites below the confluence of Buckhorn, Guy Sandy, and Rock creeks on an alluvial terrace system that bordered Rock Creek (Barr 1965; Osborn and Hartley 2008). Additional archeological surveys, usually associated with construction projects, have occurred in the recreation area since then. For example, an archeological survey in 2008 evaluated auger test holes for new toilet facilities at the Buckhorn Loops E and F, The Point, Blackjack Road Point Area, Upper Loop Point Campground, Guy Sandy Boat

Table 6. Monthly average surface elevations for Lake of the Arbuckles, January 2004 to June 2015.

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
2015	862	863	863	864	876	885						
2014	867	867	867	867	866	867	866	866	866	864	863	863
2013	867	866	866	866	866	870	869	869	868	868	867	867
2012	867	868	870	872	872	872	871	869	868	868	867	867
2011	871	871	871	871	871	870	869	868	866	866	867	868
2010	873	872	873	873	873	873	873	872	872	872	871	871
2009	868	868	867	867	875	874	872	872	872	874	873	873
2008	871	871	873	873	872	872	872	871	870	870	869	868
2007	869	871	872	874	874	875	877	873	872	872	871	871
2006	870	870	870	871	873	872	871	870	869	868	868	868
2005	874	873	873	873	873	873	872	872	872	872	871	871
2004	870	869	871	871	871	871	873	873	872	872	874	873

Elevations are in feet above mean sea level based on the National Geodetic Vertical Datum (NGVD) and rounded to the nearest foot. Months with an average elevation change of greater than 0.6 m (2 ft) are colored yellow. In January, 2015, (orange) the lake level reached a record low. Five months later, in June 2015, the average elevation was near record highs and the actual maximum elevation was 891.52 ft. Data are from the US Army Corps of Engineers (http://www.swt-wc.usace.army.mil/ARBUcharts.html, accessed 17 July 2015).

Launch, and at Guy Sandy Campground (plate 1; Osborn and Hartley 2008). Except for chert fragments found in one Buckhorn Loop E auger hole, no artifacts were found in the test holes. Six other test holes drilled near the chert-containing hole also failed to recover any artifacts (Osborn and Hartley 2008).

In 1968, the US Bureau of Reclamation turned over the maintenance and operation of the lake to the Arbuckle Master Conservancy District and the dam and reservoir are currently managed by the US Army Corps of Engineers, which charts the daily surface elevations of the lake (US Army Corps of Engineers 2014). Table 6 summarizes the average monthly lake levels since January 2004, but for the curious, lake levels beginning in January 1994 can be accessed on the US Army Corps of Engineers website, http://www.swt-wc.usace.army.mil/ARBUcharts.html. Since January 2004, the average monthly change in lake level has been relatively constant, rarely fluctuating any more than 0.6 m (2 ft). During the wet summer months of July to August 2007, lake elevations fluctuated 1.2 m (4 ft). Since January 2004, a record average monthly low of 263 m (862 ft) was reached in January 2015. This condition rapidly changed during the extremely wet months of May and June 2015. By June 18, 2015, the reservoir was at 271.74 m (891.52 ft) above the top of the "flood pool" elevation of 270 m (885 ft).

Roots of trees, shrubs, and other vegetation help stabilize the Lake of the Arbuckles shoreline. The abundant vegetation and minor lake-level fluctuations contribute to reducing lakeshore erosion. Nevertheless, high water and flooding may disaggregate and erode the soil near the shoreline.

Wake from motor boats may splash against the shore, potentially generating minor erosion, but the lake includes wakeless and no boat areas. Wakeless areas include anywhere where "No Wake" buoys are present, within Guy Sandy Harbor, and within 46 m (150 ft) of all docks, launch ramps, boats at anchor, boats from which people are fishing, and shoreline areas near campgrounds. Boating is excluded from the area around the Point Picnic Area, west of the Buckbrush Trail West, south of Buckhorn Campground's Loop D, and the Goddard Youth Camp cove (Noble 2013).

Paleontological Resource Inventory, Monitoring, and Protection

All paleontological resources are non-renewable and subject to science-informed inventory, monitoring, protection, and interpretation as outlined by the 2009 Paleontological Resources Preservation Act (see Appendix B). As of July 2015, Department of the Interior regulations associated with the Act were still being developed.

Abundant Paleozoic marine invertebrate fossils are exposed in road cuts and other outcrops south of Lake of the Arbuckles. See the "Paleontological Resources" section for additional information about the types of fossils present in the area. The Goddard Youth Camp in Chickasaw National Recreation Area maintains fossils collected from nearby Paleozoic rocks, and the Hunton Group, exposed south of Lake of the Arbuckles, is well known for trilobites and brachiopods (Noel Osborn, Chickasaw National Recreation Area, Chief of Resource Management, written communication, 13 August 2014). Although, at the time of the writing of this report, fossil theft has not been documented in Chickasaw National Recreation Area, it may occur. Chickasaw National Recreation Area management is in the process of developing a plan that will address a paleontological inventory and assessment of fossils in the recreation area, as well as methods to prevent illegal collecting (National Park Service 2008). In addition paleontological resources were identified as a geologic resource for assessment via the Natural Resource Condition Assessment.

As part of the paleontological resource management plan, fossil localities and associated geologic data will be documented, and the conditions of the fossil resources will be evaluated using resource stability indicators, such as rates of erosion and human activity. Various methods will be used to protect the fossils, such as stabilizing fossils in the field or placing them in a museum collection. Shelters may be constructed over specimens to protect them from erosion or other ground-disturbing activity. A qualified paleontologist will survey new construction sites for potential fossil resources and will evaluate the significance of any newly discovered fossils (National Park Service 2008). Important sites will be patrolled and monitored to prevent theft and damage from erosion. Chickasaw National Recreation Area staff members will also work with Goddard Youth Camp staff members to conduct programs emphasizing paleontological resource protection and stewardship.

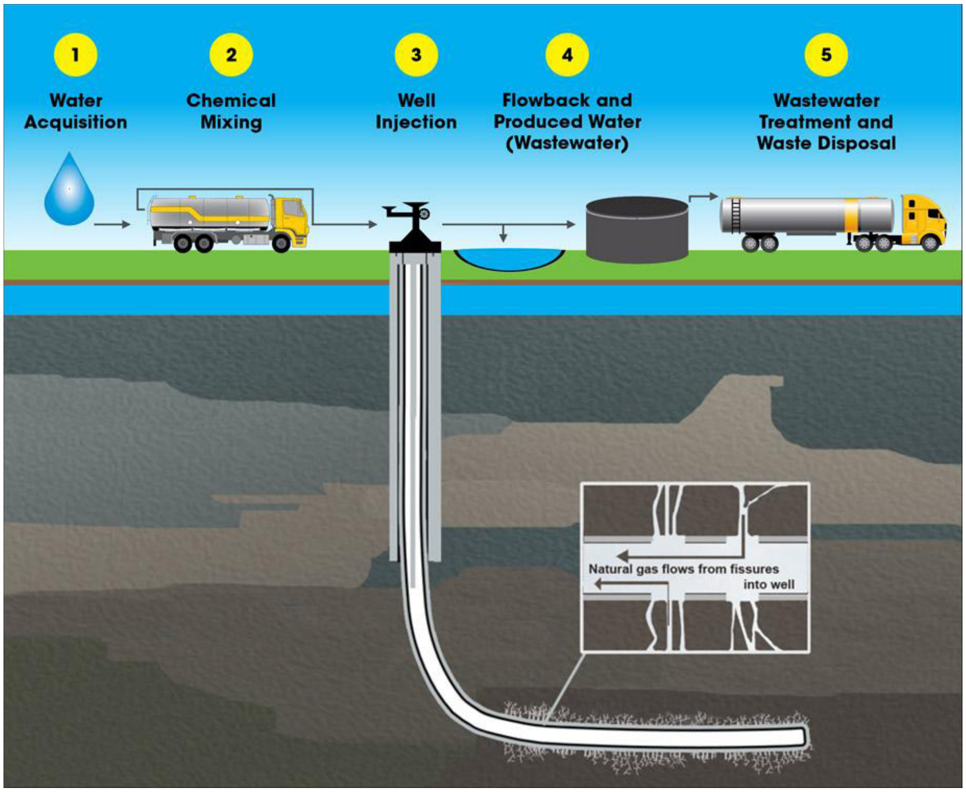

Figure 28. Schematic of hydraulic fracturing (fracking). Horizontal blue line represents an aquifer, which is isolated from the well bore by steel casing and cement. The drill pipe becomes horizontal at approximately 460 m (1,500 ft). Environmental Protection Agency graphic, available at: http://www2.epa.gov/hfstudy/hydraulic-fracturing-water-cycle (accessed 24 April 2015).

