National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science

Tuzigoot National Monument

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2019/2017

ON THE COVER
Photograph of the Tuzigoot landscape. This view, looking west towards the Black Hills, shows the hilltop pueblo in the monument (left-hand side of the photograph in the middle ground) and an open-water section of Tavasci Marsh. The town of Jerome is in the foothills (right-hand side of the photograph in the background). NPS photograph available at https://www.nps.gov/tuzi/learn/photosmultimedia/photogallery.htm (accessed 3 August 2017).

THIS PAGE
Photograph of the hilltop pueblo at the monument. The Tuzigoot ruins drape down a hill composed of the Verde Formation. The ruins themselves also are composed of stones from the Verde Formation, and the formation underlies the Verde Valley. The Black Hills (in the background) are composed of Precambrian rocks, which are as much as 1.7 billion years old. Photograph by Katie KellerLynn (Colorado State University).

Tuzigoot National Monument

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

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Executive Summary

The Geologic Resources Inventory (GRI) provides geologic map data and pertinent geologic information to support resource management and science-informed decision making in more than 270 natural resource parks throughout the National Park System. The GRI is one of 12 inventories funded by the National Park Service (NPS) Inventory and Monitoring Program. The Geologic Resources Division of the NPS Natural Resource Stewardship and Science Directorate administers the GRI.

This report synthesizes discussions from a scoping meeting held in 2006 and a follow-up conference call held in 2017; Appendix A has participant lists. Chapters of this report highlight the monument's geologic setting and significance, describe its distinctive geologic features, outline the geologic history leading to the present-day landscape, summarize the geologic issues facing resource managers, and provide information about the associated GRI GIS map data.

Tuzigoot National Monument lies in the stunning Verde Valley of central Arizona. According to the monument's foundation document (National Park Service 2016), the valley constitutes a "unique landscape setting" and is an "other important resource and value." Distinctive geologic features of the valley include Precambrian rocks exposed in the Black Hills west of the monument; colorful Paleozoic sedimentary rocks, which crop out in cliffs that surround the valley; the Great Unconformity made famous by its exposure at the bottom of the Grand Canyon; sedimentary and volcanic rocks of the Hickey Formation, which make up the lava-capped mesas in the summit region of the Black Hills; the Verde Formation, which underlies the valley floor and composes the monument's bedrock; and surficial deposits, which record the evolution of the Verde River.

The Verde River, which flows generally southeastward across the Verde Valley, has been an active agent of landscape change for more than 2 million years. As the river incised the Verde Formation (the monument's bedrock), it left a distinct record of surficial deposits and landforms (e.g., river terraces). It also created the conspicuous oxbow (abandoned river channel) near the monument. During archeological excavation in the 1930s, the oxbow inspired a name for the monument—"Tuzigoot"—meaning "crooked water" in Apache. Today, the oxbow contains Tavasci Marsh, which is within the monument, and Pecks Lake, which is nearby and west of the monument.

Ancestral Native American people, called the "Southern Sinagua" by archeologists, built the Tuzigoot pueblo on a ridge composed of the Verde Formation and using material composed of the formation. The summit of the ridgeline is 36 m (120 ft) above the Verde River floodplain. Today from the top of the pueblo, visitors can see the beautiful green ribbon of the Verde River, which was the lifeblood of the Southern Sinagua, who lived here between 1125 and 1400 CE (Houk 1995). Visitors also can see the former mining town of Jerome and the now-silent smelter in Clarkdale, which attest to a legacy of mining in the area.

This report is supported by GRI GIS data compiled from three source maps:

- Lehner (1958) was the source map used in compiling the GRI GIS data, tuzi_geology.mxd. A poster, "Bedrock Geologic Map of Tuzigoot National Monument" (in pocket), illustrates these data. Mapping by Lehner (1958) was completed at a scale of 1:48,000 and covers the Clarkdale quadrangle. Table 3 in the "Geologic Features and Processes" chapter of this report highlights the map units used by Lehner (1958) within the monument.
- House and Pearthree (1993) was the source map used in compiling the GRI GIS data, clar_geology.mxd. A poster, "Surficial Geologic Map of Tuzigoot National Monument" (in pocket), illustrates these data. Mapping by House and Pearthree (1993) was completed at a scale of 1:24,000 and covers the Clarkdale quadrangle. Table 4 in the "Geologic Features and Processes" chapter highlights the map units of House and Pearthree (1993) that occur within the monument.
- DeWitt et al. (2008, scale 1:100,000) was the source map used in compiling the GRI GIS data, motu_geology.mxd. A poster, "Geologic Map of Tuzigoot National Monument" (in pocket), illustrates these data. The motu_geology.mxd data cover the Clarkdale and eight other quadrangles (Munds Draw, Page Spring, Hickey Mountain, Cottonwood, Cornville, Lake Montezuma, Middle Verde, and Camp Verde) as well as parts of the Casner Butte and Walker Mountain quadrangles. These data provide seamless geologic mapping for both Tuzigoot and

Montezuma Castle National Monuments, thereby facilitating correlation (and resource management) between these two NPS areas. Table 5 in the "Geologic Features and Processes" chapter highlights the map units of DeWitt et al. (2008) that occur within Tuzigoot National Monument.

In addition to the aforementioned three tables (3, 4, and 5), which highlight the map units within the monument, this report contains six other tables that highlight the GRI GIS data:

- Table 1 provides a comparison of various features in the monument (e.g., Tavasci Marsh, bedrock underlying the hilltop pueblo, and active channels) as mapped by the source map authors. Table 1 is in the "Geologic Setting and Significance" chapter of this report.
- Table 2 provides a correlation of selected map units among the three source maps that are not within the monument but are of interest for its geologic story, such as the Precambrian Deception Rhyolite (bedrock map unit **PCd**), which are the oldest rocks of the Verde Valley. Table 2 is in the "Geologic Setting and Significance" chapter of this report.
- Table 6 summarizes the geologic resource management issues at the monument and associates them with relevant geologic map units. This table, in "Geologic Resource Management Issues" chapter, also connects map units to the monument's foundation document (National Park Service 2016), highlighting "fundamental resources and values," "other important resources and values," and "interpretive themes." The issues in table 6 and the following discussions are ordered with respect to management priority and include the following: disturbed lands; mine tailings; climate change; flooding; Quaternary faults and earthquakes; slope movements; caves and karst resource management; paleontological resource inventory, monitoring, and protection; geothermal resource management, and instream mining.
- Tables 7, 8, and 9 in the "Geologic Map Data" chapter list the GRI GIS data layers in tuzi_geology.mxd (source map: Lehner 1958), clar_geology.mxd (source map: House and Pearthree 1993), and motu_geology.mxd (source map: DeWitt et al. 2008), respectively.

Other chapters or parts of this report include the following:

- Figure 10 is a geologic time scale based on the international chronostratigraphic chart (International Commission on Stratigraphy 2018); the figure shows the associated geologic eras, periods, and epochs, which are mentioned throughout this report.
- A timeline in the "Geologic History" chapter of this report makes a very long story short. Precambrian rocks (more than 1.7 billion years old) mark the beginning of the geologic history leading up to the present day. The timeline highlights the major geologic events in the monument's landscape evolution, including deposition of its bedrock—the Verde Formation.
- "Literature Cited" is a bibliography of references cited in this GRI report; many of these references are available online, as indicated by an Internet address included as part of the reference citation. If monument managers are interested in other investigations and/or a broader search of the scientific literature, the NPS Geologic Resources Division has collaborated with—and funded—the NPS Technical Information Center (TIC) to maintain a subscription to GEOREF (the premier online geologic citation database). Multiple portals are available for NPS staff to access this database. Monument staff should contact Tim Connors (NPS Geologic Resources Division) for instructions to access GEOREF.
- "Additional Resources" provides online sources of information related to the geologic resource management issues discussed in this report. Of particular note is the "Natural Hazards in Arizona" map viewer at https://azgs.arizona.edu/center-natural-hazards. The Arizona Geological Survey (AZGS) maintains this tool.
- Appendix A provides a list of people who participated in the scoping meeting for the monument in 2006 as well as those who participated in a follow-up conference call in 2017. The list serves as a legacy document and reflects participants' names, affiliations, and positions at the time of scoping and the conference call.
- Appendix B lists laws, regulations, and NPS policies that specifically apply to geologic resources in the National Park System. The NPS Geologic Resources Division can provide policy assistance, as well as technical expertise, regarding the monument's geologic resources.

Products and Acknowledgments

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

GRI Products

The GRI team undertakes three tasks for each park in the Inventory and Monitoring program: (1) conduct a scoping meeting and provide a summary document (i.e., National Park Service 2006), (2) provide digital geologic map data in a geographic information system (GIS) format, and (3) provide a GRI report (this document). The GRI team created these products for the use by 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 to be addressed in the GRI report. Following the scoping meeting, the GRI map team converts the geologic maps identified in the mapping plan to GIS data in accordance with the GRI data model. After the map is completed, the GRI report team uses these data, as well as the scoping summary and additional research, to prepare the GRI report. The GRI team conducts no new fieldwork in association with their products.

The compilation and use of natural resource information by park managers is called for in the 1998 National Parks Omnibus Management Act (§ 204), National Park Service *Management Policies 2006*, and the Natural Resources Inventory and Monitoring Guideline (NPS-75). "Additional Resources" 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 the GRI website (http://go.nps.gov/gri).

Acknowledgments

The GRI team thanks the participants of the 2006 scoping meeting and 2017 conference call (see Appendix A) for their assistance in this inventory. Thanks very much to the Arizona Geological Survey and the US Geological Survey for their maps of the area; this report could not have been completed without them. Thanks to Trista Thornberry-Ehrlich (Colorado State University) for producing many of the graphics in this report.

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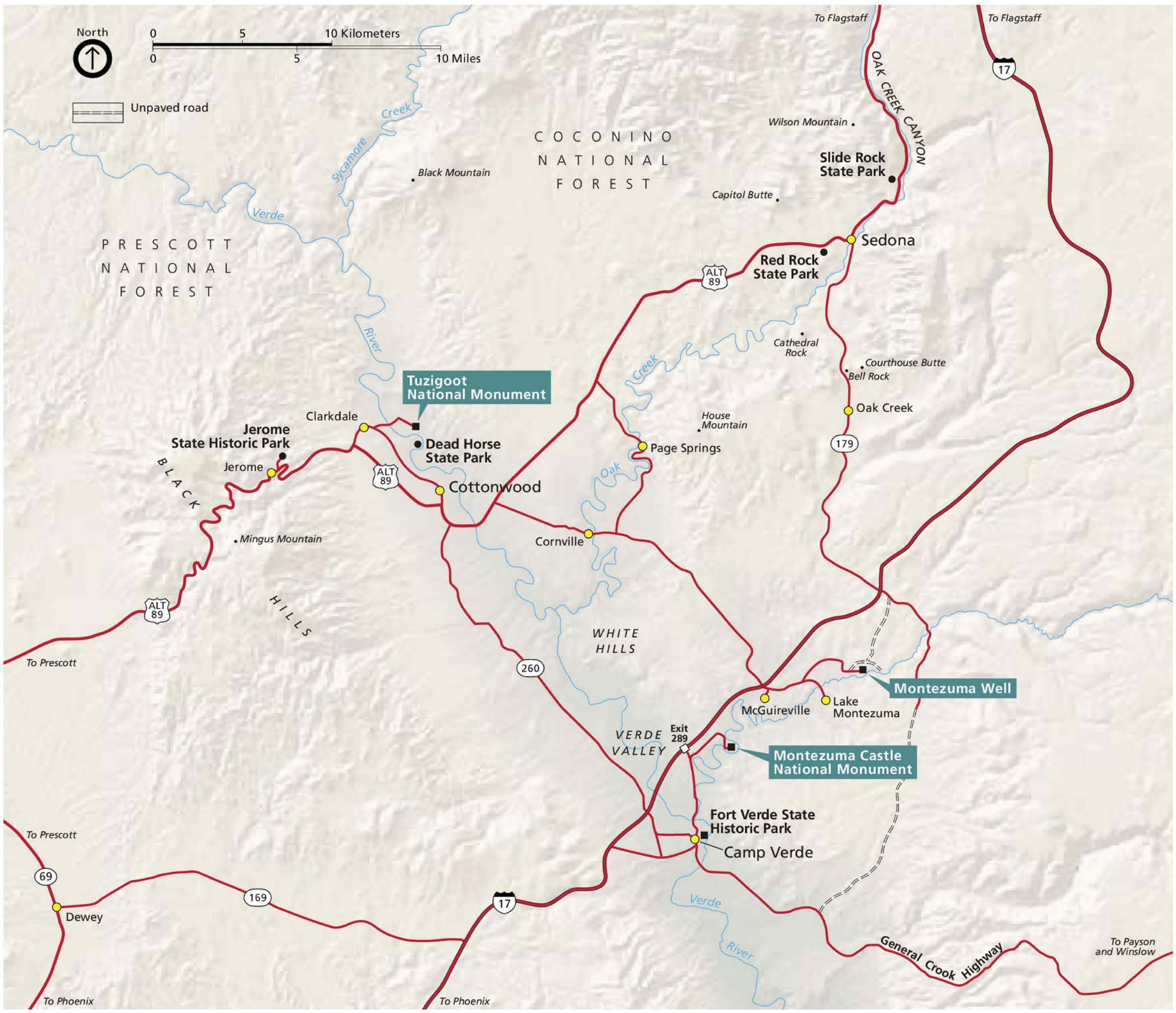

Figure 1. Location map for Tuzigoot National Monument.
The monument is along the Verde River in central Arizona. The closest town is Clarkdale. Many national and state parks are in this scenic part of the state. Other National Park Service areas in the vicinity include Montezuma Castle National Monument, which consists of the Castle and Well Units (see GRI report by KellerLynn in review). State parks include Fort Verde State Historic Park, Dead Horse State Park, Jerome State Historic Park, Red Rock State Park, and Slide Rock State Park. NPS map.

Geologic Setting and Significance

This chapter describes the regional geologic setting of the monument and summarizes connections between geologic resources and other park resources.

Park Establishment

On 25 July 1939, under the authority of the Antiquities Act of 1906, President Franklin D. Roosevelt designated Tuzigoot National Monument. The monument is in Yavapai County, Arizona. The closest town is Clarkdale (fig. 1). "Tuzigoot"—named during the 1930s' archeological excavation of the site—is Apache for "crooked water," describing the oxbow (abandoned meander) of the Verde River that now contains Tavasci Marsh and Pecks Lake (fig. 2). Tavasci Marsh is the largest freshwater marsh in Arizona that is unconnected to the Colorado River (Stoutamire 2011); it is a fundamental resource and value of the monument (National Park Service 2016). Pecks Lake is outside the monument's boundary.

The National Park Service administers 155 ha (382 ac) within a legislative boundary of 338 ha (834 ac) at the monument (fig. 2). The NPS-administered lands encompass the hilltop pueblo of Tuzigoot, the museum/visitor center, an access road to these aforementioned locales, and Tavasci Marsh, which the National Park Service acquired in a land exchange with the Bureau of Land Management and Phelps Dodge Corporation in 2005.

The Verde River is a primary interpretive theme of the monument (National Park Service 2016). Because of the great abundance of readily available, good quality water in a region where water is at a premium, people have inhabited the Verde Valley for centuries. Ancient ruins throughout the area attest to a long and varied history (Twenter and Metzger 1963). The monument contains the largest and best preserved of the many Southern Sinaguan ruins in the Verde Valley. This pueblo ("village") flourished between 1125 and 1400 CE (common era, preferred to AD).

From 1933 to 1935, Louis Caywood and Edward Spicer of the University of Arizona excavated the Tuzigoot ruins. Caywood and Spicer received funding and a workforce from the federal Civil Works Administration and Works Project Administration. In 1935–1936, with additional federal funding, the ruins were prepared for public display, and the visitor center/museum was constructed in a Pueblo Revival style. The visitor center/museum is one of the last New Deal–era buildings still used for its originally designed purpose (National Park Service 2016). On 15 October 1966, the National Register of Historic Places listed the Tuzigoot National Monument Archeological District.

Prehistoric land use in the Verde Valley included farming and construction of irrigation canals, construction of buildings (using the monument's bedrock [Verde Formation] as building stone), and mining of salt (Sutton 1953). During the Miocene Epoch (23.0 million–5.3 million years ago), salt formed as part of the Verde Formation (mapped as evaporite deposits [**Tve**] by DeWitt et al. 2008; see GRI GIS data, motu_geology.mxd). Today, farming, cattle ranching, mining, and urban development are the major land uses (Blasch et al. 2007).

Similar to prehistoric land use, the primary, present-day use of surface water in the Verde Valley is for irrigation of agricultural fields. Many irrigation ditches downstream from the Clarkdale stream-gaging station divert water from the Verde River for this purpose. Groundwater (including spring water) is the source for all domestic, municipal, and industrial water. Some groundwater is also used for irrigation.

Two distinct water sources feed Tavasci Marsh (Beisner et al. 2014). First, the natural source is older, high-elevation recharge entering the marsh at seeps and springs; the largest of which is Shea Spring (fig. 2). The recharge zone for these springs is the Mogollon Rim to the east of the monument (see "Regional Geologic Setting"). The second source of water is younger, low-elevation recharge from Pecks Lake. Water from the Verde River (via Brewer's Tunnel) feeds Pecks Lake. Notably, flooding in February 2019 destroyed Brewer's Tunnel and dam. No rebuilding of the dam is planned (Tina Greenawalt, Tuzigoot and Montezuma Castle National Monuments, chief of Natural Resources, written communication, 3 June 2019).

Regional Geologic Setting

The Verde Valley (see "Verde Valley") lies in a transition zone between two physiographic provinces: the Basin and Range and the Colorado Plateau (fig. 3). The transition zone has characteristics of both provinces. For example, it contains basin-fill sediments (in basins) and uplifted crystalline bedrock (in ranges) characteristic of the Basin and Range as well as flat-lying sedimentary rocks associated with the Colorado Plateau. Moreover, the transition zone, which is a region severely deformed by faulting and uplift, reflects

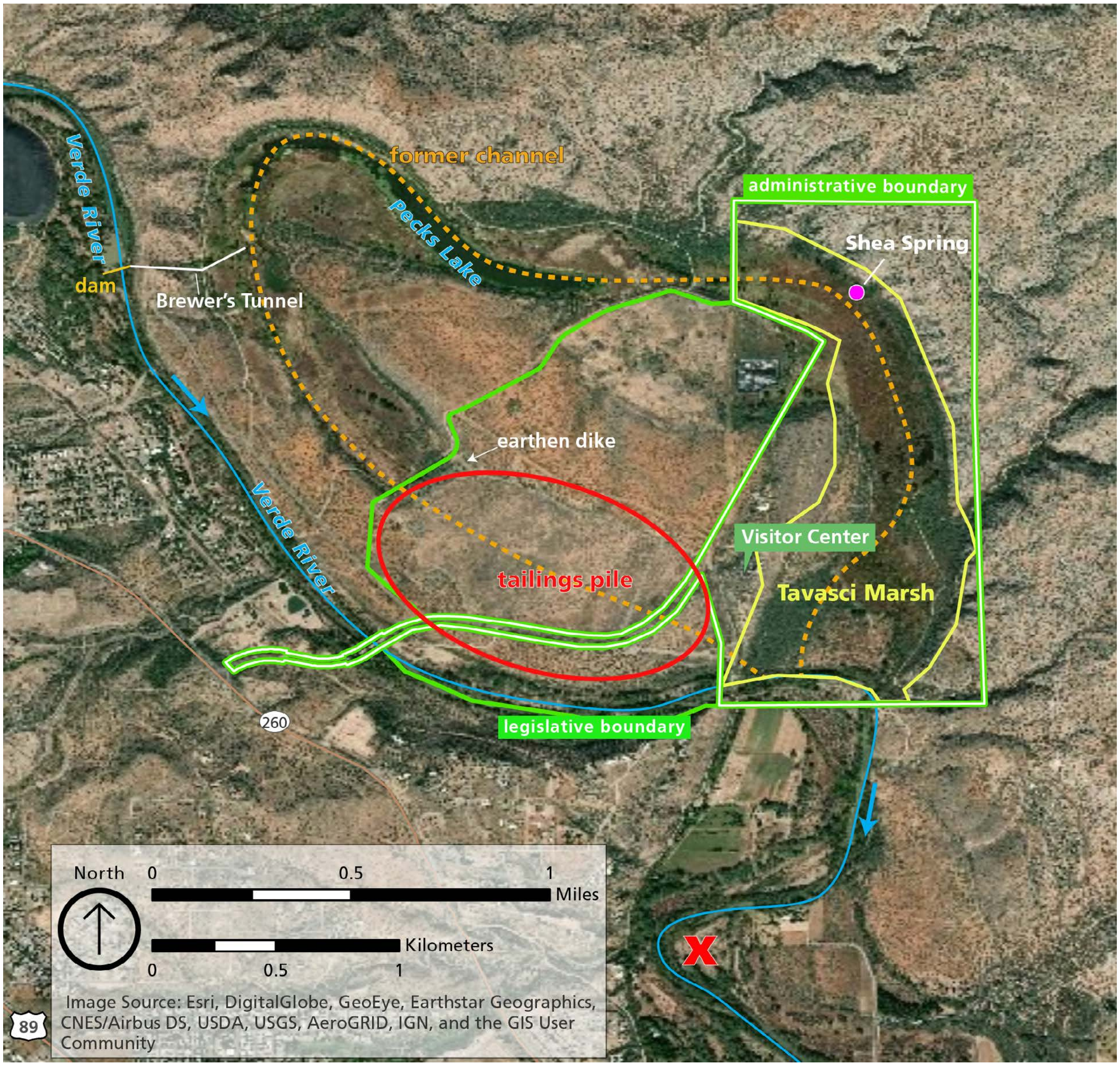

Figure 2. Annotated satellite image of the Verde River near Tuzigoot National Monument.
The National Park Service administers 155 ha (382 ac) (dark green outline) within a legislative boundary (light green outline) that encompasses 338 ha (834 ac) of Tuzigoot National Monument. The blue line marks the present-day channel of the Verde River. Blue arrows mark the direction of streamflow, which is north to south. Tavasci Marsh (outlined in yellow) encompasses much of the administrative boundary. Shea Spring (pink dot) and associated unnamed springs are a source of water to Tavasci Marsh. Pecks Lake is another source of water to the marsh. About 2,600 years ago, the Verde River breached a meander bend and formed an oxbow (abandoned channel). The hashed, orange line marks the former channel. Today, Tavasci Marsh and Pecks Lake are located in the abandoned channel, and mine tailings (circled in red) fill the entrance to the abandoned meander. An earthen dam bounds the northwest side of the tailings pile. At the downstream end of the abandoned meander, the former valley floor now stands several meters higher than the modern active channel. Water from the Verde River (piped through Brewer's Tunnel) supplied Pecks Lake. Flooding in February 2019 destroyed Brewer's Tunnel and dam. No rebuilding of the dam is planned (Tina Greenawalt, Tuzigoot and Montezuma Castle National Monuments, chief of Natural Resources, written communication, 3 June 2019). The red "X" (downstream from the monument) marks an inactive sand-and-gravel mining operation (see "Instream Mining"). Graphic by Rebecca Port (Geologic Resources Division) after Cook et al. (2010b, figure 13) and an NPS image available at https://www.nps.gov/tuzi/learn/nature/wetlands-and-marshes.htm (accessed 10 October 2017).

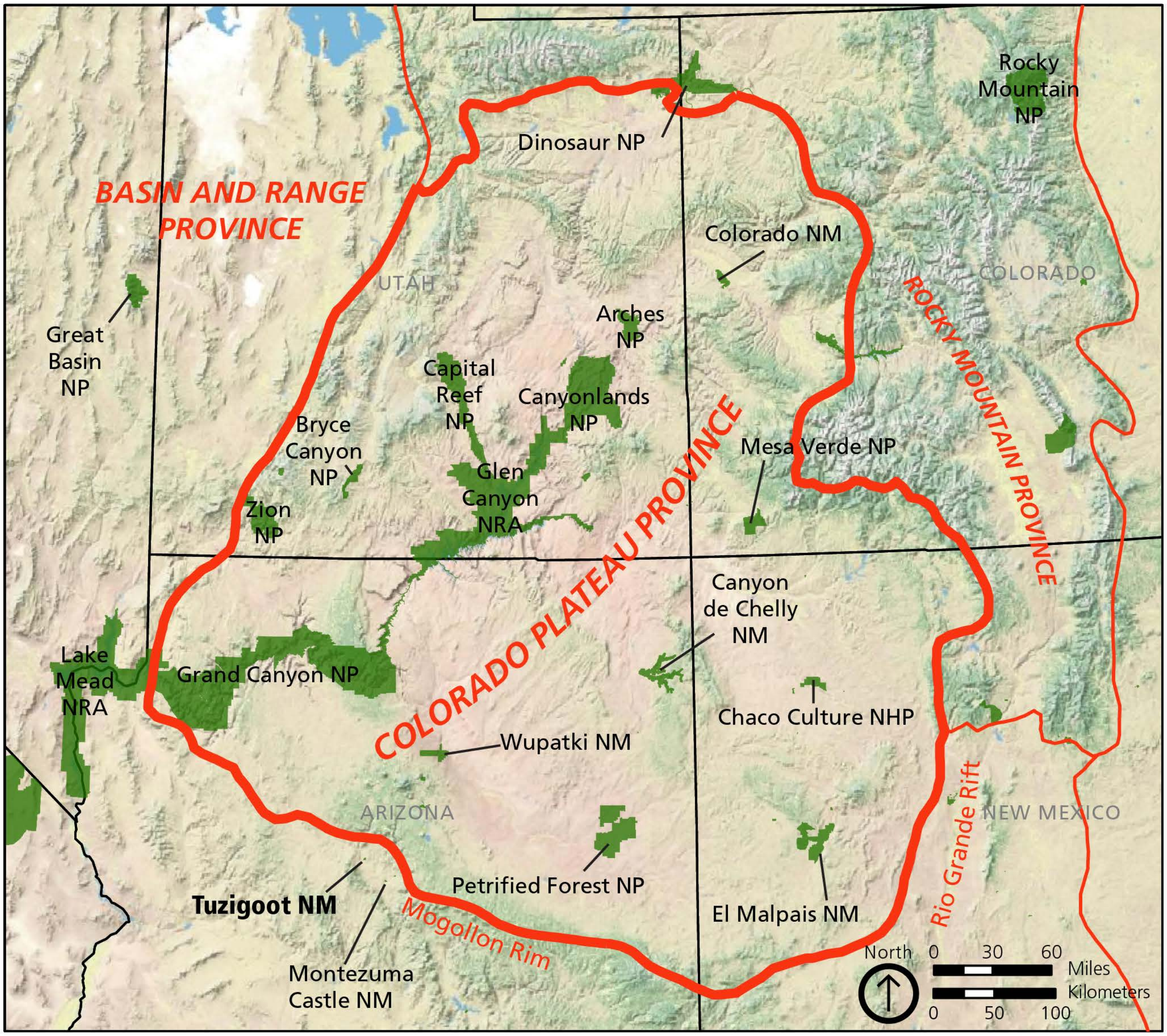

Figure 3. Map of the Four Corners Area of Utah, Colorado, Arizona, and New Mexico. Located in a transition zone between the Colorado Plateau and Basin and Range physiographic provinces, Tuzigoot National Monument is one of many NPS areas in the region. The figure shows these areas in green; labels identify a selection of them. NM = national monument. NP = national park. NRA = national recreation area. Shaded relief imagery compiled by Jason Kenworthy and annotated by Rebecca Port (NPS Geologic Resources Division) from ESRI Arc Image Service, ESRI World Shaded Relief.

episodes of extension (pulling apart of Earth's crust) and normal faulting that are indicative of the Basin and Range (fig. 4) as well as episodes of compression (squeezing together of Earth's crust) and reverse faulting that are indicative of the Colorado Plateau.