In the *Geological Monitoring* chapter about paleontological resources, Santucci et al. (2009) described five methods and vital signs for monitoring in situ paleontological resources: (1) erosion (geologic factors), (2) erosion (climatic factors), (3) catastrophic geohazards, (4) hydrology/bathymetry, and (5) human access/public use. The Geologic Resources Division can provide useful information to facilitate paleontological resource management.

External Mineral Exploration and Development

The National Park Service works with adjacent land managers and other permitting entities to help ensure that National Park System resources and values are not adversely impacted by external mineral exploration and development. Potential impacts include groundwater and surface water contamination, erosion and siltation, introduction of exotic plant species, reduction of wildlife habitat, impairment of viewsheds and night skies, excessive noise, and diminished air quality. Visitor safety and overall degradation of the visitor experience are particular concerns. The NPS Geologic Resources Division Energy and Minerals program provides additional information (National Park Service 2013a).

Hydrocarbon Exploration and Induced Seismicity

Oklahoma's primary hydrocarbon producing region is west of Chickasaw National Recreation Area. Hydrocarbon exploration may contribute brine to the mineralized springs in the recreation area, but this hypothesis remains untested. Increased hydraulic fracturing (fracking) and horizontal drilling has raised concerns about aquifer depletion and contamination (fig. 28). Well casings in hydrocarbon exploration and production wells may extend to 60 m (200 ft) or deeper if needed to isolate the well bore from fresh groundwater. Although freshwater is known to exist as deep as 555 m (1,820 ft) in the Arbuckle-Simpson aquifer, most water wells in the aquifer are generally less than 30 m (100 ft) deep (Christenson et al. 2009; Oklahoma Water Resources Board 2014). In the subsurface west of Chickasaw National Recreation Area, the Lower Mississippian–Upper Devonian Woodford Shale (**MDsw**) is one potential candidate for horizontal drilling and fracking.

Hydraulic fracturing and the underground disposal of salty water produced by the fracking process may also trigger earthquakes, a process termed "induced seismicity" or "triggered seismicity" (Holland 2011; US Geological Survey 2011; Darold and Holland 2014; Oklahoma Geological Survey 2014). The "produced

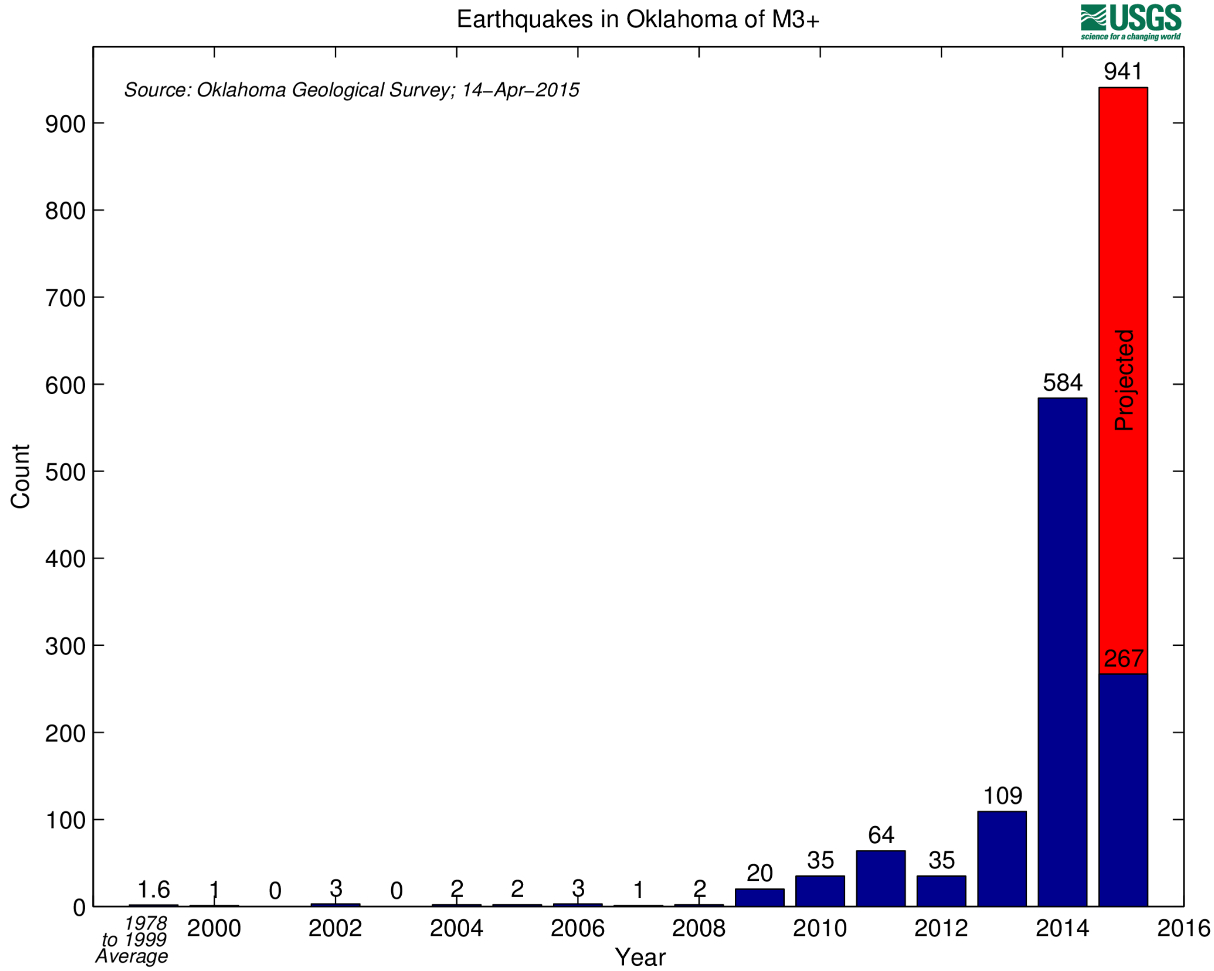

Figure 29. Oklahoma earthquakes of magnitude 3.0 and greater, 1978 to April 14, 2015. Since October 2013, earthquakes in Oklahoma have increased significantly. Wastewater from hydrocarbon production that is injected into the subsurface contributes to these earthquakes. Graph from US Geological Survey, available at http://earthquake.usgs.gov/earthquakes/states/?region=Oklahoma (accessed 31 July 2015).

water" is salty (also known as "brine") and is primarily naturally occurring water that exists with the oil and gas beneath the surface (Oklahoma Geological Survey 2015). As the oil and gas is extracted, so is the water. That water is separated from the oil and gas and re-injected into disposal wells Fracking fluid is a minor percentage of this "produced water" (Oklahoma Geological Survey). Fracking itself does not appear to generate large numbers of earthquakes or earthquakes with a magnitude of more than 3 on the Richter scale (Darold and Holland 2014). As much as 10% of observed earthquakes may be due to fracking, but this estimate is probably high. The Oklahoma Geological Survey investigates any allegation of a fracking-triggered earthquake and seriously assesses the cause of any Oklahoma earthquake (Holland 2011; Oklahoma Geological Survey 2015).

Disposal of water injected into wells is more likely to trigger earthquakes than fracking itself. For many years, "produced water" in Oklahoma has been injected into Underground Injection Control (UIC) Class II wells. According to the Oklahoma Geological Survey (2015, p. 1), "it [is] very likely that the majority of recent earthquakes, particularly those in central and north-central Oklahoma, are triggered by the injection of produced water in disposal wells." These wells are regulated by the EPA to protect drinking water sources and are all deep wells well out of reach of groundwater aquifers. The Arbuckle Group is one of the most used geologic units for wastewater injection in Oklahoma (Noel Osborn, Chickasaw National Recreation Area, Chief of Resource Management, written communication, 3 December 2014).

Injection wells, however, are not designed with earthquakes in mind (US Geological Survey 2011; Darold and Holland 2014). Wastewater injected into areas with faults may increase the underground pore pressure and lubricate a fault plane, which may cause the fault to slip. From 1978 to 2008, the long-term average earthquake rate in Oklahoma was about 1.5 magnitude 3.0 or larger earthquakes per year (Oklahoma Geological Survey 2015). During 2013, the rate had increased to two magnitude 3.0 earthquakes per week and in 2015 the rate is about 2.5 magnitude 3.0 earthquakes per day (fig. 29; Oklahoma Geological Survey 2015). Earthquake analyses by the US Geological Survey and Oklahoma Geological Survey indicate that wastewater injected into deep geological formations is a contributing factor to the heightened earthquake activity since 2009, which includes 20 magnitude 4.0 to 4.8 earthquakes (US Geological Survey and Oklahoma Geological Survey 2014). Fluid injection may have triggered the largest earthquake in Oklahoma history that occurred on November 5, 2011, when a magnitude 5.6 earthquake shook the ground near Prague, Oklahoma, approximately 110 km (70 mi) north-northeast of Chickasaw National Recreation Area. The Prague earthquake damaged several homes and the historic Benedictine Hall at St. Gregory's University in Shawnee.

Injection-induced seismicity has been documented for almost 50 years. Collaborative research by the US Geological Survey and the Oklahoma Geological Survey continues to quantify the changes in earthquake rate, assess the implications of small and moderate earthquake activity for large earthquakes, and evaluate possible links between earthquakes and wastewater disposal from oil and gas production activities. In addition, the Oklahoma Geological Survey has increased the number of its seismic monitoring stations. Data from the Oklahoma seismic network (also viewable online http://www.okgeosurvey1.gov/, accessed 17 July 2015) are shared in real-time with the US Geological Survey National Earthquake Information Center in Golden, Colorado. For more information, also refer to the Oklahoma Geological Survey Induced Seismicity website: http://www.okgeosurvey1.gov/pages/earthquakes/induced-seismicity.php (accessed 17 July 2015) or the Earthquakes in Oklahoma website: http://earthquakes.ok.gov/ (accessed 31 July 2015).

Seismic risk was identified as a geologic resource for assessment via the Natural Resource Condition Assessment (Noel Osborn, Chickasaw National Recreation Area, Chief of Resource Management, email, 8 June 2015).

Aggregate Quarries

Quarries that mine aggregate material from the aquifer outcrop east of the park are associated with potential hazards that may affect the springs in Chickasaw National Recreation Area. Several abandoned water-filled gravel pits in Vanoss Formation (**PNvc**) and Simpson Group (**Obm** and **Ooj**) rocks are mapped within a kilometer of the recreation area's eastern border (Blome et al. 2013). The large North Troy Quarry is approximately 13 km (8 mi) east of the recreation area and mines coarse and fine aggregate for concrete and other uses. Active quarries must dewater deep pits, and these large withdrawals of water from the aquifer threaten groundwater flow to springs and streams in Chickasaw National Recreation Area.

Abandoned Mineral Lands

According to the NPS Abandoned Mineral Lands (AML) database, Chickasaw National Recreation Area contains two surface mines identified as "high priority" for hazard and impact mitigation (Burghardt et al. 2014). Suggested recommendations for mitigation are included in the AML database.

As with all AML sites, these features at Chickasaw National Recreation Area present a variety of resource management issues such as visitor and staff safety and environmental quality of air, water, and soil. Abandoned mineral lands were identified as a geologic resource for assessment via the Natural Resource Condition Assessment (Noel Osborn, Chickasaw National Recreation Area, Chief of Resource Management, email, 8 June 2015). Burghardt et al. (2014) and the NPS AML Program website provides further information (National Park Service 2013b).

Table 7. Summary of the geologic history of southern Oklahoma

Major Phase	Time Frame (age span)	Period	Tectonic Events	Depositional Events
4	Permian to Present-Day (from 299 million years ago)	Quaternary	Midcontinent remains relatively tectonically stable except for the New Madrid Earthquakes (1811-1812 CE). A new surge of earthquakes in Oklahoma may be due to fluid injection wells.	Major erosion and deposition in floodplains of gravel, sand, silt, and clay.
		Neogene	Shoreline of the ancestral Gulf of Mexico, which had almost reached the corner of southeastern Oklahoma, retreats southward.	No deposits in the region of Chickasaw National Recreation Area.
		Paleogene		
		Cretaceous	Uplift of Rocky Mountains causes regional eastward tilting and east-flowing river systems. Shallow inland sea spreads from the Gulf to Arctic Ocean and includes western and southern Oklahoma.	Marine limestone and non-marine sandstone and clay are deposited in southeastern Oklahoma.
		Jurassic	Gulf of Mexico and Atlantic Ocean continue to open.	Major erosion removes deposits from southern Oklahoma.
		Triassic	Pangaea begins to break apart.	
		Permian	Major land masses come together to form Pangaea.	Western basins fill with red shales, sandstones, and evaporates.
3	Late Mississippian through Pennsylvanian (331 million–299 million years ago)	Pennsylvanian (Late)	Arbuckle anticline forms from continued compression. Beds are overturned. Reverse and thrust faults displace strata.	Conglomerates are deposited in alluvial fans as uplifted areas are eroded.
		Pennsylvanian (Early and Middle)	Slow uplift and faulting of the Hunton and Tishomingo anticlines on the continental margin.	
		Mississippian (Late)		
2	Late Cambrian through Middle Mississippian (500 million–331 million years ago)	Mississippian	Subsidence of present-day southern Oklahoma and accompanying sea level rise.	Incursion of a shallow sea. Carbonate rocks deposited on a broad marine platform.
		Devonian		
		Silurian		
		Ordovician		
		Cambrian (Late)		
1	Early to Middle Cambrian (541 million–500 million years ago)	Cambrian	Rifting of present-day southern Oklahoma.	Igneous rocks were intruded and extruded.

Adapted from Christenson et al. (2011, table 1) with additional information from Blome et al. (2013) and Johnson (2008). Age 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.

Geologic History

This section describes the chronology of geologic events that formed the present landscape of Chickasaw National Recreation Area.

The geologic history of southern Oklahoma involves four major geologic phases (table 7). The initial phase began with rifting of the North American craton near present-day southern Oklahoma. Paleozoic strata exposed in the Chickasaw National Recreation Area represent the second and third major geological events in the history of the Arbuckle Mountains. Toward the end of the Cambrian Period through the Middle Mississippian Period, shallow marine sediments were deposited in present-day southern Oklahoma. In the Pennsylvanian Period, sea level fell as the southern margin of proto-North America was compressed, uplifted and deformed by folding and faulting (Donovan and Butaud 1993; Tapp 1995; Christenson et al. 2011; Blome et al. 2013). The final phase in the evolution of the Arbuckle Mountains involved millions of years of erosion as the mountainous landscape was worn down to today's rolling hills. The region was tilted, resulting in southeast-flowing streams. Deposits of gravel, sand, silt, and clay mark old stream channels, as well as current river and floodplain environments.

Phase 1. Rifting of the Craton: Early through Middle Cambrian Period, 541 Million to 500 Million Years Ago

During the Early and Middle Cambrian Period (541 million to 500 million years ago), extensional forces pulled apart Earth's crust in the area of present-day southern Oklahoma, and a rift zone developed that consisted of deep basins separated by steep normal faults (table 7). Fractures and faults in the crust provided conduits for magma that either solidified beneath the surface as an intrusive igneous rock or erupted into the rift zone and cooled to form an extrusive igneous rock. These Cambrian rocks, along with older Precambrian igneous and metamorphic units, became the basement rocks of Oklahoma upon which the younger sedimentary rocks were deposited (Johnson 2008; Christenson et al. 2011; Blome et al. 2013).

As the igneous rocks cooled and became denser, the rift basins began to subside. In present-day southern Oklahoma, depth to these basement rocks ranges from 9,000–12,000 m (30,000–40,000 ft) (Johnson 2008). Sediments filled the basins, forming a thick trough that is referred to as the Southern Oklahoma "Aulacogen." An aulacogen is a sediment-filled continental rift basin that is bounded by steep normal faults. The northwest–southeast-trending Southern Oklahoma Aulacogen extends about 400 km (250 mi) from southeastern Oklahoma into the Texas Panhandle (Johnson et al. 1988; Christenson et al. 2011). More than 5,000 m (17,000 ft) of Cambrian and Early Ordovician sedimentary rock filled the aulacogen. By comparison, the Cambrian–Ordovician continental shelf that formed north of the aulacogen accumulated approximately 2,000 m (6,500 ft) of sedimentary rock (Ham 1973).

Phase 2. Shallow Seas Flood the Craton: Late Cambrian through Middle Mississippian Periods, 500 Million to 330 Million Years Ago

Late Cambrian through Ordovician Periods

During the Late Cambrian (500 million to 485 million years ago) and Early Ordovician (485 million to 470 million years ago), shallow seas advanced onto the continent, flooding most of proto-North America from Mexico to Canada (fig. 30). A narrow highland, known as the Transcontinental Arch, extended from northern Minnesota southwestward into Arizona and New Mexico. Devoid of all vegetation (land plants had yet to evolve), the Transcontinental Arch was a stark landscape of blowing sand, silt, and clay. Eroded sediment from the highland helped fill the rift basins and spread across the broad, submarine ramp that tilted gently to the south in present-day southern Oklahoma.