Basin and Range

The Basin and Range is a sprawling area that stretches from southeastern Oregon to northern Mexico and encompasses more than half of Arizona; about half of New Mexico and Utah; parts of California, Idaho, Oregon, and Texas; and the entire state of Nevada (Kiver and Harris 1999). As the name implies, the province has mountain ranges—more than 400, if all the small ranges are included—with basins between them.

The Black Hills (west of the monument) are an excellent example of a "range" in the Basin and Range; they are the first major range west of the Colorado Plateau (see "Colorado Plateau"). The uplifted mountain block, referred to as a "fault-block range," is bounded on the

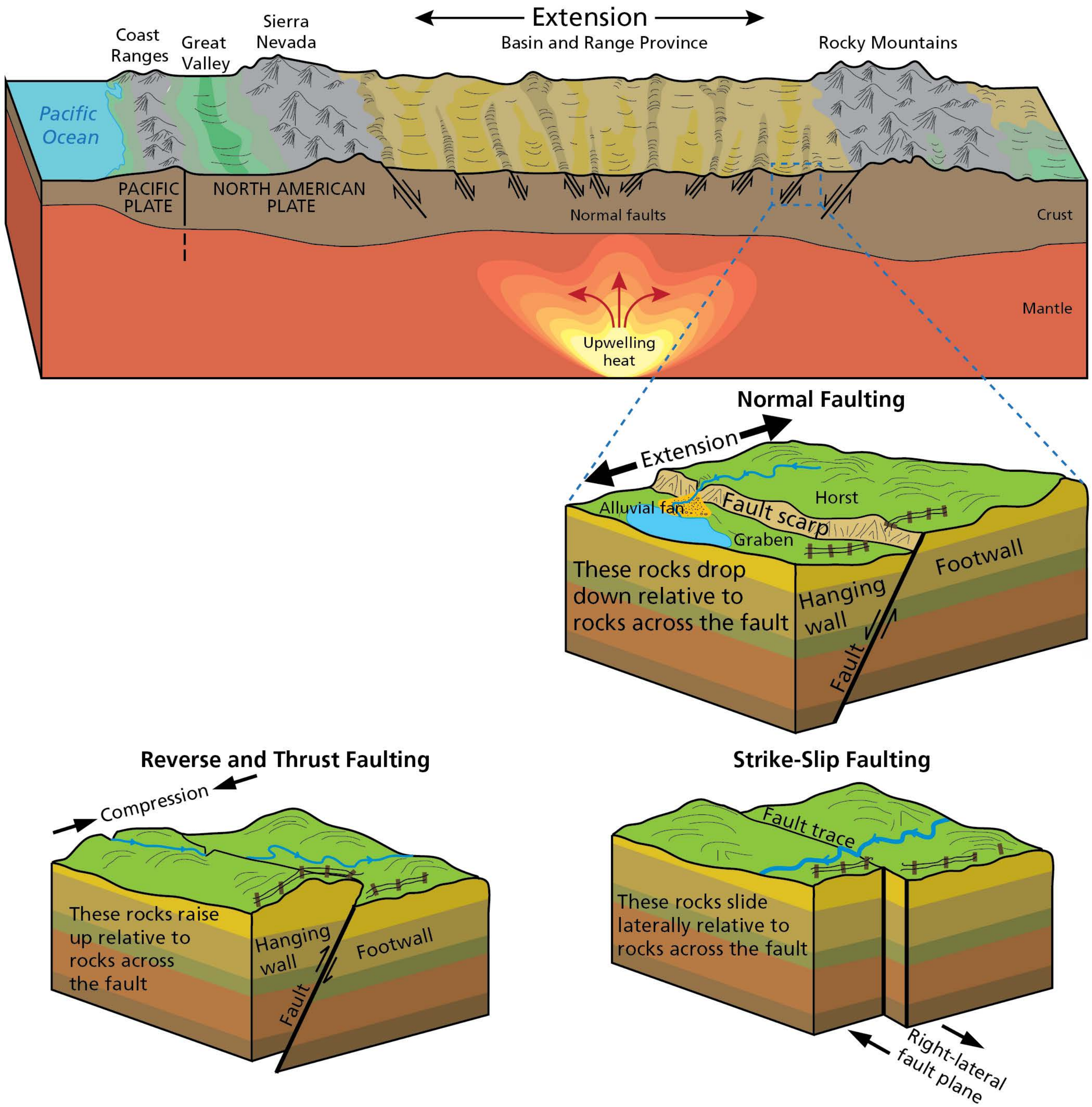

Figure 4. Graphic of Basin and Range extension, normal fault, and other fault types. Extension (pulling apart of Earth's crust) in the Basin and Range physiographic province has caused the crust to thin and crack, creating normal faults. Mountains have been uplifted and basins dropped down along these faults, producing the distinctive alternating pattern of linear mountain ranges (referred to as "horsts") and basins (referred to as "grabens") of the Basin and Range. A fault plane is the locus of movement. Footwalls are below the fault plane, and hanging walls are above. Faults mapped near the monument are normal faults. Reverse and strike-slip are the other two principal types of faults. In a reverse fault, crustal compression (squeezing together) moves the hanging wall up relative to the footwall. A thrust fault is a type of reverse fault that has a dip angle of less than 45°. In a strike-slip fault, movement is horizontal. When movement across a strike-slip fault is to the right, it is a right-lateral strike-slip fault, as illustrated above. When movement is to the left, it is a left-lateral strike-slip fault. Graphic by Trista Thornberry-Ehrlich (Colorado State University), incorporating a figure by Idaho Geologic Survey (2011, p. 2).

east by the Verde fault and on the west by the Coyote fault. The Black Hills moved upward along these faults as the adjacent basins, now marked by the Verde Valley (on the east) and Lonesome Valley (on the west), moved downward. With an elevation of 2,391 m (7,844 ft) above sea level, the highest peak in the Black Hills is Woodchute Mountain. Relief between the Verde Valley and Woodchute Mountain is about 1,400 m (4,500 ft). On the west side of the Black Hills, relief between the center of Lonesome Valley and the top of Woodchute Mountain is about 900 m (3,000 ft).

The Basin and Range landscape started forming about 15 million years ago when Earth's crust began pulling apart. In general, north–south-oriented structural basins, which dropped down along normal faults, separate adjacent uplifted mountain ranges (fig. 4). In some parts of the Basin and Range, for example in the Sonoran Desert subprovince of southern Arizona, the orientation is more northwest to southeast (see GRI report about Casa Grande Ruins National Monument by KellerLynn 2018). Faults shown in the GRI GIS data for Tuzigoot National Monument are normal faults (see bedrock geologic map poster and geologic map poster, in pocket); the fault segments closest to the monument are part of the Verde fault zone (see "Quaternary Faults and Earthquakes").

Many of the basins in the Basin and Range were closed (having no drainage outlet) for much of their histories. Closed basins receive an ever-increasing accumulation of erosional debris, referred to as "basin fill." The bedrock at the monument (Verde Formation) is an example of a basin-filling unit. In much of the Verde Valley, the Verde Formation consists of lacustrine deposits ("lake beds"), including limestone, which is indicative of an ancient lake contained within the basin (see "Verde Formation"). During basin filling, sediment shed from the surrounding highlands, including alluvial fans at the mouths of tributary drainages, is deposited and not transported out of the basin by streamflow. Sediments that make up the Verde Formation accumulated before the through-flowing Verde River cut its way into the basin fill and started transporting sediments out of the basin.

Colorado Plateau

Bounded on the west by the Basin and Range, the Colorado Plateau is a high-elevation region of flat-lying strata in multihued cliffs, broad mesas, steep-sided canyons, and badlands (Baars 1983). The Colorado Plateau comprises deep carved canyons and flat-topped mesas formed by compressional mountain building and erosional episodes, as well as periods of extension and volcanism.

The Colorado Plateau is roughly centered on the Four Corners area of Arizona, Utah, Colorado, and New Mexico (fig. 3). Incorporating 35 National Park System units (organized into the Northern and Southern Colorado Plateau Networks), the Colorado Plateau physiographic province contains the highest concentration of parklands in North America (Kiver and Harris 1999). Spectacular scenery and geology typifies most of these special areas. Many also celebrate fascinating cultural periods and an ancient North American civilization.

The Colorado River, for which the Colorado Plateau was named, and its primary tributaries (Green, Little Colorado, San Juan, and Virgin Rivers) drain most (about 90%) of the plateau southward. A few rivers in the high plateau section (western edge) drain northward and then westward into the Great Basin—the huge "water trap" of the Basin and Range province. A small part of the eastern plateau drains into the Rio Grande.

East of the monument, an abrupt cliff referred to as the "Mogollon Rim" bounds the Colorado Plateau. The Mogollon Rim is a prominent 320-km- (200-mi-) long escarpment. It looms above the floor of the Verde Valley as a sheer precipice ranging in height from 300 to 600 m (1,000 to 2,000 ft). Its elevation is 1,800–2,100 m (6,000–7,000 ft) above sea level along the northern part of the valley and 1,500–1,800 m (5,000–6,000 ft) along the eastern part of the valley. The rim is serrate in outline because youthful streams such as Oak Creek and Sycamore Creek cut steep-walled canyons back into the tableland of the plateau. At places these streams are severing parts of the plateau from the main mass, forming outlying mesas such as Black Mountain (figs. 1 and 5). Inward of the Mogollon Rim, the surface of the plateau is relatively flat, forming an even skyline, except locally where volcanic mountains such as San Francisco and Bill Williams Mountains interrupt this regularity (Lehner 1958).

Verde Valley

The Verde Valley is the monument's viewshed. The Black Hills bound the west side of the valley; the Mogollon Rim bounds the east (see "Regional Geologic Setting"). The Verde River—one of Arizona's last free-flowing river systems—flows through the valley. The river has cut a generally southeastward course through the rugged terrain of central Arizona.

Generally, historians, geologists, and geographers divide the Verde River into upper, middle, and lower reaches (Byrkit 1978). The monument lies along the middle reach, which is below Sycamore Creek but above Fossil Creek (fig. 5). The upper reach contains the headwaters at Big Chino Valley, 150 km (90 mi) northwest of the

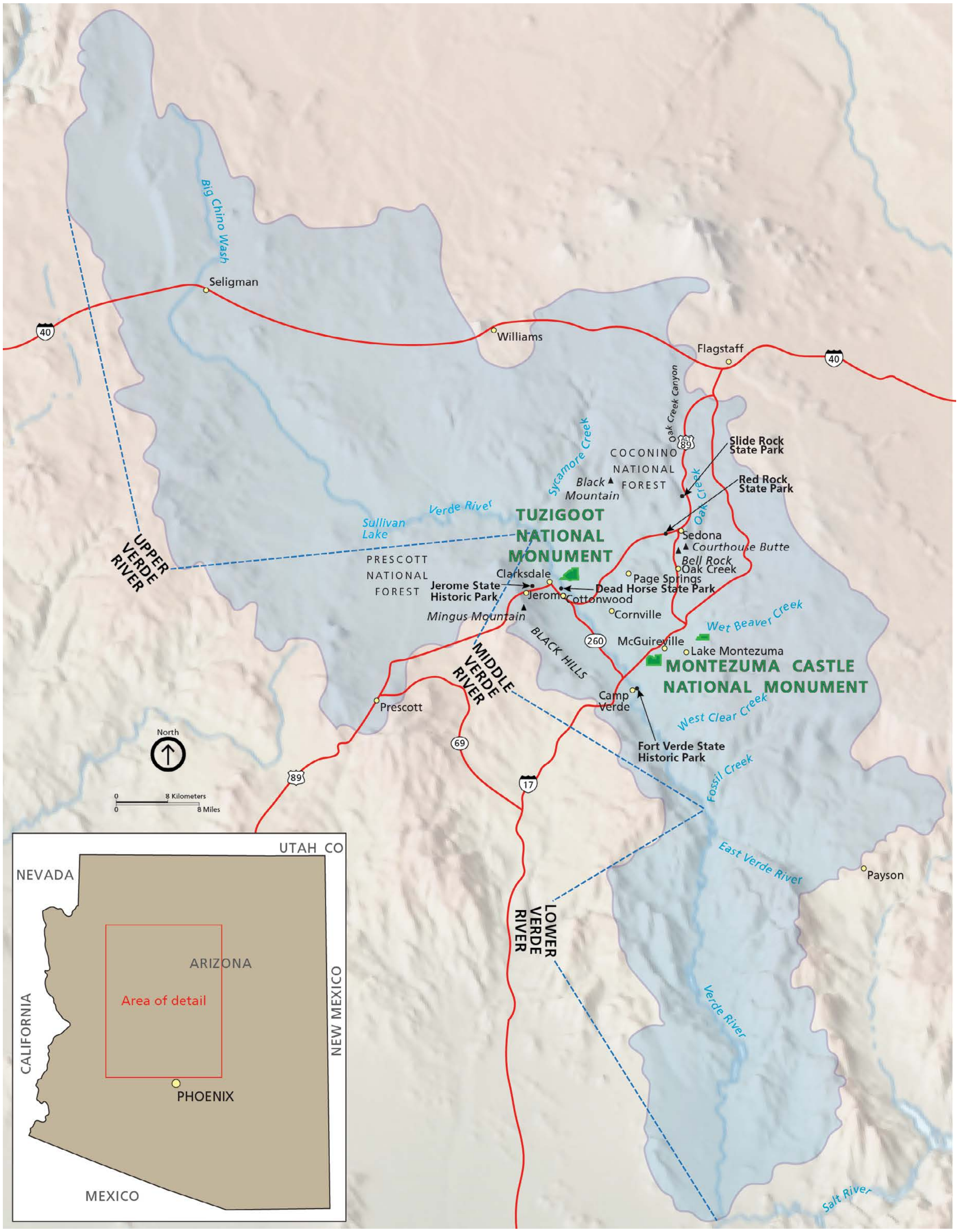

Figure 5. Location map of the Verde River watershed.
The monument is in the Verde Valley of central Arizona. Blue shading delineates the Verde River watershed. Historically the Verde River has been divided into three reaches: upper (above Sycamore Creek), middle (below Sycamore Creek but above Fossil Creek), and lower (below Fossil Creek to the confluence with the Salt River). The monument is located along the middle Verde River. The river is perennial below Sullivan Lake. The figure primarily highlights geographic features (e.g., towns, national and state parks, and named landforms) in the middle Verde Valley. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Friends of the Verde River graphic at https://verderiver.org/verde-watershed-restoration-coalition/vwrc-in-action/state-of-the-watershed/ (accessed 21 August 2019).

monument. The lower reach consists of the segment below Fossil Creek to the confluence with the Salt River east of Phoenix (fig. 5).

The total length of the Verde River, including Big Chino Wash and its tributaries, is about 380 km (240 mi). In the upper reach, Sullivan Dam roughly coincides with the location where the tributaries of Big Chino Wash form a main channel named "Verde River" on USGS topographic maps (Cook et al. 2010b). From just below Sullivan Lake, the Verde River is perennial for about 230 km (140 mi) (Arizona Department of Water Resources 2014), which is a distinctive characteristic among rivers in Arizona (Pearthree 1996).

The Verde River flows through a variety of rock types with varying susceptibility to erosion. In areas where the river flows through resistant bedrock, the valley is steep and narrow, and alluvial deposits and the floodplain are limited in extent. By contrast, near the monument, the Verde River flows through the relatively erodible, ancient lake beds of the Verde Formation, and the river valley is broad, the floodplain is relatively wide, and the potential for significant changes in channel position is great (Pearthree 1996).

Oxbow Formation

As indicated by young terrace deposits (**Qyt**; see surficial geologic map poster, in pocket), the Verde River flowed around the north side of Tuzigoot less than 5,000 years ago (House and Pearthree 1993). Mapping by Cook et al. (2010a) further refined the timing of oxbow formation at 2,600 years ago; work by Davis and Turner (1986) supports this interpretation. When the river breached the neck of the meander and the active channel shifted to the south side of the "Tuzigoot hill," an oxbow (abandoned meander) remained (fig. 2).

Hilltop Pueblo

Between 1125 and 1400 CE, ancestral Native American people, called the "Southern Sinagua" by archeologists, built a hilltop pueblo in what is now the monument. The pueblo drapes down a ridgeline composed of Verde Formation "lake beds," which the source maps by Lehner (1958), House and Pearthree (1993), and DeWitt et al. (2008) mapped as Verde Formation, lacustrine deposits (**QTv**); Verde Formation, lacustrine facies (**Tvl**); and Verde Formation, limestone (**Tvls**), respectively. According to Caywood and Spicer (1935), the builders of the pueblo selected and planned the site to take advantage of the most commanding area available, whether for purposes of protection or for the sheer beauty of the location.

The Southern Sinagua made use of readily available local building materials supplied by the Verde Formation. The pueblo began as a small cluster of rooms then expanded to 110 rooms including a second and possibly third story. The pueblo rises 36 m (120 ft) above the floor of the Verde Valley (fig. 6).

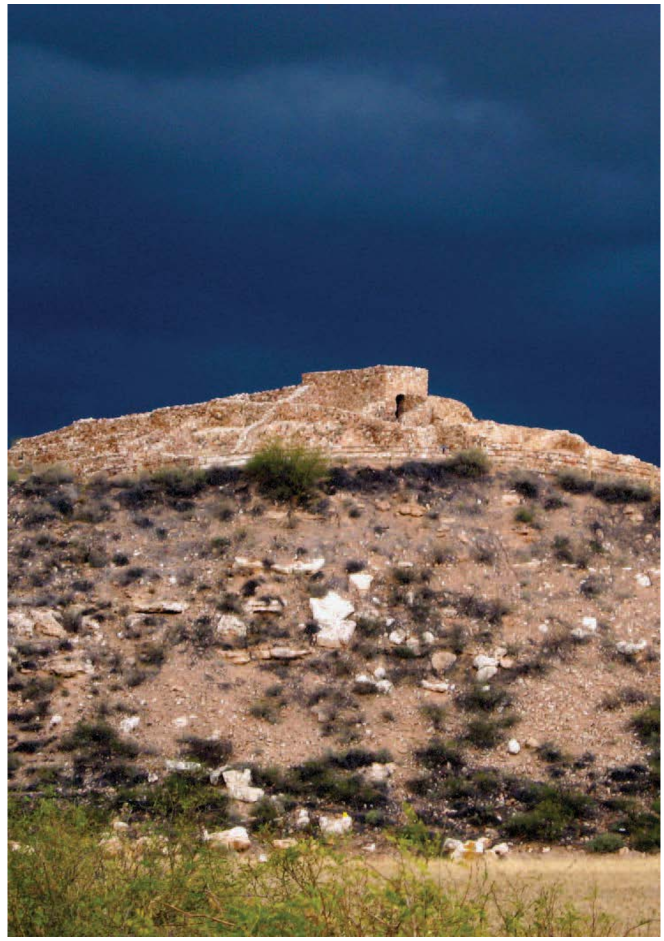

**Figure 6. Photograph of hilltop pueblo.
By about 1150 CE, ancestral Native American people, called the "Southern Sinagua" by archeologists, began building large pueblos, some on hilltops, such as Tuzigoot, and some in alcoves in cliffs, such as Montezuma Castle. The hilltop pueblo at Tuzigoot rises more than 36 m (120 ft) above the valley floor. NPS photograph from National Park Service (2016, p. 18).**

Caywood and Spicer (1935) concluded that the first building that took place at the pueblo was on the summit of the ridge. This deduction is borne out by the remaining evidence of rooms at the top of the ridge that show a clear succession of building and long occupation. By contrast, the rooms at the lowest levels of the ridge offer no indications of long periods of occupation.

According to Caywood and Spicer (1935), the top of the ridge on which the pueblo was built is composed

Figure 7. Photograph of pueblo walls. Southern Sinaguan builders used the Verde Formation in construction of a large pueblo at Tuzigoot. The earliest walls consist of partially consolidated conglomerate composed of basalt, sandstone, and some limestone boulders in a soft matrix of limy material. Walls farther down the slope (see inside-cover photograph) were constructed later than those at the summit. These "younger" walls are composed of material (i.e., irregular blocks of white or pinkish limestone and limy sandstone) that is more homogeneous than the earliest walls. NPS photograph from National Park Service (2016, p. 31).

of partially consolidated conglomerate (a coarse-grained, generally unsorted, sedimentary rock), made up of basalt, red sandstone, and some hard limestone boulders in a soft matrix of limy material. The Southern Sinagua used this material in constructing the earliest walls of the pueblo (fig. 7).

Notably, none of the source map authors included "conglomerate" as part of the Verde Formation, so published geologic mapping does not corroborate Caywood and Spicer's description. All three source maps, however, included "gravel" as part of the Verde Formation, and because gravel is the unconsolidated equivalent of conglomerate (Bates and Jackson 1984), perhaps Caywood and Spicer were describing a remnant gravel deposit (too small to be mapped at a scale of 1:24,000 or greater) at the top of the Tuzigoot hill. A gravel deposit at this location would be farther east than other mapped Verde Formation gravel deposits (**QTvg** of Lehner 1958, **Tvg** of House and Pearthree 1993, and **Tvg** of DeWitt et al. 2008), which are abundant on the slopes west of the monument (see posters, in pocket). Deposits of Verde Formation gravel are primarily concentrated along the eastern flank of the Black Hills and occur as rounded, high-standing hillocks that are conspicuously gray colored. Lehner (1958) suggested that these beds were deposited primarily as fans, which extended into the old Verde lake, periodically interrupting accumulation of fine-grained lake deposits. The result is an intertonguing or interfingering of gravel and lake deposits.

Most of the building stone used in construction of the hilltop pueblo—and according to Caywood and Spicer (1935), the exclusive material of all but the earliest walls—consists of irregular blocks of soft limestone and limy sandstone, white or sometimes pinkish in color. This description by Caywood and Spicer (1935) clearly characterizes the Verde Formation lake beds, which all three source maps interpreted as composing the hill on which the Tuzigoot pueblo was built (map units **QTv**, **Tvl**, and **Tvls**).

Mining History

Nearby towns to the monument, namely Jerome (fig. 8) and Clarkdale, are associated with mining of a massive copper sulfide deposit. Sulfide refers to a mineral compound characterized by the linkage of sulfur with a metal, in this case copper. The copper-bearing deposit at Jerome is exposed at the surface in Precambrian rocks (see "Precambrian Rocks"), which were uplifted as part of the Black Hills block (see "Basin and Range").

Although mining in the area started as early as the 1870s, operations at Jerome did not commence until 1883. Two mines—the United Verde Copper Company and United Verde Extension Company—were located in Jerome. Clarkdale, which is 6 km (4 mi) east–northeast of Jerome and about 2 km (1 mi) east of the monument, grew around a smelter and concentrator for the United Verde Copper Company mine. Clarkdale is owned and controlled by the Phelps Dodge Corporation. The United Verde Extension Company mine and the United Verde Copper Company mine closed in 1938 and 1953, respectively. The smelter in Clarkdale closed in 1951; the concentrator remained active until 1953 (Lehner 1958).

The ore at the United Verde Copper Company mine was high grade: some of the sulfide contained as much as 40% copper, some siliceous (silica-rich) ore contained more than 200 ounces of silver per ton, and some oxide (mineral group composed of oxygen plus an element or elements) ore contained more than 3 ounces of gold per ton (Alenius 1968). The ore from the United Verde Extension Company mine differed from United Verde Copper Company mine ore. That ore is dominantly a very high-grade chalcocite (black or dark lead-gray mineral, Cu_2S) with an average of 15% to 22% copper and only 2 ounces of silver per ton (Lindgren 1926).

The monument is on land once owned by United Verde/Phelps Dodge. The corporation sold the site to Yavapai County for $1 so that an archeological excavation could be completed under the auspices of federal works projects (see “Park Establishment”). The County in turn transferred the land to the federal government. Attesting to the rich copper sulfide deposits in the area, the monument’s museum contains several pieces of copper ore (i.e., azurite and malachite), which were probably used by ancestral Native Americans for pigments to color their garments and bodies (Lehner 1958). Attesting to a history or mining, tailings (milled ore considered too poor in copper to justify further treatment) from the former United Verde Copper Company mine are adjacent to the hilltop pueblo (see “Geologic Resource Management Issues”).

The youngest map units in the monument reflect a legacy of mining (see table 1; figs. 2 and 9). Lehner (1958) mapped quarry and tailings features as artificial fill (**Qaf**). House and Pearthree (1993) mapped areas of tailings (**Qaf2**) and quarry (**Qaf1**); tailings (**Qaf2**) occur within the legislative boundary of the monument. DeWitt et al. (2008) mapped tailings as artificial fill (**Qa**).

Table 1. Comparison among source map units within Tuzigoot National Monument.

Feature	Lehner (1958)	House and Pearthree (1993)	DeWitt et al. (2008)
Tailings	Artificial fill (**Qaf**)	Tailings (**Qaf2**)	Artificial fill (**Qa**)
Active channel deposits	Riverwash (**Qr**)	Active channels of major streams (**Qyr**)	Alluvium (**Qal**)
Tavasci Marsh	Terrace deposits (**Qt**)	Young terraces (**Qyt**)	Terrace gravel (**Qt**)
Verde River deposits (terraces)	Terrace deposits (**Qt**)	Young terraces (**Qyt**) Chuckwalla terrace, younger (**Qct2**) Chuckwalla terrace, older (**Qct1**) Montezuma terraces (**Qmt**)	Terrace gravel (**Qt**)
Tributary stream deposits (alluvial fans)	None mapped	Young piedmont alluvium (**Qyp**) Sheepshead group, older (**Qs1**)	None mapped
Hilltop pueblo	Verde Formation, lacustrine deposits (**QTv**)	Verde Formation, lacustrine facies (**Tvl**)	Verde Formation, limestone (**Tvls**)
Shea Spring and adjacent hillslope	Verde Formation, lacustrine deposits (**QTv**)	Verde Formation, lacustrine facies (**Tvl**)	Verde Formation, undivided sedimentary rocks (**Tvs**)
Monument bedrock	Verde Formation, lacustrine deposits (**QTv**)	Verde Formation, lacustrine facies (**Tvl**)	Verde Formation, undivided sedimentary rocks (**Tvs**) Verde Formation, limestone (**Tvls**)
Reported age of Verde Formation	Tertiary to Pleistocene (probably Pliocene)	Tertiary (Miocene and Pliocene), 8.5 million–2.5 million years old	Pliocene and Miocene, 7 million–2 million years ago
Rock types included in Verde Formation	Limestone, siltstone, and claystone	Freshwater limestone, sandstone, siltstone, and marl	**Tvs**: limestone, claystone, silty limestone, and siltstone **Tvls**: limestone and silty limestone

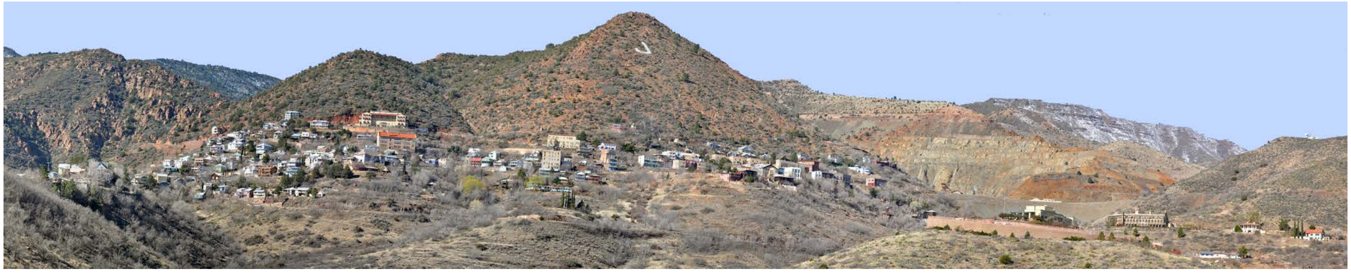

Figure 8. Panoramic photograph of Jerome, Arizona.
This view of the historic mining town is from the Jerome Cemetery. The white "J" (for Jerome) is on a hill locally known as Cleopatra Hill. The United Verde open-pit copper mine, which ceased operations in 1953, and the United Verde Extension mine, which ceased operations in 1938, are to the right of Jerome. This panoramic image, which compiles 28 vertical images in two stacked rows, was created with Autostitch; the stitched images may differ from reality. Original photographs were taken on 11 March 2013. Photograph by Finetooth (Own work) [CC BY-SA 3.0 (https://creativecommons.org/licenses/by-sa/3.0) or GFDL (http://www.gnu.org/copyleft/fdl.html)], via Wikimedia Commons. The photograph is available at https://commons.wikimedia.org/wiki/File%3AJerome%2C_Arizona%2C_wider_panorama.jpg (accessed 14 November 2017).

Figure 9. Photograph of mine tailings.
The legislative boundary of the monument contains approximately 49 ha (121 ac) of mine tailings (Qaf2) as mapped by House and Pearthree (1993). Deposition began in 1927 when the United Verde Copper Company began disposing of copper tailings from its Clarkdale, Arizona, milling operations. In 2007 (after this picture was taken), the Phelps Dodge Corporation capped the tailings pile with a 0.6-m- (2-ft-) thick layer of soil and rock topped by a seed mixture of native plants. Initial plans deemed the plants capable of surviving with local rainfall, thereby requiring no irrigation, and the thickness of the cap sufficient to ensure that all rainfall would either be used by the plant community or evaporate, thus minimizing seepage of minerals and heavy metals from the tailings into the groundwater or the Verde River. However, studies completed to inform a restoration plan for Tavasci Marsh revealed metals and trace elements commonly associated with mining in water, sediment, plants, and aquatic biota (larvae and fish) (see "Mine Tailings"). Photograph by Katie KellerLynn (Colorado State University) taken in May 2006.

Geologic Features and Processes

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

Precambrian Rocks

The Verde Valley has a remarkable geologic history, spanning back more than a billion years. As mapped and described by Lehner (1958), the oldest rocks of the Verde Valley are the Precambrian Deception Rhyolite (**PCd**; table 2). Anderson et al. (1971) isotopically dated zircon from the upper part of the Deception Rhyolite that yielded an apparent age of 1,820 ± 10 million years (i.e., about 1.82 billion years). DeWitt et al. (2008) suggested that an age of 1,740 million years (1.74 billion years) may be more accurate based on unpublished U-Pb zircon data by S. A. Bowring (cited in Karlstrom and Bowring 1991). The closest exposure of the Deception Rhyolite is about 5 km (3 mi) west of the monument in the Black Hills (see bedrock geologic map poster, in pocket).

Lehner (1958) mapped the Deception Rhyolite and other similarly aged rocks in the Verde Valley as "Precambrian" (**PC** map units) whereas House and Pearthree (1993) and DeWitt et al. (2008) mapped the same rocks as "Early Proterozoic" (**X** map units). Traditionally and literally, the Precambrian defines and encompasses all the rocks before the Cambrian Period (now delineated as beginning 541.0 million years ago; fig. 10). The term "Precambrian" still has widespread use, although more recent interpretations and mapping commonly divide this long period (90% of geologic time) into three eons: Hadean (~4.6 billion–4.0 billion years ago), Archean (4.0 billion–2.5 billion years ago), and Proterozoic (2.5 billion–541.0 million years ago). The Archean and Proterozoic are further divided. The "Early Proterozoic" Era (also referred to as the "Paleoproterozoic" Era, 2.5 billion–1.6 billion years ago) is significant for the monument's geologic story.

Table 2. Correlation of selected source map units not within Tuzigoot National Monument.

Generalized Name	Lehner (1958)	House and Pearthree (1993)	DeWitt et al. (2008)
Other Verde Formation units/informal members	Verde Formation, gravel deposits (**QTvg**) Verde Formation, volcanic rocks (**QTvv**)	Verde Formation, gravel facies (**Tvg**)	Verde Formation, lacustrine rocks (**Tvl**) Verde Formation, gravel (**Tvg**) Verde Formation, travertine (**Tvt**) Verde Formation, evaporite rocks (**Tve**) *Note*: **Taby** (alkali basalt), **Tby** (basalt), and **Tdy** (dacite) of "younger volcanic and sedimentary rocks" are equivalent to **QTvv** of Lehner (1958), but DeWitt et al. (2008) did not map them as part of the Verde Formation.
Hickey Formation	Hickey Formation, volcanic rocks (**Thv**) Hickey Formation, sedimentary rocks (**Ths**)	Basalt (**Tb**) Note: **Tb** includes both Hickey Formation and basalt flows in the Verde Formation.	Hickey Formation, alkali basalt (**Thab**) Hickey Formation, basalt (**Thb**) Hickey Formation, trachyandesite (**Tha**) Hickey Formation, basalt and sedimentary rocks (**Thbs**) Hickey Formation, sedimentary rocks and basalt (**Thsb**) Hickey Formation, sedimentary rocks (**Ths**)

Table 2 (continued). Correlation of selected source map units not within Tuzigoot National Monument.

Generalized Name	Lehner (1958)	House and Pearthree (1993)	DeWitt et al. (2008)
Paleozoic rocks	Kaibab Limestone, Toroweep Formation, and Coconino Sandstone are not exposed in the Clarkdale quadrangle, so Lehner (1958) did not map them.	Sedimentary rocks (**PZs**)	Kaibab Limestone (**Pk**) Kaibab Limestone and Toroweep Formation, undivided (**Pkt**) Toroweep Formation and Coconino Sandstone, undivided (**Ptc**) Note: DeWitt et al. (2008) covers a larger area than Lehner (1958).
	Supai Formation, upper member (**Psu**)	Sedimentary rocks (**PZs**)	Schnebly Hill Formation (**Psh**)
	Supai Formation, middle member (**Psm**)	Sedimentary rocks (**PZs**)	Hermit Formation (**Ph**)
	Supai Formation, lower member (**PPNsl**)	Sedimentary rocks (**PZs**)	Supai Formation (**PNs**)
	Redwall Limestone (**Mr**)	Sedimentary rocks (**PZs**)	Redwall Limestone (**Mr**)
	None mapped	Sedimentary rocks (**PZs**)	Redwall Limestone and Martin Formation, undivided (**Mdm**)
	Martin Formation (**Dm**)	Sedimentary rocks (**PZs**)	Martin Formation (**Dm**)
	None mapped	Sedimentary rocks (**PZs**)	Martin Formation and Tapeats Sandstone, undivided (**DCmt**)
	Tapeats Sandstone (**Ct**)	Sedimentary rocks (**PZs**)	Tapeats Sandstone (**Ct**)
Precambrian/ Early Proterozoic rocks	Gabbro (**PCg**) Quartz porphyry (**PCq**) Grapevine Gulch (**PCgg**) Deception Rhyolite (**PCd**)	Metavolcanics (**Xmv**)	"**X**" map units Tonalitic rocks (4 map units) Gabbroic rocks (19 map units) *Note*: Descriptions by DeWitt et al. (2008) identify which "gabbroic rocks" are part of Deception Rhyolite (6 map units) and which are part of Grapevine Gulch Formation (7 map units).

In the 541 million years that have passed since Precambrian time, geologic processes above and below Earth's surface have dramatically altered most rocks of Precambrian age. Consequently, Precambrian rocks are typically grouped and described in broad terms consisting of rock types, for example "Precambrian igneous and metamorphic rocks," because clues to their origins have been destroyed. House and Pearthree (1993), for example, grouped the Precambrian rocks in the vicinity of the monument and referred to them as Early Proterozoic "metavolcanics" (**Xmv**; volcanic rocks that have been subjected to metamorphism). Grouping of bedrock units by these authors also is likely due to a focus on the surficial deposits of the Verde Valley (table 4). Nonetheless, the Precambrian rocks in the Verde Valley are distinctive compared to Precambrian rocks elsewhere because even though regional metamorphism (and hydrothermal alteration around the ore deposits at Jerome) altered Precambrian rocks in the Black Hills, investigators have been able to determine the original nature of these rocks and map them as separate units (Anderson and Creasey 1958). Lehner (1958), for example, mapped four Precambrian units: two by formation name (Deception Rhyolite and Grapevine Gulch Formation) and two by rock type (gabbro and quartz porphyry). DeWitt et al. (2008), which covers a greater area than the map by Lehner (1958), mapped 25 Precambrian units by rock type (see GRI GIS data). DeWitt et al. (2008) incorporated the Deception Rhyolite and Grapevine Gulch Formation as part of Early Proterozoic "gabbroic rocks" (table 2).

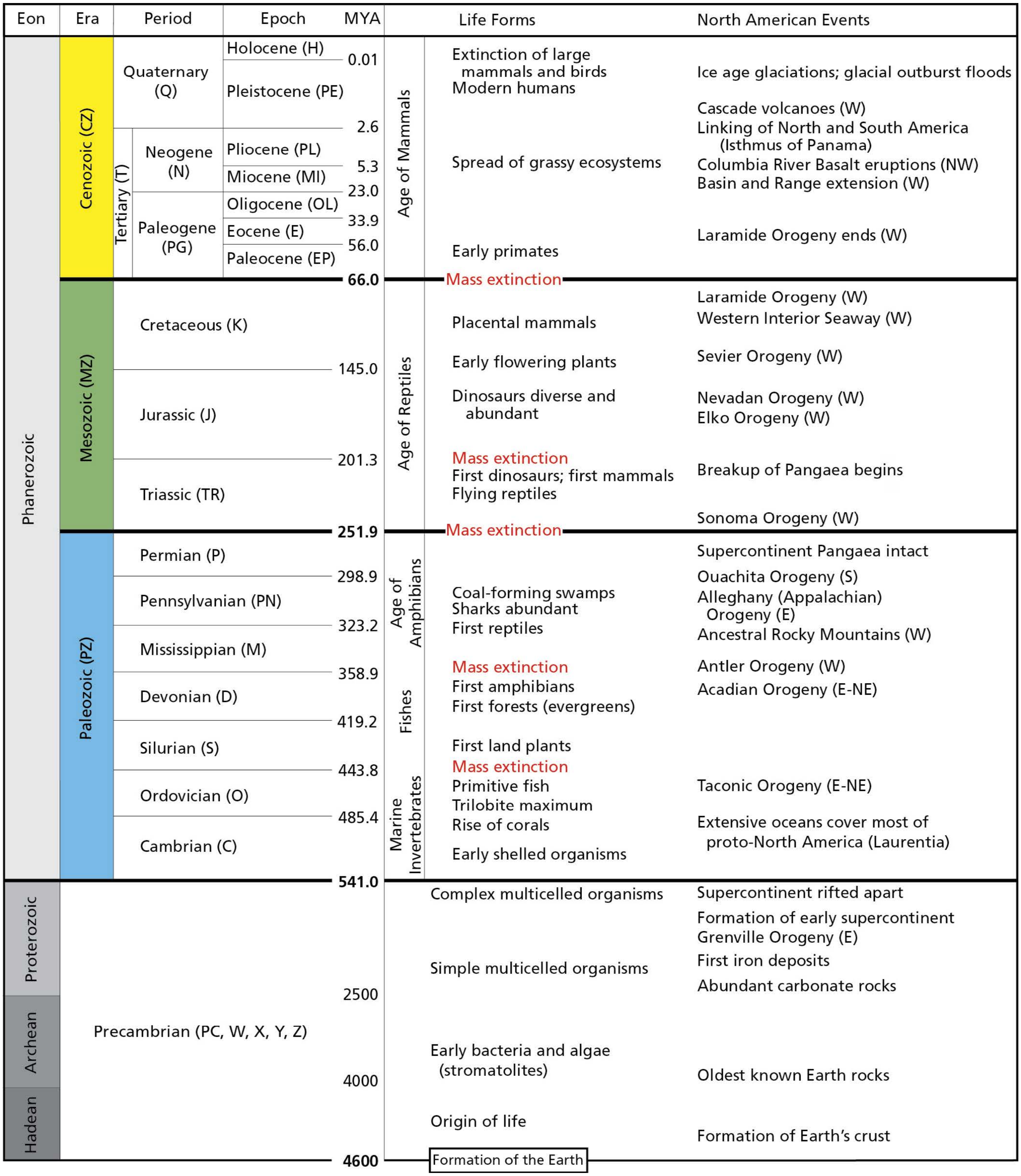

Figure 10. Geologic time scale.
The geologic time scale puts the divisions of geologic time in stratigraphic order, with the oldest divisions at the bottom and the youngest at the top. GRI map abbreviations for each time division are in parentheses. Rocks in the GRI GIS data are Precambrian (PC) or Early Proterozoic (X), Paleozoic (PZ), Tertiary (T), and Quaternary (Q). Compass directions in parentheses indicate the regional locations of events. Boundary ages are millions of years ago (MYA). NPS graphic using dates from the International Commission on Stratigraphy (2018).

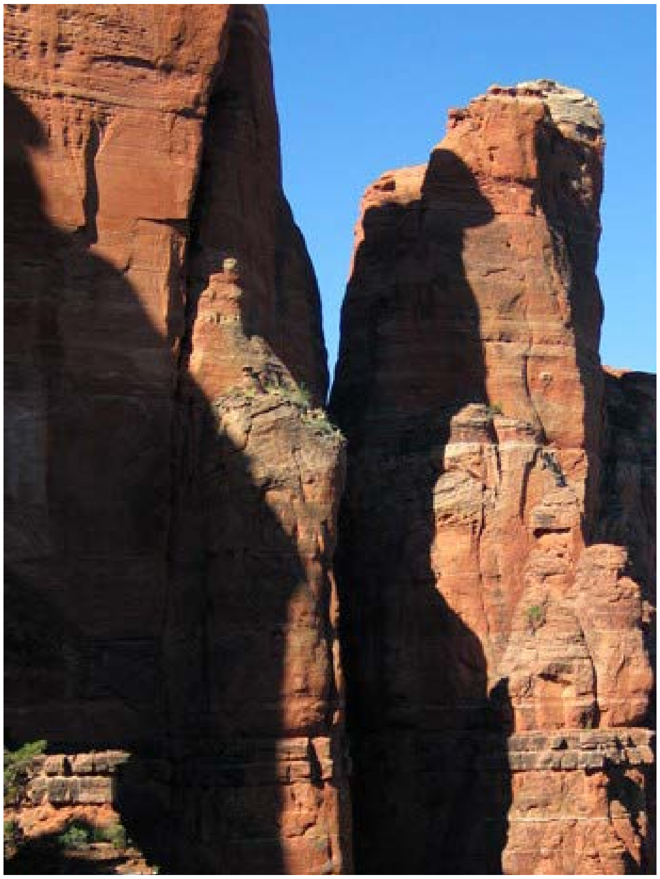

Figure 11. Photograph of the Schnebly Hill Formation.
The uppermost part of the Supai Group, now known as the Schnebly Hills Formation (see table 2), characterizes the famous "red rock country" near Sedona. This is one of the most picturesque areas of the Verde Valley due to the brilliant red color and great thicknesses of the rocks of the Supai Group, which have eroded into steep-walled cliffs, buttes, and spires. The Schnebly Hill Formation was deposited during the early Permian Period (298.9 million–272.9 million years ago). Photograph by Ron Blakey (Northern Arizona University).

Paleozoic Rocks

Cliffs and mountains surrounding the Verde Valley expose rocks of the Paleozoic Era (541.0 million–251.9 million years ago), including the colorful, widespread Supai Formation (now formally known as the Supai Group) (fig. 11). In geologic terminology, a "formation" is the fundamental rock-stratigraphic unit. It is mappable, lithologically distinct (with respect to rock type and other characteristics such as color, mineral composition, and grain size) from adjoining strata, and has definable upper and lower contacts. Considerations such as the scale of base maps, purpose of a mapping project, the kind and number of exposures of the strata, the experience and skill of the mapper(s), and the extent of previous geologic study and mapping of surrounding areas determine the "mappability" of unit. As the building block of geologic nomenclature, a formation may be divided into "members" or combined with other formations into a "group." The US Geologic Names Lexicon ("Geolex"; https://ngmdb.usgs.gov/Geolex/search) is a national compilation of names and descriptions of geologic units, including formation, members, and groups. The terms "Formation," "Member," and "Group" are capitalized when they are part of an official name (i.e., found in Geolex).

Depending on the objective of a mapping project, source map authors of the GRI GIS data for the monument included from one to 11 Paleozoic map units (table 2). Changes in interpretation, including correlation of the rocks in the Verde Valley to those in the Grand Canyon (fig. 12), affected the number of units mapped. For example, Lehner (1958) divided the Supai Formation into three members: lower (**PPNsl**), middle (**Psm**), and upper (**Psu**). Since mapping by Lehner (1958), McKee (1975) elevated the Supai Formation to group status and divided it into four formations, oldest to youngest: Watahomigi, Manakacha, and Wescogame Formations, and the Esplanade Sandstone. These four formations compose the lower member (**PPNsl**) of Lehner (1958). The middle member (**Psm**) has been reassigned to the Hermit Formation, and the upper member (**Psu**) has been reassigned to the Schnebly Hill Formation (Blakey and Knepp 1989; Blakey 1990). This interpretation is in wide use today. For the most part, DeWitt et al. (2008) followed this revised nomenclature, which was a primary reason for adding it to the GRI GIS data for the monument (see "Geologic Map Data").

Unconformities

The Paleozoic rocks in the Verde Valley unconformably overlie the Precambrian rocks. Layers of rock are referred to as "conformable" where they are found to have been deposited essentially without interruption. Although particular sites may exhibit conformable beds representing significant spans of geologic time, no place on Earth contains a full set of conformable strata. Breaks in conformable strata are called "unconformities." Each unconformity represents a period when deposition ceased or where erosion removed previously formed rocks. Because unconformities may be widespread across a region, they can be useful for correlating rock units and tectonic history over long distances, for example between the Grand Canyon and the Verde Valley (fig. 12).

The Great Unconformity, perhaps the world's most famous unconformity, is another distinction of the

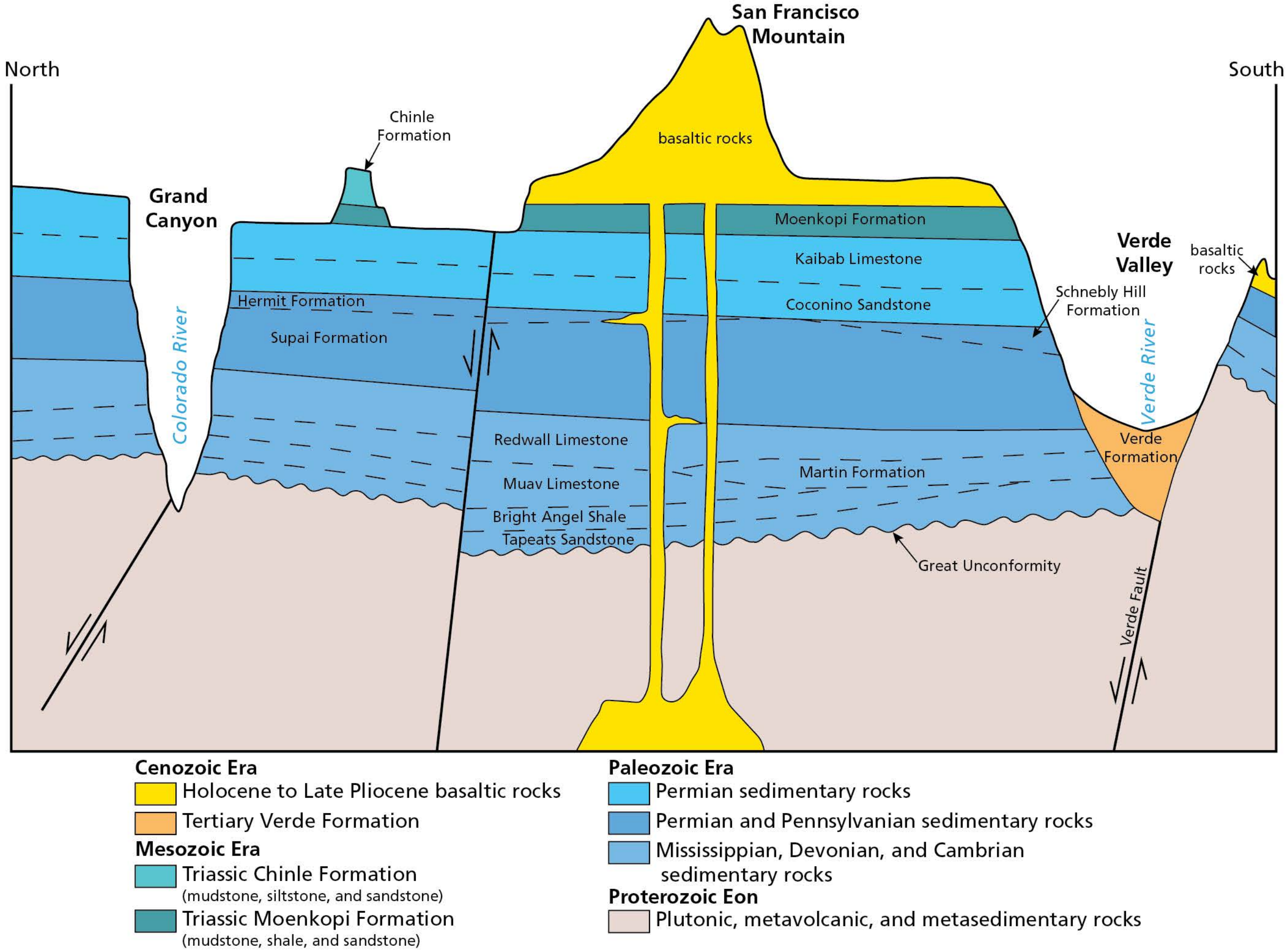

Figure 12. Generalized cross section between the Verde Valley and Grand Canyon. Tuzigoot National Monument is in the Verde Valley, which is underlain by the Verde Formation. In the time since mapping by Lehner (1958), the rocks exposed in the Verde Valley have been correlated with rocks in the Grand Canyon region. Formation names on the cross section follow DeWitt et al. (2008). The Bright Angel Shale, Muav Limestone, Moenkopi Formation, and Chinle Formation are not included in the GRI GIS data. The Great Unconformity, which is the surface between the Proterozoic (also referred to as "Precambrian") rocks and the Paleozoic (Cambrian) Tapeats Sandstone, is marked on the figure. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Blasch et al. (2007, figure 23).

Verde Valley's rock record. Most people know and recognize the Great Unconformity by its appearance (and excellent exposure) at the bottom of the Grand Canyon (fig. 13). In 1869, John Wesley Powell—the one-armed soldier, explorer, ethnologist, and geologist who led the first trip down the Colorado River by boat, including the first trip through the Grand Canyon—was the first person to record this exceptional unconformity. Five-hundred-million-year-old (Cambrian) sandstone is above the unconformity; 1.75-billion-year-old (Precambrian) gneiss (a metamorphic rock with alternating bands of dark and light minerals) is below the unconformity. In the Verde Valley, the Great Unconformity represents 1.2 billion years of geologic time between the Precambrian igneous rocks in the Black Hills and the Paleozoic (Cambrian) Tapeats Sandstone encircling the valley.

Notably, the entire Mesozoic Era (251.9 million–66.0 million years ago) is missing from the middle Verde Valley's rock record, though Triassic rocks (Moenkopi Formation) crop out just to the north in the upper reaches of Sycamore Canyon (figs. 1 and 5). Mesozoic rocks of similar age were probably deposited in the Verde Valley but were subsequently removed by erosion (Twenter and Metzger 1963).