In the Arbuckle anticline area, as much as 2,000 m (6,700 ft) of Arbuckle Group rocks formed on the carbonate ramp (Ham 1973; Johnson 1991; Christenson et al. 2011; Blome et al. 2013). The widespread marine limestones, shales, and sandstones of the Simpson Group (Obm and Ooj) were deposited above the Arbuckle Group. In the Chickasaw National Recreation Area, the Simpson Group is about 550–610 m (1,800–2,000 ft) thick (Blome et al. 2013). The Upper Ordovician, limestone-rich lower part of the Viola Group (**Ov**) and deeper-marine Sylvan Shale (**Os**) were deposited above the Simpson Group. Well-oxygenated marine conditions supported an abundant population

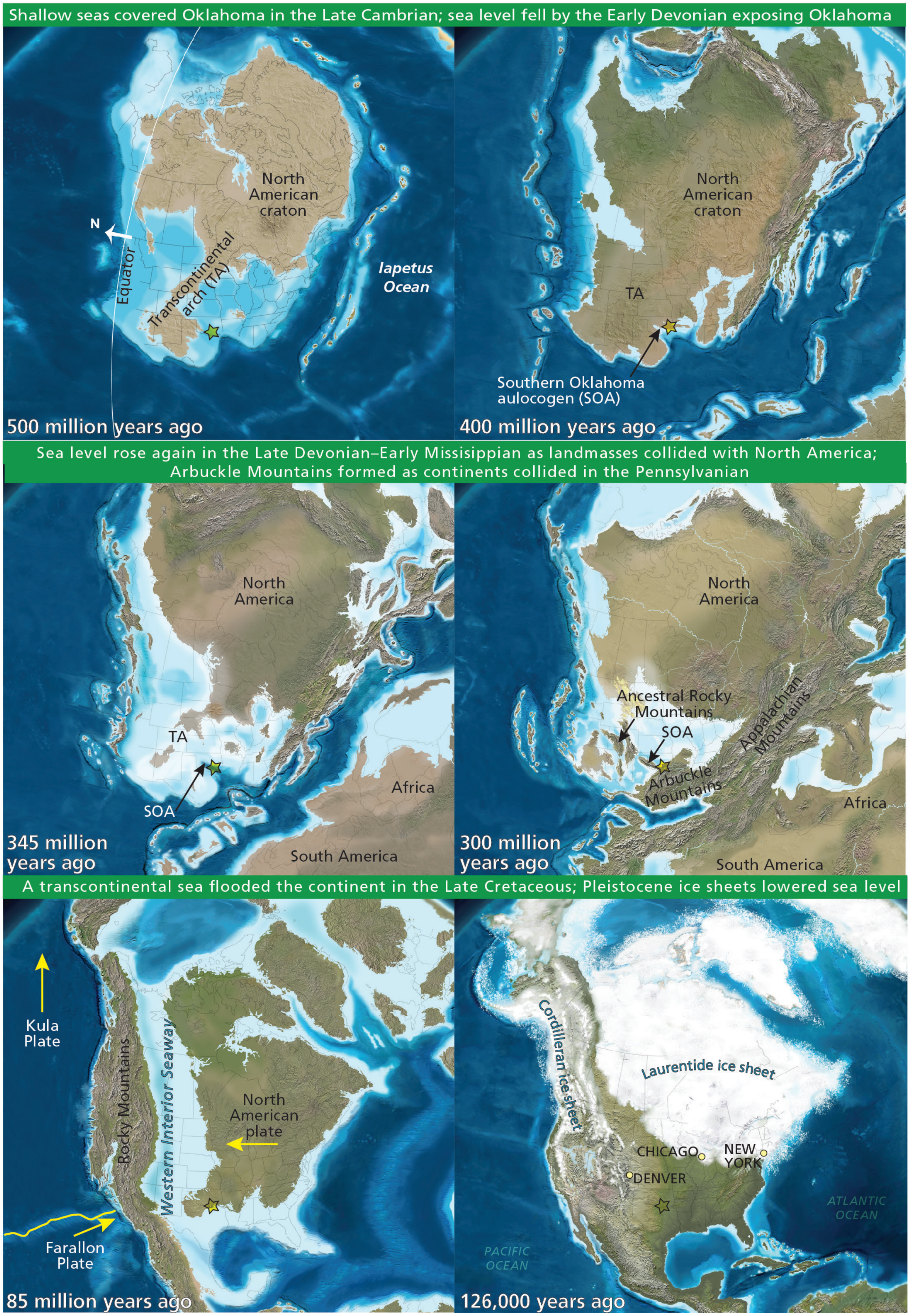
Shallow seas covered Oklahoma in the Late Cambrian; sea level fell by the Early Devonian exposing Oklahoma
North American craton
N
Equator
Transcontinental arch (TA)
Iapetus Ocean
500 million years ago
North American craton
TA
Southern Oklahoma aulocogen (SOA)
400 million years ago
Sea level rose again in the Late Devonian–Early Missisippian as landmasses collided with North America;
Arbuckle Mountains formed as continents collided in the Pennsylvanian
North America
TA
SOA
Africa
South America
345 million years ago
North America
Ancestral Rocky Mountains
SOA
Appalachian Mountains
Arbuckle Mountains
Africa
South America
300 million years ago
A transcontinental sea flooded the continent in the Late Cretaceous; Pleistocene ice sheets lowered sea level
Kula Plate
Rocky Mountains
Western Interior Seaway
North American plate
Farallon Plate
85 million years ago
Cordilleran ice sheet
Laurentide ice sheet
CHICAGO
NEW YORK
DENVER
PACIFIC OCEAN
ATLANTIC OCEAN
126,000 years ago

Figure 30. Paleogeographic maps of North America. The star represents the relative location of Chickasaw National Recreation Area. By the Late Cambrian (500 million years ago [mya]), southern Oklahoma was south of the Equator (white line) and covered by a shallow sea. By 400 mya, sea level fell and the shoreline retreated from Oklahoma and the Transcontinental Arch (TA) in the Silurian and Early Devonian periods. Tectonic plate collisions around the margins of proto-North America caused another sea level rise in the Late Devonian–Early Mississippian periods about 345 mya, inundating much of the continent. Deep marine water filled the Southern Oklahoma Aulacogen (SOA). As South America and Africa continued to suture onto North America in the Pennsylvanian Period (about 300 mya), the Arbuckle Mountains formed in southern Oklahoma and the Ancestral Rocky Mountains rose in Colorado. Approximately 85 mya, the Western Interior Seaway spread from the Arctic Ocean to the Gulf of Mexico, which encroached into southeastern Oklahoma. Western Oklahoma lay on the eastern margin of the interior sea. Yellow arrows indicate the general direction of plate movement. During the Pleistocene Epoch, continental glaciers flowed south into the midcontinent but not as far as Oklahoma. Alpine glaciers in the Rocky Mountains contributed meltwater to major streams that flowed from northwest to southeast through Oklahoma. Maps compiled by Trista Thornberry-Ehrlich (Colorado State University) with annotations by the author. Base paleogeographic maps created by Ron Blakey (Colorado Plateau Geosystems, Inc.), available at http://cpgeosystems.com/index.html (accessed 7 May 2014).

of marine invertebrates, such as trilobites, brachiopods, graptolites, and bryozoans.

The incursion of shallow seas onto the ancestral North American continent coincided with the Avalonian and Taconic orogenies (mountain-building episodes) that were transforming the eastern margin of proto-North America into an active subduction zone and constructing mountains that would eventually become the Appalachians. Periodically throughout the Paleozoic Era, proto-North America converged with other tectonic plates, initiating orogenic episodes along the margins of the continent and causing sea level to rise and transgress onto the continent. During times of tectonic quiescence, the seas slowly retreated (regressed) from the midcontinent and exposed sediments to erosion, which stripped away rock and sediment.

Silurian through Middle Mississippian Periods

The Silurian Period (443 million to 419 million years ago) through Early Devonian Period (419 million to 393 million years ago) was a time of tectonic quiescence. Sea level fell and the shoreline regressed from all but the southeastern-most corner of present-day Oklahoma and the Southern Oklahoma Aulacogen (fig. 30). The argillaceous limestones, oolitic limestones, chert concretions, marly shale, and open marine fauna (brachiopods, trilobites and crinoids) of the Hunton Group (**Dhu** and **SOhl**) represent fluctuating sea levels and near-shore marine environments that formed during this overall marine regression (Johnson et al. 1988).

Beginning in the Middle Devonian Period (393 million to 323 million years ago) and continuing into the Middle Mississippian Period (347 million to 331 million years ago), plate collisions generated subduction zones along the western and southern margins of proto-North America (fig. 30). The sea once again advanced onto the continent, depositing the dark, fissile shale of the Woodford Shale (**MDsw**) over the old erosion surface. The lack of benthic (bottom-dwelling) organisms in the Woodford Shale suggests that deposition occurred under anaerobic conditions, which are commonly found in deeper marine environments (Johnson et al. 1988). Similar Upper Devonian–Early Mississippian deep-marine shales were deposited along the western and eastern margins of proto-North America. In the map area, the Woodford Shale ranges from 61 to 213 m (200–700 ft) thick, thickening to the south in the Arbuckle Mountains (Johnson 2008; Blome et al. 2013).