Figure 13. Photograph of the Great Unconformity in Grand Canyon National Park.
Of the many unconformities (gaps) in geologic strata throughout the world, the Great Unconformity is probably the most well-known. Above and below the unconformity, the rocks represent vastly different origins and times in Earth's history. The unconformity represents a gap of 1.25 billion years in the Grand Canyon's rock record. Lisa Graves (left) and Bob Biek (right) have their hands on the Great Unconformity at Blacktail Canyon (between Colorado River Mile 120 to 121). The unconformity is well displayed at this popular stop on the Colorado River within the Grand Canyon. Photograph courtesy of Bob Biek (Utah Geological Survey).

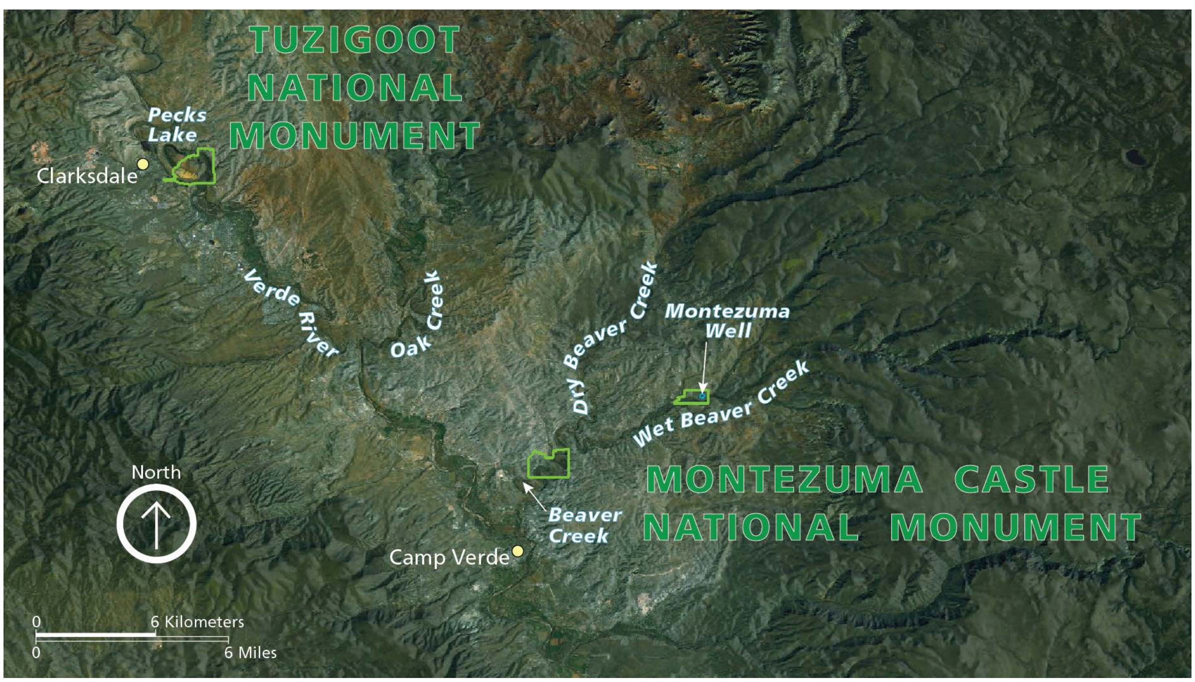

Figure 14. Annotated satellite image of the middle Verde Valley.
The Verde Formation, which makes up the bedrock of the monument, appears as a white "dusting" over much of the Verde Valley. The formation covers a generally elliptical area of about 840 km2 (330 mi2). Graphic by Trista Thornberry-Ehrlich (Colorado State University) using base imagery from ESRI ArcGIS World Imagery.

Hickey Formation

The Cenozoic Era (the past 66 million years) follows the Mesozoic Era, which is "missing" from the Verde Valley (see "Unconformities"). The oldest Cenozoic strata in the Verde Valley are the Tertiary Hickey Formation, sedimentary rocks (table 2). These rocks are composed chiefly of former stream deposits.

Following deposition of these sedimentary rocks, most of which eroded away, several periods of volcanic activity ensued. The Tertiary Hickey Formation, volcanic rocks (table 2), represents this volcanic episode. Using the potassium-argon (K-Ar) dating method on basalt (whole rock) of the Hickey Formation, McKee and Anderson (1971) acquired ages of 10.1 million ± 400,000 to 14.0 million ± 600,000 years old for this episode of volcanism.

The Black Hills had not yet been uplifted when the Hickey Formation erupted, so great quantities of lava spread across the landscape. Mingus Mountain represents a major eruptive center. Thick accumulations of Hickey Formation basalt are exposed at the top of Mingus Mountain, as well as on Hickey and Woodchute Mountains. Today, these mountains compose the summit region of the Black Hills.

Verde Formation

The monument's bedrock consists of the Tertiary, and by some accounts Quaternary (see "Age of the Verde Formation"), Verde Formation, which underlies the Verde Valley (figs. 12 and 14). The formation is complex and consists of sedimentary rocks such as limestone, mudstone, claystone, siltstone, sandstone, and marl (an earthy mixture of clay and calcium carbonate), as well as evaporite ("salts" deposited from aqueous solution as a result of extensive or total evaporation) and gravel deposits (composed of pebbles and cobbles representative of surrounding bedrock) (fig. 15). In addition, Lehner (1958) included volcanic rocks (map unit **QTvv**, e.g., lava flows) as part of the Verde Formation, though not within the monument (table 3). Furthermore, DeWitt et al. (2008) included travertine (map unit **Tvt**) as part of the Verde Formation, though not within the monument (table 5). Travertine is especially abundant near Montezuma Well (see GRI report about Montezuma Castle National Monument by KellerLynn in review).

The Verde Formation accumulated in a down-dropped structural basin whose boundaries, according to Twenter and Metzger (1963), were about the same as those of the present-day Verde Valley. Notably, the Verde basin predates the modern, through-flowing Verde River and associated valley (see "Age of the Verde Formation").

For much of its 5-million-year history, the Verde basin was "closed" (no outflowing drainage) because of structural subsidence related to Basin and Range extension. Damming of drainage by lava flows associated with the Verde Formation at the southern end of the basin also may have played a role in closing off the basin, which led to the accumulation of basin-filling sediments and the formation of a lake. Intermittent tributary streams, flowing into the basin from the surrounding highlands, carried loads of very coarse to very fine rock fragments. Tributary streams deposited the coarse fragments (gravel and sand) along the margin of the basin, primarily as alluvial fans, and carried the fine fragments (silt) out onto the floor of the basin. Limestone precipitated in the deeper waters of the lake. Mudstone developed in shallower water as well as in isolated ponds that bordered the lake. During dry periods, evaporite deposits accumulated along with mudstone in ephemeral ponds (Twenter and Metzger 1963). Travertine formed in parts of the basin where groundwater discharged onto the land surface, forming terraces or mounds (see GRI report about Montezuma Castle National Monument by KellerLynn in review).

Since its initial description and naming by Jenkins (1923), the Verde Formation's complexity has resulted in differences in interpretation and mapping by various investigators throughout the Verde Valley and within the monument (table 1). Twenter and Metzger (1963) were the first to map the formation into facies; each facies has a characteristic set of properties—such as color, mineral constituents, grain size, and sedimentary structures—owing to its deposition in a particular environment (fig. 15). The source maps by Lehner (1958) and House and Pearthree (1993) mapped all the exposures within the monument as ancient lake beds, that is, lacustrine deposits (**QTv**) and lacustrine facies (**Tvl**), respectively (see bedrock and surficial geologic map posters, in pocket). Similarly, DeWitt et al. (2008) mapped the rocks underlying the hilltop pueblo as limestone (**Tvls**) (lake deposits in the deepest part of the basin) but mapped the hillslope adjacent to Tavasci Marsh as undivided sedimentary rocks (**Tvs**, consisting of limestone, claystone, silty limestone, and siltstone) (see geologic map poster, in pocket; and table 1). Differences in mapping and interpretation highlight the complexity of the Verde Formation and the variety of settings within the Verde basin at the time of deposition.

Age of the Verde Formation

The age of the Verde Formation is significant because, on the one hand, it corresponds to the timing of Basin and Range extension in central Arizona and tectonic development of the Verde basin, and on the other hand, to the timing of incision of the Verde River and

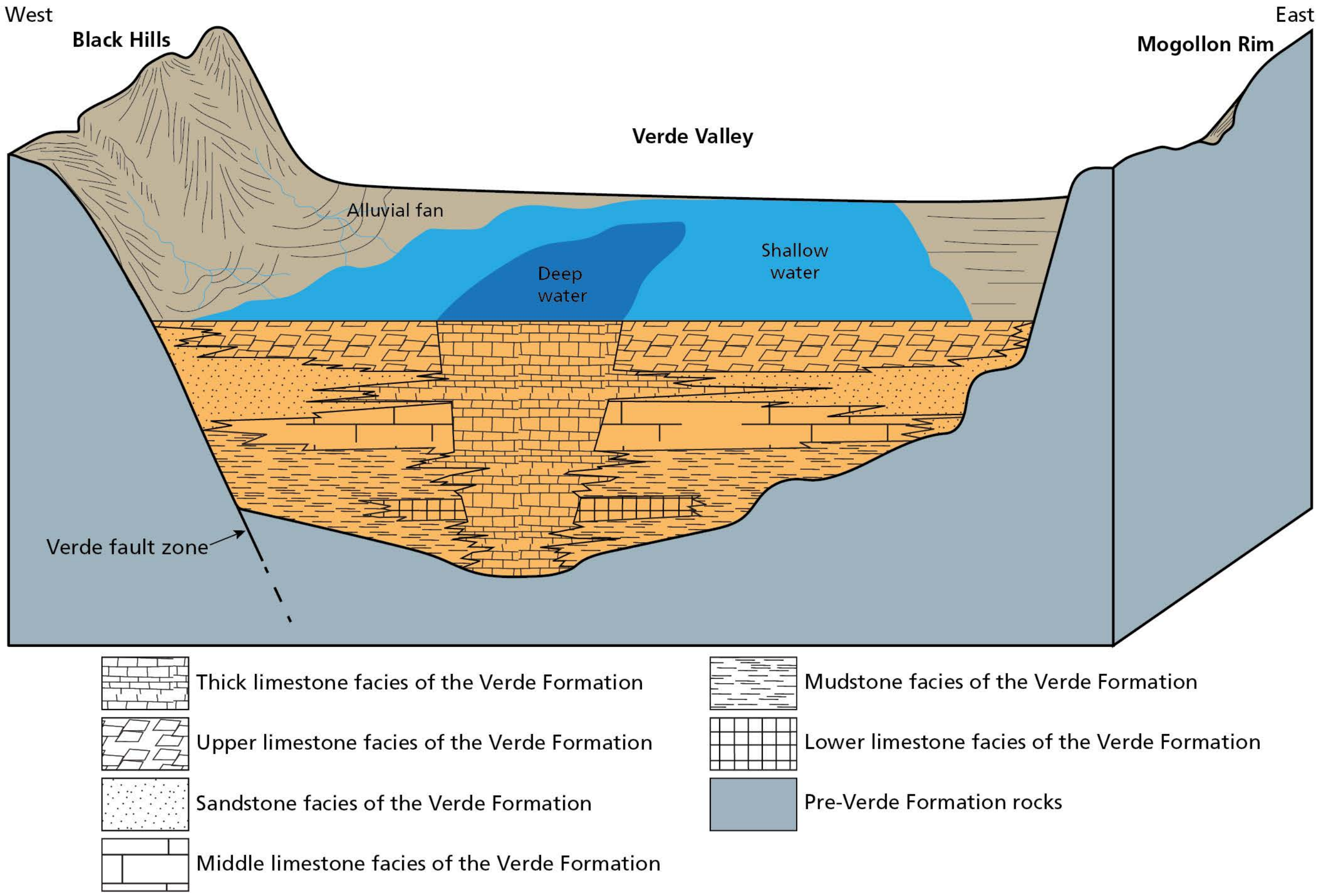

Figure 15. Graphic of Verde Formation facies.
Facies record changes within the depositional setting, particularly differences among adjacent units. Each facies has a characteristic set of properties, for example, color, lithology (e.g., type and size of rock fragments), texture, and sedimentary structures. Twenter and Metzger (1963) were the first to divide the Verde Formation into facies. They defined six facies: The thick, limestone facies developed in deep water; it is undifferentiated and includes the upper, middle, and lower limestone faces, which extend laterally from the thick limestone faces. The sandstone facies consists of coarse grains of alluvial fans from tributary valleys. The mudstone facies consists of fine-grained sediments deposited in shallow lake waters, as well as evaporite minerals. Travertine, which is distinctive to the area surrounding Montezuma Well, was not included in this model by Twenter and Metzger (1963). Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Twenter and Metzger (1963, figure 25).

development of the Verde Valley. These two geologic events are key to understanding the monument's geologic setting.

The age of the Verde Formation has been reported as old as Miocene and as young as Pleistocene. Jenkins (1923) proposed a late Pliocene or very early Pleistocene age whereas Mahard (1949) concluded that the Verde Formation is of Pleistocene age. Anderson and Creasey (1958) stated that the age is uncertain but that the Verde Formation was clearly younger than the Hickey Formation; on their map (plate 1) the suggested age is Pliocene or Pleistocene. Based on potassium-argon (K-Ar) ages (5.5 million ± 200,000 years and 4.5 million ± 200,000 years) from basalt (whole rock), McKee and Anderson (1971) considered the Verde Formation to be Pliocene. Nations et al. (1982) summarized the fossil occurrences in the Verde Formation, which indicated a late Pliocene (Blancan) age for the upper part of the formation. Geolex (the official compilation of names and descriptions of US geologic units) reports a geologic age of Miocene and Pliocene, which covers 23.0 million to 2.6 million years ago.

With respect to the source maps, Lehner (1958) provided a tentative age that extended from the late Tertiary, probably Pliocene, to the Pleistocene Epoch. This age assignment is represented by the "**T**" for Tertiary and "**Q**" for Quaternary in the map unit symbols (**QTvv**, **QTvg**, and **QTv**) used by Lehner (1958). House and Pearthree (1993) correlated the formation to the Tertiary (late Miocene to Pliocene Epochs), which is represented by the "**T**" in the map unit symbols used in that project (**Tvg**, **Tvl**, and **Tvu**). DeWitt et al. (2008) interpreted the formation as Pliocene and Miocene, with four of the informal members—undivided sedimentary rocks (**Tvs**), lacustrine rocks (**Tvl**), limestone (**Tvls**), and gravel (**Tvg**)—accumulating from Miocene to Pliocene time while travertine (**Tvt**) accumulated during only the Pliocene Epoch and evaporite beds (**Tve**) accumulated during only the Miocene Epoch.

A few investigators have provided numeric ages. Bressler and Butler (1977) concluded that the Verde basin experienced nearly continuous sedimentation from approximately 7.5 million to 2.5 million years ago. House and Pearthree (1993) suggested a numeric age of approximately 8.5 million to 2.5 million years for the Verde Formation. DeWitt et al. (2008) reported an age of about 7 million to 2 million years old for the Verde Formation. Interpreters at the monument could use any of these numeric ages in interpretive talks or materials; this report uses the dates of House and Pearthree (1999) (see "Geologic History").

Surficial Deposits

The term "surficial deposits" refers to the unconsolidated sediments lying on the ground surface, typically above bedrock. Various geologic agents such as rivers, tributary streams, wind, and gravity work these sediments into landforms such as terraces, alluvial fans, loess (windblown dust), and talus.

House and Pearthree (1993) provided a detailed interpretation of the surficial deposits in the Verde Valley. They divided these deposits into two categories: groups and terraces. Groups and terraces developed after deposition of the Verde Formation, starting about 2.5 million years ago (House and Pearthree 1993; see "Geologic History" chapter).

Groups consist of surficial deposits on the piedmont (the gently sloping area at the base of a mountain); these deposits are remnants of alluvial fans that entered the main Verde Valley from tributary drainages. Although the characteristic landform of groups is an alluvial fan, a group may include some terraces (discussed below) in the tributary drainage. With the exception of the Sheepshead group, which has no corresponding terraces, the piedmont groups are roughly correlated with river terraces. Groups (alluvial-fan deposits) show that net downcutting of the Verde Valley has included some periods of aggradation (accumulation/buildup of sediments).

Terraces are the characteristic landform of rivers, in this case the middle Verde River. Terraces, which are former, now-abandoned floodplains, step up from the modern floodplain. They record downward incision of the river through time, so older terraces are higher above the modern river channel than younger terraces. Multiple terraces indicate that incision of the valley was not steady (Connell et al. 2005). In the case of the Verde Valley, incision, for the most part, has characterized the past 2.5 million years (Pearthree 1996). This long-term tendency may be related to regional uplift associated with Basin and Range extension during the Pliocene, Pleistocene, and Holocene Epochs (Péwé 1978; Menges and Pearthree 1989). Major stream downcutting and basin dissection was initiated when the through-going Verde River began to breach the natural dam at the southeastern end of the valley (see "Verde Formation"). This transformation occurred sometime in the latest Pliocene Epoch (Bressler and Butler 1978; Nations et al. 1981).

With respect to the modern Verde River floodplain and channel, all three of the source maps designate a single surficial deposit/map unit: Lehner (1958) referred to the material as riverwash (**Qr**). House and Pearthree (1993) mapped active channels of major streams (**Qyr**). DeWitt et al. (2008) mapped alluvium (**Qal**) (table 1).

Table 3. Bedrock map (Lehner 1958; tuzi_geology.mxd) units in Tuzigoot National Monument.

Refer to table 5 for definitions of geologic terms. The geologic time periods are part of the Cenozoic Era, which extends from 66 million years ago to today (fig. 10).

Period (Epoch)	Map Unit (symbol)	Geologic Description
Quaternary (Holocene)	Artificial Fill (**Qaf**)	Quarry and tailings features related to historic mining activity and mineral resource development.
Quaternary (Holocene)	Riverwash (**Qr**)	Fine to coarse, poorly sorted gravel in stream channels.
Quaternary (Holocene)	Terrace deposits (**Qt**)	Consist of a wide succession, and mixture, of unconsolidated clay, silt, sand, and gravel; finely stratified; deposited by the Verde River on its floodplain. The alluvial river terraces are 2–3 m (5–10 ft) high and border the wide wash of the riverbed. Most of the sediment was derived from Paleozoic rocks; locally, much of the silt was derived from heterogeneous poorly sorted lake beds of the Verde Formation. The deposits are unconsolidated except where they are locally cemented by caliche.
Quaternary (Pleistocene) and Tertiary (probably Pliocene)	Verde Formation, Lacustrine deposits (**QTv**)	Limestone, siltstone, and claystone.

Table 4. Surficial map (House and Pearthree 1993; clar_geology.mxd) units in Tuzigoot National Monument.

Refer to table 5 for definitions of geologic terms. The geologic time periods are part of the Cenozoic Era, which extends from 66 million years ago to today (fig. 10).

Period (Epoch)	Map Unit (symbol)	Geologic Description
Quaternary (Holocene)	Tailings (**Qaf2**)	Areas mapped as tailings.
Quaternary (Holocene)	Active channels of major streams (**Qyr**)	Silt, sand, gravel, and cobbles in the active channel and floodplain of the Verde River.
Quaternary (late Holocene) Less than 5,000 years ago	Young terraces (**Qyt**)	Relatively thin terrace deposits along the Verde River. Composed of coarse gravel facies of abandoned channels and bars or fine sand facies deposited in low velocity, slack-water areas during large floods. Less than about 6 m (20 ft) above the lowest portions of river channels and almost always found directly adjacent to the channels. The principal exception to this is at Pecks Lake, where a meander of the Verde River has evidently been cut off quite recently leaving a low area covered with late Holocene deposits.
Quaternary (late Holocene) Less than 5,000 years ago	Young piedmont alluvium (**Qyp**)	Modern channel deposits and low terraces along piedmont drainage courses. Also includes small alluvial fans that have prograded onto the youngest terraces of the Verde River. Extremely coarse sand, gravel, cobbles, and boulders (near the Black Hills) to more fine-grained silt, sand, and gravel.
Quaternary (Late Pleistocene) 125,000–10,000 years ago	Sheepshead group Older (**Qs1**)	The older, stratigraphically higher unit of two in the Sheepshead group. Consists of primarily fine-grained sediments (clay, silt, and sand) with lesser amounts of gravel. Because these sediments are derived from the Verde Formation, the soil is very calcareous.
Quaternary (Middle Pleistocene to early Holocene) 250,000–5,000 years ago	Chuckwalla terraces Younger terraces (**Qct2**)	The younger terrace of two Chuckwalla terraces. About 6 to 12 m (20 to 40 ft) above modern river channels. Typically, deposits are coarse gravel facies of relict channels and bars and are less than 5 m (3 ft) thick. Proximal to the present position of the Verde River. Limited areal extent and restricted to the interior of narrow canyon reaches.
Quaternary (Middle Pleistocene to early Holocene) 250,000–5,000 years ago	Chuckwalla terraces Older terraces (**Qct1**)	The older terrace of two Chuckwalla terraces. Ranges from about 12 to 18 m (40 to 60 ft) above modern river channels. Typically, deposits are coarse gravel facies of relict channels and bars and are less than 5 m (3 ft) thick. Proximal to the present position of the Verde River. Limited areal extent and restricted to the interior of narrow canyon reaches.
Quaternary (Middle Pleistocene) ~500,000 years ago	Montezuma terraces (**Qmt**)	Typically composed of coarse gravel. Situated 25 to 30 m (80 to 100 ft) above modem river channels.
Tertiary (late Miocene to Pliocene) 8.5 million to 2.5 million years ago	Verde Formation Lacustrine facies (**Tvl**)	Composed of freshwater limestone, sandstone, siltstone, and marl.

Table 5. Geologic map (DeWitt et al. 2008; motu_geology.mxd) units in Tuzigoot National Monument.

The geologic time periods are part of the Cenozoic Era, which extends from 66 million years ago to today (fig. 10). Geologic terms are defined below.

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

Boulder—A detached rock fragment, generally somewhat rounded or otherwise distinctively shaped by abrasion during transport. A boulder is the largest rock fragment recognized by sedimentologists; it is greater than 256 mm (10 in) in diameter.

Calcareous—Containing calcium carbonate (CaCO3).

Caliche—A hard layer of cemented calcium carbonate, commonly on or near the surface in arid and semiarid regions.

Clay—A detrital particle that is less than 1/256 mm (0.00015 in) in diameter.

Claystone—An indurated rock with more than 67% clay-sized minerals.

Cobble—A rock fragment larger than a pebble and smaller than a boulder, having a diameter in the range of 64 to 256 mm (2.5 to 10 in), being somewhat rounded or otherwise modified by abrasion in the course of transport.

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

Gravel—An unconsolidated, natural accumulation of rock fragments that are greater than 2 mm (1/12 in) in diameter; deposits may contain boulders, cobbles, and/or pebbles.

Limestone—A sedimentary rock consisting chiefly of the mineral calcite (calcium carbonate, CaCO3).

Limy—Containing lime (CaO).

Marl—An unconsolidated sedimentary rock or soil consisting of clay and lime (CaO).

Piedmont—A gently sloping area at the base of a mountain front. Also, describes a feature (e.g., plain, slope, or glacier) at the base of a mountain or mountain range.

Sand—A detrital particle ranging from 1/16 to 2 mm (0.0025 to 0.08 in) in diameter.

Sandstone—Clastic sedimentary rock composed of predominantly sand-sized grains.

Silt—A detrital particle ranging from 1/256 to 1/16 mm (0.00015 to 0.0025 in) in diameter, thus smaller than sand.

Siltstone—A clastic sedimentary rock composed of silt-sized grains.

Period (Epoch)	Map Unit (symbol)	Geologic Description
Quaternary (Holocene)	Artificial Fill (**Qa**)	Anthropogenic structures that include waste piles and tailings ponds.
Quaternary (Holocene)	Alluvium (**Qal**)	Sand, gravel, and silt in present-day streambeds. Includes minor terrace deposits along streams. Simplified from House (1994) and House and Pearthree (1993) in the Verde River valley. Thickness highly variable, 2–20 m (7–70 ft).
Quaternary (Holocene and Pleistocene)	Terrace gravel (**Qt**)	Well-sorted gravel deposits along major streams. Simplified from House (1994) and House and Pearthree (1993) in the Verde River valley. Thickness 2–10 m (7–30 ft).
Tertiary (Pliocene and Miocene)	Verde Formation Undivided sedimentary rocks (**Tvs**)	Includes limestone, claystone, silty limestone, and siltstone. Thickness variable.
Tertiary (Pliocene and Miocene)	Verde Formation, Limestone (**Tvls**)	Limestone and silty limestone. Thickness variable.

Geologic History

This chapter highlights the chronology of geologic events that formed the present-day landscape of the monument. The geologic features mentioned in the timeline are described in the "Geologic Features and Processes" chapter.