The Middle–Upper Mississippian Caney Shale (**Mc**) contains invertebrate fossils such as conodonts, goniatites, and cephalopods that suggest well-circulated, open marine environments (Blome et al. 2013). The Caney Shale is correlative with the Stanley Group, mapped in the Arkoma Basin and the central Ouachita Mountains of eastern Oklahoma and Arkansas (Johnson et al. 1988; Shaulis et al. 2012). The Stanley Group is composed of deep-marine fan deposits, turbidites, and volcanic tuffs, and it signals the influx of clastic sediments derived from the Alleghenian Orogeny to the east and a volcanic island arc terrane approaching from the south (Johnson et al. 1988; Shaulis et al. 2012).

Phase 3. Uplift and Deformation: Late Mississippian through Pennsylvanian Periods, 331 Million to 299 Million Years Ago

A series of tectonic plate collisions in the Late Mississippian (331 million to 323 million years ago) and Pennsylvanian (323 million to 299 million years ago) along the margins of the continent formed the Appalachian Mountains to the east, the Ouachita Mountains in Arkansas and Oklahoma, and initiated the uplift of the ancestral Rocky Mountains in Colorado. At the time, proto-North America was near the equator, surrounded by tropical seas, which spread into the interior of the continent (Bunker et al. 1988). In present-day southern Oklahoma and in the region of the Southern Oklahoma Aulacogen, folding and thrusting generated regional uplifts and deep basins (Johnson et al. 1988). Pennsylvanian strata in the deepest basins, such as the Anadarko Basin, are at least 5,000 m (16,000 ft) thick.

The Late Mississippian–Early Pennsylvanian Wichita Orogeny uplifted the Arbuckle Mountains and produced the broad northwest–southeast-trending Hunton and Tishomingo anticlines (Johnson et al. 1988; Cardott and Chaplin 1993; Allen 2000; Blome et al. 2013). The Mill Creek syncline formed between these two uplifts and was filled by the sandstone, gray and red shale, limestone conglomerate, and fossiliferous limestone of the Deese Group (**PNd**). Basins rapidly subsided in southern Oklahoma, filling with shale, sandstone, and limestone of the Springer Formation (**PNMs**), and Atoka and Wapanucka formations (**PNaw**) (Johnson 2008).

The Arbuckle Orogeny followed the Wichita Orogeny and produced almost all of the intense folding and major northwest-southwest oriented faulting that is currently preserved in the Arbuckle Mountains (Cardott and Chaplin 1993; Allen 2000; Blome et al. 2013). The surface of the Deese Group was eroded prior to deposition of the Upper Pennsylvanian Vanoss Formation (**PNvs** and **PNvc**). By the Late Pennsylvanian, present-day south-central Oklahoma had been uplifted. Erosion of the exposed carbonate rocks produced the limestone conglomerate that formed the alluvial fans of the Vanoss Formation (fig. 30; Ham 1973; Donovan and Heilen 1988; Donovan and Butaud 1993).

Pennsylvanian rocks contain more reservoirs of oil and gas in Oklahoma than any other geologic period (Boyd 2002). They also contain coal deposits in eastern Oklahoma. Fossil collectors target Pennsylvanian rocks for their exceptional variety and preservation of invertebrate marine fauna, such as brachiopods, crinoids, and bryozoans, as well as shark teeth, petrified wood, and fossil leaves (Johnson 2008).

Phase 4. Erosion Shapes the Modern Landscape: Permian through Quaternary Periods, the Past 299 Million Years.

Permian Period

The Pennsylvanian mountains remained high in the Early Permian, contributing sediment to a shallow sea that spread from west Texas and southeastern New Mexico into western Oklahoma and Nebraska (Johnson 2008). In the Arbuckle Mountains, sediments accumulated and solidified into the shale and sandstone of the Stratford Formation (**Ps**), the youngest Paleozoic formation mapped in the vicinity of Chickasaw National Recreation Area (Blome et al. 2013).

In the later part of the Paleozoic Era, the global landmasses were coming together and would eventually form the supercontinent Pangaea (fig. 31). In the Pennsylvanian and Permian periods, a large portion of the growing supercontinent was centered on the south polar ice cap. The growth and shrinkage of glaciers on the polar ice cap caused world-wide sea level fluctuations. As sea level rose and fell, distinctive stratigraphic cycles developed that consisted of layered marine limestone (representing high sea level), evaporites (representing falling sea level), and terrigenous clastic sediments (representing low sea level). These cycles characterize the Pennsylvanian (323 million to 299 million years ago) and Permian (299 million to 252 million years ago) strata of the midcontinent. The end of the Paleozoic Era (252 million years ago) is marked by the most severe mass extinction event ever to occur on Earth (fig. 5).

Triassic and Jurassic Periods

By the Early Triassic Period, the major landmasses had come together to form Pangaea (fig. 31). Pangaea began to break apart later in the Triassic Period (252 million to 201 million years ago). Rifting along the eastern and southern margins of North America initiated the opening of the Atlantic Ocean and Gulf of Mexico. Erosion stripped any Triassic and Jurassic deposits from present-day southern Oklahoma. An active tectonic margin and subduction zone formed along the western

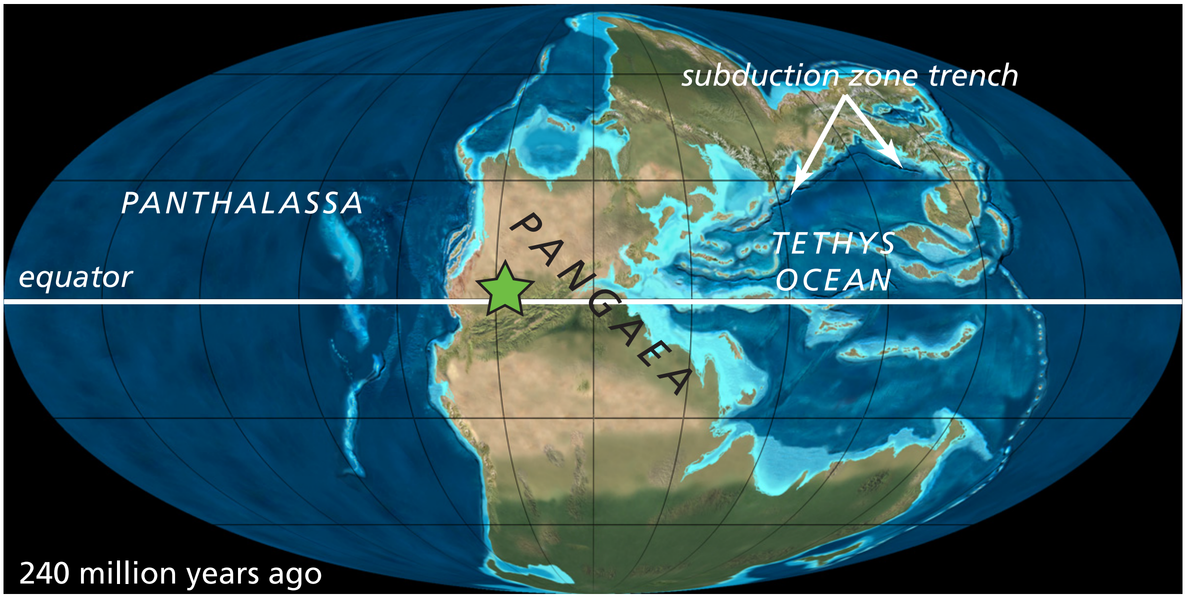

Figure 31. Pangaea. By the Early Triassic Period, all major landmasses had come together to form the supercontinent Pangaea. The C-shaped landmass stretched from pole to pole and surrounded much of the Tethys Ocean. The spine of the "C" was adjacent to a long subduction zone. Much of Earth's surface was covered by a large ocean called Panthalassa. The green star marks the approximate location of Chickasaw National Recreation Area. Annotated by the author. Base paleogeographic map created by Ron Blakey (Colorado Plateau Geosystems, Inc.), available at http://cpgeosystems.com/index.html (accessed 7 May 2014).

margin of North America in the Jurassic Period (201 million to 145 million years ago), producing abundant volcanic activity as plate convergence continued. Triassic and Jurassic fossils in Oklahoma include dinosaur bones, crocodiles, turtles, and fish.

Cretaceous through Quaternary Periods

Millions of years of erosion transformed southeastern Oklahoma into an area of low mountains and hills (Johnson 2008). In the Cretaceous Period (145 to 66 million years ago), plate convergence caused sedimentary strata to be folded and thrust eastward over Precambrian basement rocks, forming mountains along the western margin of North America. These mountains were separated from the midcontinent by the Western Interior Seaway (fig. 30).