The following timeline makes a very long story short:

- Earth forms about 4.6 billion years ago (Precambrian or Hadean Era; fig. 10).
- The Deception Rhyolite is emplaced more than 1.7 billion years ago (Precambrian or Early Proterozoic Era).
- The Great Unconformity develops between about 1.7 billion and 500 million years ago. It represents more than a billion years of "missing" geologic time between the Precambrian igneous rocks exposed in the Black Hills and the Cambrian sandstones that encircle the Verde Valley.
- Starting with the Cambrian Tapeats Sandstone, Paleozoic sediments accumulate along a shoreline that stretches from Sonora, Mexico, to British Columbia, Canada. About 165 million years after the Tapeats Sandstone is deposited, the Devonian Martin Limestone builds up in an ocean basin. Then, the Mississippian Redwall Limestone is deposited in shallow, tropical ("near the equator") seas.
- Beginning about 300 million years ago, the area of the Verde Valley emerges from tropical seas, and the Pennsylvanian and Permian Supai Formation (now formally known as the "Supai Group"; see "Paleozoic Rocks") is deposited first in coastal deltas that cover the earlier marine deposits then in a variety of primarily continental settings.
- Continental conditions continue in the Permian Period as the Hermit Formation is deposited in fluvial mud flats, the Schnebly Hill Formation is deposited in coastal dunes, and the Coconino Sandstone is deposited in inland dunes. The Toroweap Formation and Kaibab Limestone originate farther west as marine sediments.
- Another unconformity, representing 185.9 million years of "missing" geologic time, develops between the Permian Period (ending 251.9 million years ago) and Tertiary time (beginning 66.0 million years ago).
- The Colorado Plateau begins to uplift about 60 million years ago.
- Basin and Range extension begins about 15 million years ago (Shafiqullah et al. 1980).
- The Hickey Formation (sedimentary rocks and basalt) accumulates between 14.5 million and 11 million years ago (McKee and Elston 1980). The Black Hills had not yet uplifted when the Hickey Formation erupts onto the landscape.
- At about 14 million years ago, the Black Hills are rising as the Verde basin is dropping down along the Verde fault zone.
- The Verde Formation accumulates in the down-dropped Verde basin between about 8.5 million and 2.5 million years ago (age from House and Pearthree 1993; see table 1).
- Extensive erosion of the landscape takes place, including development of pediment (erosion) surfaces on the flanks of the Black Hills.
- About 2.5 million years ago, the Verde River begins to incise the Verde Formation (House and Pearthree 1993).
- The Verde River and its tributaries create terraces (mapped as "terraces" by House and Pearthree 1993) and alluvial fans (mapped as "groups" by House and Pearthree 1993). The chronology (oldest to youngest) of deposits in the Verde Valley is Oxbow group (2.5 million–800,000 years ago), Oxbow terraces (2.0 million–800,000 years ago), Montezuma alluvial fan complex and terraces (approximately 500,000 years ago), Chuckwalla group (250,000–10,000 years ago), Chuckwalla terraces (250,000–5,000 years ago), Sheepshead group (less than 125,000 years ago), young terraces (less than 5,000 years ago), and young piedmont alluvium (less than 5,000 years ago). The following occur within the monument: Montezuma terraces (**Qmt**), Chuckwalla terraces (**Qc1** and **Qc2**), Sheepshead group (**Qs1**), young terraces (**Qyt**), and young piedmont alluvium (**Qyp**).
- The distinctive oxbow near the monument forms about 2,600 years ago (Cook et al. 2010a).
- Ongoing geomorphic changes, primarily caused by flooding of the Verde River, take place. Modern river and tributary-stream deposits mark active channels (see table 1).
- The United Verde Company/Phelps Dodge Corporation disposes of mine tailings (see table 1). The youngest map units in the monument reflect a legacy of mining.

Geologic Resource Management Issues

Geologic features and processes are integral to the monument's landscape and history. Some geologic features and processes may require management for safety, protection of infrastructure, and preservation of natural and cultural resources. Some past human activities may have impacted geologic features and processes and require mitigation.

The NPS Geologic Resources Division provides technical and policy support for geologic resource management issues in three emphasis areas: (1) geologic heritage, (2) active processes and hazards, and (3) energy and minerals management (see http://go.nps.gov/grd). With respect to the issues discussed in this chapter, staff from the geologic heritage emphasis area can assist with paleontological resource inventory, monitoring, and protection as well as cave and karst resource management. Staff from the active processes and hazards emphasis area can assist with disturbed lands, mine tailings, flooding, Quaternary faults and earthquakes, and slope movements. Staff from the energy and minerals management emphasis area can assist with issues associated with instream mining. Depending on the precise need, staff from either the active processes and hazards emphasis area or energy and minerals management emphasis area can assist with geothermal resource management. Monument managers are encouraged to contact the NPS Geologic Resources Division for assistance with the geologic resource management issues listed in this chapter. Monument staff can formally request assistance via the Solution for Technical Assistance Requests ("STAR": https://irma.nps.gov/Star/).

Resource managers may find *Geological Monitoring* (Young and Norby 2009) useful for addressing geologic resource management issues. The manual provides guidance for monitoring vital signs—measurable parameters of the overall condition of natural resources. Each chapter of *Geological Monitoring* covers a different geologic resource and includes detailed recommendations for resource managers, suggested methods of monitoring, and case studies. Resource managers may contact the GRI team to request a PDF copy of the manual or individual chapters of the manual. Content is also available on the Geological Monitoring website (https://go.nps.gov/geomonitoring).

In addition, the Arizona Geological Survey (AZGS)'s "Natural Hazards in Arizona" map viewer is a handy tool for resource managers (https://azgs.arizona.edu/center-natural-hazards). The original and updated map viewers show active faults, earthquake epicenters, flood potential, and landslides, as well as fire risk and earth fissures, though these final two hazards are not considered geologic resource management issues at the monument. "Additional Resources" lists other web-based information about natural hazards.

The NPS Geologic Resources Division administers the Geoscientists-in-the-Parks (GIP) and Mosaics in Science programs, which provide internships that place scientists (typically undergraduate students) in parks to complete science-related projects. A GIP or Mosaics in Science intern may be able to work on the issues discussed in this chapter. Monument managers are encouraged to contact the NPS Geologic Resources Division about the placement of a geoscience intern in the monument. More information is available at the programs' websites (http://go.nps.gov/gip and http://go.nps.gov/mosaics).

During the 2006 scoping meeting, for which a scoping summary (National Park Service 2006) was prepared, and the 2017 conference call, participants (listed in Appendix A) identified the geologic resource management issues discussed in this chapter. Most of these issues can be associated with particular geologic map units, as shown in table 6. Climate change, however, is broad in scope and not associated with any particular map unit. Nevertheless, because of the potential disruption that climate change may cause to monument resources, including geologic resources, a discussion of climate change is included in this chapter. Climate change planning, however, is beyond the scope of the GRI program, and monument managers are directed to the NPS Climate Change Response Program to address issues related to climate change (https://www.nps.gov/orgs/ccrp/index.htm).

In order to make connections between Tuzigoot and Montezuma Castle National Monuments, table 6 is organized with map units from DeWitt et al. (2008), rather than Lehner (1958) or House and Pearthree (1993). In addition to map units, table 6 highlights park significance by listing core components—such as fundamental resources and values, other important resources and values, and interpretive themes—from the monument's foundation document (National Park Service 2016). In table 6, particular maps units are associated with core components, which typically do not change over time and are expected to be used in future planning and management efforts (National Park Service 2016). Further discussion and potential resource management actions for each issue follow table 6. Discussions of the issues are ordered with respect to management priority.

Disturbed Lands

Human development of Tavasci Marsh and adjacent parts of the Verde River oxbow has drastically altered the marsh from its natural condition. Anthropogenic alteration of the marsh began in the 1880s and included the construction of irrigation ditches through the marsh, drainage of portions of the marsh for cattle ranching, and leveling parts of the marsh for dairy farming and raising crops. Stoutamire (2011) compiled a comprehensive history of the development and management of Tavasci Marsh.

Diversion of water from the Verde River into Tavasci Marsh constitutes another change to natural conditions. Originally used for irrigating crops and watering cattle, water was diverted to the marsh through the oxbow (abandoned channel). Then in 1914, the United Verde Copper Company built a dam and enlarged the diversion tunnel (Brewer's Tunnel; see fig. 2) creating Pecks Lake, which was intended to be part of a housing development, including a 9-hole golf course, for mining employees. Notably, in February 2019, flooding destroyed Brewer's Tunnel and dam. No rebuilding of the dam is planned (Tina Greenawalt, Tuzigoot and Montezuma Castle National Monuments, chief of Natural Resources, written communication, 3 June 2019).

Land leveling of the marsh and increased outflow from Pecks Lake may have resulted in topographic and hydrologic conditions that are extremely favorable for the expansion of cattails (*Typha* spp.). Cattails, which now cover nearly 70% of the marsh area, have usurped open water and natural transition zones to the detriment of adjacent dry mesquite bosque and other wetland plant communities (Ryan and Parsons 2009). Notably, mitigation efforts that involve earth moving and cattail removal could remobilize sediment-bound metals and trace elements into the water column (Beisner et al. 2014).

Restoration of the marsh's hydrology will require identifying the natural outlet and restoring the artificially constructed hydrology of the Pecks Lake–Tavasci Marsh system to its natural conditions (National Park Service 2006). Restoration activities or changes in source water are likely to significantly change water chemistry and affect sediments, plants, macroinvertebrates, and fish (Beisner et al. 2014).

Another potential category related to erosion and other impacts is the use and maintenance of water diversions for irrigation canals. Several large diversions are located off the Verde River, near the monument (Matt Guebard, Tuzigoot and Montezuma Castle National Monuments, chief of Cultural Resources, written communication, 4 June 2019).

Mine Tailings

As mapped by House and Pearthree (1993), the legislative boundary of Tuzigoot National Monument contains approximately 49 ha (121 ac) of tailings (**Qaf2**), equating to 14.9% of the area covered by the legislative boundary (fig. 2). Lehner (1958) and DeWitt et al. (2008) mapped these deposits as artificial fill (**Qt**) (see posters, in pocket). The mine tailings do not contain resources related to the purpose and significance of the monument, so the National Park Service does not wish to acquire them and proposes that this land be removed from the legislative boundary (National Park Service 2011).

Deposition of mine tailings began in 1927 when the United Verde Copper Company started disposing of milled copper ore from its Clarkdale, Arizona, operations (Peterson et al. 1978). Copper ore disposed of as tailings is regarded as too poor in value to be treated further. An estimated 3.6 million metric tons (4.0 million tons) of copper mine tailings were deposited (Beisner et al. 2014). The tailings are an estimated 15 m (50 ft) thick (National Park Service 2015a). Disposal operations started with construction of an earthen dike across an oxbow of the Verde River; the dike was built at the northwestern end of the present tailings deposit (fig. 2). Tailings were placed in the abandoned channel southeast of the dike. Disposal by the United Verde Copper Company continued until 1929 when the mine and mill shut down. Phelps Dodge Corporation acquired the mining operations in 1935 and resumed disposal until 1953 when the Clarkdale smelter was permanently closed (National Park Service 1992).

Since initial deposition of tailings, alternations to the pile have taken place. For example, local residents complained to Phelps Dodge about windblown dust, which consisted of fine tailings material, so in 1956 the corporation initiated an irrigation program to lessen the nuisance. The surface of the tailings pile was graded and diked so water from Pecks Lake could be pumped to the site and distributed over the entire surface by gravity flow (National Park Service 1992). In 1981, the Town of Clarkdale began to pump treated effluent water from the town's wastewater treatment plant for discharge on top of the tailings impoundment. The EPA subsequently ordered the town to cease effluent disposal on the tailings.

In 2007, the Phelps Dodge Corporation capped the tailings pile with a high-density polyethylene liner and 0.9 m (3 ft) of soil. In addition, the corporation constructed rock-lined channels to route storm water away from the capped area and revegetated the pile with native grasses (Beisner et al. 2014). Initially, the effort received recognition for implementing principles of sustainable development (Verde Independent 2007). In 2014, preliminary studies to support restoration of Tavasci Marsh revealed hazardous substances associated with mining in water, sediment, plants, and aquatic biota (e.g., dragonfly larvae and fish) (Beisner et al. 2014). Findings by Beisner et al. (2014) included the following:

- Water analyses showed that concentrations for arsenic exceeded the US Environmental Protection Agency primary drinking water standard of 10 micrograms per liter at all sampling sites.
- Sediment analyses showed that all surficial and core sediment samples exceeded or were within sample concentration variability of at least one threshold sediment quality guideline for arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), mercury (Hg), nickel (Ni), lead (Pb), and zinc (Zn). Several sediment sites were also above or were within sample concentration variability of severe or probable effect sediment quality guidelines for As, Cd, and Cu. Three sediment cores collected in the marsh have greater metal and trace element concentrations at depth for bismuth (Bi), Cd, Cu, Hg, indium (In), Pb, antimony (Sb), tin (Sn), tellurium (Te), and Zn.
- Plant analyses showed arsenic concentration was greater in cattail roots compared with surrounding sediment at Tavasci Marsh.
- Aquatic biota analyses showed that concentrations of As, Ni, and selenium (Se) from yellow bullhead catfish (*Ameiurus natalis*) in Tavasci Marsh exceeded the 75th percentile of several other regional studies. Mercury concentration in dragonfly larvae and fish from Tavasci Marsh were similar to or greater than concentrations in Tavasci Marsh sediment.
- Radioisotope dating indicated that the elevated metal and trace element concentrations are associated with sediments deposited before 1963.
- Surface waters at Tavasci Marsh may contain conditions favorable for methylmercury (a very poisonous form of mercury that forms when bacteria react with mercury in water, soil, or plants. Methylmercury was used to preserve grain fed to animals) (see "Disturbed Lands").

Based on findings of Beisner et al. (2014), the Phelps Dodge restoration plan for the mine tailings requires extensive revisions. Future work suggested in Beisner et al. (2014) included a biologic risk assessment utilizing the data collected in that study to provide monument managers with additional information for their remediation and restoration plan. Monument managers are working with the NPS Environmental Compliance and Cleanup Branch, US Geological Survey, and US Fish and Wildlife Service to develop a contamination cleanup plan for Tavasci Marsh (Shawn Mulligan, NPS Environmental Compliance and Cleanup Branch, chief, written communication, 26 July 2019).

Potential resource management actions related to tailings include the following:

- Determining the hydrologic connections among the tailings, the Verde River, and Tavasci Marsh. For example, what is the likelihood of a complete pathway for contaminants to migrate to the river, marsh, or other park resources? (Shawn Mulligan, NPS Environmental Compliance and Cleanup Branch, chief, written communication, 26 July 2019). Sources of information include Springer and Haney (2008), Beisner et al. (2014), and Paretti et al. (2018).
- Initiating an investigation under the guidance of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA, known as "Superfund") to determine the nature and extent of contamination and evaluate response action alternatives.
- Reaching out to other NPS areas (e.g., for example, Grant-Kohrs Ranch National Historic Site; see GRI report by Thornberry-Ehrlich 2007) to review remediation strategies for addressing contamination.
- Investigating the possibility of working with industry and the local community to reduce continued contamination by building a partial diversion of the Verde River flowing into Tavasci Marsh (ideally the marsh would be fed solely from groundwater springs).
- Investigating potential collaboration with the Audubon Society because Tavasci Marsh is designated as an "Important Bird Area."
- Continuing to work with the Sonoran Desert Network and Northern Arizona University to conduct water sampling and other projects such as bird surveys, and ongoing research, respectively (National Park Service 2016).

Climate Change

According to the monument's foundation document (National Park Service 2016), climate change and its associated influences are threats to the following resources: the hilltop pueblo and related archeological resources, Tavasci Marsh, cultural continuity and

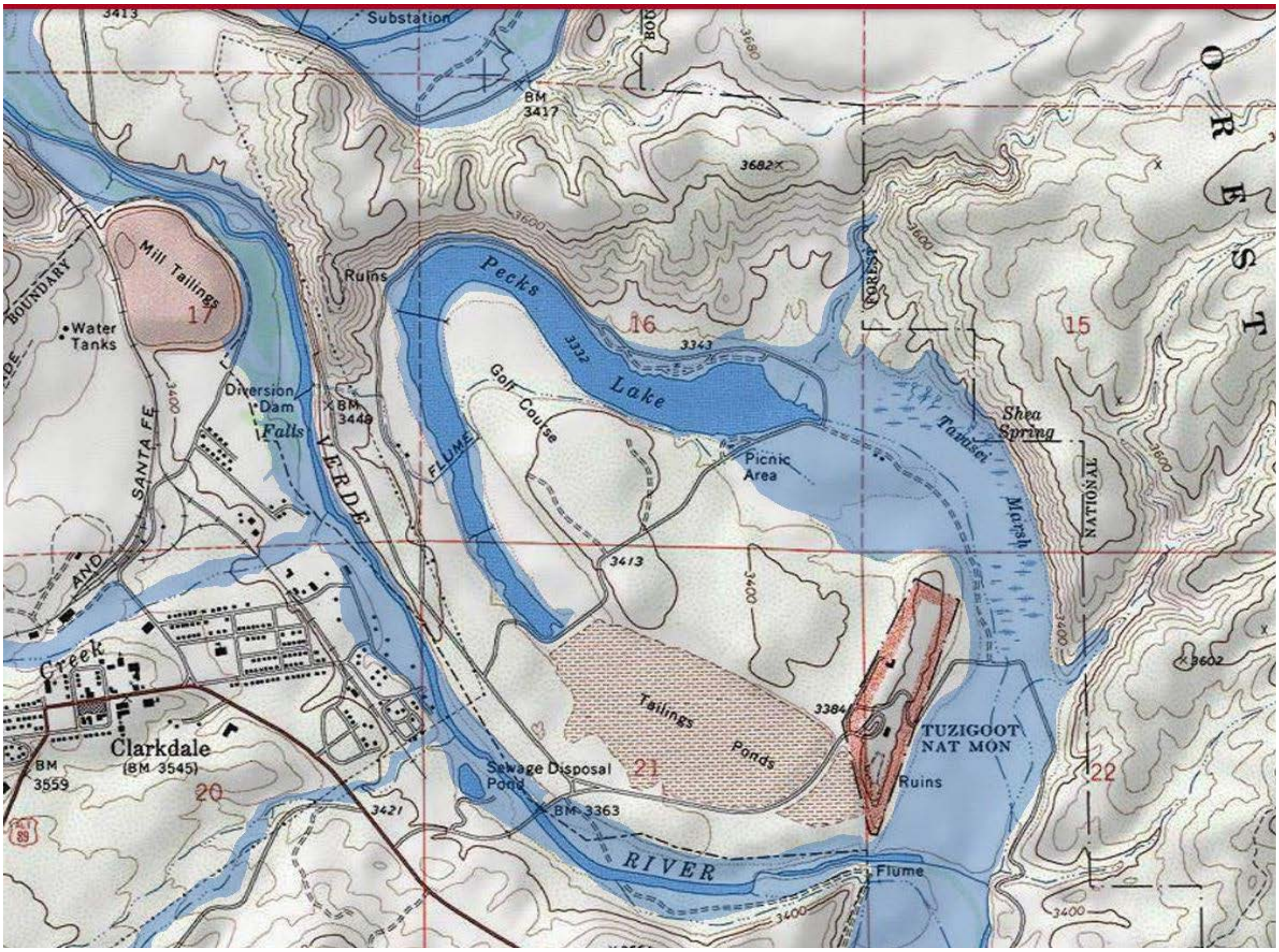

Figure 16. Map of flood potential.
The figure shows areas with flood potential as represented by the 100- and 500-year flood zones determined by the Federal Emergency Management Agency (FEMA) digital flood insurance rate maps (DFIRM) database, dated May 2010. Light-blue areas have high flood potential. Notably, Pecks Lake, Tavasci Marsh, and a portion of the road into the monument have the potential to flood. The topographic base map (ca. 1973) shows tailings "ponds," which are now filled with a tailings pile (see "Mine Tailings"). Graphic generated from AZGS "Natural Hazards in Arizona" map viewer (accessed 22 August 2019).

landscapes, the visitor center/museum, flora and fauna, and recreational values. Associated influences include increases in mean annual temperature, fire frequency, drought events, storm frequency, and storm intensity, as well as a decrease in water resources.

Among others, the foundation document noted the following climate–change related threats, which are associated with geologic features or processes at the monument:

- Weathering. A warmer and drier climate and more intense seasonal rain events may accelerate weathering of pueblo remnants, historic visitor center/museum, trails, and other park infrastructure.
- Water resources. A warmer and drier landscape will mean a decrease in water resources, which are important for sustaining the existing ecological systems and cultural landscape at the monument, as well as park operations, including visitor services. Monument managers have a baseline inventory of Shea Spring and the associated unnamed springs that feed Tavasci Marsh (Sonoran Desert Network 2009). A single well in the Verde Formation provides a public water supply to resident NPS staff and visitors (National Park Service 1992).
- Aeolian processes. Significant wind events have the potential to create safety risks such as dust storms and cause "sand blasting" of the hilltop pueblo and visitor center/museum.

The Sonoran Desert Network completed a weather and climate inventory (Davey et al. 2007) that identified a weather station within the monument's boundaries and 31 other nearby weather stations. The station within the monument has been gathering data since 1911. A weather station in Jerome, 6 km (4 mi) west of the monument, has the longest data record in the area (1897–present). These stations are part of the National Weather Service (NWS) Cooperative Observer Program (COOP), which has been a foundation of the US climate program for decades and continues to play an important role. Volunteers make daily manual measurements, consisting of maximum and minimum temperatures, observation-time temperature, daily precipitation, daily snowfall, and snow depth (Davey et al. 2007).

The Sonoran Desert Network is monitoring climate at the monument by compiling and analyzing climate information from existing long-term stations. Network staff members analyze and interpret these data in annual climate monitoring reports and resource briefs, and refer to them in most reports for other vital signs (Sonoran Desert Network 2009). Monahan and Fisichelli (2014) completed a climate change resource brief that provided information about the historical range of variability and trends in temperature and precipitation at the monument.

Climate change planning—including a vulnerability assessment, scenario plan, and adaptation strategy—is a medium priority management need at the monument (National Park Service 2016). A climate change vulnerability assessment would help monument managers develop plausible science-based scenarios that would inform strategies and adaptive management activities that would allow mitigation or adjustment to climate realities. A climate change vulnerability assessment and scenario planning could be completed in cooperation with the NPS Climate Change Response Program. As of June 2019, monument managers were working with the University of Pennsylvania to develop a vulnerability assessment strategy for the ruins (Matt Guebard, Tuzigoot and Montezuma Castle National Monuments, chief of Cultural Resources, written communication, 4 June 2019).

Additional climate change impacts, risks, and adaptation information for the southwest is presented in the Fourth National Climate Assessment (Reidmiller et al. 2018) and is available online at https://nca2018.globalchange.gov/chapter/front-matter-guide/.

Flooding

During scoping in 2006, Phil Pearthree (Arizona Geological Survey) noted the following flood hazards along the Verde River within and near the monument:

Figure 17. Photograph of channel cutting. According to Gwilliam et al. (2017), extreme precipitation events can cause localized flooding and erosion, for example, along the Tavasci outflow ditch (shown here). As mapped by House and Pearthree (1993), erosion took place in young terrace deposits (Qyt). NPS photograph from Gwilliam et al. (2017, figure 2-11).

inundation of floodplains, lateral bank erosion, and focused erosion on the outsides of meander bends. Scoping participants suggested that flooding and associated channel change could impact the road into the monument (National Park Service 2006). The AZGS "Natural Hazards in Arizona" map viewer shows high flood potential areas, including those in the monument (fig. 16).

Most geomorphic work, including channel changes, takes place during floods (fig. 17). The potential for changes in channel morphology and shifts in channel position during large floods is greatest in areas where young terraces (**Qyt**; mapped by House and Pearthree 1993) are extensive (Pearthree 1996; see surficial geologic map poster, in pocket). Additionally, flood waters flowing from tributary drainages result in the introduction of large pulses of coarse gravelly sediment into the Verde River channel following precipitation events (Cook et al. 2010b).

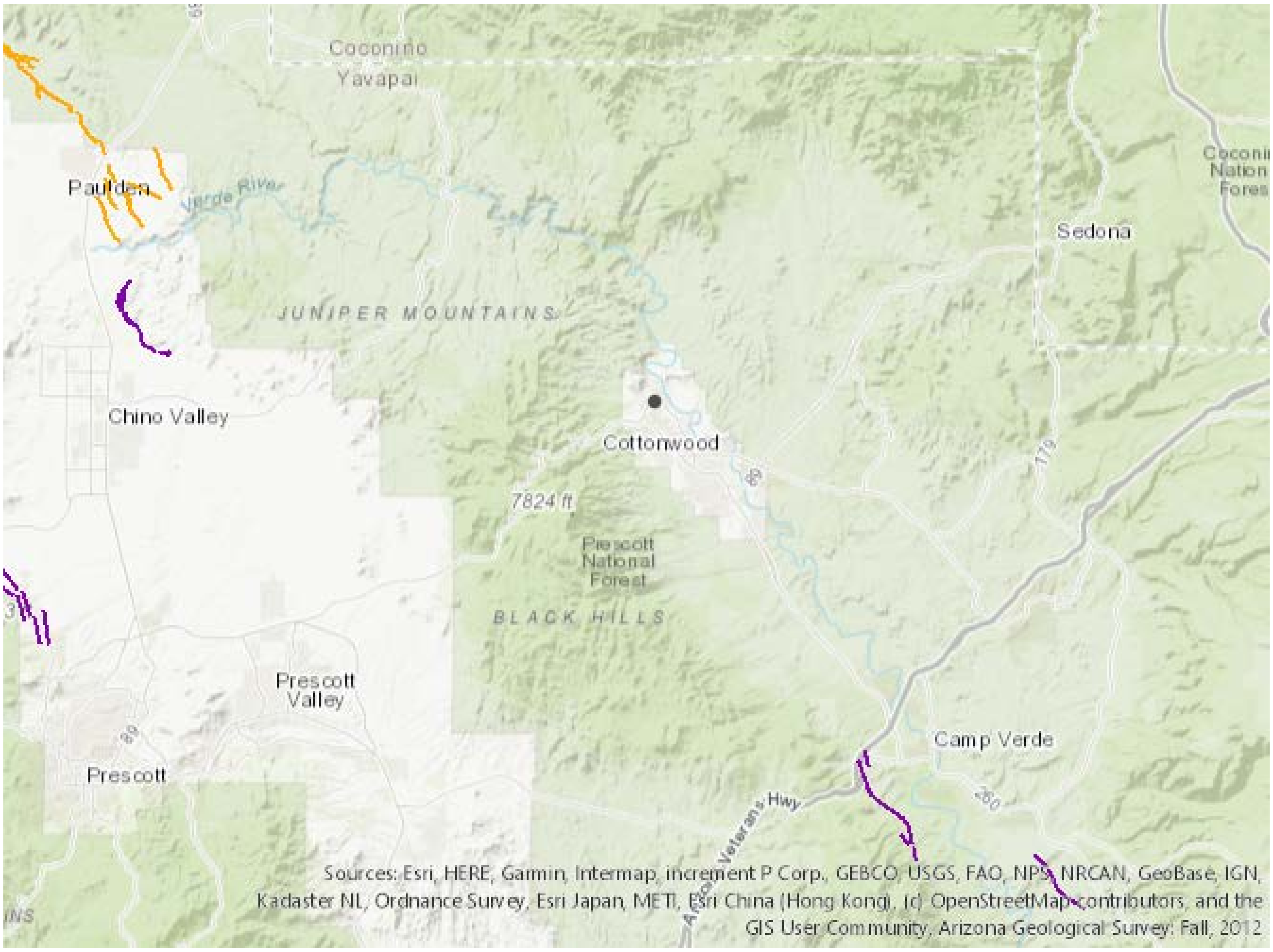

Figure 18. Map of active faults near Tuzigoot National Monument.
"Active" faults are those that have moved during the Quaternary Period (the past 2.6 million years). For orientation, the black dot on the figure marks Clarkdale (the nearest town to the monument). The closest active fault to the monument is the Camp Verde scarp (purple line, west of Camp Verde), which is part of the Verde fault zone. The Camp Verde scarp was active less than 130,000 years ago. The Cottonwood Basin fault (purple line) is southeast of the Camp Verde scarp. It was active less than 750,000 years ago. The Big Chino fault (orange lines), which was active less than 15,000 years ago, and the Little Chino fault (purple lines), which was active less than 130,000 years ago, are northwest of the monument. The purple lines on the western edge of the figure mark the Prescott Valley graben (down-dropped basin); movement there took place less than 750,000 years ago. Map generated from AZGS "Natural Hazards in Arizona" map viewer (accessed 6 May 2019).