Seawater spread northward from the Gulf of Mexico and southward from the Arctic until the seaway extended from today's Gulf of Mexico to the Arctic Ocean, a distance of about 5,000 km (3,000 mi) (Kauffman 1977). A portion of the Gulf of Mexico encroached into southeastern Oklahoma, but did not reach as far north as Chickasaw National Recreation Area (fig. 30; Johnson et al. 1988; Johnson 2008). Cretaceous rocks in southeastern Oklahoma contain shark teeth and marine invertebrate fossils (Johnson 2008).

The shoreline of the Gulf of Mexico continued to retreat southward in the Paleogene (66 million to 23 million years ago) and Neogene (23 million to 2.6 million years ago) periods. As sea level fell, the highlands in south-central and southeastern Oklahoma eroded, providing fine-grained silt and clay to northeastern Texas (Johnson 2008).

The Quaternary Period, the past 2.6 million years of Earth history, is divided into two epochs: (1) the glacial ice ages of the Pleistocene Epoch, and (2) the interglacial Holocene Epoch. All but the most recent 11,700 years is included in the Pleistocene Epoch, which is characterized by massive continental glaciations (ice ages) (fig. 30). Glaciers advanced no farther south than northeastern Kansas, but meltwater from Rocky Mountain alpine glaciers fed major rivers in Oklahoma. Glacial meltwater and increased precipitation in the Pleistocene Epoch created an Oklahoma landscape of southeast-trending rivers and abandoned river terraces (Johnson 2008). The unconsolidated sand, silt, clay, and gravel (**Qal**) deposited along the creeks in Chickasaw National Recreation Area are more recent, Holocene deposits (Blome et al. 2013).

Geologic Map Data

This chapter summarizes the geologic map data available for Chickasaw National Recreation Area. A poster (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 available at the GRI publications website: http://go.nps.gov/gripubs.

Geologic Maps

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

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

Source Maps

The GRI team digitizes paper maps and converts digital data to conform to the GRI GIS data model. The GRI GIS data set includes essential elements of the source maps such as map unit descriptions, a correlation chart of units, a map legend, map notes, cross sections, figures, and references. The GRI team used the following sources to produce the GRI GIS data set for Chickasaw National Recreation Area. These sources also provided information for this report.

Blome, C. D., D. J. Lidke, R. R. Wahl, and J. A. Golab. 2013. Geologic map of Chickasaw National Recreation Area, Murray County, Oklahoma (scale 1:24,000). U. S. Geological Survey Scientific Investigations Map 3258 and pamphlet, Reston, Virginia. http://pubs.usgs.gov/sim/3258/

GRI GIS Data

The GRI team implements a GIS data model that standardizes map deliverables. The data model is available at http://go.nps.gov/gridatamodel. This data model dictates GIS data structure, including layer architecture, feature attribution, and relationships within ESRI ArcGIS software. The GRI team digitized the data for Chickasaw National Recreation Area using data model version 2.1. The GRI Geologic Maps website, http://go.nps.gov/geomaps, provides more information about GRI map products.

GRI GIS data are also available through the NPS Integrated Resource Management Applications (IRMA) portal (https://irma.nps.gov/App/Portal/Home). Enter "GRI" as the search text and select a park from the unit list.

The following components are part of the data set:

- A GIS readme file (chic_gis_readme.pdf) that describes the GRI data formats, naming conventions, extraction instructions, use constraints, and contact information;
- Data in ESRI geodatabase GIS format;
- Layer files with feature symbology (table 8);
- Federal Geographic Data Committee (FGDC)-compliant metadata;
- An ancillary map information document (chic_geology.pdf) that contains information captured from source maps such as map unit descriptions, geologic unit correlation tables, legends, cross-sections, and figures;

- An ESRI map document (chic_geology.mxd) that displays the GRI GIS data; and
- A KML/KMZ version of the data viewable in Google Earth (table 8).

Table 8. Geology data layers in the Chickasaw National Recreation Area GIS data.

Data Layer	On Poster?	Google Earth Layer?
Geologic Cross Section Lines	Yes	Yes
Geologic Attitude Observation Localities (strike and dip)	No	No
Mine Point Features (wells)	No	No
Map Symbology	No	No
Folds	Yes	Yes
Faults	Yes	Yes
Collapsed and Mega-Brecciated Strata Boundaries	Yes	Yes
Collapsed and Mega-Brecciated Strata	Yes	Yes
Geologic Contacts	Yes	Yes
Geologic Units	Yes	Yes

GRI Map Poster

A poster of the GRI digital geologic data draped over a shaded relief image of the recreation area and surrounding area is included with this report. Not all GIS feature classes (data layers) of the digital geologic data are included on the poster (table 8). Geographic information and selected park features have been added to the graphic. Digital elevation data and added geographic information are not included in the GRI GIS data set, but are available online from a variety of sources. Contact GRI for assistance locating these data.

Map Unit Properties Table

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

Use Constraints

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

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

Glossary

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

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

alluvium. Stream-deposited sediment.

anaerobic. Said of an organism (esp. a bacterium) that can live in the absence of free oxygen; said of conditions that exist only in the absence of free oxygen.

angular unconformity. An unconformity between two groups of rocks whose bedding planes are not parallel or in which the older, underlying rocks dip at a different angle (usually steeper) than the younger, overlying strata.

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

antidune. An ephemeral or transient bed form formed on a stream bed (rarely preserved in sediments), similar to a dune but traveling upstream as the individual sand particles move downcurrent, and characterized by erosion on the downstream slope and deposition on the upstream slope. Syn: regressive sand wave.

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

arkose. A commonly coarse-grained, pink or reddish sandstone consisting of abundant feldspar minerals.

artesian. Describes groundwater confined under hydrostatic pressure.

artesian pressure. Hydrostatic pressure of artesian water, often expressed in terms of pounds per square inch at the land surface; or height, in feet above the land surface, of a column of water that would be supported by the pressure.

artesian spring. A spring from which water flows under artesian pressure, usually through a fissure or other opening in the confining bed above the aquifer.

artesian system. Any system incorporating the following: a water source, a body of permeable rock bounded by bodies of distinctly less permeable rock, and a structure enabling water to percolate into and become confined in the permeable rock under pressure distinctly greater than atmospheric.

artesian well. A well that taps confined groundwater. Water in the well rises above the level of the top of the aquifer under artesian pressure.

aulacogen. A sediment-filled continental rift that trends at a high angle to the adjacent continental margin or orogeny. A narrow, elongate basin that extends into the craton either from a passive-margin basin or from a mountain belt that formed from a passive-margin basin.

axis. 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. That part of stream discharge that is not attributable to direct runoff from precipitation or melting snow. It is sustained by groundwater discharge.

basement. The undifferentiated rocks, commonly igneous and metamorphic, that underlie rocks exposed at the surface, commonly sedimentary. In many regions the basement is of Precambrian age, but it may be much younger. Also, Earth's crust below sedimentary deposits that extends down to the Mohorovicic discontinuity.

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 (40 to 80 in) and distinguishable from beds above and below.

bed form. A bedding surface feature that is an individual element of the morphology of a mobile granular or cohesive bed that develops due to local deposition and/or erosion in response to the interaction of a flowing current of air or water.

bedding. Depositional layering or stratification of sediments.

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

benthic. Pertaining to the ocean bottom or organisms living on or in the substrate; also, referring to that environment.

block. A pyroclast ejected in a solid state with a diameter greater than 64 mm (2.5 in).

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

bioturbation. The reworking of sediment by organisms.

bivalve. Having a shell composed of two distinct, but equal or nearly equal, movable valves, which open and shut.

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

breccia. A coarse-grained, generally unsorted sedimentary rock consisting of cemented angular clasts more than 2 mm (0.08 in) across.

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

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

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

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

calcrete. A term for a pedogenic calcareous soil, e.g., limestone consisting of surficial sand and gravel cemented into a hard mass by calcium carbonate precipitated from solution and redeposited through the agency of infiltrating waters, or deposited by the escape of carbon dioxide from vadose water.

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

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

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

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

cephalopod. A marine mollusk of the class Cephalopoda, characterized by a head surrounded by tentacles and, in most fossil forms, by a straight, curved, or coiled calcareous shell divided into chambers. Range: Cambrian to Holocene.

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

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

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

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

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

confined aquifer. An aquifer bounded above and below by confining beds. An aquifer containing confined groundwater.

confined groundwater. Groundwater under pressure significantly greater than that of the atmosphere. Its upper surface is the bottom of a confining bed.

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

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

convergent plate boundary. A boundary between two plates that are moving toward each other. Essentially synonymous with "subduction zone" but used in different contexts.

craton. The relatively old and geologically stable interior of a continent.

crinoid. A marine invertebrate (echinoderm) that uses a stalk to attach itself to a substrate; "arms" are used to capture food. Range: Paleozoic to Holocene, though very common in the Paleozoic and rare today.

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

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

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

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

distal. Said of a sedimentary deposit consisting of fine clastics and formed farthest from the source area.

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

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

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

echinoderm. Any solitary marine benthic (rarely pelagic) invertebrate characterized by radial symmetry, an endoskeleton formed of plates or ossicles composed of crystalline calcite, and a water-vascular system.

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

evaporite. A sedimentary rock composed primarily of minerals produced from a saline solution as a result of extensive or total evaporation of the solvent (usually water).

evapotranspiration. Loss of water from a land area through transpiration (passage of water vapor from a living body through a membrane) of plants and evaporation from the soil and surface-water bodies. Also, the volume of water lost through evapotranspiration.

extension. A type of deformation where Earth's crust is pulled apart.

extrusion. The emission of lava onto Earth's surface; also, the rock so formed.

extrusive. Describes igneous rock that has been erupted onto the surface of the Earth.

facies (sedimentary). The depositional or environmental conditions reflected in the sedimentary structures, textures, mineralogy, fossils, and other components of a sedimentary rock.

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

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

fissile. Capable of being easily split along closely spaced planes.

flow regime. A condition of stream flow defined on the basis of mode of sediment transport, bed form, and flow resistance. Lower flow regime is a flow regime characterized by relatively low sediment transport rates (largely as bed load) and bed forms that are out of phase with the water surface, including ripple, dune, and lower plane bed. Upper flow regime is a flow regime of a unidirectional current that is characterized by relatively high sediment transport rates (with considerable suspended load), bed forms that are in phase with the water surface, including upper plane bed, in-phase waves, and antidunes.

fluvial. Of or pertaining to a river or rivers.

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

footwall. The lower wall of a fault. Compare to "hanging wall."

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

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

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

gastropod. Any mollusk belonging to the class Gastropoda, characterized by a distinct head with eyes and tentacles and, in most, by a single calcareous shell that is closed at the apex, sometimes spiraled, not chambered, and generally asymmetrical (e.g., a snail). Range: Upper Cambrian to Holocene.

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

graptolite. An extinct colonial marine organism belonging to the class Graptolithina, characterized by a cup- or tube-shaped, highly resistant exoskeleton of organic composition, arranged with other individuals along one or more branches (stipes) to form a colony. Commonly occur in black shales.

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

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

hanging wall. The upper wall of a fault. Compare to "footwall."

hydraulic conductivity. The ease with which water moves through spaces or pores in soil or rock.

hydrostatic pressure. The pressure exerted by the water at any given point in a body of water at rest. The hydrostatic pressure of groundwater is generally due to the weight of water at higher levels in the saturated zone.

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

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

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

intrusion. The process of emplacement of magma into preexisting rock. Also, the igneous rock mass formed.

intrusive. Pertaining to intrusion, both the process and the rock body.

ion. An atom or molecule in which the total number of electrons is not equal to the total number of protons, giving the atom or molecule a net positive or negative electrical charge.

isotope. One of two or more species of the same chemical element having the same number of protons in the nucleus, but differing from one another by having a different number of neutrons.

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

klippe. An erosional remnant of a thrust sheet that is completely surrounded by exposure of the footwall. Plural: klippen.

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

lamination. The finest stratification or bedding in a sedimentary rock, typically exhibited by shales and fine-grained sandstones.

lentil. A minor rock-stratigraphic unit of limited geographic extent that thins out in all directions.

limb. One side of a structural fold.

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

losing stream. A stream or reach of a stream that contributes water to the zone of saturation; its channel lies above the water table. Also called an "influent stream."

lower plane bed. A bed configuration of the lower flow regime that is characterized by a flat, almost featureless surface and very low rates of sediment transport.

marl. A term loosely applied to a variety of materials, most of which occur as loose, earthy deposits consisting primarily of a mixture of clay and calcium carbonate; specifically an earthy substance containing 35%–65% clay and 65%–35% carbonate.

marlstone. A sedimentary rock composed of marl.

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

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

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

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

member. A lithostratigraphic unit with definable contacts; a subdivision of a formation.

micrite. The semiopaque crystalline matrix in limestones, consisting of chemically precipitated carbonate mud with crystals less than 4 microns in diameter.

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

nodule. A small, irregularly rounded knot, mass, or lump of a mineral or mineral aggregate, normally having a warty or knobby surface and no internal structure, and usually exhibiting a contrasting composition from the enclosing sediment or rock matrix in which it is embedded.

normal fault. A fault in which the hanging wall appears to have moved downward relative to the footwall; the angle of dip is usually 45°–90°.

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

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

orogeny. A mountain-building event.

ostracode. Any aquatic crustacean belonging to the subclass Ostracoda, characterized by a two-valved (shelled), generally calcified carapace with a hinge along the dorsal margin. Range: Lower Cambrian to Holocene.

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

pelecypod. Any benthic aquatic mollusk belonging to the class Pelecypoda, characterized by a bilaterally symmetrical bivalve shell, a hatchet-shaped foot, and sheetlike gills. Range: Ordovician to Holocene.

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

plane bed. A flat, almost featureless surface that is produced by the interaction of a unidirectional current flowing over a mobile sediment bed (see upper plane bed; lower plane bed).

plate tectonics. A theory of global tectonics in which the lithosphere is divided into about 20 rigid plates that interact with one another at their boundaries, causing seismic and tectonic activity along these boundaries.

porosity. The percentage of total void space in a volume of rock or unconsolidated deposit.

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

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.

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

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

rip-up clast. A mud clast that has been "ripped up" by currents from a semiconsolidated mud deposit and transported to a new depositional site.

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

saturated. Being a solution that is unable to absorb or dissolve any more of a solute (e.g., calcium carbonate).

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

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

sedimentary. Pertaining to or containing sediment.

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

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

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

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

solute. A dissolved substance, e.g., calcium carbonate.

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

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

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

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

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

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

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

subduction. The process of one lithospheric plate descending beneath another.

subduction zone. A long, narrow belt in which subduction takes place.

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

supersaturated. A solution that contains more of the solute (e.g., calcium carbonate) than is normally present when equilibrium is established between the saturated solution and undissolved solute.

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

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

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

terrigenous. Describes material or a feature derived from the land or a continent.

thalweg. The line connecting the lowest/deepest points along a stream bed; the line of maximum depth.

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

thrust sheet. The body of rock above a large-scale thrust fault whose surface is horizontal or very gently dipping.

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

transmissivity. A measure of the amount of water that can be transmitted horizontally through a unit width by the full saturated thickness of the aquifer under a hydraulic gradient of 1.

travertine. A chemical sedimentary rock—the spongy or less compact variety is tufa—composed of precipitated calcium carbonate (predominantly calcite and aragonite) from spring-fed, heated and/or ambient-temperature waters.

trilobite. Any marine arthropod belonging to the class Trilobita, characterized by a three-lobed ovoid outer skeleton, divided lengthwise into axial and side regions and transversely into cephalon ("head"), thorax (middle), and pygidium ("tail"). Range: Lower Cambrian to Permian.

trough cross-bedding. Cross-bedding in which the lower bounding surfaces are curved surfaces or erosion; it results from local scour and subsequent deposition.

unconfined groundwater. Groundwater that has a water table; that is, water not confined under pressure beneath a confining bed.

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

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

unsaturated zone. A subsurface zone between the land surface and the water table that includes air, gases, and water held by capillary action.

upper plane bed. A bed configuration under a unidirectional current that is characterized by a flat, almost featureless surface over which sediment transport is intense, both in suspension and on the bed.

varve. Any cyclic sedimentary couplet, as in certain shales and evaporates. Commonly deposited in a body of still water.

vug. A small cavity in rock, commonly lined with crystals of a different mineral composition from the enclosing rock.

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

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Additional References

These additional references, resources, and websites may be of use to resource managers. Web addresses are valid as of July 2015. 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) *Energy and Minerals; Active Processes and Hazards; Geologic Heritage*: http://nature.nps.gov/geology/
- NPS Geologic Resources Inventory: http://www.nature.nps.gov/geology/inventory/index.cfm.
- NPS Geoscientist-In-the-Parks (GIP) internship and guest scientist program: http://www.nature.nps.gov/geology/gip/index.cfm
- NPS Views program (geology-themed modules are available for Geologic Time, Paleontology, Glaciers, Caves and Karst, Coastal Geology, Volcanoes, and a variety of geologic parks): http://www.nature.nps.gov/views/

NPS Resource Management Guidance and Documents

- 1998 National parks omnibus management act: http://www.gpo.gov/fdsys/pkg/PLAW-105publ391/pdf/PLAW-105publ391.pdf
- Management Policies 2006 (Chapter 4: Natural resource management): http://www.nps.gov/policy/mp/policies.html
- NPS-75: Natural resource inventory and monitoring guideline: http://www.nature.nps.gov/nps75/nps75.pdf
- NPS Natural resource management reference manual #77: http://www.nature.nps.gov/Rm77/
- Geologic monitoring manual (Young, R., and L. Norby, editors. 2009. Geological monitoring. Geological Society of America, Boulder, Colorado): http://nature.nps.gov/geology/monitoring/index.cfm
- NPS Technical Information Center (TIC) (Denver, Colorado; repository for technical documents): http://www.nps.gov/dsc/technicalinfocenter.htm