With respect to the timing of floods, major perennial tributaries drain the area north and east of the Verde River and flow in a southwesterly direction toward the main river. Because these tributaries drain areas of significantly higher elevation and receive more rain and snow than the Verde Valley itself, flood events can occur during the winter, spring, and summer (National Park Service 2015b). The largest recorded floods in Clarkdale have taken place in the winter. The largest flood on record occurred in February 1993. On 20 February 1993, the river crested at 8.64 m (28.36 ft) and was running at 1,500 m^3/s (53,200 cfs). For comparison, floodwaters on 15 February 2019 were running at 590 m^3/s (20,900 cfs), and on 1 July 2019, the river was in non-flood stage and running at 1.93 m^3/s (57.4 cfs) (US Geological Survey 2019).

The US Geological Survey operates eight stream-gaging stations in the Verde River watershed (fig. 5; National Park Service 2015b). One of these gauges (09504000) is located at Clarkdale (see https://waterdata.usgs.gov/usa/nwis/uv?09504000).

In *Geological Monitoring* (Young and Norby 2009), the chapter "Fluvial Geomorphology: Monitoring Stream

Systems in Response to a Changing Environment" by Lord et al. (2009) provided an overview of river and stream dynamics, described possible stressors that may lead to channel instability, and suggested guidelines and methods for monitoring streams and rivers. The chapter discussed the following vital signs: (1) watershed landscape (vegetation, land use, surficial geology, slopes, and hydrology), (2) hydrology (frequency, magnitude, and duration of streamflow rates), (3) sediment transport (rates, modes, sources, and types of sediment), (4) channel cross section, (5) channel planform, and (6) channel longitudinal profile. Because differences exist in budget, staffing, and management needs and objectives, Lord et al. (2009) provided three levels of monitoring protocols. This information may be useful for monument managers in monitoring floods and planning for changes in the dynamic Verde River system.

Quaternary Faults and Earthquakes

Source map authors did not map any faults within the monument. The closest mapped fault segments occur in the Precambrian and Paleozoic rocks west of the monument (see bedrock geologic map poster and geologic map poster, in pocket). These mapped fault segments are part of the Verde fault zone, which runs along the base of the Black Hills. The Verde fault zone is responsible for the formation of the down-dropped Verde basin. Normal faults, which are typical of tectonism in the Basin and Range, characterize the fault zone (fig. 4).

Most of the offset on the Verde fault zone took place during the late Miocene and Pliocene Epochs (Bressler and Butler 1978; Nations et al. 1981), during which time Tertiary rocks were displaced as much as 1,000 m (3,000 ft) (Twenter and Metzger 1963). Evidence of recent (Quaternary) offset is limited to an 8-km- (5-mi-) long section of fault scarps, called the Camp Verde scarp by Menges and Pearthree (1983), in the southern part of the Verde fault zone (fig. 18). A scarp is a line of cliffs formed by faulting or erosion. The slip rate along this portion of the fault is estimated at less than 0.2 mm (0.008 in) per year. The Verde fault zone last ruptured the ground surface about 50,000 years ago (Bausch and Brumbaugh 1997).

According to an earthquake hazard evaluation for Yavapai County (Bausch and Brumbaugh 1997), movement on the Verde fault would produce near-field earthquakes, which occur within approximately 16 km (10 mi) from the epicenter and generate rough, jerky, high-frequency seismic waves that are generally efficient in causing short buildings, such as single-family homes, to vibrate.

The maximum credible earthquake on the Verde fault is 7.25. If the maximum credible event were to take place, the effects to Yavapai County would be extensive. These effects include failure of unreinforced masonry and resonance in reinforced, 2–3-story-high concrete structures. The duration (20–30 seconds) of strong motion and the maximum horizontal accelerations (1.2 g) will be great enough to cause damage to other structures. Limited areas near the Verde River, Big Chino Wash, and smaller stream valleys that are underlain by relatively unconsolidated sediment and shallow groundwater will be susceptible to liquefaction–induced ground failure.

Earthquake monitoring in Arizona occurs at seismograph stations throughout the state (fig. 19). Two seismograph networks—the Northern Arizona Seismograph Network (NASN) and the Arizona Broadband Seismograph Network (ABSN)—maintain most of these stations. These two networks are members of a cooperative statewide network called the Arizona Integrated Seismic Network (AISN) whose common purpose is to collect, distribute, and do research on earthquakes occurring in the state of Arizona (Arizona Earthquake Information Center 2010). Each year, ABSN seismometers, for example, record hundreds of earthquakes in Arizona (Arizona Geological Survey 2019).

Recent felt events include a magnitude 5.3 earthquake near Duncan, Arizona, on 28 June 2014, which was felt throughout southeastern Arizona; a magnitude 4.1 earthquake near Black Canyon City, Arizona, which shook Phoenix and was felt by perhaps millions of people on 1 November 2015; and a magnitude 3.1 earthquake registered in Flagstaff, Arizona, on 5 November 2018.

The *Geological Monitoring* chapter about earthquakes and seismic activity (Braile 2009) described six methods and vital signs for understanding earthquakes and monitoring seismic activity: (1) monitoring earthquakes, (2) analysis and statistics of earthquake activity, (3) analysis of historical and prehistoric earthquake activity, (4) earthquake risk estimation, (5) geodetic monitoring and ground deformation, and (6) geomorphic and geologic indications of active tectonics. This information may be useful for understanding ground shaking and other earthquake hazards at the monument.

Slope Movements

A lidar map of the hilltop pueblo and aerial lidar coverage for the entire monument were created in 2014 (Matt Guebard, Tuzigoot and Montezuma Castle National Monuments, chief of Cultural Resources,

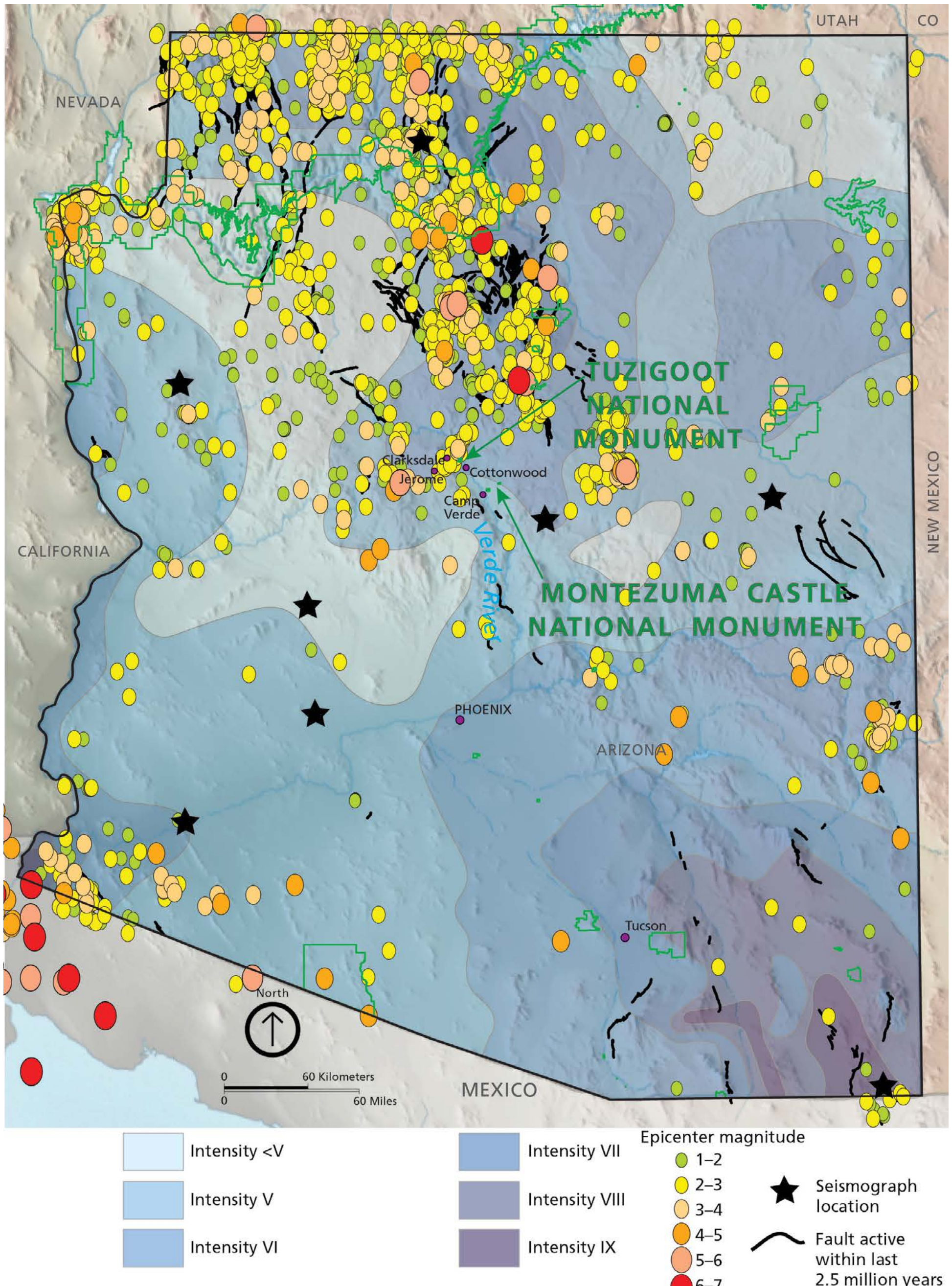

Figure 19. Map of active faults, earthquakes, and seismograph stations in Arizona.
Each year hundreds of unfelt and several felt earthquakes occur in Arizona. These earthquakes generally take place within a swath from the north-northwestern part of the state to the southeastern part of the state. The Yuma area (southwestern corner of the state) also has earthquakes. The maximum credible earthquake on the Verde fault zone is 7.25. In addition to active faults (black lines), this map shows seismograph stations (black stars). It also delineates Modified Mercalli Scale (MMS) intensities of the 1887 Sonoran earthquake, 1940 Imperial Valley earthquake in southern California (felt in the Yuma area), and three magnitude-6 earthquakes in the early 1900s, which caused damage in the Flagstaff–Grand Canyon region. These MMS intensities show that the state has been subject to intensities of up to IX, resulting in considerable damage to designed structures. Green outlines represent the boundaries of NPS areas; green arrows point to Tuzigoot and Montezuma Castle National Monuments, which also are labeled. Graphic by Trista Thornberry-Ehrlich (Colorado State University) using AZGS graphics and data available at the AZGS "Natural Hazards in Arizona" map viewer, Earthquakes information website, and an Arizona Earthquake Information Center map (accessed 19 April 2018).

written communication, 4 June 2019). Lidar data have application in monitoring slope movements. The *Geological Monitoring* chapter about slope movements (Wieczorek and Snyder 2009), for example, discusses the use of lidar in monitoring landslides. Wieczorek and Snyder (2009) also described five vital signs for understanding and monitoring slope movements: (1) types of landslides, (2) landslide causes and triggers, (3) geologic materials in landslides, (4) measurement of landslide movement, and (5) assessment of landslide hazards and risks. The NPS Geologic Resources Division could provide additional assistance to monument managers in analyzing lidar data, if needed. Additionally, the Geologic Resources Division has the equipment and software to conduct close-range photogrammetry where the camera is close to the subject and typically hand-held or on a tripod, but also may be attached to a low altitude unmanned vehicle. The result is a 3D model. The NPS Geologic Resources Division's Photogrammetry website (http://go.nps.gov/grd_photogrammetry) provides information and examples of a variety of applications of photogrammetry for resource management.

Other source of information about slope movements includes a landslide handbook (Highland and Bobrowsky 2008) published by the US Geological Survey (USGS) that provides guidance and helps resource managers understand landslides. Moreover, the USGS Landslide Hazards Program's website (http://landslides.usgs.gov/) and the NPS Geologic Resources Division's Geohazards (http://go.nps.gov/geohazards) and *Geological Monitoring* websites provide detailed information regarding slope movements, monitoring, and mitigation options.

Caves and Karst Resource Management

The Federal Cave Resources Protection Act of 1988 requires the identification of "significant caves" on federal lands. For the National Park Service, the regulations stipulate that all caves on NPS properties are "significant." The act also requires the regulation or restriction of use as needed to protect cave resources and the inclusion of significant caves in land management planning. In addition, the act imposes penalties for harming a cave or cave resources and exempts park managers from releasing specific locations of significant caves in response to a Freedom of Information Act (FOIA) request (see Appendix B). Other laws, such as the Archeological Resources Protection Act, also provide park managers with tools to protect specific resources found within caves (and on the surface) by exempting their nature and location from FOIA requests.

Similar to caves, a variety of laws, regulations, and policies guide the management of karst resources (see Appendix B and https://www.nps.gov/subjects/caves/cave-karst-protection.htm). The National Park Service manages karst terrain to maintain the inherent integrity of its water quality, spring flow, drainage patterns, and caves. The NPS Cave and Karst website (https://www.nps.gov/subjects/caves/index.htm) provides more information.

Evaluation of Cave and Karst Programs and Issues at US National Parks (Land et al. 2013) did not report any cave or karst resources in the monument. Nevertheless, the monument's bedrock (Verde Formation) hosts caves elsewhere, for example at Montezuma Castle National Monument (see GRI report by KellerLynn in review), so the potential may exist. During the 2006 scoping meeting, for example, participants suggested that the newly acquired Tavasci Marsh area had the potential for caves and karst features (National Park Service 2006). Notably, springs are indicative of karst, and Shea Spring and associated unnamed springs are a source of water to Tavasci Marsh.

To date, an inventory of karst features at Tavasci Marsh has not been conducted. Monument managers are encouraged to contact the NPS Geologic Resources Division with questions and concerns about resource management and park planning with respect to caves and karst. The *Geological Monitoring* chapter by Toomey (2009) is applicable for caves and karst resource management.

Paleontological Resource Inventory, Monitoring, and Protection

All paleontological resources are nonrenewable and subject to science-informed inventory, monitoring, protection, and interpretation as outlined by the 2009 Paleontological Resources Preservation Act (see Appendix B). As of September 2019, Department of the Interior regulations associated with the act were in the surnaming process.

The paleontological resource inventory, monitoring, and protection report for the monument (Tweet et al. 2008) reported the following about the Verde Formation:

- The Verde Formation has the potential to contain body fossils (evidence of past organisms) of plants, mollusks, ostracodes, fish, amphibians, bats, rodents, rabbits, camelids, unidentified artiodactyls (even-toed ungulates), tapirids (odd-toed ungulates), and equids (horses).
- The Verde Formation has the potential to yield trace fossils (evidence of life activities, rather than an

organism itself) such as mammal tracks, which have been documented, for example, at "Elephant Hill" in Montezuma Castle National Monument (see GRI report about Montezuma Castle National Monument by KellerLynn in review).

In addition to the Verde Formation, the paleontological resource inventory, monitoring, and protection report for the monument (Tweet et al. 2008) noted the following potential sources of paleontological material:

- Eroded fossils (mostly marine invertebrates) from nearby Paleozoic rocks may be transported into the monument by the Verde River. These fossils would be deposited in the stream channel and on the floodplain.
- Surficial deposits (e.g., terrace gravel and alluvial fan deposits) may contain remains of Quaternary fauna, such as testudinids (tortoise), equids, camelids (camels), and proboscideans (elephants and extinct relatives) (Robert McCord, Arizona Museum of Natural History, paleontologist, personal communication *in* Tweet et al. 2008, p. 123).
- The distribution of packrats (*Neotoma* spp.) suggests that ancient middens could be present in Sonoran Desert Network parks, though the relatively level topography (i.e., lack of cliffs dwellings and rock shelters) makes the existence of packrat middens less likely in Tuzigoot than at other parks within the network. Fossil packrat middens, which can provide important paleoecological information, typically occur in caves or rock shelters and rock crevices (see "Caves and Karst Resource Management"); they resemble piles or mounds of plant material with a dark glossy coating of crystallized packrat urine. If a packrat midden is discovered, the NPS Geologic Resources Division maintains a list of researchers studying middens in the Southwest and can facilitate communication between monument managers and these researchers.
- Fossils also can occur in cultural contexts. Because the monument was established to preserve Southern Sinaguan ruins, finding fossils among cultural artifacts is possible. Kenworthy and Santucci (2006) provided an overview of NPS fossils found in cultural resource contexts. In addition to documenting a fossil found in a cultural context as a paleontological resource, such a fossil will also require input from an archeologist. A fossil found in a cultural context may be culturally sensitive, for example subject to Native American Graves Protection and Repatriation Act (NAGPRA), and should be regarded as such until determined otherwise. The Western Archeological and Conservation Center and the NPS Geologic Resources Division can coordinate additional documentation/research of such material.
- Museum collections are another source of fossil material. Curators have identified specimens at the Museum of Northern Arizona as coming from two Verde Formation fossil localities in or near the monument. Making arrangements with staff at the Museum of Northern Arizona to investigate old finds could yield fossil material. The monument's museum collections have no confirmed fossil material (Tweet et al. 2008).

The paleontological resource inventory, monitoring, and protection report for the monument (Tweet et al. 2008) made the following recommendations regarding paleontological resources:

- Monument managers consider conducting a field inventory for paleontological resources to more fully document in situ fossil occurrences at the monument. A Geoscientists-In-the-Parks (GIP) or Mosaics in Science intern could carry out a field inventory.
- Monument managers consider conducting a formal site documentation and condition assessment of the two fossil localities recorded by the Museum of Northern Arizona. A GIP or Mosaics in Science intern could carry out a field inventory.
- Monitor fossil sites—including those already known and any sites discovered during a future field inventory—at least once a year (Tweet et al. 2008). 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.
- While conducting their usual duties, monument staff members are encouraged to observe exposed bedrock, old river deposits, and the modern Verde River channel for fossil material. If monument staff members discover fossil material, they should document these finds with photographs using a common item (e.g., a pocketknife) for scale. Fossils and their associated geologic context (rock or sediment matrix) should be documented but left in place unless this material is subject to imminent degradation by artificially accelerated natural processes or direct human impacts. Staff should contact the NPS Geologic Resources Division about fossil discoveries.
- Monument staff should contact the NPS Geologic Resources Division for any additional assistance regarding paleontological resource management or interpretation.

Geothermal Resource Management

Sixteen units within the National Park System contain features (e.g., hot springs, geysers, mud pots, and fumaroles) designated as "significant" by the Geothermal Steam Act of 1970 (as amended in 1988; see Appendix B) and require monitoring. Tuzigoot National Monument is not one of these.

Past volcanism and ongoing tectonism are associated with geothermal activity in the Verde Valley (Ross and Farrar 1980). Ross and Farrar (1980) completed a map showing the potential geothermal-resource areas in the valley.

A hot spring is defined as a thermal spring whose water has a higher temperature than that of the human body, that is, higher than about 37°C (98°F) (Meinzer 1923). The closest hot spring to the monument is Verde Hot Springs, which is about 80 km (50 mi) to the southeast, near Childs, Arizona (National Park Service 2006). The measured water temperature at Verde Hot Springs was 39°C (102°F). By comparison, two wells near the monument had water measured at 19°C (66°F) and 20°C (68°F) (Ross and Farrar 1980).

The recorded temperature of Shea Spring—20.3°C (68.5°F)—is warmer than the average annual air temperature (17.3°C [63.1°F]) measured at the monument, so that spring is thermal (has a temperature appreciably above the mean annual temperature of the atmosphere in the vicinity of the spring), though not a "hot spring" by definition. The water feeding Shea Spring warms as it moves through the subsurface following recharge as precipitation (Beisner et al. 2014).

The *Geological Monitoring* chapter about geothermal systems and hydrothermal features (Heasler et al. 2009) describes five methods and vital signs for understanding geothermal systems and monitoring hydrothermal features: (1) thermal feature location, (2) thermal feature extent, (3) temperature and heat flow, (4) thermal water discharge, and (5) fluid chemistry. These may be useful for understanding geothermal resource management. The Geological Monitoring website provides additional information. All geothermal reports of the Arizona Geological Survey and it predecessors (e.g., Arizona Bureau of Mines) are available at the AZGS online document repository (http://repository.azgs.az.gov/). The AZGS webpages about geothermal energy (http://azgs.arizona.edu/energy/geothermal-arizona) provide additional information.

Instream Mining

Sand and gravel mining within the Verde River floodplain influences channel alignment, headcut propagation, downstream degradation, bank erosion, and streamside vegetation. Extraction of sand and gravel from the floodplain may result in sediment transport, changes in channel configuration, and altered stream courses (Simons, Li and Associates 1985).

No instream mining occurs upstream near the monument. A study by Simons, Li, and Associates (1985) highlighted a sand and gravel mining operation about 0.8 km (0.5 mi) downstream from the monument (fig. 2). The USGS Mineral Resource Data System records this sand and gravel pit as privately owned (see https://mrdata.usgs.gov/mrds/show-mrds.php?dep_id=10186843; accessed 22 August 2019).

The National Park Service has documented no impacts associated with this downstream mining operation (National Park Service 1992). Moreover, the Arizona State Mine Inspector Office has not conducted a recent inspection (since the 1990s) of this site, which indicates it is no longer in operation (Tim Evans, Arizona State Mine Inspector Office, assistant mine inspector, telephone communication, 2 May 2019).

Monument staff can monitor proposals for renewed operations through participating in permitting procedures (see Bain 2011). The National Park Service works with adjacent land managers and other permitting entities to help ensure that external mineral exploration and development do not adversely affect NPS resources and values. 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's Energy and Minerals website (http://go.nps.gov/grd_energyminerals) provides information. In addition, the Arizona Department of Mines and Mineral Resources (ADMMR) was consolidated with the Arizona Geological Survey in 2011. The Arizona Geological Survey now maintains the ADMMR mining records in a repository of mineral and mining information that includes databases, books, photographs, periodicals, files for individual mines, mine map repository files, and mining district data (see "Additional Resources").

Table 6. Geologic resource management issues at Tuzigoot National Monument.

Map Unit of DeWitt et al. (2008) (symbol)	Description of Geologic Features and Associated Geologic Resource Management Issues	Core Components
Artificial fill (**Qa**)	**Mine Tailings** The legislative boundary of the monument contains a large tailings pile consisting of waste rock from past mining and milling operations. Trace elements from metals and other hazardous substances associated with past mining are contaminating water, soil, and biota at Tavasci Marsh. The monument's foundation document classified Tavasci Marsh as being in poor condition due to environmental contamination from the tailings pile. **Caves and Karst Resource Management** The relationship among contaminants from copper-mine tailings (**Qa**), the Verde River (**Qt** and **Qal**), Tavasci Marsh (**Qt**), the Verde Formation (**Tvs** and **Tvls**), which contains caves and karst in the region (e.g., Montezuma Castle National Monument), should be studied to ensure that contaminants are not entering a karst (or any other type of) aquifer within the Verde Formation. The main aquifers in the Verde Valley are the conglomerate, sandstone, and limestone facies of the Verde Formation (Hahman and Campbell 1980).	Tailings, which DeWitt et al. (2008) mapped as artificial fill (**Qa),** are not a fundamental resource and value.
Alluvium (**Qal**)	**Flooding** Marking the Verde River, DeWitt et al. (2008) mapped alluvium (**Qal**) whereas House and Pearthree (1993) mapped active channels (**Qyr**). Active channels (**Qyr**) are likely to change position during floods, potentially impacting infrastructure such as the road into the monument. **Quaternary Faults and Earthquakes** Areas near the Verde River underlain by relatively unconsolidated sediment and shallow groundwater will be susceptible to liquefaction (ground failure) during an earthquake. **Caves and Karst Resource Management** The relationship among the Verde River (**Qt** and **Qal**), Tavasci Marsh (**Qt**), the Verde Formation (**Tvs** and **Tvls**), which contains caves and karst in the region (e.g., Montezuma Castle National Monument), and contaminants from copper-mine tailings (**Qa**) should be studied to ensure that contaminants are not entering a karst (or any other type of) aquifer within the Verde Formation. The main aquifers in the Verde Valley are the conglomerate, sandstone, and limestone facies of the Verde Formation (Hahman and Campbell 1980). **Paleontological Resource Inventory, Monitoring, and Protection** The Verde River may transport eroded fossils (mostly marine invertebrates) from nearby Paleozoic rocks into the monument. If transport takes place, these fossils would be re-deposited in alluvium (**Qal**). **Instream Mining** Instream mining alters natural flow regimes and exacerbates flooding impacts. A sand and gravel pit (**Qal** and **Qt**) is located about 0.8 km (0.5 mi) downstream from the monument (fig. 2); the operation is not currently active. Impacts to the monument were never studied.	The Verde River and its tributaries is an interpretive theme.

Table 6 (continued). Geologic resource management issues at Tuzigoot National Monument.