Climate Change Resources

- NPS Climate Change Response Program Resources: http://www.nps.gov/subjects/climatechange/resources.htm
- US Global Change Research Program: http://globalchange.gov/home
- Intergovernmental Panel on Climate Change: http://www.ipcc.ch/

Geological Surveys and Societies

- Oklahoma Geological Survey: http://www.ogs.ou.edu/homepage.php
- US Geological Survey: http://www.usgs.gov/
- Geological Society of America: http://www.geosociety.org/
- American Geophysical Union: http://sites.agu.org/
- American Geosciences Institute: http://www.americangeosciences.org/
- Association of American State Geologists: http://www.stategeologists.org/

US Geological Survey Reference Tools

- National geologic map database (NGMDB): http://ngmdb.usgs.gov/
- Geologic names lexicon (GEOLEX; geologic unit nomenclature and summary): http://ngmdb.usgs.gov/Geolex/geolex_home.html
- Geographic names information system (GNIS; official listing of place names and geographic features): http://gnis.usgs.gov/
- GeoPDFs (download searchable PDFs of any topographic map in the United States): http://store.usgs.gov (click on "Map Locator")
- Publications warehouse (many publications available online): http://pubs.er.usgs.gov
- Tapestry of time and terrain (descriptions of physiographic provinces): http://tapestry.usgs.gov/Default.html

Appendix A: Scoping Participants

The following people attended the GRI scoping meeting for Chickasaw National Recreation Area, held on17-18 October 2007, or the follow-up report writing conference call, held on 11 March 2014. Discussions during these meetings supplied a foundation for this GRI report. The scoping summary document is available on the GRI publications website: http://go.nps.gov/gripubs.

2007 Scoping Meeting Participants

Name	Affiliation	Position
Back, Jennifer	NPS WRD Water Rights Branch	Hydrologist
Blome, Charles	USGS	Geologist
Burrough, Steve	NPS Chickasaw National Recreation Area	Chief, Resource Management
Carter, Darryl	NPS Chickasaw National Recreation Area	Geologist/bio-tech
Covington, Sid	NPS Geologic Resources Division	Geologist
Faith, Jason	USGS, Oklahoma State University	Geologist
Graham, John	Colorado State University	Geologist, GRI Report Writer
Jarrell, Tim	NPS Chickasaw National Recreation Area	Facility Manager
McCurry, Gail	NPS Chickasaw National Recreation Area	Chief, Administration
Noble, Bruce	NPS Chickasaw National Recreation Area	Superintendent
Osborn, Noel	Oklahoma Water Resources Board	Geologist
Parker, Ron	NPS Chickasaw National Recreation Area	Chief, Interpretation
Peoples, Precious	NPS Chickasaw National Recreation Area	Biologist
Ransmeier, Melanie	NPS Geologic Resources Division	GIS Specialist
Smith, David V.	USGS	Geophysicist
Staples, Susie	NPS Chickasaw National Recreation Area	Secretary
Suneson, Neil	Oklahoma Geological Survey	Geologist

2014 Conference Call Participants

Name	Affiliation	Position
Blome, Charles	US Geological Survey	Geologist, science center director
Graham, John	Colorado State University	Geologist. GRI report writer
Kenworthy, Jason	NPS Geologic Resources Division	Geologist, GRI reports coordinator
Osborn, Noel	Chickasaw National Recreation Area	Chief of Resource Management
Parker, Ron	Chickasaw National Recreation Area	Chief of Interpretation

Appendix B: Geologic Resource Laws, Regulations, and Policies

The NPS Geologic Resources Division developed this table to summarize laws, regulations, and policies that specifically apply to National Park Service minerals and geologic resources. The table does not include laws of general application (e.g., Endangered Species Act, Clean Water Act, Wilderness Act, National Environmental Policy Act, or National Historic Preservation Act). The table does include the NPS Organic Act when it serves as the main authority for protection of a particular resource or when other, more specific laws are not available. Information is current as of July 2015. Contact the NPS Geologic Resources Division for detailed guidance.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Caves and Karst Systems	**Federal Cave Resources Protection Act of 1988, 16 USC §§ 4301 – 4309** requires Interior/Agriculture to identify "significant caves" on Federal lands, regulate/restrict use of those caves as appropriate, and include significant caves in land management planning efforts. Imposes civil and criminal penalties for harming a cave or cave resources. Authorizes Secretaries to withhold information about specific location of a significant cave from a Freedom of Information Act (FOIA) requester. **National Parks Omnibus Management Act of 1998, 16 USC § 5937** protects the confidentiality of the nature and specific location of cave and karst resources.	**36 CFR § 2.1** prohibits possessing/destroying/disturbing…cave resources…in park units. 43 CFR Part 37 states that all NPS caves are "significant" and sets forth procedures for determining/releasing confidential information about specific cave locations to a FOIA requester.	**Section 4.8.1.2** requires NPS to maintain karst integrity, minimize impacts. **Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity. **Section 4.8.2.2** requires NPS to protect caves, allow new development in or on caves if it will not impact cave environment, and to remove existing developments if they impair caves. **Section 6.3.11.2** explains how to manage caves in/adjacent to wilderness.
Paleontology	**National Parks Omnibus Management Act of 1998, 16 USC § 5937** protects the confidentiality of the nature and specific location of paleontological resources and objects. **Paleontological Resources Preservation Act of 2009, 16 USC § 470aaa et seq.** provides for the management and protection of paleontological resources on federal lands.	**36 CFR § 2.1(a)(1)(iii)** prohibits destroying, injuring, defacing, removing, digging or disturbing paleontological specimens or parts thereof. **Prohibition in 36 CFR § 13.35** applies even in Alaska parks, where the surface collection of other geologic resources is permitted. Regulations in association with 2009 PRPA are being finalized (July 2015).	**Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity. **Section 4.8.2.1** emphasizes Inventory and Monitoring, encourages scientific research, directs parks to maintain confidentiality of paleontological information, and allows parks to buy fossils only in accordance with certain criteria.
Rocks and Minerals	**NPS Organic Act, 16 USC § 1 et seq.** directs the NPS to conserve all resources in parks (including rock and mineral resources), unless otherwise authorized by law.	**36 CFR § 2.1** prohibits possessing, destroying, disturbing mineral resources…in park units.	**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
Park Use of Sand and Gravel	**Materials Act of 1947, 30 USC § 601** does not authorize the NPS to dispose of mineral materials outside of park units.	None applicable.	**Section 9.1.3.3** clarifies that only the NPS or its agent can extract park-owned common variety minerals (e.g., sand and gravel), and: -only for park administrative uses; -after compliance with NEPA and other federal, state, and local laws, and a finding of non-impairment; -after finding the use is park's most reasonable alternative based on environment and economics; -parks should use existing pits and create new pits only in accordance with park-wide borrow management plan; -spoil areas must comply with Part 6 standards; and -NPS must evaluate use of external quarries. Any deviation from this policy requires a written waiver from the Secretary, Assistant Secretary, or Director.
Upland and Fluvial Processes	**Rivers and Harbors Appropriation Act of 1899, 33 USC § 403** prohibits the construction of any obstruction on the waters of the United States not authorized by congress or approved by the USACE. **Clean Water Act 33 USC § 1342** requires a permit from the USACE prior to any discharge of dredged or fill material into navigable waters (waters of the US [including streams]). **Executive Order 11988** requires federal agencies to avoid adverse impacts to floodplains. (see also **D.O. 77-2**) **Executive Order 11990** requires plans for potentially affected wetlands (including riparian wetlands). (see also D.O. 77-1)	None applicable.	**Section 4.1** requires NPS to manage natural resources to preserve fundamental physical and biological processes, as well as individual species, features, and plant and animal communities; maintain all components and processes of naturally evolving park ecosystems. **Section 4.1.5** directs the NPS to re-establish natural functions and processes in human-disturbed components of natural systems in parks, unless directed otherwise by Congress. **Section 4.4.2.4** directs the NPS to allow natural recovery of landscapes disturbed by natural phenomena, unless manipulation of the landscape is necessary to protect park development or human safety. **Section 4.6.4** directs the NPS to (1) manage for the preservation of floodplain values; [and] (2) minimize potentially hazardous conditions associated with flooding. **Section 4.6.6** directs the NPS to manage watersheds as complete hydrologic systems and minimize human-caused disturbance to the natural upland processes that deliver water, sediment, and woody debris to streams. **Section 4.8.1** directs the NPS to allow natural geologic processes to proceed unimpeded. Geologic processes…include…erosion and sedimentation…processes. **Section 4.8.2** directs the NPS to protect geologic features from the unacceptable impacts of human activity while allowing natural processes to continue.

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