Map Unit of DeWitt et al. (2008) (symbol)	Description of Geologic Features and Associated Geologic Resource Management Issues	Core Components
Terrace gravel (**Qt**)	**Disturbed Lands** Tavasci Marsh (mapped as **Qt** by DeWitt et al. 2008) has been subject to past disturbances such as construction of irrigation ditches, drainage for cattle ranching, and leveling for dairy farming and raising crops. **Flooding** Multiple units mapped by House and Pearthree (1993) correlate to the terrace gravel (**Qt**) of DeWitt et al. (2008): ● Young terraces (**Qyt**) are weakly consolidated and susceptible to bank erosion, although riparian vegetation tends to stabilize them. Most if not all **young** terraces (**Qyt**) are subject to inundation during large floods. Potential for changes in channel morphology and shifts in channel position during large floods is greatest in areas where young terraces (**Qyt**) are extensive. ● Young piedmont alluvium (**Qyp**) in the monument includes small alluvial fans that have prograded onto the young terraces (**Qyt**) of the Verde River; these areas are subject to inundation during large floods. ● In contrast to **Qyt** and **Qyp**, Chuckwalla terraces (**Qct2** and **Qct1**) are not inundated during large floods and are fairly resistant to stream erosion (see surficial geologic map poster, in pocket). **Quaternary Faults and Earthquakes** Areas near the Verde River underlain by relatively unconsolidated sediment and shallow groundwater will be susceptible to liquefaction (ground failure) during an earthquake. **Caves and Karst Resource Management** The relationship among the Verde River (**Qt** and **Qal**), Tavasci Marsh (**Qt**), the Verde Formation (**Tvs** and **Tvls**), which contains caves and karst in the region (e.g., Montezuma Castle National Monument), and contaminants from copper-mine tailings (**Qa**) should be studied to ensure that contaminants are not entering a karst (or any other type of) aquifer within the Verde Formation. The main aquifers in the Verde Valley are the conglomerate, sandstone, and limestone facies of the Verde Formation (Hahman and Campbell 1980). **Paleontological Resource Inventory, Monitoring, and Protection** Surficial deposits may contain Quaternary fossil fauna. Surficial deposits include terrace gravel (**Qt**) as mapped by DeWitt et al. (2008) as well as following units mapped by House and Pearthree (1993): **Qyp**, **Qs1**, **Qct2**, **Qct1**, and **Qmt**. **Instream Mining** Instream mining alters natural flow regimes and exacerbates flooding impacts. A sand and gravel pit (**Qt** and **Qal**) is located about 0.8 km (0.5 mi) downstream from the monument; the operation is not currently active. Impacts to the monument were never studied.	The Verde River and its tributaries is an interpretive theme. Tavasci Marsh (mapped as **Qt** by DeWitt et al. 2008) is a fundamental resource and value. Tavasci Marsh is associated with an abandoned river meander (oxbow) of the Verde River, which DeWitt et al. (2008) mapped as **Qt**; the Verde River is an interpretive theme.

Table 6 (continued). Geologic resource management issues at Tuzigoot National Monument.

Map Unit of DeWitt et al. (2008) (symbol)	Description of Geologic Features and Associated Geologic Resource Management Issues	Core Components
Verde Formation, limestone (**Tvls**)	**Slope Movements** Neither the source maps (at scales 1:24,000; 1:48,000; and 1:100,000) nor the AZGS "Natural Hazards in Arizona" map viewer show landslide deposits within or near the monument. However, scoping participants noted that rain events have generated small landslides on the northeastern boundary of the monument. In addition, monitoring indicates movement in the eastern slope of the monument's main hill (Matt Guebard, Tuzigoot and Montezuma Castle National Monuments, chief of Cultural Resources, written communication, 4 June 2019), resulting in a crack from the top of the pueblo down the southern slope (National Park Service 2006). Monument staff is monitoring this crack and the pueblo's reaction to it (National Park Service 2006). **Caves and Karst Resource Management** The Verde Formation hosts caves elsewhere in the Verde Valley (see GRI report about Montezuma Castle National Monument by KellerLynn in review). Within the monument, springs issuing from the formation are indicative of karst. The relationship among the Verde Formation (**Tvs** and **Tvls**), the Verde River (**Qt** and **Qal**), Tavasci Marsh (**Qt**), and contaminants from copper-mine tailings (**Qa**) should be studied to ensure that contaminants are not entering a karst (or any other type of) aquifer within the Verde Formation. The main aquifers in the Verde Valley are the conglomerate, sandstone, and limestone facies of the Verde Formation (Hahman and Campbell 1980). **Paleontological Resource Inventory, Monitoring, and Protection** The Verde Formation at the monument contains fossil marine invertebrates (National Park Service 2014). The Museum of Northern Arizona has a record of two Verde Formation fossil sites associated with the monument. One of these sites is a quarry at Pecks Lake; this site yielded tortoise remains. The other site yielded one plant and five gastropod fossils. The exact location of this other site—and whether it is within the legislative or administrative boundary—is unclear (Justin Tweet, NPS Geologic Resources Division, paleontologist, email communication, 14 November 2017). In addition to museum collections, fossils from the Verde Formation can occur in cultural contexts.	The hilltop pueblo and related archeological resources, which are a fundamental resource and value, are composed of the Verde Formation.
Verde Formation, undivided sedimentary rocks (**Tvs**)	**Caves and Karst Resource Management** The Verde Formation hosts caves elsewhere in the Verde Valley (see GRI report about Montezuma Castle National Monument by KellerLynn in review). Within the monument, springs issuing from the formation are indicative of karst. The relationship among the Verde Formation (**Tvs** and **Tvls**), the Verde River (**Qt** and **Qal**), Tavasci Marsh (**Qt**), and contaminants from copper-mine tailings (**Qa**) should be studied to ensure that contaminants are not entering a karst (or any other type of) aquifer within the Verde Formation. The main aquifers in the Verde Valley are the conglomerate, sandstone, and limestone facies of the Verde Formation (Hahman and Campbell 1980). **Paleontological Resource Inventory, Monitoring, and Protection** The Verde Formation at the monument contains fossil marine invertebrates (National Park Service 2014). The Museum of Northern Arizona has a record of two Verde Formation fossil sites associated with the monument. One of these sites is a quarry at Pecks Lake; this site yielded tortoise remains. The other site yielded one plant and five gastropod fossils. The exact location of this other site—and whether it is within the legislative or administrative boundary—is unclear (Justin Tweet, NPS Geologic Resources Division, paleontologist, email communication, 14 November 2017). In addition to museum collections, fossils from the Verde Formation can occur in cultural contexts. **Geothermal Resource Management** Water issuing from the Verde Formation at Shea Spring is geothermal, though the spring is not a "hot spring" by definition.	Shea Spring, which issues from **Tvs**, is a source of water to Tavasci Marsh, which is a fundamental resource and value.

Geologic Map Data

A geologic map in GIS format is the principal deliverable of the GRI program. The GRI GIS data produced for the monument follow the source maps listed here and include components described in this chapter. Three posters (in pocket) display bedrock, surficial, and geologic map data draped over imagery of the monument and surrounding area. Complete GIS data are available at the GRI publications website (http://go.nps.gov/gripubs).

Geologic Maps

A geologic map is the fundamental tool for depicting the geology of an area. Geologic maps are two-dimensional representations of the three-dimensional geometry of rock and sediment at or beneath the land surface (Evans 2016). The colors on a geologic map indicate the rock types or deposits present in an area, as well as the ages of these rocks and deposits. For example, on the bedrock geologic map for the monument (Lehner 1958), pinks and browns represent the oldest (Precambrian) rocks whereas yellows represent the youngest (Quaternary) deposits. In addition to color, rocks and deposits are delineated as map units, and each map unit is labeled by a symbol. Usually, the map unit symbol consists of an uppercase letter indicating the age (e.g., **PC** for Precambrian or **Q** for Quaternary) and lowercase letters indicating the rock formation's name or the type of deposit (e.g., **v** for the Verde Formation in **QTv** of Lehner [1958]; see tables 1, 2, 3, 4, and 5). Other symbols on geologic maps depict the contacts between map units, structures such as faults or folds, and linear features such as dikes. Some map units, such as landslide deposits, mark locations of past geologic hazards, which 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.

Geologic maps are typically one of two types: bedrock or surficial. Bedrock map units are differentiated based on age and/or rock type and commonly have formation names. Bedrock geologic maps encompass older, typically more consolidated sedimentary, metamorphic, and/or igneous rocks. Lehner (1958) is the source map for the bedrock GRI GIS data for the monument (tuzi_geology.mxd). Surficial geologic maps typically display deposits that are unconsolidated and formed during the past 2.6 million years (Quaternary Period). Surficial map units are differentiated by geologic process or depositional environment. House and Pearthree (1993) is the source map for the surficial GRI GIS data for the monument (clar_geology.mxd).

The GRI GIS data for the monument also include mapping by DeWitt et al. (2008). In this report, the DeWitt et al. (2008) map is referred to as a "geologic" map to differentiate it from the "bedrock geologic map" of Lehner (1958) and the "surficial geologic map" of House and Pearthree (1993). The DeWitt et al. (2008) map and data contain both surficial and bedrock map units, though the focus of DeWitt et al. (2008) was on bedrock. Surficial map units included on the map by DeWitt et al. (2008) were simplified from House and Pearthree (1993) and House (1994).

Source Maps

The GRI team does not conduct original geologic mapping. The team compiles existing data by digitizing paper maps or converting digital data to conform to the GRI GIS data model. GRI GIS data include essential elements of source maps such as map unit descriptions, a correlation chart of units, a map legend, map notes, cross sections, figures, and references. These items are included in the GRI ancillary map information document (moca_tuzi_geology.pdf), which is included with the GRI GIS data.

Initially, the GRI team produced bedrock (tuzi_geology.mxd) and surficial (clar_geology.mxd) map data for the monument using source maps by Lehner (1958) and House and Pearthree (1993), respectively (fig. 20). Lehner (1958) provided 1:48,000-scale bedrock map data (tuzi_geology.mxd) that cover the Clarkdale quadrangle. House and Pearthree (1993) provided 1:24,000-scale surficial map data (clar_geology.mxd) that cover the Clarkdale quadrangle. In 2018, the GRI team added a geologic map by DeWitt et al. (2008) to the GRI GIS data for the monument (fig. 20). DeWitt et al. (2008) provided 1:100,000-scale geologic map data (motu_geology.mxd) that cover the Munds Draw, Clarkdale, Page Spring, Hickey Mountain, Cottonwood, Cornville, Lake Montezuma, Middle Verde, and Camp Verde quadrangles, and parts of the Casner Butte and Walker Mountain quadrangles (fig. 21).

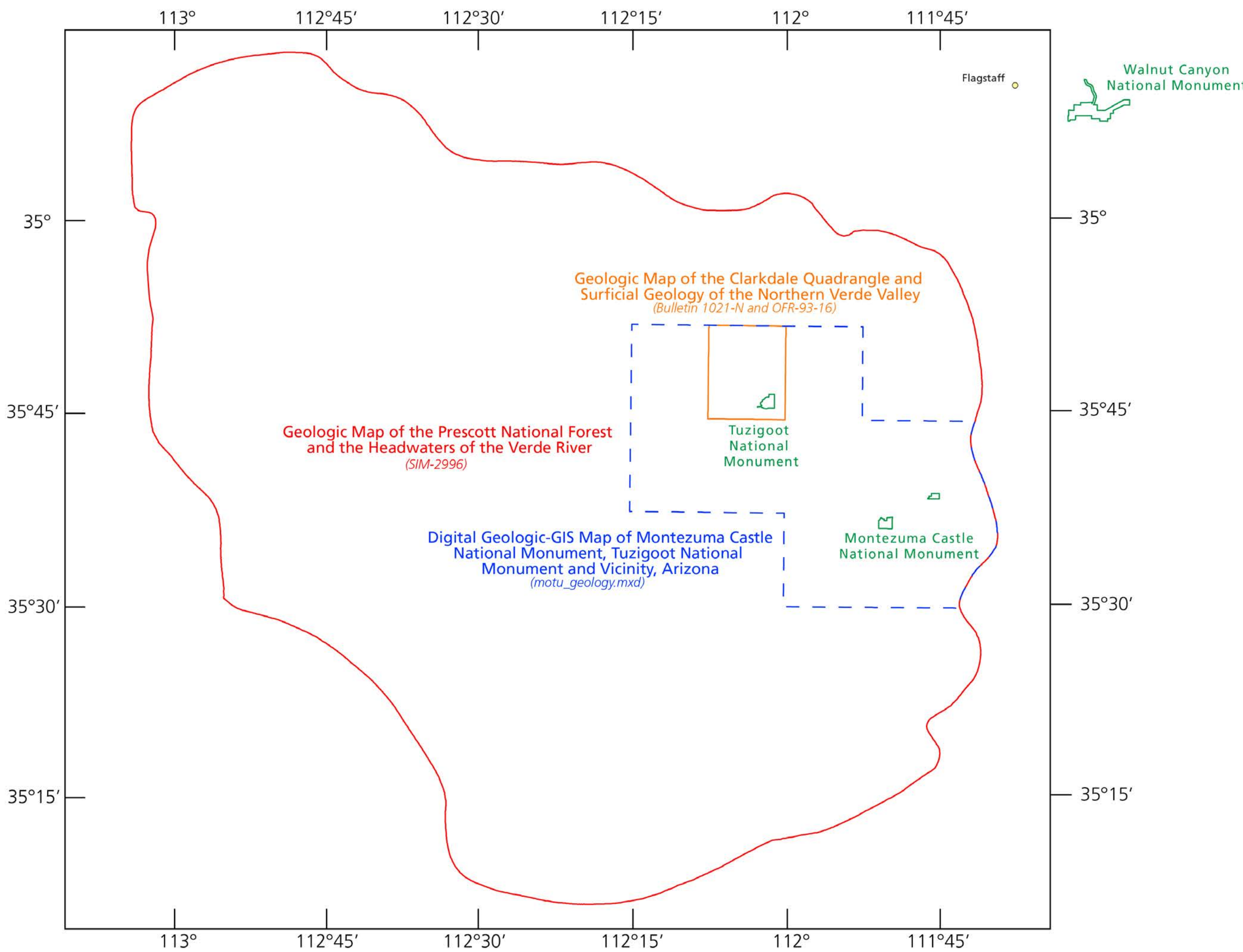

Figure 20. Index map for the monument's GRI GIS data.
The figure displays the extent of GRI GIS data produced for Tuzigoot and Montezuma Castle National Monuments as well as the extent of the source maps used to produce these data. The dashed blue line on the figure shows the extent of the GRI GIS data for these two monuments (motu_geology.mxd). The source map for these data is DeWitt et al. (2008) (i.e., USGS Scientific Investigations Map SIM-2996). The full extent of DeWitt et al. (2008) is delineated by the red line. Only a portion of this source map is included in the GRI GIS data (motu_geology.mxd) as depicted by the dashed blue line on the figure. In addition, the GRI GIS data for Tuzigoot National Monument include source maps by Lehner (1958) (i.e., USGS Bulletin 1020-N) and House and Pearthree (1993) (i.e., AZGS Open-File Report OFR-93-16), which cover the Clarkdale quadrangle (outlined in orange). The figure shows the boundaries (in green) of Tuzigoot National Monument as well as the Castle and Well Units of Montezuma Castle National Monument. GRI graphic by James Winter (Colorado State University).

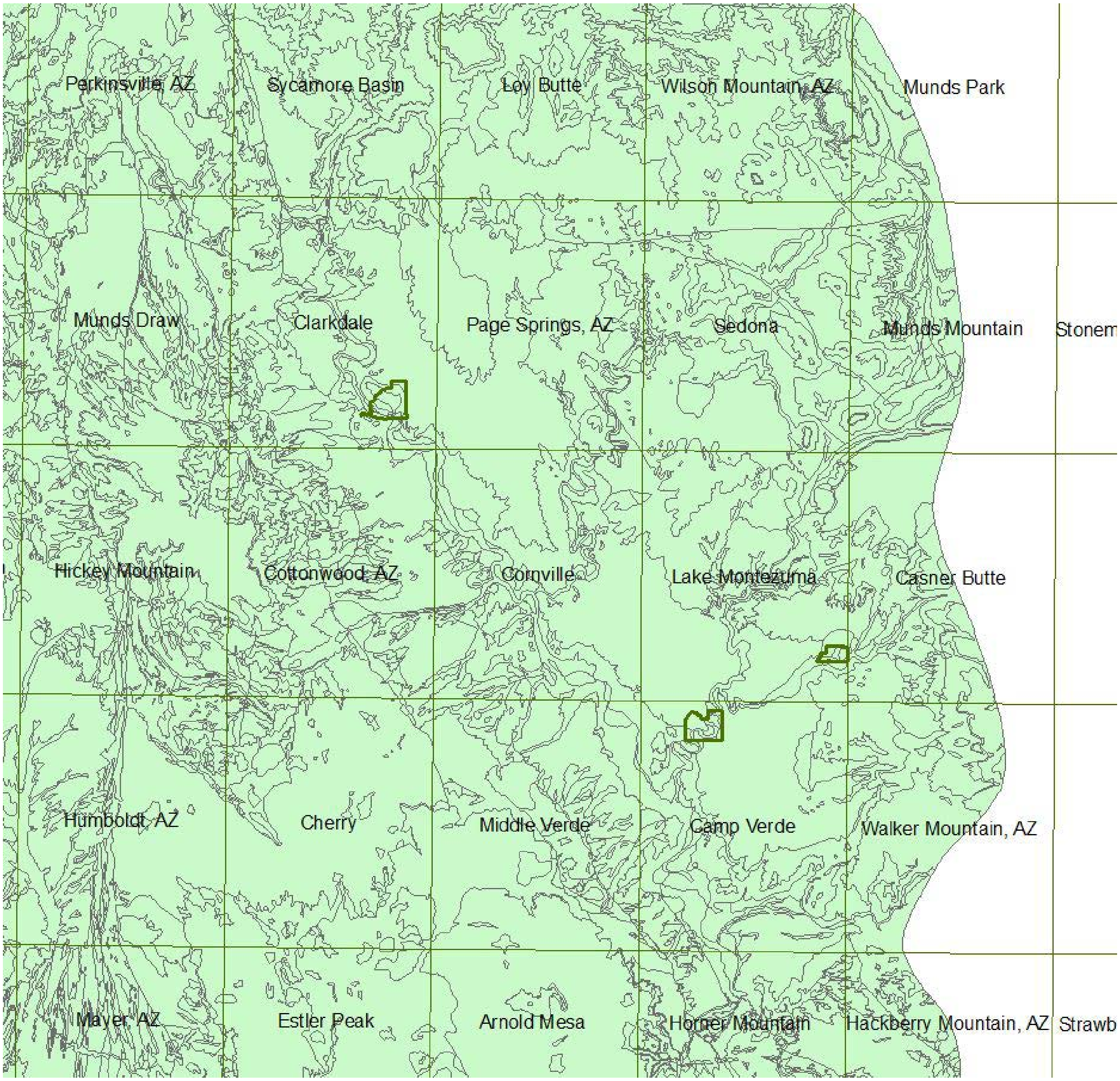

Figure 21. Graphic of quadrangles in the Verde Valley.
Geologic mapping of a portion of the area shown on the graphic is included in the GRI GIS data for Tuzigoot and Montezuma Castle National Monuments (motu_geology.mxd). The GRI GIS data incorporate nine 7.5-minute quadrangles—Munds Draw, Clarkdale, Page Springs, Hickey Mountain, Cottonwood, Cornville, Lake Montezuma, Middle Verde, and Camp Verde—and parts of two other quadrangles—Casner Butte and Walker Mountain. The dark green outlines on the figure represent the boundaries of Tuzigoot National Monument (in the Clarkdale quadrangle) and Montezuma Castle National Monument (Well Unit in the Lake Montezuma quadrangle; Castle Unit in the Camp Verde quadrangle). Graphic by Stephanie O'Meara (Colorado State University).

The GRI team named the map-data files for the monument using the following abbreviations: "tuzi" (in reference to the NPS park code) for the bedrock geologic map of Tuzigoot National Monument (source map: Lehner 1958), "clar" (in reference to the Clarkdale quadrangle) for the surficial geologic map of Tuzigoot National Monument (source map: House and Pearthree 1993), and "motu" for the geologic map by DeWitt et al. (2008), which covers both Montezuma Castle ("mo") and Tuzigoot ("tu") National Monuments.

GRI GIS Data

The GRI team standardizes map deliverables using a data model. The GRI GIS data for the monument were compiled using data model version 2.3, which is available online (http://go.nps.gov/gridatamodel). The data model dictates GIS data structure, including layer architecture, feature attribution, and relationships within ESRI ArcGIS software. The GRI website (http://go.nps.gov/gri) provides more information about the program's map products.

GRI GIS data are available on the GRI publications website and through the NPS Integrated Resource Management Applications portal (IRMA; 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 GRI GIS data for the monument:

- A text document (moca_tuzi_geology_gis_readme.pdf) that describes the GRI data formats, naming conventions, extraction instructions, use constraints, and contact information;
- Data in ESRI (10.1) geodatabase GIS format;
- Layer files with feature symbology (see tables 7, 8, and 9);
- Federal Geographic Data Committee (FGDC)–compliant metadata;
- An ancillary map information document (moca_tuzi_geology.pdf) that contains information captured from source maps such as map unit descriptions, geologic unit correlation tables, legends, cross sections, and figures;
- ESRI map documents (tuzi_geology.mxd, clar_geology.mxd, and motu_geology.mxd) that display the GRI GIS data;
- A version of the data viewable in 2.2 KML/KMZ format for use with Google Earth;
- A version of the data viewable via auto-generated ArcGIS online map service ("web service")

Table 7. GRI GIS data layers for bedrock geologic map (Lehner 1958; tuzi_geology.mxd).

Data Layer	On Poster?	Google Earth Layer?
Geologic Attitude and Observation Points	No	No
Fault Symbology	Yes	No
[Geologic] Cross Section Lines (D–D')	Yes	No
Faults	Yes	Yes
Geologic Contacts	Yes	Yes
Mine Area Feature Boundaries	No	No
Mine Area Features	No	No
Geologic Units	Yes	Yes

Table 8. GRI GIS data layers for surficial geologic map (House and Pearthree 1993; clar_geology.mxd).

Data Layer	On Poster?	Google Earth Layer?
Surficial Contacts	Yes	Yes
Surficial Units	Yes	Yes

Table 9. GRI GIS data layers for geologic map (DeWitt et al. 2008; motu_geology.mxd).

Data Layer	On Poster?	Google Earth Layer?
Geologic Attitude Observation Localities	No	No
Geologic Sample Localities	No	No
Volcanic Point Features	No	No
Hazard Feature Lines	No	Yes
Geologic Line Features	No	Yes
Map Symbology	Yes	No
Faults	Yes	Yes
Folds	Yes	Yes
Linear Dikes	Yes	Yes
Deformation Area Boundaries	No	Yes
Deformation Areas	No	Yes
Geologic Contacts	Yes	Yes
Geologic Units	Yes	Yes

GRI Map Posters

Three posters that display the GRI GIS data draped over a shaded relief image of the monument and surrounding area are included with this report. The "Bedrock Geologic Map of Tuzigoot National Monument" poster shows the data from tuzi_geology.mxd (source map: Lehner 1958). The "Surficial Geologic Map of Tuzigoot National Monument" poster shows the data from clar_geology.mxd (source map: House and Pearthree 1993). The "Geologic Map of Tuzigoot National Monument" poster shows a portion of the data from motu_geology.mxd (source map: DeWitt et al. 2008). Not all GIS feature classes are included on the posters (see tables 7, 8, and 9). The GRI team added geographic information and selected park features to the posters. Digital elevation data and added geographic information are not included in the GRI GIS data but are available from a variety of online sources. Monument managers may contact the GRI team for assistance locating these data.

Use Constraints

Graphic and written information provided in this report is not a substitute for site-specific investigations. Monument managers should neither permit nor deny ground-disturbing activities based upon the information provided here. Monument managers may contact the GRI team with questions.

Minor inaccuracies may exist with respect to the locations of geologic features in the GRI GIS data and on the posters. Based on the source map scales—1:24,000 for House and Pearthree (1993), 1:48,000 for Lehner (1958), and 1:100,000 for DeWitt et al. (2008)—as well as US National Map Accuracy Standards, the geologic features represented in the GRI GIS data and on the posters are expected to be horizontally within 12 m (40 ft), 24 m (80 ft), or 51 m (167 ft), respectively, of their true locations.

Future Mapping Projects

During the 2017 conference call, geologists from the Arizona Geological Survey suggested that mapping by Cook et al. (2010b) and Cook et al. (2010a) would provide more updated surficial mapping for the Verde River and Verde River tributaries, including Beaver and Wet Beaver Creeks, which flow in Montezuma Castle National Monument. Sheet C of Cook et al. (2010b, "Verde River map") covers Tuzigoot National Monument. Sheet D of Cook et al. (2010a, "tributaries map") covers Montezuma Castle National Monument. Notably, Cook et al. (2010a, "tributaries map") has GIS data, which would facilitate incorporation into the GRI GIS data model.

Of potential interest to monument managers: As part of the mapping project, both Cook et al. (2010b, "Verde River map") and Cook et al. (2010a, "tributaries map") conducted a geoarcheological evaluation of these river corridors. Thus, the reports contain information about the archeological resources along the 3-km- (2-mi-) wide mapping project corridors. Documented archeological attributes include associated terrace surface(s); whether the site was deeply buried or exposed on the modern ground surface; whether artifacts appeared to be reworked by erosion into secondary contexts; radiocarbon dates; and a brief, general description of the archeological materials and features found at the site, including temporally sensitive artifact types. These data and associated reports are available at the Arizona Geological Survey's document repository.

If monument managers are interested in acquiring updated mapping by Cook et al. (2010a, 2010b) as part of their GRI GIS data, they can contact the NPS Geologic Resources Division and/or Inventory and Monitoring Division. The next generation of NPS inventories (termed "inventories 2.0"), which are estimated to begin in 2020, may support additional geologic mapping and GIS coverages.

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Additional Resources

These websites, online information, and books may be of use for geologic resources management and interpretation at Tuzigoot National Monument. Complete URLs for websites referenced in the report narrative are included here.

Arizona Geological Survey (AZGS) Outreach and Education

- Ask a Geologist (most commonly asked questions and online form for submitting questions): http://azgs.arizona.edu/ask-a-geologist
- Arizona Geology Blog (more than 4,500 posts since 2007): http://blog.azgs.arizona.edu/
- Document Repository (more than 1,000 publications dating from 1915 to the present): http://repository.azgs.az.gov/
- Down-to-Earth series (a collection of geologic booklets for the lay public): http://repository.azgs.az.gov/facets/results/og%3A1452
- Facebook (more than 15,400 followers as of 12 December 2017): https://www.facebook.com/AZ.Geological.Survey/
- Flickr (approximately 560 photographs since 2015): https://www.flickr.com/photos/azgs/
- Twitter (approximately 5,600 followers as of 12 December 2017): https://twitter.com/AZGeology
- YouTube channel (more than 100 videos): https://www.youtube.com/user/azgsweb/playlists

Arizona Mine Data and Mining Information

- AZGS mine data (files for approximately 21,000 mines, thousands of maps, and more than 6,000 historic photographs): http://minedata.azgs.arizona.edu/
- AZGS "Mining in Arizona" website: https://azgs.arizona.edu/minerals/mining-arizona
- Arizona State Mine Inspector: https://asmi.az.gov/

Climate Change Information

- Intergovernmental Panel on Climate Change: http://www.ipcc.ch/
- NPS Climate Change Response Program Resources: http://www.nps.gov/subjects/climatechange/resources.htm
- The Climate Analyzer (an interactive website that allows users to create custom graphs and tables from historical and current weather-station data; the Sonoran Desert Network relies on these data): http://www.climateanalyzer.org/
- US Global Change Research Program (Southwest chapter): https://nca2018.globalchange.gov/chapter/25/.

Geological Surveys and Societies

- American Geophysical Union: http://sites.agu.org/
- American Geosciences Institute: http://www.americangeosciences.org/
- Arizona Geological Survey: http://www.azgs.az.gov/
- Association of American State Geologists: http://www.stategeologists.org/
- Geological Society of America: http://www.geosociety.org/
- US Geological Survey (USGS): http://www.usgs.gov/

Natural Hazards in Arizona

- AZGS "Natural Hazards in Arizona" map viewer includes earth fissures, active faults, earthquake epicenters, flood potential, fire risk index, and landslides: https://uagis.maps.arcgis.com/apps/webappviewer/index.html?id=98729f76e4644f1093d1c2cd6dabb584
- Arizona's Earth Fissure Center: http://www.azgs.az.gov/EFC.shtml
- Arizona Earthquake Information Center and Northern Arizona Seismograph Network (Northern Arizona University): https://www.cefns.nau.edu/Orgs/aeic/index.html
- Arizona Broadband Seismic Network (operated by AZGS): https://www.fdsn.org/networks/detail/AE/
- AZGS information about earthquakes, including time-lapse video of historic earthquake epicenters of Arizona and information about the June 2014, M 5.3 earthquake in Duncan, Arizona: http://azgs.arizona.edu/center-natural-hazards/earthquakes
- AZGS information about volcanoes in Arizona; http://azgs.arizona.edu/center-natural-hazards/volcanism
- Southern Arizona Seismic Observatory (University of Arizona): https://www.geo.arizona.edu/saso/
- USGS Earthquake Hazards Program (information by region—Arizona): https://earthquake.usgs.gov/earthquakes/byregion/arizona.php
- USGS landslide hazards: https://www.usgs.gov/natural-hazards/landslide-hazards
- USGS earthquake catalog: https://earthquake.usgs.gov/earthquakes/search/

NPS Geologic Information, Interpretation, and Education

- *America's Geologic Heritage: An Invitation to Leadership* by the NPS Geologic Resources Division and American Geosciences Institute (AGI). Published in 2015 by AGI. https://www.nps.gov/subjects/geology/upload/GH_Publicaton_Final.pdf
- Desert Research Learning Center (works with park managers to develop resource education products relating to natural resources in parks): https://www.nps.gov/im/sodn/drlc.htm
- NPS Geologic Resources Division's Education website: http://go.nps.gov/geoeducation
- NPS Geology/America's Geologic Legacy (take a geologic tour or learn about park landforms, geologic wonders, and rocks and minerals): http://go.nps.gov/geology
- NPS Geodiversity Atlas (search by park): https://www.nps.gov/articles/geodiversity-atlas-map.htm
- NPS Geologic Resources Division Photogrammetry: http://go.nps.gov/grd_photogrammetry.
- NPS Cave and Karst Information: https://www.nps.gov/subjects/caves/index.htm

NPS Geologic Assistance for Park Managers

- NPS Geologic Resources Division (Lakewood, Colorado): http://go.nps.gov/grd
- NPS Geologic Resources Inventory: http://go.nps.gov/gri
- NPS Geologic Resources Inventory data model: http://go.nps.gov/gridatamodel.
- NPS Geoscientist-in-the-Parks (GIP) internship and guest scientist program: http://go.nps.gov/gip
- NPS Mosaics In Science internship program: http://go.nps.gov/mosaics
- NPS Solution for Technical Assistance Requests (STAR): https://irma.nps.gov/Star/.

NPS Resource Management Guidance and Documents

- Integrated Resource Management Applications (IRMA): https://irma.nps.gov/App/Portal/Home.
- See Appendix B of the GRI report.
- 1998 National parks omnibus management act: http://www.gpo.gov/fdsys/pkg/PLAW-105publ391/pdf/PLAW-105publ391.pdf
- Geological Monitoring by Rob Young and Lisa Norby. Published in 2009 by the Geological Society of America. Available online at http://go.nps.gov/geomonitoring
- Management Policies 2006 (Chapter 4: Natural resource management): http://www.nps.gov/policy/mp/policies.html
- NPS-75: Natural resource inventory and monitoring guideline: https://irma.nps.gov/DataStore/Reference/Profile/622933
- NPS Natural resource management reference manual #77: https://irma.nps.gov/DataStore/Reference/Profile/572379
- NPS Technical Information Center (TIC) (Denver, Colorado; repository for technical documents): https://www.nps.gov/dsc/technicalinfocenter.htm

US Geological Survey (USGS) Reference Tools

- National Geologic Map Database (NGMDB): http://ngmdb.usgs.gov/ngmdb/ngmdb_home.html
- US Geologic Names Lexicon (Geolex; geologic unit nomenclature and summary): http://ngmdb.usgs.gov/Geolex/search
- Geographic Names Information System (GNIS; official listing of place names and geographic features): https://www.usgs.gov/core-science-systems/ngp/board-on-geographic-names/domestic-names
- GeoPDFs (download PDFs of any topographic map in the United States): http://store.usgs.gov (click on "Map Locator")
- Publications warehouse (USGS publications available online): http://pubs.er.usgs.gov
- Tapestry of Time and Terrain (descriptions of physiographic provinces): http://pubs.usgs.gov/imap/i2720/

Appendix A: Scoping Participants

The following people attended the GRI scoping meeting, held on 10 May 2006, or the follow-up report writing conference call, held on 6 December 2017. 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.

2006 Scoping Meeting Participants

Name	Affiliation	Position
Ron Blakey	Northern Arizona University	Geology professor
Maggie Bowler	Tuzigoot and Montezuma Castle National Monuments	Archeological technician
Dennis Casper	Tuzigoot and Montezuma Castle National Monuments	Biologist
Kathy Davis	Tuzigoot and Montezuma Castle National Monuments	Superintendent
Travis Ellison	Tuzigoot and Montezuma Castle National Monuments	Archeological technician
Michele Girard	NPS Southern Arizona Office	Ecologist
Andy Hubbard	NPS Sonoran Desert Network	Network coordinator
Katie KellerLynn	Colorado State University	Geologist/research associate
Lisa Norby	NPS Geologic Resources Division	Geologist
Phil Pearthree	Arizona Geological Survey	Geologist
Melanie Ransmeier	NPS Geologic Resources Division	GIS specialist
John Schroeder	Tuzigoot and Montezuma Castle National Monuments	Archeologist
Paul Umhoefer	Northern Arizona University	Geology professor
Laurie Wirt	US Geological Survey	Geologist

2017 Conference Call Participants

Name	Affiliation	Position
Tim Connors	NPS Geologic Resources Division	Geologist/GRI maps coordinator
Mike Conway	Arizona Geological Survey	Geologist
Dorothy FireCloud	Tuzigoot and Montezuma Castle National Monuments	Superintendent
Brian Gootee	Arizona Geological Survey	Geologist
Tina Greenawalt	Tuzigoot and Montezuma Castle National Monuments	Chief of Natural Resources
Matt Guebard	Tuzigoot and Montezuma Castle National Monuments	Chief of Cultural Resources
Evan Gwilliam	NPS Sonoran Desert Network	Ecologist
Lucas Hoedl	Tuzigoot and Montezuma Castle National Monuments	Park archeologist
Katie KellerLynn	Colorado State University	Geologist/research associate
Jason Kenworthy	NPS Geologic Resources Division	Geologist/GRI reports coordinator
Justin Mossman	NPS Southern Arizona Office	Management and program analyst
Stephanie O’Meara	Colorado State University	Geologist/GIS specialist/data manager
Vince Santucci	NPS Geologic Resources Division	Paleontologist
Justin Tweet	NPS Geologic Resources Division	Paleontologist

Appendix B: Geologic Resource Laws, Regulations, and Policies

The NPS Geologic Resources Division developed this table to summarize laws, regulations, and policies that specifically apply to NPS minerals and geologic resources. The table does not include laws of general application (e.g., Endangered Species Act, Clean Water Act, Wilderness Act, National Environmental Policy Act, or National Historic Preservation Act). The table does include the NPS Organic Act when it serves as the main authority for protection of a particular resource or when other, more specific laws are not available. Information is current as of December 2018. 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, 54 USC § 100701** protects the confidentiality of the nature and specific location of cave and karst resources. **Lechuguilla Cave Protection Act of 1993, Public Law 103-169** created a cave protection zone (CPZ) around Lechuguilla Cave in Carlsbad Caverns National Park. Within the CPZ, access and the removal of cave resources may be limited or prohibited; existing leases may be cancelled with appropriate compensation; and lands are withdrawn from mineral entry.	**36 CFR § 2.1** prohibits possessing/destroying/disturbing…cave resources…in park units. **43 CFR Part 37** states that all NPS caves are "significant" and sets forth procedures for determining/releasing confidential information about specific cave locations to a FOIA requester.	**Section 4.8.1.2** requires NPS to maintain karst integrity, minimize impacts. **Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity. **Section 4.8.2.2** requires NPS to protect caves, allow new development in or on caves if it will not impact cave environment, and to remove existing developments if they impair caves. **Section 6.3.11.2** explains how to manage caves in/adjacent to wilderness.
Paleontology	**National Parks Omnibus Management Act of 1998, 54 USC § 100701** protects the confidentiality of the nature and specific location of paleontological resources and objects. **Paleontological Resources Preservation Act of 2009, 16 USC § 470aaa et seq.** provides for the management and protection of paleontological resources on federal lands.	**36 CFR § 2.1(a)(1)(iii)** prohibits destroying, injuring, defacing, removing, digging or disturbing paleontological specimens or parts thereof. **Prohibition in 36 CFR § 13.35** applies even in Alaska parks, where the surface collection of other geologic resources is permitted. **43 CFR Part 49** (in development) will contain the DOI regulations implementing the Paleontological Resources Preservation Act.	**Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity. **Section 4.8.2.1** emphasizes Inventory and Monitoring, encourages scientific research, directs parks to maintain confidentiality of paleontological information, and allows parks to buy fossils only in accordance with certain criteria.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Recreational Collection of Rocks Minerals	**NPS Organic Act, 54 USC. § 100101 et seq.** directs the NPS to conserve all resources in parks (which includes rock and mineral resources) unless otherwise authorized by law. **Exception: 16 USC. § 445c (c)** Pipestone National Monument enabling statute. Authorizes American Indian collection of catlinite (red pipestone).	**36 C.F.R. § 2.1** prohibits possessing, destroying, disturbing mineral resources…in park units. **Exception: 36 C.F.R. § 7.91** allows limited gold panning in Whiskeytown. **Exception: 36 C.F.R. § 13.35** allows some surface collection of rocks and minerals in some Alaska parks (not Klondike Gold Rush, Sitka, Denali, Glacier Bay, and Katmai) by non-disturbing methods (e.g., no pickaxes), which can be stopped by superintendent if collection causes significant adverse effects on park resources and visitor enjoyment.	**Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity.
Geothermal	**Geothermal Steam Act of 1970, 30 USC. § 1001 et seq. as amended in 1988**, states ● No geothermal leasing is allowed in parks. ● "Significant" thermal features exist in 16 park units (the features listed by the NPS at **52 Fed. Reg. 28793-28800** (August 3, 1987), plus the thermal features in Crater Lake, Big Bend, and Lake Mead). ● NPS is required to monitor those features. ● Based on scientific evidence, Secretary of Interior must protect significant NPS thermal features from leasing effects. **Geothermal Steam Act Amendments of 1988, Public Law 100--443** prohibits geothermal leasing in the Island Park known geothermal resource area near Yellowstone and outside 16 designated NPS units if subsequent geothermal development would significantly adversely affect identified thermal features.	None applicable.	**Section 4.8.2.3** requires NPS to ● Preserve/maintain integrity of all thermal resources in parks. ● Work closely with outside agencies. ● Monitor significant thermal features.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Mining Claims (Locatable Minerals)	**Mining in the Parks Act of 1976, 54 USC § 100731 et seq.** authorizes NPS to regulate all activities resulting from exercise of mineral rights, on patented and unpatented mining claims in all areas of the System, in order to preserve and manage those areas. **General Mining Law of 1872, 30 USC § 21 et seq.** allows US citizens to locate mining claims on Federal lands. Imposes administrative and economic validity requirements for "unpatented" claims (the right to extract Federally-owned locatable minerals). Imposes additional requirements for the processing of "patenting" claims (claimant owns surface and subsurface). Use of patented mining claims may be limited in Wild and Scenic Rivers and OLYM, GLBA, CORO, ORPI, and DEVA. **Surface Uses Resources Act of 1955, 30 USC § 612** restricts surface use of unpatented mining claims to mineral activities.	**36 CFR § 5.14** prohibits prospecting, mining, and the location of mining claims under the general mining laws in park areas except as authorized by law. **36 CFR Part 6** regulates solid waste disposal sites in park units. **36 CFR Part 9, Subpart A** requires the owners/operators of mining claims to demonstrate bona fide title to mining claim; submit a plan of operations to NPS describing where, when, and how; prepare/submit a reclamation plan; and submit a bond to cover reclamation and potential liability. **43 CFR Part 36** governs access to mining claims located in, or adjacent to, National Park System units in Alaska.	**Section 6.4.9** requires NPS to seek to remove or extinguish valid mining claims in wilderness through authorized processes, including purchasing valid rights. Where rights are left outstanding, NPS policy is to manage mineral-related activities in NPS wilderness in accordance with the regulations at **36 CFR Parts 6 and 9A**. **Section 8.7.1** prohibits location of new mining claims in parks; requires validity examination prior to operations on unpatented claims; and confines operations to claim boundaries.
Nonfederal Oil and Gas	**NPS Organic Act, 54 USC § 100751 et seq.** authorizes the NPS to promulgate regulations to protect park resources and values (from, for example, the exercise of mining and mineral rights). Individual Park Enabling Statutes: • **16 USC § 230a** (Jean Lafitte NHP & Pres.) • **16 USC § 450kk** (Fort Union NM), • **16 USC § 459d-3** (Padre Island NS), • **16 USC § 459h-3** (Gulf Islands NS), • **16 USC § 460ee** (Big South Fork NRRA), • **16 USC § 460cc-2(i)** (Gateway NRA), • **16 USC § 460m** (Ozark NSR), • **16 USC § 698c** (Big Thicket N Pres.), • **16 USC § 698f** (Big Cypress N Pres.)	**36 CFR Part 6** regulates solid waste disposal sites in park units. **36 CFR Part 9, Subpart B** requires the owners/operators of nonfederally owned oil and gas rights outside of Alaska to • demonstrate bona fide title to mineral rights; • submit an Operations Permit Application to NPS describing where, when, how they intend to conduct operations; • prepare/submit a reclamation plan; and • submit a bond to cover reclamation and potential liability. **43 CFR Part 36** governs access to nonfederal oil and gas rights located in, or adjacent to, National Park System units in Alaska.	**Section 8.7.3** requires operators to comply with 9B regulations.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Federal Mineral Leasing (Oil, Gas, and Solid Minerals)	**The Mineral Leasing Act, 30 USC § 181 et seq., and the Mineral Leasing Act for Acquired Lands, 30 USC § 351 et seq.** do not authorize the BLM to lease federally owned minerals in NPS units. **Combined Hydrocarbon Leasing Act, 30 USC §181**, allowed owners of oil and gas leases or placer oil claims in Special Tar Sand Areas (STSA) to convert those leases or claims to combined hydrocarbon leases, and allowed for competitive tar sands leasing. This act did not modify the general prohibition on leasing in park units but did allow for lease conversion in GLCA, which is the only park unit that contains a STSA. **Exceptions: Glen Canyon NRA (16 USC § 460dd et seq.), Lake Mead NRA (16 USC § 460n et seq.), and Whiskeytown-Shasta-Trinity NRA (16 USC § 460q et seq.)** authorizes the BLM to issue federal mineral leases in these units provided that the BLM obtains NPS consent. Such consent must be predicated on an NPS finding of no significant adverse effect on park resources and/or administration. American Indian Lands Within NPS Boundaries Under the **Indian Allottee Leasing Act of 1909, 25 USC §396, and the Indian Leasing Act of 1938, 25 USC §396a, §398 and §399, and Indian Mineral Development Act of 1982, 25 USCS §§2101-2108**, all minerals on American Indian trust lands within NPS units are subject to leasing. **Federal Coal Leasing Amendments Act of 1975, 30 USC § 201** prohibits coal leasing in National Park System units.	**36 CFR § 5.14** states prospecting, mining, and…leasing under the mineral leasing laws [is] prohibited in park areas except as authorized by law. **BLM regulations at 43 CFR Parts 3100, 3400, and 3500** govern Federal mineral leasing. **43 CFR Part 3160** governs onshore oil and gas operations, which are overseen by the BLM. Regulations re: Native American Lands within NPS Units: • **25 CFR Part 211** governs leasing of tribal lands for mineral development. • **25 CFR Part 212** governs leasing of allotted lands for mineral development. • **25 CFR Part 216** governs surface exploration, mining, and reclamation of lands during mineral development. • **25 CFR Part 224** governs tribal energy resource agreements. • **25 CFR Part 225** governs mineral agreements for the development of Indian-owned minerals entered into pursuant to the **Indian Mineral Development Act of 1982, Pub. L. No. 97-382, 96 Stat. 1938** (codified at **25 USC §§ 2101-2108**). • **30 CFR §§ 1202.100-1202.101** governs royalties on oil produced from Indian leases. • **30 CFR §§ 1202.550-1202.558** governs royalties on gas production from Indian leases. • **30 CFR §§ 1206.50-1206.62 and §§ 1206.170-1206.176** governs product valuation for mineral resources produced from Indian oil and gas leases. • **30 CFR § 1206.450** governs the valuation coal from Indian Tribal and Allotted leases. • **43 CFR Part 3160** governs onshore oil and gas operations, which are overseen by the BLM.	**Section 8.7.2** states that all NPS units are closed to new federal mineral leasing except Glen Canyon, Lake Mead and Whiskeytown-Shasta-Trinity NRAs.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Nonfederal minerals other than oil and gas	**NPS Organic Act, 54 USC §§ 100101 and 100751**	NPS regulations at **36 CFR Parts 1, 5, and 6** require the owners/ operators of other types of mineral rights to obtain a special use permit from the NPS as a **§ 5.3** business operation, and **§ 5.7 – Construction of buildings or other facilities**, and to comply with the solid waste regulations at **Part 6**.	**Section 8.7.3** states that operators exercising rights in a park unit must comply with **36 CFR Parts 1 and 5**.
Coal	**Surface Mining Control and Reclamation Act of 1977, 30 USC § 1201 et. seq.** prohibits surface coal mining operations on any lands within the boundaries of a NPS unit, subject to valid existing rights.	**SMCRA Regulations at 30 CFR Chapter VII** govern surface mining operations on Federal lands and Indian lands by requiring permits, bonding, insurance, reclamation, and employee protection. **Part 7** of the regulations states that National Park System lands are unsuitable for surface mining.	None applicable.
Uranium	**Atomic Energy Act of 1954** Allows Secretary of Energy to issue leases or permits for uranium on BLM lands; may issue leases or permits in NPS areas only if president declares a national emergency.	None applicable.	None applicable.
Common Variety Mineral Materials (Sand, Gravel, Pumice, etc.)	**Materials Act of 1947, 30 USC § 601** does not authorize the NPS to dispose of mineral materials outside of park units. **Reclamation Act of 1939, 43 USC §387**, authorizes removal of common variety mineral materials from federal lands in federal reclamation projects. This act is cited in the enabling statutes for Glen Canyon and Whiskeytown National Recreation Areas, which provide that the Secretary of the Interior may permit the removal of federally owned nonleasable minerals such as sand, gravel, and building materials from the NRAs under appropriate regulations. Because regulations have not yet been promulgated, the National Park Service may not permit removal of these materials from these National Recreation Areas. **16 USC §90c-1(b)** authorizes sand, rock and gravel to be available for sale to the residents of Stehekin from the non-wilderness portion of Lake Chelan National Recreation Area, for local use as long as the sale and disposal does not have significant adverse effects on the administration of the national recreation area.	None applicable.	**Section 9.1.3.3** clarifies that only the NPS or its agent can extract park-owned common variety minerals (e.g., sand and gravel), and: ● only for park administrative uses; ● after compliance with NEPA and other federal, state, and local laws, and a finding of non-impairment; ● after finding the use is park's most reasonable alternative based on environment and economics; ● parks should use existing pits and create new pits only in accordance with park-wide borrow management plan; ● spoil areas must comply with Part 6 standards; and ● NPS must evaluate use of external quarries. Any deviation from this policy requires a written waiver from the Secretary, Assistant Secretary, or Director.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Coastal Features and Processes	**NPS Organic Act, 54 USC § 100751 et. seq.** authorizes the NPS to promulgate regulations to protect park resources and values (from, for example, the exercise of mining and mineral rights). **Coastal Zone Management Act, 16 USC § 1451 et. seq**. requires Federal agencies to prepare a consistency determination for every Federal agency activity in or outside of the coastal zone that affects land or water use of the coastal zone. **Clean Water Act, 33 USC § 1342/ Rivers and Harbors Act, 33 USC 403** require that dredge and fill actions comply with a Corps of Engineers Section 404 permit. **Executive Order 13089** (coral reefs) (1998) calls for reduction of impacts to coral reefs. **Executive Order 13158** (marine protected areas) (2000) requires every federal agency, to the extent permitted by law and the maximum extent practicable, to avoid harming marine protected areas. *See also "Climate Change"*	**36 CFR § 1.2(a)(3)** applies NPS regulations to activities occurring within waters subject to the jurisdiction of the US located within the boundaries of a unit, including navigable water and areas within their ordinary reach, below the mean high water mark (or OHW line) without regard to ownership of submerged lands, tidelands, or lowlands. **36 CFR § 5.7** requires NPS authorization prior to constructing a building or other structure (including boat docks) upon, across, over, through, or under any park area. *See also "Climate Change"*	**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 4.8.1** requires NPS to allow natural geologic processes to proceed unimpeded. NPS can intervene in these processes only when required by Congress, when necessary for saving human lives, or when there is no other feasible way to protect other natural resources/ park facilities/historic properties. **Section 4.8.1.1** requires NPS to: ● Allow natural processes to continue without interference, ● Investigate alternatives for mitigating the effects of human alterations of natural processes and restoring natural conditions, ● Study impacts of cultural resource protection proposals on natural resources, ● Use the most effective and natural-looking erosion control methods available, and avoid new developments in areas subject to natural shoreline processes unless certain factors are present. *See also "Climate Change"*

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Climate Change	**Secretarial Order 3289** (Addressing the Impacts of Climate Change on America's Water, Land, and Other Natural and Cultural Resources) (2009) requires DOI bureaus and offices to incorporate climate change impacts into long-range planning; and establishes DOI regional climate change response centers and Landscape Conservation Cooperatives to better integrate science and management to address climate change and other landscape scale issues. **Executive Order 13693** (Planning for Federal Sustainability in the Next Decade) (2015) established to maintain Federal leadership in sustainability and greenhouse gas emission reductions.	*No applicable regulations, although the following NPS guidance should be considered:* **Coastal Adaptation Strategies Handbook (Beavers et al. 2016)** provides strategies and decision-making frameworks to support adaptation of natural and cultural resources to climate change. **Climate Change Facility Adaptation Planning and Implementation Framework**: The NPS Sustainable Operations and Climate Change Branch is developing a plan to incorporate vulnerability to climate change (Beavers et al. 2016b). **NPS Climate Change Response Strategy** (2010) describes goals and objectives to guide NPS actions under four integrated components: science, adaptation, mitigation, and communication. **Policy Memo 12-02** (Applying National Park Service Management Policies in the Context of Climate Change) (2012) applies considerations of climate change to the impairment prohibition and to maintaining "natural conditions". **Policy Memo 14-02** (Climate Change and Stewardship of Cultural Resources) (2014) provides guidance and direction regarding the stewardship of cultural resources in relation to climate change. **Policy Memo 15-01** (Climate Change and Natural Hazards for Facilities) (2015) provides guidance on the design of facilities to incorporate impacts of climate change adaptation and natural hazards when making decisions in national parks. *Continued in 2006 Management Policies column*	**Section 4.1** requires NPS to investigate the possibility to restore natural ecosystem functioning that has been disrupted by past or ongoing human activities. This would include climate change, as put forth by Beavers et al. (2016). *NPS guidance, continued:* **DOI Manual Part 523, Chapter 1** establishes policy and provides guidance for addressing climate change impacts upon the Department's mission, programs, operations, and personnel. **Revisiting Leopold: Resource Stewardship in the National Parks** (2012) will guide US National Park natural and cultural resource management into a second century of continuous change, including climate change. **Climate Change Action Plan** (2012) articulates a set of high-priority no-regrets actions the NPS will undertake over the next few years **Green Parks Plan** (2013) is a long-term strategic plan for sustainable management of NPS operations.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Upland and Fluvial Processes	**Rivers and Harbors Appropriation Act of 1899, 33 USC § 403** prohibits the construction of any obstruction on the waters of the United States not authorized by congress or approved by the USACE. **Clean Water Act 33 USC § 1342** requires a permit from the USACE prior to any discharge of dredged or fill material into navigable waters (waters of the US [including streams]). **Executive Order 11988** requires federal agencies to avoid adverse impacts to floodplains. (see also **D.O. 77-2**) **Executive Order 11990** requires plans for potentially affected wetlands (including riparian wetlands). (see also **D.O. 77-1**)	None applicable. ***2006 Management Policies, continued:*** **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.	**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. ***continued in Regulations column***

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

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